Full set of replies to referee's and mark-up of changes for Monks et al. (acp-2014-881)

Reply to Referee #1

We are grateful to the referee for their comments and insights and recognising the substantial challenge in preparing this review.

This article represents a significant effort towards summarizing the state of knowledge regarding tropospheric ozone and its impacts. It is thematically comprehensive, and generally well-written. It suffers from some redundancies and hiccups typical of an article with so many contributing authors; I encourage the authors to pay particle attention to editing for this before final publication (some specific examples are included below).

My primary critique is that the article is quite Euro-centric, some sections more than others. Given the author affiliation and the association with the ACCENT project, this is not surprising, but needs to be addressed prior to publication. In present-form the article requires some caveat ("with a focus on Europe") in the title, abstract, and throughout the text. Alternatively, to accurately reflect the title and goals of the paper the authors need to address this issue on two fronts.

In revision, we have made strenuous attempts to meet this criticism head on! We have reviewed each section in order to ensure balance. There has been more explicit mention of N.American/Asian locations in some sections. On reflection, the failing, if any, maybe that some of the examples are from Europe and I think the perceived bias in references is influenced by this. Closer examination does not hold this to be true uniformly.

The first is including discussion of results from non-European projects. Two examples of this: in the context of biomass burning (4.2), there was no discussion of the ARCTAS project which provided significant insights into the role of boreal fires on atmospheric composition. Similarly the megacities section (4.1) made no reference to the MILAGRO campaign in Mexico City, a tremendously comprehensive megacity field campaign.

We have revised the text to add mention of the MILAGRO campaign, which was indeed an oversight on our part considering the amount of work published about Mexico City. References have been added where appropriate, e.g.:

P32764, L15-19: "Other megacities in which vehicles are cited as the top or among the top sources of ozone precursors are Cairo, Delhi, Istanbul, Los Angeles, New York, Mexico City, Sao Paulo, and the Ruhr-Rhein metropolitan region (Bon et al., 2011; Chelani, 2012; de Fatima et al., 2012; Parrish et al., 2011; Khoder, 2009; Im and Kanakidou, 2012; Melkonyan and Kuttler, 2012)."

as well as text:

P32765, L26 – 32766, L2: "The emissions from megacities also have an effect on the surrounding region. In many cases the urban areas have been identified to be VOC-limited, where high NOx concentrations in the cities suppress ozone concentrations (Im and Kanakidou, 2012; Tie et al., 2013). For example, a modeling study conducted in the context of the MILAGRO measurement campaign in Mexico City identified that reductions in VOC emissions led to decreases in maximum ozone concentrations while NOx emission reductions led to increased maximum ozone concentrations, demonstrating that the urban core of the Mexico City metropolitan area was VOC-limited – a conclusion supported by the in-situ measurements. The surrounding mountain/rural areas were

identified as mostly NOx-limited, although the range of these areas was meteorologically dependent (Song et al., 2010). This suppression of ozone by high NOx has been identified as generally more characteristic of extratropical megacities in the Northern Hemisphere (despite the Mexico City example), relative to tropical cities, because of differences in transport patterns."

Details of ARCTAS where already included in the Arctic section (Alvarado et al. (2010), Wespes et al (2010) and Singh et al (2010)), explicit mention of ARCTAS has been added. With respect to the biomass burning section, ARCTAS and a cross-link to the Arctic section has been added.

Section 4 is also poorly organized – it seems a grab bag of topics. Topics such as lightning (4.7) and biomass burning (4.2), halogens (4.4) appear to belong in Section 2.3 (precursors). I suggest a re-organization.

Following referee#2's advice an explanation as to the rationale for this assortment has been added to the text and it has been retitled.

Minor Comments

I include some additional minor comments below.

1. Overall: inconsistency of units; suggest using ppb throughout (and converting all references using ug/m3)

Done

2. Pg. 32712, lines 14-29: This content doesn't seem to fit particularly well in the introduction, and is a bit redundant with the review in section 2.1. I suggest merging this paragraph into that section. It is also worth noting that the end of this paragraph is a bit misleading as it could leave the reader with the impression that this debate is still alive.

Removed from introduction and merged with section 2.1

3. Pg 32714: The tropospheric ozone budget is quite precisely quantified here (3 significant figures on the burden!), but a discussion of uncertainty and variability in model budgets (beyond the regionality discussed in Figure 2) is lacking.

The uncertainty has been added as suggested to the budget terms here: STE 550+/-140 and burden 335+/-10 for the observationally-derived terms, and Dep 1000/-200 and Chem 450+/-300 for the model terms. Variability between models in the burden is of the order of 10%; interannual variability in a single model is far less (probably 5-10 Tg). The variability and uncertainty is discussed in the papers cited.

4. Section 2.1.1: It would be useful is the authors could include some discussion of the relevant timsescales of processes in this section.

A reference to typical timescales for reactive chemistry has been added.

5. Pg 32720, line 9: language needs to be corrected.

Section has been rewritten.

6. Section 2.1.2d: Obvious missing reference/discussion: Kurpius and Goldstein, GRL, 2003

Reference added

7. Page 32729 lines 26-30 & 32730 lines 1-3: Specify whether these are surface, profile or column concentrations

Clarified - surface concentrations.

8. Page 32731, lines 1-3: This list of factors should also include meteorology beyond transport (rain, radiation, temperature, etc), as well as changing surface cover (e.g. vegetation).

Text amended to reflect this.

9. Page 32733, lines 19-22: This sentence requires a reference – unclear if the citation from the previous sentence applies here.

Wilson et al, (2012) and Colette et al (2011) references added.

10. Page 32745, lines 15-17: Sindelarova et al. is not an appropriate reference here (an application, not the model description). MEGAN v2.1 also includes an algorithm for CO_2 inhibition of isoprene emissions.

Reference amended and text added

11. Page 32758, lines 16, 21: Remove the repetition of line 16 of line 21. The specific reference to rice is also odd, there are many more crops affected by ozone...a list of vegetation types affected and some references would be useful.

Removed odd sentence on rice and overhauled section to make it cover crops and vegetation affected by ozone.

"Typical ozone effects on plants include reduced growth, less seed production, lower functional leaf area and earlier leaf senescence. Data compilation studies have shown that many species of plants are sensitive to ozone, including: agricultural crops such as wheat, tomato, soybean and rice and salad crops such as lettuce, spinach and onion (Mills et al., 2007a); grassland species such as clover species, buttercup and harebell (Hayes et al., 2007, Mills et al., 2007b); and tree species such as beech, birch and Holm oak (Karlsson et al., 2007). These effects impact on the important ecosystem services provided by plants, including food security, carbon sequestration, timber production, and protection against soil erosion, avalanches and flooding."

12. Page 32760, line 2: Tai et al. show that climate reduced global yields by 11% (not > 20%)

Modified (10%)

13. Page 32762, line 8-9: What does "the fundamental processes involved" mean? Please elaborate.

Sentence added "For example, the radiative forcing from aerosols has a larger uncertainty because we are less sure of the changes in aerosol since the pre-industrial, both in terms of their magnitude and geographical distribution, but also because the aerosol forcing originates from changes in multiple different aerosol types, including mixtures of different aerosol species, with highly uncertain optical properties (Fuzzi et al., 2015)"

14. Page 32763, line 1-2: Needs reference.

Reference added (Zhu et al, 2012)

15. Page 32763, line 28: also domestic biofuel use?

Added

16. Page 32764: lines 25-29: needs a reference (particularly for the role that evaporative emissions played in this event)

Elansky et al. reference details this. New Zvyagintsev et al. reference added

17. Page 32770: lines 15-17: needs reference.

Section deleted as unpublished. Figure 30 changed to one from Parrington et al. (2013)

18. Section 4.3: This might also be a good place to note the potential impacts of biofuels on ozone concentrations, via changes to vegetation and BVOC emissions (e.g. Ashworth et al., 2012; Porter et al., 2012).

Sentence added on biofuels and ozone/AQ.

19. Section 4.5: This section does not seem to be particularly relevant to a review of tropospheric ozone. The key elements of the role of NOx have been discussed elsewhere.

The aim of this section was to demonstrate the wider linkages of ozone chemistry through Nr to the nitrogen cycle. The premise being that these are often treated in isolation.

20. Section 4.7: The basic chemistry described in this section is redundant with earlier descriptions of ozone formation. Please harmonize.

Chemistry in this section has been cut-down

21. Section 4.7: the discussion of how lightning relates to aerosols is not relevant to this review.

Removed and section restructured.

22. Page 32794, lines 1-11: In addition to several studies which show high methane leakage from fracking operations, the authors should note the Allen et al., PNAS, 2013 study which provides the counter-example of low measured leakage rates.

Added Allen reference and also recent PNAS Kang (2014) reference

23. Section 4.10: This section is quite long, and should be edited to re-focus on implications for ozone.

There has been much debate as to the effect on oxidation chemistry of the radical pathways detailed on section 4.10. The authors feel there is significant value in the section in full.

24. Page 32803, lines 20-25: A number of studies identified the role of intercontinental transport of ozone in ozone exceedances prior to the publication of the HTAP report in 2010. As written, this sentence is a bit misleading.

Changes made to remove incorrect implication.

25. Page 32805, lines 14-18: unclear what scenario this mortality reduction corresponds to – is this the result of reductions of European emissions only?

Yes, this only applies to European emission's. Text clarified.

26. Section 5.3, 5.2, and to some degree 5.1 need to be merged and redundancies eliminated.

These sections have been reviewed and there is some blurriness around the edges, they have been edited to drive greater self-consistency.

27. Section 5.4: Tai et al., GRL, 2013 recently showed the "climate penalty" has been substantially overestimated. The discussion should be modified in light of this.

Discussion modified to include "There is some debate as to the magnitude of any climate penalty e.g. Tai et al. (2013) indicates that in the presence of CO_2-isoprene interaction, the projected change in isoprene emission by 2050 will be largely offset or even reverse in sign, leading to much reduced sensitivity of ozone and SOA (by >50%) to climate and natural vegetation."

28. Page 32808, lines 14-16: It is not clear why emissions that were constructed for radiative forcing purposes would be inappropriate for air quality purposes. Please justify any concerns about quality of these emission inventories, and why they might therefore still be appropriate for climate projections.

We have aimed to clarify this point in the text, added two sentences to the referenced lines. The revised text now reads:

"Pioneering studies relied on projections originally designed for climate projections (SRES, Nakicenovic et al., 2000 or RCPs, van Vuuren et al., 2011), but the ozone precursor information in such scenarios was solely provided to assess radiative forcing and their use for surface air quality projections constitutes a deviation from their original purpose. The various scenarios make differing assumptions for future air pollution emissions and therefore, describe a wide range of future emissions over large world regions. Any downscaling in regions that exhibit large spatial heterogeneities could be problematic leading to inaccurate results (Amann et al., 2013). The use of emission projections relying on policy relevant emissions factors such as the Global Energy Assessment (Riahi et al., 2012), the ECLIPSE (Klimont et al., 2013a, b) or PEGASOS datasets are more reliable."

29. Page 32810, lines 10-22: duplication with Section 5.4.

While this is true, we have tried to make all sections self-contained and this is an important part of the AQ & CC discussion, as embedded in this forward look. My preference is to keep it.

Reply to Referee #2

This is a very interesting review paper. At first I was slightly daunted by its length, but it actually was a very easy and enjoyable read. It provides a very nice up-to-date review of what is a complex topic, simultaneously providing a good introduction to the subject, whilst exploring some of the latest research findings. I expect to use it as a recommended paper for my students (UGs and PGs).

I think the paper should be published subject to minor revisions.

We are grateful to the referee for the comments and insights on the paper. We have dealt with all the comments and list below (in brief) the changes made.

I though the title of the paper was rather cumbersome and not quick to understand. I would suggest something more concise.

The title has been chosen to reflect scales and roles of ozone.

Throughout the paper, but particularly towards the front, ensure that all acronyms and chemical formula are defined.

Noted and checked.

P. 32712, lines 26-30. I believe that the reference to Bloss et al (2005) refers to the high OH concentrations in the tropical lower troposphere rather than the greater ozone production from long-lived HCs there. As it stands, this is not clear. Whilst it is expected that there will be greater oxidation of the long-lived HCs in tropical lower troposphere, the production of ozone does rather depend on the amount of NOx present. Fig. 2 relates to this. Whilst the plots indicate high ozone production in the tropical lower troposphere, the non-linear scale for the legends tends to hide some of the variation at the higher rates. Note axes labels are missing from the upper panels.

The Bloss paper shows fraction of methane loss by atmospheric region which is referred to in the context of the highlighted sentence. We agree that ozone production is a combination with NOx availability as mentioned.

P. 32716, lines 21-23. “Considering : : :”. This is not a sentence.

Sentence rewritten.

P. 32717, lines 5-6. I suggest including a reference to Reaction R3, for example, for the regeneration of OH.

Added

P. 32717, lines 6-8. This says that production of O3 is shown schematically in Fig.
3. Although Fig. 3 was not what I had expected which was a figure that would show schematically the reactions involved in the formation of ozone. I think this would be a useful additional figure.

New figure 3 added for methane oxidation cycle.

P. 32717 discusses Fig 3 including the transition from point A to B and from point C to B. I also think it is useful to discuss moving from point A towards the origin and from point C towards the origin.

Text has been revised to highlight the points and the transitions in differing ozone formation/destruction regimes.

P. 32718, line 12, suggest “which can be readily”.

Done

P. 32718 discusses the impact of deposition in rural areas in such a way that it seems to suggest that deposition is not important in urban areas. Of course in urban areas there is the added impact of the NOx titration effect, but that doesn’t mean that deposition isn’t still an important ozone sink.

Having looked at this, we are not sure that we get the same inference from the text.

P. 32729, line 9. I didn’t fully understand what was meant by “by treating the vegetation to fully close stomata”. Please clarify.

This section of text has been rewritten.

Structure of section 2.1.2. This seemed a bit odd, with the end of section b introducing sections c, d and e, which all seemed to be sub-sections of b. Consider restructuring the headings.

These are all separate features of the uptake, though obviously interrelated. Sections kept as was.

P. 32722, line 14, suggest “deposition rates to water”

Done

Structure of section 2.1.3. I suggest giving the sub-headings letters a, b, etc. I also suggest perhaps separating stratospheric-tropospheric exchange and summer monsoons.
I don’t see the need for them to be together.

Separate section headings made and STE separated from seasonal transport patterns as suggested.

P. 32733, lines 14-18. “this behaviour”, which I take to be the decreasing trend in high percentiles is said to be in part due to increasing hemispheric ozone levels, but this would lead to reduced ozone. Please clarify.

Sentence modified to “This behaviour has been interpreted as resulting from the combined effect of regional pollution controls since 1990 (Vautard et al., 2006) and increasing hemispheric ozone levels (Derwent and Hjellbrekke, 2013)”.

P. 32734, line 6, “non-significance of the trends”. Urban or rural background?

Rural background added

Section 2.3.2 relates to “evolution” of emissions and yet, quite a lot of the text at the end of this section is on uncertainties, which might fit better in treh following section 2.3.3. in uncertainties.

We feel though while this might be correct, that the benefits from such a major reorganisation might be counterproductive.

P. 32738, line 5, suggest “among these inventories”.

Done

P. 32738, line 7, suggest “lowest and highest”.

Done

End of section 2.3.2.a is about shipping emissions. These do not seem to specifically relate to Europe or N. America, so I suggest some restructuring.

Section restructured and shipping pulled out as a separate section.

P. 32739 lines 21-22, suggest “For India, the range of values proposed by the different groups is even larger,: : :”

Done

P. 32739 line 26, suggest “Figures 7 and 10”

Done (with new Figure numbers)

P. 32740 line 13. When you say “deterioration” of emissions, do you actually mean “varying deterioration”?

Change made

P. 32740 line 21. “most countries”.

Deleted “the”

P. 32741 line 1. “on a few”.

Added “a”

P. 32741 line 6. “information on”.

Added “on”

P. 32741 line 8. “uncertainties in”.

Changed

P. 32741 line 20, says that Figure 14 also highlights the “growing” importance of emissions from Africa. It doesn’t actually highlight this as it only shows 2005 data. It does however show that in 2005, African emissions are comparable to emissions from other regions.

Referee is correct removed “growing”.

P. 32742 line 24-26. This is confusing as it says an example of “variability” is : : :: : :the “constant” high fire episodes.

Sentence rewritten

P. 32743 line 9. I would also suggest that Fig. 17 shows large differences for breal regions as well.

Agreed.

P. 32743 line 12. “limit in”.

“limit to the accuracy” is OK

P. 32743 line 29. “remain in”.

Done

P. 32744 line 6. “taken as constant”.

Done

P. 32744 lines 18-19. “fire plumes”.

Changed to from fires

P. 32744 line 23. “fire emissions”.

Done

P. 32746, line 11, suggest “lowest and highest”.

Done

P. 32747, line 16, should refer to Fig 21b not 22b.

Done

P. 32750, lines 8-9, suggest “during a 2 year period”.

Done

P. 32750, lines 13-15, I am not sure of the relevance of this within this section.

As this section deals with a climatological view, the impact of Saharan dust seemed to fit best here.

P. 32751, line 13, suggest “than would be”.

Deleted “what”

P. 32752, line 1, refers to Figure 26. As well as ozone, this figure includes PM10, which is not discussed in the text and is actually not relevant.

Agreed (as per referee#3) - PM10 is present owing to source of data, thought best not to doctor figure. The figure caption has been expanded to explain significance of result.

P. 32752, line 10, suggest “coupling at the”.

Left as is – two things can be a couple

P. 32752, line 20, “emission”.

Done

P. 32753, lines 22-24. It is not clear why there is an interim target and the “High Level” maximum daily mean (one being 40 ppb than the other). Please clarify.

These are nomenclature used by WHO to indicate high and significant health impacts from ozone. Text added to indicate this.

P. 32756, line 18. It would be helpful to provide the definition of SOMO here. It is given later on page 32801.

Cross referenced to section 5.

P. 32756, line 22. Surely this should be “calculated” increases in health effects?

Agreed and changed

P. 32757, lines 1-13. Again the comments here seem to refer to actual increases in ozone impacts depending on the choice of SOMO. Surely these should be calculated impacts.

Yes, these are indeed calculated impacts based on measurements and models.

P. 32758, lines 12-13. This could be defined as AOT40 as again this used later in the paper.

Added AOT40 and cross link to section 5.

Section 4 Topics. It is not clear to me why the various topics are ordered in the way they are. I would suggest ordering the topics something along the lines of emission sources, chemistry, specific regions, general topics (such as modelling and nitrogen cycle).

A new introduction has been added here to overview the selection of topics (as per referee #3).

P. 32763, lines 23, suggest “concentrations have been observed”.

Done

P. 32765, Up until now ozone levels have been given as mixing ratios. I realise that here they are given as mass densities because of the units of the thresholds, but I think it would be helpful to be consistent with the earlier text to give the values in mixing ratios (even if this means giving the values in both units).

Units have been standardised.

P. 32765, line 20. The 3 needs to be a subscript.

Done

P. 32765, line 22, suggest “avoided by such policies”.

OK, as is

P. 32765, line 24. What is meant by “small but substantial”?

It means low fractions which have large health impacts.

P. 32768, lines 3-4, “Tropical biomass burning dominates : : :”. It would be good to give the percentage contribution from this biomass to burning emissions to compare to boreal fires.

Page 32768, states in terms of carbon that only 9% is boreal, therefore 91% in tropical.

P. 32768, line 17. “boreal”.

done

P. 32768, line 21. “BORTAS was to”.

done

P. 32769, line 4. “drivers of the OPE”.

done

P. 32769, line 26. “algorithms”

done

P. 32769, line 29 – p. 32770, lines 1-3. I am confused by the comment that boreal fires emit products up to 10 km, and then the subsequent comments which limit emission to below 4 km. Please clarify.

Text modified to "Depending on the fire radiative power (FRP) and size of the fire, Freitas et al., (2007) have shown that plumes from fires are likely able to reach 10 km altitude. Based on a statistical analysis of 5 years of satellite observation by MISR over North America, Val Martin et al., (2010) have shown that the median altitude of plumes is found below 3 km altitude for boreal forest fires. A significant fraction (4-12%) of those plumes are thus injected above the boundary layer and are more spread-out vertically depending on the stability conditions. In comparison, tropical biomass burning plumes are mostly limited to the first km of the atmosphere."

P. 32770, line 16. “have a strong impact on meeting air : : :”.

Section removed owing to unpublished results.

P. 32770, line 17. “Figure 30”.

Figure changed

P. 32770, line 18. “July 2012 in the frame”

Removed

P. 32770, lines 23-24. “and given plume age : : :..pathway apparently).” I really don’t understand the point being made here. In fact I am really not very sure what message is trying to be conveyed with respect to Figure 30.

Removed

P. 32772, line 20. “of its key”.

Done

Section 4.4 Halogens, first paragraph. I would prefer to see the reactions given on separate lines rather than integrated within the text.

Done

P. 32777, line 20. “to O3”.

Done

P. 32777, line 28. “Bromine is twice as important as chlorine as an ozone sink”.

Done

P. 32782, lines 8 and 9. “reported for the tropics”.

Done

P. 32785, line 1. “At the continental”.

Done

P. 32786, line 8. “can be a significant”.

OK

P. 32787, lines 22-23. If the power is given for over the land, why not for over the ocean? Having said that, the rest of the paragraph suggest that other parameterisations may be better, so perhaps there is no need to give any values (i.e. remove the bit in brackets).

Done

P. 32798, line 16. What is the Advanced Light Source?

Added synchrotron - http://www-als.lbl.gov/

P. 32799, line 23. “in its excited”.

Done

P. 32802, line 2. “100s”.

Done

P. 32805, lines 2-5. “even if : : :. penalty”. This is confusing. Please clarify.

Sentence rewritten.

P. 32805, line 16. “deaths”.

Done

P. 32806, first paragraph. Comments relate to 20% emission changes. The emissions of exactly which chemical species were changed?

In all precursors

Section 5.4. Most of the material on page 32807 is about the science of the impact of climate change on ozone and it is not until the next page that this section really deals with the policy context, which is what section 5 is about.

Agreed, there are some blurry lines between these sections. It was aimed that one would look at policy and the second at the science of the situation.

P. 32808, line 9. “impacts”.

Done

P. 32812, last paragraph. I think it would be good to mention personal exposure monitors here.

References and a sentence added for personal exposure methods.

P. 32813, lines 3-6. It seems a bit odd to add this bit about the whitefly in the conclusions when it hasn’t been mentioned before.

The aim here was to give a broad perspective on future directions and new slightly left-field directions, hence the inclusion of the whitefly.

Throughout the paper, but particularly towards the front, ensure that all acronyms and chemical formula are defined.

644 Noted and reviewed throughout manuscript.
645
646 Be consistent with the use of upper case letters, particularly when referring the specific regions, e.g.
647 polar regions, boreal regions, tropics. Also stratosphere-troposphere exchange, chlorophyll, dissolved
648 organic matter, background ozone

649 Noted and reviewed throughout manuscript.
650
651 The text on a number of figures was rather small. Please make sure it is legible in the
652 final paper.
653
654 Noted
655
656 Fig. 4. Although the RC terms are defined in the text, none of the other terms are.
657 They should either explained in the text or figure caption.
658
659 Added link to nomenclature in text
660
661 Fig. 7. According to the figure headings some of these emissions are for the USA and
662 others for N. America. The caption should reflect this.
663
664 Figure redrawn to ensure consistency.
665
666 Fig. 8. “data for Canada”.
667
668 Done
669
670 Fig. 17. “see Fig. 17-1b” makes no sense.
671
672 Cross reference updated
673
674 Fig. 18. “of the mass”., “from Sofiev et al. (2013).”
675
676 Corrected
677
678 Fig. 21. In the caption please indicate for the fight hand panel whether “This study” is
679 a bottom up or top down study.
680
681 The "This study" from the Tohjima paper is a top-down estimate, figure amended.
682
683 Fig. 27. The two panels would be more comparable if they were both either daily maxima or annual
684 means.
685
686 This may well be true, but this is as they are published in the paper.
687
688 Fig. 29. Define MMM and T which are used in the title.
689
690 Done
691
692 Fig. 32. States that the values plotted are losses. However as the values are negative, they are
693 actually negative production terms. The x-axes labels are rather unclear.

The negative terms represent loss terms.

Fig. 35 need more explanation.

More commentary has been added to the figure legend.

Fig. 37. “emission increases”, “leakage rates”.

Done

I didn’t see Figure 39 referred to in the text.

Added

Reply to Referee #3

The authors have clearly invested much effort in compiling an interesting discussion on tropospheric ozone. The level of detail in the different sections, and even within sections, is not always well balanced, and the authors may wish to consider narrowing the scope in some places to ensure that the key messages are clearly distilled, with specific suggestions provided below. In general, it would be stronger if the authors can provide where possible a more critical assessment of the studies they are reviewing, or reconcile disparate findings. I generally agree with the major suggestions of the other reviewers.

We thank the referee for this comments and insights. We accept that the paper has inhomogeneities and have tried the upmost to harmonise them. The paper is substantial and in line with the other referee's wishes a more critical tone has been taken with respect to the outcomes of the review.

General comments

The abstract could be misleading by emphasizing the challenges of reducing surface level ozone without acknowledging the substantial improvements in air quality that have been achieved due to air pollution regulations; peak ozone pollution levels have responded to local and regional emission reductions. As an example: Simon, H., A. Reff, B. Wells, J. Xing and N. Frank (2014). "Ozone Trends Across the United States over a Period of Decreasing NOx and VOC Emissions." Environmental Science & Technology 49(1): 186-195. The comment on ozone as a short-lived climate pollutant is a slightly awkward in that the mitigation would involve the precursors, and the net impact on climate depends on which precursors are controlled. A stronger abstract would provide more specific conclusions, or possibly recommendations. For example, what is the knowledge across scales needed for addressing air quality and climate, and does it exist or remain to be generated?

The abstract has been rewritten to draw some conclusions in terms of what is required.

When prior reviews are mentioned, why not give a 1-2 sentence summary of their main conclusions (e.g., Monks et al. 2009 P32718 and throughout the text)?

This is quite challenging, as they do cover some breadth. Clear pointers have been added to text to signpost the elements that can be found in these reviews.

The level of detail given for deposition seems deeper than that provided for chemistry (some is later, but that's not obvious here). It would help to give a rationale for the relative attention given to these processes. The scope seems very broad for the seasonal transport patterns section, some of which might fit with the climate variability section, which also seems connected to discussion in 2.4.

New figures have been added to balance the chemistry section.

As per the suggestion of referee#2 and this referee the section on transport has been restructured to focus the seasonal transport questions.

Can anything be said in Section 2.3.3 about which regional emission inventories are most accurate in their representation of trends or total amount of emissions? Are there top-down constraints from satellites on in situ measurements that can distinguish between the various estimates? A recommendation would be very useful.

This would be a review in itself. There is an undoubted need for what you are asking. Some of this is covered in the framework on GEIA (http://www.geiacenter.org/), but there is a need for more critical evaluation.
Sections 3 and 5 might be best focused solely on Europe, but if the U.S.A. is discussed, it should be noted that the criteria for the ozone standard are reviewed periodically, and the most recent assessment was just completed, e.g. http://www.epa.gov/ncea/isa/

The links and context of the USA NAAQS ozone work has been added to the paper, as it provides needed wider context for the reader. Details have been added to section 3 and 5.

Section 4 should open with a rationale for why the selected topics are the most pressing ones to discuss here. A revised title, rather than "Topics", should also strive to convey their importance. Section 4.2 overlaps earlier discussion.

A rationale has been added and the section title changed to recent advances.

Agreed, there is a measure overlap, the aim of the earlier section is to look at emission inventories and the later one experimental evidence.

Specific comments:

p. 32712 The Intro here fails to communicate what the current paradigm is for what controls tropospheric ozone.

At the suggestion of referee#1 the introduction was restructured and this material moved to section 2.1. This has now been integrated to give a better overview of the required paradigm.

P32715. The phrasing of something well understood but remains a challenge seems a bit contradictory.

Agreed, added in practice to give the correct emphasis to the challenge.

P32718 L24-25. Is this specific to deposition? Might be worth illustrating how the diurnal variability varies with geographic location, at the surface vs. at altitude to emphasize the importance of multiple spatial scales mentioned in the abstract.

The climatological view of ozone is dealt with in section 2.4. There is clear merit in this idea, but it probably is beyond the scope of what can be achieved in this review.

P32721 L3. What does "positive and negative effects" mean here? Is deposition ever reversing and becoming a source?

Sentence modified to "For example, surface water has been found to both enhance and reduce deposition rates."

P32724. Can any conclusions be drawn here about the sign of the change of climate change on long-range transport?

HTAP (2010) says "Changes in climate will affect meteorological transport processes as well as the chemical environment and lifetime of the transported pollutants and hence the concentrations of pollutants arriving at downwind continents." Of the papers mentioned Glotfelty et al (2014) suggest

a larger impact on the US from East Asian Emissions and Doherty et al (2013) showed stronger chemistry than transport positive climate feedbacks on ozone. This has been added to text.

P32727. 30-year periods may yet be a bit short for screening out the influence of low frequency climate variability (e.g., PDO, AMO)?

The following sentence can be added to the end of line 13 on page 32727

"The influence on ozone of low frequency climate variability on time scales longer than 30 years has not yet been assessed due to continuous ozone data sets being limited to durations shorter than 30-40 years."

P32732. What other factors could be at play besides those put forth in the Parrish et al. "untested hypothesis"? Might the question be better posed as quantifying the relative importance of these factors at the individual locations of the measurements?

The purpose of Section 2.2 is merely to give a brief history of changes in tropospheric ozone. The Parrish et al. study gives very recent insight into current and developing research on ozone changes. Mentioning their hypothesis allows the reader to understand where research on this topic might head in the future, but in this particular section we don't want to further this discussion by adding our own hypotheses on top of those of Parrish et al.

A related point is on P32735, another possibility is that the measurements may reflect natural climate variability internal to the climate system that a climate model would not represent.

This is a valid point and we now mention this possibility in lines 3-6 on page 32735. "These differences may reflect poor representation of emission changes or ozone changes due to natural sources, or they may reflect more fundamental weaknesses in resolving key chemical or dynamical processes or climate variability over continental regions."

P32733. Shifting seasonal cycles over the U.S.A. have recently been discussed by:

Simon, H., A. Reff, B. Wells, J. Xing and N. Frank (2014). "Ozone Trends Across the United States over a Period of Decreasing NOx and VOC Emissions." Environmental Science & Technology 49(1): 186-195.

Bloomer, B. J., K. Y. Vinnikov and R. R. Dickerson (2010). "Changes in seasonal and diurnal cycles of ozone and temperature in the eastern U.S." Atmospheric Environment 44: 2543-2551.

Clifton, O. E., A. M. Fiore, G. Correa, L. W. Horowitz and V. Naik (2014). "Twentyfirst century reversal of the surface ozone seasonal cycle over the northeastern United States." Geophysical Research Letters 41(20): 2014GL061378.

This advice is most useful and the references have been added to the discussion on shifting seasonal cycles.

P32471 L20. How does Figure 14 show growth of emissions? The caption suggests that we are only shown 2005 here?

Text has been changed (as per referee#2) to note magnitudes rather than “growth”

P32749. Some explanation for why the global satellite data do not provide a complete picture would be useful. It might be worth noting that there are direct tropospheric ozone retrievals, e.g.: Liu, X., et al. (2006), First directly retrieved global distribution of tropospheric column ozone from GOME: Comparison with the GEOS-CHEM model, J. Geophys. Res., 111, D02308, doi:10.1029/2005JD006564.

The section is dealing with ozone at a climatological scale. Details of the Liu et al reference has been added but a longer discourse on satellite ozone seems to detailed within this context. References are present to guide reader on this topic.

P32762. The scientifically dubious statement seems overly strong, since it is only fairly recently that computer models have included stratospheric and tropospheric ozone chemistry to enable a combined estimate of RF from ozone.

This has been changed to “fraught”.

P32767 “surprisingly small”. If one considers the lower ozone production efficiency in urban plumes, is this so surprising?

Removed surprising, it is often a truism as to what one finds “surprising”.

P32773 “factor of five difference”. Are these models all using state-of-the-art isoprene oxidation schemes? This reference may also be relevant: Ito, A., S. Sillman, and J. E. Penner (2009), Global chemical transport model study of ozone response to changes in chemical kinetics and biogenic volatile organic compounds emissions due to increasing temperatures: Sensitivities to isoprene nitrate chemistry and grid resolution, J. Geophys. Res., 114, D09301, doi:10.1029/2008JD011254. How certain is the temperature-driven increase in biogenic emissions in light of CO2-driven suppression?

This is a good question, a recent paper by Squire et al, (ACP, 2015) has highlighted this as an issue. A comment has been added to this section. The Ito work was already discussed in this section.

P32803. How important are plumes from one continent to the next versus diffuse background such as resulting from global methane and NOx?

The best answer to this questions is given in HTAP (2010) - Part D 'Answers to Policy-Relevant Science Questions'
(http://www.htap.org/publications/2010_report/2010_Final_Report/HTAP%202010%20Part%20D%20110407.pdf)

"To quantify the relative importance of emission changes outside each of these regions, as compared to emission changes inside each of these regions, we defined the Relative Annual Intercontinental Response (RAIR) metric. RAIR is defined as the sum of the changes in the annual, regionally-averaged concentration within a region due to a 20% decrease in emissions in the three other regions divided by the sum of the changes in concentration within a region due to a 20% decrease in emissions in all four regions. The value of the metric ranges from 0%, indicating no intercontinental influence, up to 100%, indicating that air quality in a region is completely dominated by intercontinental sources."

For O_3, Table 3.1 of HTAP (2010) gives RAIR values for North America (32%), Europe (43%), East Asia (40%) and South Asia (32%).

Therefore, the diffuse impacts are generally assumed to dominate; additionally enhanced plumes do occur but make a relatively small contribution on the whole, depending on receptor location and meteorology.

P32805. The U.S. context seems out of place since the previous discussion was on future climate change impacts versus emission changes. There have been several U.S. studies on that topic and reviewing those seems more appropriate here.

The section referred to deals with the "background" ozone contribution to the future ozone exceedances which is both an issue in the literature for the US and Europe. In the main this details current observations and model attributions of this.

P32808. Not all projections assume air pollution declines. See for example Prather, M., M. Gauss, T. Berntsen, I. Isaksen, J. Sundet, I. Bey, G. Brasseur, F. Dentener, R. Derwent, D. Stevenson, L. Grenfell, D. Hauglustaine, L. Horowitz, D. Jacob, L. Mickley, M. Lawrence, R. von Kuhlmann, J.-F. Muller, G. Pitari, H. Rogers, M. Johnson, J. Pyle, K. Law, M. van Weele and O. Wild (2003). "Fresh air in the 21st century?" Geophysical Research Letters 30(2): 1100.

Reference and discussion added on future directions.

P32809. Why is IPCC 2007 cited rather than 2013?

Reference updated and changed to chapter lead.

The conclusions section reads more as a continuation of discussion, including mentioning tomato volatiles, which doesn't seem to fit. Seems better to focus on robust conclusions that can be drawn from the studies reviewed in the paper, or provide recommendations for tackling some of the challenges outlined on P32811.

In the conclusions, an attempt to summarise in brief the position but also look to the future as to what some of the new avenues and challenges might be. In some senses the challenge as to the robust conclusions of this paper is a fair one and a few summary sentences have been added.

The number of figures could probably be reduced, and it would help if figure captions could communicate the relevance of the figure to our understanding of tropospheric ozone. For example, why is PM10 (Fig 26), the nitrogen cascade (Fig 33), methane from fracking (as opposed to other sources; Fig 37), RO2 isomerisation to QOOH (Fig 38) highlighted here?

Given the length of the paper, the authors did not feel there was an overabundance of figures. It is fair that the captions could be sharper, and they have all been reviewed to more give the relevance as requested. In particular

Figure 27 (old 26) – PM10 is present owing to source of data. The figure caption has been expanded to explain significance of result.

Figure 34 (old 33) – more commentary on nitrogen sources and ozone added to caption

Figure 38 (old 37) – shown as dramatic example of methane emissions. Text details other work on NMVOC emissions from fracking.

Figure 39 (old 38) – is to help the reader with the chemistry.

Figure 2. Why not use the more recent ACCMIP models?

Figure 2 is a good representation to match the text. There is good referencing to the ACCMIP models.

Fig 3. What is assumed here for BVOC? How sensitive is this picture to assumptions in the UKCA mechanism? Why is this referred to as a 'schematic' in the text (p 32717)? Please explain the significance of A/B/C labels in the caption.

It is not schematic – text changed.

A/B/C –added caption

As mentioned earlier the Squire et al (2015) reference has been added to the text that explicitly deals with this good point.

Fig 7. Can the same colors or symbols be used for the same inventories across the different panels?

Figure redrawn and colours and symbols matched.

Fig 11. What are LDGVs? What are "real driving conditions"? How important are these differences to the ozone distributions?

Caption amended to explain these are light-duty good vehicles under real world driving conditions rather than test-cycle. In relationship to the importance, in the UK it has been shown that the failure of these standards on the older vehicles has impacted measured NO_2.

Fig 13. Is this the best estimate, or the only available one? How does this differ in other world regions?

Figure 13 is an example (as it says in text). Caption has been expanded to include key point re. VOC speciation.

Fig 18. Is there a diurnal cycle in the fire emissions, and if so, how does that combine with the injection height variation in terms of the impact on tropospheric ozone?

There is indeed a study of the diurnal variation of the fires injection height in the Sofiev et al. paper. They indicate for example: "Diurnal variation of the injection height is huge: one can practically consider two independent datasets – one for daytime and one for nighttime, with transition during morning and evening." This has been added to the text.

Fig 41. Is this deemed by the authors to be the best approach to attributing ozone?
There are numerous studies attempting to do so over the USA and elsewhere.

Figure 42 (old 41) is illustrative of an ozone measurement system. There is no implicit endorsement as to the approach.

Table 2. How were these megacities selected? It's hard to know what to take away with the different statistics being used for comparison.

The megacities in the table were selected based on data that was available from peer-reviewed papers or otherwise reliable sources, for a somewhat longer time period (so as to not present ozone episodes), while still trying to present a geographic mix of locations. A table with comparable data (e.g., annual average hourly data or daily 8hr maximums) could have been created, however this then limits the data to one world region, as truly comparable data would likely only be possible for Europe or the US. Global comparisons of ozone data definitely exist, but tend to focus on rural sites, and not urban areas. The aim was to give an impression of O_3 values in megacities that do not represent extreme episodes.

Does Table 3 repeat information in Figure 40?

Table 3 is more complete than Figure 41 (old Figure 40)

Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer.

P.S. Monks,[1] A.T. Archibald,[2] A. Colette,[3] O. Cooper,[4] M. Coyle,[5] R. Derwent,[6] D. Fowler,[5] C. Granier,[4,7,8] K.S. Law,[8] G.E. Mills,[9] D.S. Stevenson,[9,10] O. Tarasova,[10,11] V. ~~Thouret~~[11],Thouret,[12] E. von Schneidermesser,[12,13] R. Sommariva,[1] O.~~Wild~~[13] Wild[14] and M.L. ~~Williams~~[14]Williams[15]

[1]Department of Chemistry, University of Leicester, Leicester, LE1 7RH, UK.

[2]NCAS-Climate, Department of Chemistry, University of Cambridge, Cambridge, CB1 1EW, UK

[3]INERIS, National Institute for Industrial Environment and Risks, Verneuil-en-Halatte, France

[4]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado, USA.

[5]NERC Centre for Ecology and Hydrology, Penicuik, Edinburgh, EH26 0QB, UK.

[6]rdscientific, Newbury, Berkshire, RG14 6LH, UK.

[7]NOAA Earth System Research Laboratory, Chemical Sciences Division, Boulder, CO, USA

[8] Sorbonne Universités, UPMC Univ. Paris 06; Université Versailles St-Quentin; CNRS/INSU, LATMOS-IPSL, Paris, France

[9]~~School~~[9]NERC Centre for Ecology and Hydrology, Environment Centre Wales, Deiniol Road, Bangor, LL57 2UW, UK

[10]School of GeoSciences, The University of Edinburgh, EH9 3JN, UK.

[10]~~WMO~~[11]WMO, Geneva, Switzerland.

[11]~~Laboratoire~~[12]Laboratoire d'Aérologie (CNRS and Université Paul Sabatier), Toulouse, France.

[12]~~Institute~~[13]Institute for Advanced Sustainability Studies, Potsdam, Germany.

[13]~~Lancaster~~[14]Lancaster Environment Centre, Lancaster University, LA1 4VQ, UK

[14]~~MRC~~[15]MRC-PHE Centre for Environment and Health, Kings College London, 150 Stamford Street, London SE1 9NH, UK.

Formatted: Tab stops: 10.99 cm, Left

Abstract

Ozone holds a certain fascination in atmospheric science. It is ubiquitous in the atmosphere, central to tropospheric oxidation chemistry, yet harmful to human and ecosystem health as well as being an important greenhouse gas. It is not emitted into the atmosphere but is a by-product of the very oxidation chemistry it largely initiates. Much effort is focussed on the reduction of surface levels of ozone owing to its health and vegetation impacts but recent efforts to achieve reductions in exposure at a country scale have proved difficult to achieve ~~due~~owing to increases in background ozone at the zonal hemispheric scale. There is also a growing realisation that the role of ozone as a short-lived climate pollutant could be important in integrated air quality climate-change mitigation. This review examines current understanding of the processes regulating tropospheric ozone at global to local scales from both measurements and models. It takes the view that knowledge across the scales is important for dealing with air quality and climate change in a synergistic manner. The review shows that there remain a number of clear challenges for ozone such as explaining surface trends, incorporating new chemical understanding, ozone-climate coupling as well as a better assessment of impacts. There is a clear and present need to treat ozone across the range of scales, a transboundary issue, but with an emphasis on the hemispheric scales. New observational opportunities are offered both by satellites and small sensors that bridge the scales.

Contents

1. Introduction

Ozone is central to the chemistry of the troposphere owing to its role in the initiation of photochemical oxidation processes *via* direct reaction, photolysis and the subsequent reactions of the photoproducts to form the hydroxyl radical ~~(Monks, 2005)~~(Monks, 2005). Tropospheric ozone is also recognised to be a threat to human health (WHO, 2003;Lim et al., 2012), to have a deleterious impact on vegetation ~~(WHO, 2003;Lim et al., 2012)~~(Fowler et al., 2009)~~, to have a deleterious impact on vegetation (Fowler et al., 2009) and, through plant damage it impedes the uptake of carbon into the biosphere (Sitch et al., 2007). It is also an important tropospheric greenhouse gas~~ and, through plant damage it impedes the uptake of carbon into the biosphere (Sitch et al., 2007) as well as impacting built infrastructure (Kumar and Imam, 2013). It is also an important tropospheric greenhouse gas ~~(IPCC, 2007;Stevenson et al., 2013)~~(IPCC, 2007;Stevenson et al., 2013) and is referred to as a short-lived climate pollutant ~~(Shindell et al., 2012)~~(Shindell et al., 2012).

Ozone-related deaths are estimated to make up about 5-20% of all those related to air pollution e.g. ~~(Silva et al., 2013;Anenberg et al., 2009;Lim et al., 2012;Brauer et al., 2012)~~(Silva et al., 2013;Anenberg et al., 2009;Lim et al., 2012;Brauer et al., 2012). The OECD ~~(OECD, 2012)~~(OECD, 2012) have stated that "without new policies, by 2050, air pollution is set to become the world's top environmental cause of premature mortality." The report goes on to state that "Because of their ageing and urbanised populations, OECD countries are likely to have one of the highest premature death rates from ground-level ozone".

While ozone has a relatively short atmospheric lifetime, typically hours, in polluted urban regions where concentrations of its precursors are high, its lifetime in the free troposphere is of the order of several weeks ~~(Stevenson et al., 2006;Young et al., 2013)~~(Stevenson et al., 2006;Young et al., 2013), sufficiently long for it to be transported over intercontinental scales. Thus in addition to its role as a priority pollutant on an urban scale, it may influence air quality on a hemispheric scale ~~(Akimoto, 2003;HTAP, 2010).~~(Akimoto, 2003;HTAP, 2010). There is little doubt that ozone is a multifarious molecule. Recently, Simpson et al ~~(Simpson et al., 2014)~~(Simpson et al., 2014) described ozone as the "persistent menace~~.~~". Figure 1 shows some of the key interactions that drive ozone concentrations in the troposphere and some of the feedbacks.

~~Historically, tropospheric ozone was thought to be rather unimportant in atmospheric chemistry terms, being controlled by its main source in the stratosphere and subsequently transported by synoptic scale subsidence and turbulent mixing to the surface, where it is destroyed (Junge, 1962). If tropospheric ozone photochemistry was important at all, then this was limited to highly polluted locations such as to the Los Angeles basin (Leighton, 1961). On this basis, long-range transport appeared to be the dominant process with the tropospheric ozone budget controlled by stratosphere-troposphere exchange and surface destruction. The spring-time ozone maximum which occurred simultaneously with the annual influx of radioactive tracers from the stratosphere, confirmed the importance of transport processes. Crutzen (Crutzen, 1973) proposed the contrary position that photochemical ozone production involving hydrocarbons and oxides of nitrogen may take place throughout the unpolluted troposphere. Furthermore, Chameides and Walker (Chameides and Walker, 1973) suggested that ozone in the lower troposphere was entirely controlled by atmospheric chemistry. These latter suggestions were strongly contested (Chatfield and Harrison,~~

~~1976;Fabian and Pruchniewicz, 1977) and have been the subject of much debate over the intervening years (Monks, 2000).~~

This review examines current understanding of the processes regulating tropospheric ozone at global to local scales from both measurements and models. It takes the view that knowledge across the scales is important for dealing with air quality and climate change in a synergistic manner. It would be a herculean task to review all the literature on ozone, therefore much of the focus of this review is on the recent findings and discoveries relating to tropospheric ozone. It builds on earlier integrative reviews such as Brasseur et al ~~(Brasseur et al., 2003)~~(Brasseur et al., 2003) and the ACCENT reviews ~~(Fowler et al., 2009;Isaksen et al., 2009;Monks et al., 2009;Laj et al., 2009)~~(Fowler et al., 2009;Isaksen et al., 2009;Monks et al., 2009;Laj et al., 2009).

The review has four major sections. The first reviews the control of ozone across the scales, looking at the interplay of chemistry, transport and deposition, and includes a brief climatological picture of ozone. The second major section details the major impact of ozone with respect to health, ecosystems and climate, while the third section highlights several current topics in relation to ozone in the troposphere. The final section briefly overviews some of the policy context and issues in relation to tropospheric ozone. In the conclusion, some future directions and issues with relation to ozone are discussed.

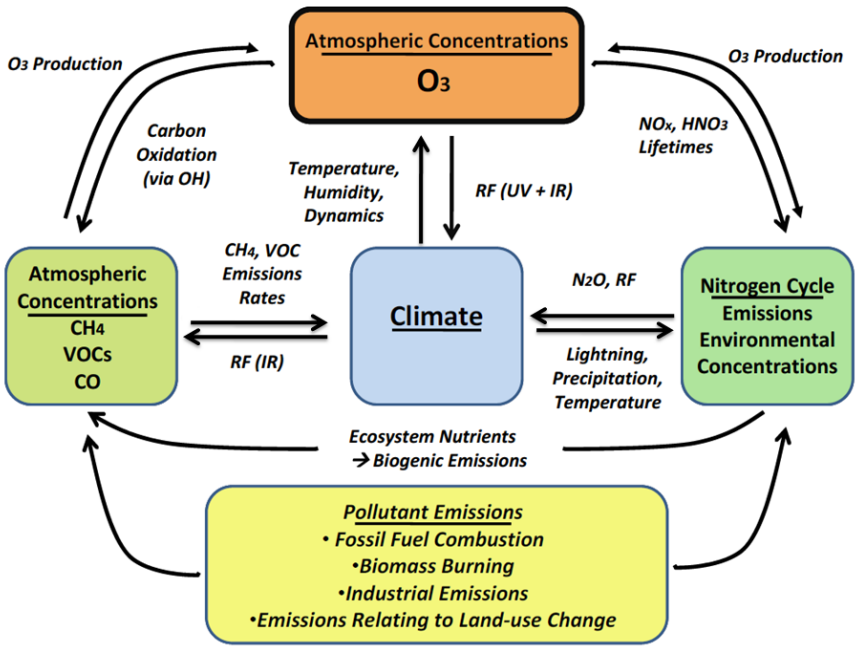


Figure 1 – Schematic representation of the interactions of ozone in the earth system ~~(EPA, 2009)~~(EPA, 2009).

2 Ozone – control, precursors and climatology

2.1 What controls ozone?

The annual variation in ozone concentration at any given spatial scale depends on a number of factors, such as the proximity to large sources of ozone precursors, geographical location and the prevailing meteorological conditions ~~(Logan, 1985)~~(Logan, 1985). The tropospheric ozone budget at a given location is dependent on both photochemical processes and physical processes, including photochemical production and destruction of ozone, transport from upwind sources and removal at the Earth's surface ~~(Monks, 2000;Lelieveld and Dentener, 2000)~~(Monks, 2000;Lelieveld and Dentener, 2000).

Given the substantial stratospheric ozone concentrations, transport from the stratosphere was long thought to be the dominant source of ozone in the troposphere ~~(Danielsen, 1968;Junge, 1962;Fabian and Pruchniewicz, 1977)~~(Danielsen, 1968;Junge, 1962;Fabian and Pruchniewicz, 1977;Chatfield and Harrison, 1976). Photochemical mechanisms for the generation of ozone were first identified in work carried out in California in the 1950s ~~(Haagen-Smit, 1952)~~(Haagen-Smit, 1952) and until the 1970's high ozone was thought to be a local phenomenon associated with air pollution~~.~~ (Leighton, 1961). Early in the 1970's Crutzen ~~(Crutzen, 1973)~~(Crutzen, 1973) and Chameides and Walker ~~(Chameides and Walker, 1973)~~(Chameides and Walker, 1973) suggested that tropospheric ozone originated mainly from production within the troposphere by photochemical oxidation of CO and hydrocarbons catalysed by HO_x and NO_x. Since then, improved understanding of the importance of both natural and anthropogenic sources of ozone precursors has highlighted the dominance of this ozone source, and recent model assessments suggest that chemical production contributes about 5000 Tg/yr to global tropospheric ozone ~~(Stevenson et al., 2006;Young et al., 2013)~~(Stevenson et al., 2006;Young et al., 2013). In contrast, the net global source of ozone from stratosphere-troposphere exchange (STE) is estimated to be about 550±140 Tg/yr based on observational constraints ~~(Olson et al., 2001;McLinden et al., 2000)~~(Olson et al., 2001;McLinden et al., 2000). The removal of ozone through dry deposition to vegetation and other surfaces at ground level remains poorly constrained on the global scale, although model assessments driven by observed ecosystem fluxes, vegetation types and meteorology suggest net removal of about 1000±200 Tg/yr ~~(Stevenson et al., 2006)~~(Stevenson et al., 2006). Balancing the global tropospheric ozone budget therefore requires that there is net chemical production of about 450±300 Tg/yr ~~(Stevenson et al., 2006)~~(Stevenson et al., 2006). Note that this term is constrained by the estimated STE and deposition terms and by the global tropospheric ozone burden of about 335±10 Tg, and that uncertainty in the absolute magnitude of gross ozone chemical production and destruction remains relatively large ~~(Wild, 2007)~~(Wild, 2007;Wu et al., 2007).

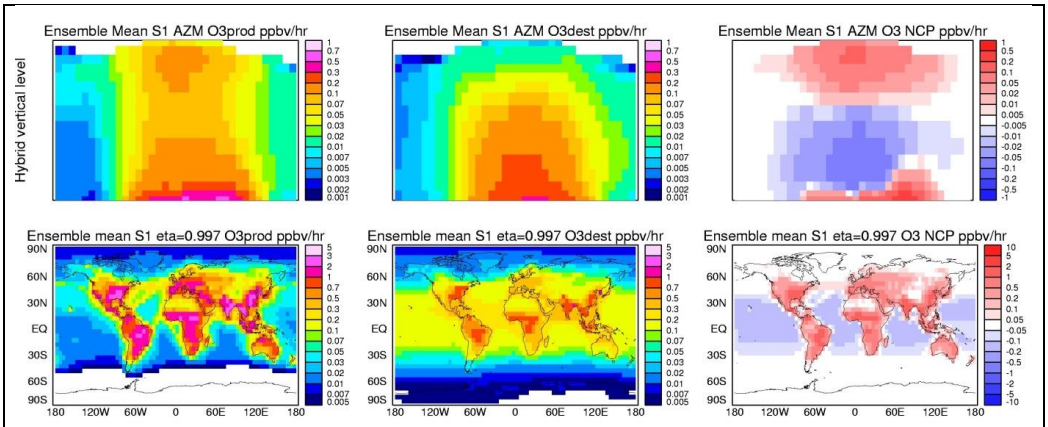


Figure 2 - Multi-model mean (20 models) year 2000 ozone budgets (units: ppb/hr). Top row: annual zonal mean (AZM) chemical production; chemical destruction; net chemical production. Vertical scale is from surface to approximately 100 hPa. Bottom row: maps of same quantities in the surface model layer ~~(Stevenson et al., 2006)~~(Stevenson et al., 2006).

These global budgets mask substantial regional variation (see Figure 2) which spans the wide range of chemical environments present in the troposphere. Troposphere-wide chemical production of ozone from long-lived hydrocarbons such as methane is greatest in the tropical lower troposphere where OH radical concentrations are high ~~(Bloss et al., 2005)~~(Bloss et al., 2005)~~,~~ and in continental regions and parts of the free troposphere with fresh NOx emissions. Chemical destruction of ozone is largest in the lower troposphere where water vapour concentrations are high and in highly polluted regions where there is direct removal by reaction with NO. This latter condition is commonly referred to as chemical titration of ozone, and is typically short-lived as the NO_2 formed subsequently catalyses further ozone formation once it has been transported into cleaner environments. Localised halogen-catalysed ozone destruction may also affect surface ozone in ~~polar~~Polar-regions during spring time (see Halogens section). Consequently, net chemical production occurs over most of the continental boundary layer where precursor concentrations are high and in the upper troposphere, where destruction is slow ~~(Wild and Palmer, 2008;von Kuhlmann et al., 2003b, a).~~(Wild and Palmer, 2008;von Kuhlmann et al., 2003b, a). Net chemical destruction occurs in the mid-troposphere and marine boundary layer where precursor concentrations are low and in localised urban and Polar Regions under *titration* (*via* reaction with NO) and halogen destruction conditions, respectively. Despite large changes in the emissions of ozone precursors and in net chemical production, the general location of these net production and loss regimes is thought to have changed little since preindustrial times ~~(Wild and Palmer, 2008)~~(Wild and Palmer, 2008). However, spatial heterogeneity of anthropogenic precursor emissions and of biogenic hydrocarbons ~~(Zare et al., 2014)~~(Zare et al., 2014), along with strong diurnal variability in chemical processes, deposition and meteorology, suggests that local ozone production and loss regimes in the boundary layer may be much more diverse than indicated by these coarse, regional-scale assessments.

2.1.1 Role of Chemistry

The basic chemistry that leads to the production and destruction of ozone has been detailed elsewhere ~~(Monks, 2005;Ehhalt, 1999;Jenkin and Clemitshaw, 2000)~~(Monks, 2005;Ehhalt, 1999;Jenkin and Clemitshaw, 2000). Ozone (O_3) photochemical production in the troposphere occurs by hydroxyl radical oxidation of carbon monoxide (CO), methane (CH_4), and non-methane hydrocarbons (generally referred to as NMHC) in the presence of nitrogen oxides (NO_x). The mechanism of ozone formation in the troposphere, although very well understood, remains a challenge ~~that will, no doubt, require many more years of research to fully unravel.~~in practice that will, no doubt, require many more years of research to fully unravel. Typical photochemical timescales in the atmosphere are quite short (in the order of seconds to tens of minutes) (Seinfeld and Pandis, 2006). In brief, the production of ozone in the troposphere relies, fundamentally, on the photolysis of NO_2 (reaction ~~1~~R1) and the subsequent association of the photoproduct $O(^3P)$ (the ground electronic state oxygen atom) with O_2 *via* reaction 2 through a termolecular reaction with a third body (M being used to represent any third co-reactant i.e. N_2):

$$NO_2 + hv \rightarrow NO + O(^3P) \quad (~~1~~R1)$$

$$O(^3P) + O_2 + M \rightarrow O_3 + M \quad (~~2~~R2)$$

The difficulty with understanding the production of O_3 in the troposphere comes about through the manifold ways in which NO and NO_2 are interconverted. The rapid interconversion between the two compounds allows them to be treated as a chemical family – NO_x. (NB photolysis of NO_2 is fast, and approximately altitude independent – ~~J_1~~$j_1 \approx 10^{-2}$ s^{-1}). For example, the reactions

$$HO_2 + NO \rightarrow NO_2 + OH \quad (~~3~~R3)$$

$$O_3 + NO \rightarrow NO_2 + O_2, \quad (~~4~~R4)$$

both convert NO into NO_2. Considering reactions 1,2 and 4 one can derive a ratio of $[NO]/[NO_2]$ that depends on the local concentration of O_3 and the rate coefficients for reaction (4) and the photolysis frequency for reaction (1) (at the surface the pseudo first order rate constant k_2' ($k_2*[O_2]*[M]$) is sufficiently fast that it is not a rate limiting step). This ratio is termed the Leighton ratio ~~(Leighton, 1961)~~(Leighton, 1961) and also allows for an expression to be derived for the equilibrium concentration of O_3. Whilst this chemistry is important, particularly in urban areas, it does not represent a mechanism for the net production of O_3 in the troposphere. ~~Considering~~With the addition of volatile organic compounds, such as CO~~:~~ *viz*

$$CO + OH (+O_2) \rightarrow CO_2 + HO_2 \quad (~~5~~R5)$$

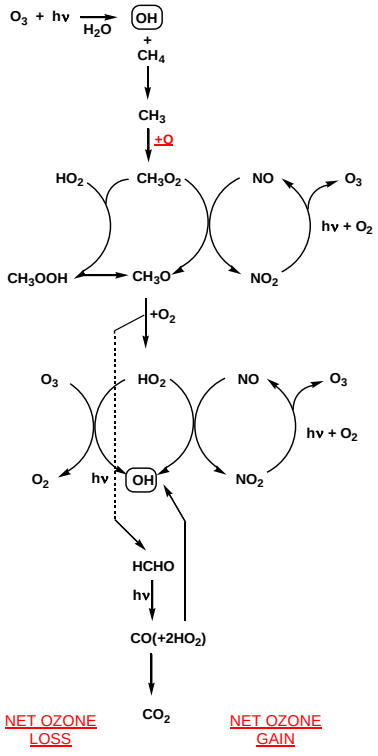
~~We are able~~It is possible to write a mechanism for the formation of O_3 that is propagated *via* VOC (Volatile Organic Compound) and NO_x (reactions (5), (3), (2) and (1)). In this series of reactions O_3 is used as a source of the hydroxyl radical (OH) through:

$$O_3 + hv \rightarrow O(^1D) + O_2 \quad (~~6~~R6)$$

$$O(^1D) + H_2O \rightarrow OH + OH, \quad (~~7~~R7)$$

where $O(^1D)$ is the electronic excited state atomic oxygen formed through photolysis at wavelengths <320 nm. However, the presence of VOC (CO) and NO_x, allow OH to be regenerated (R3) and promote formation of O_3 through NO_2 photolysis. The production of O_3 in the troposphere, mediated

through the reactions involving VOC (CH_4) and NO_x can be shown schematically in Figure 3~~:~~ and in relationship to changing precursor concentrations in Figure 4.



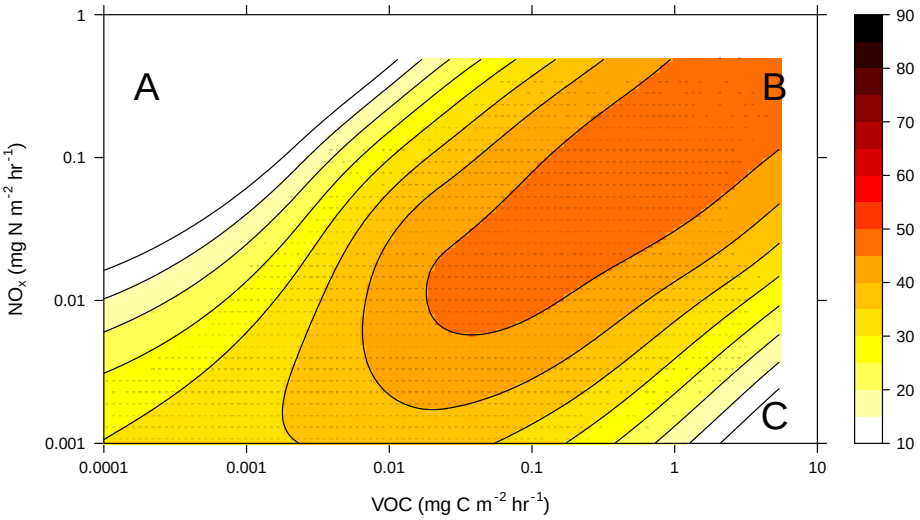


Figure 3 - O_3 mixing ratios (ppb) as a function of VOC and NOx emissions as computed using the UKCA model of atmospheric chemistry (Archibald et al., 2011). Three main regions are identified. Top

~~left corner: region of NOx saturation and O_3 titration. Bottom right corner: region of VOC saturation and O_3 destruction. Diagonal elements: efficient conversion of NO-NO_2 and hence O_3 production increasing with increasing VOC and NOx emissions (NB log_{10} scales for emissions).~~ **Figure 3** - Simplified mechanism for the photochemical oxidation of CH_4 in the troposphere (Lightfoot et al., 1992)

Formatted: French (France)

~~Figure 3~~

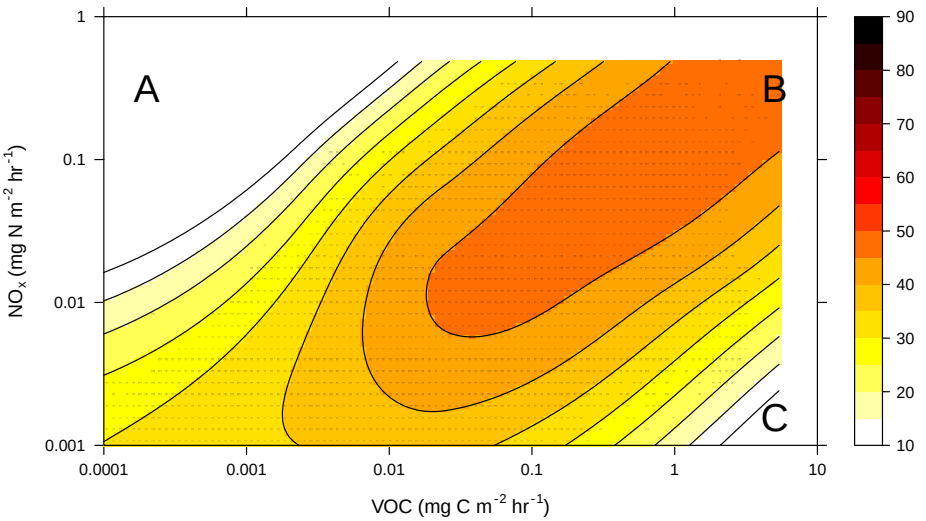


Figure 4 - O_3 mixing ratios (ppb) as a function of VOC and NOx emissions as computed using the UKCA model of atmospheric chemistry (Archibald et al., 2011). Three main regions are identified. Top left corner (A): region of NOx saturation and O_3 titration. Bottom right corner (C): region of VOC saturation and O_3 destruction. Diagonal elements (A-C, B-C): efficient conversion of NO-NO_2 and hence O_3 production increasing with increasing VOC and NOx emissions (NB log_{10} scales for emissions).

Figure 4 highlights the non-linearity of the O_3-VOC-NO_x system. The O_3 mixing ratios presented in Figure ~~3~~4 are generated from ~~photo-chemical~~photochemical modelling output generated using the UKCA model ~~(O'Connor et al., 2014;Archibald et al., 2011)~~(O'Connor et al., 2014;Archibald et al., 2011). Regions in Figure ~~3~~4 where there is net O_3 destruction (top left (A) and bottom right corners~~)~~ (C)) are typically referred to as the VOC limited and NO_x limited regimes. VOC limited refers to the fact that the production of O_3 is limited by the input of VOC (see e.g. ~~(Zhou et al., 2014)~~(Zhou et al.,

2014)). This can be rationalized by moving from point A to point B along a line of constant NO_x emissions and increasing VOC emissions. Moving in this direction it is evident from Figure ~~3~~4 that O_3 production increases. A similar case applies for the NO_x limited regime where this time moving from point C to point B requires increasing NO_x emissions and results in increasing O_3 mixing ratios.

This general mechanism of OH initiated O_3 formation can be extended to more complex VOC such as alkanes:

$$C_2H_6 + OH + O_2 \rightarrow C_2H_5O_2 + H_2O \qquad (~~8~~R8)$$

$$C_2H_5O_2 + NO \rightarrow C_2H_5O + NO_2 \qquad (~~9~~R9)$$

Where $C_2H_5O_2$ represents a member of a group of radicals termed organic peroxy radicals (RO_2 – where R is used to represent alkyl, ally, or aryl groups), all of which possess the ability to convert NO to NO_2. The fate of the alkyl oxy radical (C_2H_5O) is more complex and can result in the formation of HO_2 and other VOCs. It is the organic atmospheric chemistry of RO_2 that remains the great challenge to our full understanding of the production of O_3 in the troposphere. Recent advances in our understanding of the fate of RO2 in the atmosphere are reviewed in section 4.10.

There are added complexities to the chemistry outlined above owing to the variety of sources of OH e.g. from the photolysis of HONO ~~(Kim et al., 2014)~~(Kim et al., 2014), HCHO and the reaction of ozone with alkenes. The Monks et al review ~~(Monks et al., 2009)~~(Monks et al., 2009) looked at much of the variety of ozone photochemistry in more detail.

2.1.2 Role of Deposition

The concentration of ozone in the surface boundary layer is regulated by three processes: atmospheric transport, chemical production/destruction and losses to surface by dry deposition. Ozone is physically transported to the surface by atmospheric turbulence which ~~is~~can be readily measured or modelled using well established methods. The rate of ozone removal at the surface strongly influences the exposure of vegetation and the human population to ozone and is responsible for much of the nocturnal decline in surface ozone in rural areas as deposition to the surface consumes ozone beneath a nocturnal temperature inversion. During the day, vertical transport of ozone to the surface layers is generally sufficient to maintain mixing ratios within 10% of the boundary layer mean values, except in urban areas or near major roads, where local nitric oxide sources remove ozone by titration ~~(Colette et al., 2011)~~(Colette et al., 2011). Thus the interplay between dry deposition of ozone in the surface layers and mixing from higher levels in the atmosphere plays a major role in regulating ozone exposure of ecosystem and the human population. The mixing in surface layers is largely driven by wind and its interaction with frictional drag at the surface. The large diurnal variability in ozone mixing ~~rations~~ratios in rural areas and its variability with altitude has been used to quantify the spatial variability in ozone exposure at the surface.

Ozone dry deposition has been widely measured using micrometeorological methods, which average the flux to the surface at the field to landscape scale, over typically (10^4-10^6 m^2) ~~(Fowler et al., 2009)~~(Fowler et al., 2009). The controlling processes in ozone deposition are generally simulated

numerically using a resistance analogy ~~(Erisman et al., 1994)~~(Erisman et al., 1994), as illustrated in ~~Fig 4~~Figure 5. Correct parameterisation in models is critical to the determination of ozone budgets ~~(Val Martin et al., 2014)~~(Val Martin et al., 2014).

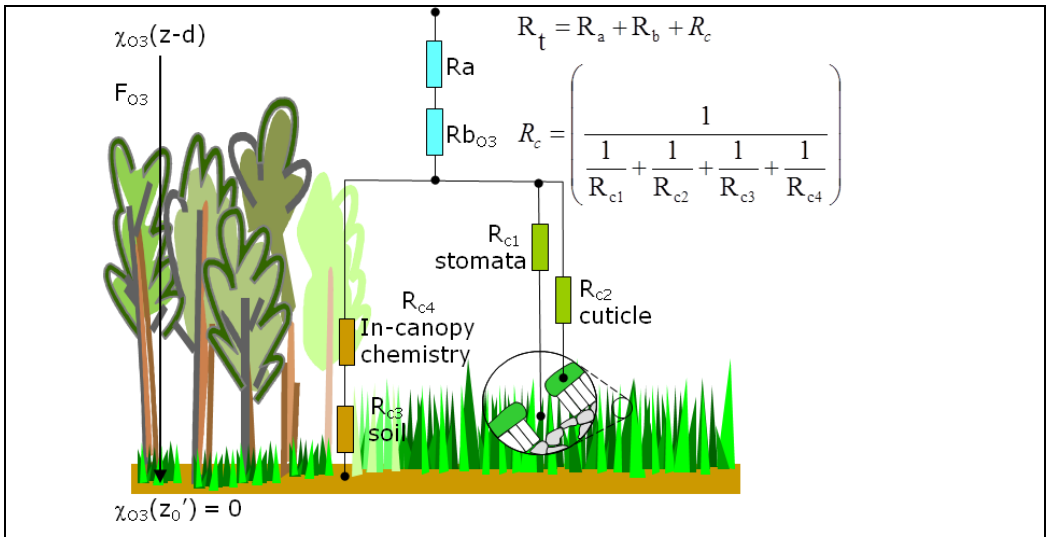


Figure ~~4~~5 - The resistance analogy for ozone deposition to vegetation and soil~~.~~ (for details of nomenclature see text).

Ozone is a reactive gas and deposits readily on most surfaces simply by oxidative reactions ~~(Grontoft, 2004)~~(Grontoft, 2004). Many studies have concluded that stomatal uptake is the main factor regulating surface fluxes, but as stomata are usually open ~~only a fraction of the time~~during daylight hours, the smaller rates of deposition to non-stomatal surfaces are often a dominant component of the annual deposition to the surface ~~(Fowler et al., 2009)~~(Fowler et al., 2009).

Considering the main sinks for ozone deposition at the surface in turn:

a) Stomatal Uptake

Plants open their stomata to take up CO_2 for photosynthesis and regulate stomatal opening to minimise water loss by transpiration ~~(Farquhar et al., 1980)~~(Farquhar et al., 1980). This also allows the uptake of other gases that may not benefit the plant, including ozone, which as a powerful oxidant, generates free radicals within the apoplast and cell fluids and is responsible for damage to cell metabolism ~~(Mills et al., 2011)~~(Mills et al., 2011a). Stomatal opening is controlled by water pressure in the guard cells which the plant regulates depending on: light, in general stomata open during the day and close at night; carbon dioxide concentration~~; plant water~~, with increasing CO_2 above current ambient inducing partial closure; soil water content, with stomata closing in drier soils to ~~control~~reduce water loss; temperature, ~~in most conditions~~with an increase in temperature ~~increases~~increasing stomatal opening~~.~~ up to a species-specific maxima above which stomatal closing is induced; humidity, with greatest stomatal opening under low vapour pressure deficits and stomatal closing occurring at high vapour pressure deficits to conserve plant water; and phenology

Formatted: Font: +Body (Calibri)

Formatted: Normal

Formatted: Font: +Body (Calibri), Font color: Black

Formatted: Font: +Body (Calibri), Font color: Black

Formatted: Font: +Body (Calibri), Font color: Black

Formatted: Font: +Body (Calibri), Font color: Black

Formatted: Font: +Body (Calibri), Font color: Black

Formatted: Font: +Body (Calibri), Font color: Black

with stomatal conductance reducing as plants age. An example of the range of stomatal responses to these environmental and plant controls can be found for wheat in Grünhage et al. (Grünhage et al., 2012). Other factors can affect stomatal opening although not as directly as those listed above~~: the age of a plant has an influence as older cells become damaged and respond more slowly to stimuli; pollutant gases or~~, for example, aerosols can damage the guard cells or block stomata~~;~~ and surface water ~~blocks~~can also block stomata.

The diffusion pathway through stomata as with atmospheric fluxes, can be quantified using a resistance analogy as illustrated in ~~Figure~~Fig. 4. The inverse of stomatal resistance is stomatal conductance (*gs*) and is widely used by plant scientists to quantify stomatal exchanges of CO_2 and H_2O~~. The inverse of the total resistance between a reference height in the atmosphere and the absorbing surfaces is referred to as a deposition velocity (V_d) and is widely used to quantify dry deposition of pollutant gases in transport and deposition models.~~, and has also been used to develop stomatal flux-based risk assessments for ozone (Emberson et al., 2000;Mills et al., 2011b). The processes responsible for controlling stomatal function have been extensively studied in the field and laboratory leading to a variety of instruments and models to quantify stomatal resistance, *Rc*1, or conductance, *gs*.

b) Non-Stomatal Uptake

The reaction of ozone with external surfaces of vegetation is referred to as non-stomatal uptake. In controlled conditions in the laboratory, the flux may be measured quite straightforwardly by treating the vegetation in order to fully close the stomata. In the field, there is the complication that multiple sinks are present (leaf surfaces, senescent vegetation, soil and water~~).~~) as well as stomatal opening. The usual approach to quantify non-stomatal deposition is by the difference between the total deposition flux and the stomatal flux, choosing surfaces to minimise the soil and senescent vegetation components. With reference to Figure 4~~5~~, once R_{c1} has been determined from measurements or by modelling the sum of R_{c2}, R_{c3} and R_{c4} (non-stomatal, R_{ns}) can be calculated as the residual term:

$$R_{ns} = \left(\frac{1}{R_c} - \frac{1}{R_{c1}}\right)^{-1} \quad (~~10~~1)$$

Whether it is possible to separate the components of R_{ns} (R_{c2} – external surfaces, R_{c3} – soil, R_{c4} – in-canopy chemistry) depends on the nature of the measurement site and canopy and there are some models available based on measurements over bare soil, senescent vegetation and in-canopy chemistry ~~(Launiainen et al., 2013;Fares et al., 2013;Fares et al., 2012;Bueker et al., 2012;Tuzet et al., 2011;Stella et al., 2011)~~(Launiainen et al., 2013;Fares et al., 2013b;Fares et al., 2012;Bueker et al., 2012;Tuzet et al., 2011;Stella et al., 2011). Many research groups have taken this approach and Table 1 provides a summary of some of the different estimates of the values for R_{ns} in the literature.

Table 1 - Selected estimates of the non-stomatal resistance for ozone to snow, water, soil and plant surfaces from measurements.

Reference	Type	Surface	R_{ns}, s m^{-1}
~~(Chang et al., 2002)~~(Chang et al., 2002)	~~chamber~~Chamber	Agricultural soil (no data on moisture content)	*ca* 625 *ca* 475
~~(Wesely et al.,~~	Field µmet	Wet bare soil	1000 ± 100

Formatted: Font: +Body (Calibri), Font color: Black
Formatted: Font: +Body (Calibri), Font color: Black
Formatted: Font: +Body (Calibri), Font color: Black
Formatted: Font: +Body (Calibri), Font color: Black
Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri), Font color: Black
Formatted: Font: +Body (Calibri), Font color: Black
Formatted: Font: +Body (Calibri), Italic, Font color: Black
Formatted: Font: +Body (Calibri), Font color: Black, Not Superscript/ Subscript
Formatted: Font: +Body (Calibri), Font color: Black
Formatted: Font: +Body (Calibri), Font color: Black, Not Superscript/ Subscript
Formatted: Font: +Body (Calibri), Font color: Black
Formatted: Font: +Body (Calibri), Font color: Black
Formatted: Font: +Body (Calibri), Italic, Font color: Black
Formatted: Font: +Body (Calibri), Font color: Black, Not Superscript/ Subscript
Formatted: Font: +Body (Calibri), Italic, Font color: Black
Formatted: Font: +Body (Calibri), Font color: Black, Not Superscript/ Subscript
Formatted: Font: MPHV, 9.5 pt, Font color: Black
Formatted: Normal, Left, Don't adjust space between Latin and Asian text, Don't adjust space between Asian text and numbers

~~1981)~~(Wesely et al., 1981)			(370 – 2100)
		Snow -11°C	2000 ± 200
		-5°C	3500 ± 200
		-1 to 2 °C	3300 ± 300
		Lake water	9000 ± 300
~~(Sanchez et al., 1997)~~(Sanchez et al., 1997)	Field µmet	Semi-arid steppe (wet and dry)	Dry 275 Wet 437
~~(Rondon et al., 1993)~~(Rondon et al., 1993)	Field chambers	Coniferous trees	200 – 330
~~(Granat and Richter, 1995)~~(Granat and Richter, 1995)	Field chambers	Pine	500 – 2500
~~(Coe et al., 1995)~~(Coe et al., 1995)	Field µmet	Sitka spruce	ca 133
~~(Fowler et al., 2001)~~(Fowler et al., 2001)	Field µmet	Dry moorland	200 – 400
~~(Grantz et al., 1995)~~(Grantz et al., 1995)	Field µmet	Wet and dry grape	Dry 1020 Wet 292[a]
~~(Grantz et al., 1997)~~(Grantz et al., 1997)	Field µmet	Wet and dry cotton	Dry 770 Wet 3030
~~(Zhang et al., 2002)~~(Zhang et al., 2002)[b]	Field µmet	Wet and dry: Mixed forest Deciduous forest Corn Soybean Pasture	 244 – 970 397 – 1831 308 – 1332 137 – 735 571 – 879
~~(Gerosa et al., 2005)~~(Gerosa et al., 2005) ~~(Gerosa et al., 2009)~~(Gerosa et al., 2009)	Field µmet	Mediterranean Oak (Quercus ilex)	Dry 249 Wet 177 Avg 67 ~~–~~ 204
~~(McKay et al., 1992)~~(McKay et al., 1992) and references therein	Laboratory chambers and field	Sea water & saline solutions	650 – 6600
~~(Gallagher et al., 2001)~~(Gallagher et al., 2001)	Field µmet	Coastal waters	950 ± 70
~~(Coyle et al., 2009)~~(Coyle et al., 2009)	Field µmet	Potatoes Wet canopy Dry canopy	276
~~(Neirynck et al., 2012)~~(Neirynck et al., 2012)	Field µmet	Temperate Forest	136

a from data reported in ~~(Grantz et al., 1997)~~(Grantz et al., 1997)
b data derived from references therein

The literature reviewed in Table 1 reports estimates of R_{ns}, although few examine the controlling factors. In some of the studies, surface factors affecting ozone deposition, other than stomatal uptake, have been considered. ~~The main focus of work has been on the effects of~~For example, surface water ~~and researchers have~~ has been found to both ~~positive~~enhance and ~~negative effects on~~reduce deposition rates. The remainder of studies have considered solar radiation or surface temperature and found deposition rates increased with both variables, as well as in-canopy chemistry.

c) Solar Radiation and Surface Temperature

Given its reactive nature it is not unreasonable to find effects of surface temperature on R_{ns} and indications of such an effect were first reported by Rondon et al ~~(Rondon et al., 1993)~~(Rondon et al., 1993). In their measurements of ozone deposition to a coniferous forest they found that the surface resistance to ozone was much lower than that predicted by stomatal conductance alone and the residual term (R_{ns}) varied with air temperature, radiation and stomatal conductance. It was proposed that this effect was due to temperature increasing the reaction rates of ozone with organic compounds on the canopy surface. Coyle et al ~~(Coyle et al., 2009)~~(Coyle et al., 2009) found similar results in measurements for ozone uptake by potatoes, while also showing that surface wetness could enhance or reduce non-stomatal uptake depending on the initial status of the cuticles. While ~~(Fowler et al., 2001)~~(Fowler et al., 2001) showed a clear reduction in R_{ns} with increasing total solar radiation and temperature. Cape et al ~~(Cape et al., 2009)~~(Cape et al., 2009) examined deposition to metals and artificial leaf surfaces and found a strong temperature response, which yielded activation energies for the reaction of ~30 kJ mol^{-1}, similar to that found by Fowler *et al* ~~(Fowler et al., 2001)~~(Fowler et al., 2001) for moorland of 36 kJ mol^{-1} and from other unpublished studies ~~(Coyle et al., 2009)~~(Coyle et al., 2009). The simplest explanation of non-stomatal ozone deposition is that it represents the thermal decomposition of ozone at the surface, which increases with surface temperature. Other, more complex processes have been suggested including rapid reactions with very reactive hydrocarbon compounds ~~(Hogg et al., 2007)~~(Hogg et al., 2007).

d) In-canopy chemistry

The reaction of ozone with nitric oxide (NO) is an important cause of reduced ozone concentrations in urban areas. The same reaction also reduces ozone concentrations close to the surface where soil emissions of NO are large. Some types of vegetation such as coniferous forests also emit highly reactive volatile organic compounds ~~(Di Carlo et al., 2004)~~(Di Carlo et al., 2004) which can rapidly deplete ozone concentrations immediately above the canopy ~~(Neirynck et al., 2012;Stjernberg et al., 2012)~~(Neirynck et al., 2012;Stjernberg et al., 2012;Kurpius and Goldstein, 2003). Over some forest canopies the major non-stomatal sink has been attributed to these reactions although the compound(s) responsible have not been identified. Other transient events such as grass cutting, which releases very reactive hydrocarbons ~~(Davison et al., 2008)~~(Davison et al., 2008) can also lead to enhanced ozone deposition as a result ~~(Coyle, 2005)~~(Coyle, 2005).

e) Deposition to Water

It has often been assumed that ozone deposition rates to water will be small and relatively constant as ozone has a low solubility in water. The resistance of a water layer to the uptake of ozone by dissolving and diffusing the gas is very large and values of $3x10^5$ to $8x10^5$ s m^{-1} have been suggested ~~(Wesely et al., 1981)~~(Wesely et al., 1981). They concluded that the far lower values found in their measurements (Table 1) resulted from surface chemical reactions, which has been supported by further work since then. However measurements have shown that over vegetated surfaces deposition can be either enhanced or suppressed by the presence of water films (~~(Fuentes et al., 1992)~~(Fuentes et al., 1992)), ~~(Padro, 1994)~~(Padro, 1994)), ~~(Grantz et al., 1995;Grantz et al., 1997)~~(Grantz et al., 1995;Grantz et al., 1997), ~~(Pleijel et al., 1995)~~(Pleijel et al., 1995)), ~~(Coyle et al., 2009)~~(Coyle et al., 2009)) while over open water deposition varies with water chemistry, turbidity and agitation. The deposition velocity of ozone to open water is generally small, ~0.001 to 0.04 cm s^{-1}

~~(Wesely et al., 1981;Chang et al., 2004)~~(Wesely et al., 1981;Chang et al., 2004) and increases in deposition velocities to sea water have been observed with disturbance to the surface. McKay et al ~~(McKay et al., 1992)~~(McKay et al., 1992) showed that increasing concentrations of chemical surfactants in the seawater also enhanced deposition (see Table 1 for typical resistance values). These results show that although deposition rates to water are generally small they can be significant if other reactive compounds are present in the water, a conclusion also supported by measurements to wet vegetated canopies. Research into ozone reactivity and solubility for the ozone water treatment industry has highlighted the role of pH. Ganzeveld et al have explored the impact of dry deposition of ozone over oceans ~~(Ganzeveld et al., 2009)~~(Ganzeveld et al., 2009). On a global scale, model studies indicate that deposition to the ocean constitutes almost 40% of the total annual surface dry deposition of ozone, far larger than that from any other land cover class ~~(Hardacre et al., 2014)~~(Hardacre et al., 2014).

2.1.3 Transport and mixing processes

a) ~~2.1.3.1~~ Long-range transport

Formatted: Numbered + Level: 1 + Numbering Style: a, b, c, … + Start at: 1 + Alignment: Left + Aligned at: 0.63 cm + Indent at: 1.27 cm

Research over the past two decades has clearly shown that ozone and ozone precursors are regularly exported from their emission source, or point of production, to receptor regions far downwind on the regional, intercontinental and even hemispheric scale (see reviews by Stohl and Eckhardt ~~(Stohl and Eckhardt, 2004)~~(Stohl and Eckhardt, 2004), Monks et al. ~~(Monks et al., 2009)~~(Monks et al., 2009), National Research Council ~~(Council, 2009b)~~(Council, 2009b) and ~~(HTAP, 2010)).~~(HTAP, 2010)). These transport pathways are predominantly from west to east at mid-latitudes with in situ and satellite-based observations showing that pollution plumes (anthropogenic and biomass burning) not only travel from North America to Europe, or from East Asia to North America, but can also circle the globe ~~(Jacob et al., 1999;Jaffe and et al., 1999;Lewis et al., 2007;Wild et al., 2004)~~(Jacob et al., 1999;Jaffe and et al., 1999;Lewis et al., 2007;Wild et al., 2004).

Formatted: Font: 11 pt

The scientific community has a very good understanding of the meteorological mechanisms that export pollution from the boundary layer of a source region (warm conveyor belts, deep convection, and horizontal advection) and then transport these plumes through the free troposphere towards the downwind receptor region. The most recent development is the conceptualization of intercontinental transport within an isentropic framework that illustrates how transport of pollution plumes from East Asia are constrained by the thermal structure of the atmosphere, preferentially impacting the high elevation terrain of the western USA rather than the relatively low-lying eastern USA ~~(Brown-Steiner and Hess, 2011)~~(Brown-Steiner and Hess, 2011). The major uncertainty concerning long-range transport is estimating the contribution of the imported pollution to the total quantity of pollution at the surface of the receptor region. Some unique chemical tracers of upwind pollution sources do exist, for example, stable lead isotopes can indicate events when Asian

particulate matter reaches the surface of California ~~(Ewing et al., 2010)~~(Ewing et al., 2010). However, at present there are no routine and widespread monitoring methods that can distinguish ozone and ozone precursors produced in a receptor region, such as California, from the same species produced in an upwind region, such as East Asia.

The only feasible method for quantifying the impact of imported pollution at the surface of a receptor region is to use chemical transport models or chemistry-climate models. Such models have been used for this purpose since the 1990s but until recently their effectiveness has been limited by their coarse horizontal resolution, typically 2x2 degrees ~~(HTAP, 2010).~~(HTAP, 2010). Such large grid cells artificially dilute the imported pollution plumes as well as local emissions of ozone precursors in the receptor region, and also smooth the topography of the receptor region, removing the influence of terrain-driven transport mechanisms that affect the mixing of imported pollution down to the surface. However, recent model studies have used finer scale grids to avoid the problems associated with coarse resolution models ~~(Lin et al., 2012b;Huang et al., 2013;Zhang et al., 2014;Choi et al., 2014)~~(Lin et al., 2012b;Huang et al., 2013;Zhang et al., 2014;Choi et al., 2014). Because these finer resolution models provide more realistic simulations of observed pollution plumes scientists have greater confidence in their quantification of the contribution of imported pollution at the surface of a receptor region. Despite the improvements afforded by finer resolution, a recent study of the quantity of background ozone advected into western North America shows monthly mean differences as great at 10 ppbv between models, with the discrepancy attributed to differences in the way that the models handle lightning NO_x, biogenic isoprene emissions and chemistry, wildfires, and stratosphere-to-troposphere transport ~~(Fiore et al., 2014)~~(Fiore et al., 2014).

Future climate change may affect the contribution of long-range transport downwind effects ~~(Glotfelty et al., 2014;Doherty et al., 2013)~~(Glotfelty et al., 2014;Doherty et al., 2013)~~.~~. HTAP (2010) suggests "changes in climate will affect meteorological transport processes as well as the chemical environment and lifetime of the transported pollutants and hence the concentrations of pollutants arriving at downwind continents." Glotfelty et al. (2014) suggest a larger impact on the US from East Asian Emissions and Doherty et al. (2013) showed stronger chemistry than transport positive climate feedbacks on increased ozone.

~~2.1.3.2 Seasonal transport patterns:~~

b) Stratosphere-troposphere exchange ~~and summer monsoons~~

Formatted: Numbered + Level: 1 + Numbering Style: a, b, c, … + Start at: 1 + Alignment: Left + Aligned at: 0.63 cm + Indent at: 1.27 cm

The tropospheric ozone burden varies seasonally as measured by the remotely sensed AURA OMI/MLS tropospheric column product ~~(Ziemke et al., 2006)~~(Ziemke et al., 2006). The region of the Earth with the strongest seasonal ozone variation is the northern mid-latitudes where the ozone burden is at a minimum in October and November and then increases by 30% through winter and spring until it reaches a maximum in June ~~(Cooper et al., 2014)~~(Cooper et al., 2014). Much of this seasonal variability can be explained by the flux of ozone from the stratosphere to the troposphere with a Northern Hemisphere peak flux in May and a minimum flux in November occurring predominantly in mid-latitudes (Hsu and Prather, 2009). Until recently ozone transport from the stratosphere to the troposphere was believed to be dominated by processes such as tropopause folds and gravity wave breaking, with little attribution given to deep convection ~~(Stohl et al.,~~

~~2003)~~(Stohl et al., 2003). However, a new model-based estimate that accounts for deep convection penetrating the lowermost stratosphere increases the Northern Hemisphere peak stratosphere-to-troposphere ozone flux by 19% and shifts the peak month from May to June ~~(Tang et al., 2011)~~(Tang et al., 2011). Sudden STE events are well known to influence ground-based ozone measurements over a short period (see e.g. ~~(Dempsey, 2014;Zanis et al., 2003)~~(Dempsey, 2014;Zanis et al., 2003)).

While the tropospheric ozone burden responds seasonally to the flux from the stratosphere the response is not uniform with altitude or latitude. Terao et al. ~~(Terao et al., 2008)~~(Terao et al., 2008) using a chemical transport model calculated the stratospheric contribution to monthly mean ozone above four ozonesonde sites between 75° N and 36° N. At 500 hPa the stratospheric contribution to ozone is ~40% during spring and 25% in autumn at high latitudes, and 35-40% during spring and 10-15% during autumn at mid latitudes. At 800 hPa these values are slightly less on a percent scale but much less on an absolute scale, being ~20 ppbv during spring and 5-7 ppbv during autumn with relatively little latitudinal gradient. Model estimates of the stratospheric contribution to surface ozone are smaller than those for 800 hPa but the estimates vary greatly depending on the model used and the region under consideration. For example, Lamarque et al. ~~(Lamarque et al., 2005)~~(Lamarque et al., 2005) estimated that the monthly mean stratospheric contribution to a range of sites in the mid-latitudes and tropics of both hemispheres is always less than 5 ppbv, regardless of season. In contrast, a study using a different model estimated the stratospheric contribution to US surface ozone during late spring 2010 as being < 5 ppbv along the Gulf coast, 8-13 ppbv across the eastern US, and 10-20 ppbv across the high elevations of the western USA ~~(Lin et al., 2012a)~~(Lin et al., 2012a). More recently Hess et al have claimed that that a large portion of the measured ozone change in the sub-tropical NH are not due to changes in emissions, but can be traced to changes in large-scale modes of ozone variability ~~(Hess et al., 2014)~~(Hess et al., 2014).this

c) Seasonal transport patterns e.g. summer monsoons

In addition to the seasonal influence of stratosphere-troposphere exchange, ozone varies seasonally at most sites around the world ~~(Oltmans et al., 2013)~~(Oltmans et al., 2013) simply due to shifting wind patterns associated with migratory mid-latitude cyclone tracks or the transition between winter and summer monsoons. For example, Mauna Loa Observatory, Hawaii in the northern tropics is influenced by westerly air masses from Asia in the spring when it is located beneath the subtropical jet stream. But in autumn the subtropical jet stream is far to the north leaving the site well within the tropical belt which reduces transport from Asia resulting in 25% decrease in monthly median ozone ~~(Lin et al., 2014b)~~(Lin et al., 2014b). Similarly, Bermuda in the subtropical North Atlantic Ocean receives westerly transport from North America during winter and spring, but during summer the westward and northward expansion of the Azores-Bermuda High advects tropical air masses to Bermuda reducing ozone mixing ratios by 50% ~~(Moody et al., 1995)~~(Moody et al., 1995). The North American Summer Monsoon becomes established above central North America during July and August producing a stationary upper tropospheric anticyclone that traps ozone precursors lofted from the surface as well as large quantities of lightning NO_x ~~(Cooper et al., 2009)~~(Cooper et al., 2009). Over several days the ozone precursors enhance tropospheric ozone within the anticyclone by as much as 30-40 ppbv compared to sites upwind of the anticyclone ~~(Cooper et al., 2007)~~(Cooper et al., 2007). Ozonesondes launched from Ahmedabad, western India indicate that an upper tropospheric ozone enhancement does not occur during the Asian Summer Monsoon despite the presence of an

anticyclonic recirculation similar to that found above North America during its summer monsoon. Instead, an abrupt decrease in tropospheric column ozone is observed above Ahmedabad with the onset of the Asian Summer Monsoon, with decreases occurring at all levels of the troposphere ~~(Ojha et al., 2014)~~(Ojha et al., 2014).

d) ~~2.1.3.3~~ Climate variability

While mean climatic conditions are typically established over a 30-year period, climate variability occurs on much shorter time scales of one to several years. Short-term climate variability modifies the long-range transport pathways that channel ozone plumes on regional and intercontinental scales, and also impacts regional-scale ozone photochemistry by modifying cloud cover. The impact of climate variability on ozone transport and chemistry is a relatively new field of study that has explored the effects of such phenomena as El Niño/Southern Oscillation (ENSO), the Pacific–North American (PNA) pattern and the North Atlantic Oscillation (NAO). "The influence on ozone of low frequency climate variability on time scales longer than 30 years has not yet been assessed due to continuous ozone data sets being limited to durations shorter than 30-40 years."

ENSO has been shown to modulate the tropospheric ozone burden across the tropical Pacific Ocean with lower tropospheric column ozone corresponding to the cloudiest regions ~~(Ziemke and Chandra, 2003;Sekiya and Sudo, 2014)~~(Ziemke and Chandra, 2003;Sekiya and Sudo, 2014). Zeng and Pyle ~~(Zeng and Pyle, 2005)~~(Zeng and Pyle, 2005) calculated an anomalously large increase of stratosphere-troposphere exchange following a typical El Niño year, increasing the global tropospheric ozone burden. In addition, changes in emissions, especially biomass burning, associated with ENSO affect the ozone burden across the tropics ~~(Doherty et al., 2006)~~(Doherty et al., 2006). ENSO has also been linked to column ozone changes above Europe with positive anomalies of tropospheric ozone column and surface ozone occurring in the spring following an El Niño year, for a variety of reasons including changes in STE, biomass burning emissions and pollution transport pathways from Asia and North America ~~(Koumoutsaris et al., 2008)~~(Koumoutsaris et al., 2008). Voulgarakis *et al.* ~~(Voulgarakis et al., 2010)~~(Voulgarakis et al., 2010) used a global chemical transport model to determine the interannual variability of the global tropospheric ozone burden for the period 1996-2000 which included the strong El Niño event of 1997-1998. They found that 79% of the interannual variability was due to changes in meteorology (mostly stratosphere-troposphere exchange) and only 11% was due to changes in emissions. Changes in cloudiness contributed a small but non-negligible amount (6%) to the interannual variability. ENSO and the Pacific –North American (PNA) pattern also control the transport of ozone from East Asia to Mauna Loa, Hawaii. A springtime decrease in transport from Asia to Mauna Loa over the period 1980-2011 has resulted in no significant ozone trend, while an increase in transport during autumn has produced a very strong ozone trend of 3.5 ± 1.4 ppb decade^{-1} ~~(Lin et al., 2014b)~~(Lin et al., 2014b).

The transport of ozone and other pollutants across the North Atlantic Ocean and the Arctic is heavily influenced by the NAO. During the high phase of the NAO, wintertime pollutant transport into the Arctic is enhanced by 70% compared to times dominated by the low phase, with the major source region being Europe, followed by North America ~~(Eckhardt et al., 2003)~~(Eckhardt et al., 2003). The NAO has also been shown to modulate ozone at the high elevation site of Izaña in the subtropical

Formatted: Numbered + Level: 1 + Numbering Style: a, b, c, … + Start at: 1 + Alignment: Left + Aligned at: 0.63 cm + Indent at: 1.27 cm

Formatted: Normal, Line spacing: single

Formatted: Font: Calibri

North Atlantic Ocean ~~(Cuevas et al., 2013)~~(Cuevas et al., 2013), with a relaxation of the predominantly high positive phase of the NAO since the mid-1990s allowing increased ozone transport from North America and the lower stratosphere to Izaña in more recent years. Across Europe surface ozone observations tend to correlate positively with the NAO ~~(Pausata et al., 2012)~~(Pausata et al., 2012).

While transport of ozone from the stratosphere to the troposphere has a strong seasonal cycle, recent work has also explored changes in the stratosphere-to-troposphere ozone flux and its impact on the tropospheric ozone budget. Several modelling studies have given evidence for such a link ~~(Young et al., 2013;Kawase et al., 2011;Hess and Zbinden, 2013;Voulgarakis et al., 2011;Oman et al., 2013)~~(Young et al., 2013;Kawase et al., 2011;Hess and Zbinden, 2013;Voulgarakis et al., 2011;Oman et al., 2013), even demonstrating that the Mount Pinatubo eruption of 1991 reduced the flux of ozone from the stratosphere to the troposphere until 1995 ~~(Tang et al., 2013)~~(Tang et al., 2013). According to a model-based analysis, the interannual variability of the ozone mass flux from the stratosphere to the troposphere is on the order of 15% for the Northern Hemisphere and 6% for the Southern Hemisphere ~~(Olsen et al., 2013)~~(Olsen et al., 2013). Correlations between remotely sensed ozone in the lowermost stratosphere and mid-troposphere indicate that 16% of the northern hemisphere mid-latitude tropospheric interannual ozone variability is controlled by the flux from the stratosphere ~~(Neu et al., 2014)~~(Neu et al., 2014). Ordoñez et al. ~~(Ordonez et al., 2007)~~(Ordonez et al., 2007) showed that the positive ozone trends and anomalies in the lower free troposphere over Europe during the 1990s were probably due to enhanced stratospheric ozone contributions (dominated by changes in lower stratospheric ozone concentrations rather than by variations of cross-tropopause air mass transport), particularly in winter–spring. Similarly, Tarasick et al. ~~(Tarasick et al., 2005)~~(Tarasick et al., 2005) using the ozonesonde network over Canada, and Terao et al. ~~(Terao et al., 2008)~~(Terao et al., 2008) using a global model for the northern extratropics found positive correlations between ozone in the troposphere and the lowermost stratosphere. Using the same data as Ordoñez et al. (2007) for the lowermost stratosphere, Logan et al. ~~(Logan et al., 2012)~~(Logan et al., 2012) found no trends in ozone for the decades 1978-1989, 1990-1999, 2000-2009, except for a marginally significant decrease in winter for 1978-1989, driven by very low values in early 1989 and an increase in winter and spring for 1990-1999. They found no evidence in the time series for the lowermost stratosphere from either ozonesondes over North America ~~(Tarasick et al., 2005)~~(Tarasick et al., 2005) or from satellite data ~~(McPeters et al., 2007)~~(McPeters et al., 2007) to suggest that changes in stratospheric input can explain the increase in ozone over Europe in the 1980s. However, increases in stratospheric ozone after 1993 may have contributed to the increase in tropospheric ozone in the 1990s.

2.2 Changing ozone – a brief history

The German chemist C.F. Schönbein is credited with the discovery of ozone in 1839 ~~(Schönbein, 1843)~~(Schönbein, 1843) and its presence in the atmosphere was one of his earliest concerns ~~(Braslavsky and Rubin, 2011)~~(Braslavsky and Rubin, 2011). Early work by Hartley identified its UV spectrum and its role as a UV filter in the atmosphere ~~(Hartley, 1881)~~(Hartley, 1881).

Modelling studies coupled to limited surface measurements from the late 1800s and early 1900s indicate that ozone concentrations have changed across all scales of the troposphere during the modern era due to enhanced emissions of precursors from industrialisation. A recent assessment (Cooper et al., 2014) of the most reliable historical ozone records (reliable due to the quantitative measurement methods employed), indicates that surface tropospheric ozone levels in western Europe increased by a factor of 3-5 between the late 1800s and late 1900s, and by a factor of 2 between the 1950s and 1990s ~~(Wilson et al., 2012;Parrish et al., 2012;Marenco et al., 1994;Staehelin et al., 1994;Volz and Kley, 1988)~~(Wilson et al., 2012;Parrish et al., 2012;Marenco et al., 1994;Staehelin et al., 1994;Volz and Kley, 1988). Many locations around the world monitored ozone in the late 1800s and early 1900s using the semi-quantitative Schönbein ozonoscope ~~(Marenco et al., 1994;Bojkov, 1986)~~(Marenco et al., 1994;Bojkov, 1986). These estimates indicate that surface ozone was much lower in those days compared to modern times, but the uncertainty of the measurements is so great that no accurate estimate can be made of the absolute increase in ozone (see the review by ~~(Cooper et al., 2014)~~(Cooper et al., 2014)).

Recent modelling studies ~~(Young et al., 2013;Lamarque et al., 2005)~~(Young et al., 2013;Lamarque et al., 2005) suggest that the tropospheric ozone burden in 1850 was 30% lower than the present day (see Figure ~~5~~6), with the largest contribution to the change coming from the northern hemisphere extratropics. Most current global models are still unable to reproduce the low surface ozone concentrations reliably observed at Montsouris near Paris at the end of the 19th century ~~(Young et al., 2013;Hauglustaine and Brasseur, 2001)~~(Young et al., 2013;Hauglustaine and Brasseur, 2001), despite the models having more detailed chemistry schemes, improved emissions estimates and finer spatial resolution (e.g. ~~(Lamarque et al., 2010)~~(Lamarque et al., 2010)). This suggests either problems with interpretation of the original observations and their context, or weaknesses in our assessment of precursor emissions or in our current understanding of atmospheric processes ~~(Mickley et al., 2001)~~(Mickley et al., 2001). However, the inclusion of bromine chemistry can help models to approach the low ozone values measured at Montsouris in the late 1800s ~~(Parrella et al., 2012)~~(Parrella et al., 2012).

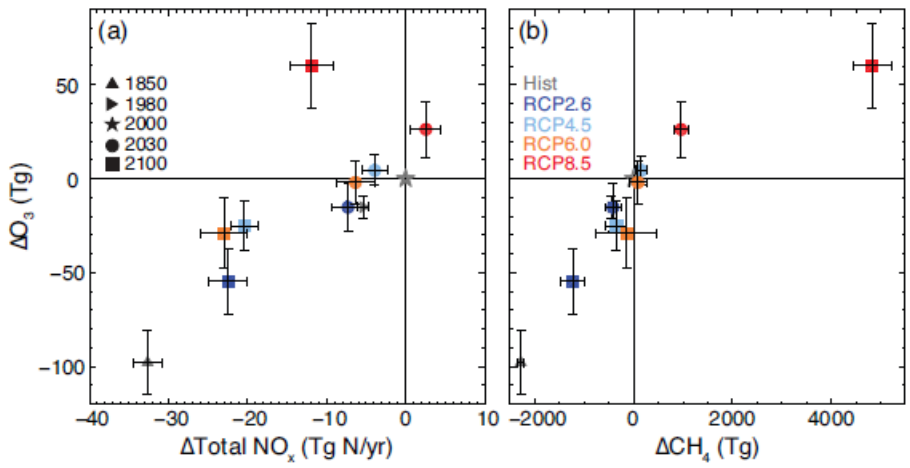


Figure ~~5~~6 - Ensemble mean change in the tropospheric ozone burden compared to the year 2000 simulation as a function of (a) changes in total NOx emissions and (b) changes in the tropospheric

methane burden. Error bars indicate±1 std. dev. of the changes in ozone, NOx emissions and methane burdens, calculated from the spread of the models. Different colours represent the different scenarios, whereas different symbols represent the different time slices. ~~(Young et al., 2013)~~(Young et al., 2013)

Establishing quantitative ozone trends from observations is important for testing our understanding of the processes affecting ozone in the troposphere and for the attribution of these ozone changes to changes in precursor emissions, removal processes and meteorology. It is also important from an air quality perspective for determining the effect of emission controls and for identifying the extent to which surface ozone is locally or regionally controllable. Observed ozone trends are a challenge to interpret as there are a number of factors that may be responsible ~~(Cape, 2008)~~(Cape, 2008) including (a) changes in anthropogenic emissions of precursors (local, regional and global), (b) effects of biomass burning (both regional and global), (c) changes in Stratosphere-Troposphere exchange, (d) changes in geographical emission patterns~~ and~~, (e) changes in ~~meteorological~~land cover and (f) changes in meteorology e.g. transport patterns, rain, radiation, temperature etc. Long time series of high quality measurement data are required in order to detect the trend above the large inter-annual variation ~~(Staehelin, 2003;Weatherhead et al., 1998;Weatherhead et al., 2002)~~(Staehelin, 2003;Weatherhead et al., 1998;Weatherhead et al., 2002) and the sensitivity of the extracted trends to location necessitates that this is done at a range of sites to ensure representativeness and permit attribution of the observed changes. Jonson et al. ~~(Jonson et al., 2006)~~(Jonson et al., 2006) have discussed some of these effects in relation to ozone trends.

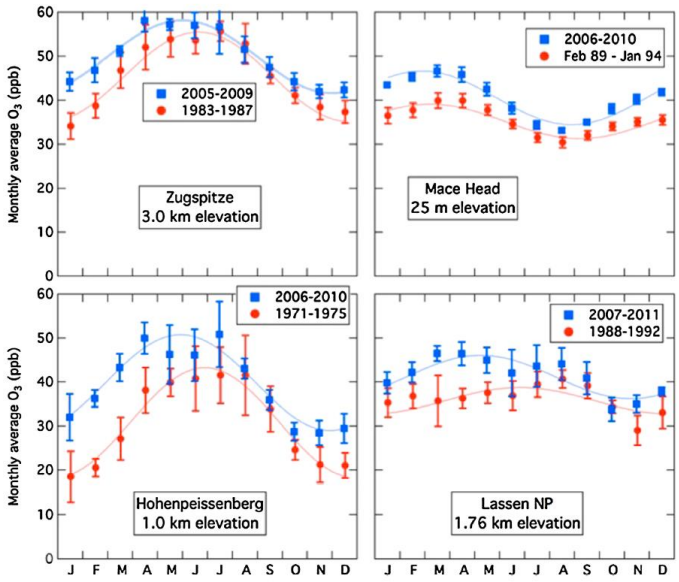
Global tropospheric ozone trends were recently assessed by the Intergovernmental Panel on Climate Change ~~(IPCC, 2013)~~(IPCC, 2013), and by Cooper et al. (2014) who provided an expanded discussion and update to the IPCC assessment. Following is a summary of the findings from Cooper et al. (2014). Prior to the 1970s, the only rural or remote quantitative ozone measurements outside of western Europe were some short-term observations from Antarctica ~~(Wexler et al., 1960)~~(Wexler et al., 1960) and Mauna Loa, Hawaii ~~(Junge, 1962)~~(Junge, 1962) during the late 1950s. By the early and mid-1970s quantitative and continuous ozone measurements were made at several rural and remote locations around the world for the purposes of detecting long-term changes in the global composition of the atmosphere. Continuous records in southern Germany began at the rural hilltop site of Hohenpeissenberg in 1971 and the mountaintop site of Zugspitze (2670 m) in 1978, and measurements began at the summit of Whiteface Mountain in upstate New York in 1973. Ozone measurements at remote sites were established by the U.S. National Oceanic and Atmospheric Administration at its baseline observatories of Mauna Loa, Hawaii (1973), Barrow, Alaska (1973), the South Pole (1975), and American Samoa (1976) ~~(Oltmans et al., 2013)~~(Oltmans et al., 2013). Routine ozonesonde profiles became available in Germany, the US, Japan and Antarctica in the early 1970s ~~(Oltmans et al., 2013)~~(Oltmans et al., 2013) and ship-borne monitoring of the marine boundary layer of the North and South Atlantic Oceans began in the late 1970s ~~(Lelieveld et al., 2004)~~(Lelieveld et al., 2004). The number of urban rural and remote monitoring sites has continued to grow from the 1970s to the present day.

All available northern hemisphere surface monitoring sites indicate increasing ozone from 1950-1979 until 2000-2010, with 11 of 13 sites having statistically significant trends of 1-5 ppbv decade^{-1}, corresponding to >100% ozone increases since the 1950s, and 9-55% ozone increases since the

1970s. In the southern hemisphere only 6 sites are available since the 1970s, all indicating increasing ozone with 3 having statistically significant trends of 2 ppbv decade^{-1}. Ozone monitoring in the free troposphere since the 1970s is even more limited than at the surface. Significant positive trends since 1971 have been observed using ozonesondes above Western Europe, Japan and coastal Antarctica (rates of increase range from 1-3 ppbv decade^{-1}), but not at all levels. In addition, aircraft have measured significant upper tropospheric trends in one or more seasons above the north-eastern USA, the North Atlantic Ocean, Europe, the Middle East, northern India, southern China and Japan. Notably, no site or region has shown a significant negative ozone trend in the free troposphere since the 1970s. From 1990 until 2010, surface ozone trends have varied by region. Western Europe showed increasing ozone in the 1990s followed by a levelling off, or decrease since 2000. In the eastern US rural surface ozone has decreased strongly in summer, is largely unchanged in spring, and has increased in winter. In contrast, few rural sites in the western US indicate decreasing ozone, with half of all rural sites showing a significant increase in spring. The decrease in ozone in Europe and the eastern USA is consistent with the decrease in ozone precursors in those regions. Meanwhile in East Asia surface ozone is generally increasing where ozone precursor emissions are growing.

Parrish et al. ~~(Parrish et al., 2013)~~(Parrish et al., 2013) demonstrate that another manifestation of changes in tropospheric O_3 is a shift of the seasonal cycle at northern mid-latitudes so that the observed peak concentrations now appear earlier in the year than they did in previous decades (see Figure ~~6~~7). The rate of this shift has been about 3 to 6 days per decade since the 1970s. Parrish et al. (2013) put forward an untested hypothesis that this shift may be due to changes in atmospheric transport patterns combined with spatial and temporal changes in emissions. This study relied on three long term (> 20 years) rural datasets in western Europe and one in the western USA. Cooper et al. ~~(Cooper et al., 2014)~~(Cooper et al., 2014) also explored this topic using 21-year data sets from one additional site in western Europe and 5 additional sites in the USA, all in rural locations but more heavily influenced by regional ozone precursor emissions than those examined by Parrish et al. (2013). Of these 6 sites only three showed an earlier seasonal ozone peak, therefore the seasonal shift in the ozone cycle is not universal for time periods of 21 years or less. Similar shifts in the ozone seasonal cycle have been observed in the continental USA (Clifton et al., 2014;Simon et al., 2015;Bloomer et al., 2010).

Formatted: Subscript



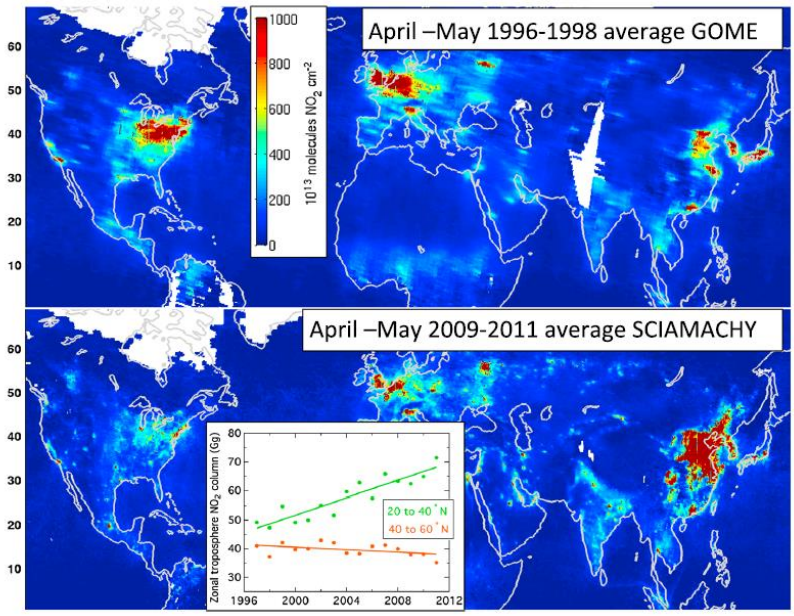


Figure ~~67~~ – a) Comparison of O_3 seasonal cycles at three European and one North American site for two periods separated by 17 to 35 years. The data points and error bars indicate 5 year averages and standard deviations of monthly averaged data for the indicated time periods. The curves of the respective colours are sine function fits to the data. b) Comparison of satellite measured springtime tropospheric NO_2 columns during two time periods separated by 13 years. The inset shows the temporal change in the total zonal troposphere NO_2 column for two Northern Hemisphere Latitude bands. ~~(Parrish et al., 2013)~~(Parrish et al., 2013).

1740

Episodic peak ozone levels in rural areas of Europe have been declining during the last three decades due to regional pollution emission controls applied to the VOC and NO_x emissions from fossil fuel combustion associated with motor vehicles and power plants ~~(Jonson et al., 2006;Jenkin, 2008;Derwent et al., 2010)~~(Jonson et al., 2006;Jenkin, 2008;Derwent et al., 2010). Long-term downward trends have been observed at many long-running rural monitoring stations in the EMEP ozone monitoring network~~,~~ and appear to be more pronounced at those stations where initial episodic peak levels were highest and insignificant at those stations where initial levels were lowest ~~(Derwent and Hjellbrekke, 2013)~~(Derwent and Hjellbrekke, 2013)~~. The decreasing trend of highest percentiles is compatible with the known emissions reductions~~. This behaviour has been interpreted as resulting from the combined effect of regional pollution controls since 1990 ~~(Vautard et al., 2006)~~(Vautard et al., 2006)~~, and this behaviour has also been interpreted as resulting from the combined effect of regional pollution controls~~ and increasing hemispheric ozone levels ~~(Derwent and Hjellbrekke, 2013)~~(Derwent and Hjellbrekke, 2013). In contrast, episodic ozone levels in the high NOx environments of major European towns and cities are now rising towards the levels found in the rural areas surrounding them, as exhaust gas catalysts fitted to petrol and diesel motor vehicles reduce the scavenging of ozone by chemical reaction with emitted nitric oxide~~.~~ (Wilson et al., 2012;Colette et al., 2011).

Formatted: Font: Calibri

Formatted: Font: Calibri

Whereas the vast majority of the scientific literature on ozone trends relies on rural supersites dedicated to the assessment of long term atmospheric change, the records of regulatory monitoring networks are becoming progressively long enough to complete such assessments. In the 1990s European air quality legislation began to include some targets with regards to the ozone monitoring network, so that the network now includes several thousand sites, a few hundred of which have records longer than 10 years. The size and diversity of the data gathered in the Airbase repository (maintained by EEA) offers an unprecedented view into air quality trends in Europe, provided that (1) 10-yr records can be considered long-enough to assess trends, and (2) the station representativeness of thousands of urban and rural background sites can be compared to the handful of supersites used elsewhere. Colette et al ~~(Colette et al., 2011)~~(Colette et al., 2011) and Wilson et al. (2012) (Wilson et al., 2012) propose such assessments and conclude that the dominating picture is towards an increase of ozone in urban areas or non-significance of the rural background trends. They both report that the fraction of sites with an increasing trend is smaller when looking at peaks compared to daily means, but their findings suggest that the earlier reports of opposite signs of trends ~~(Vautard et al., 2006)~~(Vautard et al., 2006) does not hold for this more recent period using this alternate monitoring dataset. By including urban stations in their analysis, Colette et al. (2011) also find an enhanced contribution of upwards trends, hence consolidating the results of Derwent and Hjellbrekke ~~(Derwent and Hjellbrekke, 2013)~~(Derwent and Hjellbrekke, 2013) regarding the fact that urban areas are gradually becoming closer to rural levels.

The anthropogenic contributions to the observed trends are difficult to extract from the measurements, and reflect changes in both the magnitude and distribution of precursor emissions. While global average ozone responds to changes in global precursor emissions, trends at a given location are influenced by local, regional and global emission changes that may offset each other. Multi-model ensemble studies of the contribution of regional anthropogenic emission changes to

regional and global surface ozone conducted under the LRTAP task force on Hemispheric Transport of Air Pollution, HTAP, ~~(Fiore et al., 2009;HTAP, 2010)~~(Fiore et al., 2009;HTAP, 2010) have been used to assess the relative contributions of long range transport and regional emission changes to regional ozone ~~(Wild et al., 2012)~~(Wild et al., 2012). These show annual mean surface ozone increases of nearly 0.3 ppb/yr at northern mid-latitudes between 1960-1980, similar to observed changes (e.g., ~~(Parrish et al., 2012)~~(Parrish et al., 2012)), but small net decreases in surface ozone over Europe and North America since 1990 when anthropogenic emissions over these regions are believed to have peaked. A recent comparison between ozone observations at northern mid-latitudes and output from three current chemistry-climate models shows that the models (1) overestimate ozone mixing ratios, on average by ~5 to 17 ppbv in the year 2000, (2) capture only ~50% of ozone changes observed over the past five to six decades, and little of observed seasonal differences, and (3) capture ~25 to 45% of the rate of change of the long-term changes ~~(Parrish et al., 2014)~~(Parrish et al., 2014). These differences may reflect poor representation of emission changes or ozone changes due to natural sources, or they may reflect more fundamental weaknesses in resolving key chemical ~~or~~, dynamical processes or climate variability over continental regions. Further detailed analysis of the spatial and seasonal variability of local and regional ozone trends should provide a more critical test of our current understanding of the processes affecting ozone as represented in current models.

Formatted: Left, Indent: First line: 0 cm, Space After: 10 pt, Border: Bottom: (No border)

2.3 Ozone precursors

The spatial and temporal distribution of ozone and its precursors are in large part driven by the distribution of their emissions. An accurate knowledge of the surface emissions and of their evolution with time is therefore essential to support the analysis and modelling of air quality and climate change interactions. Up-to-date and consistent emissions are moreover required for the forecasting of the atmospheric composition ~~(Frost et al., 2012)~~(Frost et al., 2012).

Gridded global, regional, and national emission estimates exist for many of the pollutants that are important for understanding and analysing the distribution of ozone and its precursors, i.e. NOx, CO, CH_4 and volatile organic compounds (VOCs). Some of these inventories are publicly available, whereas others are developed by individual research groups or government agencies to study specific aspects of emissions or atmospheric processes and are not always easy to access. In this paper, we will focus only on publicly available datasets.

Some inventories provide global coverage with relatively coarse spatial resolution, while others focus only on a specific region for selected species, and provide information at a very high spatial resolution; other inventories consider only specific sectors (such as traffic, shipping, etc.)

Over the past few years, several inventories providing the distribution of surface emissions of gaseous and particulate species were developed, at both the global and regional scales. This section will review the main advances during the past few years concerning surface emissions having the potential to impact ozone distributions and trends. The section will also discuss the current information on emissions uncertainties and we will briefly review the most recent studies using

inverse modelling techniques to evaluate and optimize emission inventories.

2.3.1 Quantification of global emissions of ozone precursors during the past decades

Most anthropogenic emissions estimates are developed using the same methodology, based on the product of estimates for activity data for different sectors and emission factors (mass emitted per activity unit). Activity data are obtained from records provided by different countries or from international organizations such as the International Energy Agency or the United Nations. This leads to a country-based quantification of emissions, which are then gridded using different types of proxies such as population, traffic, ship routes or location of power plants/factories. The quality of the gridding depends on the quality and availability of the proxies, and therefore varies strongly among the different regions of the world.

The data used for the quantification of emissions are not always consistent and many inventory developers adjust these data based on expert judgment. *A priori* emission factors are not always available or reported for all countries and for the differing emission sectors. They depend on different factors such as the level of economic development and the type of technology used in each region.

The emissions inventories developed in the past years cover both global and regional scales. Some of these inventories provide emissions at the country level; some provide emissions for a few species or for a larger number of species, and some provide emissions for one year, a few years or a few decades. The main inventories providing emissions of gaseous and particulate compounds currently used in global modelling or analysis of the atmospheric composition at the global scale and its evolution are: ACCMIP (1850-2000 on a decadal time scale; ~~(Lamarque et al., 2010)~~(Lamarque et al., 2010)) and its extension MACCity (monthly averages for the 1980-2010 period; ~~(Granier et al., 2011)~~(Granier et al., 2011)); EDGARv4.2 (1970-2008; ~~(Janssens-Maenhout et al., 2011)~~(Janssens-Maenhout et al., 2011)) and HTAPv2 (2008 and 2010;~~(Janssens-Maenhout et al., 2012)~~(Janssens-Maenhout et al., 2012)); ECLIPSE (2005-2050; ~~(Klimont et al., 2013c)~~(Klimont et al., 2013b)); RETRO (1960-2000;~~(Schultz et al., 2007a)~~(Schultz et al., 2007a)); HYDE (1890-1990; ~~(van Aardenne et al., 2001)~~(van Aardenne et al., 2001)); POET (1990 and 2000;~~(Granier et al., 2005)~~(Granier et al., 2005)); EDGAR3.2 (year 2000; ~~(Olivier et al., 2005)~~(Olivier et al., 2005)).

Several inventories also provide emissions at the regional scale for different regions of the world. Among these inventories, the TNO-MACC ~~(Kuenen et al., 2011)~~(Kuenen et al., 2011) and TNO-MACCII ~~(Kuenen et al., 2014)~~(Kuenen et al., 2014) provide emissions for Europe at a high spatial resolution ($1/8^{th}$ x $1/6^{th}$ degree), based on the EMEP ~~(Droge et al., 2010)~~(Droge et al., 2010) emissions reported by the European countries. In North America, the US Environmental Protection Agency (EPA) provides emissions since 1980 for the USA (available at http://www.epa.gov/ttnchie1/), and Environment Canada provides non-gridded emissions for Canada since 1985 (available at: http://www.ec.gc.ca). Inventories are provided for Asia by the REAS-v1 (0.5x0.5 degree spatial resolution; ~~(Ohara et al., 2007)~~(Ohara et al., 2007)~~) and REAS v2 (0.25x0.25 degree spatial resolution; (Kurokawa et al., 2013a)). The MEIC dataset (available at meicmodel.org) also provides emissions for China, at a 0.25x0.25 degree resolution, and Sahu et al~~) and REAS-v2 (0.25x0.25 degree spatial resolution; (Kurokawa et al., 2013b)). The MEIC dataset (available at meicmodel.org) also provides emissions for China, at a 0.25x0.25 degree resolution, and Sahu et al ~~(Sahu et al., 2012)~~(Sahu et al., 2012) provide emissions at a 1x1 degree resolution for India, as well as Garg et al. (~~(Garg et al.,~~

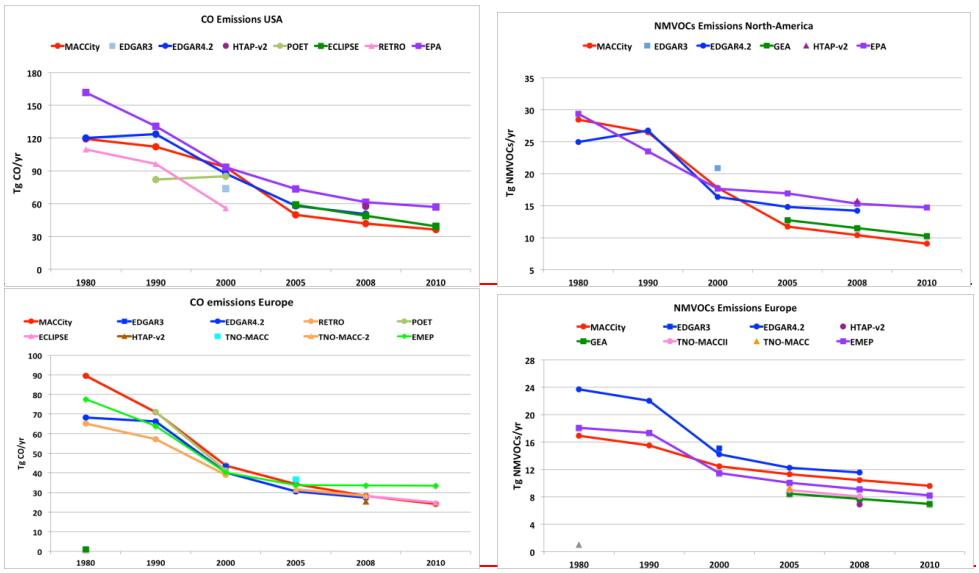
~~2006)~~(Garg et al., 2006) not gridded emissions). Recently, an inventory was also developed for Africa by Liousse et al. ~~(Liousse et al., 2014)~~(Liousse et al., 2014) at a 0.25x0.25 degree spatial resolution.

2.3.3 Evolution of emissions in different regions since the 1980s

During the past three decades and the past few years, surface anthropogenic emissions have shown large changes in a few regions of the world. This section will focus on changes in emissions in Europe, North America and Asia. There is still little information on emissions changes in other areas of the world, and no detailed evaluation of the trends in emissions in these other regions can be made.

a. Emissions in Europe and North America

The implementation of emissions policies reductions in Europe and in North America over the past few decades has led to significant decreases in the emissions of ozone precursors. The agreement between available global and regional inventories is rather good among ~~the global and regional~~these inventories providing emissions of CO and NOx for Europe and of NOx for North America, with differences of 20-30% between the lowest and ~~largest~~highest proposed values. However, larger differences are obtained between inventories providing CO in the USA and NMVOCs in all regions, as shown in Figure ~~7~~8.



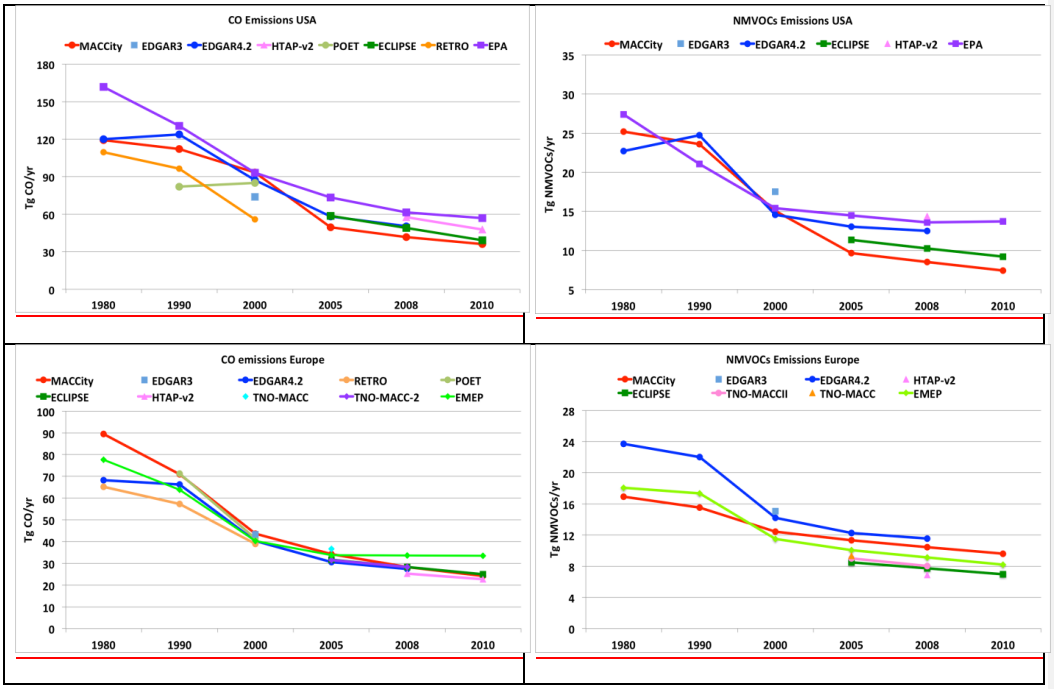


Figure ~~78~~ - Emissions of CO and NMVOCs in the USA and ~~of NMVOCs in~~ Europe (Western and Central Europe~~).~~) from various emission inventories.

Formatted: Justified

A detailed analysis of the changes in emissions of ozone precursors in Europe between 2003 and 2009 has been performed by Kuenen et al ~~(Kuenen et al., 2014)~~(Kuenen et al., 2014). This analysis has been extended in Figure ~~8~~9 by adding emissions for USA and in Canada for the same period. These data highlight the significant decrease in the emissions of NOx, CO and NMVOC over the European and North American continental regions. The changes in Figure ~~8~~9 include shipping activities around Europe and the European seas. In contrast to industrial activities and to transportation in continental areas of Europe and North America, policies leading to the reduction of emissions from shipping have not yet been defined or implemented, resulting in significant increases in these emissions.

~~It is worth noting that nearly 70% of ship emissions occur within 400 km of coastlines, causing air quality problems through the formation of ground level ozone, sulphur emissions and particulate matter in coastal areas and harbours with heavy traffic (Eyring et al., 2010). Offshore shipping sources of NOx may become significant as land based emissions decline (Eyring et al., 2010;Jonson et al., 2009;Dalsøren et al., 2010). The impact of ship emissions on tropospheric oxidants is mainly caused by the relatively large fraction of NOx in ship exhaust. Dalsoren et al (Dalsøren et al., 2010) have shown that typical increases in yearly average surface ozone concentrations in the most impacted areas from shipping emissions are 0.5–2.5 ppbV. Transport emissions are predicted to be a significant contributor to US and European ozone by 2050 (Hauglustaine and Koffi, 2012).~~

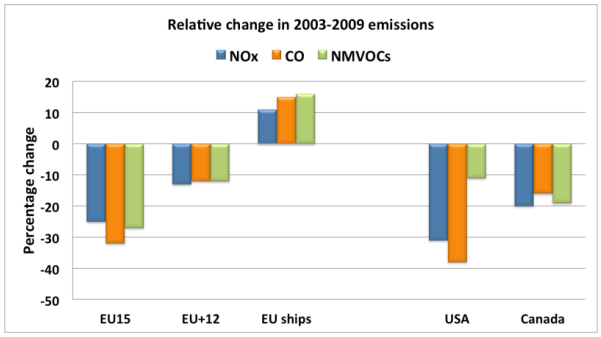


Figure ~~8~~9 - Relative change in NOx, CO and NMVOCs emissions from 2003 to 2009 (from Kuenen et al., 2014), per country group: EU15 includes the EU Member States in 1995 as well as Norway and Switzerland, EU+12 includes the 12 New Member States, EU ships refers to all European sea regions combined. USA emissions are from the USA Environmental Protection Agency (EPA) and data ~~from~~for Canada are from Environment Canada.

b. Emissions in Asia

Emissions in Asia have shown dramatic increases over the past few years, which are now well documented, more particularly for China. Figure ~~9~~10 shows the changes in the emissions of NOx, CO and SO_2 for different Asian regions since 1980: the data in Figure ~~9~~10 highlight the very large increase in NOx emissions in China over the past few years. The main reason for these emissions changes are increases in coal use for energy generation and industrial activities, as well as a large increase in the number of vehicles ~~(Kurokawa et al., 2013b). Zhao et al.~~ (Kurokawa et al., 2013a). Zhao et al. ~~(Zhao et al., 2013)~~(Zhao et al., 2013) have examined the impact of anthropogenic emissions control in China and have shown that these control measures have led to a decrease in the emissions factors and emissions for most compounds, except for nitrogen oxides.

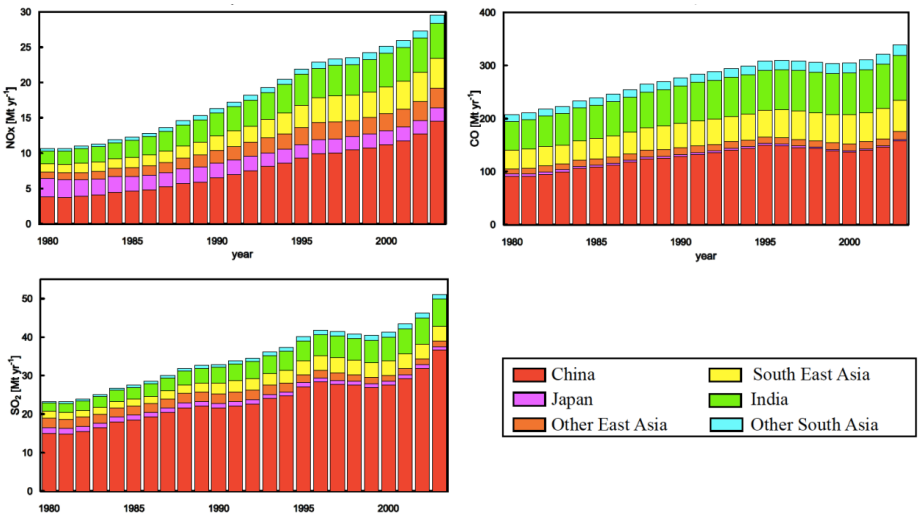


Figure ~~9~~10 - Evolution of surface emissions of CO, NOx and SO_2 for each Asian region (from Kurokawa et al., 2013).

Comparisons between the regional and global inventories show significant differences, as shown in Figure ~~10~~11 (Granier et al., in preparation, 2014): these figures show the total anthropogenic emissions of NOx in China and India from 1980 to 2010, based on the data provided by the inventories mentioned in Section 2.3.1. All the inventories show an increase in the emissions over the years of the NOx emissions, but the magnitude of the emissions and the rate of increase differ significantly between the datasets. There is a difference of about 50% between the lowest and highest total emissions in China. For India, the range of values proposed by the different groups ~~are~~is even larger, with a factor of about 2.5 between the lowest and highest emissions. Since NOx concentration levels are a key factor in the production of ozone (see Section 2.1), such large differences in the emissions could make the analysis of ozone concentrations and their trends rather difficult to achieve.

It should be noted that ~~Figure 10~~Figures 8 and 11 does not display any evaluation of the uncertainties on the inventories: since the data used for developing the inventories (activity data, emission factors) are not provided with estimates of the uncertainties, no estimation of the uncertainties on the emissions can be made.

Formatted: Space After: 0 pt, Widow/Orphan control

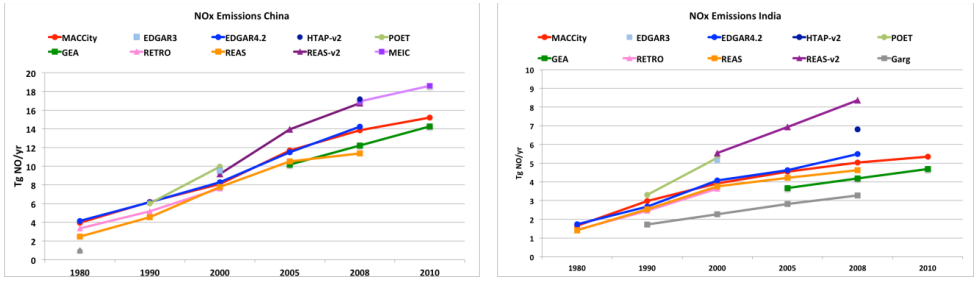


Figure ~~10~~11 - Evolution of NOx emissions in China and India from 1980 to 2010 provided by different global and regional inventories (Units are Tg NO/year)

c) Shipping

It is worth noting that nearly 70% of ship emissions occur within 400 km of coastlines, causing air quality problems through the formation of ground-level ozone, sulphur emissions and particulate matter in coastal areas and harbours with heavy traffic (Eyring et al., 2010). Offshore shipping sources of NOx may become significant as land based-emissions decline (Eyring et al., 2010;Jonson et al., 2009;Dalsøren et al., 2010). The impact of ship emissions on tropospheric oxidants is mainly caused by the relatively large fraction of NOx in ship exhaust. Dalsoren et al (Dalsøren et al., 2010) have shown that typical increases in yearly average surface ozone concentrations in the most impacted areas from shipping emissions are 0.5–2.5 ppbV. Transport emissions are predicted to be a significant contributor to US and European ozone by 2050 (Hauglustaine and Koffi, 2012).

Formatted: Normal, Indent: Left: 0 cm

2.3.4 Uncertainties in anthropogenic emissions in different regions

As indicated in the previous section, most emission datasets are provided without any information on uncertainties on the data used for quantifying the emissions. Several sources of uncertainties

have been identified, which will be summarized in this section.

Activity data and emission factors are generally provided without any information on their uncertainties. Emission factors are empirical functional relations between pollutant emissions and the activity that causes them: a comparison of emission factors is shown on Figure ~~11~~12, which displays measurements of emission factors in Chinese cities from different studies ~~(Huo et al., 2012)~~(Huo et al., 2012). This study has shown that the differences between emission factors are larger for older vehicles than for newer vehicles, which could be an indication of varying deterioration of emissions ~~when~~as vehicles get older.

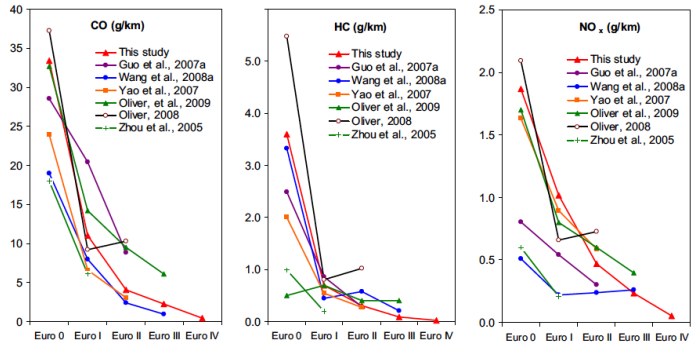


Figure ~~11~~12 - Comparison of emission factors of the LDGVs (light-duty goods vehicles) under real world driving conditions from different studies showing the greater variation for older vehicles. Note that the emission measurement technologies are different among these studies (from ~~(Huo et al., 2012)~~(Huo et al., 2012)).

The seasonal, weekly and daily variations of the emissions are generally not provided with inventories, and are not well characterized. Simple temporal profiles have been developed to describe the changes in emissions over a day, a week and a season, as shown in Figure ~~12~~13 for the European LOTOS-EUROS model ~~(Kuenen et al., 2011)~~(Kuenen et al., 2011). These profiles depend on the emission sectors. The same diurnal profiles are applied for all days of the week and to every country in the model domain for all periods, without taking into account differences in the way of living in different countries and its change with time. Similar profiles are not available for most ~~the~~ countries of the world, leading to large uncertainties in the temporal profiles of the emissions.

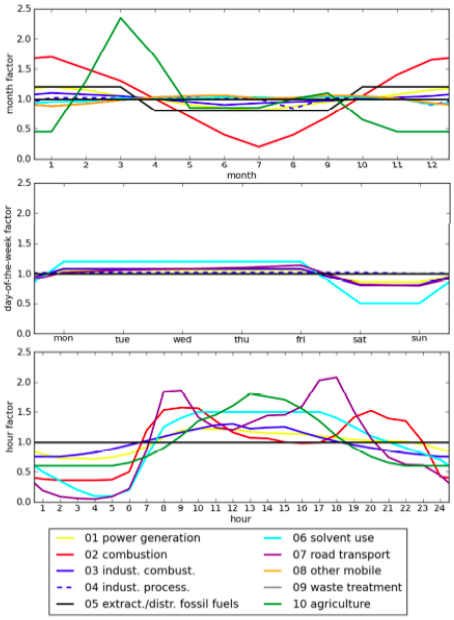


Figure ~~12~~13 - Monthly (top), weekly (middle) and hourly (bottom) time profiles applied to anthropogenic emissions in Europe for different sectors (from Kuenen et al., 2011).

Good speciation of the NMVOCs lumped species is important for inventories. The translation of speciation into global and sometimes regional models chemical schemes is generally poor: a gridded speciated dataset has been developed as part of the RETRO inventory ~~(Schultz et al., 2007a)~~(Schultz et al., 2007a), and has not been revised or updated since. This speciation is currently applied to most global inventories, for all the past and future decades. In different regions, VOC speciated inventories have been developed for specific emission sectors often based on a few individual measurements that are extrapolated with dubious reliability to related unmeasured emission sources. An example of such a speciation is shown in Figure ~~13~~14 for China ~~(Wei et al., 2008)~~(Wei et al., 2008). Li et al. ~~(Li et al., 2014)~~(Li et al., 2014a) have developed a speciation for Asia, which provides emissions of a large set of VOCs for different model chemical schemes, for individual VOCs and lumped species.

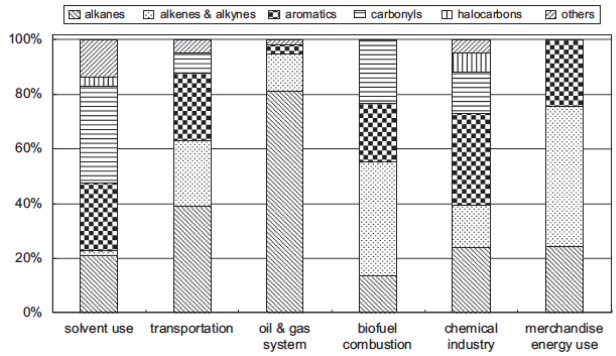


Figure ~~13~~14 - Chemical speciation for various emission sectors in China ~~(Wei et al., 2008)~~(Wei et al., 2008)~~.~~ showing the wide variation of VOCs with source that need to be represented in emission inventories.

Detailed information ~~of~~on the proxies used for the determination of the distribution in space of the emissions, i.e. on the proxies used for gridding emissions are also lacking. Other large uncertainties ~~on~~in the emissions are linked with resources (oil and gas) extraction and flaring, and to inland and international shipping. Emissions from agricultural practices (cattle, fertilizers, agriculture waste burning) are also very uncertain.

In order to summarize the uncertainties on anthropogenic emissions, we have calculated, for all the inventories mentioned in Section 2.3.1 the minimum, average and maximum values of the emissions for different world regions for NOx, CO and NMVOCs emissions in 2005. The ranges shown in Figure ~~14~~15 cannot be considered as a quantification of uncertainties, but they provide information on the differences between currently available datasets. Detailed evaluations of the uncertainties on anthropogenic emissions have started: for example, a methodology applying Monte Carlo simulations to quantify the uncertainties, represented as probability distributions, for the emissions of several compounds in China was proposed by Zhao et al. ~~(Zhao et al., 2011)~~(Zhao et al., 2011).

Figure ~~14~~15 also highlights the ~~growing of~~ emissions in Africa and the rest of Asia (all Asian regions except China and India), regions where more detailed information is required for a better analysis and modelling of the global atmospheric composition.

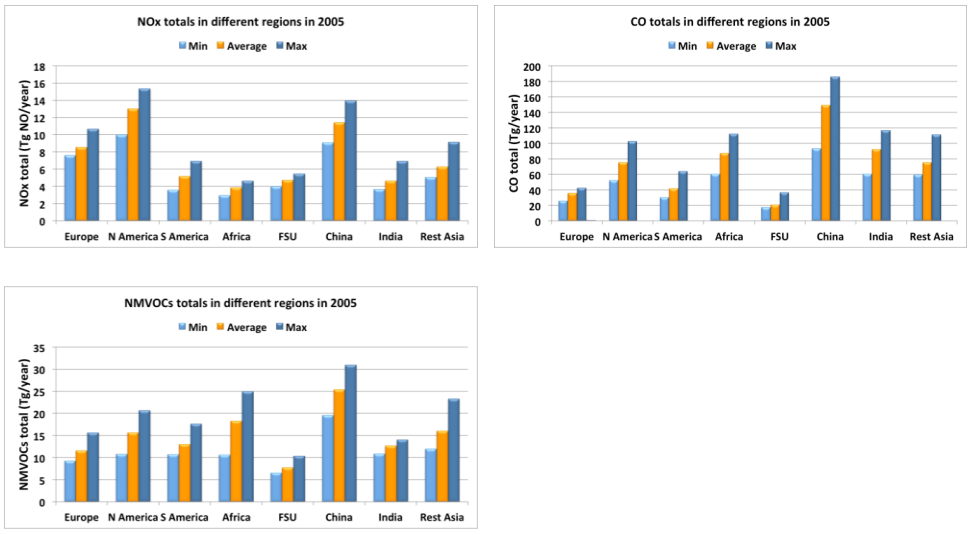


Figure ~~14~~15 - Minimum, average and maximum emissions taken from various inventories of NOx, CO and NMVOCs for different regions of the world in 2005. The emissions of NOx are reported in Tg NO/year.

2.3.5 Emissions from fires

~~In the last few decades biomass burning has been recognized as an important source of ozone~~

~~precursors (Hao and Liu, 1994;Schultz et al., 2008). Since wildfires are strongly dependent on meteorological conditions, drought episodes and human behaviour, they have a large interannual variability~~ In the last few decades biomass burning has been recognized as an important source of ozone precursors (Hao and Liu, 1994;Schultz et al., 2008;Turquety et al., 2007). Since wildfires are strongly dependent on meteorological conditions, drought episodes and human behaviour, they have a large interannual variability ~~(Duncan et al., 2003)~~(Duncan et al., 2003)~~,~~ and the resulting emissions are very variable in time and space. It is therefore important to accurately characterize fire emissions, since they will partly drive the short-term variability of ozone precursors and ozone ~~(Parrington et al., 2012)~~(Parrington et al., 2012). A review of the impact of biomass burning emissions on ozone was published by Jaffe and Wigder ~~(Jaffe and Wigder, 2012)~~(Jaffe and Wigder, 2012).

The first inventories relied on data reported by forest services, observations from the ground and from aircraft. Since the late 1990s, several inventories providing emissions from fires have been developed based on observation of active fires and burnt areas by satellites, and more recently of fire radiative energy. Other inventories have also been developed, through the representation of fires in biogeochemical models. The most recent global datasets providing a spatial distribution of the emissions of ozone precursors from fires are: MACCity (monthly, 1960-2008, 0.5x0.5 degree resolution; ~~(Granier et al., 2011)~~(Granier et al., 2011)), GFAS (daily, 2003 to present, 0.5x0.5 degree resolution; ~~(Kaiser et al., 2012)~~(Kaiser et al., 2012)), GFEDv2 (monthly, 1997-2010, 0.5x0.5 degree resolution)and GFEDv3 (monthly, 1997-2010, 0.5x0.5 degree resolution) ~~(van der Werf et al., 2006;van der Werf et al., 2010)~~(van der Werf et al., 2006;van der Werf et al., 2010), IS4FIRES (daily, 2000-2013, 0.1x0.1 degree resolution, ~~(Sofiev et al., 2009)~~(Sofiev et al., 2009)), FINN (daily, 2002-current, 1x1 km resolution, ~~(Wiedinmyer et al., 2011)~~(Wiedinmyer et al., 2011)), GUESS-ES (monthly, 1970-2009, 1x1 degree resolution, ~~(Knorr et al., 2012)~~(Knorr et al., 2012)), GICC (monthly, 1900-2005, 0.5x0.5 degree resolution, ~~(Mieville et al., 2010)~~(Mieville et al., 2010)), Kloster (monthly, 1900-2004, 1.9x2.5 degree resolution, ~~(Kloster et al., 2010)~~(Kloster et al., 2010)), RETRO (monthly, 1980-2000; 0.5x0.5 degree resolution, ~~(Schultz et al., 2008)~~(Schultz et al., 2008)).

The inventories providing daily emissions have highlighted the very large variability of emissions from fires in the different regions of the world. Only datasets providing emissions at a high temporal resolution are able to provide information on short and intense fire episodes, which happen often in different regions of the world, as a result of specific weather conditions or human-ignited fires. An example of this variability is shown on Figure ~~15~~16, from the FINN datasets ~~(Wiedinmyer et al., 2011)~~(Wiedinmyer et al., 2011), which also highlights the ~~constant~~large number of high fire episodes in each hemisphere.

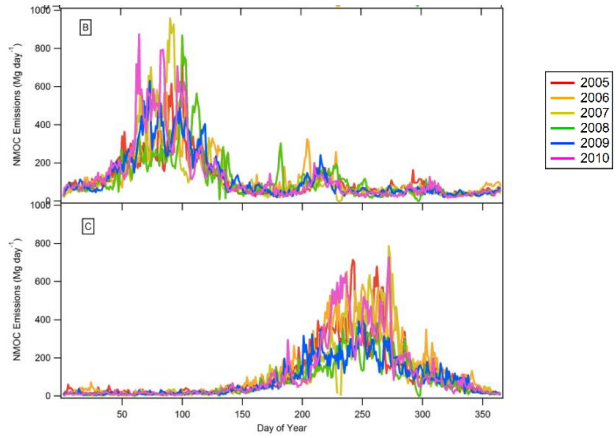


Figure ~~15~~16 - Daily emissions of NMVOC from fires for 2005 through 2010 for the Northern Hemisphere (top) and the Southern Hemisphere (bottom) as represented in the FINN dataset ~~(Wiedinmyer et al., 2011)~~(Wiedinmyer et al., 2011).

Several studies have evaluated the differences between estimates of fire inventories, and have highlighted the large differences remaining between available datasets in different regions. Figure ~~16~~17 displays a comparison of several of the datasets previously detailed, for carbon monoxide in Africa and South America (from ~~(Granier et al., 2011)~~(Granier et al., 2011)). Differences in the emissions for each year, as well as in the interannual variability of the emissions are very large. It should be noted that the AMMA inventory for Africa, which includes the use of satellite observations as well as local information on the fires provides significantly larger emissions than the other inventories, which are based either on satellite data only, or on fires modelling.

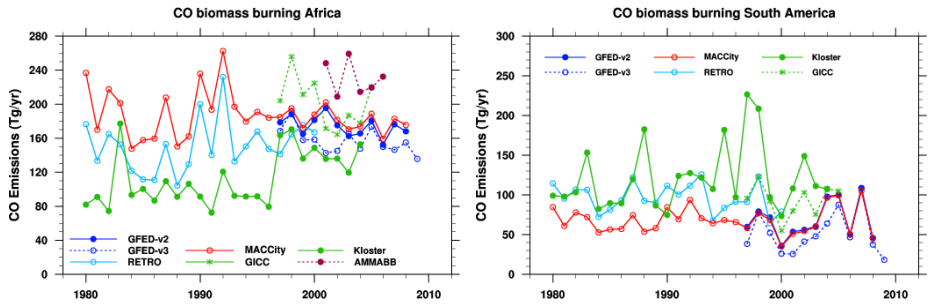


Figure ~~16~~17 - Emissions of CO in Africa (left column) and South America (right column) from 1980 to 2009; from ~~(Granier et al., 2011)~~(Granier et al., 2011).

Another view of the differences between datasets is provided in Figure ~~17~~18, where CO emissions from different estimates are reported for different biomes (from ~~(Kaiser et al., 2013)~~(Kaiser et al., 2013)). The largest differences are reports for peat and savannah fires. The seasonal variation shown in these datasets is relatively consistent, except for temperate forests, where the consistency is very low.

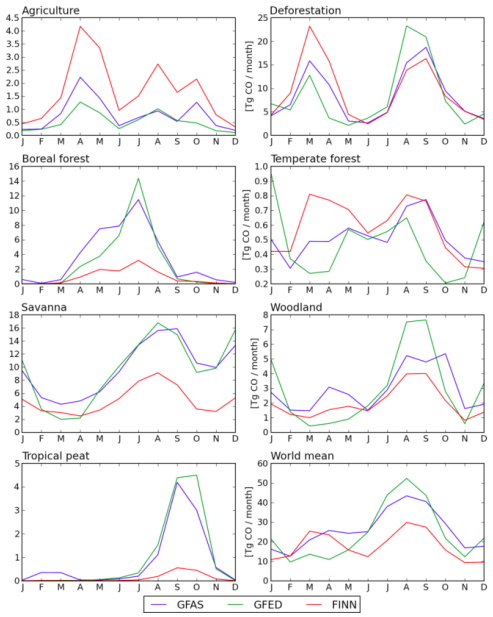


Figure ~~17~~18 - Mean seasonal CO emissions for 7 biomes associated with dominant fire type in GFED (see Figure 17~~-1b~~) and the world for 2003 until 2011. Emissions are shown for three different fire emission inventories: GFAS, GFED and FINN ~~(Kaiser et al., 2013)~~(Kaiser et al., 2013).

The differences shown in Figure ~~17~~18 demonstrate a limit to the accuracy of emissions resulting from biomass burning. In turn, these impact on the distribution of ozone precursors and ozone through uncertainties on burned area, fuel load, emission factors and injection heights.

Data on burned areas from long-term monitoring have become available only recently, i.e. after 1995, and these data have been evaluated only for a few regions. The satellite data provide good information on spatial and temporal patterns of fire occurrence, but so far they have not provided quantitative information with high accuracy (e.g., ~~(Giglio and Kendall, 2004)~~(Giglio and Kendall, 2004)). These data complement data on fires in the mid-latitude regions, which are well monitored in many countries. However, monitoring by tropical countries is still scattered and scarce, owing to limited resources at the local level for records and accessibility. The effect of temporal resolution of fire emissions on models has been recently explored ~~(Marlier et al., 2014)~~(Marlier et al., 2014).

The amount of fuel load and the combustion factors are calculated either from ecosystem models or through empirical formulas: these quantities depend on the fire severity, the fuel characteristics (foliage and biomass density, moisture, vegetation type, organic content and moisture of the soil) and the rate of spreading. These factors are highly variable and different studies have shown that large uncertainties still remain ~~on~~in the spatial and temporal variation of this quantity. A study by Knorr et al. ~~(Knorr et al., 2012)~~(Knorr et al., 2012) has shown that the choice of the burned area dataset has by far the largest impact on interannual variability of simulated emissions, and that for the quantification of the total global emissions, burned area and combustion completeness have the largest impact on emissions for most species.

Emissions factors for the different species are generally taken as constant for each type of ecosystem

in different countries. However, emissions from a fire depend on the fuel type and fire characteristics, and they are often poorly determined. Most inventories currently use the emission factors compiled by Akagi et al. ~~(Akagi et al., 2011)~~(Akagi et al., 2011) or the Andreae and Merlet ~~(Andreae and Merlet, 2001)~~(Andreae and Merlet, 2001) compilation and following updates. Results from different studies nevertheless stress that more complete combustion, as in flaming fires, would lead to a larger fraction of highly oxidized species (e.g., CO_2, NOx), while smouldering fires release more material in reduced form (e.g., CO, NH_3 and NMVOC species), which indicates that emission factors may vary with season, and that fire characteristics can be very different from one fire to another even within the same geographical location. Emissions factors from peat fires are not well quantified with different studies reporting a wide range of values ~~(Akagi et al., 2011)~~(Akagi et al., 2011).

The lifetime of the species released ~~in~~from fires depends on chemical processes in ~~fires~~fire plumes and therefore on the vertical distribution of the plumes. The plume injection height can be critical in the impact of biomass burning~~.~~ (Leung et al., 2007). Several studies have proposed plume models or parameterization of the top height of the plumes, based on empirical methods or on the use of satellite observations ~~(Tosca et al., 2011;Martin et al., 2010)~~(Tosca et al., 2011;Martin et al., 2010). A determination of the vertical profiles of fires emissions at the global scale was proposed by Sofiev et al. ~~(Sofiev et al., 2013)~~(Sofiev et al., 2013), based on satellite observations and semi-empirical formulas. An example is shown in Figure ~~18~~19, which highlights the importance of meteorology in the day-night variation of the height of fire plumes. It is worth noting that the diurnal variation of the injection height is significant such that one can practically consider two independent datasets, one for daytime and one for nighttime, with transition during morning and evening (Sofiev et al., 2013). The influence on ozone can be a combination of injection height and frequency ~~(Williams et al., 2012)~~(Williams et al., 2012).

Formatted: Font: Calibri

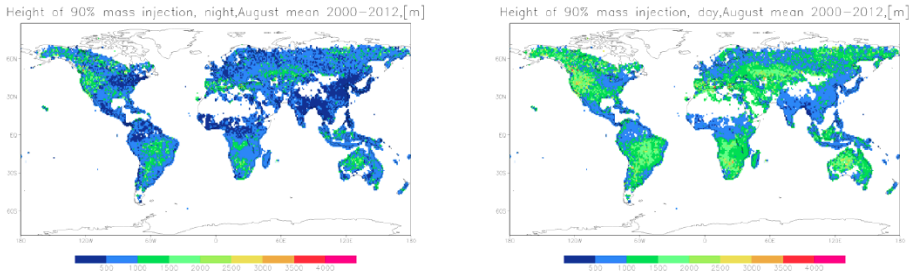


Figure ~~18~~19 - Injection height (in m) for 90% of the mass injection for night (left) and day (right) for August ~~for~~from biomass burning ~~from (Sofiev et al., 2013)~~(Sofiev et al., 2013).

2.3.7 Natural emissions

Natural processes in the atmosphere, vegetation and oceans lead to the emissions of a wide range of compounds ~~(Granier et al., 2004)~~(Granier et al., 2004). Emissions resulting from lightning are discussed in Section 4.7. This section only focuses on emissions of hydrocarbons from vegetation, since they can have a large impact on the distribution of ozone and its precursors and because terrestrial vegetation is the dominant source of atmospheric VOCs ~~(Guenther et al., 1995)~~(Guenther et al., 1995). The emissions of isoprene and monoterpenes are the largest, but many other

Formatted: Space After: 0 pt, Don't adjust space between Latin and Asian text, Don't adjust space between Asian text and numbers

compounds are also emitted. Many studies performed during the past few years have used MEGAN (Model of Emissions of Gases and Aerosols from Nature) to quantify the emissions of biogenic VOCs to the atmosphere. MEGAN is a model system calculating temporal and spatial rates of emission of chemical compounds from terrestrial ecosystems to the atmosphere under varying environmental conditions. It was first introduced by Guenther et al. ~~(Guenther et al., 1995;Guenther et al., 2006;Guenther et al., 2003;Guenther et al., 1993)~~(Guenther et al., 1995;Guenther et al., 2006;Guenther et al., 2003;Guenther et al., 1993). The most recent version of the model, MEGAN v2.1 was introduced in Guenther et al. ~~(Guenther et al., 2012)~~(Guenther et al., 2012) ~~and Sindelarova et al. (Sindelarova et al., 2014).~~. The current algorithm takes into account the impact of past and present temperature, light (sun-lit and sun-shaded leaves), leaf age, CO_2 inhibition of isoprene emissions and losses of primary emissions in the canopy and soil moisture.

Examples of emissions of isoprene, monoterpenes and methanol in 2003 are shown in Figure ~~19~~20, together with the relative contribution of the different biogenic VOCs to the total amount emitted. Isoprene emissions account for 56% of the total, which indicates that the emissions of the other BVOCs and their chemical oxidation schemes (see section 4.3 and 4.10) also need to be taken into account when simulating the atmospheric composition of the atmosphere.

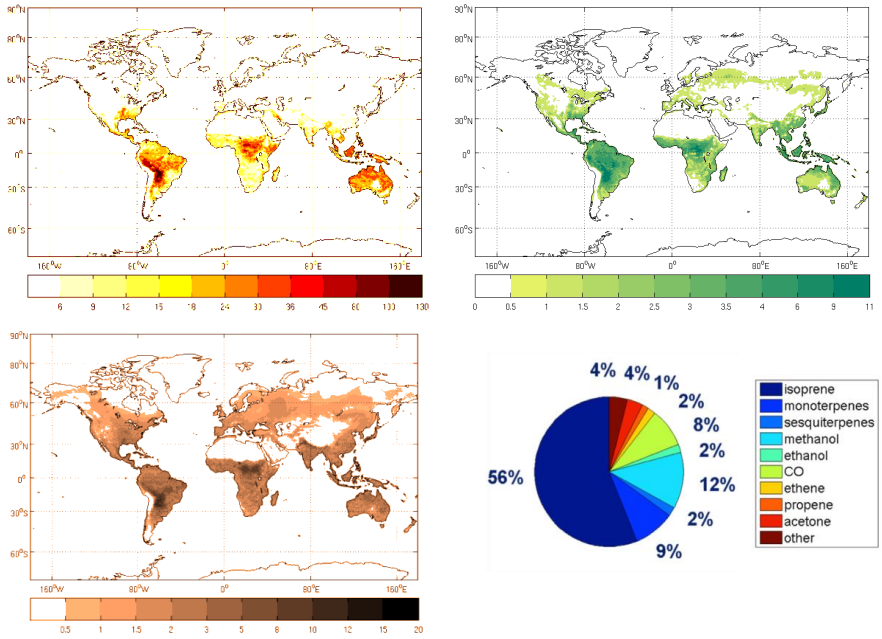


Figure ~~19~~20 - Mean annual emissions (in ($mg.m^{-2}.day^{-1}$) of isoprene (top left), monoterpenes (top right), methanol (bottom left), and contribution of each BVOCs to the annual global total average (bottom right) ~~(Sindelarova et al., 2014)~~(Sindelarova et al., 2014).

Previous studies show significant differences between the total amount of BVOCs emitted by vegetation ~~(Sindelarova et al., 2014)~~(Sindelarova et al., 2014). These differences are related to the large uncertainties of different factors driving BVOCs emissions, such as radiation amount, leaf

temperature, and parameterization of the soil moisture factor or the representation of canopy processes. There are also large differences in the vegetation types and in the distribution of plant functional types used in different models and/or their assignment with BVOCs emission activity.

Other methods have been used to calculate the emissions of BVOCs by the vegetation. Arneth et al. (2007) ~~(Arneth et al., 2007)~~(Arneth et al., 2007) have for example calculated the emissions using a dynamic global vegetation model (LPJ-GUESS, ~~(Sitch et al., 2003)~~(Sitch et al., 2003)) and a physiological BVOCs emission algorithm. Studies conducted using the LPJ-GUESS model ~~(Arneth et al., 2011)~~(Arneth et al., 2011) have shown that variations of driving input data such as meteorology and vegetation description among different models might lead to substantially different emission estimates.

Figure ~~20~~21 shows the differences between previous estimates of global total isoprene emissions: the difference between the lowest and ~~largest~~highest estimate is 65%. In ~~figure 20~~Figure 21, the three values indicated by green bars correspond to an optimization of isoprene emissions using inverse modeling techniques and formaldehyde satellite observations (see next section). The difference between the highest and lowest value is about a factor of two, which highlights the large uncertainties on the determination of isoprene emissions.

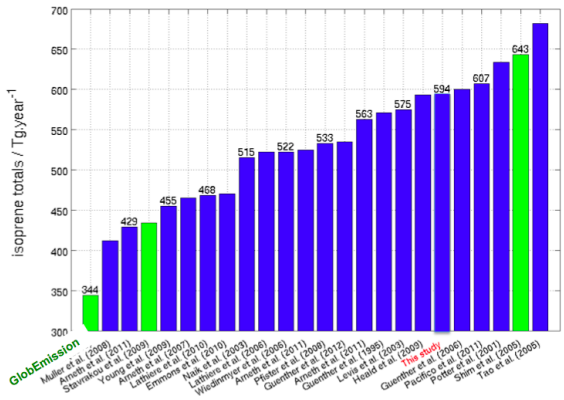


Figure ~~20~~21 - Isoprene global total estimated from different studies. Studies highlighted in green used formaldehyde satellite data and an inversion modeling technique to constrain isoprene emissions ~~(Sindelarova et al., 2014)~~(Sindelarova et al., 2014).

2.3.8 Evaluation and optimization of emissions using inverse modelling techniques

Inverse modelling techniques have been widely used during the past few years to optimize surface emissions so that simulated atmospheric concentrations can reproduce observed concentrations. Most recent studies either minimize the weighted distance between model and observations (variational approach) or minimize the error variance of the estimated parameters (Kalman Filter techniques) ~~(Saide et al., 2011)~~(Saide et al., 2011). Differences between the distributions provided by the models and the observations are not only due to inaccuracies on the quantification of emissions, errors in the model data (meteorological fields for example), but also in the representation of

physical and chemical processes in the models: all these factors need to be taken into account in inverse systems ~~(Elbern et al., 2007)~~(Elbern et al., 2007). Estimates of emissions using inverse techniques also depend on the *a-priori* emission dataset used, on the meteorological fields used to drive the models used that infer emissions ~~(Arellano and Hess, 2006)~~(Arellano and Hess, 2006), and on the data used in the optimization of the emissions ~~(Hooghiemstra et al., 2012)~~(Hooghiemstra et al., 2012). A review of the current capabilities of inverse techniques to better quantify surface emissions in North America using satellite observations was published by Streets et al., 2013 ~~(Streets et al., 2013)~~(Streets et al., 2013).

These techniques have been mostly applied to the species for which observations from satellite are available or for the optimization of local/regional emissions when comprehensive observation datasets exist. Therefore, most studies have discussed the optimization of greenhouse gases (CO_2 and CH_4), of ozone precursors CO and NO_2, of aerosols and their precursors (see ~~(Fuzzi et al., 2014)~~(Fuzzi et al., 2015) companion paper), and of biogenic emissions using satellite observations of formaldehyde.

Several studies have applied inverse modelling techniques to the optimization of CO emissions using observations from surface networks ~~(Petron et al., 2004)~~(Petron et al., 2004) as well as observations from the MOPITT and IASI satellite instruments. Most of these studies using satellite data have concluded that the a-priori anthropogenic emissions of CO might be underestimated as indicated in Figure ~~21a~~22a ~~(Fortems-Cheiney et al., 2011)~~(Fortems-Cheiney et al., 2011) and 22b ~~(Tohjima et al., 2014)~~(Tohjima et al., 2014), more particularly at mid-latitudes of the northern hemisphere in winter ~~(Kopacz et al., 2010;Stein et al., 2014)~~(Kopacz et al., 2010;Stein et al., 2014). However, an analysis of satellite and aircraft observations has also shown that emissions inventories in North America might provide overestimated values ~~(Miller et al., 2008)~~(Miller et al., 2008). Emissions resulting from fires have also been optimized, and showed that current surface inventories might underestimate fires in boreal regions ~~(Pfister et al., 2005)~~(Pfister et al., 2005). Inverse techniques have also provided information on the seasonal cycles of emissions from fires, for example in Africa as shown by Chevallier et al. ~~(Chevallier et al., 2009)~~(Chevallier et al., 2009).

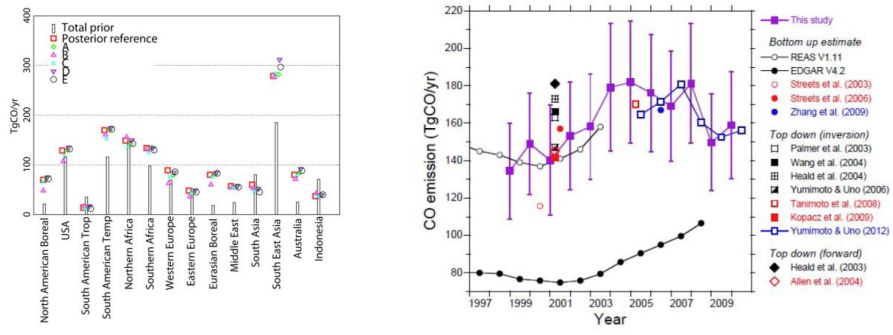


Figure ~~21~~22 - (a, left): Annual total posterior CO emissions per region for year 2004 compared to the a priori reference : the different cases correspond to tests on different errors in the model ~~(Fortems-Cheiney et al., 2011)~~(Fortems-Cheiney et al., 2011). (b, right) : Comparison of estimated CO annual

Formatted: Font: 11 pt

Formatted: Font: 11 pt

Formatted: Font: 11 pt

Formatted: Font: 11 pt

emissions in China from inventories and inverse studies; the "This Study" refers to a top down estimate ~~(Tohjima et al., 2014)~~(Tohjima et al., 2014).

Several studies have used satellite NO_2 column observations to constrain nitrogen oxide emission inventories through inverse or forward modeling ~~(Martin et al., 2004;Kim et al., 2009;Lamsal et al., 2011;Wang et al., 2012)~~(Martin et al., 2004;Kim et al., 2009;Lamsal et al., 2011;Wang et al., 2012). These studies exploited the relatively short lifetime of tropospheric nitrogen oxides, which ranges from several hours to a few days. As a result, NO_2 has its largest concentrations in the boundary layer close to emission sources, making measurements of NO_2 columns well suited to improving our knowledge of the emissions of NO_x. Two examples of optimizations of NOx emissions using satellite observations are given in Figure ~~22~~23. Figure ~~22a~~23a shows a quantification of emissions trends in China as provided by an inventory and optimized using the ~~SAIAMACHY~~SCIAMACHY/GOME observation for the 1996-2004 period is shown in Figure ~~22~~23 ~~(Zhang et al., 2007)~~(Zhang et al., 2007). From 1996 to 2004, NOx emissions over East Central China region increased by 61% according to the inventory, while a 95% increase in the NO_2 columns was obtained from the satellite observations during the same period. Stavrakou et al. ~~(Stavrakou et al., 2008)~~(Stavrakou et al., 2008) have evaluated the changes in the emissions in different regions of the world from 1997 to 2006 using an inverse method and found larger increases in the optimized emissions when compared to prior emissions in the Far East region, and emissions decreasing faster than in the inventories in North America.

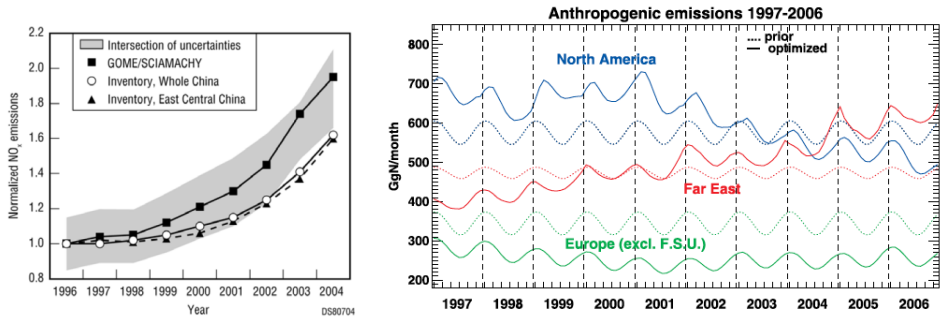


Figure ~~22~~23 - Temporal evolution of NOx emissions over China from the Zhang et al. (2007) inventory and inverse method using satellite observations. All data are normalized to the year 1996 ~~(Zhang et al., 2007)~~(Zhang et al., 2007).

Optimization of the emissions of several other compounds have also been evaluated through inverse methods constrained by satellite observations, such as isoprene, methanol or formaldehyde ~~(Stavrakou et al., 2011;Stavrakou et al., 2009;Palmer et al., 2003;Wells et al., 2014;Barkley et al., 2013)~~(Stavrakou et al., 2011;Stavrakou et al., 2009;Palmer et al., 2003;Wells et al., 2014;Barkley et al., 2013) and other studies have focused on the optimizations of the emissions from different sectors, such as ships (~~(de Ruyter de Wildt et al., 2012;Vinken et al., 2014)~~(de Ruyter de Wildt et al., 2012;Vinken et al., 2014).

Formatted: Font: 11 pt

Formatted: Font: 11 pt

2.4 A climatological view of ozone/linkages across the scales

The available observations show that tropospheric ozone is highly variable both in space and time, on long and short scales. Over the remote oceans, observations show low ozone amounts within the tropical Hadley circulation with little or no vertical gradient in mole fraction, then higher concentrations at mid latitudes, with an increase with height, corresponding to the additional source of tropospheric ozone from STE as well as in-situ chemistry (See ~~figures 23~~Figures 24 and ~~24~~25). Over the continents and nearby oceans in the lower troposphere different behaviour is observed depending on the level of the ozone precursors. Analysis of the seasonal-diurnal variations allows separating the following types of ozone variations in the extra-tropics ~~(Tarasova et al., 2007)~~(Tarasova et al., 2007): clean background, rural, semi-polluted non-elevated, semi-polluted semi-elevated, elevated and ~~polar~~Polar/remote marine. For the "clean background" regime in the Northern hemisphere the seasonal maximum is observed in March-April, both for night and day. For those sites with a double maximum or a wide spring-summer maximum, the spring maximum appears both for day and night, while the summer maximum is more pronounced for daytime and hence can be attributed to photochemical processes. There is much debate as to the origin on the spring maximum likely a combination of dynamical/transport processes and photochemistry ~~(Monks, 2000)~~(Monks, 2000).

In July, northern summer, major regions of elevated lower troposphere ozone are observed over USA, Europe and East Asia from urban/industrial activities and regions of elevated ozone over the tropics due to both biomass burning and other human activities. Satellite observations of tropospheric ozone have revealed much detail about the spatial distribution including the discovery of the regional tropospheric ozone maximum off southwest Africa over the Atlantic Ocean (Figure ~~23~~24) and the oscillation of tropospheric ozone over the Indonesian Archipelago in synchronicity with El Niño ~~(Ziemke et al., 2010)~~(Ziemke et al., 2010). In highly dynamic regions such as the Mediterranean basin ~~(Lelieveld et al., 2002;Lelieveld et al., 2009)~~(Lelieveld et al., 2002;Lelieveld et al., 2009), the strength of the meteorological systems (Azores anticyclone and Middle Eastern depression) are key factors in explaining both the variability and the anomalies of ozone in the lower troposphere in this region ~~(Doche et al., 2014)~~(Doche et al., 2014). Recent observations have suggested there is a summertime free tropospheric ozone pool over the Mediterranean ~~(Zanis et al., 2014;Kalabokas et al., 2013)~~(Zanis et al., 2014;Kalabokas et al., 2013).

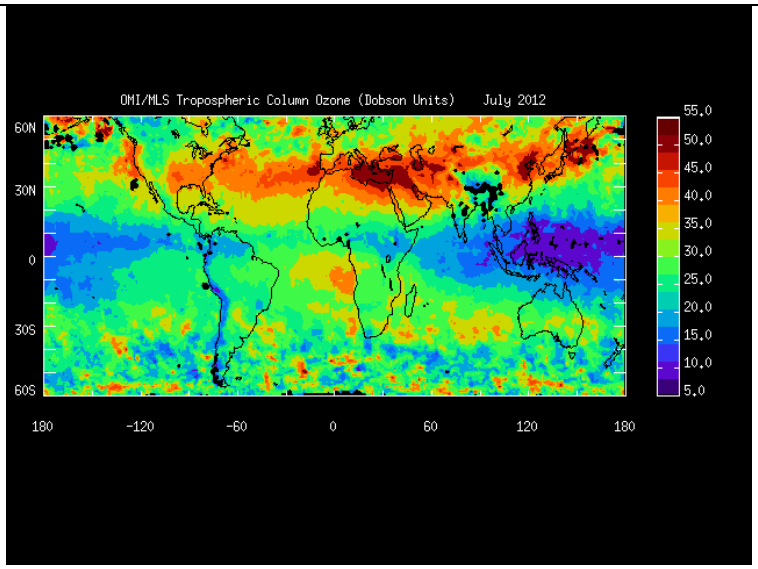


Figure ~~23~~24 - Tropospheric ozone columns determined by residual from OMI observations of total column O_3 and MLS observations of stratospheric O_3 ~~(Ziemke et al., 2006)~~(Ziemke et al., 2006). Plots retrieved from http://acd-ext.gsfc.nasa.gov/Data_services/cloud_slice/index.html#nd

The data in Figure ~~23~~24 clearly highlights the benefits offered by satellite data for investigating the global distribution of tropospheric ozone. However, it should be kept in mind that such data give an incomplete picture ~~(Monks and Bierle, 2011)~~(Monks and Bierle, 2011) which requires complementary observing systems ~~(Laj et al., 2009)~~(Laj et al., 2009)~~. For example, the AMMA campaign (Redelsperger et al., 2006) and associated analysis performed with the in situ MOZAIC (Sauvage et al., 2005) and SHADOZ data (Thompson et al., 2003a;Thompson et al., 2003b) have revealed a somewhat different feature of ozone distribution (both in terms of amount of the tropospheric columns and in the location of the maxima) over Western and Southern Africa including the adjacent Atlantic Ocean. In July, when biomass burning mainly occurs over the southern tropical part of Africa, the tropospheric ozone column is about 45 DU over the continent (Thompson et al., 2014;Sauvage et al., 2005;Sauvage et al., 2006). Export of polluted air masses is observed throughout the Gulf of Guinea up to the coast of West Africa in the northern hemisphere. Reeves et al.~~. It is worth noting that there are direct tropospheric ozone retrievals from satellite data (Liu et al., 2006). The AMMA campaign (Redelsperger et al., 2006) and associated analysis performed with the in-situ MOZAIC (Sauvage et al., 2005) and SHADOZ data (Thompson et al., 2003a;Thompson et al., 2003b) have revealed a somewhat different feature of ozone distribution (both in terms of amount of the tropospheric columns and in the location of the maxima) over Western and Southern Africa including the adjacent Atlantic Ocean. In July, when biomass burning mainly occurs over the southern tropical part of Africa, the tropospheric ozone column is about 45 DU over the continent ~~(Reeves et al., 2010)~~(Thompson et al., 2014;Sauvage et al., 2005;Sauvage et al., 2006)~~ provide a clear characterisation~~. Export of ~~the ozone distribution~~polluted air masses is observed throughout the ~~troposphere over~~Gulf of Guinea up to the coast of West Africa ~~during~~in the ~~monsoon period. Thanks to previous analysis based on MOZAIC data~~northern hemisphere. Reeves et al.~~ (Sauvage et al.,~~

Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)

~~2007a;Sauvage et al., 2005)~~(Reeves et al., 2010) ~~and~~provide a clear characterisation of the ~~regular~~ ozone ~~soundings~~distribution throughout the troposphere over ~~Cotonou~~West Africa during ~~2 years~~the monsoon period. Owing to previous analysis based on MOZAIC data ~~(Thouret et al., 2009)~~(Sauvage et al., 2007a;Sauvage et al., 2005)~~, it has been shown that the biomass burning seasons in both hemispheres impact the tropospheric ozone profiles in both hemisphere as well. As a consequence, a picture like the so called "Ozone paradox" (Thompson and Hudson, 1999) was shown to be no longer valid (Sauvage et al., 2006) owing to the insight provided by additional in-situ observations. Recent work has shown evidence for the removal of ozone in Saharan dust plumes (Andrey et al., 2014) which is correlated with both dust loading and total amount of water present.~~

and the regular ozone soundings over Cotonou over 2 years (Thouret et al., 2009), it has been shown that the biomass burning seasons in both hemispheres impact the tropospheric ozone profiles in both hemispheres as well. As a consequence, a picture like the so-called "Ozone paradox" (Thompson and Hudson, 1999) was shown to be no longer valid (Sauvage et al., 2006) owing to the insight provided by additional in-situ observations. Recent work has shown evidence for the removal of ozone in Saharan dust plumes (Andrey et al., 2014) which is correlated with both dust loading and total amount of water present.

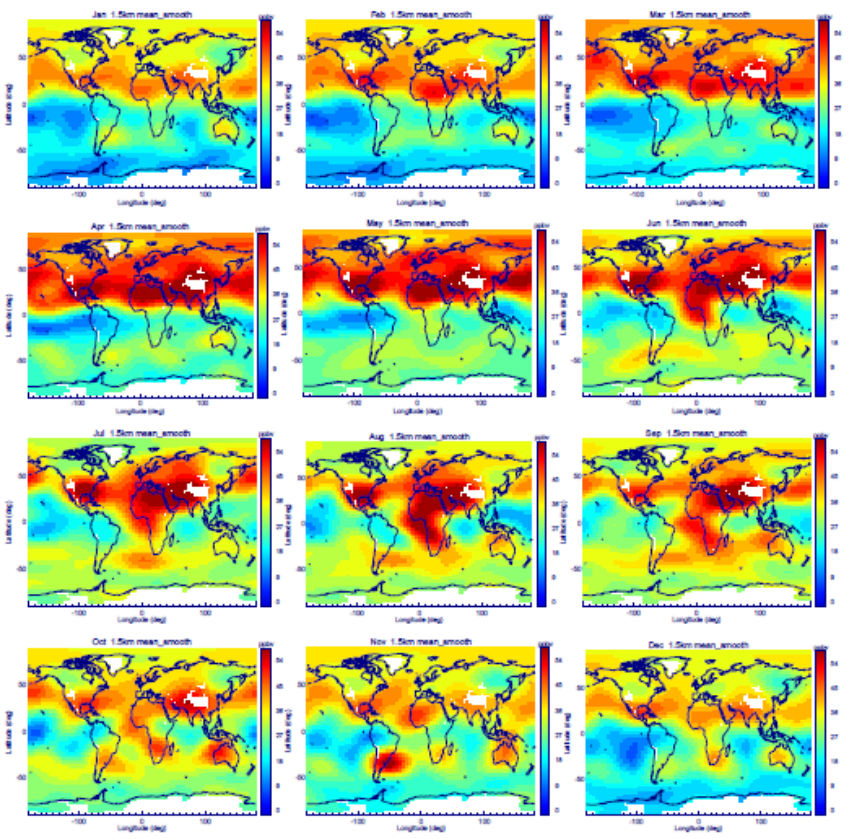


Figure ~~24~~25 – Monthly global ozone distributions at 1.5 km a.s.l from trajectory mapped ozone soundings ~~(Liu et al., 2013a)~~(Liu et al., 2013a).

Formatted: Font: +Body (Calibri)

Formatted: Font: +Body (Calibri)

Formatted: Font: +Body (Calibri)

Formatted: Font: +Body (Calibri)

Formatted: Font: +Body (Calibri)

At coastal or island sites in the tropics diurnal variation in ozone generally show a minimum during the daytime. Occasional air transport events from the mid-latitudes bring in higher ozone concentrations ~~(Lawrence and Lelieveld, 2010)~~(Lawrence and Lelieveld, 2010). The mole fractions are low, typically 5 – 20 ppb, and the annual maximum occurs in June to September, southern winter, a characteristic of ozone in the southern hemisphere troposphere. For more continental tropical regional sources of ozone due to precursor emissions from such activities as biomass burning (e.g. ~~(Ojha et al., 2014;Cristofanelli et al., 2010)~~(Ojha et al., 2014;Cristofanelli et al., 2010)), land clearing, agriculture and human settlements may cause occasional elevated ozone concentrations~~.~~ (Jacob et al., 1996). The seasonal ozone variation may be affected by these activities which can be influenced by seasonal meteorological conditions such as the occurrence of a wet/dry seasons ~~(Valks et al., 2014;Rama Gopal et al., 2014;Cristofanelli et al., 2010)~~(Valks et al., 2014;Rama Gopal et al., 2014;Cristofanelli et al., 2010;Sinha et al., 2014). Under stable conditions, ozone depletion due to ozone deposition and NO titration will occur. The diurnal variation of ozone will generally be characterized by lower concentrations at night and higher concentrations during the daytime (see e.g. ~~(Rama Gopal et al., 2014)~~(Rama Gopal et al., 2014)). Vegetation cover plays an important role together with local meteorology in (natural) trace gas emissions. For example, tropical forests and plantations are among the greatest emitters of isoprene, a reactive hydrocarbon species which is involved in the photochemical cycle of tropospheric ozone (see section 4.3). Replacement of tropical forest by agriculture (e.g. palm trees) may cause potential future elevated ozone levels ~~(Hewitt et al., 2009;MacKenzie et al., 2011)~~(Hewitt et al., 2009;MacKenzie et al., 2011) (see Figure ~~25~~26).

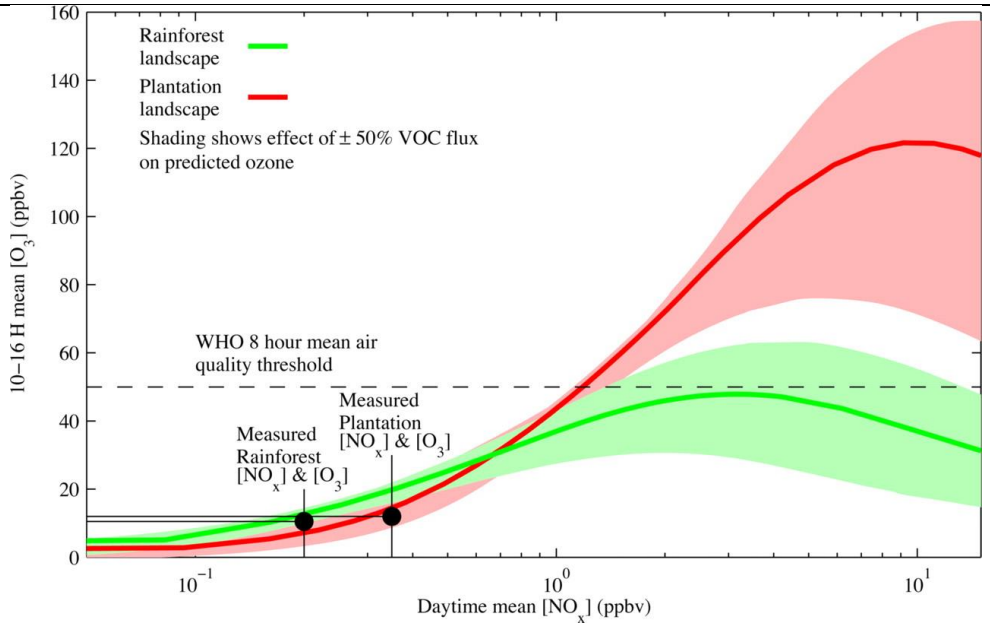


Figure ~~25~~26 – Sensitivity of daytime (10.00-16.00 h) average ozone concentrations to [NOx] in the boundary layer for isoprene and monoterpene emission rates measured in a rainforest and palm oil landscape ~~(Hewitt et al., 2009)~~(Hewitt et al., 2009).

High latitude sites may be influenced by the near continuous presence of snow or ice cover ~~(Helmig et al., 2007)~~(Helmig et al., 2007). Polar sites may have wind directions that remain relatively constant for months. Coastal sites may have ozone depletion events, which are related to halogen chemistry ~~(Simpson et al., 2007)~~(Simpson et al., 2007), and which is evident for example at Barrow during northern spring, March to May ~~(Oltmans et al., 2012)~~(Oltmans et al., 2012). The high reflectivity of snow and ice influences the photochemical reaction rates, because more UV radiation is available than ~~what~~ would be expected for these latitudes if one assumes a global average value for the surface UV albedo. In stable conditions with bright sunlight, local photochemical production has been observed due to NO_x emission from the snow ~~(Helmig et al., 2008a;Helmig et al., 2008b)~~(Helmig et al., 2008a;Helmig et al., 2008b) and this is evident at the South Pole during November to February, centred on southern summer. The ozone concentrations in background air at the South Pole peak in winter/spring and fall to a minimum in summer/autumn as with other southern hemisphere sites.

Moving to the urban scale the local coupling of NO_x and O_3 is important in that reductions in NO can contribute to increases in ozone ~~(Kley et al., 1994)~~(Kley et al., 1994). In areas of high NOx, as is often observed in urban areas, ozone levels can be suppressed through the following reaction:

$$NO + O_3 \rightarrow NO_2 + O_2$$ (~~4~~R4)

This phenomenon, sometimes dubbed 'NOx titration', thereby leads to the counter-intuitive effect that reducing NOx (NO) reduces the amount of ozone being suppressed and actually increases ozone ~~(Heal et al., 2013b;Sicard et al., 2013)~~(Heal et al., 2013a;Sicard et al., 2013). The spatial variability of ozone in larger urban areas can be very much driven by "titration" ~~(Escudero et al., 2014)~~(Escudero et al., 2014). Figure ~~26~~27 shows the gradual increase in urban ozone, moving towards background levels, driven by reducing NOx emissions over the last couple of decades in the UK, decreasing the suppression of ozone. Figure ~~27~~28 shows the "titration" in urban areas across Europe from modelling studies, showing the widespread nature of this effect and the need to couple the regional and hemispheric picture to the urban. In a sense there is an urban decrement driven by this process. Conversely, there has been some work looking at megacity impacts on regional ozone ~~(Tie et al., 2013;Beirle et al., 2011;Guttikunda et al., 2005)~~(Tie et al., 2013;Beirle et al., 2011;Guttikunda et al., 2005) (see also Section 4.1).

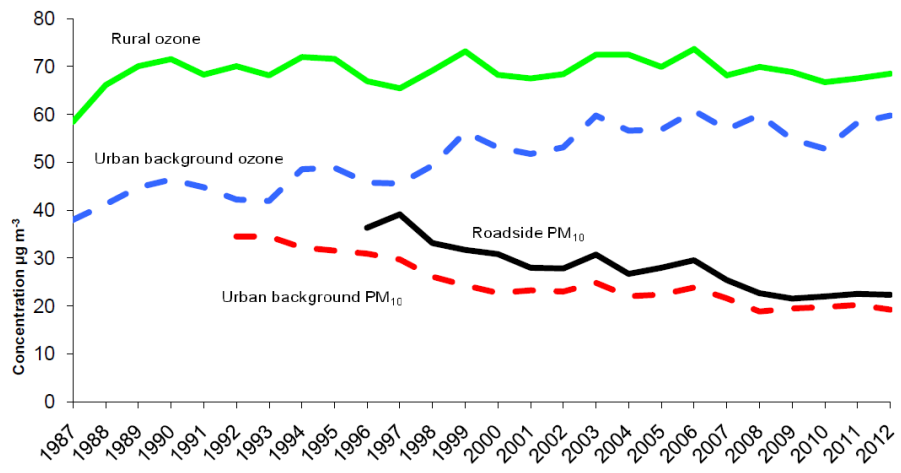


Figure ~~26~~27: Annual levels of ~~PM_{10} and~~ ozone (and PM_{10}) in the UK 1987-2012 ~~(Defra, 2013)~~(Defra, 2013)~~,~~ showing the rise of urban ozone concentrations towards the rural ones and the relatively flat rural concentrations over the last decade.

Given the strong NO_x-O_3 (sometimes referred to as O_x ~~(Zlatev et al., 1992;Yu et al., 2008)~~(Zlatev et al., 1992;Yu et al., 2008), see also Figure ~~27~~28) couple at the urban scale there are a number of issues around the role of an increase in the NO_2:NO emission ratio caused by an increase in the share of diesel vehicles in Europe and the role that may play in ozone formation ~~(Weiss et al., 2012;Carslaw et al., 2011;Carslaw, 2005)~~(Weiss et al., 2012;Carslaw et al., 2011;Carslaw, 2005). Further there are questions as to what extent spatially (along roadsides, across urban areas, regionally) primary NO_2 emissions affect ozone concentrations (see e.g. ~~(Yu et al., 2014)~~(Yu et al., 2014)). Meteorology also plays a large role in local scale ozone concentration affecting deposition and transport (e.g. ~~(Vieno et al., 2010;Francis et al., 2011)~~(Vieno et al., 2010;Francis et al., 2011)) alongside transport and dispersion in urban landscapes such as street canyons etc. (see e.g. ~~(Baker et al., 2004;Zhong et al., 2014;Kwak and Baik, 2014)~~(Baker et al., 2004;Zhong et al., 2014;Kwak and Baik, 2014)). Urban areas are dynamic regions in terms of ~~emmisions~~emmision of ozone precursers that have seen strong changes owing to emmision reduction measures (see e.g. ~~(vonSchneidemesser et al., 2011;vonSchneidemesser et al., 2010;McMeeking et al., 2012;Warneke et al., 2012;Vijayaraghavan et al., 2014)~~(vonSchneidemesser et al., 2011;vonSchneidemesser et al., 2010;McMeeking et al., 2012;Warneke et al., 2012;Vijayaraghavan et al., 2014).

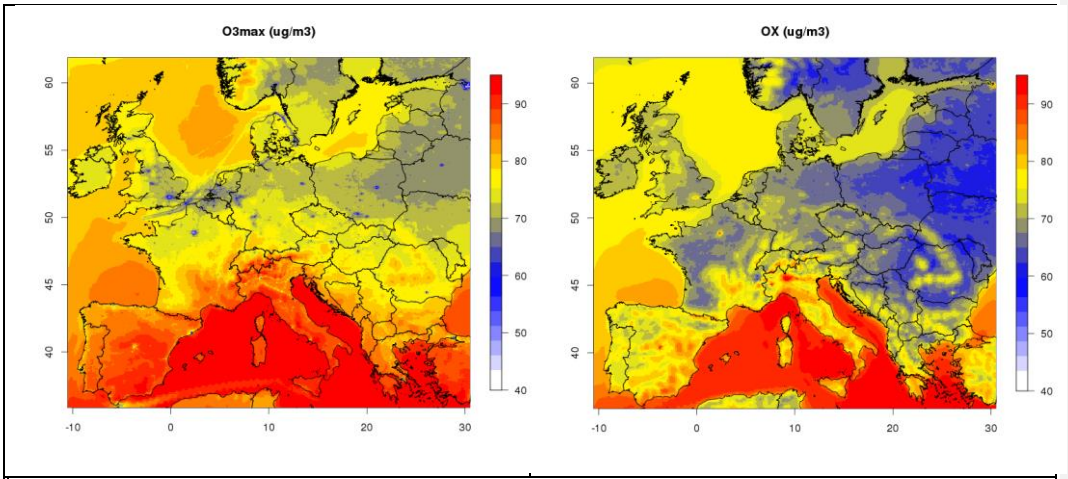


Figure ~~27~~28 - In a continental chemistry transport simulation with the CHIMERE model at a resolution of 8 km, major urban centres in Northern and Central Europe highlight the NOx titration process (left: summertime average of daily maximum ozone) while the total oxidant level (right: O_x as NO_2 + O_3, annual mean) is high in most European cities (adapted from ~~(Terrenoire et al., 2013)~~(Terrenoire et al., 2013)~~, EC4MACS project).~~).

Formatted: Subscript

3 Impacts

Surface level ozone has multiple impacts. As an oxidant it can induce respiratory problems and has been associated with premature human mortality ~~(Bell et al., 2006;Gryparis et al., 2004)~~(Bell et al., 2006;Gryparis et al., 2004). Further it can cause tree/vegetation damage ~~(Krupa and Manning, 1988)~~(Krupa and Manning, 1988), reduce photosynthesis and growth ~~(Reich and Amundson, 1985)~~(Reich and Amundson, 1985) and therefore crop yields ~~(Fiscus et al., 2005)~~(Fiscus et al., 2005) (see also ~~(Felzer et al., 2007;Ashmore, 2005)~~(Felzer et al., 2007;Ashmore, 2005) for recent reviews). Ozone is also an important greenhouse gas ~~(IPCC, 2013)~~(IPCC, 2013).

3.1 Health

Ozone has long been known to cause adverse effects on health ~~(Bates, 2005)~~(Bates, 2005). The gas is a powerful oxidant and short-term inhalation induces inflammation of the entire respiratory tract, although the nasal cavity and the zone between the conducting and gas-exchange airways are potentially more susceptible. Significant inflammation can be detected at ambient levels of ozone in controlled human exposure studies, and although there is some degree of adaptation after repeated exposures, pulmonary inflammation may persist, mainly in the terminal bronchiolar units. As well as elucidating these effects in exposure studies, which naturally exclude the most sensitive or susceptible parts of the population, associations between ozone and mortality and morbidity have also been shown in epidemiological studies, covering the population at large.

Early work on ozone health effects involved mainly exposure studies in chambers. On the basis of this work ozone was included in the first tranche of National Air Quality Standards in the US, with a standard of 80ppb as a 1 hour average, promulgated in 1971 as part of the US Clean Air Act. In

Europe, the first edition of the WHO 'Air quality guidelines for Europe' in 1987 set a 1-hour guideline value of 75-100 ppb. This guideline was also based primarily on chamber studies. Since then much more evidence has accumulated regarding ozone effects, not least from epidemiology studies, and in the 2005 Global Update ~~(WHO, 2005)~~(WHO, 2005) the most recent WHO Guideline is now 50ppb expressed as the maximum 8-hour mean in a day. The same document also sets an interim target of 80 ppb as a daily maximum 8-hour mean, and a 'High Level' of 120 ppb daily maximum 8-hour mean where it notes that "significant health effects could occur" (interim) and that a -"substantial proportion of vulnerable population ~~affected' (sic~~affected" (high).

Earlier WHO guidelines were based on these chamber studies on humans and animals, but the more recent 2005 Global Update from WHO mentioned above additionally used time series epidemiological studies ~~(WHO, 2005)~~(WHO, 2005). However, all guidelines up to and including 2005 referred to short-term exposures and health effects, but the 2005 report noted that at that time there was some evidence that long-term exposure to ozone may have chronic effects but the review concluded that the evidence was insufficient to recommend a guideline. The policy implications of these purely health-based guidelines are discussed in Section 5.

As part of their 'Year of the Air' in 2013 the European Commission requested WHO to review the health effect evidence on the pollutants covered in EU air quality legislation, including ozone. The review was in two parts, firstly a review (REVIHAAP) of the health effect evidence itself, in the form of answers to policy-relevant questions prepared by the Commission, in consultation with the WHO. The final REVIHAP report is available at http://www.euro.who.int/__data/assets/pdf_file/0004/193108/REVIHAAP-Final-technical-report-final-version.pdf . The second part of the process involved a shorter project (HRAPIE) which recommended concentration-response functions for use in health impact assessments and other quantification, for example in integrated assessment modelling to underpin the EU policy process. The HRAPIE report is available at http://www.euro.who.int/__data/assets/pdf_file/0006/238956/Health-risks-of-air-pollution-in-Europe-HRAPIE-project,-Recommendations-for-concentrationresponse-functions-for-costbenefit-analysis-of-particulate-matter,-ozone-and-nitrogen-dioxide.pdf .

The REVIHAAP report addressed three questions relating to ozone where WHO and the European Commission felt a more recent assessment was warranted. The questions posed were

(i) What new evidence on health effects has emerged since the review work done for the 2005 global update of the WHO air quality guidelines, particularly with regard to the strength of the evidence of the health impacts associated with short-term and long-term exposure to ozone?

(ii) What new health evidence has been published in relation to the evidence or likeliness(sic) of a threshold below which impacts are not expected? and

(iii) Based on currently available health evidence, what ozone metrics , health outcomes and concentration-response functions can be used for health impact assessment

The answer to the first question noted that the earlier 2005 global update found evidence only for short-term effects on mortality and morbidity. However an important advance is that several cohort studies have now emerged showing associations between long-term exposures and mortality. Of

particular importance are the studies using the large American Cancer Society cohort. A study ~~(Krewski et al., 2009)~~(Krewski et al., 2009) using single pollutant models found an association between summertime average ozone and all-cause mortality as well as cardiopulmonary mortality, although the high correlation between $PM_{2.5}$ and ozone in the summer months made it difficult to separate the effects of the two pollutants. A further study using the same cohort ~~(Jerrett et al., 2009)~~(Jerrett et al., 2009) found unstable risk estimates for ozone and all-cause, cardiopulmonary and cardiovascular mortality with only respiratory mortality being associated with ozone after adjustment for $PM_{2.5}$. For a more detailed discussion of these and other recent cohort studies ~~(Smith et al., 2009;Zanobetti and Schwartz, 2011;Lipsett et al., 2011)~~(Smith et al., 2009;Zanobetti and Schwartz, 2011;Lipsett et al., 2011) than space here permits, the reader is referred to the REVIHAAP report.

In answering the second question regarding evidence for a threshold, the REVIHAAP report noted that epidemiological studies reporting an effect of long-term exposures to ozone on mortality do not, in general permit the firm identification of a threshold. However the report did draw some conclusions which are helpful to health impact studies.

Earlier chamber exposure studies referred to above have been supplemented by more recent studies showing effects at lower levels. Studies since the 2005 global update have shown that healthy exercising human subjects showed impaired lung function at concentrations of 60ppb for 6.6 hours, relative to clean air controls ~~(Kim et al., 2011)~~(Kim et al., 2011). The report noted that the subjects were healthy adults and thus not representative of the general population, or of real-world combinations of susceptibility and exposure. The REVIHAAP report discusses a number of other studies which report adverse effects at concentrations lower than those in the above study and the reader is referred to that report for a more detailed discussion. The REVIHAAP report concluded that the evidence from epidemiological studies for a threshold for short-term exposures is inconsistent with some large multi-city studies which reported little evidence for a threshold down to near background ozone concentrations, whereas other short-term studies suggest a threshold between 10ppb and 45 ppb daily maximum 1-hour ozone. The report concluded that in summary the evidence for a threshold for short-term exposure is inconsistent but where a threshold is observed it is likely to lie below 45 ppb maximum 1 hour ozone.

The third question, relating to quantification of the health impacts of ozone overlaps with the HRAPIE project, the second part of the WHO review for the European Commission. The REVIHAAP report concluded that a range of health outcomes could be used where baseline rates are known, including all-age, all-cause, cardiovascular and respiratory mortality, and for ages 65 and over respiratory and cardiovascular hospital admissions. The report concluded that the evidence supports the use of all-year coefficients for daily maximum 8-hour average ozone concentrations. Bearing in mind the discussions on a threshold REVIHAAP recommended that cut-off points be used at 35ppb for daily maximum 8-hour ozone 'for consistency with previous work using SOMO35…' (for definition of SOMO see §5 or e.g. ~~(AQEG, 2009)~~(AQEG, 2009)). In an important further step, the report also recommended using a cut-off at 10ppb, I.e. SOMO10.

This latter step is significant in that use of SOMO10 in assessing the effects of most future control strategies already in place or proposed in Europe (and probably elsewhere) are likely to lead to increases in health impacts from ozone exposures. The conclusions of the HRAPIE report essentially

endorsed the findings of the REVIHAAP report, suggesting the use of SOMO10 and SOMO35, and an assessment of long-term exposure impacts as a sensitivity study.

Interestingly, the Impact Assessment for the EU Clean Air package published on 18 December 2013 (http://ec.europa.eu/environment/air/clean_air_policy.htm) only used SOMO35 to assess the health impact of proposed policies. This was justified on the grounds that below this level there are uncertainties in ozone modelling. However, it is convenient that using SOMO35 minimises the impact of increased ozone health impacts which are likely to result if SOMO10 is used. The policy process has yet to come to terms with the possibility that existing and planned control measures are likely to result in increased health impacts from ozone if a low threshold, or a long-term (annual or summer) average concentration is used in impact assessments. A recent modelling study ~~(Heal et al., 2013a)~~(Heal et al., 2013b) which looked at the burden of health impacts from ozone in 12 regions in the UK incorporated the uncertainty over thresholds using a population weighted daily maximum 8-hour mean ozone metric with a cut-off at 35 ppb and also with no threshold. They also incorporated future temperature increases and changes in the tropospheric baseline of ozone, and showed that as expected the assumption of zero threshold gave much larger health impacts. Moreover they showed that under a no-threshold assumption health impacts (deaths brought forward and hospital admissions) in the 'current legislation' scenario *increase* due both to the no-threshold assumption but also with the assumption of an increasing tropospheric ozone baseline. This interplay between the threshold assumption and the future trend in the tropospheric baseline has important implications for policy as discussed in section 5 below.

A not dissimilar process in followed the US context as part of the periodic review process for NAAQS (National Ambient Air Quality Standards). In 2013 the US EPA produced its most recent and substantial integrated science assessment for ozone (http://www.epa.gov/ncea/isa/).

Finally, an interesting new development bridging the gap between atmospheric chemistry and epidemiology is a time-series study of the associations between O_x (defined as $O_3 + NO_2$) and health outcomes ~~(Williams et al., 2014)~~(Williams et al., 2014). As well as having a sound basis in atmospheric chemistry given the rapid interchange between ozone and NO_2, this also has a toxicological rationale since it is probable that both ozone and NO_2 cause harmful effects *via* oxidative stress (although it is recognised that NO_2 could also act *via* other mechanisms). The study showed that the associations between O_x and mortality were stronger than for either of the two pollutants individually, but similar to the pollutants when used in a two-pollutant model. The preliminary conclusion is that in epidemiological studies of either ozone or NO_2, some form of interaction should be incorporated, either as Ox or in a two-pollutant model. Single pollutant models for ozone or NO_2 should not be used.

3.2 Ecosystems

Ozone is phytotoxic. The primary ecosystem impact of ozone is *via* the stomatal uptake of ozone followed by reaction with the internal plant tissues generating highly reactive oxidants that interfere with physiological processes (see also §2.1.2) ~~(Fowler et al., 2009;Matyssek et al., 2008;Matyssek et al., 2010)~~(Fowler et al., 2009;Matyssek et al., 2008;Matyssek et al., 2010)~~. Ozone may also react with~~

~~leaf cuticles and other external plant surfaces as well as the volatile compounds emitted by vegetation~~. Ozone may also react with leaf cuticles and other external plant surfaces as well as the volatile compounds emitted by vegetation. Typical ozone effects on plants include reduced growth, less seed production, lower functional leaf area and earlier leaf senescence. Data compilation studies have shown that many species of plants are sensitive to ozone, including: agricultural crops such as wheat, tomato, soybean and rice and salad crops such as lettuce, spinach and onion (Mills et al., 2007a); grassland species such as clover species, buttercup and harebell (Hayes et al., 2007;Mills et al., 2007b); and tree species such as beech, birch and Holm oak (Karlsson et al., 2007). These effects impact on the important ecosystem services provided by plants, including food security, carbon sequestration, timber production, and protection against soil erosion, avalanches and flooding.

Formatted: Font: Arial, 10 pt

Ozone has been recognised as a pollutant causing damage to vegetation since the 1960s and a research programme to quantify crop loss in North America was established during the 1970s ~~(Karnosky et al., 2007;Adams et al., 1982)~~(Karnosky et al., 2007;Adams et al., 1982). These early studies showed that reductions in exposure to ozone of 40% would reduce the annual costs of ozone damage by $3 billion (at 1980 prices). These early studies used metrics for ozone exposure which were simply the product of ozone mixing ratio and time above a threshold value (40ppb) and had units of ppb hours~~. Global modelling results show that China, India and the United States are currently by far the most affected countries, bearing more than half~~ (AOT 40, see also section 5). Since then, analysis of ~~all global losses and threatened areas~~data from over 700 studies of field-based ozone ~~crop~~ exposure of crops has indicated that many of our most globally important food crops such as wheat, soybean, maize and rice are sensitive or moderately sensitive to ozone ~~(Teixeira et al., 2011)~~(Mills et al., 2007a)~~. Crops such as rice have shown sensitivity to ozone. Research in Europe has improved the methods of assessment and estimates of crop loss (Emberson et al., 2009). In the US context, recent work by Ye and Unger has shown that O_3 damage decreases GPP (Gross Primary Productivity) by 4–8% on average in the eastern US and leads to significant decreases of 11–17% in east coast hot spots (Yue and Unger, 2014). Crops such as rice have shown sensitivity to ozone (Ainsworth, 2008). Work in China has looked at the ozone exposure for rice regions, finding that regions along the Yangtze and south China had the highest risks in 2000, and these risks will double or triple by 2020~~ with estimated global crop production losses owing to ozone totalling 79-121 million metric tons, worth $11-18 billion annually (USD2000) (Avnery et al., 2011a). Global modelling results show that China, India and the United States are currently by far the most affected countries, bearing more than half of all global losses and threatened areas from ozone crop exposure (Teixeira et al., 2011;Sinha et al., 2015). In the US, recent work by Yue and Unger has shown that O_3 damage decreases GPP (Gross Primary Productivity) by 4–8% on average in the eastern US and leads to significant decreases of 11–17% in east coast hot spots (Yue and Unger, 2014). Research in China has looked at the ozone exposure for rice regions, finding that regions along the Yangtze and south China regions had the highest risks in 2000, and these risks will double or triple by 2020 ~~(Tang et al., 2014)~~(Tang et al., 2014)~~. It has been recently estimated that the nationally aggregated yield loss owing to ozone in India is sufficient to feed about 94 million people living below the poverty line (Ghude et al., 2014). Future moves to biofuel crops could enhance the formation of ozone with concomitant negative health impacts (Ashworth et al., 2013;Hardacre et al., 2013).~~

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

~~Ozone risks for crops and pastures depend on exposure, leaf uptake and the plant's defence capacity (Fuhrer, 2009;Kangasjarvi et al., 1994). The extent of ozone damage has been shown to be directly proportional to the stomatal ozone flux for a range of crop plants in excess of a threshold value, recognising that vegetation has an innate capacity to detoxify oxidants~~. In India, The total economic cost losses for ozone on crop yields in the Indian states of Punjab and Haryana amounted to USD6.5 billion in the fiscal year 2012–2013 and USD3.7 billion in the fiscal year 2013–2014 (Sinha et al., 2015). It has been recently estimated that the nationally aggregated yield loss owing to ozone in India is sufficient to feed about 94 million people living below the poverty line (Ghude et al., 2014). In Europe, wheat yield losses were estimated at 14% due to ozone in the year 2000 in EU27 (plus Switzerland and Norway), equivalent to 3.2 billion Euros falling to 9% and 2 billion Euro in 2020 with implementation of current legislation (Mills and Harmens, 2011). It has been argued that plant breeding that incorporates O_3 sensitivity into selection strategies will be increasingly necessary to achieve sustainable production with changing atmospheric composition ~~(Fowler et al., 2009)~~(Wilkinson et al., 2012;Booker et al., 2009)~~. Recent analyses have shown a crop loss of 14% due to ozone in the year 2000, equivalent to 3.2 billion Euros~~. Future moves to biofuel crops could enhance the formation of ozone with concomitant negative health impacts ~~(Mills et al., 2011)~~(Hardacre et al., 2013;Ashworth et al., 2013)~~. The same authors show that semi-natural vegetation has a similar range of sensitivity to ozone as crop plants and is a cause of decreased productivity of European forests. It has been argued that plant breeding that incorporates O_3 sensitivity into selection strategies will be increasingly necessary to achieve sustainable production with changing atmospheric composition~~.

Formatted: Font color: Black

Formatted: Font color: Black

Critical levels for effects of ozone on vegetation have been set and revised at a series of LRTAP Convention workshops from 1988 to date. Initial critical levels were based on mean concentrations, followed by AOT40-based values reflecting appreciation of the cumulative nature of effects and most recently critical levels have been derived based on stomatal fluxes. The latter take into account the modifying effects of climate (temperature, vapour pressure deficit, light), soil moisture, ozone and plant growth stage (phenology) on the amount of ozone absorbed by leaves (discussed in Section 2.1.2a). Calculated using the DO_3SE model developed by Emberson et al. ~~(Booker et al., 2009)~~(Emberson et al., 2000)~~.~~

Formatted: Font color: Black

~~The reduced carbon assimilation due~~, the stomatal ozone flux method thus allows the dynamics of stomatal opening and therefore ozone uptake to be modelled throughout the growing season. For example, using the DO_3SE model parameterised for a specific species, the substantially higher stomatal uptake of 80 ppb of ozone under warm humid conditions with adequate soil moisture than at higher temperatures with lower humidity and drier soils would be captured. The flux methodology also incorporates the natural ozone detoxification capacity of plants by accumulating the Phytotoxic Ozone Dose of ozone above an ozone threshold flux of Y nmol m^{-2} s^{-1} (POD_Y, units nmol m^{-2} projected leaf area). The value for "Y" varies between species, with the highest values being for crops such as wheat and potato and the lowest for some tree species such as beech and birch. The LRTAP Convention's Modelling and Mapping Manual now contains flux-based critical levels for ozone effects on food security (wheat, potato, tomato yield), carbon sequestration and timber production (Norway spruce, beech and birch) and biodiversity in conservation-grade grasslands (Mills et al., 2011b;Mills, 2014).

The use of the flux-based methodology is supported by recent analyses indicating that field evidence of ozone effects in Europe fits more closely with areas of greatest risk when flux-based rather than AOT40-based maps are produced. Furthermore, Fares et al. (Fares et al., 2013a) showed a strong correlation between measured and modelled fluxes in a mixed pine and oak Mediterranean forest and epidemiological studies conducted in Switzerland provided supporting evidence for both critical levels for deciduous trees and the DO_3SE parameterisation.

Reduced carbon assimilation owing to ozone by forests globally has been estimated by Sitch et al ~~(Sitch et al., 2007)~~(Sitch et al., 2007) to represent a substantial contribution to the indirect radiative forcing of climate by ozone (see Figure ~~28~~29). Through these effects on the productivity of ecosystems and the potential effects on biodiversity, ozone has become the most important pollutant threat to terrestrial ecosystems globally and is likely to remain so through most of the current century. Witting et al (2009) have shown that the carbon~~-~~ sink strength of northern hemisphere forests is likely reduced by current ozone and will be further reduced in future if ozone rises therefore implying that a key carbon sink currently offsetting a significant portion of global fossil fuel CO_2 emissions could be diminished or lost in the future ~~(Wittig et al., 2009)~~(Wittig et al., 2009).

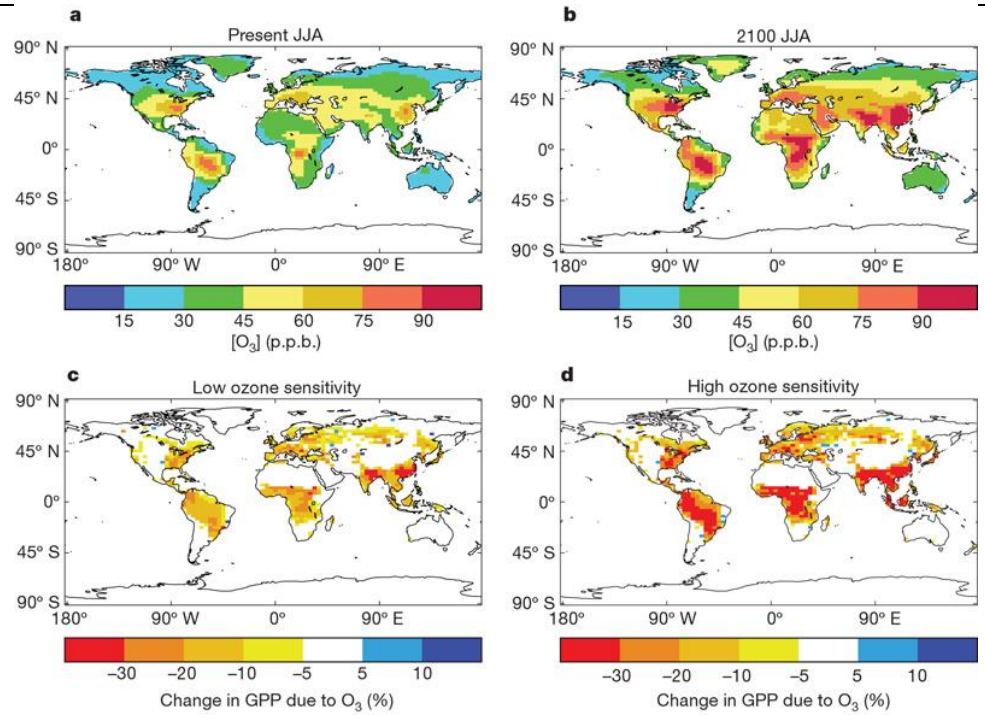


Figure ~~28~~29 - a,b - Modelled diurnal (24-h) mean surface $[O_3]$ in pbb averaged over June, July and August (JJA) for the present day (**a**) and the year 2100 under the highly polluted SRES A2 emissions scenario (**b**). **c**, **d**, Simulated percentage change in gross primary productivity (GPP) between 1901 and 2100 due to O_3 effects at fixed pre-industrial atmospheric $[CO_2]$ for 'low' (**c**) and 'high' (**d**) ozone

plant sensitivity ~~(Sitch et al., 2007)~~(Sitch et al., 2007).

In a recent review, Fuhrer looked at the ozone risk for crops and pastures in respect of future climate and concluded that the facets of exposure, leaf uptake and the plant's defence capacity are likely to change with a combination of changing anthropogenic ozone precursor emissions and climatic conditions. For example, in areas where the frequency of hot/dry periods is projected to increase ozone episodes may become more frequent and cumulative exposures will grow, but leaf uptake of ozone will decline. In contrast, in more remote rural areas with rapid warming and less drying, ozone risks are likely to grow because of increasing hemispheric transport of pollution leading to peak ozone levels at times when plant sensitivity is high ~~(Fuhrer, 2009)~~(Fuhrer, 2009). Tai et al ~~(Tai et al., 2014)~~(Tai et al., 2014) have shown that warming reduces global crop production by >~~20~~10% by 2050. In the range of the scenarios used ozone changes either exacerbate or offset a substantial part of the climate impacts. The authors note that given the competing sensitivities to heat or ozone that it is possible to measure the relative benefits for climate adaptation versus air pollution regulation for food security~~.~~ (see also (Avnery et al., 2011b)). It is of further concern that new evidence suggests that ozone can reduce the sensitivity of plants to drought by interfering with stomatal control mechanisms (Wilkinson and Davies, 2010;Wagg et al., 2012), thereby exacerbating effects of extreme weather events.

3.3 Impact of Ozone on Climate

Tropospheric ozone interacts with both solar (short-wave, SW) and terrestrial (long-wave, LW) radiation – consequently changes in its distribution can generate radiative forcings (RF) and lead to changes in climate. In their Fifth Assessment Report of climate change, IPCC found that changes in tropospheric ozone between 1750 and 2010 had generated a global mean radiative forcing of +0.40 (90% confidence range: 0.20 to 0.60) W m^{-2} ~~(Myhre et al., 2013)~~(Myhre et al., 2013).This was largely based on the ACCMIP assessment which considered changes in ozone (1850-2000) simulated by 17 different global models, and calculations from three different radiation schemes ~~(Stevenson et al., 2013)~~(Stevenson et al., 2013). The ACCMIP results were augmented by simulations back to 1750 and up to 2010 by the OsloCTM2 model ~~(Skeie et al., 2011)~~(Skeie et al., 2011), and were broadly consistent with earlier assessments from the literature.

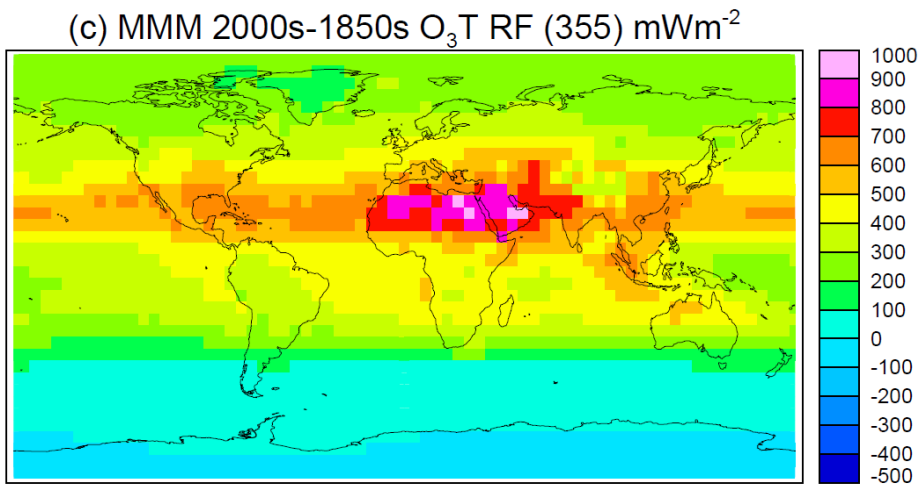


Figure ~~29~~30 - The global distribution of (annual mean) tropospheric ozone (O3T) radiative forcing (1850-2000, net SW+LW, including stratospheric adjustment, in mW m^{-2}), based on results from the multi-model mean (MMM) of the ACCMIP models, using the Edwards-Slingo radiation scheme ~~(Stevenson et al., 2013)~~(Stevenson et al., 2013). (NB the value of 0.355 W m^{-2} shown here compares to the recommended IPCC value for the 1750-2010 O3 RF of 0.40 W m^{-2}; the IPCC value includes the additional time periods 1750-1850 and 2000-2010, and also incorporates calculations with additional radiation schemes, and from other studies.)

An important feature of the O_3 RF is that, in comparison to the RFs from the well-mixed greenhouse gases, it is more spatially variable (see Figure ~~29~~30). The largest changes in ozone since 1750 have occurred over the industrial regions that are the main sources of ozone's precursors (NOx, CO, and VOCs) (see also section 2.3). The industrial emission focus is tempered somewhat by ozone's other key precursor, CH_4, which is relatively well-mixed due to its decadal lifetime, and also by ozone's lifetime of a few weeks, which allows transport to reduce zonal heterogeneities. In addition, to the variations in ozone changes, the spatial distribution of the O_3 RF also depends on other factors. The LW RF is largest where the temperature difference between the surface and the tropopause reaches a maximum: that is over land in the tropics and sub-tropics. The SW RF is largest over more reflective surfaces e.g., snow/ice and desert. The presence of clouds reduces the LW RF, and also modulates the SW RF. This combination of contributing factors leads to the net (LW+SW) O_3 RF peaking over the southern margins of the northern mid-latitudes and sub-tropics over land, and in particular over N. Africa and the Middle East (Figure ~~29~~30).

Shindell et al ~~(Shindell et al., 2009;Shindell et al., 2005)~~(Shindell et al., 2009;Shindell et al., 2005) and Stevenson et al (2013) have attributed the O_3 RF to O_3 precursor emissions (CH_4, NOx, CO and VOCs). Results from these studies are reported in the 'emissions-based' RF summary diagram of the IPCC-AR5-WGI Summary for Policymakers ~~(IPCC, 2013)~~(IPCC, 2013). Stevenson et al (2013) found that increases in anthropogenic emissions of CH_4, NOx, CO and NMVOCs are respectively responsible for 44±12% (±1 standard deviation range, based on results from 6 different global models), 31±9%,

15±3% and 9±2% of the 1850s-2000s ozone RF. All these O_3 precursors also affect the abundance of atmospheric OH, and hence the lifetime of longer-lived greenhouse gases such as CH_4. Consequently, emissions of ozone precursors generate further impacts on climate in addition to those related to changes in ozone; often these additional climate impacts occur over different timescales, and the net integrated impact on climate of emissions of a particular ozone precursor are complex to diagnose e.g. ~~(Fuglestvedt et al., 2010)~~(Fuglestvedt et al., 2010). A further complication is that net impact on atmospheric composition, and hence climate, depends upon the location of ozone precursor emissions, both in the horizontal e.g., ~~(Fry et al., 2012)~~(Fry et al., 2012) and vertical e.g. ~~(Stevenson and Derwent, 2009)~~(Stevenson and Derwent, 2009).

A major source of uncertainty in the O_3 RF is the pre-industrial distribution of ozone (see Section 2.2). The few measurements that do exist are mainly thought to be unreliable, but the two more rigorous datasets, from Montsouris in Paris and Pic du Midi, a mountain top site in central France ~~(Marenco et al., 1994)~~(Marenco et al., 1994), suggest that current generation models significantly overestimate late 19th century ozone levels ~~(Cooper et al., 2014)~~(Cooper et al., 2014). Cooper et al. (2014) highlight that global models significantly underestimate recent trends in surface ozone, suggesting that they overestimate past ozone levels. Consequently, there are suggestions that the ozone RF may be substantially underestimated (also see, e.g., ~~(Mickley et al., 2001)~~(Mickley et al., 2001)). It is unclear how these apparent discrepancies in surface ozone translate into uncertainties in O_3 RF, which is more strongly related to changes in the upper troposphere. The error estimate quoted by IPCC makes only a cursory attempt to include this source of uncertainty. Other sources of uncertainty are estimated from the model spread in the 1850-2000 change in ozone, and differences between radiation schemes. Nevertheless, the uncertainties associated with O_3 RF are far smaller than those due to, e.g., aerosol, because the key source of uncertainty is the O_3 change rather than our understanding of the fundamental processes involved. For example, the radiative forcing from aerosols has a larger uncertainty because we are less sure of the changes in aerosol since the pre-industrial, both in terms of their magnitude and geographical distribution, but also because the aerosol forcing originates from changes in multiple different aerosol types, including mixtures of different aerosol species, with highly uncertain optical properties (Fuzzi et al., 2015).

The spatial structure of the climate response to a particular radiative forcing is not directly related to the spatial distribution of the RF, but the climate response is typically spread out over the same latitudes e.g. ~~(Shindell et al., 2010)~~(Shindell et al., 2010).

The efficacy, or relative effectiveness of an O_3 RF relative to a CO_2 RF in generating a global mean surface temperature change, has been estimated by Hansen et al. ~~(Hansen et al., 2005)~~(Hansen et al., 2005) and Stuber et al. ~~(Stuber et al., 2005)~~(Stuber et al., 2005). For stratospherically adjusted RFs, Stuber et al (2005) found that the tropospheric O_3 efficacy has values in the range 0.7-1.7, with O_3 changes in the lower troposphere showing higher efficacies than the upper troposphere, and O_3 changes in the extra-tropical N. Hemisphere showing higher efficacies than globally uniform changes. The spatial dependence of the efficacy appears to relate to the interactions with climate feedback mechanisms e.g., ~~(Shindell, 2014)~~(Shindell, 2014).

It is quite arbitrary (and often ~~scientifically dubious~~fraught) to consider RFs owing to ozone changes in the troposphere and stratosphere separately, not least because the tropopause is often difficult to locate (e.g., ~~(Prather et al., 2011)~~(Prather et al., 2011)), and because coherent ozone changes often

straddle the tropopause e.g. ~~(Gauss et al., 2006;Shindell et al., 2013)~~(Gauss et al., 2006;Shindell et al., 2013). Changes in tropopause height and morphology associated with climate change (e.g., ~~(Wilcox et al., 2012)~~(Wilcox et al., 2012)~~) suggest that there may be very important chemistry-climate feedbacks related to ozone, such as those related to changes in the Brewer-Dobson Circulation (e.g. (Hegglin and Shepherd, 2009)).~~

~~4 Topics~~

) suggest that there may be very important chemistry-climate feedbacks related to ozone, such as those related to changes in the Brewer-Dobson Circulation (e.g. (Hegglin and Shepherd, 2009;Nowack et al., 2015)).

4 Recent Advances

The topics in this section have been selected to represent areas of active research highlighting recent advances associated with key sources or with particular chemical environments. The diversity of topics reflect the improved understanding of the richer and more diverse range of interactions between atmospheric ozone, other parts of the Earth system and human activity.

4.1 Megacities

As of 2007 more than half of the world's population now lives in urban areas, and many of them in megacities~~.~~ (Zhu et al., 2012). This statistic is often cited, but what defines an 'urban' area or a 'megacity'? While these definitions evolve and differ often depending on the context, here we will consider a common definition of a megacity that is a city or urban agglomeration of greater than 10 million people~~.~~ (Molina and Molina, 2004). As per Parrish et al. (2011), megacities are dense centres of population, economic activity, and pollutant emissions, but also areas where effective pollution control strategies could realize maximum benefit ~~(Parrish et al., 2011)~~(Parrish et al., 2011). Ground-level ozone is a serious air quality issue in many of the world's megacities. Monitoring and measurement campaigns have documented ozone levels exceeding air quality standards in many megacities. For example, based on the UNECE and WHO guidelines for protection of human health, daily 8-hr ozone should not exceed 60 ppb on more than 25 days per calendar year. In Delhi, India this threshold was exceeded approximately 45 days per year on average during the 7 year period (1997-2004), a significant concern for human health in the megacity ~~(Ghude et al., 2008)~~(Ghude et al., 2008), especially since ozone concentrations there are still on the rise ~~(Chelani, 2012)~~(Chelani, 2012). While some cities have extensive monitoring of ozone (and ozone precursors, more often NOx than NOx and NMVOCs), others have limited to no measurements. Consider South America. Buenos Aires, Argentina for example, has very few ozone measurements, so that the overall situation with regard to ozone pollution cannot be thoroughly assessed for the city ~~(Zhu et al., 2012)~~(Zhu et al., 2012). Sao Paulo, Brazil on the other hand has a more extensive monitoring network and increasing ozone concentrations ~~are~~have been observed over the last decade, despite decreases in other pollutants such as NOx and CO, as well as regular violations of the national ozone air quality standard ~~(Sanchez-Ccoyllo et al., 2006;Zhu et al., 2012)~~(Sanchez-Ccoyllo et al., 2006;Zhu et al., 2012). A variety of reported ozone concentrations from megacities are shown in Table 2.

Sources of ozone precursors in megacities include, but are not limited to, traffic-related emissions, combustion of fossil fuels, solvent use, domestic biofuel usage and industrial activities such as power generation. The relative contribution of sources and specific activities leading to the local ozone precursor compound mix varies depending on location, including between cities. For example, in Sao Paulo, Brazil light-duty vehicles are run on ethanol or gasoline/ethanol mix fuels and ethanol from sugar cane accounts for 65% of all fuel consumed ~~(de Fatima et al., 2012)~~(de Fatima et al., 2012); light-duty vehicles in North America predominantly run on gasoline which in some cases contains a small fraction of ethanol; in China gasoline-powered vehicles dominate the vehicle fleet, but there is also significant use of liquefied petroleum gas (LPG) for some types of vehicles in the fleet ~~(Liu et al., 2008)~~(Liu et al., 2008). Overall, the emissions from vehicles/traffic dominate as a major (if not the main) source of ozone precursors in many megacities, especially because growing vehicle fleets

generally accompany megacity development ~~(Parrish and Zhu, 2009)~~(Parrish and Zhu, 2009). For example, Shanghai, the largest city in China with a population of roughly 23 million, has undergone rapid development; between 1996 and 2008 industrial gross output increased by ≈4 times and the number of cars increased from 0.47 to 2.61 million ~~(Tie et al., 2013)~~(Tie et al., 2013). Other megacities in which vehicles are cited as the top or among the top sources of ozone precursors are Cairo, Delhi, Istanbul, Los Angeles, New York, Mexico City, Sao Paulo, and the Ruhr-Rhein metropolitan region ~~(Chelani, 2012;de Fatima et al., 2012;Parrish et al., 2011;Khoder, 2009;Im and Kanakidou, 2012;Melkonyan and Kuttler, 2012).~~(Chelani, 2012;de Fatima et al., 2012;Parrish et al., 2011;Khoder, 2009;Im and Kanakidou, 2012;Melkonyan and Kuttler, 2012;Bon et al., 2011). In cities like Lagos in Nigeria it is a combination of traffic and open biomass burning driving large ozone exceedances from emission of NMVOCS ~~(Marais et al., 2014)~~(Marais et al., 2014).

Extreme events in terms of air quality have also been documented in a number of megacities. These result from a combination of elevated emissions and meteorological conditions (e.g., stagnant, hot, sunny) that lead to extremely high concentrations of ozone, typically for a short duration. During the summer of 2010 in Moscow, blocking anticyclonic meteorological conditions with record-breaking high temperatures led to larger than normal evaporative emissions from fuels, paints, etc, as well as emissions from a large number of forest and turf fires, in addition to the 'normal' megacity emissions~~.~~ (Zvyagintsev et al., 2011;Elansky et al., 2011). These conditions which persisted from July through mid-August resulted in maximum hourly mean concentrations of ozone that peaked at 134.2 ppbv ~~(Elansky et al., 2011)~~(Elansky et al., 2011). An oft cited example of extreme ozone was during the European heat wave during summer 2003, which adversely affect the residents of a number of European megacities. For about 2 weeks at the beginning of August a high pressure system was centred on Western Europe, resulting in record-setting temperatures exceeding 40° C, and accompanied by a persistent photochemical episode. In France, the highest hourly ozone value reached ~~417 µg m^{-3}~~;208.5 ppbV and concentrations regularly exceeded the EU threshold of ~~180 µg m^{-3}~~90 ppbV ~~(Lee et al., 2006;Vautard et al., 2005;Stedman, 2004;Tressol et al., 2008)~~(Lee et al., 2006;Vautard et al., 2005;Stedman, 2004;Tressol et al., 2008).

Because of their high population density, the adverse health effects of elevated ozone levels affect a disproportionately large fraction of the population. A recent study investigated the health impacts of air pollutants in Tehran, Iran where the annual 8 hr average ozone concentration in 2010 was ~~68.84 µg m^{-3}~~34 ppbV, with a maximum 8~~-hr~~ h concentration of ~~187 µg m^{-3}~~93.5 ppbV during the summer period. The health impact owing to ozone was estimated to cause an excess total mortality of 819 out of 47,284 people in a year, relative to 2,194 cases for PM_{10} ~~(Naddafi et al., 2012)~~(Naddafi et al., 2012). For comparison (from a study using the same method), they cited the excess total mortality for PM_{10} was 677 out of 1,308,000 people for Milan, Italy, located in the megacity region of the Po Valley ~~(Naddafi et al., 2012)~~(Naddafi et al., 2012). Cifuentes, et al. ~~(Cifuentes et al., 2001)~~(Cifuentes et al., 2001) assessed the health benefits associated with reductions of PM and O_3 from climate change mitigation strategies (2000-2020) in 4 megacities – Santiago, Sao Paulo, Mexico City, and New York. Without going into detail, substantial premature deaths could be avoided from such policies; in all cases the adverse health effects avoided from ozone were significantly less than those from PM ~~(Cifuentes et al., 2001)~~(Cifuentes et al., 2001). Generally, small but substantial associations between ozone and total mortality are found in epidemiological studies ~~(Bates, 2005)~~(Bates, 2005).

Formatted: Subscript

Formatted: Subscript

Formatted: Subscript

The emissions from megacities also have an effect on the surrounding region. In many cases the urban areas have been identified to be VOC-limited, where high NOx concentrations in the cities suppress ozone concentrations ~~(Im and Kanakidou, 2012;Tie et al., 2013)~~(Im and Kanakidou, 2012;Tie et al., 2013)~~.~~. For example, a modeling study conducted in the context of the MILAGRO measurement campaign in Mexico City identified that reductions in VOC emissions led to decreases in maximum ozone concentrations while NOx emission reductions led to increased maximum ozone concentrations, demonstrating that the urban core of the Mexico City metropolitan area was VOC-limited, a conclusion supported by the *in-situ* measurements. The surrounding mountain/rural areas were identified as mostly NOx-limited, although the range of these areas was meteorologically dependent (Song et al., 2010). This suppression of ozone by high NOx has been identified as generally more characteristic of extratropical megacities in the northern hemisphere, relative to tropical cities, because of differences in transport patterns. Tropical cities are more influenced by rapid convective transport, while the extratropical cities (despite the Mexico City example) allow for a greater build-up of local pollution ~~(Butler and Lawrence, 2009)~~(Butler and Lawrence, 2009). Local/regional transport of these air masses into the surrounding areas can lead to greater concentrations outside of the megacities. For example, in Tokyo, modelling studies showed that sea breezes developed during the daytime transported emissions from the urban centre to the north, which caused enhanced ozone in downwind areas 50-100 km away ~~(Kondo et al., 2010)~~(Kondo et al., 2010). Furthermore, regional enhancements of ozone during summer were found in the area (200 km x 200 km) surrounding the Tokyo metro area ~~(Kondo et al., 2010)~~(Kondo et al., 2010). A modelling study looking at the impacts of Istanbul (and Athens) on air quality in the East Mediterranean also found much lower concentrations of ozone within the (mega)cities owing to significant NOx emissions depressing O_3. The rural sites in the surrounding area had much higher ozone concentrations, 11-24 ppbv (9-14 ppbv) greater in summer (winter) than in the urban areas, emphasizing the importance of the megacity emissions on regional air quality ~~(Im and Kanakidou, 2012)~~(Im and Kanakidou, 2012). Further sources of emissions in areas surrounding the megacity regions also play a role in ozone formation. For example, the photochemistry in plumes transported out of London or the Ruhr-Rheine region will be influenced significantly by further emissions sources, while this is much less the case for e.g., Cairo which has far fewer emissions sources in the surrounding area ~~(Hodnebrog et al., 2011)~~(Hodnebrog et al., 2011). Biogenic emissions will also influence ozone formation downwind of cities. For the Shanghai region, results from a model study suggested that ozone formation was enhanced in the city plumes in the downwind region because of the strongly VOC-limited conditions in the plume which resulted in continuous ozone production during transport. Reasons for this were oxidation of OVOCs and CO in the plume, and biogenic isoprene emissions ~~(Tie et al., 2013)~~(Tie et al., 2013). Finally, an estimate of the footprint of southeastern megacities in South America found contributions in excess of 30% to downwind levels of surface ozone under certain conditions ~~(Zhu et al., 2012)~~(Zhu et al., 2012).

Considering ozone concentrations as a relative contribution to the global scale, megacities contribute a ~~surprisingly~~ small amount to global ozone ~~(Stock et al., 2013)~~(Stock et al., 2013). In a model 'annihilation' experiment where the emissions from grid cells containing megacities were removed, emissions from megacities contributed only 0.84% to the global average tropospheric ozone column density, proportionally smaller than the 6% of global anthropogenic ozone precursor emissions from megacities ~~(Butler et al., 2012)~~(Butler et al., 2012). This however does not represent human health exposure to ozone in megacities and is also a global average.

Previous work has shown that individual megacities are not well represented by global emission inventories compared to the detailed city-scale inventories ~~(Butler et al., 2012)~~(Butler et al., 2012), which can be an issue when trying to model ozone on a larger scale. Additional complexity is added by the non-linearity of the atmospheric chemistry involved in ozone production processes. Hodnebrog et al. investigated the importance of resolution for the representation of large scale tropospheric ozone from megacity emissions and found that higher resolution was much more important for local air pollution studies than for larger climate studies, as might be expected, due to the integration of relatively small changes over a large volume (changes in the resolution of meteorology were not considered) ~~(Hodnebrog et al., 2011)~~(Hodnebrog et al., 2011). A key point was whether or not the model resolution could capture the NOx saturated regime within the plume common to many megacities ~~(Hodnebrog et al., 2011)~~(Hodnebrog et al., 2011). That said, recent work by Siour, et al. has shown that for chemistry transport models, using a 'zooming' technique (introducing higher resolution 'zooms' to certain areas within a coarser overall resolution) allows for better representation of scale interactions, including better representation of megacity areas, such as the BeNeLux region ~~(Siour et al., 2013)~~(Siour et al., 2013). With the growing interest in the study of urbanization, more research and improved methods are still needed to develop a better understanding of pollutants such as ozone in megacities and their effects on all scales.

Table 2 - Reported mean O_3 for megacities.

Location	Mean O_3 (ppbv)*	Statistic/year	Ref
Beijing, China	31	6 site average, 2001-2006, JJAS	~~(Tang et al., 2009)~~(Tang et al., 2009)
Bangkok, Thailand	17	Annual average, 1-hr, 1995-2008	~~(Zhu et al., 2012)~~(Zhu et al., 2012)
Cairo, Egypt	46	Dec 2004-Nov 2005	~~(Khoder, 2009)~~(Khoder, 2009)
Delhi, India	24	1997-2004, annual avg	~~(Ghude et al., 2008)~~(Ghude et al., 2008)
London, UK	19 (38 μg m^{-3})	Annual average hourly data; suburban site (Eltham) 2009	http://uk-air.defra.gov.uk
Los Angeles, CA, USA	122	2005-2007, national 8-hr ozone design values (daily 8-hr max from running avgs)	~~(Cox et al., 2009)~~(Cox et al., 2009) (accessed 8.8.13)
Mexico City, Mexico	93	City plume, avg from flight measurements, MIRAGE-MEX campaign	~~(Tie et al., 2009)~~(Tie et al., 2009)
Tehran, Iran	34 (68.84 μg m^{-3})	2010, annual 8-hr avg	~~(Naddafi et al., 2012)~~(Naddafi et al., 2012)

*concentrations originally reported in μg m^{-3} were converted to ppbv using the simple conversion of 1 ppb = 2.0 μg m^{-3}, assuming 1 atm pressure and 25° C.

4.2 Biomass burning

Wildfires/Biomass burning are the second largest source of carbon dioxide emissions, after fossil fuel combustion with ca. 1-2 GtC/year ~~(IPCC, 2013)~~(IPCC, 2013). Tropical biomass burning dominates total emissions with boreal fires (50-70°N) accounting for around 9% of all fire carbon emissions. Burning is thus a major component of the carbon cycle having a direct global impact on climate ~~(van der Werf et al., 2010)~~(van der Werf et al., 2010). Further, there is also an indirect impact because biomass burning is a significant source of ozone precursors (e.g. CO, NOx, VOCs) and aerosol particles. Indeed, Jaffe and Widger ~~(Jaffe and Wigder, 2012)~~(Jaffe and Wigder, 2012) estimated that global wildfires produce approximately 170 Tg of ozone per year, which is 3.5% of all tropospheric ozone production. However, as they pointed out, many areas of uncertainty remain in wildfire-related ozone production. These uncertainties centre around the interplay of fire emissions, chemical reactions within the plumes, aerosols effects on chemistry and radiation and atmospheric dynamics (local and downwind meteorological patterns). These factors, along with a strong interannual variability of the fire activity itself, make the assessment of global impact a challenge. The impact of boreal forest fires is less documented and quantified than tropical biomass burning.

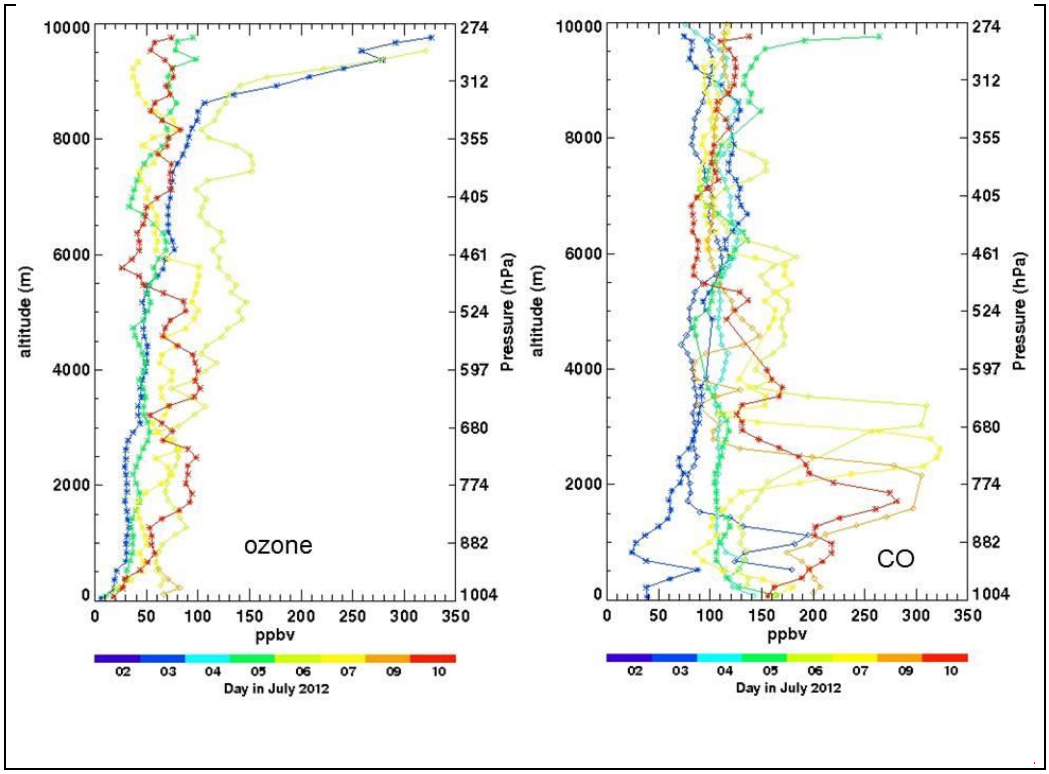
Recently, the atmospheric chemistry challenge of biomass burning in ~~Boral~~Boreal regions provided the motivation for the Quantifying the impact of BOReal forest fires on Tropospheric oxidants over the Atlantic using Aircraft and Satellites (BORTAS) campaign, held in July-August 2010 and 2011 over Eastern Canada and Western Atlantic. The objective of BORTAS ~~where~~was to better understand the chemical evolution of plumes emitted from the burning of biomass, with a particular emphasis on the net production of tropospheric ozone and downwind impacts on air quality (~~(Palmer et al., 2013)~~(Palmer et al., 2013) and references therein) (see Figure 31). Parrington et al ~~(Parrington et al., 2013)~~(Parrington et al., 2013) have shown that ozone formation increases with plume age. They used NMHC ratios (extensively described for this BORTAS campaign in ~~(Lewis et al., 2013)~~(Lewis et al., 2013)) to estimate photochemical ages of the observed biomass burning plumes between 0 and 10 days. Parrington et al., ~~(Parrington et al., 2013)~~(Parrington et al., 2013) found that Ozone Production Efficiency (OPE) increased with plume ages as calculated by NMHC ratios. They show $\Delta O_3/\Delta CO$ enhancement ratios increasing from 0.020±0.008 ppbv/ppbv in plumes with photochemical ages less than 2 days to 0.55±0.29 ppbv/ ppbv in plumes with photochemical ages greater than 5 days. According to this study, it seems that the aerosol loading is one of the main ~~driver~~drivers of such OPE, as aged plumes were typically associated with low aerosol loading and relatively high OPE. In one of the BORTAS flights that made multiple interceptions of a plume with high aerosol loading, Parrington et al. (2013) report that the photolysis rate of NO_2 was reduced by a factor of approximately 2 within this plume, suggesting that increased optical depth of the plume can reduce the photolysis rate of NO_2 to form ozone.

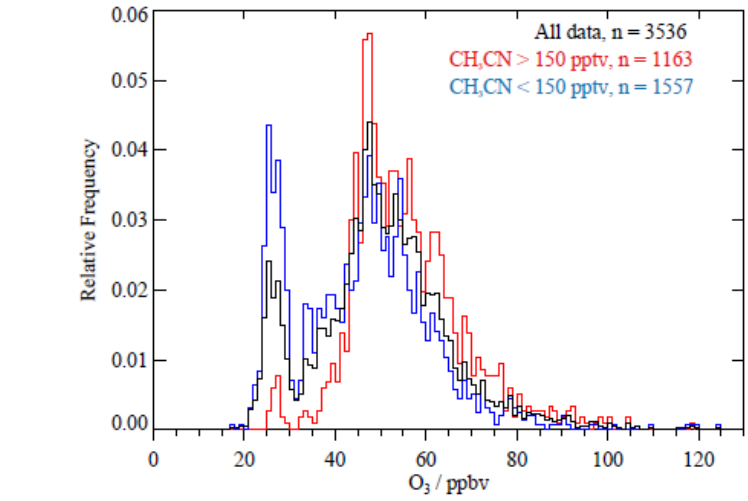
Still in the frame of BORTAS and WMO-GAW programme, results exploring NMVOC ozone precursors from measurements of biomass-burning ~~(Lewis et al., 2013)~~(Lewis et al., 2013) have suggested that biomass burning can be the largest fractional contributor to observed benzene, toluene, ethene and propene levels in many global locations. The extrapolated widespread biomass burning contribution to atmospheric benzene, a heavily regulated air pollutant, suggesting a pragmatic approach when setting air quality targets as tailpipe and solvent emissions decline in developed countries.

Jaffe and Widger (2012) also indicated that boreal wildfires are likely to produce less NOx on average than fires in other biomes. This observation makes sense with a more obvious impact of biomass burning on ozone production in the tropics than at mid-high northern latitudes. However, boreal wildfires may have diverse impacts on the global ozone distribution as they are also often linked to convection and pyro-convection allowing thus the injection of ozone precursors and particulate matter up to the upper troposphere-lower stratosphere where long-range transport processes can widely distribute the emissions. Subsequent photochemical processes leading to ozone production and their impact on larger scale may be different than in the tropics. Several groups are actively developing ~~algorithm~~algorithms and models to ~~propose~~derive appropriate injections heights for biomass burning emissions (e.g. ~~(Kaiser et al., 2012;Freitas et al., 2007)~~(Kaiser et al., 2012;Freitas et al., 2007)~~). Depending on the fire radiative power (FRP), it is shown that boreal forest fires are likely able to emit products up to 10 km altitude with a maximum between 1 and 4 km altitude for fires with the highest radiative power, while tropical biomass burning is limited to the first km of the atmosphere. ~~). Depending on the fire radiative power (FRP) and size of the fire, Freitas et al. (Freitas et al., 2007) have shown that plumes from fires are likely able to reach 10 km altitude. Based on a statistical analysis of 5 years of satellite observation by MISR (Multi-angle Imaging Spectrometer) over North America, Val Martin et al. (Martin et al., 2010) have shown that the median altitude of plumes is found below 3 km altitude for boreal forest fires. A significant fraction (4-12%) of those plumes are injected above the boundary layer and are more spread-out vertically depending on the atmospheric stability conditions. In comparison, tropical biomass burning plumes are mostly limited to the first km of the atmosphere.

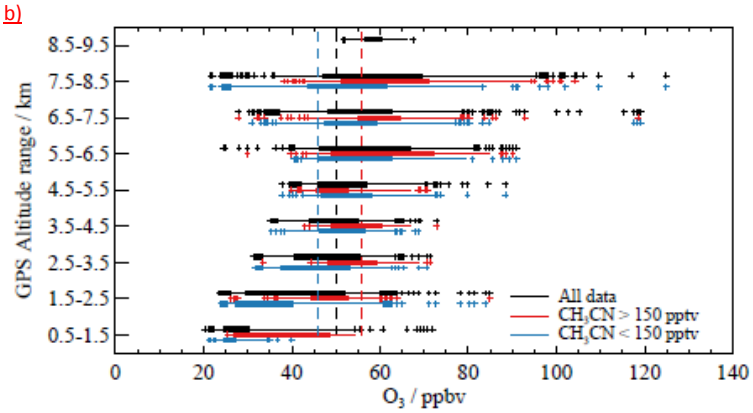
Numerous studies report high mixing ratios of biomass burning products, CO in particular, measured in the middle to upper troposphere and eventually up to the lower stratosphere, thousands of km from the fire sources (e.g. ~~(Nedelec et al., 2005;Cammas et al., 2009;Fromm et al., 2010;Elguindi et al., 2010)~~(Nedelec et al., 2005;Cammas et al., 2009;Fromm et al., 2010;Elguindi et al., 2010)). Biomass burning signatures from Canadian forest fires have also been observed in the lower troposphere at the Pico Observatory on the opposite of the North Atlantic ~~(Val Martin et al., 2006)~~(Val Martin et al., 2006). Implications for the ozone budget in Boreal regions are not as direct as in the Tropics. Photochemical impact remains uncertain. Clearly, long range transported biomass burning plumes can influence Europe ~~(Cook et al., 2007;Real et al., 2007)~~(Cook et al., 2007;Real et al., 2007) though the impact is variable ~~(Hudman et al., 2004)~~(Hudman et al., 2004). More recently, European fires in Portugal and Russia have been shown to contribute to air pollution ~~(Tressol et al., 2008;Martins et al., 2012)~~(Tressol et al., 2008;Martins et al., 2012) and the frequency is expected to increase with climate change ~~(Carvalho et al., 2011)~~(Carvalho et al., 2011)~~. Long range transport of biomass burning products from Siberia can influence the west coast of the North American continent (Seattle, Vancouver) and such haze may have strong impact on meeting their air quality standards. Figures 30 summarizes ozone and CO profiles recorded over Vancouver in the beginning of July 2012 recorded in the frame of IAGOS. Further details and profiles may be found on the dedicated MACC web pages: http://www.iagos.fr/macc under the rubric "Profile of the day" in relation to the huge fires in summer 2012. Figure 30 also illustrates the difficulty in assessing the ozone production from such boreal wildfires based on *in-situ* measurements (of limited compounds). Differing profiles over Vancouver have different $\Delta O_3/\Delta CO$ (from almost 0 to 1) and given plume age is increasing everyday (same source, same receptor, same transport pathway apparently). Finally, it is noticeable that the

highest ozone concentrations in the lower troposphere are observed on the last day of this time-series. Besides their impact on air quality over populated mid-latitudes, boreal fires are also of particular importance for the Arctic region. For example, the ARCTAS mission held in April 2008 and June-July 2008 was designed to observe spring time fires from Siberia, and summertime fires plumes from Canada and Siberia along with their impact on Arctic pollution (Jacob et al., 2010) (see also section 4.8).





b)



~~**Figure 30 –** Ozone and Carbon monoxide vertical profiles over Vancouver recorded by IAGOS (http://www.iagos.org/) in July 2012 (Courtesy of Hannah Clark).~~ **Figure 31** – a) Frequency distribution for ozone over the BORTAS (Palmer et al., 2013) flights , the black line are the measured mixing ratios, where the red line shows the distribution of measurements identified as biomass burning plumes using a threshold of CH_3CN mixing ratios greater than 150 pptv, and the blue line shows measurements made in air masses with CH_3CN mixing ratios less than 150 pptv. ; b) the same data plotted as a box and whisker (solid boxes show the range of the 25th to 75th percentiles and whiskers show the range of the 5th to 95th percentiles with outliers shown as plus symbols) (GPS) altitide profile (Parrington et al., 2013).

Formatted: Space After: 0 pt, Line spacing: single, Don't adjust space between Latin and Asian text, Don't adjust space between Asian text and numbers

Formatted: Font: +Body (Calibri), English (U.K.)

Biomass burning in the tropics has long been recognized as the major source of tropospheric ozone locally and regionally ~~(Fishman et al., 1990;Thompson et al., 1996;Sauvage et al., 2006;Jonquieres et al., 1998;Thompson et al., 2003c)~~(Fishman et al., 1990;Thompson et al., 1996;Sauvage et al., 2006;Jonquieres et al., 1998;Thompson et al., 2003c). Tropospheric seasonal cycles of ozone are in phase with the local biomass burning season (coinciding with the dry season) of each region. It is worth noting one exception over Equatorial Africa (Gulf of Guinea and adjacent continent) which is impacted by two biomass burning regions, one from each hemisphere. For example, over Lagos,

Nigeria, ozone enhanced layers are observed in December-February when burning occurs regionally and also in July-August when biomass burning occurs over southern Equatorial Africa ~~(Sauvage et al., 2005;Sauvage et al., 2007b)~~(Sauvage et al., 2005;Sauvage et al., 2007b). Such processes have been further investigated in the frame of AMMA ~~(Reeves et al., 2010;Thouret et al., 2009;Mari et al., 2008)~~(Reeves et al., 2010;Thouret et al., 2009;Mari et al., 2008). Similarly, over Brazzaville, the seasonal cycle of ozone peaks in July-August but a secondary maximum appears in January-February due to transport of ozone and precursors from fires occurring in the northern hemisphere ~~(Sauvage et al., 2005;Sauvage et al., 2007b)~~(Sauvage et al., 2005;Sauvage et al., 2007b). Thus, the so-called zonal wave-one as described by Thompson et al., 1999 and Sauvage et al., 2006, which describe the ozone maximum over the South Atlantic and adjacent continents clearly designates biomass burning as the main contributor of the ozone burden in the tropical lower to middle troposphere at least. Biomass burning in the tropics may have a global impact too. The extreme El-Nino event in 1997 and the consequent long lasting fires in Indonesia ~~(Siegert et al., 2001)~~(Siegert et al., 2001) have contributed to the increase of CO and other trace gases (e.g. CO_2) observed globally from late 1997 through 1998.

4.3 Role of biogenics in the formation of ozone

There is much debate as to the influence of biogenic VOCs in urban ~~(Calfapietra et al., 2013)~~(Calfapietra et al., 2013), regional and global ozone budgets. Variation in natural plant emissions of ozone precursors can influence ozone concentrations. Goldstein and Galbally suggested we cannot account for the loss of approximately half the non-methane organic carbon entering the atmosphere ~~(Goldstein and Galbally, 2007)~~(Goldstein and Galbally, 2007) much of biogenic origin.

Much of the focus on biogenic VOCs and ozone is on isoprene and the monoterpenes owing to their apparent dominance of the global VOC budgets (see Figure ~~21~~22). New insights from field observations, models and quantum chemistry into isoprene chemistry and its impacts have been recently reviewed by Whalley et al. ~~(Whalley et al., 2014)~~(Whalley et al., 2014). Some of the new radical chemistry from isoprene oxidation is detailed in section 4.10 and the emissions in section 2.3. This section deals with the relationships between biogenics and formation of ozone.

Work by Hewitt et al has suggested that the circadian rhythms of the isoprene emitters have an effect on the ozone budgets ~~(Hewitt et al., 2011)~~(Hewitt et al., 2011) (see Figure ~~31~~32), but there has been some debate as to the nature of the circadian control ~~(Keenan and Niinemets, 2012)~~(Keenan and Niinemets, 2012).

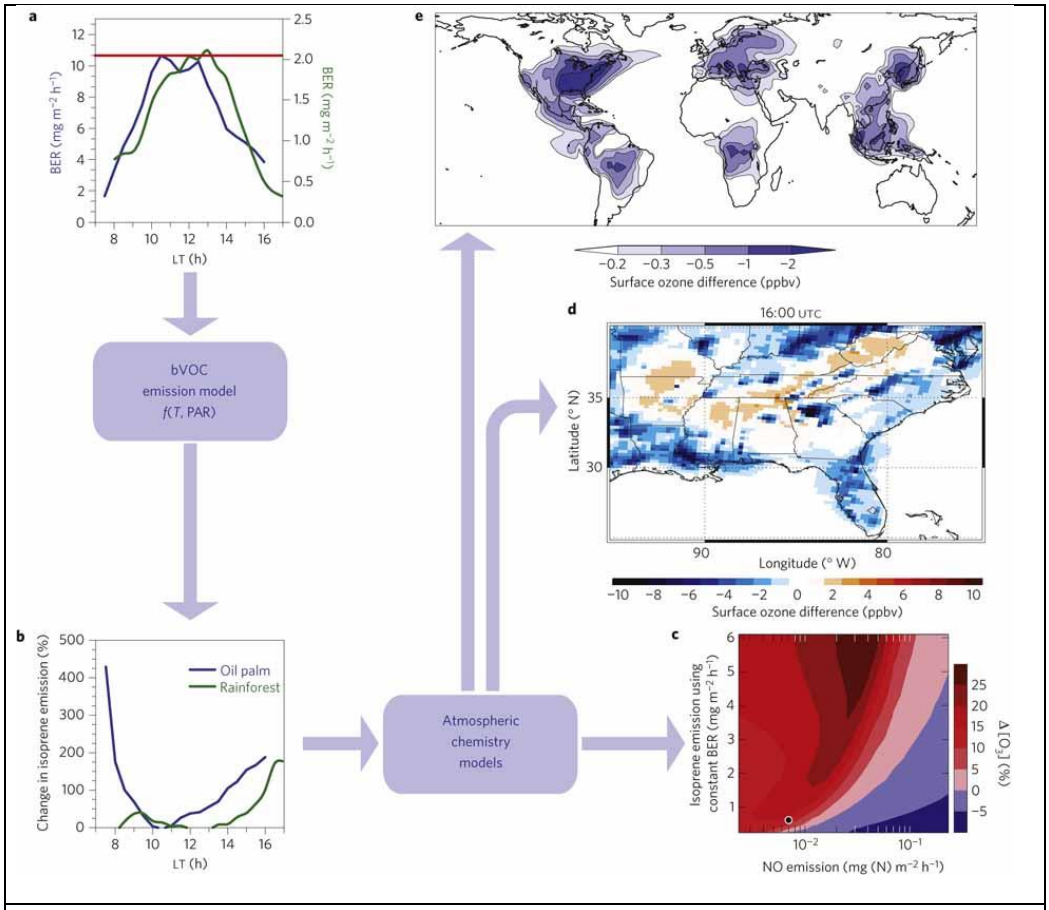


Figure ~~31~~32 - The effect of a circadian rhythm based biogenic emission rate (BER) on ozone; a) The oil palm plantation (blue) and rainforest (green) BERs of isoprene compared with a constant BER (red). **b**, The differences in isoprene emission rates between constant (red line in **a**) and circadian-controlled BERs (oil palm: blue; rainforest: green); **c**, Changes in ground-level ozone resulting from changing isoprene and nitrogen oxide emission rates. **d**, Changes in regional-scale modelled ground-level ozone for 11:00 LT using an 'oil palm' circadian-controlled BER compared with a constant BER. **e**, Changes in global-scale modelled ground-level ozone for July using the same scenario as **d** ~~(Hewitt et al., 2011)~~(Hewitt et al., 2011).

Model calculations have indicated that the biogenic isoprene emissions represent a major uncertainty in the achievement of AOT40 levels by a factor of at least two ~~(EEA, 2009)~~(EEA, 2009). The impact of North American (NA) isoprene on European ozone has been assessed and it has been shown that future increases in NA isoprene emissions could offset decreases in EU surface O_3 resulting from controls on NA anthropogenic emissions ~~(Fiore et al., 2011)~~(Fiore et al., 2011). Archibald et al. have shown that there is a significant impact of mechanism uncertainties on the global impact of isoprene chemistry on ozone ~~(Archibald et al., 2011)~~(Archibald et al., 2011). Recent estimates from Zare et al ~~(Zare et al., 2014)~~(Zare et al., 2014) found BVOC to be the most significant contributor to ozone formation over land areas in the NH enhancing the mixing ratio by about 11%. In the Pearl River Delta in China ~~(Situ et al., 2013)~~(Situ et al., 2013) ozone is sensitive to the BVOC

levels particularly in urban areas. At a regional European scale, biogenic emissions increase O_3, locally, while reducing $PM_{2.5}$ levels ~~(Tagaris et al., 2014)~~(Tagaris et al., 2014). At the city scale, modelling has shown that O_3 concentration can be increased by 37 ppb in Seoul, Korea owing to biogenic isoprene emission and transport of ~~it~~its key oxidation products into the metropolitan area ~~(Lee et al., 2014)~~(Lee et al., 2014).

The role of isoprene nitrates has been highlighted as a key uncertainty in ozone and NOx chemistry ~~(Horowitz et al., 2007)~~(Horowitz et al., 2007). In the tropics regional simulation of ozone is shown to be very sensitive to the removal and export of NOx by isoprene nitrates ~~(Paulot et al., 2012)~~(Paulot et al., 2012). For example, in South America and New Guinea, the high ratio of isoprene to-NOx emissions makes isoprene nitrates chemistry the primary sink of NOx. Paulot et al. (2012) suggest that the impact of isoprene photooxidation on tropical ozone is not limited to the regional scale but can have a long-range effect as a result of dynamic and photochemical processes such as efficient vertical mixing (through deep convection) and low boundary layer HOx (as a result of high biogenics and low NOx emissions). It is suggested that these physical and chemical conditions, promote the oxidation of isoprene outside of the boundary layer, where its contribution to ozone production is amplified ~~(Paulot et al., 2012)~~(Paulot et al., 2012). Enhancing the isoprene oxidation mechanism for isoprene-nitrates in a global model and running it over the USA, Mao et al ~~(Mao et al., 2013)~~(Mao et al., 2013) have shown that the dependence of surface ozone on isoprene emission is positive throughout the U.S., even if NO_x emissions are reduced by a factor of 4, as well as the chemistry leading to the export of nitrates to the background atmosphere. Browne et al ~~(Browne et al., 2014)~~(Browne et al., 2014) have shown that the monoterpene nitrates have the potential to impact ozone levels over the remote continental boundary layer. The change in global O_3 burden due to an increase in BVOC emissions associated with temperature depends critically on the assumed treatment for the fraction of NOx recycled from isoprene nitrates ~~(Ito et al., 2009)~~(Ito et al., 2009).

~~There is significant debate about the role of a wide range of biogenics in ozone chemistry under future climate e.g. (Andersson and Engardt, 2010) with up to a factor five difference between different models for Europe (Langner et al., 2012b). A limiting role of increased CO_2 on the potential of ozone precursor emissions from the vegetation has been recently noted at the global scale (Lathiere et al., 2010). Earlier studies showed that the vegetation response to climate change is important in driving BVOC emissions and subsequent formation of ozone (Sanderson et al., 2003).~~

A future uncertainty revolves around the impact of biofuels on ozone concentrations, via changes to vegetation (Ashworth et al., 2013) and BVOC emissions (Porter et al., 2012).

There is significant debate about the role of a wide range of biogenics in ozone chemistry under future climate e.g. (Andersson and Engardt, 2010;Wiedinmyer et al., 2006) with up to a factor five difference between different models for Europe (Langner et al., 2012c). It has been recently shown that the choice of isoprene chemical schemes in climate models can be important (Squire et al., 2015). A limiting role of increased CO_2 on the potential of ozone precursor emissions from the vegetation has been recently noted at the global scale (Lathiere et al., 2010). Earlier studies showed that the vegetation response to climate change is important in driving BVOC emissions and subsequent formation of ozone (Sanderson et al., 2003).

Several other studies have focused only on the regional impact of climate change ~~(Langner et al., 2012a;Langner et al., 2012b;Andersson and Engardt, 2010;Manders et al., 2012;Hedegaard et al.,~~

Formatted: Font: +Body (Calibri)

~~2008;Hedegaard et al., 2013b;Katragkou et al., 2011)~~(Langner et al., 2012a;Langner et al., 2012c;Andersson and Engardt, 2010;Manders et al., 2012;Hedegaard et al., 2008;Hedegaard et al., 2013b;Katragkou et al., 2011). They found a general increase of ozone concentrations owing to increasing biogenic emissions and favourable conditions for the build-up of ozone pollution as a result of increased temperature, more frequent summer blocking and heat waves and increased shortwave radiation. Whereas all these studies agreed on the main outcome of climate change on ozone in Europe, they also pointed out significant differences depending on the regional climate model used. The main factors influencing these differences are the projections of cloud cover and frequency of stagnation episodes that are highly variable across the ensembles of regional climate projections.

4.4 Halogens

Halogens (chlorine, bromine, iodine) influence the concentrations of ozone in the troposphere either directly, by reacting with O_3 itself ~~(~~e.g.~~,~~.

$Br + O_3 \rightarrow BrO + O_2$~~),~~ (R10)

or indirectly, by affecting its sources and sinks. Indirect influence results in production or destruction of O_3, depending on the conditions. Halogens, especially chlorine, react with VOCs to form peroxy radicals, which convert NO into NO_2, and change the OH/HO_2 ratio ~~(~~e.g.~~,~~. *via*

$BrO + HO_2 \rightarrow HOBr + O_2$~~,~~ (R12)

followed by HOBr photolysis to give OH). Reactions between halogen species and nitrogen oxides also affect the NO/NO_2 ratio, and form stable compounds, which can act as nitrogen reservoirs and allow long-range transport of O_3 precursors. A detailed model analysis by Saiz-Lopez et al ~~(Saiz-Lopez et al., 2012a)~~(Saiz-Lopez et al., 2012a) estimated that halogens are responsible for up to 10% yearly depletion of the total tropospheric O_3 column (and up to 20% in the tropical troposphere), especially in the middle and upper troposphere. The model calculations by Parrella et al. ~~(Parrella et al., 2012)~~(Parrella et al., 2012) and Long et al. ~~(Long et al., 2014)~~(Long et al., 2014) generally agree with these estimates. The Long et al. (2014) model analysis suggest that models may overestimate the role of bromine (and the extent of ozone destruction), because they tend to overestimate marine aerosol, especially in the Southern Hemisphere.

Our understanding of the role of halogens in ozone chemistry ultimately depends on our understanding of the physio-chemical processes that release, transform and destroy halogen species into the atmosphere. There are significant uncertainties in our knowledge of the source processes and geographical distribution of halogens and severe limitations in the databases of chemical kinetics parameters ~~(Abbatt et al., 2014)~~(Abbatt et al., 2014). Part of the problem is related to the difficulty in measuring halogens species at the low concentrations found in the atmosphere ~~(Finlayson-Pitts, 2010)~~(Finlayson-Pitts, 2010): this area of research has been very active in recent years and many of the most recent advancements in our knowledge are related to developments in the field of analytical chemistry, particularly mass spectrometry.

Formatted: Subscript

Very detailed reviews have been published in recent years both on halogen chemistry in general Saiz-Lopez & von Glasow ~~(Saiz-Lopez and von Glasow, 2012)~~(Saiz-Lopez and von Glasow, 2012) and on specific aspects of halogen chemistry, such as bromine ~~(Sander et al., 2003)~~(Sander et al., 2003), iodine ~~(Saiz-Lopez et al., 2012b;Carpenter, 2003)~~(Saiz-Lopez et al., 2012b;Carpenter, 2003) and ~~polar~~Polar chemistry ~~(Simpson et al., 2007)~~(Simpson et al., 2007). These reviews detail the broader picture of halogen chemistry and the focus hereafter will be on recent advances that directly affect tropospheric ozone.

Overall, observations of halogen species in the boundary layer show a consistent picture across the globe (see ~~(Saiz-Lopez and von Glasow, 2012)~~(Saiz-Lopez and von Glasow, 2012)), with comparable levels of reactive halogens in different unpolluted/semi-polluted regions, and more variable levels of reactive halogens in continental/coastal environments, reflecting the larger variability in their sources and sinks under polluted conditions.

The major source of chlorine and bromine in the boundary layer is known to be sea-salt: current model parameterizations are able to reproduce measured BrO levels in the unpolluted MBL reasonably well ~~(Keene et al., 2009;Sommariva and von Glasow, 2012;Saiz-Lopez et al., 2012a)~~(Keene et al., 2009;Sommariva and von Glasow, 2012;Saiz-Lopez et al., 2012a). However, models struggle to reproduce total bromine and particulate bromide concentrations and their diurnal cycles, suggesting that our understanding may be limited by the lack of speciation of bromine in current analytical techniques.

Inorganic chlorine observations are better constrained, although concurrent measurements of Cl_2 and HOCl, especially under semi-polluted conditions ~~(Keene et al., 2009;Lawler et al., 2009;Lawler et al., 2011)~~(Keene et al., 2009;Lawler et al., 2009;Lawler et al., 2011), are difficult to reconcile and BrCl, which the models predict as one of the major components of total Br, has not been detected in marine environments. It is unclear whether the models-measurements disagreements are due to instrumental issues or to some fundamental problem in our understanding of the chemistry, particularly in the aqueous phase ~~(Long et al., 2014;Sommariva and von Glasow, 2012)~~(Long et al., 2014;Sommariva and von Glasow, 2012), but they make it difficult to accurately assess the effect of chlorine and bromine on ozone under unpolluted and semi-polluted conditions.

In the past few years, several groups have reported observations of significant concentrations of $ClNO_2$ (from 80 ppt to over 2000 ppt) in a variety of environments and under different conditions ~~(Osthoff et al., 2008;Kercher et al., 2009;Thornton et al., 2010;Mielke et al., 2011;Mielke et al., 2013;Phillips et al., 2012;Riedel et al., 2012;Riedel et al., 2013;Wagner et al., 2012)~~(Osthoff et al., 2008;Kercher et al., 2009;Thornton et al., 2010;Mielke et al., 2011;Mielke et al., 2013;Phillips et al., 2012;Riedel et al., 2012;Riedel et al., 2013;Wagner et al., 2012). These studies indicate that nocturnal formation of $ClNO_2$, *via* reaction of N_2O_5 with aerosol chloride, followed by its photolysis at sunrise to form Cl + NO_2 is a strong and widespread source of reactive chlorine in the polluted troposphere. In addition, to kick starting VOC oxidation in the morning before the formation of OH, the $ClNO_2$ mechanism also acts as a NOx reservoir, preventing NO_2 loss overnight as HNO_3 and hence making it available in the morning to form O_3. Although these two effects are not yet fully decoupled and understood (see discussion in ~~(Young et al., 2014)~~(Young et al., 2014)), it is clear that this chemistry is potentially very important for ozone formation in polluted environments. Osthoff et al. ~~(Osthoff et al., 2008)~~(Osthoff et al., 2008), Thornton et al. ~~(Thornton et al., 2010)~~(Thornton et al., 2010)

estimated that up to 13 ppb additional ozone can be formed *via* this chemistry. It must be noted, however, that the actual impact on local ozone may be much less than that, because of the effect of transport and local circulation on ozone levels ~~(Sarwar et al., 2012;Simon et al., 2010;Simon et al., 2009)~~(Sarwar et al., 2012;Simon et al., 2010;Simon et al., 2009). Furthermore, model analysis suggests that recirculation of air masses from urban coastal areas over the ocean may lead to high Cl_2 levels during the night, thus increasing VOC oxidation and ozone formation at sunrise ~~(Pechtl and von Glasow, 2007)~~(Pechtl and von Glasow, 2007), a mechanism which has particular relevance for coastal megacities.

There are several inconsistencies in the observations of reactive iodine, especially under conditions representative of the open ocean: for example, Carpenter et al. ~~(Carpenter et al., 2010)~~(Carpenter et al., 2010) highlighted the discrepancy between observations of IO made by different groups at the Cape Verde islands, while Mahajan et al. ~~(Mahajan et al., 2010)~~(Mahajan et al., 2010), found that IO concentrations in the eastern Pacific did not agree with the observations of Chlorophyll-a and Dissolved Organic Matter, and were much lower than the SCIAMACHY satellite observations. Additionally, the measured emission rates of iodinated VOCs are unable to explain the observed levels of IO and I_2 ~~(Carpenter et al., 2013;Jones et al., 2010b;Grossmann et al., 2013;Lawler et al., 2014)~~(Carpenter et al., 2013;Jones et al., 2010b;Grossmann et al., 2013;Lawler et al., 2014). Several mechanisms have been introduced to explain the observations and are still under active discussion (e.g., ~~(Lawler et al., 2014;Carpenter et al., 2013;MacDonald et al., 2014)~~(Lawler et al., 2014;Carpenter et al., 2013;MacDonald et al., 2014)). Some of these discrepancies may be explained by assuming seasonal or yearly cycles of the iodine sources, but there are also several uncertainties in the iodine chemical mechanism ~~(Sommariva et al., 2012;Saiz-Lopez et al., 2012b)~~(Sommariva et al., 2012;Saiz-Lopez et al., 2012b). The many uncertainties in iodine sources and chemistry make it difficult to assess accurately the role of iodine as ozone sink in unpolluted/semi-polluted conditions, especially over the open ocean. Although the sources and chemistry of iodine species are still being debated, it is well established that iodine species do not react with VOC and, when NOx levels are high, they form stable iodine nitrates (INOx) which can be taken up on aerosol, leading to net loss of NOx (and hence O_3). In addition, recycling of INO_3 in the gas-phase ~~(~~

$INO_3 + I \rightarrow I_2 + NO_3$~~)~~ (R13)

may increase ozone depletion by up to 60% ~~(Mahajan et al., 2009)~~(Mahajan et al., 2009).

The interaction between iodine and ozone also leads to the formation of ultra-fine particles under certain conditions (e.g. coastal regions with strong emissions of iodine from macro-algae, ~~(McFiggans, 2005)~~(McFiggans, 2005)), although this process, and its impact on local O_3 concentrations, is not yet completely understood. Recent work has shown increased O_3 deposition velocities during low tides, owing to direct deposition to macro-algae and/or to ~~a~~ O_3 involvement in iodine-mediated particle formation ~~(McFiggans et al., 2010)~~(McFiggans et al., 2010).

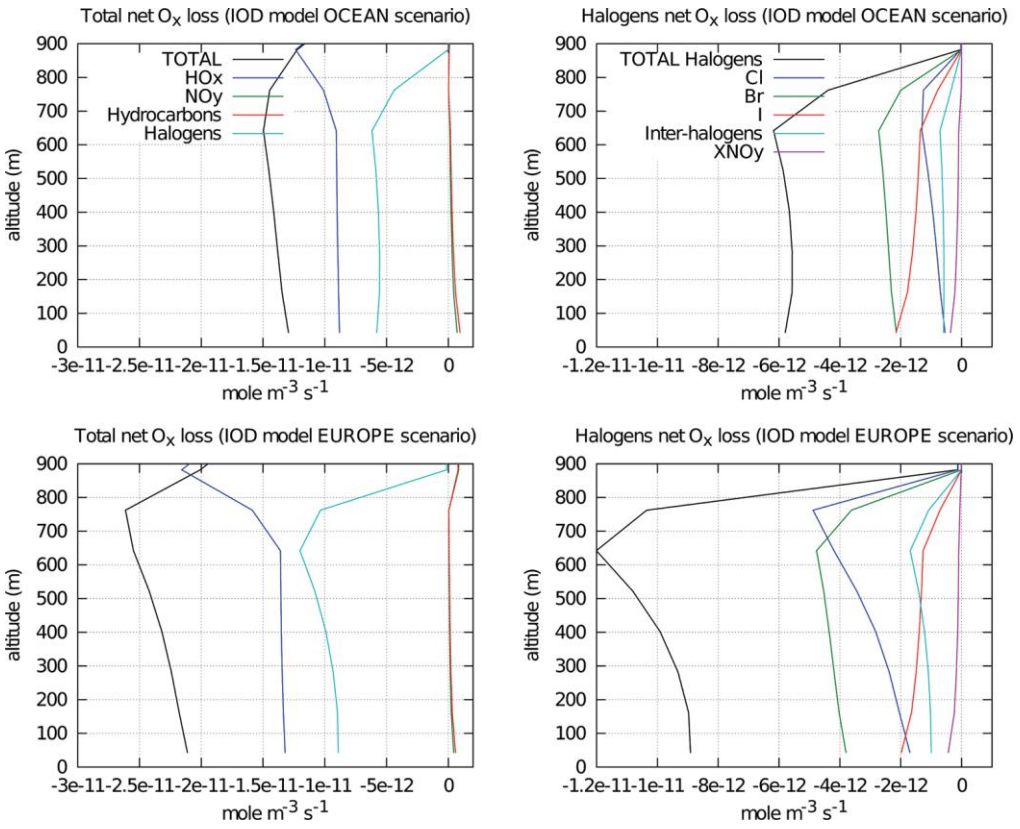


Figure ~~3233~~ - Vertical profiles at ~~12:00~~midday of total and ~~halogens~~halogen induced net O_x loss in an unpolluted (OCEAN scenario) and semi-polluted (EUROPE scenario) marine boundary layer ~~(Sommariva and von Glasow, 2012)~~(Sommariva and von Glasow, 2012).

All recent observational and modelling studies of halogen chemistry generally agree that reactive halogen species are present in the unpolluted/semi-polluted marine boundary layer at levels that result in significant depletion of tropospheric ozone and loss of Ox. Read et al. ~~(Read et al., 2008)~~(Read et al., 2008), Sommariva & von Glasow ~~(Sommariva and von Glasow, 2012)~~(Sommariva and von Glasow, 2012) and Saiz-Lopez et al. ~~(Saiz-Lopez and von Glasow, 2012)~~(Saiz-Lopez and von Glasow, 2012) calculated the contribution of halogens to ozone destruction using different models. The results, varying from 3 to 14 ppb per day, indicate that halogens overall are the second most important sink for Ox in unpolluted and semi-polluted conditions, accounting for up to a third of total ozone loss in the tropical troposphere (Figure ~~32~~33). Bromine is ~~about~~ twice more important than chlorine as ozone sink, and iodine is potentially more efficient than bromine although its concentration shows a steeper vertical gradient, making it less important than bromine and chlorine above 500-600 m (Sommariva & von Glasow, 2012). It must also be noted that the co-presence of iodine and bromine makes the loss of ozone more efficient than if bromine alone were present, due to the multiplying effect of inter-halogens reactions (e.g., IO + BrO, ~~(Read et al., 2008)~~(Read et al., 2008)).In polluted regions, due to the higher concentrations of NOx, the oxidation of VOC by Cl and,

to a lesser extent, Br, results in net ozone production. For example, Finley & Saltzmann ~~(Finley and Saltzman, 2008)~~(Finley and Saltzman, 2008) calculated that the levels of dihalogens (up to 26 ppt of Cl_2 and up to 9 ppt of Br_2) observed in California could account for up to 10% of measured ozone.

The role of halogens in the boundary layer is likely to be impacted, and possibly become even more relevant for O_3 photochemistry, by changes in the Earth System, which may alter the formation of marine aerosol, as well as increased emissions of acids and acid precursors, which affect the halogen activation processes ~~(Long et al., 2014)~~(Long et al., 2014).

At ~~polar~~Polar latitudes (> 60°), periodic ozone depletion events (ODE) have been observed since the mid-1980s and have been linked to bromine release from the snowpack ~~(Simpson et al., 2007)~~(Simpson et al., 2007) with observed BrO levels ranging from 5 to 41 ppt ~~(Roscoe et al., 2014;Saiz-Lopez and von Glasow, 2012)~~(Roscoe et al., 2014;Saiz-Lopez and von Glasow, 2012). Recently, novel observations of BrO ~~(Liao et al., 2011)~~(Liao et al., 2011) have shown that "BrO clouds" tend to be distributed homogeneously over scales of a few km during ODE, while Salawitch et al. ~~(Salawitch et al., 2010)~~(Salawitch et al., 2010) found that BrO columns are correlated with the height of the tropopause, although some "hotspots" are related to free tropospheric or stratospheric intrusions.

There is much less information regarding iodine and chlorine in Polar Regions. Chlorine presence has been inferred only by VOC ratios in the past; recently Pohler et al. ~~(Pohler et al., 2010)~~(Pohler et al., 2010) and Liao et al. ~~(Liao et al., 2014)~~(Liao et al., 2014) have reported the first observations of OClO (up to 24 ppt) and Cl_2 (up to 100 ppt), respectively, in the Arctic. These findings suggest that Cl may enhance O_3 depletion in the Polar Regions, mostly *via* its close coupling with bromine chemistry (with the ClO + BrO reaction contributing up to 73% to ozone depletion). Iodine species (IO) have been detected in Antarctica at levels comparable to BrO (~20 ppt, ~~(Saiz-Lopez et al., 2008)~~(Saiz-Lopez et al., 2008)), which increase O_3 loss rate by up to 3 times. Only one study reported IO in the Arctic at <3.4 ppt ~~(Mahajan et al., 2010)~~(Mahajan et al., 2010); whether this is due to differences between the two ~~polar~~Polar regions (e.g., biological communities or sea ice characteristic) is at present unclear.

Many questions remain on the mechanism of release of chlorine/bromine species from the snowpack (see ~~(Abbatt et al., 2012)~~(Abbatt et al., 2012) for a detailed review). An important issue is whether it can explain observed HOx and NOx levels ~~(Saiz-Lopez et al., 2008;Bloss et al., 2010)~~(Saiz-Lopez et al., 2008;Bloss et al., 2010), as well as observed halogens levels. A modelling study by Thomas et al. ~~(Thomas et al., 2011)~~(Thomas et al., 2011), Thomas et al. ~~(Thomas et al., 2012)~~(Thomas et al., 2012) indicated that up to 10 ppt of tropospheric BrO can be explained by a mechanism involving nitrate formation in the interstitial snow; if this is the case, the resulting formation of NOx may compensate the depletion of O_3 due to reactive Br, possibly leading to net ozone formation. Additionally, since bromine release is connected with first-year sea ice ~~(Saiz-Lopez and von Glasow, 2012)~~(Saiz-Lopez and von Glasow, 2012), changes in sea ice formation due to climatic change are likely to affect ozone photochemistry significantly.

The importance of localized sources of halogens, such as salt lakes, salt beds, saline soils and marshes, for O_3 photochemistry is at present unclear. Large concentrations of bromine and iodine (up to 200 ppt of BrO ~~(Tas et al., 2005)~~(Tas et al., 2005) and up to 10 ppt of IO, ~~(Zingler and Platt,~~

~~2005)~~(Zingler and Platt, 2005)) have been reported over the Dead Sea (Israel) causing O_3 as low as 2 ppb; however, observations in other locations have shown much lower values (e.g., 6 ppt of BrO and 15 ppt of ClO over the Great Salt Lake, ~~(Stutz et al., 2002)~~(Stutz et al., 2002)). The database of observations is very sparse and shows large variability between different locations, suggesting that the local characteristics (e.g, latitude, pH, geology, ecosystem and local meteorology) of the salt lakes are crucial in determining the strength of halogen emissions and therefore of the magnitude of the ODE they trigger ~~(Smoydzin and von Glasow, 2009)~~(Smoydzin and von Glasow, 2009)

Chlorine and bromine species have also been detected in volcanic plumes at ppm and ppb levels, respectively ~~(Saiz-Lopez and von Glasow, 2012)~~(Saiz-Lopez and von Glasow, 2012), leading to ozone depletion inside the plume which can persist for at least 3 days and possibly longer (see ~~(von Glasow, 2010)~~(von Glasow, 2010), for a detailed discussion). Similar chemistry may be expected from other types of volcanic activity, such as volcanic fields, vents, fumaroles, etc... and may affect ozone levels both in the boundary layer and in the free troposphere. The extent to which halogens from volcanic activity affect ozone photochemistry on a larger (regional/global) scale depends on several variables, including the type, frequency and extent of volcanic activity, the mixing with the background air and the synoptic circulation.

Besides the injection of halogen species by volcanic activity (see above), the main sources of halogens in the free troposphere are believed to be the oxidation of halocarbons, the uplift of aerosol and stratospheric intrusions ~~(Saiz-Lopez and von Glasow, 2012)~~(Saiz-Lopez and von Glasow, 2012), although direct observations are scarce. Pommier et al. ~~(Pommier et al., 2012)~~(Pommier et al., 2012) found evidence of biomass burning from Siberian fires as a source of BrO (>5 ppt) in the Arctic free troposphere, although the release mechanism is unclear; Roscoe et al., ~~(Roscoe et al., 2014)~~(Roscoe et al., 2014) compared ground based and remote sensing measurements in Antarctica and concluded that they could only be reconciled by assuming large amounts of BrO at high altitudes, in broad agreement with the findings by Koo et al. ~~(Koo et al., 2012)~~(Koo et al., 2012).

Jones et al. ~~(Jones et al., 2010a)~~(Jones et al., 2010a) found a strong association between high altitude ODEs and atmospheric low pressure systems which drive the formation of large scale BrO clouds over Antarctica. Free troposphere-boundary layer dynamic may also be important outside the Polar Regions. For example, Long et al. (2014) suggested that the accumulation of insoluble bromine in the free troposphere (*via* sulphur oxidation by HOBr and/or HBr condensation on aerosol) may explain the observed Br enrichment of submicron aerosol after entrainment of these species back in the boundary layer. These recent findings suggest the presence of large concentrations of inorganic Br at high altitudes in the troposphere and model calculations show that they may account for 3-15% reduction in tropospheric O_3 ~~(von Glasow and Crutzen, 2004)~~(von Glasow and Crutzen, 2004). Lary ~~(Lary, 2005)~~(Lary, 2005) has examined the role of halogens in the free troposphere using chemical data assimilation technique and concluded that chlorine and bromine can affect significantly the levels of methane (10-50% of the total oxidation rate) and ozone in the upper troposphere, especially at ~~polar~~Polar and tropical latitudes.

Recently, IO has also been observed in the tropical and sub-tropical free troposphere at concentrations between 0.2 and 0.4 ppt ~~(Dix et al., 2013;Puentedura et al., 2012)~~(Dix et al., 2013;Puentedura et al., 2012). Assuming 0.5 ppt of BrO and 0.6 ppt of IO, Dix et al. (2012) estimated

that iodine accounts for 11% and 26% of total ozone loss in the free troposphere and in the boundary layer-free troposphere transition region, respectively.

Formatted: List Paragraph1

4.5 Tropospheric ozone and global perturbation of the nitrogen cycle

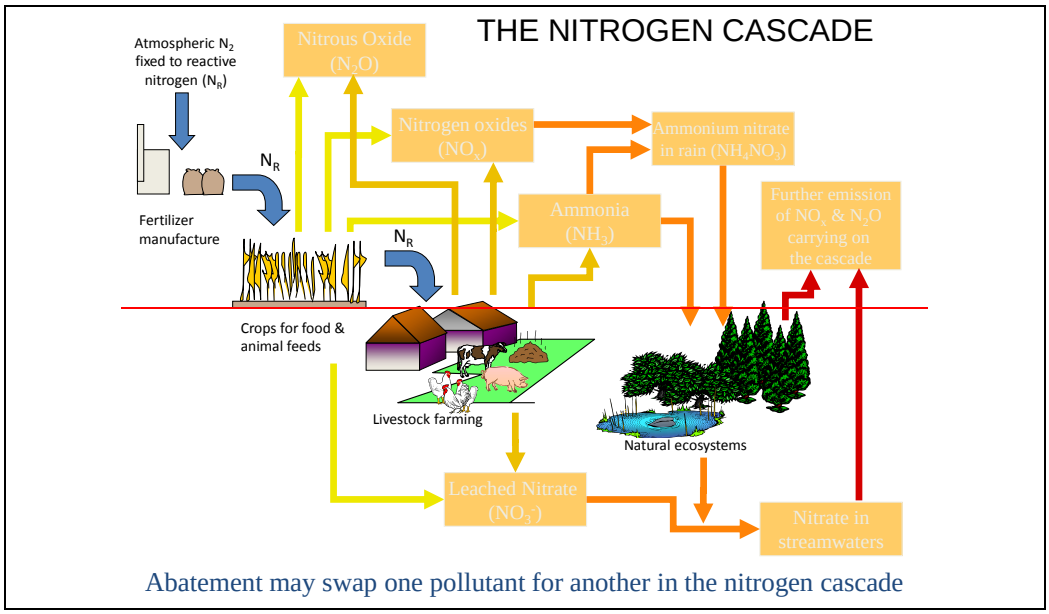
The drivers of enhanced tropospheric ozone are emissions of the precursors, NOx and VOC, and viewed globally the hot spots for ozone production coincide with the areas of largest NOx emissions ~~(Stevenson et al., 2006)~~(Stevenson et al., 2006), most notably in Europe, North America and Asia. Thus the effects of elevated tropospheric ozone are coupled to anthropogenic emissions of NOx, an important anthropogenic contribution to the current global cycling of fixed nitrogen (Nr), to distinguish it from the atmospheric reservoir of unreactive N_2. Recent assessments of the global nitrogen cycle have quantified the major natural and anthropogenic fluxes of Nr ~~(Sutton et al., 2011;Galloway et al., 2004)~~(Sutton et al., 2011;Galloway et al., 2004). The scale of the human perturbation of the global nitrogen cycle is substantial, with approximately half of the 413 Tg-N annual fixation of atmospheric nitrogen into reactive oxidized NO_y and reduced, NH_x forms ~~(Fowler et al., 2013b)~~(Fowler et al., 2013b) contributed by anthropogenic activities ~~(Lu et al., 2013)~~(Lu et al., 2013). Within this total, most of the nitrogen fixed annually is by industrial production of ammonia in Haber-Bosch industrial plants and within soils and oceans by microbial processes. Only a small fraction of this Nr is emitted to the atmosphere (see Figure ~~33~~34). The emissions most important for tropospheric ozone production are of NOx from combustion, in vehicles and industry, which totals approximately 40Tg-N annually, just 10% of total Nr production.

While the focus of this review is tropospheric ozone, it is important to recognise the wider impacts of the human perturbation of the nitrogen cycle ~~(Fowler et al., 2014).~~(Fowler et al., 2015). These include eutrophication of terrestrial and marine ecosystems, reductions in biodiversity of terrestrial ecosystems over Europe and North America, widespread effects on human health from the aerosols containing nitrogen compounds and radiative effects on global climate and reductions in stratospheric ozone from elevated N_2O emission, as detailed by Erisman et al ~~(Erisman et al., 2013)~~(Erisman et al., 2013). The negative effects of contamination of the environment by nitrogen compounds has been extensively documented for Europe ~~(Sutton et al., 2011)~~(Sutton et al., 2011) and North America ~~(Suddick et al., 2013)~~(Suddick et al., 2013). However, evidence from Asia and especially China and India is increasing rapidly and the absolute values for deposition of Nr in these regions are among the largest globally and effects on ozone production and terrestrial eutrophication are widespread.

Relatively little research on the effects of nitrogen emission has been reported ~~for~~ in the tropics, but new evidence from work in SE Asia by Hewitt et al ~~(Hewitt et al., 2009)~~(Hewitt et al., 2009) suggests that these regions are very sensitive to emissions of NOx which are projected to increase substantially over coming decades as natural rainforest ecosystems are replaced by agriculture e.g. plantations of oil palm.

One of the distinctive features of the nitrogen cycle is the rapid transformation of nitrogen compounds within, and transfers between the atmosphere, vegetation, soils, fresh and marine

waters. Thus emissions of oxidized nitrogen to the atmosphere are rapidly oxidized and deposited into terrestrial ecosystems, where it may be transformed into amino acids and subsequently decomposed to ammonium following decay and returned to the atmosphere as ammonia. In the processes within this short sequence, the NO_x in the atmosphere may have generated ozone, reduced the lives of humans breathing NH_4NO_3 containing aerosols and contributed to species loss in terrestrial ecosystems. The same emitted N atom may have contributed to a series of different effects within the Earth system before it is returned back to the atmospheric reservoir as N_2 following denitrification in soils or within the ocean. This effect has been referred to as the nitrogen cascade ~~(Galloway et al., 2003)~~(Galloway et al., 2003) and shows a very large range of effects of reactive nitrogen on climate, terrestrial and marine ecosystems and on human health. A full analysis of the global effect of nitrogen has yet to be completed, but assessments have been recently published for Europe ~~(Sutton et al., 2011)~~(Sutton et al., 2011) and for North America ~~(Suddick et al., 2013)~~(Suddick et al., 2013).



Abatement may swap one pollutant for another in the nitrogen cascade

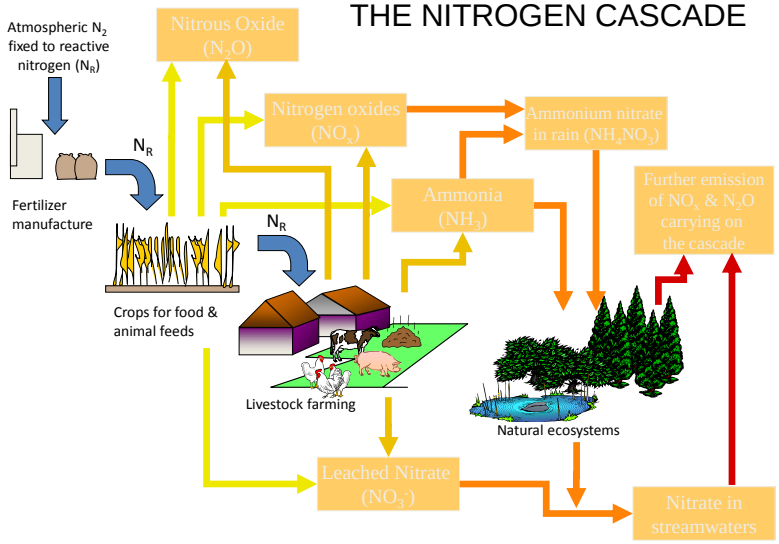


Figure ~~33~~34 - The nitrogen cascade adapted from ~~(Sutton et al., 2011)~~(Sutton et al., 2011) showing the interrelationships of nitrogen sources of importance for the production of ozone.

Field Code Changed

Formatted: English (U.K.)

Models are the integrator of the chemical and physical knowledge with respect to ozone in the atmosphere. They are much relied on for analysis of observational data, hindcasting, policy support and forecasting across a range of temporal and spatial scales. Models vary much in scale, resolution and with physical/chemical complexity.

One further aspect for consideration is the coupling between tropospheric ozone, carbon uptake in the terrestrial biosphere and nitrogen ~~(Simpson et al., 2014)~~(Simpson et al., 2014). It has been recently shown that limitations of available nitrogen for sufficient plant growth reduce the negative impact of tropospheric ozone on carbon uptake in plants, leading to a smaller indirect change in radiative forcing than previously calculated ~~(Kvalevåg and Myhre, 2013)~~(Kvalevåg and Myhre, 2013).

4.6 Challenges in modelling ozone

With respect to current global ozone, Young et al. ~~(Young et al., 2013)~~(Young et al., 2013) compared modelled (ACCMIP models) and observed (ozone-sonde and satellite (OMI/MLS)) present-day spatial distributions and seasonality of global tropospheric ozone. The models captured the seasonality well at most locations. Based on the comparison to OMI/MLS data the models typically overestimated annual mean tropospheric column ozone at 0-50°N by ≈0-30% and underestimate it at 0-50°S by ≈0-25%. Similarly, re-analysis model data for ozone from MACC shows biases of -5% to +10% with respect to ozonesondes and aircraft data in the extratropics, but with larger negative biases in the tropics ~~(Inness et al., 2013)~~(Inness et al., 2013). These results indicate that models don't fully represent the processes controlling the present-day ozone distribution.

Parrish et al. ~~(Parrish et al., 2014)~~(Parrish et al., 2014) have shown that three of the ACCMIP models, driven by trends in emissions, underestimate observed trends in surface ozone over the period since ~1950, at NH mid-latitudes; similar results have been found earlier, e.g. ~~(Schultz et al., 2007b)~~(Schultz et al., 2007b). Cooper et al. ~~(Cooper et al., 2014)~~(Cooper et al., 2014) extended this analysis to show that models also underestimate trends in other regions. These observations suggest that modelled ozone appears to be rather too insensitive to emissions perturbations (or possibly that historical emissions changes are not well described, see section 2.3). Emissions remain a key uncertainty for global models ~~(Frost et al., 2012)~~(Frost et al., 2012).

Hess and Zbinden ~~(Hess and Zbinden, 2013)~~(Hess and Zbinden, 2013) and Hess et al. ~~(Hess et al., 2014)~~(Hess et al., 2014) find that the evolution of stratospheric ozone, and how this ozone is transported into the troposphere, is a major determinant of historical inter-annual variability of NH mid-latitude ozone throughout the troposphere, and may have significantly contributed to long-term trends. This work indicates that global models need a detailed representation of stratospheric and UT/LS processes in order to simulate ozone trends and variability correctly.

Further challenges to models include, the representation of different aspects of ozone chemistry (e.g., isoprene: ~~(Archibald et al., 2010;Dunker et al., 2014)~~(Archibald et al., 2010;Dunker et al., 2014); halogens: ~~(Yang et al., 2005;Saiz-Lopez et al., 2012a)~~(Yang et al., 2005;Saiz-Lopez et al., 2012a); chemical mechanism ~~(Saylor and Stein, 2012)~~(Saylor and Stein, 2012)) and deposition ~~(Val Martin et al., 2014)~~(Val Martin et al., 2014). For models to represent many of these processes, adequate resolution is required ~~(Colette et al., 2014)~~(Colette et al., 2014).

A couple of studies ~~(Wu et al., 2007;Wild, 2007)~~(Wu et al., 2007;Wild, 2007) have argued that much of the variance in ozone production across models can be explained by differences in NOx emissions, inclusion of nonmethane volatile organic compounds (NMVOCs, mostly biogenic isoprene) and ozone influx from stratosphere-troposphere exchange. Model tagging offers insights into separating processes such as transport and chemistry (see e.g. ~~(Garny et al., 2011)~~(Garny et al., 2011)).

The challenge for global modellers is prioritising and including all relevant processes in a model with sufficient resolution and while keeping it sufficiently computationally efficient so that it can be useful for a wide range of studies.

A large range of models are used to address ground-level ozone at the regional scale ~~(Kukkonen et al., 2012)~~(Kukkonen et al., 2012). Taking into account only emission control policies for the present or near future (2010 or 2020), several multi-model exercises have been conducted in support to the Clean Air For Europe programme (CAFE). The CityDelta project ~~(Cuvelier et al., 2007)~~(Cuvelier et al., 2007) aimed to predict the impact and uncertainty of emission reductions of several emission scenarios for 2010 in several European cities. The same exercise was carried out at the larger scale of the European continent (EuroDelta: ~~(van Loon et al., 2007)~~(van Loon et al., 2007)). At the continental scale the efficiency of emission reductions was demonstrated but models provided a large spread of responses in city centres. The ability of an ensemble of six chemistry transport models to capture recent observed ozone trends was also discussed by Colette et al. ~~(Colette et al., 2012)~~(Colette et al., 2012). They found that models efficiently captured the increase in NOx saturated areas, such as the Benelux region and the decrease in NOx limited areas (many rural regions in Europe). The quantitative skill of the model was however difficult to retrieve owing to the lack of significant trends throughout Europe over the period selected for the experiment. They also emphasized that modelled

trends where highly sensitive to the trends in precursors prescribed in the inventory which exhibited some significant inconsistencies compared to observations of NO_2, in particular.

A regional model comparison of ozone is shown in Figure ~~34~~35. The comparison found that no one model was the 'best' model on all days, indicating that no single air quality model could currently be relied upon to inform policymakers robustly in terms of NO*x*- versus VOC-sensitivity. For this reason coupled to basic statistical arguments, it was argued that it is important to maintain diversity in model approaches ~~(Derwent et al., 2014)~~(Derwent et al., 2014).

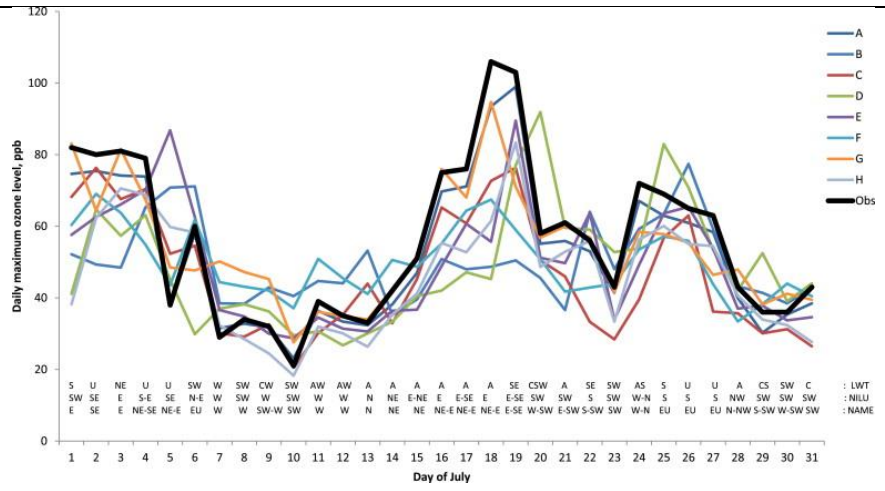


Figure ~~34~~35 - Daily maximum hourly ozone concentrations for eight models A-H in a comparison exercise against observations for July 2006 at Harwell, Oxfordshire, UK. Also shown are the daily advection regimes as Lamb Weather types (LWT), NILU FLEXTRA trajectories (NILU) and NAME air history maps (NAME), see ~~(Derwent et al., 2014)~~(Derwent et al., 2014)

With respect to regional models Kukkonen et al. ~~(Kukkonen et al., 2012)~~(Kukkonen et al., 2012) have highlighted the most prominent gaps of knowledge for chemical weather forecasting models; these include emission inventories, the integration of numerical weather prediction and atmospheric chemical transport models, boundary conditions and nesting of models, data assimilation of the various chemical species (see e.g. ~~(Gaubert et al., 2014)~~(Gaubert et al., 2014)), improved understanding and parameterization of physical processes, better evaluation of models against data and the construction of model ensembles.

It is clear that next generation models will push to greater resolution on the regional scale ~~(Colette et al., 2014)~~(Colette et al., 2014).

4.7 Lightning

Globally, lightning flashes occur about 50 times per second, equal to 4.3 million times per day and roughly 1.5 billion times per year. Lightning flashes dissociate N_2 molecules, leading to NO production ~~(Schumann and Huntrieser, 2007)~~(Schumann and Huntrieser, 2007), a key source of NOx in much of the troposphere, especially the tropical upper troposphere ~~(Schumann and Huntrieser, 2007;Grewe, 2008;Grewe et al., 2012a;Levy et al., 1996).~~(Schumann and Huntrieser, 2007;Grewe, 2008;Grewe et al., 2012a;Levy et al., 1996). More than 80% of summertime upper tropospheric NOx above the eastern United States is produced by lightning ~~(Cooper et al., 2009)~~(Cooper et al., 2009) and can be significant contributor to surface ozone ~~(Hudman et al., 2009)~~(Hudman et al., 2009). Lightning NOx (NO_2) has been detected from space ~~(Beirle et al., 2010;Choi et al., 2005)~~(Beirle et al., 2010;Choi et al., 2005). The lightning produced NO perturbs atmospheric composition in several ways relevant to climate, as NO is an important determinant of OH/HO_2 ratios *via* the reaction:

$$HO_2 + NO \rightarrow NO_2 + OH$$

(~~3~~R3)

~~The NO_2 photolyses to release an oxygen atom that can go on to form ozone:~~

~~$NO_2 + h\nu \rightarrow NO + O(^3P)$ (1)~~

~~$O(^3P) + O_2 + M \rightarrow O_3 + M$ (2)~~

Given sufficient UV radiation and a supply of HO_2, NOx will efficiently generate O_3 (see section 2.1.1). Figure ~~35~~36 shows modelled contribution of individual sectors in terms of NOx emissions, including lightning, to the tropospheric ozone column ~~(Grewe et al., 2012a)~~(Grewe et al., 2012a). Toumi et al ~~(Toumi et al., 1996)~~(Toumi et al., 1996) highlighted that O_3 production from lightning NOx (L_{NOx}) may represent an important positive climate feedback, if a warmer world generates more lightning ~~(Reeve and Toumi, 1999)~~(Reeve and Toumi, 1999).

However, in addition to leading to O_3 production~~,~~ (see section 2.1.1), equation (~~3~~R3) enhances OH. This increases the methane removal *via* the reaction:

$$CH_4 + OH + O_2 \rightarrow CH_3O_2 + H_2O$$

~~(11~~(R14)

shortening the CH_4 lifetime, and hence reducing its atmospheric concentration, exerting reducing radiative forcing (RF) (e.g. ~~(Derwent et al., 2001;Wild, 2007;Wild et al., 2001)~~(Derwent et al., 2001;Wild, 2007;Wild et al., 2001)).

~~Enhanced levels of OH will tend to increase production of all secondary aerosols (e.g., including sulphate), which would increase the magnitude of the negative radiative forcing owing to aerosols (e.g. (Stevenson et al., 2005)).~~

~~The catalytic cycle of O_3 production described by equations (1-3) is terminated when NOx is removed by the reaction:~~

~~$NO_2 + OH + M \rightarrow HNO_3 + M$. (12)~~

~~This and other analogous reactions produce various forms of nitrates, including nitrate aerosol. Enhanced levels of nitrate aerosol, which typically scatters solar radiation, will exert a negative RF~~

~~(e.g. (Shindell et al., 2009)), although specific studies of nitrate aerosol associated with L_{NOx} are apparently lacking.~~

Any perturbations to NOx (including lightning) will potentially lead to climate feedbacks *via* the biosphere, through deposition of NO_3 and O_3, and impacts on the carbon cycle (e.g. enhanced or reduced uptake of CO_2 by vegetation; ~~(Sitch et al., 2007;Felzer et al., 2007)~~(Sitch et al., 2007;Felzer et al., 2007)). It is unclear if the net effect on CO_2 would result in a positive or negative RF.

Most studies suggest more lightning (NOx) in a warmer world ~~(Schumann and Huntrieser, 2007;Williams, 2005;Banerjee et al., 2014)~~(Schumann and Huntrieser, 2007;Williams, 2005;Banerjee et al., 2014), but these are typically based on the Price and Rind ~~(Price and Rind, 1992)~~(Price and Rind, 1992) parametrization that links L_{NOx} emissions to cloud top height (raised to the power 4.9 over land; to a lower power over ocean). Other parametrizations link L_{NOx} emissions to cloud ice (see e.g. ~~(Finney et al., 2014;Tost et al., 2007)~~(Finney et al., 2014;Tost et al., 2007)), and as warming increases, ice declines, and so does LNOx ~~(Jacobson and Streets, 2009)~~(Jacobson and Streets, 2009). In addition, some schemes relate L_{NOx} to aerosols ~~(Yuan et al., 2012;Venevsky, 2014)~~(Yuan et al., 2012;Venevsky, 2014), with potentially complex links between climate and L_{NOx}. With global warming, tropical stability increases ~~(Held and Soden, 2006;Chou et al., 2013)~~(Held and Soden, 2006;Chou et al., 2013) tending to reduce convection. However, the tropopause tends to rise, allowing convection to reach greater heights. In the Price and Rind (1992) scheme, the higher tropopause affect typically dominates, although there can be regional increases/decreases in some models (e.g., Stevenson et al., 2005).

In summary, the literature suggests that L_{NOx} increases lead to higher levels of O_3, OH, nitrate, and secondary aerosols in general, but less CH_4, and have unknown impacts on CO_2. It remains unclear if the net impact of increases in L_{NOx} on climate is warming or cooling; it is also unclear if L_{NOx} represents a positive or negative climate feedback.

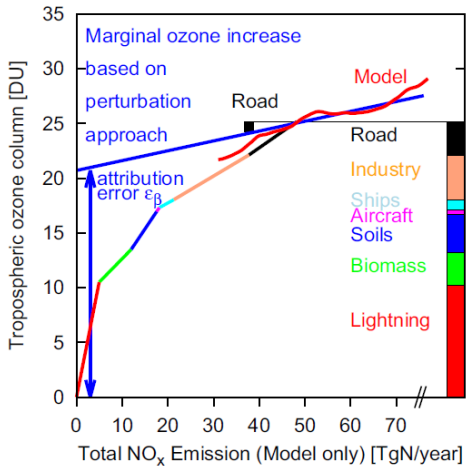


Figure ~~35~~36 - Contribution of individual sectors in terms of NOx emissions to the tropospheric ozone column ~~(Grewe et al., 2012b)~~(Grewe et al., 2012b).

4.8 Arctic

The Arctic is under-going rapid change as a result of global warming. This can, in part, be attributed to production of ozone from tropical and mid-latitude emissions of ozone precurors, especially methane. Climate change together with economic drivers, is also opening up the Arctic to new sources of pollution, such as shipping or oil/gas extraction which may lead to siginificant local or regional increases in surface ozone and associated impacts on Arctic air quality and deposition to fragile ecosystems ~~(Law and Stohl, 2007)~~(Law and Stohl, 2007).

Observed Arctic O_3 mixing ratios vary between 20 and 40 ppbv at the surface and increase with altitude up to the tropopause (8-10 km) ~~(Hirdman et al., 2010)~~(Hirdman et al., 2010). Even though annual data on Arctic O_3 is rather limited, significant differences can be seen in the seasonal cycle at different locations, driven by both remote and local processes (see Figure ~~36~~37) ~~(Hirdman et al., 2010)~~(Hirdman et al., 2010). Certain sites, such as Barrow (Alaska) or Alert (Canada), show evidence of halogen influenced depletion during the spring months. As discussed in section 4.4, halogen chemistry over sea-ice or snow covered regions can lead to very low or even near-zero O_3 concentrations near the surface in the Arctic spring (e.g. ~~(Barrie et al., 1988)~~(Barrie et al., 1988)). Other sites, such as Zeppelin, exhibit a spring maximum. Higher concentrations in the spring appear to be due to O_3 formation from precursors related to the breakdown of Arctic Haze at this time of year in the lower and middle tropopshere ~~(Emmons et al., 2003)~~(Emmons et al., 2003). Arctic Haze builds up during the winter each year as a result of transport of mid-latitude pollution into the ~~polar~~Polar dome (e.g. ~~(Barrie et al., 1981)~~(Barrie et al., 1981)) and contains elevated levels of O_3 precursors (CO, VOCs, NO_x) as well as PAN, an important source of NOx (e.g. ~~(Hov et al., 1989)~~(Hov et al., 1989)).

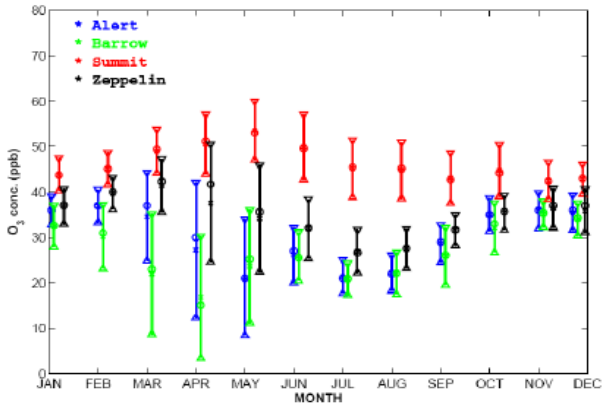


Figure ~~36~~37 - Seasonal cycle of O_3 at various surface sites in the Arctic. From ~~(Hirdman et al., 2010)~~(Hirdman et al., 2010).

Summit, which is at a higher elevation (3 km), on Greenland, has a late spring/ early summer maximum, likely owing to transport of polluted air masses, primarily from North America, but which could also include a contribution from snow NOx emissions (e.g. ~~(Grannas et al., 2007)~~(Grannas et al.,

2007)) or from the stratosphere. There are indications that O_3 concentrations continue to increase in the Arctic both at the surface and at higher altitudes in the troposphere. Hess and Zbinden ~~(Hess and Zbinden, 2013)~~(Hess and Zbinden, 2013) reported an increasing trend in the European Arctic middle troposphere (500 hPa) of 0.36+/-0.23 ppb/yr from ozonesonde measurements over the period 1996-2010, and Oltmans et al. ~~(Oltmans et al., 2006;Oltmans et al., 2013)~~(Oltmans et al., 2006;Oltmans et al., 2013) reported a trend of 0.87+/-0.50 %/yr from surface measurements in 1992-2004 at Alert in the Canadian Arctic.

Several studies have examined sources of pollution transported to the Arctic~~.~~ (Mauzerall et al., 1996). In a multi-model assessment, Shindell et al. ~~(Shindell et al., 2008)~~(Shindell et al., 2008) examined precursor emission sensitivities to emissions from different mid-latitude source regions on the Arctic and found, for example, European CO emissions to be important in the winter. However, surface Arctic O_3 in winter was most sensitive to European NO_x owing to the domination of strong titration (O_3 removal) in air masses. This was also confirmed by Hirdman et al ~~(Hirdman et al., 2010)~~(Hirdman et al., 2010)). Emissions from Asia and Europe have been found to be important sources of Arctic O_3 in spring in the free troposphere together with stratospheric injection although relative contributions vary between studies and years ~~(Wespes et al., 2012;Shindell et al., 2008)~~(Wespes et al., 2012;Shindell et al., 2008)~~.~~. Based on analysis of ARCTAS data (Jacob et al., 2010), Wespes et al. (2012) found that European anthropogenic emissions were important for lower tropospheric summertime Arctic O_3 in contrast to a previous study ~~(Shindell et al., 2008)~~(Shindell et al., 2008). Production of O_3 from PAN decomposition in air masses transported from mid-latitudes has also been identified as an important source of Arctic tropospheric ozone in the summer months ~~(Walker et al., 2012)~~(Walker et al., 2012). Indeed, aircraft observations collected during POLARCAT-IPY show elevated PAN and CO concentrations in air masses transported from Asian and North American anthropogenic emission regions in summer 2008 (~~(Law et al., 2014)~~(Law et al., 2014) and references therein). Boreal forest fires are also an important source of PAN and, due to their proximity to the Arctic, plumes can be transported to high latitudes during the spring and summer months ~~(Brock et al., 2011;Singh et al., 2010)~~(Brock et al., 2011;Singh et al., 2010). Whilst little O_3 production appears to occur close to boreal fires ~~(Alvarado et al., 2010;Paris et al., 2010)~~(Alvarado et al., 2010;Paris et al., 2010), several recent studies have shown O_3 production downwind from boreal fires in the Arctic during the summer months ~~(Wespes et al., 2012;Parrington et al., 2012;Thomas et al., 2013)~~(Wespes et al., 2012;Parrington et al., 2012;Thomas et al., 2013). Nevertheless, O_3 production is higher in air masses influenced by anthropogenic emissions.

However, global and regional models still struggle to capture vertical distributions of trace gases, including ozone in the Arctic. CO concentrations are often underestimated even in multi-model simulations carried out as part of the POLARCAT model inter-comparison project (POLMIP) using the same emission datasets ~~(Monks et al., 2014;Emmons et al., 2014)~~(Monks et al., 2014;Emmons et al., 2014). Discrepancies appear to be related to either differences in oxidative capacity (OH) or vertical transport of pollutants from mid-latitude source regions into the Arctic. Modelled concentrations of NOy species such as PAN or HNO_3 also show large variability and siginificant discrepancies compared to measurements ~~(Arnold et al., 2014)~~(Arnold et al., 2014) pointing to lack in our understanding about chemical processing in polluted air masses transported to the Arctic (Law et al., 2014).

As a short-lived climate forcer, tropospheric O_3 contributes to Arctic warming. For example, Shindell et al. ~~(Shindell et al., 2006)~~(Shindell et al., 2006) estimated that anthropogenic emission increases

since 1900 could be responsible for 25% of surface temperature changes in the Arctic. Shindell ~~(Shindell, 2007)~~(Shindell, 2007), based on the results from one model, estimated that about 50% of the Arctic radiative forcing owing to ozone may be coming from O_3 produced at mid-latitudes (impacting poleward heat transport) and about 50% from ozone produced in the Arctic. New local sources of pollution may also impact Arctic O_3 in the future such as increased emissions from shipping ~~(Granier et al., 2006)~~(Granier et al., 2006) or oil and gas production. Dalsøren et al. ~~(Dalsoren et al., 2013)~~(Dalsoren et al., 2013) examined impacts of future shipping on radiative forcing in the Arctic and found, particularly in the high-end scenario (from ~~(Corbett et al., 2010)~~(Corbett et al., 2010)), that O_3 radiative forcing from shipping is important in the summer and transit season (May to October) when sea-ice is at a minimum.

4.9 Unconventional oil and natural gas production: "fracking" and air quality

Fossil fuel energy production is rapidly transforming and expanding owing to unconventional oil and natural gas extraction techniques, with implications for regional-scale ozone production. Unconventional oil and natural gas is extracted from tight geological formations (such as sandstone, coal and shale) through the use of hydraulic fracturing (also known as fracking) and directional drilling ~~(Field et al., 2014;Bickle, 2012)~~(Field et al., 2014;Bickle, 2012). These techniques allow wells to be drilled vertically into a shale formation and then horizontally through the formation, after which a mixture of water, sand and chemicals is pumped into the well at high pressure, fracturing the rock and allowing oil and gas to escape.

In the USA, the most extensive extractors of unconventional gas/oil, the shale plays (a name for the deposits) are located in many large basins across the country, primarily in the Rocky Mountains, Great Plains and the Appalachian Mountains. In terms of natural gas, the most productive shale plays are the Marcellus Shale (West Virginia, Pennsylvania, New York) ~~(Kargbo et al., 2010)~~(Kargbo et al., 2010) and the Haynesville-Bossier Shale (Texas and Louisiana). The greatest unconventional oil production is from the Bakken (North Dakota, Montana), Eagle Ford (Texas) and the Niobrara (Wyoming and Colorado) shale formations ~~(Administration, 2014a).~~(Administration, 2014b).

In 2012 the USA produced 8.9 million barrels of oil per day (this includes crude oil, shale oil, oil sands and natural gas liquids), the third largest producer in the world, behind Russia and Saudi Arabia. However, the USA is the world leader in producing oil and natural gas from hydraulic fracturing with 1.6 million barrels per day extracted from tight oil formations in 2012. Projections suggest that hydraulic fracturing will produce 4.5 million barrels per day by 2035, accounting for most of the US increase in oil production ~~(BP, 2013)~~(BP, 2013). The US is poised to become the largest producer of liquid fuels in the world, primarily due to tight oil growth ~~(BP, 2014b)~~(BP, 2014a).

In 2012 the USA was the world's largest producer of natural gas, producing 681 billion cubic meters (Bcm). US production of shale gas output is projected to rise from 255 Bcm/yr in 2012 (37% of total production) to 672 Bcm/yr in 2035 ~~(BP, 2014a).~~(BP, 2014b). Shale gas was just 2% of US natural gas production in 2004 but by 2035 it will be 63%. However, these oil and natural gas projections are highly uncertain with the quantity of oil produced in 2040 differing by a factor of two under a scenario of high oil and gas resources vs a scenario of low oil and gas resources ~~(Administration, 2014b)~~(Administration, 2014a).

With the increase in unconventional oil and natural gas has come an increase in fugitive emissions of hydrocarbons to the atmosphere in quantities great enough to influence local and regional-scale ozone production ~~(Katzenstein et al., 2003;Kemball-Cook et al., 2010;Edwards et al., 2014)~~(Katzenstein et al., 2003;Kemball-Cook et al., 2010;Edwards et al., 2014). This impact was revealed in an unexpected way during early 2008 when hourly average ozone mixing ratios exceeded 140 ppbv during February in the rural Upper Green River Basin, of Wyoming ~~(Schnell et al., 2009)~~(Schnell et al., 2009). In situ measurements revealed that the high wintertime ozone levels were due to a strong temperature inversion that trapped NO_x and hydrocarbon emissions from the natural gas industry. The trapping of the emissions was facilitated by high mountains on three sides of the basin. A key contributor to the ozone formation was deep snow cover which reinforced the temperature inversion, and also reflected UV radiation back through the inversion layer, essentially doubling the amount of available UV radiation necessary for ozone production. This phenomenon has also been observed in the Uintah Basin, Utah, impacted by both oil and natural gas extraction ~~(Edwards et al., 2013;Edwards et al., 2014)~~(Edwards et al., 2013;Edwards et al., 2014). Multiple years of data from these two regions demonstrate that without deep snow cover, the high ozone values do not occur ~~(Oltmans et al., 2014)~~(Oltmans et al., 2014). Recent work in the UK context ~~(Sommariva et al., 2014)~~(Sommariva et al., 2014) has shown the range and difference in UK shale VOC profiles.

The impact of emissions from the oil and natural gas industry on ozone outside of these rural, mountain-ringed basins is less certain. For example, field studies have been carried out across the Denver-Julesburg Basin in north-eastern Colorado to quantify emissions from the oil and natural gas industry but accurate estimates for some gases are complicated by emissions from nearby urban areas ~~(Pétron et al., 2012)~~(Pétron et al., 2012). However, relationships between particular VOCs can be used to clearly distinguish oil and natural gas emissions from urban emissions. VOC measurements from a site on the northern edge of the Denver metropolitan area were analysed to demonstrate that more than 50% of the VOC-OH reactivity was attributable to emissions from oil and natural gas operations, indicating that these emissions are a significant source of ozone precursors ~~(Gilman et al., 2013)~~(Gilman et al., 2013).

Several recent studies using chemical transport models suggest that emissions from the oil and natural gas industry can produce local and regional scale ozone enhancements ~~(Kemball-Cook et al., 2010;Rodriguez et al., 2009;Carter and Seinfeld, 2012;Olaguer, 2012)~~(Kemball-Cook et al., 2010;Rodriguez et al., 2009;Carter and Seinfeld, 2012;Olaguer, 2012). The reliability of these modelling studies is limited by the emissions inventories which are difficult to accurately produce owing to the heterogeneity of sources: type of gases emitted from a shale play; number of active well heads; integrity of infrastructure; emissions associated with well-completion vs. well operation; usage of venting or flaring ~~(Field et al., 2014)~~(Field et al., 2014). The most recent U.S. EPA estimates indicate that NO_x emissions from US petroleum and related industries only amounted to 5% of total US anthropogenic NO_x emissions in 2013, but doubled between 2004 and 2013 ~~(Agency, 2014)~~(Agency, 2014). Likewise VOC emissions increased by a factor of four over the same period, accounting for 14% of total US anthropogenic VOC emissions in 2013. However, these U.S. EPA estimates are highly uncertain. The U.S. EPA recently stated that it had not anticipated the tremendous nationwide growth in this sector and that it has limited directly-measured air emissions data from several important oil and gas production processes. The report recommends that the EPA

produce a comprehensive strategy for improving air emissions estimates for oil and natural gas production ~~(Agency, 2013)~~(Agency, 2013). Until the emission inventories can be improved great uncertainty will surround model estimates of the impact of the oil and natural gas industry on ozone pollution.

One final consideration of the potential for the oil and gas industry to affect tropospheric ozone is through its impact on global methane levels. Methane leaks from the oil natural gas industry may be a contributing factor to the renewed increase in global methane concentrations ~~(Nisbet et al., 2014)~~(Nisbet et al., 2014). For example, hydraulic fracturing in Utah may locally leak 6 to 12% of gas production to the air ~~(Karion et al., 2013)~~(Karion et al., 2013)~~. Figure 37 shows data from a series of studies including satellite remote sensed data that all show significant methane leakage beyond official EPA estimates (Schneising et al., 2014;Kort et al., 2014). However, owing to the great uncertainty of many aspects of global methane emissions, especially from US unconventional oil and natural gas activities, much more research is required to understand the impact of unconventional oil and natural gas activities on global methane concentrations (Brandt et al., 2014)~~. Kang et al (Kang et al., 2014) have highlighted the issue of abandoned wells and their significance. Figure 38 shows data from a series of studies including satellite remote sensed data that all show significant methane leakage beyond official EPA estimates (Schneising et al., 2014;Kort et al., 2014). However, owing to the great uncertainty of many aspects of global methane emissions, especially from US unconventional oil and natural gas activities (see e.g. (Allen et al., 2013)), much more research is required to understand the impact of unconventional oil and natural gas activities on global methane concentrations (Brandt et al., 2014).

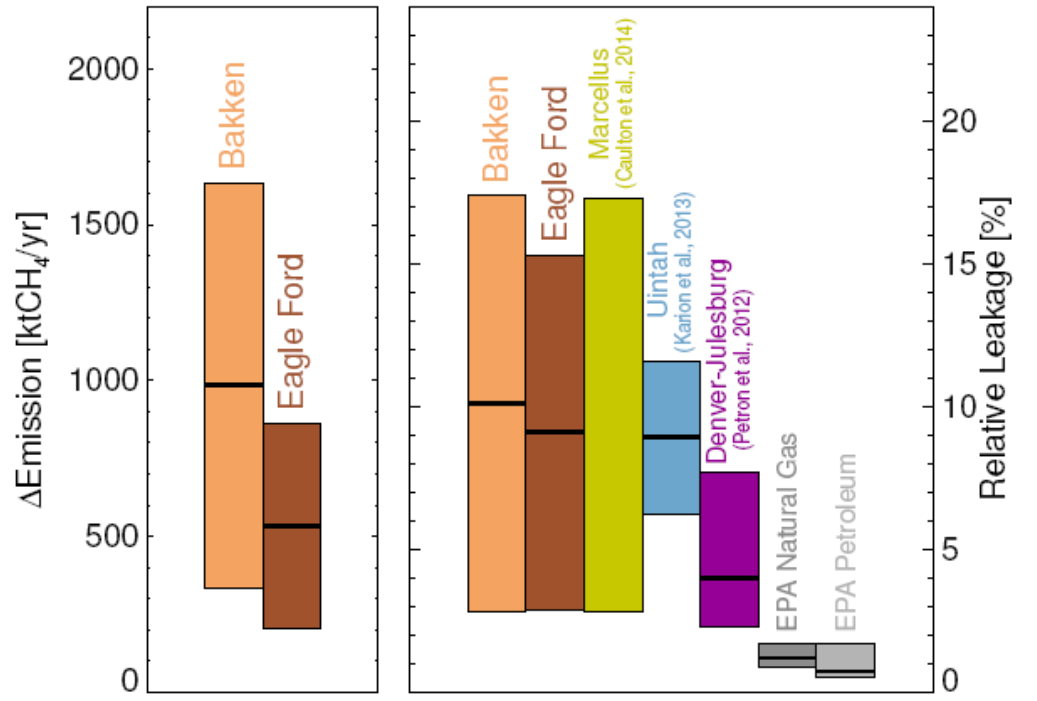


Figure ~~37~~38 - Estimated methane emissions are shown for the targeted regions Bakken in light

brown, and Eagle Ford in dark brown from satellite remote sensing measurements ~~(Schneising et al., 2014)~~(Schneising et al., 2014). Shown are absolute emission ~~increase~~increases (2009–2011 relative to 2006–2008) in the left panel, and the leakage ~~rate~~rates relative to production in the right panel, with the 1σ uncertainty ranges. For comparison, leakage estimates from previous studies in Marcellus (2012) ~~(Caulton et al., 2014)~~(Caulton et al., 2014), Uintah (2012) ~~(Karion et al., 2013)~~(Karion et al., 2013), Denver-Julesburg (2008) ~~(Pétron et al., 2012)~~(Pétron et al., 2012) . EPA bottom-up inventory estimates for natural gas and petroleum systems (2011) are shown for comparison ~~(EPA, 2014)~~(EPA, 2014).

4.10 Radical Chemistry, Radical changes

Radicals are central to the chemistry of the atmosphere; from the destruction of O_3 in the stratosphere, to the production and destruction of O_3 in the troposphere, radicals drive atmospheric composition change ~~(Monks, 2005)~~(Monks, 2005). The inorganic HO_x radicals (OH, HO_2) are regarded by many in the field of atmospheric chemistry as the most influential of all radicals, as such a great amount of effort has gone into understanding their impacts and fate in the atmosphere ~~(Heard and Pilling, 2003;Monks, 2005;Stone et al., 2012)~~(Heard and Pilling, 2003;Monks, 2005;Stone et al., 2012).

Recent laboratory and modelling studies have shifted attention to improved understanding of the fate and role of organic radicals. The organic radicals of importance to atmospheric chemistry can be classified as organic peroxy radicals (RO_2) (section 2.1.1), organic oxy radicals (RO) and the so called Criegee intermediates (CI), a class of bi-radical compounds believed to be formed mainly from the reaction of O_3 with alkenes.

In the following section we briefly review the main aspects of the chemistry of organic radicals and highlight the latest discoveries in their chemistry. Significant use of the review of Orlando and Tyndall ~~(Orlando and Tyndall, 2012)~~(Orlando and Tyndall, 2012) is made and for further details we refer the reader to their work.

RO_2 are produced in the atmosphere by the OH (and NO_3) initiated oxidation of VOCs. Once formed RO_2 are lost *via* reactions with NO, HO_2 and other RO_2. Whilst reactions with halogens (X) and halogen oxides (XO) have been known about for several decades, their importance for inclusion in studies of tropospheric O_3 chemistry has traditionally been expected to be small (see section 4.4 for more details). The RO_2 + NO reaction is known to have two product channels. The first forming NO_2, hence propagating tropospheric O_3 formation; the second channel leads to the production of an organic nitrate ($RONO_2$) *via* a complex rearrangement, the exact mechanism of which is still uncertain ~~(Dibble, 2008)~~(Dibble, 2008). We will not dwell on the chemistry of $RONO_2$ here, but suffice it to say these moieties allow O_3 precursors to be transported over great distances owing to their much longer atmospheric lifetime than NO_2. The kinetics of the RO_2 + NO reaction limit the RO_2 lifetime to only a few seconds when [NO] > 1 ppbv (see section 3.1 of Orlando and Tyndall 2012 for references). Broadly speaking the RO2 + NO reaction can be classed as the most important of the RO_2 loss reactions to include for modelling O_3 production in the troposphere. The products of the reaction between RO_2 and HO_2 depend strongly on the structure of the RO_2 ~~(Orlando and Tyndall, 2012)~~(Orlando and Tyndall, 2012). Traditionally the reaction between RO_2 and HO_2 has been thought

of as a radical sink, hence limiting the propagation of RO_2 + NO reactions and so reducing the potential O_3 production. The major product of this reaction for an alkyl RO_2 (R'RCHOO) is an organic hydroperoxide (ROOH), a compound that is predicted to be lost from the atmosphere *via* deposition or aqueous uptake faster than its photodissocation can reform precursor radicals. The kinetics of the self (RO_2 + RO_2) and cross reactions (RO_2 + $R'O_2$) of RO_2 (see section 3.5 of Orlando and Tyndall 2012 for references) limit the importance of these reactions to laboratory studies and parts of the atmosphere where concentrations of RO_2 are high (e.g. high BVOC emission regions).

For RO_2 to have a big impact on the composition and chemistry of the atmosphere they must propagate radical production. RO are produced almost exclusively as products of the reactions of RO_2 with NO. In general RO are very reactive and either undergo unimolecular decomposition (on the time scale of miliseconds) or react with O_2 producing HO_2 radicals (see section 2.1.1). Archibald et al., ~~(Archibald et al., 2007)~~(Archibald et al., 2007) used a box model to investigate the importance of the reaction:

$$RO + NO_2 + M \rightarrow RONO_2 + M \qquad (~~13~~R15)$$

and concluded that for CH_3O, reaction ~~13~~15 could be a significant source of CH_3ONO_2 under the high NO_2 conditions found in many megacities, but that the unimolecular decomposition and reaction of O_2 with RO limits the importance of reaction ~~13~~15 to CH_3O only.

Owing to very significant disagreement between model simulations and observations of HOx radicals in pristine environments ~~(Lelieveld et al., 2008;Whalley et al., 2011)~~(Whalley et al., 2011;Lelieveld et al., 2008), a number of recent studies have focused on trying to better understand the role of NOx free radical propagating chemistry for RO_2. In pristine environments the loss of RO_2 was traditionally thought to be dominated by the radical terminating reaction between RO_2 and HO_2. However, for acyl RO_2 (RC(O)OO) recent work has shown that the reaction of RO_2 with HO_2 has a major radical propagating product channel generating OH and RO_2 (see section 3.4 of Orlando and Tyndall 2012 for references). Based on this evidence Lelieveld et al., (2008) postulated that the reaction of RO_2 with X (where X reacted with a rate coefficient similar to that for RO_2 + NO) propagated radicals and was able to reconcile the model measurement disagreement for HO_x in the Amazon. However, Lelieveld et al. (2008) were unable to provide direct evidence for the structure of the unknown reaction partner, X. In much earlier modelling work, Frost et al., ~~(Frost et al., 1999)~~(Frost et al., 1999) speculated that near-IR absorption by RO_2 could lead to intramolecular conversion and yield HO_x radicals. Whilst a great deal of work has been performed identifying the absorbance features of RO_2 in the near IR (e.g. ~~(Kline and Miller, 2014)~~(Kline and Miller, 2014)), to date there has been almost no laboratory evidence of HO_x formation following absorption by RO_2 in the near-IR. However, Maccarone et al ~~(Maccarone et al., 2013)~~(Maccarone et al., 2013) have recently shown that arylperoxy radicals (RO_2 derived from aromatic hydrocarbons) are able to photo-dissociate in the visible spectrum to yield $O(^3P)$, and hence produce O_3 in the troposphere, without the need for NOx. As highlighted by the work of Lelieveld et al. (2008) and Frost et al (1999), modelling experiments are increasingly being used to help direct laboratory studies in the search for radical propagating reactions. Archibald et al. ~~(Archibald et al., 2009)~~(Archibald et al., 2009) investigated the possible reaction between RO_2 and OH using a simple box model of the marine boundary layer (MBL). In their study Archibald et al. (2009) suggested three different mechanisms for the RO_2 + OH reaction yielding three unique product sets, two propagating radicals and the third leading to the formation of

alcohols. The reaction they modelled was, at the time, very speculative and as such no kinetic studies had been performed. As such Archibald et al. (2009) used the kinetics of RO_2 + X and RO_2 + XO reactions as analogy. Their model calculations concluded that the RO_2 + OH reaction would have little impact on HO_x under conditions encountered in the MBL. Recently Bossolasco et al., ~~(Bossolasco et al., 2014)~~(Bossolasco et al., 2014) have measured the direct kinetics for the reaction between RO_2 and OH and have shown that it is extremely fast ($k \approx 2.8 \pm 1.4 \times 10^{-10}$ $cm^3 s^{-1}$), potentially twice as fast as the upper limit used by Archibald et al. 2009. The importance of this reaction under conditions similar to those found by Lelieveld et al. (2008) is yet to be explored.

Whilst unimolecular RO_2 isomerisations have been known about in combustion chemistry (where T > 600 K) for several decades (e.g. ~~(Hughes et al., 1992)~~(Hughes et al., 1992)), the importance of this process for the loss of RO_2 in the troposphere was thought insignificant - until recently. The RO_2 isomerisation proceeds *via* internal H atom abstraction from the terminal oxygen of the –OO group to produce what in combustion chemistry is referred to as a QOOH (see Figure ~~38~~39). Using *ab intio* calculation, Peeters et al. ~~(Peeters et al., 2009)~~(Peeters et al., 2009) and Da Silva et al. ~~(Silva et al., 2009)~~(Silva et al., 2009) independently suggested a mechanism for RO_2 isomerisations in the oxidation of isoprene that they postulated could help improve the model-measurement mismatch reported by Lelieveld et al. (2008) for HO_x in pristine conditions. The focus on isoprene peroxy radicals has led to a number of new discoveries in the lab as well as from a theoretical point of view. Thanks, largely to developments in mass spectrometry and other analytical techniques, new products (isoprene epoxydiols – IEPOX; hydroperoxyaldehydes - HPALDS) have been elucidated, and their mechanisms and impacts on reconciling the "HOx problem" tested ~~(Crounse et al., 2011;Paulot et al., 2009)~~(Crounse et al., 2011;Paulot et al., 2009). In their work on updates to the chemical mechanism of isoprene oxidation, Archibald et al. ~~(Archibald et al., 2010)~~(Archibald et al., 2010) reviewed several of the proposed mechanisms and concluded that whilst the isomerization reactions proposed by Peeters et al (2009) had the most promise in reconciling the model-measurement disagreement, the reported parameters could not be fully reconciled with atmospheric observations of other species and existing laboratory data without some degree of parameter refinement and optimization, which would probably include a reduction in the peroxy radical isomerisation rates and a consequent reduction in the OH enhancement. Indeed, Crounse et al. ~~(Crounse et al., 2011)~~(Crounse et al., 2011) provided the first laboratory evidence for the RO_2 isomerisations in the isoprene system but derived rate coefficients for the processes that where much smaller than those calculated by Peeters et al. (2009). However, modelling studies using the kinetics derived from their study suggested that 10-20% of isoprene RO_2 would undergo unimolecular isomeriations (Crounse et al., 2011) and as such this is an important process to include.

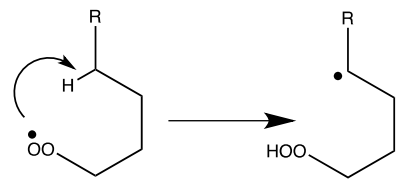


Figure ~~38~~39 - RO_2 isomerisation to QOOH. In this mechanism, well known in combustion

chemistry, the terminal O atom of the RO_2 abstracts a labile H (through the formation of a ring structured intermediate).

An astonishing amount has been learnt about the atmospheric chemistry of the Criegee Intermediates (CI) over the last few years. Pioneering work carried out at the synchrotron Advanced Light Source ~~(Taatjes et al., 2008)~~(Taatjes et al., 2008) provided the first detection and subsequent direct measurements of the kinetics of the CI ~~(Welz et al., 2012)~~(Welz et al., 2012). Traditionally CI have been thought to have been formed exclusively from the ozonolysis reaction of alkenes (as originally proposed by ~~(Criegee, 1948)~~(Criegee, 1948)). However, the recent laboratory studies on small CI have utilized novel chemical routes, which avoid the reaction with O_3. For example, a large number of groups have used CH_2I_2 as a reagent for the formation of CH_2OO (*via* photolysis and reaction with O_2). It should be noted that CH_2I_2 one of the major iodine containing VOCs emitted in the marine boundary layer ~~(Saiz-Lopez et al., 2011)~~(Saiz-Lopez et al., 2011) and may be a direct source of CI in this environment. McCarthy et al. ~~(McCarthy et al., 2013)~~(McCarthy et al., 2013) have shown that CH_2OO can also be produced *via* passing a mixture of CH_4 and O_2 through an electric discharge (through what remains an as yet unknown mechanism). Based on this evidence McCarthy et al. (2013) have postulated that it is likely that CH_2OO can be formed in the upper and free troposphere, given the large mixing ratios of CH_4 and O_2 in the upper troposphere and the relatively high density of electrical discharge (in the form of lightning flashes). Given that many of the reactions between O_3 and alkenes have small rate coefficients (~ 10^{-17} cm^3 s^{-1}) it is important that these non-ozonolysis routes to CI production be quantified using model studies in order to better understand the burden of CI in the troposphere~~.~~ (see Figure 40).

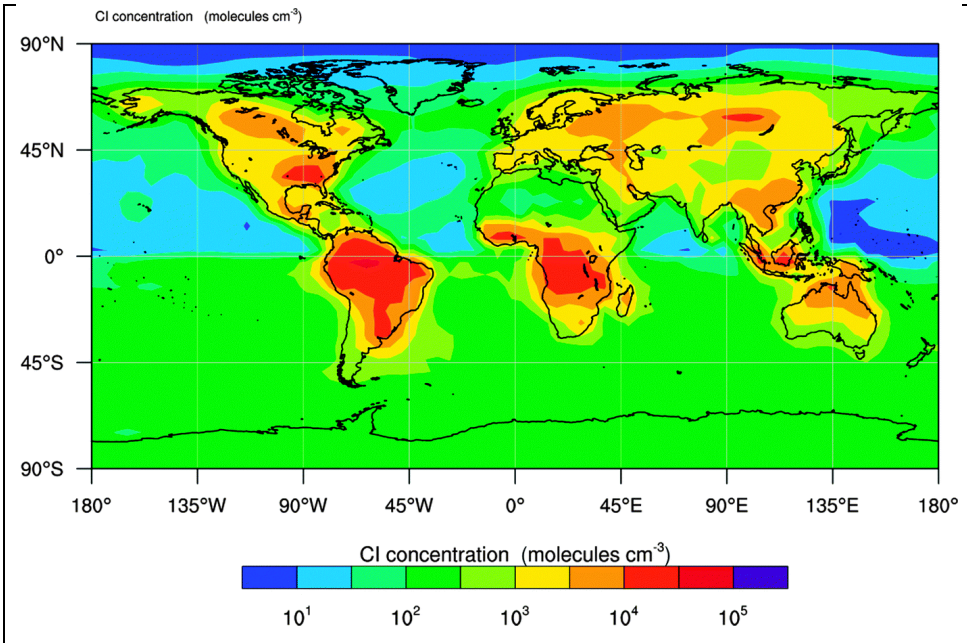


Figure ~~39~~40 – Global surface averages model concentrations of the Criegee Intermediate

concentration ~~(Taatjes et al., 2014)~~(Taatjes et al., 2014).

Of fundamental importance to understanding the chemistry of CIs is knowledge of their physical properties. McCarthy et al. (2013) have used a combination of methods to determine the geometry of CH_2OO, in good agreement with the work of Su et al. ~~(Su et al., 2014)~~(Su et al., 2014). As well as now having great insight into the geometry of CH_2OO, a number of studies have shed light on the absorption spectrum of CH_2OO in the UV/vis (e.g. ~~(Beames et al., 2012;Sheps, 2013)~~(Beames et al., 2012;Sheps, 2013)) Beames et al., (2012) and Sheps (2013) have shown that there is strong absorption by CH_2OO in the 320-400nm range. Whilst this may have implications for additional loss of CH_2OO by photolysis, the large cross section in this region has the benefit of making cavity ringdown spectroscopy laboratory studies of the kinetics of CH_2OO (and other CIs) possible – opening up a number of avenues for greater understanding of these ephemeral but crucial intermediates in the oxidation of VOCs in the atmosphere.

What seems to be emerging from the plethora of laboratory studies on the kinetics of CI reactions is that they react very fast! For example, Su et al. ~~(Su et al., 2014)~~(Su et al., 2014) have shown that the bimolecular self-reaction of CH_2OO has a rate constant near the gas kinetic limit (k = 4x10^{-10} cm^{3}s^{-1}). Su et al. (2014) determined that the reaction proceeds *via* a CH_2OO dimer – where the zwitterionic character of the CH_2OO allows for barrierless addition of the terminal O atoms with the central C atom. This dimer is predicted to dissociate to produce two CH_2O (formaldehyde) and O_2 in ~~it's~~its excited electronic state ($O_2(^1\Sigma_g)$). Such a fast self-reaction has implications for the analysis of previous laboratory studies in this system. Similarly fast kinetics have been observed for CIs reacting with organic acids. Using a combination of time resolved laboratory experiments, Welz et al. (2014) ~~(Welz et al., 2014)~~(Welz et al., 2014) have very recently shown that the reactions of the C1 and C2 CIs with HCOOH and CH_3COOH are several orders of magnitude faster than previously inferred from alkene ozonolysis reactions (k~1.0x10^{-10}cm^{3}s^{-1}). Although products of the reaction were not detected, it is likely that highly condensable products will form, potentially contributing to SOA formation and growth. Although it is interesting to note that the CI seem more reactive than RO_2 with a number of compounds, it is paramount to understand the dominant loss processes of the CI in order to understand their abundance. Before many of these direct kinetic experiments were performed it was widely assumed that in the troposphere the reaction with H_2O would dominate over other loss reactions, in spite of slow (although uncertain) kinetics. Welz et al. ~~(Welz et al., 2012)~~(Welz et al., 2012)reported an upper limit for the CH_2OO + H_2O reaction rate coefficient (k=4 x10^{-15}cm^{3}s^{-1}). Relative rate experiments have yielded a number of other estimates of the rate coefficient for this. Ouyang et al. ~~(Ouyang et al., 2013)~~(Ouyang et al., 2013), who studied the reaction of NO_2 with CH_2OO, estimated k=2.5 x10^{-17}cm^{3}s^{-1}. In their study, Ouyang et al. were able to show that the reaction produces NO_3 – the most important oxidant at night. So far inclusion of this reaction into modelling studies has not been performed and estimates of the importance of this process for night-time chemistry are needed. Based on detection of HCHO, Stone et al. ~~(Stone et al., 2014)~~(Stone et al., 2014)were able to put an upper limit on the reaction of the CI with H_2O of k=9 x10^{-17} cm^{3}s^{-1}, significantly smaller than the estimates for this reaction by Welz et al. (2012). They suggested that this much lower reactivity may mean that previous conclusions from modelling studies where H_2O

was calculated as the dominant loss process may need to be revised. Combining the results of Welz et al. (2014) and Stone et al. (2014) we speculate that it is possible that in many environments where organic acids are present at the ppb level, reaction with these acids may be the dominant loss process for CI. Interestingly, Taatjes et al. ~~(Taatjes et al., 2013)~~(Taatjes et al., 2013) have shown that the *anti*-CH_3CHOO CI reacts with H_2O very fast (k = 1.0 x$10^{-14}$$cm^3s^{-1}$), suggesting that the lack of reaction between CH_2OO and H_2O may not be representative of all CI.

5 Policy context

Within the policy context, much of the focus on ozone has been on ozone as an air pollutant (e.g. ~~(OECD, 2012;EEA, 2007, 2009, 2011;Royal Society, 2008;Fowler et al., 2013a)~~(OECD, 2012;EEA, 2007, 2009, 2011;Royal Society, 2008;Fowler et al., 2013a). As recently stated the aim of much policy with respect to ozone and air quality is "to achieve levels of air quality that do not result in unacceptable impacts on, and risks to, human health and the environment" ~~(Fowler et al., 2013a)~~(Fowler et al., 2013a) (see also section 3) within some measure of reasonable cost. This process requires an understanding of the messages from research and monitoring activities to develop new insights. Policy, to date, requires methods of assessing compliance to metrics that quantify impact. Owing to the transboundary nature of ozone, much focus has been on regional and hemispheric impact of metrics and mitigation.

Throughout this section certain metrics will be detailed, the main two of which are AOT40, the seasonal accumulated exposure above 40 ppb (80 µg/m^3) during daylight hours, this is normally expressed as a cumulative exposure (ppb h or ppm h) and SOMO35 the sum of the amounts by which maximum daily 8-hour concentrations of ozone (in µg/m^3) exceed 70 µg/m^3 (35 ppb) on each day in a calendar year.

5.1 Policy Metrics for ozone

Ozone is a powerful oxidant which can cause adverse effects on human health~~,~~ and vegetation. As a result, air quality standards for ozone have been established to mitigate these effects. Ozone can also damage some materials, particularly rubber and plastics, but no standards specifically address these effects. Ozone is a unique pollutant in that different areas of the ozone concentration frequency distribution are affected by different mechanisms and hence could require significantly different policy responses. The averaging times of different ozone metrics are also of crucial importance for policy (see e.g. ~~(Pappin and Hakami, 2013;Lefohn et al., 2010)~~(Pappin and Hakami, 2013;Lefohn et al., 2010)).

Health-related standards have up to now been expressed as one hour or eight-hour averages, the latter arising originally from chamber studies of human exposures where the maximum effects were observed over exposures of around eight hours. Such short term peak ozone concentrations based on averaging times of the order of hours, such as those observed in 'smog' episodes, are formed from the well-known VOC/NOx chemistry (see section 2.1.1). These reactions occur typically over timescales of hours to a few days, in conditions of low wind speed and strong sunlight, and hence the

spatial scale of such episodes and the policy response area, is of the order of 100s to ~1,000 kilometres. Controls on precursor emissions across Europe are therefore required to mitigate these peaks within European nations. Figure ~~40~~41 shows a comparison of a number of national and international ozone air quality standards.

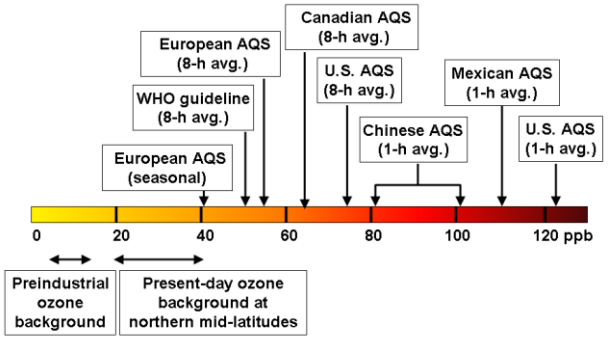


Figure ~~40~~41 – Ozone Air Quality Standards (AQS) in ppb. Different national and international standards are noted as well as estimates for northern midlatitudes of the preindustrial background (i.e., O_3 abundances with all anthropogenic emissions of NO_x, CO, VOC, and CH_4 switched off, and before current climate and stratospheric O_3 change) and the present-day baseline abundances (i.e., the statistically defined lowest abundances of O_3 in air flowing into the continents, typical of clean-air, remote marine sites) from ~~(Council, 2009a)~~(Council, 2009a).

Effects on vegetation however are more closely related to longer term exposures and in the recent EU Ambient Air Quality Directive (Directive 2008/50/EC) for example, the Target Value (see below) for the protection of vegetation is expressed in terms of AOT40 as an ~~average~~accumulated value from May to July (defined in more detail later). This longer exposure period ~~and averaging time~~, with a threshold close to the tropospheric baseline ozone level means that emission controls would be required over a much wider area than those to mitigate the health-related one/eight hour average concentrations discussed above, and could also involve other, more long-lived precursors such as methane.

Formatted: Font: +Body (Calibri)

Formatted: Font: +Body (Calibri), Font color: Black

Formatted: Font: +Body (Calibri), Font color: Black

Formatted: Font color: Black

There are several levels of 'standard' in use, with differing legal status. For example, the fundamental health effect evidence is used to inform the setting of WHO Air Quality Guidelines, below which the pollutant in question will not have adverse effects on public health. The Guidelines are set without regard to the technological, economic or social issues which might affect their achievability. In setting legally based standards however, some flexibility is often introduced to allow for difficulties of achieving the levels and/or to allow for year-to-year meteorological variability. For short-term standards this usually takes the form of allowing a number of exceedences of a given concentration over a year, and/or averaging over several years as in the case of the USA. Some health standards in place around the world are shown in Table 3.

Table 3 – Comparison of world health standards for ozone

Country/region	Ozone level (ppb)	Averaging time	Nature of level

WHO	50	Daily max. 8-hr mean	Guideline[1]
EU	60 60	8 hour running Average	Target value [2] Long Term Objective
USA	75	8 hour	National standard[3] primary and secondary
California	90 70	8 hour 1 hour	State standard not to be exceeded
UK	50	8 hour	Objective[4]
Canada	63 62	8 hour 8 hour	2015 2020 Both 'voluntary guidelines'
Mexico	80 110	8 hour 1 hour	5th maximum taken over 1 year
China	80 100	1 hour 1 hour	Grade I Grades II and III ~~(Liu et al., 2013b)~~(Liu et al., 2013b)
India	50 90	8 hour 1 hour	

Although in some cases the 'headline' concentration value in different countries' standards may be similar, the number of allowed exceedences of short term levels is crucially important in determining

[1] WHO also quotes 120ppb daily max. 8 hr mean as having 'significant health effects' and gives 80ppb daily max. 8 hr mean as an interim target.
[2] EU value not to be exceeded on more than 25 days per calendar year averaged over 3 years.
[3] USA value – the 3-year average of the fourth-highest daily maximum 8-hour average measured at each monitor in an area must not exceed 160µg/m^3/0.075 ppm
[4] UK Objective maximum 8-hour running mean in a day, not to be exceeded more than 10 times per year

their relative stringency. These criteria are shown on the footnote to the Table 3. Moreover, the status of the standards is also very important. In the USA, the National Ambient Air Quality Standard (NAAQS) for ozone has the same mandatory legal status as those for the other criteria pollutants. In the EU however this is not the case as it was recognised that no single Member State could control the ozone levels measured within its territory because of the transboundary nature of ozone formation during 'smog' episodes ~~(Royal Society, 2008)~~(Royal Society, 2008). In the EU Directives therefore, the ozone standard is a Target Value as opposed to a mandatory Limit Value in the case of the other pollutants. A Limit Value is 'to be attained within a given period and not to be exceeded once attained'. Target Values in contrast, are 'to be attained *where possible* over a given period.' The mandatory aspects of ozone control in the EU are contained within the National Emission Ceilings Directive which sets mandatory emission ceilings for individual Member States for NO_x and VOCs, which are designed, *inter alia*, to achieve reductions in ozone levels.

There are also standards in place to protect against damage to vegetation. In the EU Directive there is a Target Value of 18,000 $\mu g/m^3 \cdot$ hours for AOT40, defined as the sum of the difference between observed hourly concentrations greater than 80 $\mu g/m^3$ ($\approx$ 40 parts per billion) and 80 $\mu g/m^3$ over a given period using only the one-hour values measured between 8.00 and 20.00 Central European Time (CET) each day. In the US the 8- hourly NAAQS in Table 3 is also designed to protect against damage to vegetation, so the spatial scale of policy responses to protect against vegetation damage in the EU and the USA are potentially quite different~~.~~ (see http://www.epa.gov/ncea/isa/). In the last decade, the LRTAP Convention (Convention on Long-range Transboundary Air Pollution) has introduced stomatal flux-based critical levels for vegetation that are species-specific and relevant for protecting against effects of ozone on food security, carbon sequestration and timber production, and biodiversity (see Section 3.2 and Mills et al. (Mills et al., 2011a)for further details).

Two further recent developments have important implications for policy responses for mitigating ozone concentrations. First, the work of the CLRTAP (Convention on Long-range Transport of Atmospheric Pollutants) Task Force on Hemispheric Transport of Air Pollution has ~~shown~~highlighted that intercontinental transport of ozone and its precursors can make significant contributions to the exceedance of air quality standards and can even cause exceedances in their own right ~~(HTAP, 2010).~~(HTAP, 2010). This has already led to challenges to air quality standard enforcement in California ~~(Hand, 2014)~~(Hand, 2014). In the case of Europe this suggests that emission reduction strategies should take into account measures and policies in North America. Likewise, plans to reduce ozone in North America should take into account emissions in Asia.

The second development relates directly to potentially new metrics to protect human health from adverse effects of ozone and the existence or otherwise of a no-effect threshold. The recent review of the health effect literature by WHO ~~(WHO, 2013)~~(WHO, 2013) has concluded that there is now evidence showing associations between long term (summer mean) ozone concentrations and respiratory mortality, and weaker associations with cardiorespiratory mortality. WHO recognised the uncertainties in this area but nonetheless suggested that long-term average WHO Guidelines and a long-term (possibly a summer mean) Target Value should be considered by the European Commission.

In parallel with these conclusions, the REVIHAAP report ~~(WHO, 2013)~~(WHO, 2013) also noted that evidence for a no-effect threshold for short-term impacts was inconclusive but recommended that

SOMO10 as well as SOMO35 should be used in health impact assessments. These findings are significant for future policy on ozone. Long-term (summer) averages, as noted earlier, are partly determined by hemispheric or global emissions; to attain a threshold of 10 ppb hourly average in SOMO10 would also imply reductions of emissions on a global scale. If the evidence behind these emerging conclusions strengthens then the geographical scale of ozone reductions strategies will need to be extended beyond the regional level to hemispheric or global scales ~~(Hsu et al., 2013)~~(Hsu et al., 2013).

5.2 Ozone mitigation and baseline ozone

Observational evidence suggests that baseline ozone concentrations as they effect Europe have been rising up until about 2000 ~~(Wilson et al., 2012;Parrish et al., 2009;Simmonds et al., 2004;Jenkin, 2008;Derwent et al., 2006)~~(Wilson et al., 2012;Parrish et al., 2009;Simmonds et al., 2004;Jenkin, 2008;Derwent et al., 2006), though currently they appear to be falling (Logan et al., 2012; Parrish et al., 2012). An increasing background contribution to European ozone levels could represent a substantial future challenge to the attainment of ozone limit values ~~(Derwent et al., 2010)~~(Derwent et al., 2010). With an increasing background contribution there is a requirement to control more ozone of anthropogenic European origin to achieve the limit. Models have shown ~~(Derwent et al., 2010;Szopa et al., 2006)~~(Derwent et al., 2010;Szopa et al., 2006) that the benefit to European emission controls can be significantly counterbalanced by increasing background ozone. These results were confirmed ~~for~~in a long-term perspective (2050) ~~in~~by Colette et al. (2013) ~~that~~who emphasized that air quality legislation was indeed anticipated to bear its fruit in reducing ozone exposure in the future, even if under a business as usual scenario such as the RCP8.5, climate change and long range transport ~~constituted a heavy penalty~~.

Similarly, in the US context there has been much debate as to the contribution and quantification of background ozone and its effect on the attainment of standards ~~(Lefohn et al., 2014;Fiore et al., 2014).~~(Lefohn et al., 2014;Fiore et al., 2014;Prather et al., 2003;Fiore et al., 2002). Lefohn et al (2014) have explored the concept of an emissions-influenced background in an attempt on a continental scale to partition the controllable ozone (see Figure ~~41~~42). Fiore et al ~~(Fiore et al., 2014)~~(Fiore et al., 2014) noted that the largest model differences in the calculation of North American Background ozone, in this case a model construct, were linked to differences in contributions from the stratosphere, wildfires, lightning and isoprene chemistry. Prather et al. noted in a model study that the background ozone might be a northern hemispheric problem given future emission scenarios (Prather et al., 2003).

The recent results of the 2013 revision ~~(Amann et al., 2013)~~(Amann et al., 2013a) of the European Thematic Strategy on Air Pollution (TSAP) indicate that the reduction of 10% of the 25,000 anticipated ~~death~~deaths attributed to ozone ambitioned by the 2005 TSAP for European emission reductions should be safely achieved in 2025 with about 18,000 annual premature ~~death~~deaths under the scenario currently planned.

Fowler et al, in their recent report on research findings in support of the EU air quality policy argued that "more attention needs to be given to treating ozone as a hemispheric transboundary issue" ~~(Fowler et al., 2013a)~~(Fowler et al., 2013a) (see section 5.3).

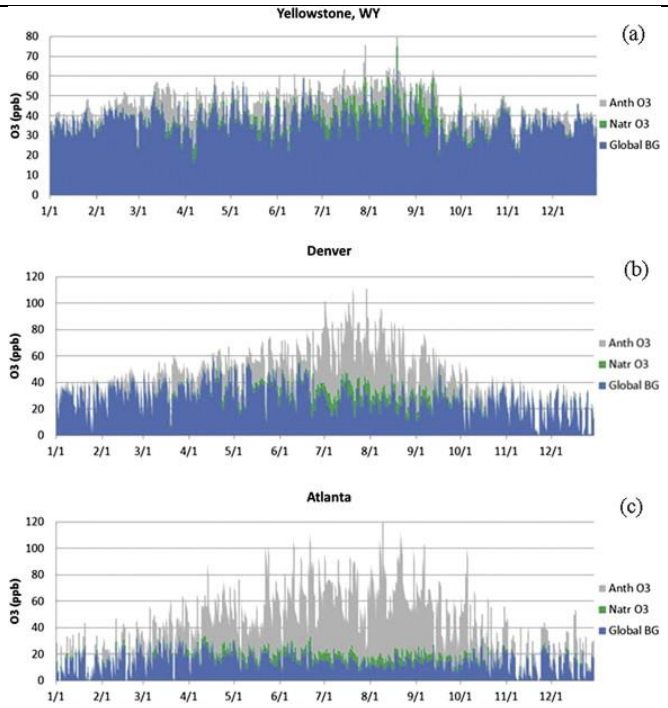


Figure ~~41~~42 - Modeled contributions of hourly GBO_3 (global tropospheric O_3 plus stratospheric O_3), natural (Natr O_3), and anthropogenic (Anth O_3) adding to total hourly O_3 for a) Yellowstone NP, b) Denver and c) Atlanta ~~(Lefohn et al., 2014)~~(Lefohn et al., 2014).

5.3 Hemispheric transport of ozone and it precursors in the policy context

Substantial efforts have been undertaken to quantify the importance of long-range transport of ozone from distant source regions as part of UNECE HTAP ~~(HTAP, 2010).~~(HTAP, 2010). More than 20 global models conducted idealised source-receptor experiments to quantify hemispheric transport of ozone and its precursors and the key findings are reported in Fiore et al ~~(Fiore et al., 2009)~~(Fiore et al., 2009) and HTAP ~~(HTAP, 2010).~~(HTAP, 2010). 20% reductions in anthropogenic precursor emissions from North American, East Asian and South Asian sources reduce annual mean EU O_3 by about 0.4, 0.2 and 0.1 ppbV, respectively ~~(HTAP, 2010).~~(HTAP, 2010). The influence of LRT has a seasonality, with the largest impact in spring (March-April: ~0.8 ppbV) and minimum impact in late summer (July-September: ~0.45 ppbV) ~~(HTAP, 2010).~~(HTAP, 2010). This influence may appear small, but the equivalent O_3 response to a 20% emission change over Europe itself is 1.5-2.0 ppbV in summertime, and is close to zero on a regional mean basis in winter when titration is important. It is

worth noting that the HTAP emission reductions (20%) have been exceeded in reality over Europe for the 1990-2009 period ~~(EEA, 2011)~~(EEA, 2011). By scaling the 20% emission changes to the actual regional emission changes and accounting for the nonlinearity in ozone responses, ~~(Wild et al., 2012)~~(Wild et al., 2012) derived the ozone trend over Europe from 1960-2000 along with the contributions from the EU, external sources (i.e. LRT) and changing atmospheric CH_4. An increase of about 6.5 ppbV is calculated between 1960 and 1990, and a slight decrease from 1990-2000. More than half of the 1960-1990 trend came from non-European sources (2.1 ppb) and CH_4 (1.6 ppb), with only 2.8 ppb from changes in EU emissions. Interestingly trans-Eurasian transport if air pollutants has been implicated in the enhancement of ozone in western China (Li et al., 2014b).

A number of studies have focussed on the contribution of increasing precursor emissions over Asia to ozone over North America. Reidmiller et al. ~~(Reidmiller et al., 2009)~~(Reidmiller et al., 2009) have used the HTAP simulations to demonstrate that precursor emissions from both East Asia and Europe influence the policy-relevant maximum 8-hour average (MDA8) ozone metric, but note that regional emission controls over North America are 2-10 times as effective at reducing this ozone metric as the equivalent controls in these foreign regions. ~~However, Lin et al., 2012,~~However, Lin et al. (Lin et al., 2012a) demonstrate that Asian emissions may contribute as much as 8-15 ppb ozone to MDA8 in the south-western US in springtime on days when ozone exceeds 60 ppb, indicating the important role that long-range transport may play in ozone exceedences. More recent work by Lin et al. ~~(Lin et al., 2014a)~~(Lin et al., 2014a) has shown that transport of the export-related Chinese pollution contributed 0.5-1.5% of ozone over the western United States in 2006. This Chinese pollution also resulted in one extra day or more of noncompliance with the US ozone standard in 2006 over the Los Angeles area and many regions in the eastern United States. Equivalent studies focussing on air quality metrics in Europe have yet to be performed, but are likely to show smaller impacts given the greater transport distances from regions showing substantial emission increases.

Formatted: Font: Calibri

Transport within Asia has been considered in a recent HTAP study showing that O_3 from East Asian sources affects the most densely populated parts of South Asia (Chakraborty et al., 2015).

5.4 Impacts of climate change

Jacob and Winner ~~(Jacob and Winner, 2009)~~(Jacob and Winner, 2009) ~~have undertaken a comprehensive review of the impact of climate change on air quality, including ozone. Despite regional differences, the dominating signal is one towards an increase of ozone levels induced by global warming (Stevenson et al., 2006), that led Wu et al (Wu et al., 2008) to coin the term "climate penalty". The possible pathways for such a penalty include increasing continental temperatures, changing atmospheric humidity and changes in the prevalence of stable, anticyclonic conditions trapping pollutants in the boundary layer and possibly leading to higher surface ozone even without changes in anthropogenic precursor emissions. These meteorological factors may be supplemented by climate-driven changes in biogenic emissions of isoprene and in dry deposition of ozone. It is worth noting that in the lower free troposphere and in remote surface regions ozone is expected to decrease owing to increased water vapour in a warmer world (Jacob and Winner, 2009).~~ and more recently von Schneidemesser et al (von Schneidemesser et al., 2015) have undertaken a comprehensive review of the impacts of climate change on air quality, including ozone. Despite regional differences, the dominating signal is one towards an increase of ozone levels induced by

global warming (Stevenson et al., 2006), that led Wu et al (Wu et al., 2008) to coin the term "climate penalty". The possible pathways for such a penalty include increasing continental temperatures, changing atmospheric humidity and changes in the prevalence of stable, anticyclonic conditions trapping pollutants in the boundary layer and possibly leading to higher surface ozone even without changes in anthropogenic precursor emissions. These meteorological factors may be supplemented by climate-driven changes in biogenic emissions of isoprene and in dry deposition of ozone. It is worth noting that in the lower free troposphere and in remote surface regions ozone is expected to decrease owing to increased water vapour in a warmer world (Jacob and Winner, 2009). There is some debate as to the magnitude of any climate penalty e.g. Tai et al. (Tai et al., 2013) indicates that in the presence of CO_2-isoprene interaction, the projected change in isoprene emission by 2050 will be largely offset or even reverse in sign, leading to much reduced sensitivity of ozone and SOA (by >50%) to climate and natural vegetation

Bloomer et al. ~~(Bloomer et al., 2009)~~(Bloomer et al., 2009) estimated the magnitude of these effects from surface ozone observations over the US at about 2.2 ppb per degree C~~.~~ and Pfister et al have shown increasing summertime ozone levels (Pfister et al., 2014) under various climate scenarios. These effects have been quantified over Europe in several model studies ~~(Colette et al., 2013;Meleux et al., 2007;Langner et al., 2012a;Langner et al., 2012b;Andersson and Engardt, 2010;Manders et al., 2012;Hedegaard et al., 2008;Hedegaard et al., 2013b;Katragkou et al., 2011)~~(Colette et al., 2013;Meleux et al., 2007;Langner et al., 2012a;Langner et al., 2012c;Andersson and Engardt, 2010;Manders et al., 2012;Hedegaard et al., 2008;Hedegaard et al., 2013b;Katragkou et al., 2011). The general order of magnitude of the climate penalty over Europe is a few ppb by the middle of the century. Langer et al ~~(Langner et al., 2012c)~~(Langner et al., 2012b) point out a larger increase at the 95th percentile of hourly ozone, suggesting that the effects of climate change may be particularly important during high ozone events. The effects of changes in isoprene emissions and dry deposition have been quantified separately by Andersson and Engardt ~~(Andersson and Engardt, 2010)~~(Andersson and Engardt, 2010) who find increases in mean ozone of up to 5 ppb by 2050 in some parts of western Europe, with as much as 60% of this change attributed to decreased dry deposition, and with increased isoprene emissions contributing up to 1 ppb. As noted above large uncertainties remain regarding the impact of climate change on biogenic emissions, with up to a factor five difference in isoprene change reported in a multi-model ensemble ~~(Langner et al., 2012b).~~(Langner et al., 2012c).

There are few studies that proposed quantitative comparisons of the relative impact of climate change and air pollution mitigation strategies on surface ozone. Existing investigations all agree on a larger impact of air quality policies~~(Tagaris et al., 2007;Hedegaard et al., 2013a;Colette et al., 2013)~~ (Tagaris et al., 2007;Hedegaard et al., 2013a;Colette et al., 2013), endorsing to the efficiency of currently planned mitigation strategies, despite external penalties brought about by climate change and long range transport.

It should be noted however that studies focusing on the ~~iimpacts~~impacts of climate change use long-term projections (typically 2050) which have substantive precursor mitigation. Given the magnitude of the response to precursors changes, the sensitivity to the choice of the scenario is worth noting ~~(Fiore et al., 2012a)~~(Fiore et al., 2012a). Pioneering studies relied on projections originally designed for climate projections (SRES ~~(Nakicenovic et al., 2000)~~(Nakicenovic et al., 2000) or RCPs ~~(van Vuuren et al., 2011)~~(van Vuuren et al., 2011)~~, but the ozone precursor information in such scenarios was~~

Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)
Formatted: Font: +Body (Calibri)

~~solely provided to assess radiative forcing and their use for surface air quality projections constitutes a deviation from their original purpose. The use of emission projections relying on policy relevant emissions factors such as the Global Energy Assessment (Riahi et al., 2012), the ECLIPSE (Klimont et al., 2013a;Klimont et al., 2013b) or PEGASOS datasets are more reliable.~~

, but the ozone precursor information in such scenarios was solely provided to assess radiative forcing and their use for surface air quality projections constitutes a deviation from their original purpose. The various scenarios make differing assumptions for future air pollution emissions and therefore, describe a wide range of future emissions over large world regions. Any downscaling in regions that exhibit large spatial heterogeneities could be problematic leading to inaccurate results (Amann et al., 2013b). The use of emission projections relying on policy relevant emissions factors such as the Global Energy Assessment (Riahi et al., 2012), the ECLIPSE (Klimont et al., 2013a) or PEGASOS datasets are more reliable.

While the implications of these effects for surface ozone and air quality policy are substantial, there is still considerable uncertainty in the magnitude of these indirect climate effects, and improved understanding of the processes controlling these atmosphere-land surface interactions is needed.

6 The future – Air Quality and Climate

Recently, pollutants that typically fall under the 'air quality' categorization have been receiving increasing attention for their role in climate change and their impact on radiative forcing. More specifically, significant focus has been on ozone, methane (as a GHG and an ozone precursor), and aerosol constituents (mostly the black carbon (BC) component). Significant potential exists for co-benefits with coordinated air quality and climate policies. A number of reviews have recently addressed various aspects of the linkages between air quality and climate, from the chemistry interactions to the policy implications ~~(von Schneidemesser and Monks, 2013;Isaksen et al., 2009;Fiore et al., 2012b;Unger, 2012).~~(von Schneidemesser and Monks, 2013;Isaksen et al., 2009;Fiore et al., 2012b;Unger, 2012). For more details, see these reviews. Here, a brief overview of the topic will be given, with a focus on ozone and the latest developments.

In addition to being an air pollutant with significant adverse health effects, ozone is also a greenhouse gas. A recent estimate of ozone's radiative forcing effect (from pre-industrial times to the present day) is +0.40 W m^{-2} ~~(Myhre et al., 2013)~~(Myhre et al., 2013), other estimates include +0.44 and +0.23 ~~(Unger, 2012;Fiore et al., 2012b).~~(Unger, 2012;Fiore et al., 2012b). For comparison, the RFs attributed to methane and CO_2 are +0.48 W m^{-2} and +1.66 W m^{-2}, respectively ~~(IPCC, 2007).~~(Myhre et al., 2013). The ozone precursors NOx, NMVOCs, and CO, have little to no direct effect on climate, but influence climate and radiative forcing through their effects on ozone and methane, as well as atmospheric oxidant concentrations and indirect ecosystem effects [~~(von Schneidemesser and Monks, 2013)~~(von Schneidemesser and Monks, 2013) and references therein]. Reductions in NMVOCs and CO tend to be synergistic and result in overall decreases in RF, although the effects can be fairly minor, especially for NMVOCs ~~(Collins et al., 2013)~~(Collins et al., 2013). The effect of NOx on climate/radiative forcing is much less straightforward. A variety of interactions, feedbacks, and ecosystem effects confound the picture for NOx, resulting in significant uncertainty and often times competing effects on climate. A variety of modelling studies have evaluated the various direct and indirect effects ~~(Collins et al., 2010;Collins et al., 2013;Shindell et al., 2009;Fry et al., 2012;Colette et al., 2011)~~(Collins et al., 2010;Collins et al., 2013;Shindell et al., 2009;Fry et al., 2012;Colette et al., 2011) and a summary can be found in von Schneidemesser and Monks ~~(von Schneidemesser and Monks, 2013)~~(von Schneidemesser and Monks, 2013). More research is needed on this topic.

Methane, an important greenhouse gas in its own right, is also an ozone precursor. With a lifetime of approximately a decade in the atmosphere, methane is well-mixed globally and therefore has a significant influence on background ozone levels. Methane is a distinct win-win possibility for air quality and climate in that reductions in methane emissions would decrease ozone, including baseline ozone, and thereby lessen adverse impacts on vegetation and human health, but also benefit climate by reducing 2 GHGs simultaneously ~~(Fry et al., 2012;Shindell et al., 2012;Isaksen et al., 2014)~~(Fry et al., 2012;Shindell et al., 2012;Isaksen et al., 2014). A model study investigated the air quality (O_3) and climate benefits of methane reductions and found that O_3 reductions were relatively linear with respect to reductions in methane emissions. In addition, the CH_4 emission reductions did not depend strongly on location, as the climate and air quality benefits were realized globally, which

would allow for the most cost effective emission controls to be implemented ~~(Fiore et al., 2008)~~(Fiore et al., 2008).

However, the interactions go both ways. Not only does ozone affect the climate, but changes owing to climate change will also influence ozone production. This effect is known as the 'climate penalty'. A variety of effects resulting from a changing climate will potentially influence ozone concentrations, some increasing ozone, some decreasing ozone ~~(Rasmussen et al., 2013)~~(Rasmussen et al., 2013). Many of these effects are associated with a significant amount of uncertainty. Climate changed induced increases in methane emissions from wetlands, stratosphere-troposphere exchange of ozone, lightning NOx, and regional stagnation all consistently lead to increased ozone when investigated, while increases in dry deposition and humidity consistently lead to decreases in ozone ~~(Fiore et al., 2012b;Isaksen et al., 2009)~~(Fiore et al., 2012b;Isaksen et al., 2009). Other climate change induced effects such as increased wildfires have a much more uncertain effect on ozone. For example, for a regional study in California, climate-related perturbations (temperature, biogenics and water vapour) led to combined peak 1 h ozone increases of up to 11 ppb ~~(Millstein and Harley, 2009)~~(Millstein and Harley, 2009).

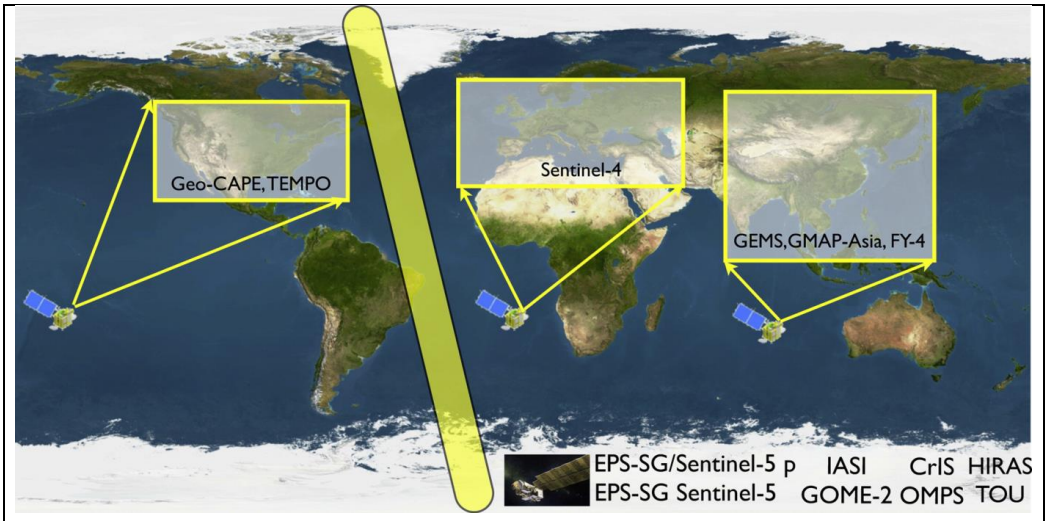
In a model ensemble study by Colette et al. ~~(Colette et al., 2012)~~(Colette et al., 2012) future (2030) air quality in Europe owing to just air quality policy or air quality and climate policy was compared. The base case included all current and planned air quality measures up to 2030 and was compared to a 'sustainable' case with the air quality as well as climate measures (2° target and energy efficiency improvements). Depending on the scenario annual mean O_3 was found to slightly increase over NOx saturated areas but the overall O_3 burden would decrease substantially, including exposure to detrimental levels of O_3 for health ~~(Kinney, 2008)~~(Kinney, 2008). The air pollution measures were responsible for the main improvements in ozone, but an additional co-benefit of at least 40% (depending on the indicator) was attributed to the climate policy ~~(Colette et al., 2012)~~(Colette et al., 2012). A study by Crawford-Brown et al. ~~(Crawford-Brown et al., 2012)~~(Crawford-Brown et al., 2012) focused on the co-benefits to O_3- and PM-related health effects resulting from implementation of climate policy in Mexico. A base case scenario was compared to a decarbonisation scenario where CO_2 emissions in Mexico would be reduced by 77% by 2050. The co-benefits to air quality were reductions in O_3 of 11-13% by 2050. The reduction in non-fatal diseases from O_3 and PM related health co-benefits was valued at $0.6 billion per year ~~(Crawford-Brown et al., 2012)~~(Crawford-Brown et al., 2012). Both of these studies show that there are significant benefits to pursuing coordinated policies for air quality and climate, and not only for the improvement of O_3 related air quality. Rypdal et al have commented on the challenges for putting tropospheric ozone in climate agreements ~~(Rypdal et al., 2005)~~(Rypdal et al., 2005).

7 Conclusions

Ozone remains central to atmospheric chemistry as the initiator, propagator and product of photochemistry. Its influence is felt on human health, ecosystems and climate. Ozone though ubiquitous remains an enigma. In many places in the Northern Hemisphere mid-latitudes ozone in some senses remains a paradox, the high summertime peak levels decreasing but the regional background levels rising ~~(Fishman et al., 2014;Parrish et al., 2012)~~(Fishman et al., 2014;Parrish et al., 2012). Globally this points to the need to treat ozone across the range of scales, a transboundary issue, but with an emphasis on the hemispheric scales ~~(Fowler et al., 2013a;Simpson et al., 2014)~~(Fowler et al., 2013a;Simpson et al., 2014). Recent air pollution episodes in Europe have pointed to the continuing need to think about the how climate change policies interact with air quality policy and what can be learnt from current episodes ~~(Monks, 2014)~~(Monks, 2014). There remain a number of clear challenges for ozone such as explaining surface trends, incorporating new chemical understanding, ozone-climate coupling as well as a better assessment of impacts.

With respect to the future, studying the atmospheric chemistry of ozone relies on the continuing interplay of laboratory studies of fundamental parameters being integrated with our best theories using numerical models and evaluated against in situ observations. This "three-legged" stool approach is generic, but is a vital model to use to understand not only ozone but the wider chemistry in the atmosphere ~~(Abbatt et al., 2014)~~(Abbatt et al., 2014).

One area implicit in this review, which hasn't been discussed explicitly, has been the role of observations in understanding, quantifying and describing ozone across the scales. Observations of ozone and its precursors underpin and drive the development of our knowledge base ~~(Laj et al., 2009)~~(Laj et al., 2009). Bowman has argued that the global nature of pollution and climate change requires a new observing system for ozone ~~(Bowman, 2013)~~(Bowman, 2013). A key feature of the system should be the ability to predict and attribute ozone to emissions. A combination of satellites, ground-based remote sensing and ground-based observations are needed with geostationary observations ~~(Lahoz et al., 2011)~~(Lahoz et al., 2011) being an observational anchor (see Figure ~~42~~43).



~~**Figure 42** - Constellation of geostationary and low-earth orbiting satellites planned for the coming decade that will measure tropospheric ozone. Current instruments that measure tropospheric ozone, e.g., TES or OMI, but will not be continued in the future are not listed. A complete description of planned satellites is available at http://www.wmo-sat.info/. (From (Bowman, 2013))~~**Figure 43** - Constellation of geostationary and low-earth orbiting satellites planned for the coming decade that will measure tropospheric ozone. Current instruments that measure tropospheric ozone, e.g., TES or OMI, but will not be continued in the future are not listed (From (Bowman, 2013)).

It is clear that space observations offer the global view and repeatability not easily available from other observing systems. Measurement of ground-level ozone from space still remains a significant challenge ~~(Foret et al., 2014;Duncan et al., 2014)~~(Foret et al., 2014;Duncan et al., 2014). There is future potential for global observations of tropospheric ozone from space either directly ~~(Sellitto et al., 2013)~~(Sellitto et al., 2013) or through a combination with models ~~(Zoogman et al., 2014;Martin, 2008)~~(Zoogman et al., 2014;Martin, 2008). Duncan et al ~~(Duncan et al., 2014)~~(Duncan et al., 2014) have recently reviewed the application of satellite data to air quality application including common mistakes to avoid.

The growth of small sensors for a range of trace species including ozone has the potential to offer insights on unheralded spatial and temporal timescales ~~(Snyder et al., 2013;Mead et al., 2013;Piedrahita et al., 2014)~~(Snyder et al., 2013;Mead et al., 2013;Piedrahita et al., 2014). As illustrated in Figure ~~43~~44, there are potential new avenues opened up for air quality monitoring by the deployment of extensive networks of these sensors~~.~~ all the way down to personal sensing (e.g. (Wheeler et al., 2011;Andersen et al., 2010)). The absolute measurement of ozone remains a challenge with some of these sensors owing to interferences ~~(Mead et al., 2013)~~(Mead et al., 2013). New developments suggest these configurations of sensor technologies can give long-term atmospheric performance for the measurements of ozone ~~(Williams et al., 2013;Bart et al., 2014)~~(Williams et al., 2013;Bart et al., 2014).

There may yet be new links and biospheric feedbacks driven by ozone to be explored. For example, the effect of elevated O_3 and whitefly herbivory significantly increased tomato volatiles, which attracted *E. Formosa* wasps and reduced the whitefly feeding on tomatoes ~~(Cui et al., 2014)~~(Cui et al., 2014).

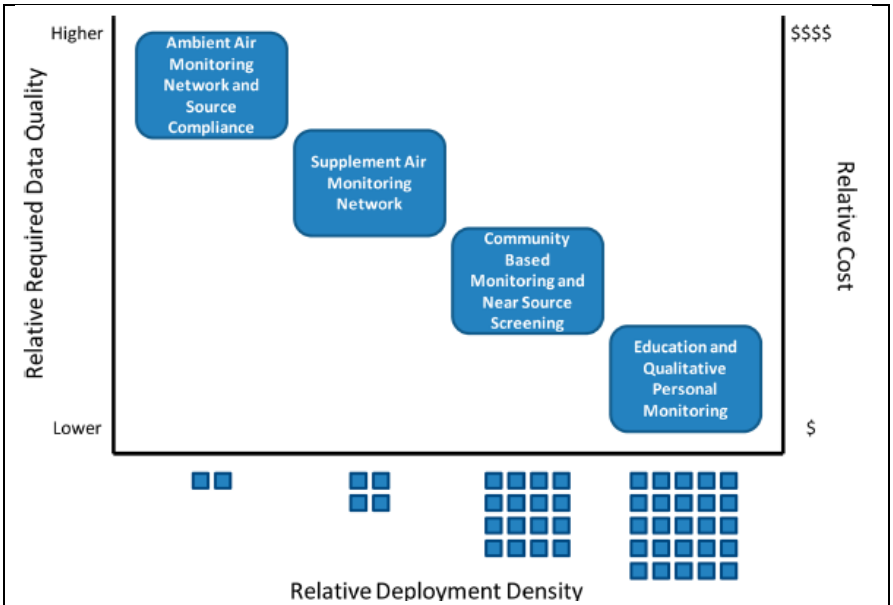


Figure ~~43~~44 – Relative data, quality, cost and deployment density for small sensor networks for air quality ~~(Snyder et al., 2013)~~(Snyder et al., 2013).

There are interesting attempts to make public outreach on the effects of ozone on plants and crops. Fishman et al, have described a establishment of an "Ozone Garden" ~~(Fishman et al., 2014)~~(Fishman et al., 2014). The garden provides real-time measurements of O_3 concentrations as well as firsthand observations of the detrimental effects of this pollutant. Meteorological data, as well as the O_3 concentrations from the monitor, are recorded and publicly disseminated in near-real time *via* the internet.

Looking forward it is clear that levels and patterns of global ozone will continue to change, impacting global warming, air quality, global food production and ecosystem function. There remains a need for continuing research to quantify impacts and interactions across all the scales. The issues around tropospheric ozone are not "solved" ~~(Guerreiro et al., 2014)~~(Guerreiro et al., 2014) and new data continues to shed light on more aspects of ozone and its interactions in the global atmosphere.

Acknowledgements

This review was prepared as part of the European Commission project ACCENT Plus (grant agreement 265119).

References

Abbatt, J., George, C., Melamed, M., Monks, P., Pandis, S., and Rudich, Y.: New Directions: Fundamentals of atmospheric chemistry: Keeping a three-legged stool balanced, Atmospheric Environment, 84, 390-391, 10.1016/j.atmosenv.2013.10.025, 2014.

Abbatt, J. P. D., Thomas, J. L., Abrahamsson, K., Boxe, C., Granfors, A., Jones, A. E., King, M. D., Saiz-Lopez, A., Shepson, P. B., Sodeau, J., Toohey, D. W., Toubin, C., von Glasow, R., Wren, S. N., and Yang, X.: Halogen activation via interactions with environmental ice and snow in the polar lower troposphere and other regions, Atmospheric Chemistry and Physics, 12, 6237-6271, 10.5194/acp-12-6237-2012, 2012.

Adams, R. M., Crocker, T. D., and Thanavibulchai, N.: An economic assessment of air pollution damages to selectes annual crops in souhtern California, J.Environ.Econ.Manage., 9, 42-58, 10.1016/0095-0696(82)90005-5, 1982.

Administration, U. S. E. I.: Drilling Productivity Report, 2014a.

Administration, U. S. E. I.: Annual Energy Outlook 2014, with projections to 2040, Washington, DC, 2014b.

Agency, U. E. P.: National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data 2014.

Agency, U. S. E. P.: EPA needs to improve air emissions data for the oil and natural gas production sector, Office of Inspector General, 2013.

Ainsworth, E. A.: Rice production in a changing climate: a meta-analysis of responses to elevated carbon dioxide and elevated ozone concentration, Global Change Biology, 14, 1642-1650, 10.1111/j.1365-2486.2008.01594.x, 2008.

Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., Crounse, J. D., and Wennberg, P. O.: Emission factors for open and domestic biomass burning for use in atmospheric models, Atmospheric Chemistry and Physics, 11, 4039-4072, 10.5194/acp-11-4039-2011, 2011.

Akimoto, H.: Global air quality and pollution, Science, 302, 1716-1719, 2003.

Alvarado, M. J., Logan, J. A., Mao, J., Apel, E., Riemer, D., Blake, D., Cohen, R. C., Min, K. E., Perring, A. E., Browne, E. C., Wooldridge, P. J., Diskin, G. S., Sachse, G. W., Fuelberg, H., Sessions, W. R., Harrigan, D. L., Huey, G., Liao, J., Case-Hanks, A., Jimenez, J. L., Cubison, M. J., Vay, S. A., Weinheimer, A. J., Knapp, D. J., Montzka, D. D., Flocke, F. M., Pollack, I. B., Wennberg, P. O., Kurten, A., Crounse, J., St Clair, J. M., Wisthaler, A., Mikoviny, T., Yantosca, R. M., Carouge, C. C., and Le Sager, P.: Nitrogen oxides and PAN in plumes from boreal fires during ARCTAS-B and their impact on ozone: an integrated analysis of aircraft and satellite observations, Atmospheric Chemistry and Physics, 10, 9739-9760, 10.5194/acp-10-9739-2010, 2010.

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Holland, M., Kiesewetter, G., Klimont, Z., Rafaj, P., Paasonen, P., Posch, M., Sander, R., Schöpp, W., Wagner, F., and Winiwarter, W.: Policy Scenarios for the Revision of the Thematic Strategy on Air Pollution, IIASA, Vienna, 2013.

Andersson, C., and Engardt, M.: European ozone in a future climate: Importance of changes in dry deposition and isoprene emissions, Journal of Geophysical Research-Atmospheres, 115, 10.1029/2008jd011690, 2010.

Andreae, M. O., and Merlet, P.: Emission of trace gases and aerosols from biomass burning, Global Biogeochemical Cycles, 15, 955-966, 2001.

Andrey, J., Cuevas, E., Parrondo, M. C., Alonso-Pérez, S., Redondas, A., and Gil-Ojeda, M.: Quantification of ozone reductions within the Saharan air layer through a 13-year climatologic analysis of ozone profiles, Atmospheric Environment, 84, 28-34, http://dx.doi.org/10.1016/j.atmosenv.2013.11.030, 2014.

Anenberg, S. C., West, J. J., Fiore, A. M., Jaffe, D. A., Prather, M. J., Bergmann, D., Cuvelier, K., Dentener, F. J., Duncan, B. N., Gauss, M., Hess, P., Jonson, J. E., Lupu, A., MacKenzie, I. A., Marmer, E., Park, R. J., Sanderson, M. G., Schultz, M., Shindell, D. T., Szopa, S., Vivanco, M. G., Wild, O., and Zang,

G.: Intercontinental Impacts of Ozone Pollution on Human Mortality, Environ. Sci. Technol., 43, 6482-6487, 10.1021/es900518z, 2009.
AQEG: Air Quality Expert Group, Ozone in the United Kingdom, HMSO, London, 2009.
Archibald, A., Khan, M., Watson, L., Clemitshaw, K., Utembe, S., Jenkin, M., and Shallcross, D.: Comment on `Long-term atmospheric measurements of C_1-C_5 alkyl nitrates in the Pearl River Delta region of southeast China'by Simpson et al., Atmospheric Environment, 41, 7369-7370, 2007.
Archibald, A., Petit, A., Percival, C., Harvey, J., and Shallcross, D.: On the importance of the reaction between OH and RO_2 radicals, Atmos. Sci. Lett., 10, 102-108, 2009.
Archibald, A., Cooke, M., Utembe, S., Shallcross, D., Derwent, R., and Jenkin, M.: Impacts of mechanistic changes on HO x formation and recycling in the oxidation of isoprene, Atmospheric Chemistry and Physics, 10, 8097-8118, 2010.
Archibald, A. T., Levine, J. G., Abraham, N. L., Cooke, M. C., Edwards, P. M., Heard, D. E., Jenkin, M. E., Karunaharan, A., Pike, R. C., Monks, P. S., Shallcross, D. E., Telford, P. J., Whalley, L. K., and Pyle, J. A.: Impacts of HO(x) regeneration and recycling in the oxidation of isoprene: Consequences for the composition of past, present and future atmospheres, Geophysical Research Letters, 38, L05804 10.1029/2010gl046520, 2011.
Arellano, A. F., and Hess, P. G.: Sensitivity of top-down estimates of CO sources to GCTM transport, Geophysical Research Letters, 33, 10.1029/2006gl027371, 2006.
Arneth, A., Niinemets, U., Pressley, S., Back, J., Hari, P., Karl, T., Noe, S., Prentice, I. C., Serca, D., Hickler, T., Wolf, A., and Smith, B.: Process-based estimates of terrestrial ecosystem isoprene emissions: incorporating the effects of a direct CO2-isoprene interaction, Atmospheric Chemistry and Physics, 7, 31-53, 2007.
Arneth, A., Schurgers, G., Lathiere, J., Duhl, T., Beerling, D. J., Hewitt, C. N., Martin, M., and Guenther, A.: Global terrestrial isoprene emission models: sensitivity to variability in climate and vegetation, Atmospheric Chemistry and Physics, 11, 8037-8052, 10.5194/acp-11-8037-2011, 2011.
Arnold, S. R., Emmons, L. K., Monks, S. A., Law, K. S., Ridley, D. A., Turquety, S., Tilmes, S., Thomas, J. L., Bouarar, I., Flemming, J., Huijnen, V., Mao, J., Duncan, B. N., Steenrod, S., Yoshida, Y., Langner, J., and Long, Y.: Biomass burning influence on high latitude tropospheric ozone and reactive nitrogen in summer 2008: a multi-model analysis based on POLMIP simulations, Atmos. Chem. Phys. Discuss., 14, 24573-24621, 10.5194/acpd-14-24573-2014, 2014.
Ashmore, M.: Assessing the Future Global Impacts of Ozone on Vegetation, Plant, Cell and Environment 28, 949-964, 2005.
Ashworth, K., Wild, O., and Hewitt, C. N.: Impacts of biofuel cultivation on mortality and crop yields, Nat. Clim. Chang., 3, 492-496, 10.1038/nclimate1788, 2013.
Baker, J., Walker, H. L., and Cai, X. M.: A study of the dispersion and transport of reactive pollutants in and above street canyons – a large eddy simulation, Atmospheric Environment, 38, 6883-6892, 10.1016/j.atmosenv.2004.08.051, 2004.
Banerjee, A., Archibald, A. T., Maycock, A. C., Telford, P., Abraham, N. L., Yang, X., Braesicke, P., and Pyle, J. A.: Lightning NOx, a key chemistry–climate interaction: impacts of future climate change and consequences for tropospheric oxidising capacity, Atmos. Chem. Phys., 14, 9871-9881, 10.5194/acp-14-9871-2014, 2014.
Barkley, M. P., De Smedt, I., Van Roozendael, M., Kurosu, T. P., Chance, K., Arneth, A., Hagberg, D., Guenther, A., Paulot, F., Marais, E., and Mao, J. Q.: Top-down isoprene emissions over tropical South America inferred from SCIAMACHY and OMI formaldehyde columns, Journal of Geophysical Research-Atmospheres, 118, 6849-6868, 10.1002/jgrd.50552, 2013.
Barrie, L. A., Hoff, R. M., and Daggupaty, S. M.: The Influence of mid-latitudinal pollution sources on haze in the Canadian Arctic, Atmospheric Environment, 15, 1407-1419, 10.1016/0004-6981(81)90347-4, 1981.
Barrie, L. A., Bottenheim, J. W., Schnell, R. C., Crutzen, P. J., and Rasmussen, R. A.: Ozone destruction and photochemical reactions at polar sunrise in the lower Arctic atmosphere, Nature, 334, 138-140, 1988.

Bart, M., Williams, D. E., Ainslie, B., McKendry, I., Salmond, J., Grange, S. K., Alavi-Shoshtari, M., Steyn, D., and Henshaw, G. S.: High Density Ozone Monitoring Using Gas Sensitive Semi-Conductor Sensors in the Lower Fraser Valley, British Columbia, Environ. Sci. Technol., 48, 3970-3977, 10.1021/es404610t, 2014.
Bates, D. V.: Ambient ozone and mortality, Epidemiology, 16, 427-429, 10.1097/01.ede.0000165793.71278.ec, 2005.
Beames, J. M., Liu, F., Lu, L., and Lester, M. I.: Ultraviolet Spectrum and Photochemistry of the Simplest Criegee Intermediate CH2OO, J Am Chem Soc, 134, 20045-20048, 2012.
Beirle, S., Huntrieser, H., and Wagner, T.: Direct satellite observation of lightning-produced NOx, Atmospheric Chemistry and Physics, 10, 10965-10986, 10.5194/acp-10-10965-2010, 2010.
Beirle, S., Boersma, K. F., Platt, U., Lawrence, M. G., and Wagner, T.: Megacity Emissions and Lifetimes of Nitrogen Oxides Probed from Space, Science, 333, 1737-1739, 10.1126/science.1207824, 2011.
Bell, M. L., Peng, R. D., and Domenici, F.: The exposure-response curve for ozone and risk of mortality and the adequacy of current ozone regulations, Environ. Health Perspect., 114, 532-536, 2006.
Bickle, M.: Shale gas extraction in the UK: a review of hydraulic fracturing, The Royal Society and The Royal Academy of Engineering, London, 2012.
Bloomer, B. J., Stehr, J. W., Piety, C. A., Salawitch, R. J., and Dickerson, R. R.: Observed relationships of ozone air pollution with temperature and emissions, Geophysical Research Letters, 36, 10.1029/2009gl037308, 2009.
Bloss, W. J., Evans, M. J., Lee, J. D., Sommariva, R., Heard, D. E., and Pilling, M. J.: The oxidative capacity of the troposphere: Coupling of field measurements of OH and a global chemistry transport model, Faraday Discussions, 130, 425-436, 10.1039/b419090d, 2005.
Bloss, W. J., Camredon, M., Lee, J. D., Heard, D. E., Plane, J. M. C., Saiz-Lopez, A., Bauguitte, S. J. B., Salmon, R. A., and Jones, A. E.: Coupling of HOx, NOx and halogen chemistry in the antarctic boundary layer, Atmospheric Chemistry and Physics, 10, 10187-10209, 10.5194/acp-10-10187-2010, 2010.
Bojkov, R. D.: Surface ozone during the 2nd half of the 19th century, Journal of Climate and Applied Meteorology, 25, 343-352, 10.1175/1520-0450(1986)025<0343:sodtsh>2.0.co;2, 1986.
Booker, F., Muntifering, R., McGrath, M., Burkey, K., Decoteau, D., Fiscus, E., Manning, W., Krupa, S., Chappelka, A., and Grantz, D.: The Ozone Component of Global Change: Potential Effects on Agricultural and Horticultural Plant Yield, Product Quality and Interactions with Invasive Species, J. Integr. Plant Biol., 51, 337-351, 10.1111/j.1744-7909.2008.00805.x, 2009.
Bossolasco, A., Farago, E. P., Schoemaecker, C., and Fittschen, C.: Rate constant of the reaction between CH_3O_2 and OH radicals, Chemical Physics Letters, 593, 7-13, 10.1016/j.cplett.2013.12.052, 2014.
Bowman, K. W.: Toward the next generation of air quality monitoring: Ozone, Atmospheric Environment, 80, 571-583, 10.1016/j.atmosenv.2013.07.007, 2013.
BP: BP Statistical Review of World Energy, 2013.
BP: BP Energy Outlook 2035: Focus on North America, 2014a.
BP: BP Energy Outlook 2035, 2014b.
Brandt, A. R., Heath, G. A., Kort, E. A., O'Sullivan, F., Petron, G., Jordaan, S. M., Tans, P., Wilcox, J., Gopstein, A. M., Arent, D., Wofsy, S., Brown, N. J., Bradley, R., Stucky, G. D., Eardley, D., and Harriss, R.: Methane Leaks from North American Natural Gas Systems, Science, 343, 733-735, 10.1126/science.1247045, 2014.
Braslavsky, S. E., and Rubin, M. B.: The history of ozone. Part VIII. Photochemical formation of ozone, Photochemical & Photobiological Sciences, 10, 1515-1520, 10.1039/c1pp05121k, 2011.
Brasseur, G. P., Prinn, R. G., and Pszenny, A. A. P.: Atmospheric Chemistry in a Changing World, Global Change - IGBP Series, Springer, 2003.
Brauer, M., Amann, M., Burnett, R. T., Cohen, A., Dentener, F., Ezzati, M., Henderson, S. B., Krzyzanowski, M., Martin, R. V., Van Dingenen, R., van Donkelaar, A., and Thurston, G. D.: Exposure

Assessment for Estimation of the Global Burden of Disease Attributable to Outdoor Air Pollution, Environ. Sci. Technol., 46, 652-660, 10.1021/es2025752, 2012.
Brock, C. A., Cozic, J., Bahreini, R., Froyd, K. D., Middlebrook, A. M., McComiskey, A., Brioude, J., Cooper, O. R., Stohl, A., Aikin, K. C., de Gouw, J. A., Fahey, D. W., Ferrare, R. A., Gao, R. S., Gore, W., Holloway, J. S., Hubler, G., Jefferson, A., Lack, D. A., Lance, S., Moore, R. H., Murphy, D. M., Nenes, A., Novelli, P. C., Nowak, J. B., Ogren, J. A., Peischl, J., Pierce, R. B., Pilewskie, P., Quinn, P. K., Ryerson, T. B., Schmidt, K. S., Schwarz, J. P., Sodemann, H., Spackman, J. R., Stark, H., Thomson, D. S., Thornberry, T., Veres, P., Watts, L. A., Warneke, C., and Wollny, A. G.: Characteristics, sources, and transport of aerosols measured in spring 2008 during the aerosol, radiation, and cloud processes affecting Arctic Climate (ARCPAC) Project, Atmospheric Chemistry and Physics, 11, 2423-2453, 10.5194/acp-11-2423-2011, 2011.
Brown-Steiner, B., and Hess, P.: Asian influence on surface ozone in the United States: A comparison of chemistry, seasonality, and transport mechanisms, Journal of Geophysical Research-Atmospheres, 116, 10.1029/2011jd015846, 2011.
Browne, E. C., Wooldridge, P. J., Min, K. E., and Cohen, R. C.: On the role of monoterpene chemistry in the remote continental boundary layer, Atmos. Chem. Phys., 14, 1225-1238, 10.5194/acp-14-1225-2014, 2014.
Bueker, P., Morrissey, T., Briolat, A., Falk, R., Simpson, D., Tuovinen, J. P., Alonso, R., Barth, S., Baumgarten, M., Grulke, N., Karlsson, P. E., King, J., Lagergren, F., Matyssek, R., Nunn, A., Ogaya, R., Penuelas, J., Rhea, L., Schaub, M., Uddling, J., Werner, W., and Emberson, L. D.: DO3SE modelling of soil moisture to determine ozone flux to forest trees, Atmospheric Chemistry and Physics, 12, 5537-5562, 10.5194/acp-12-5537-2012, 2012.
Butler, T. M., and Lawrence, M. G.: The influence of megacities on global atmospheric chemistry: a modelling study, Environmental Chemistry, 6, 219-225, 10.1071/en08110, 2009.
Butler, T. M., Stock, Z. S., Russo, M. R., van der Gon, H., and Lawrence, M. G.: Megacity ozone air quality under four alternative future scenarios, Atmospheric Chemistry and Physics, 12, 4413-4428, 10.5194/acp-12-4413-2012, 2012.
Calfapietra, C., Fares, S., Manes, F., Morani, A., Sgrigna, G., and Loreto, F.: Role of Biogenic Volatile Organic Compounds (BVOC) emitted by urban trees on ozone concentration in cities: A review, Environmental Pollution, 183, 71-80, http://dx.doi.org/10.1016/j.envpol.2013.03.012, 2013.
Cammas, J. P., Brioude, J., Chaboureau, J. P., Duron, J., Mari, C., Mascart, P., Nedelec, P., Smit, H., Patz, H. W., Volz-Thomas, A., Stohl, A., and Fromm, M.: Injection in the lower stratosphere of biomass fire emissions followed by long-range transport: a MOZAIC case study, Atmospheric Chemistry and Physics, 9, 5829-5846, 2009.
Cape, J. N.: Surface ozone concentrations and ecosystem health: Past trends and a guide to future projections, Science of the Total Environment, 400, 257-269, 10.1016/j.scitotenv.2008.06.025, 2008.
Cape, J. N., Hamilton, R., and Heal, M. R.: Reactive uptake of ozone at simulated leaf surfaces: Implications for [`]non-stomatal' ozone flux, Atmospheric Environment, 43, 1116-1123, 2009.
Carpenter, L. J.: Iodine in the marine boundary layer, Chem. Rev., 103, 4953 - 4962, 2003.
Carpenter, L. J., Fleming, Z. L., Read, K. A., Lee, J. D., Moller, S. J., Hopkins, J. R., Purvis, R. M., Lewis, A. C., Mueller, K., Heinold, B., Herrmann, H., Fomba, K. W., van Pinxteren, D., Mueller, C., Tegen, I., Wiedensohler, A., Mueller, T., Niedermeier, N., Achterberg, E. P., Patey, M. D., Kozlova, E. A., Heimann, M., Heard, D. E., Plane, J. M. C., Mahajan, A., Oetjen, H., Ingham, T., Stone, D., Whalley, L. K., Evans, M. J., Pilling, M. J., Leigh, R. J., Monks, P. S., Karunaharan, A., Vaughan, S., Arnold, S. R., Tschritter, J., Pochler, D., Friess, U., Holla, R., Mendes, L. M., Lopez, H., Faria, B., Manning, A. J., and Wallace, D. W. R.: Seasonal characteristics of tropical marine boundary layer air measured at the Cape Verde Atmospheric Observatory, Journal of Atmospheric Chemistry, 67, 87-140, 10.1007/s10874-011-9206-1, 2010.
Carpenter, L. J., MacDonald, S. M., Shaw, M. D., Kumar, R., Saunders, R. W., Parthipan, R., Wilson, J., and Plane, J. M. C.: Atmospheric iodine levels influenced by sea surface emissions of inorganic iodine, Nature Geoscience, 6, 108-111, 10.1038/ngeo1687, 2013.

Carslaw, D. C.: On the changing seasonal cycles and trends of ozone at Mace Head, Ireland, Atmos. Chem. Phys, 5, 3441-3450, 2005.
Carslaw, D. C., Beevers, S. D., Tate, J. E., Westmoreland, E. J., and Williams, M. L.: Recent evidence concerning higher NO(x) emissions from passenger cars and light duty vehicles, Atmospheric Environment, 45, 7053-7063, 10.1016/j.atmosenv.2011.09.063, 2011.
Carter, W. P. L., and Seinfeld, J. H.: Winter ozone formation and VOC incremental reactivities in the Upper Green River Basin of Wyoming, Atmospheric Environment, 50, 255-266, 10.1016/j.atmosenv.2011.12.025, 2012.
Carvalho, A., Monteiro, A., Flannigan, M., Solman, S., Miranda, A. I., and Borrego, C.: Forest fires in a changing climate and their impacts on air quality, Atmospheric Environment, 45, 5545-5553, 10.1016/j.atmosenv.2011.05.010, 2011.
Caulton, D. R., Shepson, P. B., Santoro, R. L., Sparks, J. P., Howarth, R. W., Ingraffea, A. R., Cambaliza, M. O. L., Sweeney, C., Karion, A., Davis, K. J., Stirm, B. H., Montzka, S. A., and Miller, B. R.: Toward a better understanding and quantification of methane emissions from shale gas development, Proc. Natl. Acad. Sci. U. S. A., 111, 6237-6242, 10.1073/pnas.1316546111, 2014.
Chameides, W. L., and Walker, J. C. G.: A photochemical theory for tropospheric ozone, J. Geophys. Res., 78, 8751-8760, 1973.
Chang, H. M., Chang, L. F. W., and Jeng, F. T.: Interfacial transfer resistances of ozone dry deposition over agricultural soil of Tainan County, Taiwan, Environmental Engineering Science, 19, 133-141, 2002.
Chang, W., Heikes, B. G., and Lee, M.: Ozone deposition to the sea surface: chemical enhancement and wind speed dependence, Atmospheric Environment, 38, 1053-1059, 2004.
Chatfield, R., and Harrison, H.: Ozone in the remote troposphere - mixing versus photochemistry, Journal of Geophysical Research-Oceans and Atmospheres, 81, 421-423, 10.1029/JC081i003p00421, 1976.
Chelani, A. B.: Persistence analysis of extreme CO, NO_2 and O_3 concentrations in ambient air of Delhi, Atmospheric Research, 108, 128-134, 10.1016/j.atmosres.2012.02.001, 2012.
Chevallier, F., Fortems, A., Bousquet, P., Pison, I., Szopa, S., Devaux, M., and Hauglustaine, D. A.: African CO emissions between years 2000 and 2006 as estimated from MOPITT observations, Biogeosciences, 6, 103-111, 2009.
Choi, K. C., Lee, J. J., Bae, C. H., Kim, C. H., Kim, S., Chang, L. S., Ban, S. J., Lee, S. J., Kim, J., and Woo, J. H.: Assessment of transboundary ozone contribution toward South Korea using multiple source-receptor modeling techniques, Atmospheric Environment, 92, 118-129, 10.1016/j.atmosenv.2014.03.055, 2014.
Choi, Y., Wang, Y., Zeng, T., Martin, R. V., Kurosu, T. P., and Chance, K.: Evidence of lightning NOx and convective transport of pollutants in satellite observations over North America, Geophys. Res. Lett., 32, L02805, 2005.
Chou, C., Wu, T. C., and Tan, P. H.: Changes in gross moist stability in the tropics under global warming, Climate Dynamics, 41, 2481-2496, 10.1007/s00382-013-1703-2, 2013.
Cifuentes, L., Borja-Aburto, V. H., Gouveia, N., Thurston, G., and Davis, D. L.: Assessing the health benefits of urban air pollution reductions associated with climate change mitigation (2000-2020): Santiago, Sao Paulo, Mexico City, and New York City, Environmental Health Perspectives, 109, 419-425, 10.2307/3434790, 2001.
Coe, H., Gallagher, M. W., Choularton, T. W., and Dore, C.: Canopy scale measurements of stomatal and cuticular o3 uptake by sitka spruce, Atmospheric Environment, 29, 1413-1423, 1995.
Colette, A., Granier, C., Hodnebrog, O., Jakobs, H., Maurizi, A., Nyiri, A., Bessagnet, B., D'Angiola, A., D'Isidoro, M., Gauss, M., Meleux, F., Memmesheimer, M., Mieville, A., Rouil, L., Russo, F., Solberg, S., Stordal, F., and Tampieri, F.: Air quality trends in Europe over the past decade: a first multi-model assessment, Atmospheric Chemistry and Physics, 11, 11657-11678, 10.5194/acp-11-11657-2011, 2011.
Colette, A., Granier, C., Hodnebrog, O., Jakobs, H., Maurizi, A., Nyiri, A., Rao, S., Amann, M., Bessagnet, B., D'Angiola, A., Gauss, M., Heyes, C., Klimont, Z., Meleux, F., Memmesheimer, M.,

Mieville, A., Rouïl, L., Russo, F., Schucht, S., Simpson, D., Stordal, F., Tampieri, F., and Vrac, M.: Future air quality in Europe: a multi-model assessment of projected exposure to ozone, Atmos. Chem. Phys., 12, 10613-10630, 2012.
Colette, A., Bessagnet, B., Vautard, R., Szopa, S., Rao, S., Schucht, S., Klimont, Z., Menut, L., Clain, G., Meleux, F., Curci, G., and Rouïl, L.: European atmosphere in 2050, a regional air quality and climate perspective under CMIP5 scenarios, Atmos. Chem. Phys., 13, 7451-7471, 2013.
Colette, A., Bessagnet, B., Meleux, F., Terrenoire, E., and Rouïl, L.: Frontiers in air quality modelling, Geosci. Model Dev., 7, 203-210, 10.5194/gmd-7-203-2014, 2014.
Collins, W. J., Sitch, S., and Boucher, O.: How vegetation impacts affect climate metrics for ozone precursors, Journal of Geophysical Research-Atmospheres, 115, 10.1029/2010jd014187, 2010.
Collins, W. J., Fry, M. M., Yu, H., Fuglestvedt, J. S., Shindell, D. T., and West, J. J.: Global and regional temperature-change potentials for near-term climate forcers, Atmospheric Chemistry and Physics, 13, 2471-2485, 10.5194/acp-13-2471-2013, 2013.
Cook, P. A., Savage, N. H., Turquety, S., Carver, G. D., O'Connor, F. M., Heckel, A., D., S., Whalley, L. K., Parker, A. E., Schlager , H., Singh, H. B., Avery, M. A., Sachse, G. W., Brune, W., Richter, A., Burrows, J. P., Purvis, R., Lewis, A. C., Reeves, C. E., Monks, P. S., Levine, J. S., and Pyle, D. M.: Forest fire plumes over the North Atlantic: p-TOMCAT model simulations with aircraft and satellite measurements from the ITOP/ICARTT campaign, J. Geophys. Res., 112, D10S43, doi:10.1029/2006JD007563., 2007.
Cooper, O. R., Trainer, M., Thompson, A. M., Oltmans, S. J., Tarasick, D. W., Witte, J. C., Stohl, A., Eckhardt, S., Lelieveld, J., Newchurch, M. J., Johnson, B. J., Portmann, R. W., Kalnajs, L., Dubey, M. K., Leblanc, T., McDermid, I. S., Forbes, G., Wolfe, D., Carey-Smith, T., Morris, G. A., Lefer, B., Rappengluck, B., Joseph, E., Schmidlin, F., Meagher, J., Fehsenfeld, F. C., Keating, T. J., Van Curen, R. A., and Minschwaner, K.: Evidence for a recurring eastern North America upper tropospheric ozone maximum during summer, Journal of Geophysical Research-Atmospheres, 112, 10.1029/2007jd008710, 2007.
Cooper, O. R., Eckhardt, S., Crawford, J. H., Brown, C. C., Cohen, R. C., Bertram, T. H., Wooldridge, P., Perring, A., Brune, W. H., Ren, X., Brunner, D., and Baughcum, S. L.: Summertime buildup and decay of lightning NOx and aged thunderstorm outflow above North America, Journal of Geophysical Research-Atmospheres, 114, 10.1029/2008jd010293, 2009.
Cooper, O. R., Parrish, D. D., Ziemke, J., Balashov, N. V., Cupeiro, M., Galbally, I. E., Gilge, S., Horowitz, L., Jensen, N. R., Lamarque, J. F., Naik, V., Oltmans, S. J., Schwab, J., Shindell, D. T., Thompson, A. M., Thouret, V., Wang, Y., and Zbinden, R. M.: Global distribution and trends of tropospheric ozone: An observation-based review, Elem. Sci. Anth., 2, 000029, 10.12952/journal.elementa.000029, 2014.
Corbett, J. J., Lack, D. A., Winebrake, J. J., Harder, S., Silberman, J. A., and Gold, M.: Arctic shipping emissions inventories and future scenarios, Atmospheric Chemistry and Physics, 10, 9689-9704, 10.5194/acp-10-9689-2010, 2010.
Council, C. o. t. S. o. l. T. o. A. P. N. R.: Global Sources of Local Pollution:An Assessment of Long-Range Transport of Key Air Pollutants to and from the United States, The National Academies Press, 2009a.
Council, N. R.: Global Sources of Local pollution: An Assessment of Long-Range Transport of Key Air Pollutants to and from the United States, The National Academies Press, 2009b.
Cox, P., Delao, A., Komorniczak, A., and Weller, R.: The California Almanac of Emissions and Air Quality, California Air Resources Board, 2009.
Coyle, M.: The Gaseous Exchange of Ozone

at Terrestrial Surfaces: Non-stomatal Deposition to Grassland, School of Geosciences, Faculty of Science and Engineering, The University of Edinburgh, Edinburgh, 270 pp., 2005.
Coyle, M., Nemitz, E., Storeton-West, R., Fowler, D., and Cape, J. N.: Measurements of ozone deposition to a potato canopy, Agricultural and Forest Meteorology, 149, 655-666, 2009.
Crawford-Brown, D., Barker, T., Anger, A., and Dessens, O.: Ozone and PM related health co-benefits of climate change policies in Mexico, Environ. Sci. Policy, 17, 33-40, 10.1016/j.envsci.2011.12.006, 2012.

Criegee, R.: Die Umlagerung der Dekalin-peroxydester als Folge von kationischem Sauerstoff, Justus Liebigs Annalen der Chemie, 560, 127-135, 10.1002/jlac.19485600106, 1948.
Cristofanelli, P., Bracci, A., Sprenger, M., Marinoni, A., Bonafè, U., Calzolari, F., Duchi, R., Laj, P., Pichon, J. M., Roccato, F., Venzac, H., Vuillermoz, E., and Bonasoni, P.: Tropospheric ozone variations at the Nepal Climate Observatory-Pyramid (Himalayas, 5079 m a.s.l.) and influence of deep stratospheric intrusion events, Atmos. Chem. Phys., 10, 6537-6549, 10.5194/acp-10-6537-2010, 2010.
Crounse, J. D., Paulot, F., Kjaergaard, H. G., and Wennberg, P. O.: Peroxy radical isomerization in the oxidation of isoprene, Physical Chemistry Chemical Physics, 13, 13607-13613, 2011.
Crutzen, P. J.: Photochemical reactions initiated by and influencing ozone in the unpolluted troposphere, Tellus, 26, 47-57, 1973.
Cuevas, E., Gonzalez, Y., Rodriguez, S., Guerra, J. C., Gomez-Pelaez, A. J., Alonso-Perez, S., Bustos, J., and Milford, C.: Assessment of atmospheric processes driving ozone variations in the subtropical North Atlantic free troposphere, Atmospheric Chemistry and Physics, 13, 1973-1998, 10.5194/acp-13-1973-2013, 2013.
Cui, H. Y., Su, J. W., Wei, J. N., Hu, Y. J., and Ge, F.: Elevated O_3 enhances the attraction of whitefly-infested tomato plants to Encarsia formosa, Sci Rep, 4, 10.1038/srep05350, 2014.
Cuvelier, C., Thunis, P., Vautard, R., Amann, M., Bessagnet, B., Bedogni, M., Berkowicz, R., Brandt, J., Brocheton, F., Builtjes, P., Coppalle, A., Denby, B., G., D., Graf, A., Hellmuth, O., Honoré, C., Hodzic, A., Jonson, J., Kerschbaumer, A., de Leeuw, F., Minguzzi, E., Moussiopoulos, N., Pertot, C., Pirovano, G., Rouil, L., Schaap, M., Stern, R., Tarrason, L., Vignati, E., Volta, M., White, L., Wind, P., and Zuber, A.: CityDelta: A model intercomparison to explore the impact of emission reductions in 2010 in European cities, Atmos. Environ., 41, 189-207, doi:10.1016/j.atmosenv.2006.07.036, 2007.
Dalsoren, S. B., Samset, B. H., Myhre, G., Corbett, J. J., Minjares, R., Lack, D., and Fuglestvedt, J. S.: Environmental impacts of shipping in 2030 with a particular focus on the Arctic region, Atmospheric Chemistry and Physics, 13, 1941-1955, 10.5194/acp-13-1941-2013, 2013.
Dalsøren, S. B., Eide, M. S., Myhre, G., Endresen, Ø., Isaksen, I. S. A., and Fuglestvedt, J. S.: Impacts of the Large Increase in International Ship Traffic 2000–2007 on Tropospheric Ozone and Methane, Environ. Sci. Technol., 44, 2482-2489, 10.1021/es902628e, 2010.
Danielsen, E. F.: Stratospheirc-tropospheirc exchange based on radioactivity, ozone and potential vorticity, J. Atmos. Sci., 25, 502-518, 1968.
Davison, B., Brunner, A., Ammann, C., Spirig, C., Jocher, M., and Neftel, A.: Cut-induced VOC emissions from agricultural grasslands, Plant Biol., 10, 76-85, 10.1055/s-2007-965043, 2008.
de Fatima, A. M., Fornaro, A., Dias de, F. E., Mazzoli, C. R., Martins, L. D., Boian, C., Oliveira, M. G. L., Peres, J., Carbone, S., Alvala, P., and Leme, N. P.: Ozone sounding in the Metropolitan Area of Sao Paulo, Brazil: Wet and dry season campaigns of 2006, Atmospheric Environment, 61, 627-640, 10.1016/j.atmosenv.2012.07.083, 2012.
de Ruyter de Wildt, M., Eskes, H., and Boersma, K. F.: The global economic cycle and satellite-derived NO_2 trends over shipping lanes, Geophys. Res. Lett., 39, L01802, 10.1029/2011gl049541, 2012.
Defra: Air Quality Statistics in the UK 1987-2012, Defra, London, 2013.
Dempsey, F.: Observations of stratospheric O_3 intrusions in air quality monitoring data in Ontario, Canada, Atmospheric Environment, 98, 111-122, http://dx.doi.org/10.1016/j.atmosenv.2014.08.024, 2014.
Derwent, R., Beevers, S., Chemel, C., Cooke, S., Francis, X., Fraser, A., Heal, M. R., Kitwiroon, N., Lingard, J., Redington, A., Sokhi, R., and Vieno, M.: Analysis of UK and European NOx and VOC emission scenarios in the Defra model intercomparison exercise, Atmospheric Environment, 94, 249-257, 10.1016/j.atmosenv.2014.05.036, 2014.
Derwent, R. G., Collins, W. J., Johnson, C. E., and Stevenson, D. S.: Transient behaviour of tropospheric ozone precursors in a global 3-D CTM and their indirect greenhouse effects, Climatic Change, 49, 463-487, 10.1023/a:1010648913655, 2001.
Derwent, R. G., Simmonds, P. G., O'Doherty, S., Stevenson, D. S., Collins, W. J., Sanderson, M. G., Johnson, C. E., Dentener, F., Cofala, J., Mechler, R., and Amann, M.: External influences on Europe's

air quality: Baseline methane, carbon monoxide and ozone from 1990 to 2030 at Mace Head, Ireland, Atmospheric Environment, 40, 844-855, 10.1016/j.atmosenv.2005.09.077, 2006.
Derwent, R. G., Witham, C. S., Utembe, S. R., Jenkin, M. E., and Passant, N. R.: Ozone in Central England: the impact of 20 years of precursor emission controls in Europe, Environ. Sci. Policy, 13, 195-204, 10.1016/j.envsci.2010.02.001, 2010.
Derwent, R. G., and Hjellbrekke, A.-G.: Air Pollution by Ozone Across Europe, Urban Air Quality in Europe, edited by: Viana, M., Springer, 2013.
Di Carlo, P., Brune, W. H., Martinez, M., Harder, H., Lesher, R., Ren, X. R., Thornberry, T., Carroll, M. A., Young, V., Shepson, P. B., Riemer, D., Apel, E., and Campbell, C.: Missing OH reactivity in a forest: Evidence for unknown reactive biogenic VOCs, Science, 304, 722-725, 2004.
Dibble, T. S.: Failures and limitations of quantum chemistry for two key problems in the atmospheric chemistry of peroxy radicals, Atmospheric Environment, 42, 5837-5848, 2008.
Dix, B., Baidara, S., Bresch, J. F., Hall, S. R., Schmidt, K. S., Wang, S., and Volkamer, R.: Detection of iodine monoxide in the tropical free troposphere, Proc. Natl. Acad. Sci. U. S. A., 110, 2035-2040, 10.1073/pnas.1212386110, 2013.
Doche, C., Dufour, G., Foret, G., Eremenko, M., Cuesta, J., Beekmann, M., and Kalabokas, P.: Summertime tropospheric-ozone variability over the Mediterranean basin observed with IASI, Atmos. Chem. Phys., 14, 10589-10600, 10.5194/acp-14-10589-2014, 2014.
Doherty, R. M., Stevenson, D. S., Johnson, C. E., Collins, W. J., and Sanderson, M. G.: Tropospheric ozone and El Nino-Southern Oscillation: Influence of atmospheric dynamics, biomass burning emissions, and future climate change, Journal of Geophysical Research-Atmospheres, 111, 10.1029/2005jd006849, 2006.
Doherty, R. M., Wild, O., Shindell, D. T., Zeng, G., MacKenzie, I. A., Collins, W. J., Fiore, A. M., Stevenson, D. S., Dentener, F. J., Schultz, M. G., Hess, P., Derwent, R. G., and Keating, T. J.: Impacts of climate change on surface ozone and intercontinental ozone pollution: A multi-model study, Journal of Geophysical Research: Atmospheres, 118, 3744-3763, 10.1002/jgrd.50266, 2013.
Droge, R., Kuenen, J. J. P., Pulles, M. P. J., and Heslinga, D. C.: The revised EMEP/EEA Guidebook compared to the country specific inventory system in the Netherlands, Atmospheric Environment, 44, 3503-3510, 10.1016/j.atmosenv.2010.06.020, 2010.
Duncan, B. N., Martin, R. V., Staudt, A. C., Yevich, R., and Logan, J. A.: Interannual and seasonal variability of biomass burning emissions constrained by satellite observations, Journal of Geophysical Research-Atmospheres, 108, 10.1029/2002jd002378, 2003.
Duncan, B. N., Prados, A. I., Lamsal, L. N., Liu, Y., Streets, D. G., Gupta, P., Hilsenrath, E., Kahn, R. A., Nielsen, J. E., Beyersdorf, A. J., Burton, S. P., Fiore, A. M., Fishman, J., Henze, D. K., Hostetler, C. A., Krotkov, N. A., Lee, P., Lin, M. Y., Pawson, S., Pfister, G., Pickering, K. E., Pierce, R. B., Yoshida, Y., and Ziemba, L. D.: Satellite data of atmospheric pollution for US air quality applications: Examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid, Atmospheric Environment, 94, 647-662, 10.1016/j.atmosenv.2014.05.061, 2014.
Dunker, A. M., Koo, B., and Yarwood, G.: Sensitivity of atmospheric models to rate terms within complex chemical mechanisms, Atmospheric Environment, 98, 224-230, http://dx.doi.org/10.1016/j.atmosenv.2014.08.074, 2014.
Eckhardt, S., Stohl, A., Beirle, S., Spichtinger, N., James, P., Forster, C., Junker, C., Wagner, T., Platt, U., and Jennings, S. G.: The North Atlantic Oscillation controls air pollution transport to the Arctic, Atmospheric Chemistry and Physics, 3, 1769-1778, 2003.
Edwards, P. M., Young, C. J., Aikin, K., deGouw, J., Dube, W. P., Geiger, F., Gilman, J., Helmig, D., Holloway, J. S., Kercher, J., Lerner, B., Martin, R., McLaren, R., Parrish, D. D., Peischl, J., Roberts, J. M., Ryerson, T. B., Thornton, J., Warneke, C., Williams, E. J., and Brown, S. S.: Ozone photochemistry in an oil and natural gas extraction region during winter: simulations of a snow-free season in the Uintah Basin, Utah, Atmospheric Chemistry and Physics, 13, 8955-8971, 10.5194/acp-13-8955-2013, 2013.
Edwards, P. M., Brown, S. S., Roberts, J. M., Ahmadov, R., Banta, R. M., deGouw, J. A., Dube, W. P., Field, R. A., Flynn, J. H., Gilman, J. B., Graus, M., Helmig, D., Koss, A., Langford, A. O., Lefer, B. L.,

Lerner, B. M., Li, R., Li, S.-M., McKeen, S. A., Murphy, S. M., Parrish, D. D., Senff, C. J., Soltis, J., Stutz, J., Sweeney, C., Thompson, C. R., Trainer, M. K., Tsai, C., Veres, P. R., Washenfelder, R. A., Warneke, C., Wild, R. J., Young, C. J., Yuan, B., and Zamora, R.: High winter ozone pollution from carbonyl photolysis in an oil and gas basin, Nature, advance online publication, 10.1038/nature13767, 2014.
EEA: Air Pollution in Europe 1990-2004, European Environment Agency: Copenhagen, 2007.
EEA: Assessment of ground-level ozone in EEA member countries, with a focus on long-term trends, 2009.
EEA: Air quality in Europe — 2011 report, EEA, 80, 2011.
Ehhalt, D. H.: Photooxidation of trace gases in the troposphere, Physical Chemistry Chemical Physics, 1, 5401-5408, 1999.
Elansky, N. F., Mokhov, II, Belikov, I. B., Berezina, E. V., Elokhov, A. S., Ivanov, V. A., Pankratova, N. V., Postylyakov, O. V., Safronov, A. N., Skorokhod, A. I., and Shumskii, R. A.: Gaseous admixtures in the atmosphere over Moscow during the 2010 summer, Izv. Atmos. Ocean. Phys., 47, 672-681, 10.1134/s000143381106003x, 2011.
Elbern, H., Strunk, A., Schmidt, H., and Talagrand, O.: Emission rate and chemical state estimation by 4-dimensional variational inversion, Atmospheric Chemistry and Physics, 7, 3749-3769, 2007.
Elguindi, N., Clark, H., Ordonez, C., Thouret, V., Flemming, J., Stein, O., Huijnen, V., Moinat, P., Inness, A., Peuch, V. H., Stohl, A., Turquety, S., Athier, G., Cammas, J. P., and Schultz, M.: Current status of the ability of the GEMS/MACC models to reproduce the tropospheric CO vertical distribution as measured by MOZAIC, Geosci. Model Dev., 3, 501-518, 10.5194/gmd-3-501-2010, 2010.
Emberson, L. D., Buker, P., Ashmore, M. R., Mills, G., Jackson, L. S., Agrawal, M., Atikuzzaman, M. D., Cinderby, S., Engardt, M., Jamir, C., Kobayashi, K., Oanh, N. T. K., Quadir, Q. F., and Wahid, A.: A comparison of North American and Asian exposure–response data for ozone effects on crop yields, Atmospheric Environment, 43, 1945-1953, 10.1016/j.atmosenv.2009.01.005, 2009.
Emmons, L. K., Hess, P., Klonecki, A., Tie, X., Horowitz, L., Lamarque, J. F., Kinnison, D., Brasseur, G., Atlas, E., Browell, E., Cantrell, C., Eisele, F., Mauldin, R. L., Merrill, J., Ridley, B., and Shetter, R.: Budget of tropospheric ozone during TOPSE from two chemical transport models, Journal of Geophysical Research-Atmospheres, 108, 10.1029/2002jd002665, 2003.
Emmons, L. K., Arnold, S. R., Monks, S., Huijnen, V., Tilmes, S., Law, K. S., Thomas, J. L., Raut, J.-C., Bouarar, I., Turquety, S., Long, Y., Duncan, B., Steenrod, S., Strode, S., Flemming, J., Mao, J., Langner, J., Thompson, A. M., Tarasick, D., Apel, E. C., Blake, D. R., Cohen, R. C., Dibb, J., Diskin, G. S., Fried, A., Hall, S. R., Huey, L. G., Weinheimer, A. J., Wisthaler, A., Mikoviny, T., Nowak, J., Peischl, J., Roberts, J. M., Ryerson, T., Warneke, C., and Helmig, D.: The POLARCAT Model Intercomparison Project (POLMIP): Overview and evaluation with observations Atmos. Chem. Phys. Discuss., 2014.
EPA: Assessment of the impacts of global change on regional U.S. air quality: a synthesis of climate change impacts on ground-level ozone, National Center for Environmental Assessment Washington DC, 2009.
U.S. Environmental Protection Agency (2014), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012: http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf and http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHGInventory-2014-Annexes.pdf., 2014.
Erisman, J. W., Vanpul, A., and Wyers, P.: Parameterrizaton of surface-resistance for the quantification of atmospheric deposition of acidifying pollutants and ozone, Atmospheric Environment, 28, 2595-2607, 10.1016/1352-2310(94)90433-2, 1994.
Erisman, J. W., Galloway, J. N., Seitzinger, S., Bleeker, A., Dise, N. B., Petrescu, A. M. R., Leach, A. M., and de Vries, W.: Consequences of human modification of the global nitrogen cycle, Philos. Trans. R. Soc. B-Biol. Sci., 368, 10.1098/rstb.2013.0116, 2013.
Escudero, M., Lozano, A., Hierro, J., Valle, J. d., and Mantilla, E.: Urban influence on increasing ozone concentrations in a characteristic Mediterranean agglomeration, Atmospheric Environment, 99, 322-332, http://dx.doi.org/10.1016/j.atmosenv.2014.09.061, 2014.

Ewing, S. A., Christensen, J. N., Brown, S. T., Vancuren, R. A., Cliff, S. S., and Depaolo, D. J.: Pb Isotopes as an Indicator of the Asian Contribution to Particulate Air Pollution in Urban California, Environ. Sci. Technol., 44, 8911-8916, 10.1021/es101450t, 2010.
Eyring, V., Isaksen, I. S. A., Berntsen, T., Collins, W. J., Corbett, J. J., Endresen, Ø., Grainger, R. G., Moldanova, J., Schlager, H., and Stevenson, D. S.: Assessment of Transport Impacts on Climate and Ozone: Shipping. , Atmos. Environ., 44, 4735-4771 2010.
Fabian, P., and Pruchniewicz, P. G.: Meridional distribution of ozone in the troposphere and its seasonal variations, J. Geophys. Res. , 82, 2063-2073, 1977.
Fares, S., Weber, R., Park, J.-H., Gentner, D., Karlik, J., and Goldstein, A. H.: Ozone deposition to an orange orchard: Partitioning between stomatal and non-stomatal sinks, Environmental Pollution, 169, 258-266, 10.1016/j.envpol.2012.01.030, 2012.
Fares, S., Matteucci, G., Scarascia Mugnozza, G., Morani, A., Calfapietra, C., Salvatori, E., Fusaro, L., Manes, F., and Loreto, F.: Testing of models of stomatal ozone fluxes with field measurements in a mixed Mediterranean forest, Atmospheric Environment, 67, 242-251, http://dx.doi.org/10.1016/j.atmosenv.2012.11.007, 2013.
Farquhar, G. D., Schulze, E. D., and Kuppers, M.: Response to humidity by stomata of Nicotiana-Gluaca L and Corylus-Avellana L are consisutent with the optimization of carbon-dioxide uptake with repect to water-loss, Aust. J. Plant Physiol., 7, 315-327, 1980.
Felzer, B., Cronin, T., Reilly, J. M., and Wang, X.: Impact of ozone on trees and crops, Comptes Rendus Geoscience, 339, 784-798, 2007.
Field, R. A., Soltis, J., and Murphy, S.: Air quality concerns of unconventional oil and natural gas production, Environ. Sci.-Process Impacts, 16, 954-969, 10.1039/c4em00081a, 2014.
Finlayson-Pitts, B. J.: Halogens in the Troposphere, Analytical Chemistry, 82, 770-776, 10.1021/ac901478p, 2010.
Finley, B. D., and Saltzman, E. S.: Observations of Cl_2, Br_2, and I_2 in coastal marine air, Journal of Geophysical Research-Atmospheres, 113, 10.1029/2008jd010269, 2008.
Finney, D. L., Doherty, R. M., Wild, O., Huntrieser, H., Pumphrey, H. C., and Blyth, A. M.: Using cloud ice flux to parametrise large-scale lightning, Atmos. Chem. Phys. Discuss., 14, 17817-17856, 10.5194/acpd-14-17817-2014, 2014.
Fiore, A. M., West, J. J., Horowitz, L. W., Naik, V., and Schwarzkopf, M. D.: Characterizing the tropospheric ozone response to methane emission controls and the benefits to climate and air quality, Journal of Geophysical Research-Atmospheres, 113, 10.1029/2007jd009162, 2008.
Fiore, A. M., Dentener, F. J., Wild, O., Cuvelier, C., Schultz, M. G., Hess, P., Textor, C., Schulz, M., Doherty, R. M., Horowitz, L. W., MacKenzie, I. A., Sanderson, M. G., Shindell, D. T., Stevenson, D. S., Szopa, S., Van Dingenen, R., Zeng, G., Atherton, C., Bergmann, D., Bey, I., Carmichael, G., Collins, W. J., Duncan, B. N., Faluvegi, G., Folberth, G., Gauss, M., Gong, S., Hauglustaine, D., Holloway, T., Isaksen, I. S. A., Jacob, D. J., Jonson, J. E., Kaminski, J. W., Keating, T. J., Lupu, A., Marmer, E., Montanaro, V., Park, R. J., Pitari, G., Pringle, K. J., Pyle, J. A., Schroeder, S., Vivanco, M. G., Wind, P., Wojcik, G., Wu, S., and Zuber, A.: Multimodel estimates of intercontinental source-receptor relationships for ozone pollution, Journal of Geophysical Research-Atmospheres, 114, D04301, 10.1029/2008jd010816, 2009.
Fiore, A. M., Levy, H., and Jaffe, D. A.: North American isoprene influence on intercontinental ozone pollution, Atmospheric Chemistry and Physics, 11, 1697-1710, 10.5194/acp-11-1697-2011, 2011.
Fiore, A. M., Naik, V., Spracklen, D. V., Steiner, A., Unger, N., Prather, M., Bergmann, D., Cameron-Smith, P. J., Cionni, I., Collins, W. J., Dalsoren, S., Eyring, V., Folberth, G. A., Ginoux, P., Horowitz, L. W., Josse, B., Lamarque, J. F., MacKenzie, I. A., Nagashima, T., O'Connor, F. M., Righi, M., Rumbold, S. T., Shindell, D. T., Skeie, R. B., Sudo, K., Szopa, S., Takemura, T., and Zeng, G.: Global air quality and climate, Chemical Society Reviews, 41, 6663-6683, 2012a.
Fiore, A. M., Naik, V., Spracklen, D. V., Steiner, A., Unger, N., Prather, M., Bergmann, D., Cameron-Smith, P. J., Cionni, I., Collins, W. J., Dalsoren, S., Eyring, V., Folberth, G. A., Ginoux, P., Horowitz, L. W., Josse, B., Lamarque, J. F., MacKenzie, I. A., Nagashima, T., O'Connor, F. M., Righi, M., Rumbold, S.

T., Shindell, D. T., Skeie, R. B., Sudo, K., Szopa, S., Takemura, T., and Zeng, G.: Global air quality and climate, Chemical Society Reviews, 41, 6663-6683, 10.1039/c2cs35095e, 2012b.
Fiore, A. M., Oberman, J. T., Lin, M. Y., Zhang, L., Clifton, O. E., Jacob, D. J., Naik, V., Horowitz, L. W., Pinto, J. P., and Milly, G. P.: Estimating North American background ozone in U.S. surface air with two independent global models: Variability, uncertainties, and recommendations, Atmospheric Environment, 96, 284-300, http://dx.doi.org/10.1016/j.atmosenv.2014.07.045, 2014.
Fiscus, E. L., Fitzgarrald, L. B., and Burkey, K. O.: Crop responses to ozone: uptake, modes of action, carbon assimilation and partitioning, Plant, Cell and Environment, 28, 997-1011, 2005.
Fishman, J., Watson, C. E., Larsen, J. C., and Logan, J. A.: Distribution of Tropospheric Ozone Determined from Satellite Data, Journal of Geophysical Research-Atmospheres, 95, 3599-3617, 1990.
Fishman, J., Belina, K. M., and Encarnación, C. H.: The St. Louis Ozone Gardens: Visualizing the Impact of a Changing Atmosphere, Bulletin of the American Meteorological Society, 95, 1171-1176, 10.1175/bams-d-13-00009.1, 2014.
Foret, G., Eremenko, M., Cuesta, J., Sellitto, P., Barré, J., Gaubert, B., Coman, A., Dufour, G., Liu, X., Joly, M., Doche, C., and Beekmann, M.: Ozone pollution: What can we see from space? A case study, Journal of Geophysical Research: Atmospheres, 119, 2013JD021340, 10.1002/2013jd021340, 2014.
Fortems-Cheiney, A., Chevallier, F., Pison, I., Bousquet, P., Szopa, S., Deeter, M. N., and Clerbaux, C.: Ten years of CO emissions as seen from Measurements of Pollution in the Troposphere (MOPITT), Journal of Geophysical Research-Atmospheres, 116, 10.1029/2010jd014416, 2011.
Fowler, D., Flechard, C., Cape, J. N., Storeton-West, R. L., and Coyle, M.: Measurements of ozone deposition to vegetation quantifying the flux, the stomatal and non-stomatal components, Water Air Soil Pollut., 130, 63-74, 10.1023/a:1012243317471, 2001.
Fowler, D., Pilegaard, K., Sutton, M. A., Ambus, P., Raivonen, M., Duyzer, J., Simpson, D., Fagerli, H., Fuzzi, S., Schjoerring, J. K., Granier, C., Neftel, A., Isaksen, I. S. A., Laj, P., Maione, M., Monks, P. S., Burkhardt, J., Daemmgen, U., Neirynck, J., Personne, E., Wichink-Kruit, R., Butterbach-Bahl, K., Flechard, C., Tuovinen, J. P., Coyle, M., Gerosa, G., Loubet, B., Altimir, N., Gruenhage, L., Ammann, C., Cieslik, S., Paoletti, E., Mikkelsen, T. N., Ro-Poulsen, H., Cellier, P., Cape, J. N., Horvath, L., Loreto, F., Niinemets, U., Palmer, P. I., Rinne, J., Misztal, P., Nemitz, E., Nilsson, D., Pryor, S., Gallagher, M. W., Vesala, T., Skiba, U., Brueggemann, N., Zechmeister-Boltenstern, S., Williams, J., O'Dowd, C., Facchini, M. C., de Leeuw, G., Flossman, A., Chaumerliac, N., and Erisman, J. W.: Atmospheric composition change: Ecosystems-Atmosphere interactions, Atmospheric Environment, 43, 5193-5267, 10.1016/j.atmosenv.2009.07.068, 2009.
Fowler, D., Brunkreef, B., Fuzzi, S., Monks, P. S., Sutton, M. A., Brasseur, G. P., Friedrich, R., Passante, L. G., and J.M.Jimenez-Mingo: Research Findings in support of the EU Air Quality Review, Publications office of the European Union, Luxembourg, 2013a.
Fowler, D., Coyle, M., Skiba, U., Sutton, M. A., Cape, J. N., Reis, S., Sheppard, L. J., Jenkins, A., Grizzetti, B., Galloway, J. N., Vitousek, P., Leach, A., Bouwman, A. F., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M., and Voss, M.: The global nitrogen cycle in the twenty-first century, Philos. Trans. R. Soc. B-Biol. Sci., 368, 10.1098/rstb.2013.0164, 2013b.
Fowler, D., Steadman, C., Stevenson, D., Coyle, M., Rees, B., Skiba, U. M., Sutton, M., Cape, J. N., Dore, T., Simpson, D., Zaehle, S., Stocker, B., Rinaldi, M., Facchini, C., Flechard, C., Nemitz, E., Twigg, M., Erisman, J. W., and Galloway, J.: Effects of global changes during the 21st century on the N cycle, Atmos Chem Phys Discuss, to be submitted, 2014.
Francis, X. V., Chemel, C., Sokhi, R. S., Norton, E. G., Ricketts, H. M. A., and Fisher, B. E. A.: Mechanisms responsible for the build-up of ozone over South East England during the August 2003 heatwave, Atmospheric Environment, 45, 6880-6890, 10.1016/j.atmosenv.2011.04.035, 2011.
Freitas, S. R., Longo, K. M., Chatfield, R. B., Latham, D., Silva Dias, M. A. F., Andreae, M. O., Prins, E., Gielow, R., and Carvalho Jr, J. A.: the sub-grid scale plume rise of vegetation fires in low resolution atmospheric transport models, Atmos. Chem. Phys., 7, 3385-3398, 2007.
Fromm, M., Lindsey, D. T., Servranckx, R., Yue, G., Trickl, T., Sica, R., Doucet, P., and Godin-Beekmann, S. E.: The untold story of pyrocumulonimbus, Bulletin of the American Meteorological Society, 91, 1193-1209, 10.1175/2010bams3004.1, 2010.

Frost, G. J., Ellison, G. B., and Vaida, V.: Organic peroxyl radical photolysis in the near-infrared: Effects on tropospheric chemistry, The Journal of Physical Chemistry A, 103, 10169-10178, 1999.
Frost, G. J., Falke, S. R., Granier, C., Keating, T., Lamarque, J. F., Melamed, M. L., Middleton, P., Petron, G., and Smith, S. J.: New Directions: Toward a community emissions approach, Atmospheric Environment, 51, 333-334, 10.1016/j.atmosenv.2012.01.055, 2012.
Fry, M. M., Naik, V., West, J. J., Schwarzkopf, M. D., Fiore, A. M., Collins, W. J., Dentener, F. J., Shindell, D. T., Atherton, C., Bergmann, D., Duncan, B. N., Hess, P., MacKenzie, I. A., Marmer, E., Schultz, M. G., Szopa, S., Wild, O., and Zeng, G.: The influence of ozone precursor emissions from four world regions on tropospheric composition and radiative climate forcing, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2011jd017134, 2012.
Fuentes, J. D., Gillespie, T. J., Denhartog, G., and Neumann, H. H.: Ozone Deposition onto a Deciduous Forest During Dry and Wet Conditions, Agricultural and Forest Meteorology, 62, 1-18, 1992.
Fuglestvedt, J. S., Shine, K. P., Berntsen, T., Cook, J., Lee, D. S., Stenke, A., Skeie, R. B., Velders, G. J. M., and Waitz, I. A.: Transport impacts on atmosphere and climate: Metrics, Atmospheric Environment, 44, 4648-4677, 10.1016/j.atmosenv.2009.04.044, 2010.
Fuhrer, J.: Ozone risk for crops and pastures in present and future climates, Naturwissenschaften, 96, 173-194, 10.1007/s00114-008-0468-7, 2009.
Fuzzi, S., Baltensperger, U., Carslaw, K., Decesari, S., Gon, H. D. V. d., Facchini, M. C., Fowler, D., Koren, I., Langford, B., Lohmann, U., Nemitz, E., Pandis, S., Riipinen, I., Rudich, Y., Schaap, M., Slowik, J., Spracklen, D. V., Vignati, E., Wild, M., Williams, M., and Gilardoni, S.: Particulate matter, air quality and climate: lessons learned and future needs., Atmos. Chem. Phys. Discus., to be submitted, 2014.
Gallagher, M. W., Beswick, K. M., and Coe, H.: Ozone deposition to coastal waters, Quarterly Journal of the Royal Meteorological Society, 127, 539-558, 2001.
Galloway, J. N., Aber, J. D., Erisman, J. W., Seitzinger, S. P., Howarth, R. W., Cowling, E. B., and Cosby, B. J.: The nitrogen cascade, Bioscience, 53, 341-356, 10.1641/0006-3568(2003)053[0341:tnc]2.0.co;2, 2003.
Galloway, J. N., Dentener, F. J., Capone, D. G., Boyer, E. W., Howarth, R. W., Seitzinger, S. P., Asner, G. P., Cleveland, C. C., Green, P. A., Holland, E. A., Karl, D. M., Michaels, A. F., Porter, J. H., Townsend, A. R., and Vorosmarty, C. J.: Nitrogen cycles: past, present, and future, Biogeochemistry, 70, 153-226, 10.1007/s10533-004-0370-0, 2004.
Ganzeveld, L., Helmig, D., Fairall, C. W., Hare, J., and Pozzer, A.: Atmosphere-ocean ozone exchange: A global modeling study of biogeochemical, atmospheric, and waterside turbulence dependencies, Global Biogeochemical Cycles, 23, 10.1029/2008gb003301, 2009.
Garg, A., Shukla, P. R., and Kapshe, M.: The sectoral trends of multigas emissions inventory of India, Atmospheric Environment, 40, 4608-4620, 10.1016/j.atmosenv.2006.03.045, 2006.
Garny, H., Grewe, V., Dameris, M., Bodeker, G. E., and Stenke, A.: Attribution of ozone changes to dynamical and chemical processes in CCMs and CTMs, Geosci. Model Dev., 4, 271-286, 10.5194/gmd-4-271-2011, 2011.
Gaubert, B., Coman, A., Foret, G., Meleux, F., Ung, A., Rouil, L., Ionescu, A., Candau, Y., and Beekmann, M.: Regional scale ozone data assimilation using an ensemble Kalman filter and the CHIMERE chemical transport model, Geosci. Model Dev., 7, 283-302, 10.5194/gmd-7-283-2014, 2014.
Gauss, M., Myhre, G., Isaksen, I. S. A., Grewe, V., Pitari, G., Wild, O., Collins, W. J., Dentener, F. J., Ellingsen, K., Gohar, L. K., Hauglustaine, D. A., Iachetti, D., Lamarque, F., Mancini, E., Mickley, L. J., Prather, M. J., Pyle, J. A., Sanderson, M. G., Shine, K. P., Stevenson, D. S., Sudo, K., Szopa, S., and Zeng, G.: Radiative forcing since preindustrial times due to ozone changes in the troposphere and the lower stratosphere. , Atmos. Chem. Phys., 6, 575-599, 2006.
Gerosa, G., Vitale, M., Finco, A., Manes, F., Denti, A. B., and Cieslik, S.: Ozone uptake by an evergreen Mediterranean Forest (Quercus ilex) in Italy. Part I: Micrometeorological flux measurements and flux partitioning, Atmospheric Environment, 39, 3255-3266, 2005.
Gerosa, G., Finco, A., Mereu, S., Vitale, M., Manes, F., and Denti, A. B.: Comparison of seasonal variations of ozone exposure and fluxes in a Mediterranean Holm oak forest between the

exceptionally dry 2003 and the following year, Environmental Pollution, 157, 1737-1744, 10.1016/j.envpol.2007.11.025, 2009.
Ghude, S. D., Jain, S. L., Arya, B. C., Beig, G., Ahammed, Y. N., Kumar, A., and Tyagi, B.: Ozone in ambient air at a tropical megacity, Delhi: characteristics, trends and cumulative ozone exposure indices, Journal of Atmospheric Chemistry, 60, 237-252, 10.1007/s10874-009-9119-4, 2008.
Ghude, S. D., Jena, C., Chate, D. M., Beig, G., Pfister, G. G., Kumar, R., and Ramanathan, V.: Reductions in India's crop yield due to ozone, Geophysical Research Letters, 41, 2014GL060930, 10.1002/2014gl060930, 2014.
Giglio, L., and Kendall, J. D.: Commentary on "Improving the seasonal cycle and interannual variations of biomass burning aerosol sources" by Generoso et al, Atmospheric Chemistry and Physics, 4, 585-587, 2004.
Gilman, J. B., Lerner, B. M., Kuster, W. C., and de Gouw, J. A.: Source Signature of Volatile Organic Compounds from Oil and Natural Gas Operations in Northeastern Colorado, Environ. Sci. Technol., 47, 1297-1305, 10.1021/es304119a, 2013.
Glotfelty, T., Zhang, Y., Karamchandani, P., and Streets, D. G.: Will the role of intercontinental transport change in a changing climate?, Atm. Chem. Phys., 14, 9379-9402, 2014.
Goldstein, A. H., and Galbally, I. E.: Known and Unexplored Organic Constituents in the Earth's Atmosphere, Environ. Sci. Technol., 1 March, 1515-1521, 2007.
Granat, L., and Richter, A.: Dry Deposition to Pine of Sulfur-Dioxide and Ozone at Low Concentration, Atmospheric Environment, 29, 1677-1683, 1995.
Granier, C., Artaxo, P., and Reeves, C. E.: Emissions of Atmospheric Trace compounds, Kluwer, 545 pp., 2004.
Granier, C., Niemeier, U., Jungclaus, J. H., Emmons, L., Hess, P., Lamarque, J. F., Walters, S., and Brasseur, G. P.: Ozone pollution from future ship traffic in the Arctic northern passages, Geophysical Research Letters, 33, 10.1029/2006gl026180, 2006.
Granier, C., Bessagnet, B., Bond, T., D'Angiola, A., van der Gon, H. D., Frost, G. J., Heil, A., Kaiser, J. W., Kinne, S., Klimont, Z., Kloster, S., Lamarque, J. F., Liousse, C., Masui, T., Meleux, F., Mieville, A., Ohara, T., Raut, J. C., Riahi, K., Schultz, M. G., Smith, S. J., Thompson, A., van Aardenne, J., van der Werf, G. R., and van Vuuren, D. P.: Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980-2010 period, Climatic Change, 109, 163-190, 10.1007/s10584-011-0154-1, 2011.
Grannas, A. M., Jones, A. E., Dibb, J. E., Ammann, M., Anastasio, C., Beine, H. J., Bergin, M., Bottenheim, J., Boxe, C. S., Carver, G., Chen, G., Crawford, J., Dominé, F., Frey, M. M., Guzmán, M. I., Heard, D. E., Helmig, D., Hoffmann, M. R., Honrath, R. E., Huey, L. G., Hutterli, M. A., Jacobi, H. W., Klán, P., Lefer, B., McConnell, J., Plane, J., Sander, R., Savarino, J., Shepson, P. B., Simpson, W. R., Sodeau, J. R., von Glasow, R., Weller, R., Wolff, E. W., and Zhu, T.: An overview of snow photochemistry: evidence, mechanisms and impacts, Atmos. Chem. Phys., 7, 4329-4373, 2007.
Grantz, D. A., Zhang, X. J., Massman, W. J., Denhartog, G., Neumann, H. H., and Pederson, J. R.: Effects of stomatal conductance and surface wetness on ozone deposition in field-grown grape, Atmospheric Environment, 29, 3189-3198, 1995.
Grantz, D. A., Zhang, X. J., Massman, W. J., Delany, A., and Pederson, J. R.: Ozone deposition to a cotton (Gossypium hirsutum L) field: stomatal and surface wetness effects during the California Ozone Deposition Experiment, Agric. For. Meteorol., 85, 19-31, 10.1016/s0168-1923(96)02396-9, 1997.
Grewe, V.: Impact of lightning on air chemistry and climate, in:, in: Lightning principles, Instruments and applications: Review of modern lightning research edited by: Betz, H. D., Schumann, U., and Laroche, P., Springer-Verlag Berlin Germany, 690, 2008.
Grewe, V., Dahlmann, K., Matthes, S., and Steinbrecht, W.: Attributing ozone to NOx emissions: Implications for climate mitigation measures, Atmospheric Environment, 59, 102-107, 10.1016/j.atmosenv.2012.05.002, 2012a.

Grewe, V., Dahlmann, K., Matthes, S., and Steinbrecht, W.: Attributing ozone to NOx emissions: Implications for climate mitigation measures, Atmos Environ, 59, 102-107, 10.1016/j.atmosenv.2012.05.002, 2012b.
Grontoft, T.: Measurements and modelling of the ozone deposition velocity to concrete tiles, including the effect of diffusion, Atmospheric Environment, 38, 49-58, 2004.
Grossmann, K., Friess, U., Peters, E., Wittrock, F., Lampel, J., Yilmaz, S., Tschritter, J., Sommariva, R., von Glasow, R., Quack, B., Krueger, K., Pfeilsticker, K., and Platt, U.: Iodine monoxide in the Western Pacific marine boundary layer, Atmospheric Chemistry and Physics, 13, 3363-3378, 10.5194/acp-13-3363-2013, 2013.
Gryparis, A., Forsberg, B., Katsouyanni, K., Analitis, A., Touloumi, G., Schwartz, J., Samoli, E., Medina, S., Anderson, H. R., Niciu, E. M., Wichmann, H.-E., Kriz, B., Kosnik, M., Skorkovsky, J., Vonk, J. M., and Dortbudak, Z.: Acute effects of ozone on mortality from the "Air Pollution and Health: A European Approach" Project, Am. J. Respir. Crit. Care Med., 170, 1080-1087., 2004.
Guenther, A., Hewitt, C., Erickson, D., Fall, R., Geron, C., Graedel, T., Harley, P., Klinger, L., Lerdau, M., McKay, W., Pierce, T., Scholes, R., Steinbrecher, R., Tallamraju, R., Taylor, J., and Zimmerman, P.: A global model of natural volatile organic compound emissions, J. Geophys. Res., 100, 8873-8892, 1995.
Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P. I., and Geron, C.: Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature., Atmos. Chem. Phys., 6, 3181-3210, 2006.
Guenther, A. B., Zimmerman, P. R., Harley, P. C., Monson, R. K., and Fall, R.: ISOPRENE AND MONOTERPENE EMISSION RATE VARIABILITY - MODEL EVALUATIONS AND SENSITIVITY ANALYSES, Journal of Geophysical Research-Atmospheres, 98, 12609-12617, 10.1029/93jd00527, 1993.
Guenther, A. B., Zimmerman, P. R., Harley, P. C., Monson, R. K., and Fall, R.: Isoprene and monoterpene emission ratevariability-model evaluations and sensitivity analyses, J. Geophys. Res., 98, 12609-12617, 2003.
Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., and Wang, X.: The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions, Geosci. Model Dev., 5, 1471-1492, 10.5194/gmd-5-1471-2012, 2012.
Guerreiro, C. B. B., Foltescu, V., and de Leeuw, F.: Air quality status and trends in Europe, Atmospheric Environment, 98, 376-384, http://dx.doi.org/10.1016/j.atmosenv.2014.09.017, 2014.
Guttikunda, S. K., Tang, Y., Carmichael, G. R., Kurata, G., Pan, L., Streets, D. G., Woo, J. H., Thongboonchoo, N., and Fried, A.: Impacts of Asian megacity emissions on regional air quality during spring 2001, J. Geophys. Res., 110, D20301, doi:10.1029/2004JD004921, 2005.
Haagen-Smit, A. J.: Chemistry and Physiology of Los Angeles Smog, Indust. Eng. Chem., 44, 1342, 1952.
Hand, E.: China blamed for U.S. ozone, Science, 345, 1233-1233, 2014.
Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, M., Bauer, S., Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Kelley, M., Kiang, N., Koch, D., Lean, J., Lerner, J., Lo, K., Menon, S., Miller, R., Minnis, P., Novakov, T., Oinas, V., Perlwitz, J., Perlwitz, J., Rind, D., Romanou, A., Shindell, D., Stone, P., Sun, S., Tausnev, N., Thresher, D., Wielicki, B., Wong, T., Yao, M., and Zhang, S.: Efficacy of climate forcings, Journal of Geophysical Research-Atmospheres, 110, 10.1029/2005jd005776, 2005.
Hao, W. M., and Liu, M. H.: Spatial and temporal distribution of tropical biomass burning, Global Biogeochemical Cycles, 8, 495-504, 1994.
Hardacre, C., Wild, O., and Emberson, L.: An evaluation of ozone dry deposition in global scale chemistry climate models, Atmos. Chem. Phys. Discuss., 14, 22793-22836, 10.5194/acpd-14-22793-2014, 2014.
Hardacre, C. J., Palmer, P. I., Baumanns, K., Rounsevell, M., and Murray-Rust, D.: Probabilistic estimation of future emissions of isoprene and surface oxidant chemistry associated with land-use

change in response to growing food needs, Atmospheric Chemistry and Physics, 13, 5451-5472, 10.5194/acp-13-5451-2013, 2013.
Hartley, W. N.: On the absorption spectrum of ozone, J.Chem.Soc., 39, 1881.
Hauglustaine, D. A., and Brasseur, G. P.: Evolution of tropospheric ozone under anthropogenic activities and associated radiative forcing of climate, Journal of Geophysical Research-Atmospheres, 106, 32337-32360, 10.1029/2001jd900175, 2001.
Hauglustaine, D. A., and Koffi, B.: Boundary layer ozone pollution caused by future aircraft emissions, Geophysical Research Letters, 39, L13808, 10.1029/2012gl052008, 2012.
Heal, M. R., Heaviside, C., Doherty, R. M., Vieno, M., Stevenson, D. S., and Vardoulakis, S.: Health burdens of surface ozone in the UK for a range of future scenarios, Environ. Int., 61, 36-44, 10.1016/j.envint.2013.09.010, 2013a.
Heal, M. R., Heaviside, C., Doherty, R. M., Vieno, M., Stevenson, D. S., and Vardoulakis, S.: Health burdens of surface ozone in the UK for a range of future scenarios, Environ. Int., 61, 36-44, http://dx.doi.org/10.1016/j.envint.2013.09.010, 2013b.
Heard, D. E., and Pilling, M. J.: Measurement of OH and HO_2 in the Troposphere, Chemical Reviews, 103, 5163-5198, 2003.
Hedegaard, G. B., Brandt, J., Christensen, J. H., Frohn, L. M., Geels, C., Hansen, K. M., and Stendel, M.: Impacts of climate change on air pollution levels in the Northern Hemisphere with special focus on Europe and the Arctic, Atmospheric Chemistry and Physics, 8, 3337-3367, 2008.
Hedegaard, G. B., Christensen, J. H., and Brandt, J.: The relative importance of impacts from climate change vs. emissions change on air pollution levels in the 21st century, Atmos. Chem. Phys., 13, 3569-3585, 2013a.
Hedegaard, G. B., Christensen, J. H., and Brandt, J.: The relative importance of impacts from climate change vs. emissions change on air pollution levels in the 21st century, Atmospheric Chemistry and Physics, 13, 3569-3585, 10.5194/acp-13-3569-2013, 2013b.
Hegglin, M. I., and Shepherd, T. G.: Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux, Nature Geosci, 2, 687-691, http://www.nature.com/ngeo/journal/v2/n10/suppinfo/ngeo604_S1.html, 2009.
Held, I. M., and Soden, B. J.: Robust responses of the hydrological cycle to global warming, Journal of Climate, 19, 5686-5699, 10.1175/jcli3990.1, 2006.
Helmig, D., Oltmans, S., Carlson, D., Lamarque, J.-F., Jones, A. E., Labuschagne, C., Anlauf, K., and Hayden, K.: A review of surface ozone in the polar regions, Atmos. Environ., 41, 5138-5161, doi:10.1016/j.atmosenv.2006.09.053., 2007.
Helmig, D., Johnson, B., Oltmans, S. J., Neff, W., Eisele, F., and Davis, D. D.: Elevated ozone in the boundary layer at South Pole, Atmospheric Environment, 42, 2788-2803, doi:10.1016/j.atmosenv.2006.12.032, 2008a.
Helmig, D., Johnson, B. J., Warshawsky, M., Morse, T., Neff, W. D., Eisele, F., and Davis, D. D.: Nitric oxide in the boundary-layer at South Pole during the Antarctic Tropospheric Chemistry Investigation (ANTCI), Atmospheric Environment, 42, 2817-2830, 2008b.
Hess, P., Kinnison, D., and Tang, Q.: Ensemble simulations of the role of the stratosphere in the attribution of tropospheric ozone variability, Atmos. Chem. Phys. Discuss., 14, 20461-20520, 2014.
Hess, P. G., and Zbinden, R.: Stratospheric impact on tropospheric ozone variability and trends: 1990-2009, Atmospheric Chemistry and Physics, 13, 649-674, 10.5194/acp-13-649-2013, 2013.
Hewitt, C. N., MacKenzie, A. R., Di Carlo, P., Di Marco, C. F., Dorsey, J. R., Evans, M., Fowler, D., Gallagher, M. W., Hopkins, J. R., Jones, C. E., Langford, B., Lee, J. D., Lewis, A. C., Lim, S. F., McQuaid, J., Misztal, P., Moller, S. J., Monks, P. S., Nemitz, E., Oram, D. E., Owen, S. M., Phillips, G. J., Pugh, T. A. M., Pyle, J. A., Reeves, C. E., Ryder, J., Siong, J., Skiba, U., and Stewart, D. J.: Nitrogen management is essential to prevent tropical oil palm plantations from causing ground-level ozone pollution, Proc. Natl. Acad. Sci. U. S. A., 106, 18447-18451, 10.1073/pnas.0907541106, 2009.
Hewitt, C. N., Ashworth, K., Boynard, A., Guenther, A., Langford, B., MacKenzie, A. R., Misztal, P. K., Nemitz, E., Owen, S. M., Possell, M., Pugh, T. A. M., Ryan, A. C., and Wild, O.: Ground-level ozone

influenced by circadian control of isoprene emissions, Nature Geoscience, 4, 671-674, 10.1038/ngeo1271, 2011.
Hirdman, D., Burkhart, J. F., Sodemann, H., Eckhardt, S., Jefferson, A., Quinn, P. K., Sharma, S., Strom, J., and Stohl, A.: Long-term trends of black carbon and sulphate aerosol in the Arctic: changes in atmospheric transport and source region emissions, Atmospheric Chemistry and Physics, 10, 9351-9368, 10.5194/acp-10-9351-2010, 2010.
Hodnebrog, O., Stordal, F., and Berntsen, T. K.: Does the resolution of megacity emissions impact large scale ozone?, Atmospheric Environment, 45, 6852-6862, 10.1016/j.atmosenv.2011.01.012, 2011.
Hogg, A., Uddling, J., Ellsworth, D., Carroll, M. A., Pressley, S., Lamb, B., and Vogel, C.: Stomatal and non-stomatal fluxes of ozone to a northern mixed hardwood forest, Tellus Series B-Chemical and Physical Meteorology, 59, 514-525, 10.1111/j.1600-0889.2007.00269.x, 2007.
Hooghiemstra, P. B., Krol, M. C., Bergamaschi, P., de Laat, A. T. J., van der Werf, G. R., Novelli, P. C., Deeter, M. N., Aben, I., and Rockmann, T.: Comparing optimized CO emission estimates using MOPITT or NOAA surface network observations, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2011jd017043, 2012.
Horowitz, L. W., Fiore, A. M., Milly, G. P., Cohen, R. C., Perring, A., Wooldridge, P. J., Hess, P. G., Emmons, L. K., and Lamarque, J. F.: Observational constraints on the chemistry of isoprene nitrates over the eastern United States, Journal of Geophysical Research-Atmospheres, 112, 10.1029/2006jd007747, 2007.
Hov, O., Schmidbauer, N., and Oehme, M.: Light-hydrocarbons in the Norwegian Arctic, Atmospheric Environment, 23, 2471-2482, 10.1016/0004-6981(89)90258-8, 1989.
Hsu, A., Reuben, A., Shindell, D., de Sherbinin, A., and Levy, M.: Toward the next generation of air quality monitoring indicators, Atmospheric Environment, 80, 561-570, http://dx.doi.org/10.1016/j.atmosenv.2013.07.036, 2013.
HTAP: Hemispheric Transport of Air Pollution, UNECE, Geneva 2010.
Huang, K., Fu, J. S., Hsu, N. C., Gao, Y., Dong, X. Y., Tsay, S. C., and Lam, Y. F.: Impact assessment of biomass burning on air quality in Southeast and East Asia during BASE-ASIA, Atmospheric Environment, 78, 291-302, 10.1016/j.atmosenv.2012.03.048, 2013.
Hudman, R. C., Jacob, D. J., Cooper, O. R., Evans, M. J., Heald, C. L., Park, R. J., Fehsenfeld, F. C., Flocke, F., Holloway, J., Hübler, G., Kita, K., Koike, M., Kondo , Y., Neuman, A., Nowak, J., Oltmans, S., Parrish, D., Roberts, J. M., and Ryerson, T. B.: Ozone production in transpacific Asian pollution plumes and implications for ozone air quality in California, J. Geophys. Res., 109, D23S10, doi:10.1029/2004JD004974, 2004.
Hudman, R. C., Murray, L. T., Jacob, D. J., Turquety, S., Wu, S., Millet, D. B., Avery, M., Goldstein, A. H., and Holloway, J.: North American influence on tropospheric ozone and the effects of recent emission reductions: Constraints from ICARTT observations, Journal of Geophysical Research-Atmospheres, 114, D07302, 10.1029/2008jd010126, 2009.
Hughes, K., Lightfoot, P., and Pilling, M.: Direct measurements of the peroxy–hydroperoxy radical isomerisation, a key step in hydrocarbon combustion, Chemical physics letters, 191, 581-586, 1992.
Huo, H., Yao, Z. L., Zhang, Y. Z., Shen, X. B., Zhang, Q., Ding, Y., and He, K. B.: On-board measurements of emissions from light-duty gasoline vehicles in three mega-cities of China, Atmospheric Environment, 49, 371-377, 10.1016/j.atmosenv.2011.11.005, 2012.
Im, U., and Kanakidou, M.: Impacts of East Mediterranean megacity emissions on air quality, Atmospheric Chemistry and Physics, 12, 6335-6355, 10.5194/acp-12-6335-2012, 2012.
Inness, A., Baier, F., Benedetti, A., Bouarar, I., Chabrillat, S., Clark, H., Clerbaux, C., Coheur, P., Engelen, R. J., Errera, Q., Flemming, J., George, M., Granier, C., Hadji-Lazaro, J., Huijnen, V., Hurtmans, D., Jones, L., Kaiser, J. W., Kapsomenakis, J., Lefever, K., Leitao, J., Razinger, M., Richter, A., Schultz, M. G., Simmons, A. J., Suttie, M., Stein, O., Thepaut, J. N., Thouret, V., Vrekoussis, M., Zerefos, C., and Team, M.: The MACC reanalysis: an 8 yr data set of atmospheric composition, Atmospheric Chemistry and Physics, 13, 4073-4109, 10.5194/acp-13-4073-2013, 2013.

IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 1, Historical Overview of Climate change, in: Intergovernmental Panel on Climate Change Climate change : The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Cambridge University Press, Cambridge, 2007.
IPCC: Climate Change 2013 – The Physical Science Basis, Cambridge University Press, Cambridge, 1552 pp., 2013.
Isaksen, I., Berntsen, T., Dalsøren, S., Eleftheratos, K., Orsolini, Y., Rognerud, B., Stordal, F., Søvde, O., Zerefos, C., and Holmes, C.: Atmospheric Ozone and Methane in a Changing Climate, Atmosphere, 5, 518-535, 2014.
Isaksen, I. S. A., Granier, C., Myhre, G., Berntsen, T. K., Dalsoren, S. B., Gauss, M., Klimont, Z., Benestad, R., Bousquet, P., Collins, W., Cox, T., Eyring, V., Fowler, D., Fuzzi, S., Jockel, P., Laj, P., Lohmann, U., Maione, M., Monks, P., Prevot, A. S. H., Raes, F., Richter, A., Rognerud, B., Schulz, M., Shindell, D., Stevenson, D. S., Storelvmo, T., Wang, W. C., van Weele, M., Wild, M., and Wuebbles, D.: Atmospheric composition change: Climate–Chemistry interactions, Atmospheric Environment, 43, 5138-5192, 10.1016/j.atmosenv.2009.08.003, 2009.
Ito, A., Sillman, S., and Penner, J. E.: Global chemical transport model study of ozone response to changes in chemical kinetics and biogenic volatile organic compounds emissions due to increasing temperatures: Sensitivities to isoprene nitrate chemistry and grid resolution, Journal of Geophysical Research-Atmospheres, 114, 10.1029/2008jd011254, 2009.
Jacob, D. J., Logan, J. A., and Murti, P. P.: Effect of rising Asian emissions on surface ozone in the United States, Geophys. Res. Lett., 26, 2175- 2178., 1999.
Jacob, D. J., and Winner, D. A.: Effect of climate change on air quality, Atmospheric Environment, 43, 51-63, 10.1016/j.atmosenv.2008.09.051, 2009.
Jacobson, M. Z., and Streets, D. G.: Influence of future anthropogenic emissions on climate, natural emissions, and air quality, Journal of Geophysical Research-Atmospheres, 114, 10.1029/2008jd011476, 2009.
Jaffe, D., and et al.: Transport of Asian air pollution to North America., Geophys. Res. Lett., 26, 711 - 714., 1999.
Jaffe, D. A., and Wigder, N. L.: Ozone production from wildfires: A critical review, Atmospheric Environment, 51, 1-10, 10.1016/j.atmosenv.2011.11.063, 2012.
Janssens-Maenhout, G., Petrescu, A., Muntean, M., and Blujdeau, V.: Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements, Greenhouse gas measurement and management, JRC, Ispra, Italy, 132-133, 2011.
Janssens-Maenhout, G., Dentener, F., Van Aardenne, J., Monni, S., Pagliari, V., Orlandini, L., Klimont, Z., Kurokawa, J., Akimoto, H., Ohara, T., Wankmueller, R., Battye, B., Grano, D., Zuber, A., and Keating, T.: EDGAR-HTAP: a Harmonized Gridded Air Pollution Emission Dataset Based on National Inventories, European Commission Publications Office, Ispra, Italy, 2012.
Jenkin, M. E., and Clemitshaw, K. C.: Ozone and other secondary photochemical pollutants: chemical processes governing their formation in the planetary boundary layer, Atmos. Environ,, 34, 2499-2527, 2000.
Jenkin, M. E.: Trends in ozone concentration distributions in the UK since 1990: Local, regional and global influences, Atmospheric Environment, 42, 5434-5445, 10.1016/j.atmosenv.2008.02.036, 2008.
Jerrett, M., Burnett, R. T., Pope, C. A., Ito, K., Thurston, G., Krewski, D., Shi, Y. L., Calle, E., and Thun, M.: Long-Term Ozone Exposure and Mortality, N. Engl. J. Med., 360, 1085-1095, 10.1056/NEJMoa0803894, 2009.
Jones, A. E., Anderson, P. S., Wolff, E. W., Roscoe, H. K., Marshall, G. J., Richter, A., Brough, N., and Colwell, S. R.: Vertical structure of Antarctic tropospheric ozone depletion events: characteristics and broader implications, Atmospheric Chemistry and Physics, 10, 7775-7794, 10.5194/acp-10-7775-2010, 2010a.

Jones, C. E., Hornsby, K. E., Sommariva, R., Dunk, R. M., Von Glasow, R., McFiggans, G., and Carpenter, L. J.: Quantifying the contribution of marine organic gases to atmospheric iodine, Geophysical Research Letters, 37, 10.1029/2010gl043990, 2010b.

Jonquieres, I., Marenco, A., Maalej, A., and Rohrer, F.: Study of ozone formation and transatlantic transport from biomass burning emissions over West Africa during the airborne Tropospheric Ozone Campaigns TROPOZ I and TROPOZ II, Journal of Geophysical Research-Atmospheres, 103, 19059-19073, 10.1029/98jd00819, 1998.

Jonson, J. E., Simpson, D., Fagerli, H., and Solberg, S.: Can we explain the trends in European ozone levels?, Atmos. Chem. Phys., 313, 51- 66., 2006.

Jonson, J. E., Tarrason, L., Klein, H., Vestreng, V., Cofala, J., and Whall, C.: Effects of ship emissions on European ground-level ozone in 2020, Int. J. Remote Sens., 30, 4099-4110, 10.1080/01431160902821858, 2009.

Junge, C. E.: Global ozone budget and exchange between and stratosphere and troposphere, Tellus, 14, 363-377, 1962.

Kaiser, J. W., Heil, A., Andreae, M. O., Benedetti, A., Chubarova, N., Jones, L., Morcrette, J. J., Razinger, M., Schultz, M. G., Suttie, M., and van der Werf, G. R.: Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power, Biogeosciences, 9, 527-554, 10.5194/bg-9-527-2012, 2012.

Kaiser, J. W., Andela, N., Heil, A., Leeuwen, T. T. v., Werf, G. R. v. d., Wooster, M. J., Remy, S., and Schultz, M. G.: Assessment of the Global Fire Assimilation System (GFASv1), http://gmes-atmosphere.eu, 2013.

Kalabokas, P. D., Cammas, J. P., Thouret, V., Volz-Thomas, A., Boulanger, D., and Repapis, C. C.: Examination of the atmospheric conditions associated with high and low summer ozone levels in the lower troposphere over the eastern Mediterranean, Atmospheric Chemistry and Physics, 13, 10339-10352, 10.5194/acp-13-10339-2013, 2013.

Kangasjarvi, J., Talvinen, J., Utriainen, M., and Karjalainen, R.: Plant defense systems induced by ozone, Plant Cell Environ, 17, 783-794, 10.1111/j.1365-3040.1994.tb00173.x, 1994.

Kargbo, D. M., Wilhelm, R. G., and Campbell, D. J.: Natural Gas Plays in the Marcellus Shale: Challenges and Potential Opportunities, Environ. Sci. Technol., 44, 5679, 2010.

Karion, A., Sweeney, C., Petron, G., Frost, G., Hardesty, R. M., Kofler, J., Miller, B. R., Newberger, T., Wolter, S., Banta, R., Brewer, A., Dlugokencky, E., Lang, P., Montzka, S. A., Schnell, R., Tans, P., Trainer, M., Zamora, R., and Conley, S.: Methane emissions estimate from airborne measurements over a western United States natural gas field, Geophysical Research Letters, 40, 4393-4397, 10.1002/grl.50811, 2013.

Karnosky, D. F., Skelly, J. M., Percy, K. E., and Chappelka, A. H.: Perspectives regarding 50 years of research on effects of tropospheric ozone air pollution on US forests, Environmental Pollution, 147, 489-506, 10.1016/j.envpol.2006.08.043, 2007.

Katragkou, E., Zanis, P., Kioutsioukis, I., Tegoulias, I., Melas, D., Krueger, B. C., and Coppola, E.: Future climate change impacts on summer surface ozone from regional climate-air quality simulations over Europe, Journal of Geophysical Research-Atmospheres, 116, 10.1029/2011jd015899, 2011.

Katzenstein, A. S., Doezema, L. A., Simpson, I. J., Blake, D. R., and Rowland, F. S.: Extensive regional atmospheric hydrocarbon pollution in the southwestern United States, Proceedings of the National Academy of Sciences, 100, 11975-11979, 10.1073/pnas.1635258100, 2003.

Kawase, H., Nagashima, T., Sudo, K., and Nozawa, T.: Future changes in tropospheric ozone under Representative Concentration Pathways (RCPs), Geophysical Research Letters, 38, 10.1029/2010gl046402, 2011.

Keenan, T. F., and Niinemets, U.: Circadian control of global isoprene emissions, Nature Geoscience, 5, 435-435, 10.1038/ngeo1500, 2012.

Keene, W. C., Long, M. S., Pszenny, A. A. P., Sander, R., Maben, J. R., Wall, A. J., O'Halloran, T. L., Kerkweg, A., Fischer, E. V., and Schrems, O.: Latitudinal variation in the multiphase chemical processing of inorganic halogens and related species over the eastern North and South Atlantic Oceans, Atmospheric Chemistry and Physics, 9, 7361-7385, 2009.

Kemball-Cook, S., Bar-Ilan, A., Grant, J., Parker, L., Jung, J. G., Santamaria, W., Mathews, J., and Yarwood, G.: Ozone Impacts of Natural Gas Development in the Haynesville Shale, Environ. Sci. Technol., 44, 9357-9363, 10.1021/es1021137, 2010.
Kercher, J. P., Riedel, T. P., and Thornton, J. A.: Chlorine activation by N_2O_5: simultaneous, in situ detection of $ClNO_2$ and N_2O_5 by chemical ionization mass spectrometry, Atmos. Meas. Tech., 2, 193-204, 2009.
Khoder, M. I.: Diurnal, seasonal and weekdays-weekends variations of ground level ozone concentrations in an urban area in greater Cairo, Environmental Monitoring and Assessment, 149, 349-362, 10.1007/s10661-008-0208-7, 2009.
Kim, C. S., Alexis, N. E., Rappold, A. G., Kehrl, H., Hazucha, M. J., Lay, J. C., Schmitt, M. T., Case, M., Devlin, R. B., Peden, D. B., and Diaz-Sanchez, D.: Lung Function and Inflammatory Responses in Healthy Young Adults Exposed to 0.06 ppm Ozone for 6.6 Hours, American Journal of Respiratory and Critical Care Medicine, 183, 1215-1221, 10.1164/rccm.201011-1813OC, 2011.
Kim, S., VandenBoer, T. C., Young, C. J., Riedel, T. P., Thornton, J. A., Swarthout, B., Sive, B., Lerner, B., Gilman, J. B., Warneke, C., Roberts, J. M., Guenther, A., Wagner, N. L., Dubé, W. P., Williams, E., and Brown, S. S.: The primary and recycling sources of OH during the NACHTT-2011 campaign: HONO as an important OH primary source in the wintertime, Journal of Geophysical Research: Atmospheres, 119, 2013JD019784, 10.1002/2013jd019784, 2014.
Kim, S. W., Heckel, A., Frost, G. J., Richter, A., Gleason, J., Burrows, J. P., McKeen, S., Hsie, E. Y., Granier, C., and Trainer, M.: NO_2 columns in the western United States observed from space and simulated by a regional chemistry model and their implications for NOx emissions, Journal of Geophysical Research-Atmospheres, 114, 29, 10.1029/2008jd011343, 2009.
Kinney, P. L.: Climate Change, Air Quality, and Human Health, Am. J. Prev. Med., 35, 459-467, 10.1016/j.amepre.2008.08.025, 2008.
Kley, D., Geiss, H., and Mohnen, V. A.: Tropospheric ozone at elevated sites and precursor emissions in the United-States and Europe, Atmospheric Environment, 28, 149-158, 10.1016/1352-2310(94)90030-2, 1994.
Klimont, Z., Kupiainen, K., Heyes, C., Cofala, J., Rafaj, P., Höglund-Isaksson, L., Borken, J., Schöpp, W., Winiwarter, W., Purohit, P., Bertok, I., and Sander R.: ECLIPSE V4a: Global emission data set developed with the GAINS model for the period 2005 to 2050 Key features and principal data sources 2013a.
Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., and Schoepp, W.: Global anthropogenic emissions of particulate matter, in preparation, 2013b.
Klimont, Z., Smith, S. J., and Cofala, J.: The last decade of global anthropogenic sulfur dioxide: 2000-2011 emissions, Environmental Research Letters, 8, 10.1088/1748-9326/8/1/014003, 2013c.
Kline, N. D., and Miller, T. A.: Observation of the electronic transition of C_6-C_{10} peroxy radicals, Chemical Physics Letters, 601, 149-154, 2014.
Kloster, S., Mahowald, N. M., Randerson, J. T., Thornton, P. E., Hoffman, F. M., Levis, S., Lawrence, P. J., Feddema, J. J., Oleson, K. W., and Lawrence, D. M.: Fire dynamics during the 20th century simulated by the Community Land Model, Biogeosciences, 7, 1877-1902, 10.5194/bg-7-1877-2010, 2010.
Knorr, W., Lehsten, V., and Arneth, A.: Determinants and predictability of global wildfire emissions, Atmospheric Chemistry and Physics, 12, 6845-6861, 10.5194/acp-12-6845-2012, 2012.
Kondo, Y., Takegawa, N., Matsui, H., Miyakawa, T., Koike, M., Miyazaki, Y., Kanaya, Y., Mochida, M., Kuwata, M., Morino, Y., and Shiraiwa, M.: Formation and Transport of Aerosols in Tokyo in Relation to Their Physical and Chemical Properties: A Review, J Meteorol Soc Jpn, 88, 597-624, 10.2151/jmsj.2010-401, 2010.
Koo, J. H., Wang, Y., Kurosu, T. P., Chance, K., Rozanov, A., Richter, A., Oltmans, S. J., Thompson, A. M., Hair, J. W., Fenn, M. A., Weinheimer, A. J., Ryerson, T. B., Solberg, S., Huey, L. G., Liao, J., Dibb, J. E., Neuman, J. A., Nowak, J. B., Pierce, R. B., Natarajan, M., and Al-Saadi, J.: Characteristics of tropospheric ozone depletion events in the Arctic spring: analysis of the ARCTAS, ARCPAC, and

ARCIONS measurements and satellite BrO observations, Atmospheric Chemistry and Physics, 12, 9909-9922, 10.5194/acp-12-9909-2012, 2012.
Kopacz, M., Jacob, D. J., Fisher, J. A., Logan, J. A., Zhang, L., Megretskaia, I. A., Yantosca, R. M., Singh, K., Henze, D. K., Burrows, J. P., Buchwitz, M., Khlystova, I., McMillan, W. W., Gille, J. C., Edwards, D. P., Eldering, A., Thouret, V., and Nedelec, P.: Global estimates of CO sources with high resolution by adjoint inversion of multiple satellite datasets (MOPITT, AIRS, SCIAMACHY, TES), Atmospheric Chemistry and Physics, 10, 855-876, 2010.
Kort, E. A., Frankenberg, C., Costigan, K. R., Lindenmaier, R., Dubey, M. K., and Wunch, D.: Four corners: The largest US methane anomaly viewed from space, Geophysical Research Letters, 41, 2014GL061503, 10.1002/2014gl061503, 2014.
Koumoutsaris, S., Bey, I., Generoso, S., and Thouret, V.: Influence of El Nino-Southern Oscillation on the interannual variability of tropospheric ozone in the northern midlatitudes, Journal of Geophysical Research-Atmospheres, 113, 10.1029/2007jd009753, 2008.
Krewski, D., Jerrett, M., Richard T. Burnett, Ma, R., Hughes, E., Yuanli Shi, Turner, M. C., III, C. A. P., George Thurston, Calle, E. E., and Thun, M. J.: Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality, Health Effects Institute, Boston, 2009.
Krupa, S. V., and Manning, W. J.: Atmospheric ozone: formation and effects on vegetation, Environ. Pollut., 50, 101-137, 1988.
Kuenen, J., Gon, J. H. D. v. d., Visschedijk, A., and Brugh., H. v. d.: High resolution European emission inventory for the years 2003 – 2007, TNO, Utrecht, 2011.
Kuenen, J. J. P., Visschedijk, A. J. H., Jozwicka, M., and Denier van der Gon, H. A. C.: TNO-MACC_II emission inventory: a multi-year (2003–2009) consistent high-resolution European emission inventory for air quality modelling, Atmos. Chem. Phys. Discuss., 14, 5837-5869, 10.5194/acpd-14-5837-2014, 2014.
Kukkonen, J., Olsson, T., Schultz, D. M., Baklanov, A., Klein, T., Miranda, A. I., Monteiro, A., Hirtl, M., Tarvainen, V., Boy, M., Peuch, V. H., Poupkou, A., Kioutsioukis, I., Finardi, S., Sofiev, M., Sokhi, R., Lehtinen, K. E. J., Karatzas, K., San José, R., Astitha, M., Kallos, G., Schaap, M., Reimer, E., Jakobs, H., and Eben, K.: A review of operational, regional-scale, chemical weather forecasting models in Europe, Atmos. Chem. Phys., 12, 1-87, 10.5194/acp-12-1-2012, 2012.
Kurokawa, J., Ohara, T., Morikawa, T., Hanayama, S., Janssens-Maenhout, G., Fukui, T., Kawashima, K., and Akimoto, H.: Emissions of air pollutants and greenhouse gases over Asian regions during 2000–2008: Regional Emission inventory in ASia (REAS) version 2, Atmos. Chem. Phys., 13, 11019-11058, 10.5194/acp-13-11019-2013, 2013a.
Kurokawa, J., Ohara, T., Morikawa, T., Hanayama, S., Janssens-Maenhout, G., Fukui, T., Kawashima, K., and Akimoto, H.: Emissions of air pollutants and greenhouse gases over Asian regions during 2000-2008: Regional Emission inventory in ASia (REAS) version 2, Atmospheric Chemistry and Physics, 13, 11019-11058, 10.5194/acp-13-11019-2013, 2013b.
Kvalevåg, M. M., and Myhre, G.: The effect of carbon-nitrogen coupling on the reduced land carbon sink caused by tropospheric ozone, Geophysical Research Letters, n/a-n/a, 10.1002/grl.50572, 2013.
Kwak, K. H., and Baik, J. J.: Diurnal variation of NOx and ozone exchange between a street canyon and the overlying air, Atmospheric Environment, 86, 120-128, 10.1016/j.atmosenv.2013.12.029, 2014.
Lahoz, W. A., Peuch, V. H., Orphal, J., Attié, J. L., Chance, K., Liu, X., Edwards, D., Elbern, H., Flaud, J. M., Claeyman, M., and Amraoui, L. E.: Monitoring Air Quality from Space: The Case for the Geostationary Platform, Bulletin of the American Meteorological Society, 93, 221-233, 10.1175/bams-d-11-00045.1, 2011.
Laj, P., Klausen, J., Bilde, M., Plass-Duelmer, C., Pappalardo, G., Clerbaux, C., Baltensperger, U., Hjorth, J., Simpson, D., Reimann, S., Coheur, P. F., Richter, A., De Maziere, M., Rudich, Y., McFiggans, G., Torseth, K., Wiedensohler, A., Morin, S., Schulz, M., Allan, J. D., Attie, J. L., Barnes, I., Birmili, W., Cammas, J. P., Dommen, J., Dorn, H. P., Fowler, D., Fuzzi, S., Glasius, M., Granier, C., Hermann, M., Isaksen, I. S. A., Kinne, S., Koren, I., Madonna, F., Maione, M., Massling, A., Moehler, O., Mona, L., Monks, P. S., Muller, D., Muller, T., Orphal, J., Peuch, V. H., Stratmann, F., Tanre, D., Tyndall, G., Riziq,

A. A., Van Roozendael, M., Villani, P., Wehner, B., Wex, H., and Zardini, A. A.: Measuring atmospheric composition change, Atmospheric Environment, 43, 5351-5414, 10.1016/j.atmosenv.2009.08.020, 2009.
Lamarque, J. F., Hess, P., Emmons, L., Buja, L., Washington, W., and Granier, C.: Tropospheric ozone evolution between 1890 and 1990, Journal of Geophysical Research-Atmospheres, 110, 10.1029/2004jd005537, 2005.
Lamarque, J. F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P.: Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, Atmospheric Chemistry and Physics, 10, 7017-7039, 10.5194/acp-10-7017-2010, 2010.
Lamsal, L. N., Martin, R. V., Padmanabhan, A., van Donkelaar, A., Zhang, Q., Sioris, C. E., Chance, K., Kurosu, T. P., and Newchurch, M. J.: Application of satellite observations for timely updates to global anthropogenic NOx emission inventories, Geophys. Res. Lett., 38, L05810, 10.1029/2010gl046476, 2011.
Langner, J., Engardt, M., and Andersson, C.: European summer surface ozone 1990-2100, Atmospheric Chemistry and Physics, 12, 10097-10105, 10.5194/acp-12-10097-2012, 2012a.
Langner, J., Engardt, M., Baklanov, A., Christensen, J. H., Gauss, M., Geels, C., Hedegaard, G. B., Nuterman, R., Simpson, D., Soares, J., Sofiev, M., Wind, P., and Zakey, A.: A multi-model study of impacts of climate change on surface ozone in Europe, Atmospheric Chemistry and Physics, 12, 10423-10440, 10.5194/acp-12-10423-2012, 2012b.
Langner, J., Engardt, M., Baklanov, A., Christensen, J. H., Gauss, M., Geels, C., Hedegaard, G. B., Nuterman, R., Simpson, D., Soares, J., Sofiev, M., Wind, P., and Zakey, A.: A multi-model study of impacts of climate change on surface ozone in Europe, Atmos. Chem. Phys., 12, 10423-10440, 2012c.
Lary, D. J.: Halogens and the chemistry of the free troposphere, Atmospheric Chemistry and Physics, 5, 227-237, 2005.
Lathiere, J., Hewitt, C. N., and Beerling, D. J.: Sensitivity of isoprene emissions from the terrestrial biosphere to 20th century changes in atmospheric CO2 concentration, climate, and land use, Global Biogeochemical Cycles, 24, 10.1029/2009gb003548, 2010.
Launiainen, S., Katul, G. G., Gronholm, T., and Vesala, T.: Partitioning ozone fluxes between canopy and forest floor by measurements and a multi-layer model, Agricultural and Forest Meteorology, 173, 85-99, 10.1016/j.agrformet.2012.12.009, 2013.
Law, K. S., and Stohl, A.: Arctic air pollution: Origins and impacts, Science, 315, 1537-1540, 10.1126/science.1137695, 2007.
Law, K. S., Stohl, A., Quinn, P. K., Brock, C., Burkhart, J., Paris, J. D., Ancellet, G., Singh, H. B., Roiger, A., Schlager, H., Dibb, J., Jacob, D. J., Arnold, S. R., Pelon, J., and Thomas, J. L.: Arctic Air Pollution: New Insights From POLARCAT-IPY, Bulletin of the American Meteorological Society, 10.1175/bams-d-13-00017.1, 2014.
Lawler, M. J., Finley, B. D., Keene, W. C., Pszenny, A. A. P., Read, K. A., von Glasow, R., and Saltzman, E. S.: Pollution-enhanced reactive chlorine chemistry in the eastern tropical Atlantic boundary layer, Geophysical Research Letters, 36, 10.1029/2008gl036666, 2009.
Lawler, M. J., Sander, R., Carpenter, L. J., Lee, J. D., von Glasow, R., Sommariva, R., and Saltzman, E. S.: HOCl and Cl_2 observations in marine air, Atmospheric Chemistry and Physics, 11, 7617-7628, 10.5194/acp-11-7617-2011, 2011.
Lawler, M. J., Mahajan, A. S., Saiz-Lopez, A., and Saltzman, E. S.: Observations of I_2 at a remote marine site, Atmospheric Chemistry and Physics, 14, 2669-2678, 10.5194/acp-14-2669-2014, 2014.
Lawrence, M. G., and Lelieveld, J.: Atmospheric pollutant outflow from southern Asia: a review, Atmospheric Chemistry and Physics, 10, 11017-11096, 10.5194/acp-10-11017-2010, 2010.
Lee, J. D., Lewis, A. C., Monks, P. S., Jacob, M., Hamilton, J. F., Hopkins, J. R., Watson, N. M., Saxton, J. E., Ennis, C., Carpenter, L. J., Carslaw, N., Fleming, Z., Bandy, B. J., Oram, D. E., Penkett, S. A., Slemr, J., Norton, E., Rickard, A. R., Whalley, L. K., Heard, D. E., Bloss, W. J., Gravestock, T., Smit, S. C., Stanton,

J., Pilling, M. J., and Jenkin, M. E.: Ozone photochemistry and elevated isoprene during the UK heatwave of august 2003, Atmos. Environ., 40, 7598–7613 2006.
Lee, K. Y., Kwak, K. H., Ryu, Y. H., Lee, S. H., and Baik, J. J.: Impacts of biogenic isoprene emission on ozone air quality in the Seoul metropolitan area, Atmospheric Environment, 96, 209-219, http://dx.doi.org/10.1016/j.atmosenv.2014.07.036, 2014.
Lefohn, A. S., Hazucha, M. J., Shadwick, D., and Adams, W. C.: An alternative form and level of the human health ozone standard, Inhalation Toxicology, 22, 999-1011, Doi 10.3109/08958378.2010.505253, 2010.
Lefohn, A. S., Emery, C., Shadwick, D., Wernli, H., Jung, J., and Oltmans, S. J.: Estimates of background surface ozone concentrations in the United States based on model-derived source apportionment, Atmospheric Environment, 84, 275-288, http://dx.doi.org/10.1016/j.atmosenv.2013.11.033, 2014.
Leighton, P. A.: Photochemistry of Air Pollution, Academic Press, New York, 1961.
Lelieveld, J., and Dentener, F. J.: What controls tropospheric ozone?, Journal of Geophysical Research-Atmospheres, 105, 3531-3551, 10.1029/1999jd901011, 2000.
Lelieveld, J., Berresheim, H., Borrmann, S., Crutzen, P. J., Dentener , F. J., Fischer, H., Feichter, J., Flatau, P. J., Heland, J., Holzinger, R., Korrmann, R., Lawrence, M. G., Levin, Z., Markowicz, K. M., Mihalopoulos, N., Minikin, A., Ramanathan, V., de Reus, M., Roelofs, G. J., Scheeren, H. A., Sciare, J., Schlager , H., Schultz, M., Siegmund, P., Steil, B., Stephanou, E. G., Stier, P., Traub, M., Warneke, C., Williams, J., and Zieraus, H.: Global air pollution crossroads over the Mediterranean, Science, 298, 794-799, 2002.
Lelieveld, J., van Aardenne, J., Fischer, H., de Reus, M., Williams, J., and Winkler, P.: Increasing ozone over the Atlantic Ocean, Science, 304, 1483-1487, 2004.
Lelieveld, J., Butler, T., Crowley, J., Dillon, T., Fischer, H., Ganzeveld, L., Harder, H., Lawrence, M., Martinez, M., Taraborrelli, D., and others: Atmospheric oxidation capacity sustained by a tropical forest, Nature, 452, 737-740, 2008.
Lelieveld, J., Hoor, P., Jockel, P., Pozzer, A., Hadjinicolaou, P., Cammas, J. P., and Beirle, S.: Severe ozone air pollution in the Persian Gulf region, Atmospheric Chemistry and Physics, 9, 1393-1406, 2009.
Levy, H., Moxim, W. J., and Kasibhatla, P. S.: A global three-dimensional time-dependent lightning source of tropospheric NOx, Journal of Geophysical Research-Atmospheres, 101, 22911-22922, 10.1029/96jd02341, 1996.
Lewis, A. C., Evans, M. J., Methven, J., Watson, N. M., Lee, J. D., Hopkins, J. R., Purvis, R. M., Arnold, S. R., McQuaid, J. B., Whalley, L. K., Pilling, M. J., Heard, D. E., Monks, P. S., Parker, A. E., Reeves, C. E., Oram, D. E., Mills, G., Bandy, B. J., Stewart, D., Coe, H., Williams, P., and Crosier, J.: Chemical composition observed over the mid-Atlantic and the detection of pollution signatures far from source regions, J. Geophys. Res., 112, D10S39, doi:10.1029/2006JD007584, 2007.
Lewis, A. C., Evans, M. J., Hopkins, J. R., Punjabi, S., Read, K. A., Purvis, R. M., Andrews, S. J., Moller, S. J., Carpenter, L. J., Lee, J. D., Rickard, A. R., Palmer, P. I., and Parrington, M.: The influence of biomass burning on the global distribution of selected non-methane organic compounds, Atmospheric Chemistry and Physics, 13, 851-867, 10.5194/acp-13-851-2013, 2013.
Li, M., Zhang, Q., Streets, D. G., He, K. B., Cheng, Y. F., Emmons, L. K., Huo, H., Kang, S. C., Lu, Z., Shao, M., Su, H., Yu, X., and Zhang, Y.: Mapping Asian anthropogenic emissions of non-methane volatile organic compounds to multiple chemical mechanisms, Atmospheric Chemistry and Physics, 14, 5617-5638, 10.5194/acp-14-5617-2014, 2014.
Liao, J., Sihler, H., Huey, L. G., Neuman, J. A., Tanner, D. J., Friess, U., Platt, U., Flocke, F. M., Orlando, J. J., Shepson, P. B., Beine, H. J., Weinheimer, A. J., Sjostedt, S. J., Nowak, J. B., Knapp, D. J., Staebler, R. M., Zheng, W., Sander, R., Hall, S. R., and Ullmann, K.: A comparison of Arctic BrO measurements by chemical ionization mass spectrometry and long path-differential optical absorption spectroscopy, Journal of Geophysical Research-Atmospheres, 116, 10.1029/2010jd014788, 2011.
Liao, J., Huey, L. G., Liu, Z., Tanner, D. J., Cantrell, C. A., Orlando, J. J., Flocke, F. M., Shepson, P. B., Weinheimer, A. J., Hall, S. R., Ullmann, K., Beine, H. J., Wang, Y., Ingall, E. D., Stephens, C. R., Hornbrook, R. S., Apel, E. C., Riemer, D., Fried, A., Mauldin, R. L., III, Smith, J. N., Staebler, R. M.,

Neuman, J. A., and Nowak, J. B.: High levels of molecular chlorine in the Arctic atmosphere, Nature Geoscience, 7, 91-94, 10.1038/ngeo2046, 2014.
Lim, S. S., Vos, T., Flaxman, A. D., Danaei, G., Shibuya, K., Adair-Rohani, H., Amann, M., Anderson, H. R., Andrews, K. G., Aryee, M., Atkinson, C., Bacchus, L. J., Bahalim, A. N., Balakrishnan, K., Balmes, J., Barker-Collo, S., Baxter, A., Bell, M. L., Blore, J. D., Blyth, F., Bonner, C., Borges, G., Bourne, R., Boussinesq, M., Brauer, M., Brooks, P., Bruce, N. G., Brunekreef, B., Bryan-Hancock, C., Bucello, C., Buchbinder, R., Bull, F., Burnett, R. T., Byers, T. E., Calabria, B., Carapetis, J., Carnahan, E., Chafe, Z., Charlson, F., Chen, H. L., Chen, J. S., Cheng, A. T. A., Child, J. C., Cohen, A., Colson, K. E., Cowie, B. C., Darby, S., Darling, S., Davis, A., Degenhardt, L., Dentener, F., Des Jarlais, D. C., Devries, K., Dherani, M., Ding, E. L., Dorsey, E. R., Driscoll, T., Edmond, K., Ali, S. E., Engell, R. E., Erwin, P. J., Fahimi, S., Falder, G., Farzadfar, F., Ferrari, A., Finucane, M. M., Flaxman, S., Fowkes, F. G. R., Freedman, G., Freeman, M. K., Gakidou, E., Ghosh, S., Giovannucci, E., Gmel, G., Graham, K., Grainger, R., Grant, B., Gunnell, D., Gutierrez, H. R., Hall, W., Hoek, H. W., Hogan, A., Hosgood, H. D., Hoy, D., Hu, H., Hubbell, B. J., Hutchings, S. J., Ibeanusi, S. E., Jacklyn, G. L., Jasrasaria, R., Jonas, J. B., Kan, H. D., Kanis, J. A., Kassebaum, N., Kawakami, N., Khang, Y. H., Khatibzadeh, S., Khoo, J. P., Kok, C., Laden, F., Lalloo, R., Lan, Q., Lathlean, T., Leasher, J. L., Leigh, J., Li, Y., Lin, J. K., Lipshultz, S. E., London, S., Lozano, R., Lu, Y., Mak, J., Malekzadeh, R., Mallinger, L., Marcenes, W., March, L., Marks, R., Martin, R., McGale, P., McGrath, J., Mehta, S., Mensah, G. A., Merriman, T. R., Micha, R., Michaud, C., Mishra, V., Hanafiah, K. M., Mokdad, A. A., Morawska, L., Mozaffarian, D., Murphy, T., Naghavi, M., Neal, B., Nelson, P. K., Nolla, J. M., Norman, R., Olives, C., Omer, S. B., Orchard, J., Osborne, R., Ostro, B., Page, A., Pandey, K. D., Parry, C. D. H., Passmore, E., Patra, J., Pearce, N., Pelizzari, P. M., Petzold, M., Phillips, M. R., Pope, D., Pope, C. A., Powles, J., Rao, M., Razavi, H., Rehfuess, E. A., Rehm, J. T., Ritz, B., Rivara, F. P., Roberts, T., Robinson, C., Rodriguez-Portales, J. A., Romieu, I., Room, R., Rosenfeld, L. C., Roy, A., Rushton, L., Salomon, J. A., Sampson, U., Sanchez-Riera, L., Sanman, E., Sapkota, A., Seedat, S., Shi, P. L., Shield, K., Shivakoti, R., Singh, G. M., Sleet, D. A., Smith, E., Smith, K. R., Stapelberg, N. J. C., Steenland, K., Stockl, H., Stovner, L. J., Straif, K., Straney, L., Thurston, G. D., Tran, J. H., Van Dingenen, R., van Donkelaar, A., Veerman, J. L., Vijayakumar, L., Weintraub, R., Weissman, M. M., White, R. A., Whiteford, H., Wiersma, S. T., Wilkinson, J. D., Williams, H. C., Williams, W., Wilson, N., Woolf, A. D., Yip, P., Zielinski, J. M., Lopez, A. D., Murray, C. J. L., and Ezzati, M.: A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010, Lancet, 380, 2224-2260, 2012.
Lin, J. T., Pan, D., Davis, S. J., Zhang, Q., He, K. B., Wang, C., Streets, D. G., Wuebbles, D. J., and Guan, D. B.: China's international trade and air pollution in the United States, Proc. Natl. Acad. Sci. U. S. A., 111, 1736-1741, 10.1073/pnas.1312860111, 2014a.
Lin, M., Fiore, A. M., Cooper, O. R., Horowitz, L. W., Langford, A. O., Levy, H., II, Johnson, B. J., Naik, V., Oltmans, S. J., and Senff, C. J.: Springtime high surface ozone events over the western United States: Quantifying the role of stratospheric intrusions, J. Geophys. Res., 117, D00V22, 10.1029/2012jd018151, 2012a.
Lin, M., Horowitz, L. W., Oltmans, S. J., Fiore, A. M., and Fan, S.: Tropospheric ozone trends at Mauna Loa Observatory tied to decadal climate variability, Nature Geosci, 7, 136-143, 10.1038/ngeo2066, 2014b.
Lin, M. Y., Fiore, A. M., Horowitz, L. W., Cooper, O. R., Naik, V., Holloway, J., Johnson, B. J., Middlebrook, A. M., Oltmans, S. J., Pollack, I. B., Ryerson, T. B., Warner, J. X., Wiedinmyer, C., Wilson, J., and Wyman, B.: Transport of Asian ozone pollution into surface air over the western United States in spring, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2011jd016961, 2012b.
Liousse, C., Assamoi, E., Criqui, P., Granier, C., and Rosset, R.: Explosive growth in African combustion emissions from 2005 to 2030, Environmental Research Letters, 9, 035003, 2014.
Lipsett, M. J., Ostro, B. D., Reynolds, P., Goldberg, D., Hertz, A., Jerrett, M., Smith, D. F., Garcia, C., Chang, E. T., and Bernstein, L.: Long-Term Exposure to Air Pollution and Cardiorespiratory Disease in the California Teachers Study Cohort, American Journal of Respiratory and Critical Care Medicine, 184, 828-835, 10.1164/rccm.201012-2082OC, 2011.

Liu, G., Liu, J., Tarasick, D. W., Fioletov, V. E., Jin, J. J., Moeini, O., Liu, X., Sioris, C. E., and Osman, M.: A global tropospheric ozone climatology from trajectory-mapped ozone soundings, Atmos. Chem. Phys., 13, 10659-10675, 10.5194/acp-13-10659-2013, 2013a.
Liu, H., Wang, X. M., Pang, J. M., and He, K. B.: Feasibility and difficulties of China's new air quality standard compliance: PRD case of PM2.5 and ozone from 2010 to 2025, Atmos. Chem. Phys., 13, 12013-12027, 10.5194/acp-13-12013-2013, 2013b.
Liu, Y., Shao, M., Fu, L. L., Lu, S. H., Zeng, L. M., and Tang, D. G.: Source profiles of volatile organic compounds (VOCs) measured in China: Part I, Atmospheric Environment, 42, 6247-6260, 10.1016/j.atmosenv.2008.01.070, 2008.
Logan, J. A.: Tropospheric ozone - seasonal behaviour, trends, and anthropogenic influence, Journal of Geophysical Research-Atmospheres, 90, 10463-10482, 1985.
Logan, J. A., Staehelin, J., Megretskaia, I. A., Cammas, J. P., Thouret, V., Claude, H., De Backer, H., Steinbacher, M., Scheel, H. E., Stubi, R., Frohlich, M., and Derwent, R.: Changes in ozone over Europe: Analysis of ozone measurements from sondes, regular aircraft (MOZAIC) and alpine surface sites, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2011jd016952, 2012.
Long, M. S., Keene, W. C., Easter, R. C., Sander, R., Liu, X., Kerkweg, A., and Erickson, D.: Sensitivity of tropospheric chemical composition to halogen-radical chemistry using a fully coupled size-resolved multiphase chemistry-global climate system: halogen distributions, aerosol composition, and sensitivity of climate-relevant gases, Atmospheric Chemistry and Physics, 14, 3397-3425, 10.5194/acp-14-3397-2014, 2014.
Lu, X. H., Jiang, H., Zhang, X. Y., Liu, J. X., Zhang, Z., Jin, J. X., Wang, Y., Xu, J. H., and Cheng, M. M.: Estimated global nitrogen deposition using NO2 column density, Int. J. Remote Sens., 34, 8893-8906, 10.1080/01431161.2013.853894, 2013.
Maccarone, A. T., Kirk, B. B., Hansen, C. S., Griffiths, T. M., Olsen, S., Trevitt, A. J., and Blanksby, S. J.: Direct observation of photodissociation products from phenylperoxyl radicals isolated in the gas phase, J Am Chem Soc, 135, 9010-9014, 2013.
MacDonald, S. M., Martin, J. C. G., Chance, R., Warriner, S., Saiz-Lopez, A., Carpenter, L. J., and Plane, J. M. C.: A laboratory characterisation of inorganic iodine emissions from the sea surface: dependence on oceanic variables and parameterisation for global modelling, Atmospheric Chemistry and Physics, 14, 5841-5852, 10.5194/acp-14-5841-2014, 2014.
MacKenzie, A. R., Langford, B., Pugh, T. A. M., Robinson, N., Misztal, P. K., Heard, D. E., Lee, J. D., Lewis, A. C., Jones, C. E., Hopkins, J. R., Phillips, G., Monks, P. S., Karunaharan, A., Hornsby, K. E., Nicolas-Perea, V., Coe, H., Gabey, A. M., Gallagher, M. W., Whalley, L. K., Edwards, P. M., Evans, M. J., Stone, D., Ingham, T., Commane, R., Furneaux, K. L., McQuaid, J. B., Nemitz, E., Seng, Y. K., Fowler, D., Pyle, J. A., and Hewitt, C. N.: The atmospheric chemistry of trace gases and particulate matter emitted by different land uses in Borneo, Philos. Trans. R. Soc. B-Biol. Sci., 366, 3177-3195, 10.1098/rstb.2011.0053, 2011.
Mahajan, A. S., Oetjen, H., Saiz-Lopez, A., Lee, J. D., McFiggans, G. B., and Plane, J. M. C.: Reactive iodine species in a semi-polluted environment, Geophysical Research Letters, 36, 10.1029/2009gl038018, 2009.
Mahajan, A. S., Shaw, M., Oetjen, H., Hornsby, K. E., Carpenter, L. J., Kaleschke, L., Tian-Kunze, X., Lee, J. D., Moller, S. J., Edwards, P., Commane, R., Ingham, T., Heard, D. E., and Plane, J. M. C.: Evidence of reactive iodine chemistry in the Arctic boundary layer, Journal of Geophysical Research-Atmospheres, 115, 10.1029/2009jd013665, 2010.
Manders, A. M. M., van Meijgaard, E., Mues, A. C., Kranenburg, R., van Ulft, L. H., and Schaap, M.: The impact of differences in large-scale circulation output from climate models on the regional modeling of ozone and PM, Atmospheric Chemistry and Physics, 12, 9441-9458, 10.5194/acp-12-9441-2012, 2012.
Mao, J. Q., Paulot, F., Jacob, D. J., Cohen, R. C., Crounse, J. D., Wennberg, P. O., Keller, C. A., Hudman, R. C., Barkley, M. P., and Horowitz, L. W.: Ozone and organic nitrates over the eastern United States: Sensitivity to isoprene chemistry, Journal of Geophysical Research-Atmospheres, 118, 11256-11268, 10.1002/jgrd.50817, 2013.

Marais, E. A., Jacob, D. J., Wecht, K., Lerot, C., Zhang, L., Yu, K., Kurosu, T. P., Chance, K., and Sauvage, B.: Anthropogenic emissions in Nigeria and implications for atmospheric ozone pollution: A view from space, Atmospheric Environment, 99, 32-40, http://dx.doi.org/10.1016/j.atmosenv.2014.09.055, 2014.

Marenco, A., Gouget, H., Nedelec, P., Pages, J. P., and Karcher, F.: Evidence of a long-term increase in tropospehric ozone from Pic Du Midi data series - conswquences - positive radiative forcing, Journal of Geophysical Research-Atmospheres, 99, 16617-16632, 10.1029/94jd00021, 1994.

Mari, C. H., Cailley, G., Corre, L., Saunois, M., Attie, J. L., Thouret, V., and Stohl, A.: Tracing biomass burning plumes from the Southern Hemisphere during the AMMA 2006 wet season experiment, Atmospheric Chemistry and Physics, 8, 3951-3961, 2008.

Marlier, M. E., Voulgarakis, A., Shindell, D. T., Faluvegi, G., Henry, C. L., and Randerson, J. T.: The role of temporal evolution in modeling atmospheric emissions from tropical fires, Atmospheric Environment, 89, 158-168, 10.1016/j.atmosenv.2014.02.039, 2014.

Martin, M. V., Logan, J. A., Kahn, R. A., Leung, F. Y., Nelson, D. L., and Diner, D. J.: Smoke injection heights from fires in North America: analysis of 5 years of satellite observations, Atmospheric Chemistry and Physics, 10, 1491-1510, 2010.

Martin, R. V., Parrish, D. D., Ryerson, T. B., Nicks, D. K., Chance, K., Kurosu, T. P., Jacob, D. J., Sturges, E. D., Fried, A., and Wert, B. P.: Evaluation of GOME satellite measurements of tropospheric NO_2 and HCHO using regional data from aircraft campaigns in the southeastern United States, Journal of Geophysical Research-Atmospheres, 109, D24307, 2004.

Martin, R. V.: Satellite remote sensing of surface air quality, Atmospheric Environment, 42, 7823-7843, 10.1016/j.atmosenv.2008.07.018, 2008.

Martins, V., Miranda, A. I., Carvalho, A., Schaap, M., Borrego, C., and Sa, E.: Impact of forest fires on particulate matter and ozone levels during the 2003, 2004 and 2005 fire seasons in Portugal, Science of the Total Environment, 414, 53-62, 10.1016/j.scitotenv.2011.10.007, 2012.

Matyssek, R., Sandermann, H., Wieser, G., Booker, F., Cieslik, S., Musselman, R., and Ernst, D.: The challenge of making ozone risk assessment for forest trees more mechanistic, Environmental Pollution, 156, 567-582, 10.1016/j.envpol.2008.04.017, 2008.

Matyssek, R., Karnosky, D. F., Wieser, G., Percy, K., Oksanen, E., Grams, T. E. E., Kubiske, M., Hanke, D., and Pretzsch, H.: Advances in understanding ozone impact on forest trees: Messages from novel phytotron and free-air fumigation studies, Environmental Pollution, 158, 1990-2006, 10.1016/j.envpol.2009.11.033, 2010.

McCarthy, M. C., Cheng, L., Crabtree, K. N., Martinez Jr, O., Nguyen, T. L., Womack, C. C., and Stanton, J. F.: The Simplest Criegee Intermediate (H_2CO-O): Isotopic Spectroscopy, Equilibrium Structure, and Possible Formation from Atmospheric Lightning, The Journal of Physical Chemistry Letters, 4, 4133-4139, 2013.

McFiggans, G.: Marine aerosols and iodine emissions, Nature, 433, E13-E13, 10.1038/nature03372, 2005.

McFiggans, G., Bale, C. S. E., Ball, S. M., Beames, J. M., Bloss, W. J., Carpenter, L. J., Dorsey, J., Dunk, R., Flynn, M. J., Furneaux, K. L., Gallagher, M. W., Heard, D. E., Hollingsworth, A. M., Hornsby, K., Ingham, T., Jones, C. E., Jones, R. L., Kramer, L. J., Langridge, J. M., Leblanc, C., LeCrane, J. P., Lee, J. D., Leigh, R. J., Longley, I., Mahajan, A. S., Monks, P. S., Oetjen, H., Orr-Ewing, A. J., Plane, J. M. C., Potin, P., Shillings, A. J. L., Thomas, F., von Glasow, R., Wada, R., Whalley, L. K., and Whitehead, J. D.: Iodine-mediated coastal particle formation: an overview of the Reactive Halogens in the Marine Boundary Layer (RHaMBLe) Roscoff coastal study, Atmospheric Chemistry and Physics, 10, 2975-2999, 10.5194/acp-10-2975-2010, 2010.

McKay, W. A., Stephens, B. A., and Dollard, G. J.: Laboratory measurements of ozone deposition to sea-water and other saline solutions, Atmospheric Environment Part A-General Topics, 26, 3105-3110, 1992.

McLinden, C. A., Olsen, S. C., Hannegan, B., Wild, O., Prather, M. J., and Sundet, J.: Stratospheric ozone in 3-D models: A simple chemistry and the cross-tropopause flux, Journal of Geophysical Research-Atmospheres, 105, 14653-14665, 10.1029/2000jd900124, 2000.

McMeeking, G. R., Bart, M., Chazette, P., Haywood, J. M., Hopkins, J. R., McQuaid, J. B., Morgan, W. T., Raut, J. C., Ryder, C. L., Savage, N., Turnbull, K., and Coe, H.: Airborne measurements of trace gases and aerosols over the London metropolitan region, Atmospheric Chemistry and Physics, 12, 5163-5187, 10.5194/acp-12-5163-2012, 2012.
McPeters, R. D., Labow, G. J., and Logan, J. A.: Ozone climatological profiles for satellite retrieval algorithms, Journal of Geophysical Research: Atmospheres, 112, D05308, 10.1029/2005jd006823, 2007.
Mead, M. I., Popoola, O. A. M., Stewart, G. B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J. J., McLeod, M. W., Hodgson, T. F., Dicks, J., Lewis, A., Cohen, J., Baron, R., Saffell, J. R., and Jones, R. L.: The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks, Atmospheric Environment, 70, 186-203, 10.1016/j.atmosenv.2012.11.060, 2013.
Meleux, F., Solmon, F., and Giorgi, F.: Increase in summer European ozone amounts due to climate change, Atmospheric Environment, 41, 7577-7587, 2007.
Melkonyan, A., and Kuttler, W.: Long-term analysis of NO, NO_2 and O_3 concentrations in North Rhine-Westphalia, Germany, Atmospheric Environment, 60, 316-326, 10.1016/j.atmosenv.2012.06.048, 2012.
Mickley, L. J., Jacob, D., and Rind, D.: Uncertainty in preindustrial abundance of tropospheric ozone: Implications for radiative forcing calculations, J. Geophys. Res., 106, 3389-3399, 2001.
Mielke, L. H., Furgeson, A., and Osthoff, H. D.: Observation of $ClNO_2$ in a Mid-Continental Urban Environment, Environ. Sci. Technol., 45, 8889-8896, 10.1021/es201955u, 2011.
Mielke, L. H., Stutz, J., Tsai, C., Hurlock, S. C., Roberts, J. M., Veres, P. R., Froyd, K. D., Hayes, P. L., Cubison, M. J., Jimenez, J. L., Washenfelder, R. A., Young, C. J., Gilman, J. B., de Gouw, J. A., Flynn, J. H., Grossberg, N., Lefer, B. L., Liu, J., Weber, R. J., and Osthoff, H. D.: Heterogeneous formation of nitryl chloride and its role as a nocturnal NOx reservoir species during CalNex-LA 2010, Journal of Geophysical Research-Atmospheres, 118, 10638-10652, 10.1002/jgrd.50783, 2013.
Mieville, A., Granier, C., Liousse, C., Guillaume, B., Mouillot, F., Lamarque, J. F., Gregoire, J. M., and Petron, G.: Emissions of gases and particles from biomass burning during the 20th century using satellite data and an historical reconstruction, Atmospheric Environment, 44, 1469-1477, 10.1016/j.atmosenv.2010.01.011, 2010.
Miller, S. M., Matross, D. M., Andrews, A. E., Millet, D. B., Longo, M., Gottlieb, E. W., Hirsch, A. I., Gerbig, C., Lin, J. C., Daube, B. C., Hudman, R. C., Dias, P. L. S., Chow, V. Y., and Wofsy, S. C.: Sources of carbon monoxide and formaldehyde in North America determined from high-resolution atmospheric data, Atmospheric Chemistry and Physics, 8, 7673-7696, 2008.
Mills, G., Hayes, F., Simpson, D., Emberson, L., Norris, D., Harmens, H., and Buker, P.: Evidence of widespread effects of ozone on crops and (semi-)natural vegetation in Europe (1990-2006) in relation to AOT40- and flux-based risk maps, Global Change Biology, 17, 592-613, 10.1111/j.1365-2486.2010.02217.x, 2011.
Millstein, D. E., and Harley, R. A.: Impact of climate change on photochemical air pollution in Southern California, Atmos. Chem. Phys., 9, 3745-3754, 10.5194/acp-9-3745-2009, 2009.
Monks, P. S.: A review of the observations and origins of the spring ozone maximum, Atmospheric Environment, 34, 3545-3561, 2000.
Monks, P. S.: Gas-phase radical chemistry in the troposphere, Chemical Society Reviews, 34, 376-395, 2005.
Monks, P. S., Granier, C., Fuzzi, S., Stohl, A., Williams, M. L., Akimoto, H., Amann, M., Baklanov, A., Baltensperger, U., Bey, I., Blake, N., Blake, R. S., Carslaw, K., Cooper, O. R., Dentener, F., Fowler, D., Fragkou, E., Frost, G. J., Generoso, S., Ginoux, P., Grewe, V., Guenther, A., Hansson, H. C., Henne, S., Hjorth, J., Hofzumahaus, A., Huntrieser, H., Isaksen, I. S. A., Jenkin, M. E., Kaiser, J., Kanakidou, M., Klimont, Z., Kulmala, M., Laj, P., Lawrence, M. G., Lee, J. D., Liousse, C., Maione, M., McFiggans, G., Metzger, A., Mieville, A., Moussiopoulos, N., Orlando, J. J., O'Dowd, C. D., Palmer, P. I., Parrish, D. D., Petzold, A., Platt, U., Poeschl, U., Prevot, A. S. H., Reeves, C. E., Reimann, S., Rudich, Y., Sellegri, K., Steinbrecher, R., Simpson, D., ten Brink, H., Theloke, J., van der Werf, G. R., Vautard, R., Vestreng, V.,

Vlachokostas, C., and von Glasow, R.: Atmospheric composition change - global and regional air quality, Atmospheric Environment, 43, 5268-5350, 10.1016/j.atmosenv.2009.08.021, 2009.
Monks, P. S., and Bierle, S.: Applications of Tropospheric Composition Observations from Satellites, in: The Remote Sensing of Tropospheric Composition from Space, edited by: Burrows , J. P., Platt , U., and Borrell, P., Physics of Earth and Space Environments Springer, 536, 2011.
Monks, P. S.: European pollution: Investigate smog to inform policy, Nature, 509, 427-427, 10.1038/509427a

http://www.nature.com/nature/journal/v509/n7501/abs/509427a.html#supplementary-information, 2014.
Monks, S. A., Arnold, S. R., Emmons, L. K., Law, K. S., Turquety, S., Duncan, B. N., Flemming, J., Huijnen, V., Tilmes, S., Langner, J., Mao, J., Long, Y., Thomas, J. L., Steenrod, S. D., Raut, J. C., Wilson, C., Chipperfield, M. P., Schlager, H., and Ancellet, G.: Multi-model study of chemical and physical controls on transport of anthropogenic and biomass burning pollution to the Arctic, Atmos. Chem. Phys. Discuss., 14, 25281-25350, 10.5194/acpd-14-25281-2014, 2014.
Moody, J. L., Oltmans, S. J., Levy, H., and Merrill, J. T.: Transport, climatology of tropospheric ozone - Bermuda, 1988-1991, Journal of Geophysical Research-Atmospheres, 100, 7179-7194, 10.1029/94jd02830, 1995.
Myhre, G., Shindell, D., Bréon, F. M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J. F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H.: Anthropogenic and Natural Radiative Forcing, Cambridge, UK, 2013.
Naddafi, K., Hassanvand, M. S., Yunesian, M., Momeniha, F., Nabizadeh, R., Faridi, S., and Gholampour, A.: Health impact assessment of air pollution in megacity of Tehran, Iran, Iran. J. Environ. Health Sci. Eng., 9, 10.1186/1735-2746-9-28, 2012.
Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T. Y., Kram, T., La Rovere, E. L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H. M., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S. J., Swart, R., van Rooijen, S., Victor, N., and Dadi, Z.: Special Report on Emissions Scenarios : a special report of Working Group III of the Intergovernmental Panel on Climate Change, Other Information: PBD: 3 Oct 2000, Cambridge University Press', New York, Medium: ED; Size: vp. pp., 2000.
Nedelec, P., Thouret, V., Brioude, J., Sauvage, B., Cammas, J. P., and Stohl, A.: Extreme CO concentrations in the upper troposphere over northeast Asia in June 2003 from the in situ MOZAIC aircraft data, Geophysical Research Letters, 32, 10.1029/2005gl023141, 2005.
Neirynck, J., Gielen, B., Janssens, I. A., and Ceulemans, R.: Insights into ozone deposition patterns from decade-long ozone flux measurements over a mixed temperate forest, J. Environ. Monit., 14, 1684-1695, 10.1039/c2em10937a, 2012.
Neu, J. L., Flury, T., Manney, G. L., Santee, M. L., Livesey, N. J., and Worden, J.: Tropospheric ozone variations governed by changes in stratospheric circulation, Nature Geoscience, 7, 340-344, 10.1038/ngeo2138, 2014.
Nisbet, E. G., Dlugokencky, E. J., and Bousquet, P.: Methane on the Rise-Again, Science, 343, 493-495, 10.1126/science.1247828, 2014.
O'Connor, F. M., Johnson, C. E., Morgenstern, O., Abraham, N. L., Braesicke, P., Dalvi, M., Folberth, G. A., Sanderson, M. G., Telford, P. J., Voulgarakis, A., Young, P. J., Zeng, G., Collins, W. J., and Pyle, J. A.: Evaluation of the new UKCA climate-composition model – Part 2: The Troposphere, Geosci. Model Dev., 7, 41-91, 10.5194/gmd-7-41-2014, 2014.
OECD: OECD Environmental Outlook to 2050, OECD Publishing, 2012.
Ohara, T., Akimoto, H., Kurokawa, J., Horii, N., Yamaji, K., Yan, X., and Hayasaka, T.: An Asian emission inventory of anthropogenic emission sources for the period 1980–2020, Atm. Chem. Phys., 7, 4419-4444, 2007.
Ojha, N., Naja, M., Sarangi, T., Kumar, R., Bhardwaj, P., Lal, S., Venkataramani, S., Sagar, R., Kumar, A., and Chandola, H. C.: On the processes influencing the vertical distribution of ozone over the central

Himalayas: Analysis of yearlong ozonesonde observations, Atmospheric Environment, 88, 201-211, http://dx.doi.org/10.1016/j.atmosenv.2014.01.031, 2014.
Olaguer, E. P.: The potential near-source ozone impacts of upstream oil and gas industry emissions, J Air Waste Manage, 62, 966-977, 10.1080/10962247.2012.688923, 2012.
Olivier, J. G. J., Van Aardenne, J. A., Dentener, F. J., Pagliari, V., Ganzeveld, L. N., and Peters, J. A. H. W.: Recent trends in global greenhouse gas emissions:regional trends 1970–2000 and spatial distributionof key sources in 2000, Environmental Sciences, 2, 81-99, 10.1080/15693430500400345, 2005.
Olsen, S. C., Brasseur, G. P., Wuebbles, D. J., Barrett, S. R. H., Dang, H., Eastham, S. D., Jacobson, M. Z., Khodayari, A., Selkirk, H., Sokolov, A., and Unger, N.: Comparison of model estimates of the effects of aviation emissions on atmospheric ozone and methane, Geophysical Research Letters, 2013GL057660, 10.1002/2013gl057660, 2013.
Olson, J. R., Crawford, J. H., Davis, D. D., Chen, G., Avery, M. A., Barrick, J. D. W., Sachse, G. W., Vay, S. A., Sandholm, S. T., Tan, D., Brune, W. H., Faloona, I. C., Heikes, B. G., Shetter, R. E., Lefer, B. L., Singh, H. B., Talbot, R. W., and Blake, D. R.: Seasonal differences in the photochemistry of the South Pacific: A comparison of observations and model results from PEM-Tropics A and B, J. Geophys. Res., 106, 32749-32766, 2001.
Oltmans, S., Schnell, R., Johnson, B., Pétron, G., Mefford, T., and Neely, R., III: Anatomy of wintertime ozone associated with oil and natural gas extraction activity in Wyoming and Utah, Elem. Sci. Anth., 2, 000024, 10.12952/journal.elementa.000024, 2014.
Oltmans, S. J., Lefohn, A. S., Harris, J. M., Galbally, I., Scheel, H. E., Bodeker, G., Brunke, E., Claude, H., Tarasick, D., Johnson, B. J., Simmonds, P., Shadwick, D., Anlauf, K., Hayden, K., Schmidlin, F., Fujimoto, T., Akagi, K., Meyer, C., Nichol, S., Davies, J., Redondas, A., and Cuevas, E.: Long term changes in tropospheric ozone. , Atmos. Environ., 40, 3156-3173., 2006.
Oltmans, S. J., Johnson, B. J., and Harris, J. M.: Springtime boundary layer ozone depletion at Barrow, Alaska: Meteorological influence, year-to-year variation, and long-term change, Journal of Geophysical Research, 117, D00R18, doi:10.1029/2011JD016889, 2012.
Oltmans, S. J., Lefohn, A. S., Shadwick, D., Harris, J. M., Scheel, H. E., Galbally, I., Tarasick, D. W., Johnson, B. J., Brunke, E. G., Claude, H., Zeng, G., Nichol, S., Schmidlin, F., Davies, J., Cuevas, E., Redondas, A., Naoe, H., Nakano, T., and Kawasato, T.: Recent tropospheric ozone changes – A pattern dominated by slow or no growth, Atmospheric Environment, 67, 331-351, http://dx.doi.org/10.1016/j.atmosenv.2012.10.057, 2013.
Oman, L. D., Douglass, A. R., Ziemke, J. R., Rodriguez, J. M., Waugh, D. W., and Nielsen, J. E.: The ozone response to ENSO in Aura satellite measurements and a chemistry-climate simulation, Journal of Geophysical Research-Atmospheres, 118, 965-976, 10.1029/2012jd018546, 2013.
Ordonez, C., Brunner, D., Staehelin, J., Hadjinicolaou, P., Pyle, J. A., Jonas, M., Wernli, H., and Prevot, A. S. H.: Strong influence of lowermost stratospheric ozone on lower tropospheric background ozone changes over Europe, Geophysical Research Letters, 34, L07805, 10.1029/2006gl029113, 2007.
Orlando, J. J., and Tyndall, G. S.: Laboratory studies of organic peroxy radical chemistry: an overview with emphasis on recent issues of atmospheric significance, Chemical Society Reviews, 41, 6294-6317, 10.1039/c2cs35166h, 2012.
Osthoff, H. D., Roberts, J. M., Ravishankara, A. R., Williams, E. J., Lerner, B. M., Sommariva, R., Bates, T. S., Coffman, D., Quinn, P. K., Dibb, J. E., Stark, H., Burkholder, J. B., Talukdar, R. K., Meagher, J., Fehsenfeld, F. C., and Brown, S. S.: High levels of nitryl chloride in the polluted subtropical marine boundary layer, Nature Geoscience, 1, 324-328, 2008.
Ouyang, B., McLeod, M. W., Jones, R. L., and Bloss, W. J.: NO_3 radical production from the reaction between the Criegee intermediate CH_2OO and NO_2, Physical Chemistry Chemical Physics, 15, 17070-17075, 10.1039/c3cp53024h, 2013.
Padro, J.: Observed Characteristics of the Dry Deposition Velocity of O3 and So2 above a Wet Deciduous Forest, Science of the Total Environment, 147, 395-400, 1994.

Palmer, P. I., Jacob, D. J., Fiore, A. M., Martin, R. V., Chance, K., and Kurosu, T. P.: Mapping isoprene emissions over North America using formaldehyde column observations from space, Journal of Geophysical Research-Atmospheres, 108, 2003.

Palmer, P. I., Parrington, M., Lee, J. D., Lewis, A. C., Rickard, A. R., Bernath, P. F., Duck, T. J., Waugh, D. L., Tarasick, D. W., Andrews, S., Aruffo, E., Bailey, L. J., Barrett, E., Bauguitte, S. J. B., Curry, K. R., Di Carlo, P., Chisholm, L., Dan, L., Forster, G., Franklin, J. E., Gibson, M. D., Griffin, D., Helmig, D., Hopkins, J. R., Hopper, J. T., Jenkin, M. E., Kindred, D., Kliever, J., Le Breton, M., Matthiesen, S., Maurice, M., Moller, S., Moore, D. P., Oram, D. E., O'Shea, S. J., Owen, R. C., Pagniello, C., Pawson, S., Percival, C. J., Pierce, J. R., Punjabi, S., Purvis, R. M., Remedios, J. J., Rotermund, K. M., Sakamoto, K. M., da Silva, A. M., Strawbridge, K. B., Strong, K., Taylor, J., Trigwell, R., Tereszchuk, K. A., Walker, K. A., Weaver, D., Whaley, C., and Young, J. C.: Quantifying the impact of BOReal forest fires on Tropospheric oxidants over the Atlantic using Aircraft and Satellites (BORTAS) experiment: design, execution and science overview, Atmospheric Chemistry and Physics, 13, 6239-6261, 10.5194/acp-13-6239-2013, 2013.

Pappin, A. J., and Hakami, A.: Attainment vs Exposure: Ozone Metric Responses to Source-Specific NOx Controls Using Adjoint Sensitivity Analysis, Environ. Sci. Technol., 47, 13519-13527, 10.1021/es4024145, 2013.

Paris, J. D., Stohl, A., Ciais, P., Nedelec, P., Belan, B. D., Arshinov, M. Y., and Ramonet, M.: Source-receptor relationships for airborne measurements of CO2, CO and O-3 above Siberia: a cluster-based approach, Atmospheric Chemistry and Physics, 10, 1671-1687, 2010.

Parrella, J. P., Jacob, D. J., Liang, Q., Zhang, Y., Mickley, L. J., Miller, B., Evans, M. J., Yang, X., Pyle, J. A., Theys, N., and Van Roozendael, M.: Tropospheric bromine chemistry: implications for present and pre-industrial ozone and mercury, Atmospheric Chemistry and Physics, 12, 6723-6740, 10.5194/acp-12-6723-2012, 2012.

Parrington, M., Palmer, P. I., Henze, D. K., Tarasick, D. W., Hyer, E. J., Owen, R. C., Helmig, D., Clerbaux, C., Bowman, K. W., Deeter, M. N., Barratt, E. M., Coheur, P.-F., Hurtmans, D., Jiang, Z., George, M., and Worden, J. R.: The influence of boreal biomass burning emissions on the distribution of tropospheric ozone over North America and the North Atlantic during 2010, Atmos Chem Phys, 12, 2077-2098, 2012.

Parrington, M., Palmer, P. I., Lewis, A. C., Lee, J. D., Rickard, A. R., Di Carlo, P., Taylor, J. W., Hopkins, J. R., Punjabi, S., Oram, D. E., Forster, G., Aruffo, E., Moller, S. J., Bauguitte, S. J. B., Allan, J. D., Coe, H., and Leigh, R. J.: Ozone photochemistry in boreal biomass burning plumes, Atmos. Chem. Phys., 13, 7321-7341, 10.5194/acp-13-7321-2013, 2013.

Parrish, D. D., Millet, D. B., and Goldstein, A. H.: Increasing ozone in marine boundary layer inflow at the west coasts of North America and Europe, Atmos. Chem. Phys., 9, 1303-1323, 10.5194/acp-9-1303-2009, 2009.

Parrish, D. D., and Zhu, T.: Clean Air for Megacities, Science, 326, 674-675, 10.1126/science.1176064, 2009.

Parrish, D. D., Singh, H. B., Molina, L., and Madronich, S.: Air quality progress in North American megacities: A review, Atmospheric Environment, 45, 7015-7025, 10.1016/j.atmosenv.2011.09.039, 2011.

Parrish, D. D., Law, K. S., Staehelin, J., Derwent, R., Cooper, O. R., Tanimoto, H., Volz-Thomas, A., Gilge, S., Scheel, H. E., Steinbacher, M., and Chan, E.: Long-term changes in lower tropospheric baseline ozone concentrations at northern mid-latitudes, Atmospheric Chemistry and Physics, 12, 11485-11504, 10.5194/acp-12-11485-2012, 2012.

Parrish, D. D., Law, K. S., Staehelin, J., Derwent, R., Cooper, O. R., Tanimoto, H., Volz-Thomas, A., Gilge, S., Scheel, H. E., Steinbacher, M., and Chan, E.: Lower tropospheric ozone at northern midlatitudes: Changing seasonal cycle, Geophysical Research Letters, 40, 1631-1636, 10.1002/grl.50303, 2013.

Parrish, D. D., Lamarque, J. F., Naik, V., Horowitz, L., Shindell, D. T., Staehelin, J., Derwent, R., Cooper, O. R., Tanimoto, H., Volz-Thomas, A., Gilge, S., Scheel, H. E., Steinbacher, M., and Frohlich, M.: Long-term changes in lower tropospheric baseline ozone concentrations: Comparing chemistry-climate

models and observations at northern midlatitudes, Journal of Geophysical Research-Atmospheres, 119, 5719-5736, 10.1002/2013jd021435, 2014.
Paulot, F., Crounse, J. D., Kjaergaard, H. G., Kürten, A., Clair, J. M. S., Seinfeld, J. H., and Wennberg, P. O.: Unexpected epoxide formation in the gas-phase photooxidation of isoprene, Science, 325, 730-733, 2009.
Paulot, F., Henze, D. K., and Wennberg, P. O.: Impact of the isoprene photochemical cascade on tropical ozone, Atmospheric Chemistry and Physics, 12, 1307-1325, 10.5194/acp-12-1307-2012, 2012.
Pausata, F. S. R., Pozzoli, L., Vignati, E., and Dentener, F. J.: North Atlantic Oscillation and tropospheric ozone variability in Europe: model analysis and measurements intercomparison, Atmos. Chem. Phys., 12, 6537-6376, doi:10.5194/acp-12-6357-2012, 2012.
Pechtl, S., and von Glasow, R.: Reactive chlorine in the marine boundary layer in the outflow of polluted continental air: A model study, Geophysical Research Letters, 34, 10.1029/2007gl029761, 2007.
Peeters, J., Nguyen, T. L., and Vereecken, L.: HOx radical regeneration in the oxidation of isoprene, Phys. Chem. Chem Phys., 11, 5935 - 5939, 2009.
Petron, G., Granier, C., Khattatov, B., Yudin, V., Lamarque, J. F., Emmons, L., Gille, J., and Edwards, D. P.: Monthly CO surface sources inventory based on the 2000-2001 MOPITT satellite data, Geophysical Research Letters, 31, 10.1029/2004gl020560, 2004.
Pétron, G., Frost, G., Miller, B. R., Hirsch, A. I., Montzka, S. A., Karion, A., Trainer, M., Sweeney, C., Andrews, A. E., Miller, L., Kofler, J., Bar-Ilan, A., Dlugokencky, E. J., Patrick, L., Moore, C. T., Ryerson, T. B., Siso, C., Kolodzey, W., Lang, P. M., Conway, T., Novelli, P., Masarie, K., Hall, B., Guenther, D., Kitzis, D., Miller, J., Welsh, D., Wolfe, D., Neff, W., and Tans, P.: Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study, Journal of Geophysical Research: Atmospheres, 117, D04304, 10.1029/2011jd016360, 2012.
Pfister, G., Hess, P. G., Emmons, L. K., Lamarque, J. F., Wiedinmyer, C., Edwards, D. P., Petron, G., Gille, J. C., and Sachse, G. W.: Quantifying CO emissions from the 2004 Alaskan wildfires using MOPITT CO data, Geophysical Research Letters, 32, 10.1029/2005gl022995, 2005.
Phillips, G. J., Tang, M. J., Thieser, J., Brickwedde, B., Schuster, G., Bohn, B., Lelieveld, J., and Crowley, J. N.: Significant concentrations of nitryl chloride observed in rural continental Europe associated with the influence of sea salt chloride and anthropogenic emissions, Geophysical Research Letters, 39, 10.1029/2012gl051912, 2012.
Piedrahita, R., Xiang, Y., Masson, N., Ortega, J., Collier, A., Jiang, Y., Li, K., Dick, R. P., Lv, Q., Hannigan, M., and Shang, L.: The next generation of low-cost personal air quality sensors for quantitative exposure monitoring, Atmos. Meas. Tech., 7, 3325-3336, 10.5194/amt-7-3325-2014, 2014.
Pleijel, H., Karlsson, G. P., Danielsson, H., and Sellden, G.: Surface wetness enhances ozone deposition to a pasture canopy, Atmospheric Environment, 29, 3391-3393, 1995.
Pohler, D., Vogel, L., Friess, U., and Platt, U.: Observation of halogen species in the Amundsen Gulf, Arctic, by active long-path differential optical absorption spectroscopy, Proc. Natl. Acad. Sci. U. S. A., 107, 6582-6587, 10.1073/pnas.0912231107, 2010.
Pommier, M., Mc Linden, C. A., Neuman, J. A., and Nowak, J. B.: Biomass burning in Siberia as a source of BrO to the Arctic free troposphere, Atmospheric Environment, 62, 416-423, 10.1016/j.atmosenv.2012.08.070, 2012.
Prather, M. J., Zhu, X., Tang, Q., Hsu, J. N., and Neu, J. L.: An atmospheric chemist in search of the tropopause, Journal of Geophysical Research-Atmospheres, 116, 10.1029/2010jd014939, 2011.
Price, C., and Rind, D.: A simple lightning parameterization for calculating global lightning distributions, J. Geophys. Res., 97, 9919-9933, 1992.
Puentedura, O., Gil, M., Saiz-Lopez, A., Hay, T., Navarro-Comas, M., Gomez-Pelaez, A., Cuevas, E., Iglesias, J., and Gomez, L.: Iodine monoxide in the north subtropical free troposphere, Atmospheric Chemistry and Physics, 12, 4909-4921, 10.5194/acp-12-4909-2012, 2012.
Rama Gopal, K., Lingaswamy, A. P., Arafath, S. M., Balakrishnaiah, G., Pavan Kumari, S., Uma Devi, K., Siva Kumar Reddy, N., Raja Obul Reddy, K., Reddy, R. R., Abdul Azeem, P., and Lal, S.: Seasonal

heterogeneity in ozone and its precursors (NOx) by in-situ and model observations on semi-arid station in Anantapur (A.P), South India, Atmospheric Environment, 84, 294-306, http://dx.doi.org/10.1016/j.atmosenv.2013.10.014, 2014.
Rasmussen, D. J., Hu, J. L., Mahmud, A., and Kleeman, M. J.: The Ozone-Climate Penalty: Past, Present, and Future, Environ. Sci. Technol., 47, 14258-14266, 10.1021/es403446m, 2013.
Read, K. A., Mahajan, A. S., Carpenter, L. J., Evans, M. J., Faria, B. V. E., Heard, D. E., Hopkins, J. R., Lee, J. D., Moller, S. J., Lewis, A. C., Mendes, L., McQuaid, J. B., Oetjen, H., Saiz-Lopez, A., Pilling, M. J., and Plane, J. M. C.: Extensive halogen-mediated ozone destruction over the tropical Atlantic Ocean, Nature, 453, 1232-1235, 2008.
Real, E., Law, K. S., Weinzierl, B., Fiebig, M., Petzold, A., Wild, O., Methven, J., Arnold, S., Stohl, A., Huntrierser, H., Roiger, A., Schlager, H., Stewart D. , Avery, M., Sachse, G., Browell, E., Ferrare, R., and Blake, D.: Processes influencing ozone levels in Alaskan forest fire plumes during long-range transport over the North Atlantic, J. Geophys. Res., 112, D10S41, doi:10.1029/2006JD007576, 2007.
Redelsperger, J. L., Thorncroft, C. D., Diedhiou, A., Lebel, T., Parker, D. J., and Polcher, J.: African monsoon multidisciplinary analysis - An international research project and field campaign, Bulletin of the American Meteorological Society, 87, 1739-+, 10.1175/bams-87-12-1739, 2006.
Reeve, N., and Toumi, R.: Lightning activity as an indicator of climate change, Quarterly Journal of the Royal Meteorological Society, 125, 893-903, 10.1002/qj.49712555507, 1999.
Reeves, C. E., Formenti, P., Afif, C., Ancellet, G., Attie, J. L., Bechara, J., Borbon, A., Cairo, F., Coe, H., Crumeyrolle, S., Fierli, F., Flamant, C., Gomes, L., Hamburger, T., Jambert, C., Law, K. S., Mari, C., Jones, R. L., Matsuki, A., Mead, M. I., Methven, J., Mills, G. P., Minikin, A., Murphy, J. G., Nielsen, J. K., Oram, D. E., Parker, D. J., Richter, A., Schlager, H., Schwarzenboeck, A., and Thouret, V.: Chemical and aerosol characterisation of the troposphere over West Africa during the monsoon period as part of AMMA, Atmospheric Chemistry and Physics, 10, 7575-7601, 10.5194/acp-10-7575-2010, 2010.
Reich, P. B., and Amundson, R. G.: Ambient levels of ozone reduce net photosynthesis in tree and crop species., Science, 230, 566-570., 1985.
Reidmiller, D. R., Fiore, A. M., Jaffe, D. A., Bergmann, D., Cuvelier, C., Dentener, F. J., Duncan, B. N., Folberth, G., Gauss, M., Gong, S., Hess, P., Jonson, J. E., Keating, T., Lupu, A., Marmer, E., Park, R., Schultz, M. G., Shindell, D. T., Szopa, S., Vivanco, M. G., Wild, O., and Zuber, A.: The influence of foreign vs. North American emissions on surface ozone in the US, Atmospheric Chemistry and Physics, 9, 5027-5042, 2009.
Riahi, K., Dentener, F., Gielen, D., Grubler, A., Jewell, J., Klimont, Z., Krey, V., McCollum, D., Pachauri, S., Rao, S., van Ruijven, B., van Vuuren, D. P., and Wilson, C.: Energy Pathways for Sustainable Development, in: Global Energy Assessment: Toward a Sustainable Future, edited by: Nakicenovic, N., IIASA, Laxenburg, Austria and Cambridge University Press, Cambridge, United Kingdom and New York, NY, 2012.
Riedel, T. P., Bertram, T. H., Crisp, T. A., Williams, E. J., Lerner, B. M., Vlasenko, A., Li, S.-M., Gilman, J., de Gouw, J., Bon, D. M., Wagner, N. L., Brown, S. S., and Thornton, J. A.: Nitryl Chloride and Molecular Chlorine in the Coastal Marine Boundary Layer, Environ. Sci. Technol., 46, 10463-10470, 10.1021/es204632r, 2012.
Riedel, T. P., Wagner, N. L., Dube, W. P., Middlebrook, A. M., Young, C. J., Ozturk, F., Bahreini, R., VandenBoer, T. C., Wolfe, D. E., Williams, E. J., Roberts, J. M., Brown, S. S., and Thornton, J. A.: Chlorine activation within urban or power plant plumes: Vertically resolved $ClNO_2$ and Cl_2 measurements from a tall tower in a polluted continental setting, Journal of Geophysical Research-Atmospheres, 118, 8702-8715, 10.1002/jgrd.50637, 2013.
Rodriguez, M. A., Barna, M. G., and Moore, T.: Regional Impacts of Oil and Gas Development on Ozone Formation in the Western United States, J Air Waste Manage, 59, 1111-1118, 10.3155/1047-3289.59.9.1111, 2009.
Rondon, A., Johansson, C., and Granat, L.: Dry Deposition of Nitrogen-Dioxide and Ozone to Coniferous Forests, Journal of Geophysical Research-Atmospheres, 98, 5159-5172, 1993.
Roscoe, H. K., Brough, N., Jones, A. E., Wittrock, F., Richter, A., Van Roozendael, M., and Hendrick, F.: Characterisation of vertical BrO distribution during events of enhanced tropospheric BrO in

Antarctica, from combined remote and in-situ measurements, Journal of Quantitative Spectroscopy & Radiative Transfer, 138, 70-81, 10.1016/j.jqsrt.2014.01.026, 2014.
Royal Society: Ground-level ozone in the 21st century: future trends, impacts and policy implications., The Royal Society, London, 2008.
Rypdal, K., Berntsen, T., Fuglestvedt, J. S., Aunan, K., Torvanger, A., Stordal, F., Pacyna, J. M., and Nygaard, L. P.: Tropospheric ozone and aerosols in climate agreements: scientific and political challenges, Environ. Sci. Policy, 8, 29-43, 10.1016/j.envsci.2004.09.003, 2005.
Sahu, S. K., Beig, G., and Parkhi, N. S.: Emerging pattern of anthropogenic NOx emission over Indian subcontinent during 1990s and 2000s, Atmos. Pollut. Res., 3, 262-269, 10.5094/apr.2012.021, 2012.
Saide, P., Bocquet, M., Osses, A., and Gallardo, L.: Constraining surface emissions of air pollutants using inverse modelling: method intercomparison and a new two-step two-scale regularization approach, Tellus Series B-Chemical and Physical Meteorology, 63, 360-370, 10.1111/j.1600-0889.2011.00529.x, 2011.
Saiz-Lopez, A., Plane, J. M. C., Mahajan, A. S., Anderson, P. S., Bauguitte, S. J. B., Jones, A. E., Roscoe, H. K., Salmon, R. A., Bloss, W. J., Lee, J. D., and Heard, D. E.: On the vertical distribution of boundary layer halogens over coastal Antarctica: implications for O-3, HOx, NOx and the Hg lifetime, Atmospheric Chemistry and Physics, 8, 887-900, 10.5194/acp-8-887-2008, 2008.
Saiz-Lopez, A., Plane, J. M., Baker, A. R., Carpenter, L. J., von Glasow, R., Gómez Martín, J. C., McFiggans, G., and Saunders, R. W.: Atmospheric chemistry of iodine, Chemical reviews, 112, 1773-1804, 2011.
Saiz-Lopez, A., Lamarque, J. F., Kinnison, D. E., Tilmes, S., Ordonez, C., Orlando, J. J., Conley, A. J., Plane, J. M. C., Mahajan, A. S., Santos, G. S., Atlas, E. L., Blake, D. R., Sander, S. P., Schauffler, S., Thompson, A. M., and Brasseur, G.: Estimating the climate significance of halogen-driven ozone loss in the tropical marine troposphere, Atmospheric Chemistry and Physics, 12, 3939-3949, 10.5194/acp-12-3939-2012, 2012a.
Saiz-Lopez, A., Plane, J. M. C., Baker, A. R., Carpenter, L. J., von Glasow, R., Martin, J. C. G., McFiggans, G., and Saunders, R. W.: Atmospheric Chemistry of Iodine, Chemical Reviews, 112, 1773-1804, 10.1021/cr200029u, 2012b.
Saiz-Lopez, A., and von Glasow, R.: Reactive halogen chemistry in the troposphere, Chemical Society Reviews, 41, 6448-6472, 10.1039/c2cs35208g, 2012.
Salawitch, R. J., Canty, T., Kurosu, T., Chance, K., Liang, Q., da Silva, A., Pawson, S., Nielsen, J. E., Rodriguez, J. M., Bhartia, P. K., Liu, X., Huey, L. G., Liao, J., Stickel, R. E., Tanner, D. J., Dibb, J. E., Simpson, W. R., Donohoue, D., Weinheimer, A., Flocke, F., Knapp, D., Montzka, D., Neuman, J. A., Nowak, J. B., Ryerson, T. B., Oltmans, S., Blake, D. R., Atlas, E. L., Kinnison, D. E., Tilmes, S., Pan, L. L., Hendrick, F., Van Roozendael, M., Kreher, K., Johnston, P. V., Gao, R. S., Johnson, B., Bui, T. P., Chen, G., Pierce, R. B., Crawford, J. H., and Jacob, D. J.: A new interpretation of total column BrO during Arctic spring, Geophysical Research Letters, 37, 10.1029/2010gl043798, 2010.
Sanchez-Ccoyllo, O. R., Silva Dias, P. L., Andrade, M. D., and Freitas, S. R.: Determination of O_3, CO and PM10 transport in the metropolitan area of Sao Paulo, Brazil through synoptic-scale analysis of back trajectories, Meteorology and Atmospheric Physics, 92, 83-93, 10.1007/s00703-005-0139-6, 2006.
Sanchez, M. L., Rodriguez, R., and Lopez, A.: Ozone dry deposition in a semi-arid steppe and in a coniferous forest in southern Europe, Journal of the Air & Waste Management Association, 47, 792-799, 1997.
Sander, R., Keene, W. C., Pszenny, A. A. P., Arimoto, R., Ayers, G. P., Baboukas, E., Cainey, J. M., Crutzen, P. J., Duce, R. A., H¨onninger, G., Huebert, B. J., Maenhaut, W., Mihalopoulos, N., Turekian, V. C., and Dingenen, R. V.: Inorganic bromine compounds in the marine boundary layer: A critical review, Atmos. Chem. Phys., 3 1301 – 1336, 2003.
Sanderson, M. G., Jones, C. D., Collins, W. J., Johnson, C. E., and Derwent, R. G.: Effect of climate change on isoprene emissions and surface ozone levels, Geophysical Research Letters, 30, 10.1029/2003gl017642, 2003.

Sarwar, G., Simon, H., Bhave, P., and Yarwood, G.: Examining the impact of heterogeneous nitryl chloride production on air quality across the United States, Atmospheric Chemistry and Physics, 12, 6455-6473, 10.5194/acp-12-6455-2012, 2012.
Sauvage, B., Thouret, V., Cammas, J. P., Gheusi, F., Athier, G., and Nedelec, P.: Tropospheric ozone over Equatorial Africa: regional aspects from the MOZAIC data, Atmos. Chem. Phys., 5, 311-335, 2005.
Sauvage, B., Thouret, V., Thompson, A. M., Witte, J. C., Cammas, J. P., Nedelec, P., and Athier, G.: Enhanced view of the "tropical Atlantic ozone paradox" and "zonal wave one" from the in situ MOZAIC and SHADOZ data, J. Geophys. Res. , 111, D01301, doi:10.1029/2005JD006241, 2006.
Sauvage, B., Martin, R. V., van Donkelaar, A., and Ziemke, J. R.: Quantification of the factors controlling tropical tropospheric ozone and the South Atlantic maximum, J. Geophys. Res., 112, D11309, doi:10.1029/2006JD008008, 2007a.
Sauvage, B., Thouret, V., Cammas, J. P., Brioude, J., Nedelec, P., and Mari, C.: Meridional ozone gradients in the African upper troposphere, Geophys. Res. Lett., 34, L03817, doi:10.1029/2006GL028542, 2007b.
Saylor, R. D., and Stein, A. F.: Identifying the causes of differences in ozone production from the CB05 and CBMIV chemical mechanisms, Geosci. Model Dev., 5, 257-268, 10.5194/gmd-5-257-2012, 2012.
Schneising, O., Burrows, J. P., Dickerson, R. R., Buchwitz, M., Reuter, M., and Bovensmann, H.: Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations, Earth's Future, 2014EF000265, 10.1002/2014ef000265, 2014.
Schnell, R. C., Oltmans, S. J., Neely, R. R., Endres, M. S., Molenar, J. V., and White, A. B.: Rapid photochemical production of ozone at high concentrations in a rural site during winter, Nature Geoscience, 2, 120-122, 10.1038/ngeo415, 2009.
Schönbein, C. F.: Über die Natur eigenthümlichen Grueches, welcher sich sowohl am positiven Pole einer Saüle während der Wasserelektrolys, wie auch beim Ausströmen der gewöhnlichen Elektrizität aus Spotzen entwickelt, Ann. Phys., 135, 1843.
Schultz, M., Rast, S., van het Bolscher, M., Pulles, T., Brand, R., Pereira, J., Mota, B., Spessa, A., Dalsøren, S., van Nojie, T., and Szopa, S.: Emission data sets and methodologies for estimating emissions,, Juelich, 2007a.
Schultz, M. G., Backman, L., Balkanski, Y., Bjoerndalsaeter, S., Brand, R., Burrows, J. P., Dalsoeren, S., Vasconcelos, M. d., Grodtmann, B., Hauglustaine, D. A., Heil, A., Hoelzemann, J. J., I.S.A. Isaksen, Kaurola, J., Knorr, W., Ladstaetter-Weißenmayer, A., Mota, B., Oom, D., Pacyna, J., Panasiuk, D., Pereira, J. M. C., Pulles, T., Pyle, J., Rast, S., Richter, A., Savage, N., Schnadt, C., Schulz, M., Spessa, A., Stachelin, J., Sundet, J. K., Szopa, S., Thonicke, K., Bolscher, M. v. h., Noije, T. v., Velthoven, P. v., Vik, A. F., and Wittrock, F.: REanalysis of the TROpospheric chemical composition over the past 40 years (RETRO) — A long-term global modeling study of tropospheric chemistry - Final Report, Jülich/Hamburg, Germany, 2007b.
Schultz, M. G., Heil, A., Hoelzemann, J. J., Spessa, A., Thonicke, K., Goldammer, J., Held, A. C., and Pereira, J. M.: Global Emissions from Wildland Fires from 1960 to 2000, Global Biogeochem. Cycles, 22, GB2002, doi:10.1029/2007GB003031., 2008.
Schumann, U., and Huntrieser, H.: The global lightning-induced nitrogen oxides source, Atmos. Chem. and Phys., 7, 3823-3907, 2007.
Sekiya, T., and Sudo, K.: Roles of transport and chemistry processes in global ozone change on interannual and multidecadal time scales, Journal of Geophysical Research-Atmospheres, 119, 4903-4921, 10.1002/2013jd020838, 2014.
Sellitto, P., Dufour, G., Eremenko, M., Cuesta, J., Dauphin, P., Foret, G., Gaubert, B., Beekmann, M., Peuch, V. H., and Flaud, J. M.: Analysis of the potential of one possible instrumental configuration of the next generation of IASI instruments to monitor lower tropospheric ozone, Atmos. Meas. Tech., 6, 621-635, 10.5194/amt-6-621-2013, 2013.
Sheps, L.: Absolute Ultraviolet Absorption Spectrum of a Criegee Intermediate CH2OO, The Journal of Physical Chemistry Letters, 4, 4201-4205, 2013.

Shindell, D., Faluvegi, G., Lacis, A., Hansen, J., Ruedy, R., and Aguilar, E.: Role of tropospheric ozone increases in 20th-century climate change, Journal of Geophysical Research-Atmospheres, 111, 10.1029/2005jd006348, 2006.
Shindell, D.: Local and remote contributions to Arctic warming, Geophysical Research Letters, 34, 10.1029/2007gl030221, 2007.
Shindell, D., Schulz, M., Ming, Y., Takemura, T., Faluvegi, G., and Ramaswamy, V.: Spatial scales of climate response to inhomogeneous radiative forcing, Journal of Geophysical Research-Atmospheres, 115, 10.1029/2010jd014108, 2010.
Shindell, D., Kuylenstierna, J. C. I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S. C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, N. T. K., Milly, G., Williams, M., Demkine, V., and Fowler, D.: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security, Science, 335, 183-189, 10.1126/science.1210026, 2012.
Shindell, D. T., Faluvegi, G., Bell, N., and Schmidt, G. A.: An emissions-based view of climate forcing by methane and tropospheric ozone, Geophysical Research Letters, 32, 10.1029/2004gl021900, 2005.
Shindell, D. T., Chin, M., Dentener, F., Doherty, R. M., Faluvegi, G., Fiore, A. M., Hess, P., Koch, D. M., MacKenzie, I. A., Sanderson, M. G., Schultz, M. G., Schulz, M., Stevenson, D. S., Teich, H., Textor, C., Wild, O., Bergmann, D. J., Bey, I., Bian, H., Cuvelier, C., Duncan, B. N., Folberth, G., Horowitz, L. W., Jonson, J., Kaminski, J. W., Marmer, E., Park, R., Pringle, K. J., Schroeder, S., Szopa, S., Takemura, T., Zeng, G., Keating, T. J., and Zuber, A.: A multi-model assessment of pollution transport to the Arctic, Atmospheric Chemistry and Physics, 8, 5353-5372, 2008.
Shindell, D. T., Faluvegi, G., Koch, D. M., Schmidt, G. A., Unger, N., and Bauer, S. E.: Improved Attribution of Climate Forcing to Emissions, Science, 326, 716-718, 10.1126/science.1174760, 2009.
Shindell, D. T., Lamarque, J. F., Schulz, M., Flanner, M., Jiao, C., Chin, M., Young, P. J., Lee, Y. H., Rotstayn, L., Mahowald, N., Milly, G., Faluvegi, G., Balkanski, Y., Collins, W. J., Conley, A. J., Dalsoren, S., Easter, R., Ghan, S., Horowitz, L., Liu, X., Myhre, G., Nagashima, T., Naik, V., Rumbold, S. T., Skeie, R., Sudo, K., Szopa, S., Takemura, T., Voulgarakis, A., Yoon, J. H., and Lo, F.: Radiative forcing in the ACCMIP historical and future climate simulations, Atmospheric Chemistry and Physics, 13, 2939-2974, 10.5194/acp-13-2939-2013, 2013.
Shindell, D. T.: Inhomogeneous forcing and transient climate sensitivity, Nat. Clim. Chang., 4, 274-277, 10.1038/nclimate2136, 2014.
Sicard, P., De Marco, A., Troussier, F., Renou, C., Vas, N., and Paoletti, E.: Decrease in surface ozone concentrations at Mediterranean remote sites and increase in the cities, Atmospheric Environment, 79, 705-715, 10.1016/j.atmosenv.2013.07.042, 2013.
Siegert, F., Ruecker, G., Hinrichs, A., and Hoffmann, A. A.: Increased damage from fires in logged forests during droughts caused by El Nino, Nature, 414, 437-440, 10.1038/35106547, 2001.
Silva, G. d., Graham, C., and Wang, Z.-F.: Unimolecular β-hydroxyperoxy radical decomposition with OH recycling in the photochemical oxidation of isoprene, Environ. Sci. Technol., 44, 250-256, 2009.
Silva, R. A., West, J. J., Zhang, Y., Anenberg, S. C., Lamarque, J.-F., Shindell, D. T., Collins, W. J., Dalsoren, S., Faluvegi, G., Folberth, G., Horowitz, L. W., Nagashima, T., Naik, V., Rumbold, S., Skeie, R., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Cionni, I., Doherty, R. M., Eyring, V., Josse, B., MacKenzie, I. A., Plummer, D., Righi, M., Stevenson, D. S., Strode, S., Szopa, S., and Zeng, G.: Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change, Environmental Research Letters, 8, 10.1088/1748-9326/8/3/034005, 2013.
Simmonds, P. G., Derwent, R. G., Manning, A. L., and Spain, G.: Significant growth in surface ozone at Mace Head, Ireland, 1987-2003, Atmos. Environ., 38, 4769-4778, 2004.
Simon, H., Kimura, Y., McGaughey, G., Allen, D. T., Brown, S. S., Osthoff, H. D., Roberts, J. M., Byun, D., and Lee, D.: Modeling the impact of ClNO2 on ozone formation in the Houston area, Journal of Geophysical Research-Atmospheres, 114, 10.1029/2008jd010732, 2009.
Simon, H., Kimura, Y., McGaughey, G., Allen, D. T., Brown, S. S., Coffman, D., Dibb, J., Osthoff, H. D., Quinn, P., Roberts, J. M., Yarwood, G., Kemball-Cook, S., Byun, D., and Lee, D.: Modeling

heterogeneous ClNO2 formation, chloride availability, and chlorine cycling in Southeast Texas, Atmospheric Environment, 44, 5476-5488, 10.1016/j.atmosenv.2009.09.006, 2010.
Simpson, D., Arneth, A., Mills, G., Solberg, S., and Uddling, J.: Ozone — the persistent menace: interactions with the N cycle and climate change, Current Opinion in Environmental Sustainability, 9–10, 9-19, http://dx.doi.org/10.1016/j.cosust.2014.07.008, 2014.
Simpson, W. R., von Glasow, R., Riedel, K., Anderson, P., Ariya, P., Bottenheim, J., Burrows, J., Carpenter, L. J., Frieß, U., Goodsite, M. E., Heard, D., Hutterli, M., Jacobi, H.-W., Kaleschke, L., Neff, B., Plane, J., Platt, U., Richter, A., Roscoe, H., Sander, R., Shepson, P., Sodeau, J., Steffen, A., Wagner, A., and Wolff, E.: Halogens and their role in polar boundary-layer ozone depletion, Atmos. Chem. Phys., 7, 4375-4418, 2007.
Sindelarova, K., Granier, C., Bouarar, I., Guenther, A., Tilmes, S., Stavrakou, T., Müller, J. F., Kuhn, U., Stefani, P., and Knorr, W.: Global data set of biogenic VOC emissions calculated by the MEGAN model over the last 30 years, Atmos. Chem. Phys., 14, 9317-9341, 10.5194/acp-14-9317-2014, 2014.
Singh, H. B., Anderson, B. E., Brune, W. H., Cai, C., Cohen, R. C., Crawford, J. H., Cubison, M. J., Czech, E. P., Emmons, L., Fuelberg, H. E., Huey, G., Jacob, D. J., Jimenez, J. L., Kaduwela, A., Kondo, Y., Mao, J., Olson, J. R., Sachse, G. W., Vay, S. A., Weinheimer, A., Wennberg, P. O., Wisthaler, A., and Team, A. S.: Pollution influences on atmospheric composition and chemistry at high northern latitudes: Boreal and California forest fire emissions, Atmospheric Environment, 44, 4553-4564, 10.1016/j.atmosenv.2010.08.026, 2010.
Siour, G., Colette, A., Menut, L., Bessagnet, B., Coll, I., and Meleux, F.: Bridging the scales in a eulerian air quality model to assess megacity export of pollution, Environ. Modell. Softw., 46, 271-282, 10.1016/j.envsoft.2013.04.001, 2013.
Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Global Change Biology, 9, 161-185, 10.1046/j.1365-2486.2003.00569.x, 2003.
Sitch, S., Cox, P. M., Collins, W. J., and Huntingford, C.: Indirect radiative forcing of climate change through ozone effects on the land-carbon sink, Nature, 448, 791-U794, 10.1038/nature06059, 2007.
Situ, S., Guenther, A., Wang, X., Jiang, X., Turnipseed, A., Wu, Z., Bai, J., and Wang, X.: Impacts of seasonal and regional variability in biogenic VOC emissions on surface ozone in the Pearl River delta region, China, Atmospheric Chemistry and Physics, 13, 11803-11817, 10.5194/acp-13-11803-2013, 2013.
Skeie, R. B., Berntsen, T. K., Myhre, G., Tanaka, K., Kvalevag, M. M., and Hoyle, C. R.: Anthropogenic radiative forcing time series from pre-industrial times until 2010, Atmospheric Chemistry and Physics, 11, 11827-11857, 10.5194/acp-11-11827-2011, 2011.
Smith, K. R., Jerrett, M., Anderson, H. R., Burnett, R. T., Stone, V., Derwent, R., Atkinson, R. W., Cohen, A., Shonkoff, S. B., Krewski, D., Pope, C. A., Thun, M. J., and Thurston, G.: Health and Climate Change 5 Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants, Lancet, 374, 2091-2103, 10.1016/s0140-6736(09)61716-5, 2009.
Smoydzin, L., and von Glasow, R.: Modelling chemistry over the Dead Sea: bromine and ozone chemistry, Atmospheric Chemistry and Physics, 9, 5057-5072, 2009.
Snyder, E. G., Watkins, T. H., Solomon, P. A., Thoma, E. D., Williams, R. W., Hagler, G. S. W., Shelow, D., Hindin, D. A., Kilaru, V. J., and Preuss, P. W.: The Changing Paradigm of Air Pollution Monitoring, Environ. Sci. Technol., 47, 11369-11377, 10.1021/es4022602, 2013.
Sofiev, M., Vankevich, R., Lotjonen, M., Prank, M., Petukhov, V., Ermakova, T., Koskinen, J., and Kukkonen, J.: An operational system for the assimilation of the satellite information on wild-land fires for the needs of air quality modelling and forecasting, Atmospheric Chemistry and Physics, 9, 6833-6847, 2009.
Sofiev, M., Vankevich, R., Ermakova, T., and Hakkarainen, J.: Global mapping of maximum emission heights and resulting vertical profiles of wildfire emissions, Atmospheric Chemistry and Physics, 13, 7039-7052, 10.5194/acp-13-7039-2013, 2013.

Sommariva, R., Bloss, W. J., and von Glasow, R.: Uncertainties in gas-phase atmospheric iodine chemistry, Atmospheric Environment, 57, 219-232, 10.1016/j.atmosenv.2012.04.032, 2012.
Sommariva, R., and von Glasow, R.: Multiphase Halogen Chemistry in the Tropical Atlantic Ocean, Environ. Sci. Technol., 46, 10429-10437, 10.1021/es300209f, 2012.
Sommariva, R., Blake, R. S., Cuss, R. J., Cordell, R. L., Harrington, J. F., White, I. R., and Monks, P. S.: Observations of the Release of Non-methane Hydrocarbons from Fractured Shale, Environ. Sci. Technol., 48, 8891-8896, 10.1021/es502508w, 2014.
Staehelin, J., Thudium, J., Buehler, R., Volzthomas, A., and Graber, W.: Trends in surface ozone concetrations at Arosa (Switzerland), Atmospheric Environment, 28, 75-87, 1994.
Staehelin, J.: Ozone Measurements and Trends (Troposphere), in: Encyclopedia of Physical Science and Technology (Third Edition), edited by: Meyers, R. A., Academic Press, New York, 539-561, 2003.
Stavrakou, T., Muller, J. F., Boersma, K. F., De Smedt, I., and van der A, R. J.: Assessing the distribution and growth rates of NOx emission sources by inverting a 10-year record of NO_2 satellite columns, Geophysical Research Letters, 35, L10801, 2008.
Stavrakou, T., Muller, J. F., De Smedt, I., Van Roozendael, M., van der Werf, G. R., Giglio, L., and Guenther, A.: Evaluating the performance of pyrogenic and biogenic emission inventories against one decade of space-based formaldehyde columns, Atmospheric Chemistry and Physics, 9, 1037-1060, 2009.
Stavrakou, T., Guenther, A., Razavi, A., Clarisse, L., Clerbaux, C., Coheur, P. F., Hurtmans, D., Karagulian, F., De Maziere, M., Vigouroux, C., Amelynck, C., Schoon, N., Laffineur, Q., Heinesch, B., Aubinet, M., Rinsland, C., and Muller, J. F.: First space-based derivation of the global atmospheric methanol emission fluxes, Atmospheric Chemistry and Physics, 11, 4873-4898, 10.5194/acp-11-4873-2011, 2011.
Stedman, J. R.: The predicted number of air pollution related deaths in the UK during the August 2003 heatwave, Atmos. Environ., 3, 1087-1090, 2004.
Stein, O., Schultz, M. G., Bouarar, I., Clark, H., Huijnen, V., Gaudel, A., George, M., and Clerbaux, C.: On the wintertime low bias of Northern Hemisphere carbon monoxide found in global model simulations, Atmos. Chem. Phys., 14, 9295-9316, 10.5194/acp-14-9295-2014, 2014.
Stella, P., Personne, E., Loubet, B., Lamaud, E., Ceschia, E., Beziat, P., Bonnefond, J. M., Irvine, M., Keravec, P., Mascher, N., and Cellier, P.: Predicting and partitioning ozone fluxes to maize crops from sowing to harvest: the Surfatm-O-3 model, Biogeosciences, 8, 2869-2886, 10.5194/bg-8-2869-2011, 2011.
Stevenson, D., Doherty, R., Sanderson, M., Johnson, C., Collins, B., and Derwent, D.: Impacts of climate change and variability on tropospheric ozone and its precursors, Faraday Discussions, 130, 41-57, 10.1039/b417412g, 2005.
Stevenson, D. S., Dentener, F. J., Schultz, M. G., Ellingsen, K., van Noije, T. P. C., Wild, O., Zeng, G., Amann, M., Atherton, C. S., Bell, N., Bergmann, D. J., Bey, I., Butler, T., Cofala, J., Collins, W. J., Derwent, R. G., Doherty, R. M., Drevet, J., Eskes, H. J., Fiore, A. M., Gauss, M., Hauglustaine, D. A., Horowitz, L. W., Isaksen, I. S. A., Krol, M. C., Lamarque, J. F., Lawrence, M. G., Montanaro, V., Muller, J. F., Pitari, G., Prather, M. J., Pyle, J. A., Rast, S., Rodriguez, J. M., Sanderson, M. G., Savage, N. H., Shindell, D. T., Strahan, S. E., Sudo, K., and Szopa, S.: Multimodel ensemble simulations of present-day and near-future tropospheric ozone, Journal of Geophysical Research-Atmospheres, 111, 10.1029/2005jd006338, 2006.
Stevenson, D. S., and Derwent, R. G.: Does the location of aircraft nitrogen oxide emissions affect their climate impact?, Geophysical Research Letters, 36, 10.1029/2009gl039422, 2009.
Stevenson, D. S., Young, P. J., Naik, V., Lamarque, J. F., Shindell, D. T., Voulgarakis, A., Skeie, R. B., Dalsoren, S. B., Myhre, G., Berntsen, T. K., Folberth, G. A., Rumbold, S. T., Collins, W. J., MacKenzie, I. A., Doherty, R. M., Zeng, G., van Noije, T. P. C., Strunk, A., Bergmann, D., Cameron-Smith, P., Plummer, D. A., Strode, S. A., Horowitz, L., Lee, Y. H., Szopa, S., Sudo, K., Nagashima, T., Josse, B., Cionni, I., Righi, M., Eyring, V., Conley, A., Bowman, K. W., Wild, O., and Archibald, A.: Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and

Climate Model Intercomparison Project (ACCMIP), Atmospheric Chemistry and Physics, 13, 3063-3085, 10.5194/acp-13-3063-2013, 2013.
Stjernberg, A. C. E., Skorokhod, A., Paris, J. D., Elansky, N., Nedelec, P., and Stohl, A.: Low concentrations of near-surface ozone in Siberia, Tellus Series B-Chemical and Physical Meteorology, 64, 1-13, 10.3402/tellusb.v64i0.11607, 2012.
Stock, Z. S., Russo, M. R., Butler, T. M., Archibald, A. T., Lawrence, M. G., Telford, P. J., Abraham, N. L., and Pyle, J. A.: Modelling the impact of megacities on local, regional and global tropospheric ozone and the deposition of nitrogen species, Atmos. Chem. Phys., 13, 12215-12231, 10.5194/acp-13-12215-2013, 2013.
Stohl, A., Bonasoni, P., Cristofanelli, P., Collins, W. J., Feichter, J., Frank, A., Forster, C., Gerasopoulos, E., Gäggeler, H., James, P., Kentarchos, T., Kromp-Kalb, H., Krüger, B., Land, C., Meloen, J., Papayannis, A., Priller, A., Seibert, P., Sprenger, M., Roelofs, G. J., Scheel, H. E., Schnabel, C., Siegmund, P., Tobler, L., Trickl, T., Wernli, H., Wirth, V., Zanis, P., and Zerefos, C.: Stratosphere-troposphere exchange : A review, and what we have learned from STACCATO, J. Geophys. Res., 108(D12), 8516, doi :10.1029/2002JD002490, 2003.
Stohl, A., and Eckhardt, S.: Intercontinental Transport of Air Pollution: An Introduction, Intercontinental Tranport of Air Pollution, The Handbook of Environmental Chemistry, Part G, Springer., Berlin Heidelberg New York, , 2004.
Stone, D., Whalley, L. K., and Heard, D. E.: Tropospheric OH and HO_2 radicals: field measurements and model comparisons, Chemical Society Reviews, 41, 6348-6404, 10.1039/c2cs35140d, 2012.
Stone, D., Blitz, M., Daubney, L., Howes, N. U., and Seakins, P.: Kinetics of CH_2OO reactions with SO_2, NO_2, NO, H_2O and CH_3CHO as a function of pressure, Physical Chemistry Chemical Physics, 16, 1139-1149, 2014.
Streets, D. G., Canty, T., Carmichael, G. R., de Foy, B., Dickerson, R. R., Duncan, B. N., Edwards, D. P., Haynes, J. A., Henze, D. K., Houyoux, M. R., Jacob, D. J., Krotkov, N. A., Lamsal, L. N., Liu, Y., Lu, Z., Martin, R. V., Pfister, G. G., Pinder, R. W., Salawitch, R. J., and Wecht, K. J.: Emissions estimation from satellite retrievals: A review of current capability, Atmospheric Environment, 77, 1011-1042, http://dx.doi.org/10.1016/j.atmosenv.2013.05.051, 2013.
Stuber, N., Ponater, M., and Sausen, R.: Why radiative forcing might fail as a predictor of climate change, Climate Dynamics, 24, 497-510, 10.1007/s00382-004-0497-7, 2005.
Stutz, J., Ackermann, R., Fast, J. D., and Barrie, L.: Atmospheric reactive chlorine and bromine at the Great Salt Lake, Utah, Geophysical Research Letters, 29, 10.1029/2002gl014812, 2002.
Su, Y.-T., Lin, H.-Y., Putikam, R., Matsui, H., Lin, M., and Lee, Y.-P.: Extremely rapid self-reaction of the simplest Criegee intermediate CH2OO and its implications in atmospheric chemistry, Nature chemistry, 2014.
Suddick, E. C., Whitney, P., Townsend, A. R., and Davidson, E. A.: The role of nitrogen in climate change and the impacts of nitrogen-climate interactions in the United States: foreword to thematic issue, Biogeochemistry, 114, 1-10, 10.1007/s10533-012-9795-z, 2013.
Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grenfelt, P., Grinsven, H. v., and Grizzetti, B.: The European Nitrogen Assessment: Sources, Effects and Policy Perspectives, Cambridge University Press, Cambridge, 664 pp., 2011.
Szopa, S., Hauglustaine, D. A., Vautard, R., and Menut, L.: Future global tropospheric ozone changes and impact on European air quality., Geophys. Res. Lett., 33, L14805, doi:10.1029/2006GL025860, 2006.
Taatjes, C. A., Meloni, G., Selby, T. M., Trevitt, A. J., Osborn, D. L., Percival, C. J., and Shallcross, D. E.: Direct observation of the gas-phase Criegee intermediate (CH2OO), J Am Chem Soc, 130, 11883-11885, 2008.
Taatjes, C. A., Welz, O., Eskola, A. J., Savee, J. D., Scheer, A. M., Shallcross, D. E., Rotavera, B., Lee, E. P., Dyke, J. M., Mok, D. K., and others: Direct Measurements of Conformer-Dependent Reactivity of the Criegee Intermediate CH3CHOO, Science, 340, 177-180, 2013.

Taatjes, C. A., Shallcross, D. E., and Percival, C. J.: Research frontiers in the chemistry of Criegee intermediates and tropospheric ozonolysis, Physical Chemistry Chemical Physics, 16, 1704-1718, 10.1039/c3cp52842a, 2014.
Tagaris, E., Manomaiphiboon, K., Liao, K. J., Leung, L. R., Woo, J. H., He, S., Amar, P., and Russell, A. G.: Impacts of global climate change and emissions on regional ozone and fine particulate matter concentrations over the United States, Journal of Geophysical Research: Atmospheres, 112, D14312, 2007.
Tagaris, E., Sotiropoulou, R. E. P., Gounaris, N., Andronopoulos, S., and Vlachogiannis, D.: Impact of biogenic emissions on ozone and fine particles over Europe: Comparing effects of temperature increase and a potential anthropogenic NOx emissions abatement strategy, Atmospheric Environment, 98, 214-223, http://dx.doi.org/10.1016/j.atmosenv.2014.08.056, 2014.
Tai, A. P. K., Martin, M. V., and Heald, C. L.: Threat to future global food security from climate change and ozone air pollution, Nature Clim. Change, 4, 817-821, 10.1038/nclimate2317

http://www.nature.com/nclimate/journal/v4/n9/abs/nclimate2317.html#supplementary-information, 2014.
Tang, G., Li, X., Wang, Y., Xin, J., and Ren, X.: Surface ozone trend details and interpretations in Beijing, 2001-2006, Atmospheric Chemistry and Physics, 9, 8813-8823, 2009.
Tang, H., Pang, J., Zhang, G., Takigawa, M., Liu, G., Zhu, J., and Kobayashi, K.: Mapping ozone risks for rice in China for years 2000 and 2020 with flux-based and exposure-based doses, Atmospheric Environment, 86, 74-83, http://dx.doi.org/10.1016/j.atmosenv.2013.11.078, 2014.
Tang, Q., Prather, M. J., and Hsu, J.: Stratosphere-troposphere exchange ozone flux related to deep convection, Geophysical Research Letters, 38, 10.1029/2010gl046039, 2011.
Tang, Q., Hess, P. G., Brown-Steiner, B., and Kinnison, D. E.: Tropospheric ozone decrease due to the Mount Pinatubo eruption: Reduced stratospheric influx, Geophysical Research Letters, 40, 5553-5558, 10.1002/2013gl056563, 2013.
Tarasick, D. W., Fioletov, V. E., Wardle, D. I., Kerr, J. B., and Davies, J.: Changes in the vertical distribution of ozone over Canada from ozonesondes: 1980-2001, Journal of Geophysical Research-Atmospheres, 110, D02304, 10.1029/2004jd004643, 2005.
Tarasova, O. A., Brenninkmeijer, C. A. M., Jöckel, P., Zvyagintsev, A. M., and Kuznetsov, G. I.: A climatology of surface ozone in the extra tropics: cluster analysis of observations and model results, Atmos. Chem. Phys., 7, 6099-6117, 2007.
Tas, E., Peleg, M., Matveev, V., Zingler, J., and Luria, M.: Frequency and extent of bromine oxide formation over the Dead Sea, Journal of Geophysical Research-Atmospheres, 110, 10.1029/2004jd005665, 2005.
Teixeira, E., Fischer, G., van Velthuizen, H., van Dingenen, R., Dentener, F., Mills, G., Walter, C., and Ewert, F.: Limited potential of crop management for mitigating surface ozone impacts on global food supply, Atmospheric Environment, 45, 2569-2576, 10.1016/j.atmosenv.2011.02.002, 2011.
Terao, Y., Logan, J. A., Douglass, A. R., and Stolarski, R. S.: Contribution of stratospheric ozone to the interannual variability of tropospheric ozone in the northern extratropics, Journal of Geophysical Research-Atmospheres, 113, 10.1029/2008jd009854, 2008.
Terrenoire, E., Bessagnet, B., Rouïl, L., Tognet, F., Pirovano, G., Letinois, L., Colette, A., Thunis, P., Amann, M., and Menut, L.: High-resolution air quality simulation over Europe with the chemistry transport model CHIMERE, Geoscientific Model Development, submitted, 2013.
Thomas, J. L., Stutz, J., Lefer, B., Huey, L. G., Toyota, K., Dibb, J. E., and von Glasow, R.: Modeling chemistry in and above snow at Summit, Greenland - Part 1: Model description and results, Atmospheric Chemistry and Physics, 11, 4899-4914, 10.5194/acp-11-4899-2011, 2011.
Thomas, J. L., Dibb, J. E., Huey, L. G., Liao, J., Tanner, D., Lefer, B., von Glasow, R., and Stutz, J.: Modeling chemistry in and above snow at Summit, Greenland - Part 2: Impact of snowpack chemistry on the oxidation capacity of the boundary layer, Atmospheric Chemistry and Physics, 12, 6537-6554, 10.5194/acp-12-6537-2012, 2012.

Thomas, J. L., Raut, J. C., Law, K. S., Marelle, L., Ancellet, G., Ravetta, F., Fast, J. D., Pfister, G., Emmons, L. K., Diskin, G. S., Weinheimer, A., Roiger, A., and Schlager, H.: Pollution transport from North America to Greenland during summer 2008, Atmospheric Chemistry and Physics, 13, 3825-3848, 10.5194/acp-13-3825-2013, 2013.

Thompson, A. M., Pickering, K. E., McNamara, D. P., Schoeberl, M. R., Hudson, R. D., Kim, J. H., Browell, E. V., Kirchhoff, V., and Nganga, D.: Where did tropospheric ozone over southern Africa and the tropical Atlantic come from in October 1992? Insights from TOMS, GTE TRACE A, and SAFARI 1992, Journal of Geophysical Research-Atmospheres, 101, 24251-24278, 1996.

Thompson, A. M., and Hudson, R. D.: Tropical tropospheric ozone (TTO) maps from Nimbus 7 and Earth Probe TOMS by the modified-residual method: Evaluation with sondes, ENSO signals, and trends from Atlantic regional time series, Journal of Geophysical Research-Atmospheres, 104, 26961-26975, 10.1029/1999jd900470, 1999.

Thompson, A. M., Witte, J. C., McPeters, R. D., Oltmans, S. J., Schmidlin, F. J., Logan, J. A., Fujiwara, M., Kirchhoff, V., Posny, F., Coetzee, G. J. R., Hoegger, B., Kawakami, S., Ogawa, T., Johnson, B. J., Vomel, H., and Labow, G.: Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998-2000 tropical ozone climatology - 1. Comparison with Total Ozone Mapping Spectrometer (TOMS) and ground-based measurements, Journal of Geophysical Research-Atmospheres, 108, 10.1029/2001jd000967, 2003a.

Thompson, A. M., Witte, J. C., Oltmans, S. J., Schmidlin, F. J., Logan, J. A., Fujiwara, M., Kirchhoff, V., Posny, F., Coetzee, G. J. R., Hoegger, B., Kawakami, S. J., Ogawa, T., Fortuin, J. P. F., and Kelder, H. M.: Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998-2000 tropical ozone climatology - 2. Tropospheric variability and the zonal wave-one, J. Geophys. Res., 108, PEM13.11-PEM13.21 2003b.

Thompson, A. M., Witte, J. C., Oltmans, S. J., Schmidlin, F. J., Logan, J. A., Fujiwara, M., Kirchhoff, V., Posny, F., Coetzee, G. J. R., Hoegger, B., Kawakami, S. J., Ogawa, T., Fortuin, J. P. F., and Kelder, H. M.: Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998-2000 tropical ozone climatology - 2. Tropospheric variability and the zonal wave-one, Journal of Geophysical Research-Atmospheres, 108, 10.1029/2002jd002241, 2003c.

Thompson, A. M., Balashov, N. V., Witte, J. C., Coetzee, J. G. R., Thouret, V., and Posny, F.: Tropospheric ozone increases over the southern Africa region: bellwether for rapid growth in Southern Hemisphere pollution?, Atmos. Chem. Phys., 14, 9855-9869, 10.5194/acp-14-9855-2014, 2014.

Thornton, J. A., Kercher, J. P., Riedel, T. P., Wagner, N. L., Cozic, J., Holloway, J. S., Dube, W. P., Wolfe, G. M., Quinn, P. K., Middlebrook, A. M., Alexander, B., and Brown, S. S.: A large atomic chlorine source inferred from mid-continental reactive nitrogen chemistry, Nature, 464, 271-274, 10.1038/nature08905, 2010.

Thouret, V., Saunois, M., Minga, A., Mariscal, A., Sauvage, B., Solete, A., Agbangla, D., Nedelec, P., Mari, C., Reeves, C. E., and Schlager, H.: An overview of two years of ozone radio soundings over Cotonou as part of AMMA, Atmospheric Chemistry and Physics, 9, 6157-6174, 2009.

Tie, X., Madronich, S., Li, G., Ying, Z., Weinheimer, A., Apel, E., and Campos, T.: Simulation of Mexico City plumes during the MIRAGE-Mex field campaign using the WRF-Chem model, Atmospheric Chemistry and Physics, 9, 4621-4638, 2009.

Tie, X., Geng, F., Guenther, A., Cao, J., Greenberg, J., Zhang, R., Apel, E., Li, G., Weinheimer, A., Chen, J., and Cai, C.: Megacity impacts on regional ozone formation: observations and WRF-Chem modeling for the MIRAGE-Shanghai field campaign, Atmospheric Chemistry and Physics, 13, 5655-5669, 10.5194/acp-13-5655-2013, 2013.

Tohjima, Y., Kubo, M., Minejima, C., Mukai, H., Tanimoto, H., Ganshin, A., Maksyutov, S., Katsumata, K., Machida, T., and Kita, K.: Temporal changes in the emissions of CH_4 and CO from China estimated from CH_4/CO_2 and CO/CO_2 correlations observed at Hateruma Island, Atmospheric Chemistry and Physics, 14, 1663-1677, 10.5194/acp-14-1663-2014, 2014.

Tosca, M. G., Randerson, J. T., Zender, C. S., Nelson, D. L., Diner, D. J., and Logan, J. A.: Dynamics of fire plumes and smoke clouds associated with peat and deforestation fires in Indonesia, Journal of Geophysical Research-Atmospheres, 116, 10.1029/2010jd015148, 2011.

Tost, H., Jockel, P., and Lelieveld, J.: Lightning and convection parameterization - uncertainties in global modelling, , Atmos. Chem. Phys., 7, 4553-4568, 2007.
Toumi, R., Haigh, J. D., and Law, K. S.: A tropospheric ozone-lightning climate feedback, Geophysical Research Letters, 23, 1037-1040, 10.1029/96gl00944, 1996.
Tressol, M., Ordonez, C., Zbinden, R., Thouret, V., Mari, C., Nedelec, P., Cammas, J.-P., Smit, H., Patz, H.-W., and Volz-Thomas, A.: Air pollution during the 2003 European heat wave as seen by MOZAIC airliners, Atmos. Chem. Phys., 8, 2133-2150, 2008.
Tuzet, A., Perrier, A., Loubet, B., and Cellier, P.: Modelling ozone deposition fluxes: The relative roles of deposition and detoxification processes, Agricultural and Forest Meteorology, 151, 480-492, 10.1016/j.agrformet.2010.12.004, 2011.
Unger, N.: Global Climate Forcing by Criteria Air Pollutants, in: Annual Review of Environment and Resources, Vol 37, edited by: Gadgil, A., and Liverman, D. M., Annual Review of Environment and Resources, Annual Reviews, Palo Alto, 1-+, 2012.
Val Martin, M., Honrath, R. E., Owen, R. C., Pfister, G., Fialho, P., and Barata, F.: Significant enhancements of nitrogen oxides, black carbon and ozone in the North Atlantic lower free troposphere resulting from North American boreal wildfires, J. Geophys. Res., 111, D23S60, doi:10.1029/2006JD007530, 2006.
Val Martin, M., Heald, C. L., and Arnold, S. R.: Coupling dry deposition to vegetation phenology in the Community Earth System Model: Implications for the simulation of surface O3, Geophysical Research Letters, 41, 2988-2996, 10.1002/2014gl059651, 2014.
Valks, P., Hao, N., Garcia, S. G., Loyola, D., Dameris, M., Jockel, P., and Delcloo, A.: Tropical tropospheric ozone column retrieval for GOME-2, Atmos. Meas. Tech., 7, 2513-2530, 10.5194/amt-7-2513-2014, 2014.
van Aardenne, J. A., Dentener, F. J., Olivier, J. G. J., Klein Goldewijk, C. G. M., and Lelieveld, J.: A 1° x 1° resolution dataset of historical anthropogenic trace gas emissions for the period 1890-1990, Global Biogeochem. Cycles, 15, 909-928, 2001.
van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Kasibhatla, P. S., and Arellano Jr, A. F.: Interannual variability of global biomass burning emissions from 1997 to 2004, Atmos. Chem. Phys., 6, 3423-3441, 2006.
van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009), Atmospheric Chemistry and Physics, 10, 11707-11735, 10.5194/acp-10-11707-2010, 2010.
van Loon, M., Vautard, R., Schaap, M., Bergström, R., Bessagnet, B., Brandt, J., Builtjes, P. J. H., Christensen, J. H., Cuvelier, K., Graf, A., Jonson, J. E., Krol, M., Langner, J., Roberts, P., Rouil, L., Stern, R., Tarrasón, L., Thunis, P., Vignati, E., White, L., and Wind, P.: Evaluation of long-term ozone simulations from seven regional air quality models and their ensemble average., Atmos. Environ., 41, 2083-2097, 2007.
van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S., and Rose, S.: The representative concentration pathways: an overview, Climatic Change, 109, 5-31, 2011.
Vautard, R., Honore, C., Beekmann, M., and Rouil, L.: Simulation of ozone during August 2003 heat wave and emission control scenarios, Atmos. Environ., 39, 2957-2967, 2005.
Vautard, R., Szopa, S., Beekmann, M., Menut, L., Hauglustaine, D. A., Rouil, L., and Roemer, M.: Are decadal anthropogenic emission changes in Europe consistent with surface ozone observations?, Geophys. Res. Lett., 33, L13810, doi: 10.1029/2006GL026080., 2006.
Venevsky, S.: Importance of aerosols for annual lightning production at global scale, Atmos. Chem. Phys. Discuss., 14, 4303-4325, 10.5194/acpd-14-4303-2014, 2014.
Vieno, M., Dore, A. J., Stevenson, D. S., Doherty, R., Heal, M. R., Reis, S., Hallsworth, S., Tarrason, L., Wind, P., Fowler, D., Simpson, D., and Sutton, M. A.: Modelling surface ozone during the 2003 heat-

wave in the UK, Atmospheric Chemistry and Physics, 10, 7963-7978, 10.5194/acp-10-7963-2010, 2010.
Vijayaraghavan, K., DenBleyker, A., Ma, L., Lindhjem, C., and Yarwood, G.: Trends in on-road vehicle emissions and ambient air quality in Atlanta, Georgia, USA, from the late 1990s through 2009, J Air Waste Manage, 64, 808-816, 10.1080/10962247.2014.892039, 2014.
Vinken, G. C. M., Boersma, K. F., van Donkelaar, A., and Zhang, L.: Constraints on ship NOx emissions in Europe using GEOS-Chem and OMI satellite NO2 observations, Atmospheric Chemistry and Physics, 14, 1353-1369, 10.5194/acp-14-1353-2014, 2014.
Volz, A., and Kley, D.: Evaluation of the Montsouris Series of Ozone Measurements Made in the 19th-Century, Nature, 332, 240-242, 1988.
von Glasow, R., and Crutzen, P. J.: Model study of multiphase DMS oxidation with a focus on halogens, Atmos. Chem. Phys., 4, 589-608, 2004.
von Glasow, R.: Atmospheric chemistry in volcanic plumes, Proc. Natl. Acad. Sci. U. S. A., 107, 6594-6599, 10.1073/pnas.0913164107, 2010.
von Kuhlmann, R., Lawrence, M. G., Crutzen, P. J., and Rasch, P. J.: A model for studies of tropospheric ozone and nonmethane hydrocarbons: Model description and ozone results, Journal of Geophysical Research-Atmospheres, 108, 10.1029/2002jd002893, 2003a.
von Kuhlmann, R., Lawrence, M. G., Crutzen, P. J., and Rasch, P. J.: A model for studies of tropospheric ozone and nonmethane hydrocarbons: Model evaluation of ozone-related species, Journal of Geophysical Research-Atmospheres, 108, 10.1029/2002jd003348, 2003b.
von Schneidemesser, E., and Monks, P. S.: Air Quality and Climate - synergies and trade-offs, Environmental Science: Processes & Impacts, 15, 1315-1325, 10.1039/c3em00178d, 2013.
vonSchneidemesser, E., Monks, P. S., and Plass-Duelmer, C.: Global comparison of VOC and CO observations in urban areas, Atmospheric Environment, 44, 5053-5064, 2010.
vonSchneidemesser, E., Monks, P. S., Gros, V., Gauduin, J., and Sanchez, O.: How important is biogenic isoprene in an urban environment? A study in London and Paris, Geophysical Research Letters, 38, L19804, 10.1029/2011gl048647, 2011.
Voulgarakis, A., Savage, N. H., Wild, O., Braesicke, P., Young, P. J., Carver, G. D., and Pyle, J. A.: Interannual variability of tropospheric composition: the influence of changes in emissions, meteorology and clouds, Atmospheric Chemistry and Physics, 10, 2491-2506, 2010.
Voulgarakis, A., Hadjinicolaou, P., and Pyle, J. A.: Increases in global tropospheric ozone following an El Nino event: examining stratospheric ozone variability as a potential driver, Atmos. Sci. Lett., 12, 228-232, 10.1002/asl.318, 2011.
Wagner, N. L., Riedel, T. P., Roberts, J. M., Thornton, J. A., Angevine, W. M., Williams, E. J., Lerner, B. M., Vlasenko, A., Li, S. M., Dube, W. P., Coffman, D. J., Bon, D. M., de Gouw, J. A., Kuster, W. C., Gilman, J. B., and Brown, S. S.: The sea breeze/land breeze circulation in Los Angeles and its influence on nitryl chloride production in this region, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2012jd017810, 2012.
Walker, T. W., Jones, D. B. A., Parrington, M., Henze, D. K., Murray, L. T., Bottenheim, J. W., Anlauf, K., Worden, J. R., Bowman, K. W., Shim, C., Singh, K., Kopacz, M., Tarasick, D. W., Davies, J., von der Gathen, P., Thompson, A. M., and Carouge, C. C.: Impacts of midlatitude precursor emissions and local photochemistry on ozone abundances in the Arctic, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2011jd016370, 2012.
Wang, S. W., Zhang, Q., Streets, D. G., He, K. B., Martin, R. V., Lamsal, L. N., Chen, D., Lei, Y., and Lu, Z.: Growth in NOx emissions from power plants in China: bottom-up estimates and satellite observations, Atmospheric Chemistry and Physics, 12, 4429-4447, 10.5194/acp-12-4429-2012, 2012.
Warneke, C., de Gouw, J. A., Holloway, J. S., Peischl, J., Ryerson, T. B., Atlas, E., Blake, D., Trainer, M., and Parrish, D. D.: Multiyear trends in volatile organic compounds in Los Angeles, California: Five decades of decreasing emissions, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2012jd017899, 2012.
Weatherhead, E. C., Reinsel, G. C., Tiao, G. C., Meng, X. L., Choi, D. S., Cheang, W. K., Keller, T., DeLuisi, J., Wuebbles, D. J., Kerr, J. B., Miller, A. J., Oltmans, S. J., and Frederick, J. E.: Factors affecting

the detection of trends: Statistical considerations and applications to environmental data, Journal of Geophysical Research-Atmospheres, 103, 17149-17161, 10.1029/98jd00995, 1998.
Weatherhead, E. C., Stevermer, A. J., and Schwartz, B. E.: Detecting environmental changes and trends, Phys. Chem. Earth, 27, 399-403, 10.1016/s1474-7065(02)00019-0, 2002.
Wei, W., Wang, S. X., Chatani, S., Klimont, Z., Cofala, J., and Hao, J. M.: Emission and speciation of non-methane volatile organic compounds from anthropogenic sources in China, Atmospheric Environment, 42, 4976-4988, 10.1016/j.atmosenv.2008.02.044, 2008.
Weiss, M., Bonnel, P., Kühlwein, J., Provenza, A., Lambrecht, U., Alessandrini, S., Carriero, M., Colombo, R., Forni, F., Lanappe, G., Le Lijour, P., Manfredi, U., Montigny, F., and Sculati, M.: Will Euro 6 reduce the NOx emissions of new diesel cars? – Insights from on-road tests with Portable Emissions Measurement Systems (PEMS), Atmospheric Environment, 62, 657-665, http://dx.doi.org/10.1016/j.atmosenv.2012.08.056, 2012.
Wells, K. C., Millet, D. B., Cady-Pereira, K. E., Shephard, M. W., Henze, D. K., Bousserez, N., Apel, E. C., de Gouw, J., Warneke, C., and Singh, H. B.: Quantifying global terrestrial methanol emissions using observations from the TES satellite sensor, Atmospheric Chemistry and Physics, 14, 2555-2570, 10.5194/acp-14-2555-2014, 2014.
Welz, O., Savee, J. D., Osborn, D. L., Vasu, S. S., Percival, C. J., Shallcross, D. E., and Taatjes, C. A.: Direct kinetic measurements of Criegee intermediate (CH_2OO) formed by reaction of CH_2I with O_2, Science, 335, 204-207, 2012.
Welz, O., Eskola, A. J., Sheps, L., Rotavera, B., Savee, J. D., Scheer, A. M., Osborn, D. L., Lowe, D., Murray Booth, A., Xiao, P., and others: Rate Coefficients of C1 and C2 Criegee Intermediate Reactions with Formic and Acetic Acid Near the Collision Limit: Direct Kinetics Measurements and Atmospheric Implications, Angewandte Chemie, 126, 4635-4638, 2014.
Wesely, M. L., Cook, D. R., and Williams, R. M.: Field measurement of small ozone fluxes to snow, wet bare soil, and lake water, Boundary-Layer Meteorology, 20, 459-471, 10.1007/bf00122295, 1981.
Wespes, C., Emmons, L., Edwards, D. P., Hannigan, J., Hurtmans, D., Saunois, M., Coheur, P. F., Clerbaux, C., Coffey, M. T., Batchelor, R. L., Lindenmaier, R., Strong, K., Weinheimer, A. J., Nowak, J. B., Ryerson, T. B., Crounse, J. D., and Wennberg, P. O.: Analysis of ozone and nitric acid in spring and summer Arctic pollution using aircraft, ground-based, satellite observations and MOZART-4 model: source attribution and partitioning, Atmospheric Chemistry and Physics, 12, 237-259, 10.5194/acp-12-237-2012, 2012.
Wexler, H., Moreland, W. B., and Weyant, W. S.: A preliminary report on ozone observations in little America, Antarctica, Monthly Weather Review, 88, 43-54, 10.1175/1520-0493(1960)088<0043:aprooo>2.0.co;2, 1960.
Whalley, L., Edwards, P., Furneaux, K., Goddard, A., Ingham, T., Evans, M., Stone, D., Hopkins, J., Jones, C. E., Karunaharan, A., and others: Quantifying the magnitude of a missing hydroxyl radical source in a tropical rainforest, Atmospheric Chemistry and Physics, 11, 7223-7233, 2011.
Whalley, L., Stone, D., and Heard, D.: New Insights into the tropospheric oxidation of Isoprene: Combining field measuremens, laboratory studies, chemical modelling and qualtum theory, in: Atmospheric and Aerosol Chemistry, edited by: McNeill, V. F., and Ariya, P. A., Topics in Current Chemistry, Springer, Berlin Heidelberg, 55-96, 2014.
WHO: Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide, Bonn, 2003.
WHO: WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, 2005.
WHO: Review of evidence on health aspects of air pollution – REVIHAAP Project WHO Regional Office for Europe, Copenhagen, 2013.
Wiedinmyer, C., Akagi, S. K., Yokelson, R. J., Emmons, L. K., Al-Saadi, J. A., Orlando, J. J., and Soja, A. J.: The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning, Geosci. Model Dev., 4, 625-641, 10.5194/gmd-4-625-2011, 2011.

Wilcox, L. J., Hoskins, B. J., and Shine, K. P.: A global blended tropopause based on ERA data. Part I: Climatology, Quarterly Journal of the Royal Meteorological Society, 138, 561-575, 10.1002/qj.951, 2012.
Wild, O., Prather, M. J., and Akimoto, H.: Indirect long-term global radiative cooling from NOx emissions, Geophysical Research Letters, 28, 1719-1722, 10.1029/2000gl012573, 2001.
Wild, O., Pochanart, P., and Akimoto, H.: Trans-Eurasian of ozone and its precursors, J. Geophys. Res., 109, D11302, doi:10.1029/2003JD004501, 2004.
Wild, O.: Modelling the global tropospheric ozone budget: exploring the variability in current models, Atmospheric Chemistry and Physics, 7, 2643-2660, 2007.
Wild, O., and Palmer, P. I.: How sensitive is tropospheric oxidation to anthropogenic emissions?, Geophysical Research Letters, 35, 10.1029/2008gl035718, 2008.
Wild, O., Fiore, A. M., Shindell, D. T., Doherty, R. M., Collins, W. J., Dentener, F. J., Schultz, M. G., Gong, S., MacKenzie, I. A., Zeng, G., Hess, P., Duncan, B. N., Bergmann, D. J., Szopa, S., Jonson, J. E., Keating, T. J., and Zuber, A.: Modelling future changes in surface ozone: a parameterized approach, Atmos. Chem. Phys., 12, 2037-2054, 2012.
Williams, D. E., Henshaw, G. S., Bart, M., Laing, G., Wagner, J., Naisbitt, S., and Salmond, J. A.: Validation of low-cost ozone measurement instruments suitable for use in an air-quality monitoring network, Meas Sci Technol, 24, 10.1088/0957-0233/24/6/065803, 2013.
Williams, E. R.: Lightning and climate: A review, Atmospheric Research, 76, 272-287, 10.1016/j.atmosres.2004.11.014, 2005.
Williams, J. E., van Weele, M., van Velthoven, P. F. J., Scheele, M. P., Liousse, C., and van der Werf, G. R.: The Impact of Uncertainties in African Biomass Burning Emission Estimates on Modeling Global Air Quality, Long Range Transport and Tropospheric Chemical Lifetimes, Atmosphere, 3, 132-163, 10.3390/atmos3010132, 2012.
Williams, M. L., Atkinson, R. W., Anderson, H. R., and Kelly, F. J.: Associations between daily mortality in London and combined oxidant capacity, ozone and nitrogen dioxide, Air Qual Atmos Health, DOI 10.1007/s11869-014-0249-8, 2014.
Wilson, R. C., Fleming, Z. L., Monks, P. S., Clain, G., Henne, S., Konovalov, I. B., Szopa, S., and Menut, L.: Have primary emission reduction measures reduced ozone across Europe? An analysis of European rural background ozone trends 1996–2005, Atmos. Chem. Phys., 12, 437-454, 2012.
Wittig, V. E., Ainsworth, E. A., Naidu, S. L., Karnosky, D. F., and Long, S. P.: Quantifying the impact of current and future tropospheric ozone on tree biomass, growth, physiology and biochemistry: a quantitative meta-analysis, Global Change Biology, 15, 396-424, 10.1111/j.1365-2486.2008.01774.x, 2009.
Wu, S., Mickley, L. J., Leibensperger, E. M., Jacob, D. J., Rind, D., and Streets, D. G.: Effects of 2000–2050 global change on ozone air quality in the United States, Journal of Geophysical Research: Atmospheres, 113, n/a-n/a, 2008.
Wu, S. L., Mickley, L. J., Jacob, D. J., Logan, J. A., Yantosca, R. M., and Rind, D.: Why are there large differences between models in global budgets of tropospheric ozone?, Journal of Geophysical Research-Atmospheres, 112, 10.1029/2006jd007801, 2007.
Yang, X., Cox, R. A., Warwick, N. J., Pyle, J. A., Carver, G. D., O'Connor, F. M., and Savage, N. H.: Tropospheric bromine chemistry and its impacts on ozone, J. Geophys. Res., 110, D23 311, 10.1029/2005JD006 244, 2005.
Young, C. J., Washenfelder, R. A., Edwards, P. M., Parrish, D. D., Gilman, J. B., Kuster, W. C., Mielke, L. H., Osthoff, H. D., Tsai, C., Pikelnaya, O., Stutz, J., Veres, P. R., Roberts, J. M., Griffith, S., Dusanter, S., Stevens, P. S., Flynn, J., Grossberg, N., Lefer, B., Holloway, J. S., Peischl, J., Ryerson, T. B., Atlas, E. L., Blake, D. R., and Brown, S. S.: Chlorine as a primary radical: evaluation of methods to understand its role in initiation of oxidative cycles, Atmospheric Chemistry and Physics, 14, 3427-3440, 10.5194/acp-14-3427-2014, 2014.
Young, P. J., Archibald, A. T., Bowman, K. W., Lamarque, J. F., Naik, V., Stevenson, D. S., Tilmes, S., Voulgarakis, A., Wild, O., Bergmann, D., Cameron-Smith, P., Cionni, I., Collins, W. J., Dalsoren, S. B., Doherty, R. M., Eyring, V., Faluvegi, G., Horowitz, L. W., Josse, B., Lee, Y. H., MacKenzie, I. A.,

Nagashima, T., Plummer, D. A., Righi, M., Rumbold, S. T., Skeie, R. B., Shindell, D. T., Strode, S. A., Sudo, K., Szopa, S., and Zeng, G.: Pre-industrial to end 21st century projections of tropospheric ozone from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), Atmospheric Chemistry and Physics, 13, 2063-2090, 10.5194/acp-13-2063-2013, 2013.
Yu, X., Yuan, Z., Fung, J. C. H., Xue, J., Li, Y., Zheng, J., and Lau, A. K. H.: Ozone changes in response to the heavy-duty diesel truck control in the Pearl River Delta, Atmospheric Environment, 88, 269-274, http://dx.doi.org/10.1016/j.atmosenv.2013.11.022, 2014.
Yu, Y., Sokhi, R. S., Kitwiroon, N., Middleton, D. R., and Fisher, B.: Performance characteristics of MM5-SMOKE-CMAQ for a summer photochemical episode in southeast England, United Kingdom, Atmospheric Environment, 42, 4870-4883, 10.1016/j.atmosenv.2008.02,051, 2008.
Yuan, T. L., Remer, L. A., Bian, H. S., Ziemke, J. R., Albrecht, R., Pickering, K. E., Oreopoulos, L., Goodman, S. J., Yu, H. B., and Allen, D. J.: Aerosol indirect effect on tropospheric ozone via lightning, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2012jd017723, 2012.
Yue, X., and Unger, N.: Ozone vegetation damage effects on gross primary productivity in the United States, Atmos Chem Phys, 14, 9137-9153, 2014.
Zanis, P., Trickl, T., Stohl, A., Wernli, H., Cooper, O., Zerefos, C., Gaeggleler, H., Priller, A., Schnabel, C., Scheel, H. E., Kanter, H. J., Tobler, L., Kubik, P. W., Cristofanelli, P., Forster, C., James, P., Gerasopoulos, E., Delcloo, A., Papayannis, A., and Claude, H.: Forecast, observation and modeling of a deep stratospheric intrusion event over Europe Atmos. Chem. Phys., 3, 763-777, 2003.
Zanis, P., Hadjinicolaou, P., Pozzer, A., Tyrlis, E., Dafka, S., Mihalopoulos, N., and Lelieveld, J.: Summertime free-tropospheric ozone pool over the eastern Mediterranean/Middle East, Atmospheric Chemistry and Physics, 14, 115-132, 10.5194/acp-14-115-2014, 2014.
Zanobetti, A., and Schwartz, J.: Ozone and Survival in Four Cohorts with Potentially Predisposing Diseases, American Journal of Respiratory and Critical Care Medicine, 184, 836-841, 10.1164/rccm.201102-0227OC, 2011.
Zare, A., Christensen, J. H., Gross, A., Irannejad, P., Glasius, M., and Brandt, J.: Quantifying the contributions of natural emissions to ozone and total fine PM concentrations in the Northern Hemisphere, Atmos. Chem. Phys., 14, 2735-2756, 10.5194/acp-14-2735-2014, 2014.
Zeng, G., and Pyle, J. A.: Influence of El Nino Southern Oscillation on stratosphere/troposphere exchange and the global tropospheric ozone budget, Geophysical Research Letters, 32, 10.1029/2004gl021353, 2005.
Zhang, L., Jacob, D. J., Yue, X., Downey, N. V., Wood, D. A., and Blewitt, D.: Sources contributing to background surface ozone in the US Intermountain West, Atmospheric Chemistry and Physics, 14, 5295-5309, 10.5194/acp-14-5295-2014, 2014.
Zhang, L. M., Brook, J. R., and Vet, R.: On ozone dry deposition - with emphasis on non-stomatal uptake and wet canopies, Atmospheric Environment, 36, 4787-4799, 2002.
Zhang, Q., Streets, D. G., He, K., Wang, Y., Richter, A., Burrows, J. P., Uno, I., Jang, C. J., Chen, D., Yao, Z., and Lei, Y.: NOx emission trends for China, 1995-2004: The view from the ground and the view from space, Journal of Geophysical Research-Atmospheres, 112, D22306, 2007.
Zhao, Y., Nielsen, C. P., Lei, Y., McElroy, M. B., and Hao, J.: Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China, Atmospheric Chemistry and Physics, 11, 2295-2308, 10.5194/acp-11-2295-2011, 2011.
Zhao, Y., Zhang, J., and Nielsen, C. P.: The effects of recent control policies on trends in emissions of anthropogenic atmospheric pollutants and CO_2 in China, Atmospheric Chemistry and Physics, 13, 487-508, 10.5194/acp-13-487-2013, 2013.
Zhong, J., Cai, X. M., and Bloss, W. J.: Modelling segregation effects of heterogeneous emissions on ozone levels in idealised urban street canyons: Using photochemical box models, Environmental Pollution, 188, 132-143, 10.1016/j.envpol.2014.02.001, 2014.
Zhou, W., Cohan, D. S., and Henderson, B. H.: Slower ozone production in Houston, Texas following emission reductions: evidence from Texas Air Quality Studies in 2000 and 2006, Atmos. Chem. Phys., 14, 2777-2788, 10.5194/acp-14-2777-2014, 2014.

~~Zhu, T., Melamed, M., Parrish, D., Gauss, M., Klenner, L. G., Lawrence, M., Konare, A., and Liousse, C.: Impacts of Megacities on Air Pollution and Climate, WMO, Geneva, 2012.~~
~~Ziemke, J. R., and Chandra, S.: La Nina and El Nino-induced variabilities of ozone in the tropical lower atmosphere during 1970-2001, Geophysical Research Letters, 30, 10.1029/2002gl016387, 2003.~~
~~Ziemke, J. R., Chandra, S., Duncan, B. N., Froidevaux, L., Bhartia, P. K., Levelt, P. F., and Waters, J. W.: Tropospheric ozone determined from aura OMI and MLS: Evaluation of measurements and comparison with the Global Modeling Initiative's Chemical Transport Model, Journal of Geophysical Research-Atmospheres, 111, D19303, 2006.~~
~~Ziemke, J. R., Chandra, S., Oman, L. D., and Bhartia, P. K.: A new ENSO index derived from satellite measurements of column ozone, Atmospheric Chemistry and Physics, 10, 3711–3721, 2010.~~
~~Zingler, J., and Platt, U.: Iodine oxide in the Dead Sea Valley: Evidence for inorganic sources of boundary layer IO, Journal of Geophysical Research-Atmospheres, 110, 10.1029/2004jd004993, 2005.~~
~~Zlatev, Z., Christensen, J., and Hov, O.: A Eulerian air-pollution model for Europe with nonlinear chemistry, Journal of Atmospheric Chemistry, 15, 1-37, 10.1007/bf00053607, 1992.~~
~~Zoogman, P., Jacob, D. J., Chance, K., Worden, H. M., Edwards, D. P., and Zhang, L.: Improved monitoring of surface ozone by joint assimilation of geostationary satellite observations of ozone and CO, Atmospheric Environment, 84, 254-261, 10.1016/j.atmosenv.2013.11.048, 2014.~~

Abbatt, J., George, C., Melamed, M., Monks, P., Pandis, S., and Rudich, Y.: New Directions: Fundamentals of atmospheric chemistry: Keeping a three-legged stool balanced, Atmospheric Environment, 84, 390-391, 10.1016/j.atmosenv.2013.10.025, 2014.
Abbatt, J. P. D., Thomas, J. L., Abrahamsson, K., Boxe, C., Granfors, A., Jones, A. E., King, M. D., Saiz-Lopez, A., Shepson, P. B., Sodeau, J., Toohey, D. W., Toubin, C., von Glasow, R., Wren, S. N., and Yang, X.: Halogen activation via interactions with environmental ice and snow in the polar lower troposphere and other regions, Atmospheric Chemistry and Physics, 12, 6237-6271, 10.5194/acp-12-6237-2012, 2012.
Adams, R. M., Crocker, T. D., and Thanavibulchai, N.: An economic assessment of air pollution damages to selectes annual crops in souhtern California, J.Environ.Econ.Manage., 9, 42-58, 10.1016/0095-0696(82)90005-5, 1982.
Administration, U. S. E. I.: Annual Energy Outlook 2014, with projections to 2040, Washington, DC, 2014a.
Administration, U. S. E. I.: Drilling Productivity Report, 2014b.
Agency, U. E. P.: National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data 2014.
Agency, U. S. E. P.: EPA needs to improve air emissions data for the oil and natural gas production sector, Office of Inspector General, 2013.
Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., Crounse, J. D., and Wennberg, P. O.: Emission factors for open and domestic biomass burning for use in atmospheric models, Atmospheric Chemistry and Physics, 11, 4039-4072, 10.5194/acp-11-4039-2011, 2011.
Akimoto, H.: Global air quality and pollution, Science, 302, 1716-1719, 2003.
Allen, D. T., Torres, V. M., Thomas, J., Sullivan, D. W., Harrison, M., Hendler, A., Herndon, S. C., Kolb, C. E., Fraser, M. P., Hill, A. D., Lamb, B. K., Miskimins, J., Sawyer, R. F., and Seinfeld, J. H.: Measurements of methane emissions at natural gas production sites in the United States, Proceedings of the National Academy of Sciences, 110, 17768-17773, 10.1073/pnas.1304880110, 2013.
Alvarado, M. J., Logan, J. A., Mao, J., Apel, E., Riemer, D., Blake, D., Cohen, R. C., Min, K. E., Perring, A. E., Browne, E. C., Wooldridge, P. J., Diskin, G. S., Sachse, G. W., Fuelberg, H., Sessions, W. R., Harrigan, D. L., Huey, G., Liao, J., Case-Hanks, A., Jimenez, J. L., Cubison, M. J., Vay, S. A., Weinheimer, A. J., Knapp, D. J., Montzka, D. D., Flocke, F. M., Pollack, I. B., Wennberg, P. O., Kurten, A., Crounse, J., St Clair, J. M., Wisthaler, A., Mikoviny, T., Yantosca, R. M., Carouge, C. C., and Le Sager, P.: Nitrogen

oxides and PAN in plumes from boreal fires during ARCTAS-B and their impact on ozone: an integrated analysis of aircraft and satellite observations, Atmospheric Chemistry and Physics, 10, 9739-9760, 10.5194/acp-10-9739-2010, 2010.
Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Hettelingh, J.-P., Heyes, C., Holland, M., Kiesewetter, G., Klimont, Z., Rafaj, P., Paasonen, P., Posch, M., Sander, R., Schöpp, W., Wagner, F., and Winiwarter, W.: Policy Scenarios for the Revision of the Thematic Strategy on Air Pollution, IIASA, Vienna, 2013a.
Amann, M., Klimont, Z., and Wagner, F.: Regional and Global Emissions of Air Pollutants: Recent Trends and Future Scenarios, Annu. Rev. Environ. Resour, 38, 31-55, 10.1146/annurev-environ-052912-173303, 2013b.
Andersen, P. C., Williford, C. J., and Birks, J. W.: Miniature Personal Ozone Monitor Based on UV Absorbance, Analytical Chemistry, 82, 7924-7928, 10.1021/ac1013578, 2010.
Andersson, C., and Engardt, M.: European ozone in a future climate: Importance of changes in dry deposition and isoprene emissions, Journal of Geophysical Research-Atmospheres, 115, 10.1029/2008jd011690, 2010.
Andreae, M. O., and Merlet, P.: Emission of trace gases and aerosols from biomass burning, Global Biogeochemical Cycles, 15, 955-966, 2001.
Andrey, J., Cuevas, E., Parrondo, M. C., Alonso-Pérez, S., Redondas, A., and Gil-Ojeda, M.: Quantification of ozone reductions within the Saharan air layer through a 13-year climatologic analysis of ozone profiles, Atmospheric Environment, 84, 28-34, http://dx.doi.org/10.1016/j.atmosenv.2013.11.030, 2014.
Anenberg, S. C., West, J. J., Fiore, A. M., Jaffe, D. A., Prather, M. J., Bergmann, D., Cuvelier, K., Dentener, F. J., Duncan, B. N., Gauss, M., Hess, P., Jonson, J. E., Lupu, A., MacKenzie, I. A., Marmer, E., Park, R. J., Sanderson, M. G., Schultz, M., Shindell, D. T., Szopa, S., Vivanco, M. G., Wild, O., and Zang, G.: Intercontinental Impacts of Ozone Pollution on Human Mortality, Environ. Sci. Technol., 43, 6482-6487, 10.1021/es900518z, 2009.
AQEG: Air Quality Expert Group, Ozone in the United Kingdom, HMSO, London, 2009.
Archibald, A., Khan, M., Watson, L., Clemitshaw, K., Utembe, S., Jenkin, M., and Shallcross, D.: Comment on `Long-term atmospheric measurements of C_1-C_5 alkyl nitrates in the Pearl River Delta region of southeast China'by Simpson et al., Atmospheric Environment, 41, 7369-7370, 2007.
Archibald, A., Petit, A., Percival, C., Harvey, J., and Shallcross, D.: On the importance of the reaction between OH and RO_2 radicals, Atmos. Sci. Lett., 10, 102-108, 2009.
Archibald, A., Cooke, M., Utembe, S., Shallcross, D., Derwent, R., and Jenkin, M.: Impacts of mechanistic changes on HO x formation and recycling in the oxidation of isoprene, Atmospheric Chemistry and Physics, 10, 8097-8118, 2010.
Archibald, A. T., Levine, J. G., Abraham, N. L., Cooke, M. C., Edwards, P. M., Heard, D. E., Jenkin, M. E., Karunaharan, A., Pike, R. C., Monks, P. S., Shallcross, D. E., Telford, P. J., Whalley, L. K., and Pyle, J. A.: Impacts of HO(x) regeneration and recycling in the oxidation of isoprene: Consequences for the composition of past, present and future atmospheres, Geophysical Research Letters, 38, L05804 10.1029/2010gl046520, 2011.
Arellano, A. F., and Hess, P. G.: Sensitivity of top-down estimates of CO sources to GCTM transport, Geophysical Research Letters, 33, 10.1029/2006gl027371, 2006.
Arneth, A., Niinemets, U., Pressley, S., Back, J., Hari, P., Karl, T., Noe, S., Prentice, I. C., Serca, D., Hickler, T., Wolf, A., and Smith, B.: Process-based estimates of terrestrial ecosystem isoprene emissions: incorporating the effects of a direct CO2-isoprene interaction, Atmospheric Chemistry and Physics, 7, 31-53, 2007.
Arneth, A., Schurgers, G., Lathiere, J., Duhl, T., Beerling, D. J., Hewitt, C. N., Martin, M., and Guenther, A.: Global terrestrial isoprene emission models: sensitivity to variability in climate and vegetation, Atmospheric Chemistry and Physics, 11, 8037-8052, 10.5194/acp-11-8037-2011, 2011.
Arnold, S. R., Emmons, L. K., Monks, S. A., Law, K. S., Ridley, D. A., Turquety, S., Tilmes, S., Thomas, J. L., Bouarar, I., Flemming, J., Huijnen, V., Mao, J., Duncan, B. N., Steenrod, S., Yoshida, Y., Langner, J., and Long, Y.: Biomass burning influence on high latitude tropospheric ozone and reactive nitrogen in

summer 2008: a multi-model analysis based on POLMIP simulations, Atmos. Chem. Phys. Discuss., 14, 24573-24621, 10.5194/acpd-14-24573-2014, 2014.
Ashmore, M.: Assessing the Future Global Impacts of Ozone on Vegetation, Plant, Cell and Environment 28, 949-964, 2005.
Ashworth, K., Wild, O., and Hewitt, C. N.: Impacts of biofuel cultivation on mortality and crop yields, Nat. Clim. Chang., 3, 492-496, 10.1038/nclimate1788, 2013.
Avnery, S., Mauzerall, D. L., Liu, J., and Horowitz, L. W.: Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage, Atmospheric Environment, 45, 2284-2296, 10.1016/j.atmosenv.2010.11.045, 2011a.
Avnery, S., Mauzerall, D. L., Liu, J., and Horowitz, L. W.: Global crop yield reductions due to surface ozone exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of O-3 pollution, Atmospheric Environment, 45, 2297-2309, 10.1016/j.atmosenv.2011.01.002, 2011b.
Baker, J., Walker, H. L., and Cai, X. M.: A study of the dispersion and transport of reactive pollutants in and above street canyons - a large eddy simulation, Atmospheric Environment, 38, 6883-6892, 10.1016/j.atmosenv.2004.08.051, 2004.
Banerjee, A., Archibald, A. T., Maycock, A. C., Telford, P., Abraham, N. L., Yang, X., Braesicke, P., and Pyle, J. A.: Lightning NOx, a key chemistry–climate interaction: impacts of future climate change and consequences for tropospheric oxidising capacity, Atmos. Chem. Phys., 14, 9871-9881, 10.5194/acp-14-9871-2014, 2014.
Barkley, M. P., De Smedt, I., Van Roozendael, M., Kurosu, T. P., Chance, K., Arneth, A., Hagberg, D., Guenther, A., Paulot, F., Marais, E., and Mao, J. Q.: Top-down isoprene emissions over tropical South America inferred from SCIAMACHY and OMI formaldehyde columns, Journal of Geophysical Research-Atmospheres, 118, 6849-6868, 10.1002/jgrd.50552, 2013.
Barrie, L. A., Hoff, R. M., and Daggupaty, S. M.: The Influence of mid-latitudinal pollution sources on haze in the Canadian Arctic, Atmospheric Environment, 15, 1407-1419, 10.1016/0004-6981(81)90347-4, 1981.
Barrie, L. A., Bottenheim, J. W., Schnell, R. C., Crutzen, P. J., and Rasmussen, R. A.: Ozone destruction and photochemical reactions at polar sunrise in the lower Arctic atmosphere, Nature, 334, 138-140, 1988.
Bart, M., Williams, D. E., Ainslie, B., McKendry, I., Salmond, J., Grange, S. K., Alavi-Shoshtari, M., Steyn, D., and Henshaw, G. S.: High Density Ozone Monitoring Using Gas Sensitive Semi-Conductor Sensors in the Lower Fraser Valley, British Columbia, Environ. Sci. Technol., 48, 3970-3977, 10.1021/es404610t, 2014.
Bates, D. V.: Ambient ozone and mortality, Epidemiology, 16, 427-429, 10.1097/01.ede.0000165793.71278.ec, 2005.
Beames, J. M., Liu, F., Lu, L., and Lester, M. I.: Ultraviolet Spectrum and Photochemistry of the Simplest Criegee Intermediate CH2OO, J Am Chem Soc, 134, 20045-20048, 2012.
Beirle, S., Huntrieser, H., and Wagner, T.: Direct satellite observation of lightning-produced NOx, Atmospheric Chemistry and Physics, 10, 10965-10986, 10.5194/acp-10-10965-2010, 2010.
Beirle, S., Boersma, K. F., Platt, U., Lawrence, M. G., and Wagner, T.: Megacity Emissions and Lifetimes of Nitrogen Oxides Probed from Space, Science, 333, 1737-1739, 10.1126/science.1207824, 2011.
Bell, M. L., Peng, R. D., and Domenici, F.: The exposure-response curve for ozone and risk of mortality and the adequacy of current ozone regulations, Environ. Health Perspect., 114, 532-536, 2006.
Bickle, M.: Shale gas extraction in the UK: a review of hydraulic fracturing, The Royal Society and The Royal Academy of Engineering, London, 2012.
Bloomer, B. J., Stehr, J. W., Piety, C. A., Salawitch, R. J., and Dickerson, R. R.: Observed relationships of ozone air pollution with temperature and emissions, Geophysical Research Letters, 36, 10.1029/2009gl037308, 2009.

Bloomer, B. J., Vinnikov, K. Y., and Dickerson, R. R.: Changes in seasonal and diurnal cycles of ozone and temperature in the eastern US, Atmospheric Environment, 44, 2543-2551, 10.1016/j.atmosenv.2010.04.031, 2010.
Bloss, W. J., Evans, M. J., Lee, J. D., Sommariva, R., Heard, D. E., and Pilling, M. J.: The oxidative capacity of the troposphere: Coupling of field measurements of OH and a global chemistry transport model, Faraday Discussions, 130, 425-436, 10.1039/b419090d, 2005.
Bloss, W. J., Camredon, M., Lee, J. D., Heard, D. E., Plane, J. M. C., Saiz-Lopez, A., Bauguitte, S. J. B., Salmon, R. A., and Jones, A. E.: Coupling of HOx, NOx and halogen chemistry in the antarctic boundary layer, Atmospheric Chemistry and Physics, 10, 10187-10209, 10.5194/acp-10-10187-2010, 2010.
Bojkov, R. D.: Surface ozone during the 2nd half of the 19th century, Journal of Climate and Applied Meteorology, 25, 343-352, 10.1175/1520-0450(1986)025<0343:sodtsh>2.0.co;2, 1986.
Bon, D. M., Ulbrich, I. M., de Gouw, J. A., Warneke, C., Kuster, W. C., Alexander, M. L., Baker, A., Beyersdorf, A. J., Blake, D., Fall, R., Jimenez, J. L., Herndon, S. C., Huey, L. G., Knighton, W. B., Ortega, J., Springston, S., and Vargas, O.: Measurements of volatile organic compounds at a suburban ground site (T1) in Mexico City during the MILAGRO 2006 campaign: measurement comparison, emission ratios, and source attribution, Atmospheric Chemistry and Physics, 11, 2399-2421, 10.5194/acp-11-2399-2011, 2011.
Booker, F., Muntifering, R., McGrath, M., Burkey, K., Decoteau, D., Fiscus, E., Manning, W., Krupa, S., Chappelka, A., and Grantz, D.: The Ozone Component of Global Change: Potential Effects on Agricultural and Horticultural Plant Yield, Product Quality and Interactions with Invasive Species, J. Integr. Plant Biol., 51, 337-351, 10.1111/j.1744-7909.2008.00805.x, 2009.
Bossolasco, A., Farago, E. P., Schoemaecker, C., and Fittschen, C.: Rate constant of the reaction between CH_3O_2 and OH radicals, Chemical Physics Letters, 593, 7-13, 10.1016/j.cplett.2013.12.052, 2014.
Bowman, K. W.: Toward the next generation of air quality monitoring: Ozone, Atmospheric Environment, 80, 571-583, 10.1016/j.atmosenv.2013.07.007, 2013.
BP: BP Statistical Review of World Energy, 2013.
BP: BP Energy Outlook 2035, 2014a.
BP: BP Energy Outlook 2035: Focus on North America, 2014b.
Brandt, A. R., Heath, G. A., Kort, E. A., O'Sullivan, F., Petron, G., Jordaan, S. M., Tans, P., Wilcox, J., Gopstein, A. M., Arent, D., Wofsy, S., Brown, N. J., Bradley, R., Stucky, G. D., Eardley, D., and Harriss, R.: Methane Leaks from North American Natural Gas Systems, Science, 343, 733-735, 10.1126/science.1247045, 2014.
Braslavsky, S. E., and Rubin, M. B.: The history of ozone Part VIII. Photochemical formation of ozone, Photochemical & Photobiological Sciences, 10, 1515-1520, 10.1039/c1pp05121k, 2011.
Brasseur, G. P., Prinn, R. G., and Pszenny, A. A. P.: Atmospheric Chemistry in a Changing World, Global Change - IGBP Series, Springer, 2003.
Brauer, M., Amann, M., Burnett, R. T., Cohen, A., Dentener, F., Ezzati, M., Henderson, S. B., Krzyzanowski, M., Martin, R. V., Van Dingenen, R., van Donkelaar, A., and Thurston, G. D.: Exposure Assessment for Estimation of the Global Burden of Disease Attributable to Outdoor Air Pollution, Environ. Sci. Technol., 46, 652-660, 10.1021/es2025752, 2012.
Brock, C. A., Cozic, J., Bahreini, R., Froyd, K. D., Middlebrook, A. M., McComiskey, A., Brioude, J., Cooper, O. R., Stohl, A., Aikin, K. C., de Gouw, J. A., Fahey, D. W., Ferrare, R. A., Gao, R. S., Gore, W., Holloway, J. S., Hubler, G., Jefferson, A., Lack, D. A., Lance, S., Moore, R. H., Murphy, D. M., Nenes, A., Novelli, P. C., Nowak, J. B., Ogren, J. A., Peischl, J., Pierce, R. B., Pilewskie, P., Quinn, P. K., Ryerson, T. B., Schmidt, K. S., Schwarz, J. P., Sodemann, H., Spackman, J. R., Stark, H., Thomson, D. S., Thornberry, T., Veres, P., Watts, L. A., Warneke, C., and Wollny, A. G.: Characteristics, sources, and transport of aerosols measured in spring 2008 during the aerosol, radiation, and cloud processes affecting Arctic Climate (ARCPAC) Project, Atmospheric Chemistry and Physics, 11, 2423-2453, 10.5194/acp-11-2423-2011, 2011.

Brown-Steiner, B., and Hess, P.: Asian influence on surface ozone in the United States: A comparison of chemistry, seasonality, and transport mechanisms, Journal of Geophysical Research-Atmospheres, 116, 10.1029/2011jd015846, 2011.
Browne, E. C., Wooldridge, P. J., Min, K. E., and Cohen, R. C.: On the role of monoterpene chemistry in the remote continental boundary layer, Atmos. Chem. Phys., 14, 1225-1238, 10.5194/acp-14-1225-2014, 2014.
Bueker, P., Morrissey, T., Briolat, A., Falk, R., Simpson, D., Tuovinen, J. P., Alonso, R., Barth, S., Baumgarten, M., Grulke, N., Karlsson, P. E., King, J., Lagergren, F., Matyssek, R., Nunn, A., Ogaya, R., Penuelas, J., Rhea, L., Schaub, M., Uddling, J., Werner, W., and Emberson, L. D.: DO3SE modelling of soil moisture to determine ozone flux to forest trees, Atmospheric Chemistry and Physics, 12, 5537-5562, 10.5194/acp-12-5537-2012, 2012.
Butler, T. M., and Lawrence, M. G.: The influence of megacities on global atmospheric chemistry: a modelling study, Environmental Chemistry, 6, 219-225, 10.1071/en08110, 2009.
Butler, T. M., Stock, Z. S., Russo, M. R., van der Gon, H., and Lawrence, M. G.: Megacity ozone air quality under four alternative future scenarios, Atmospheric Chemistry and Physics, 12, 4413-4428, 10.5194/acp-12-4413-2012, 2012.
Calfapietra, C., Fares, S., Manes, F., Morani, A., Sgrigna, G., and Loreto, F.: Role of Biogenic Volatile Organic Compounds (BVOC) emitted by urban trees on ozone concentration in cities: A review, Environmental Pollution, 183, 71-80, http://dx.doi.org/10.1016/j.envpol.2013.03.012, 2013.
Cammas, J. P., Brioude, J., Chaboureau, J. P., Duron, J., Mari, C., Mascart, P., Nedelec, P., Smit, H., Patz, H. W., Volz-Thomas, A., Stohl, A., and Fromm, M.: Injection in the lower stratosphere of biomass fire emissions followed by long-range transport: a MOZAIC case study, Atmospheric Chemistry and Physics, 9, 5829-5846, 2009.
Cape, J. N.: Surface ozone concentrations and ecosystem health: Past trends and a guide to future projections, Science of the Total Environment, 400, 257-269, 10.1016/j.scitotenv.2008.06.025, 2008.
Cape, J. N., Hamilton, R., and Heal, M. R.: Reactive uptake of ozone at simulated leaf surfaces: Implications for [`]non-stomatal' ozone flux, Atmospheric Environment, 43, 1116-1123, 2009.
Carpenter, L. J.: Iodine in the marine boundary layer, Chem. Rev., 103, 4953 - 4962, 2003.
Carpenter, L. J., Fleming, Z. L., Read, K. A., Lee, J. D., Moller, S. J., Hopkins, J. R., Purvis, R. M., Lewis, A. C., Mueller, K., Heinold, B., Herrmann, H., Fomba, K. W., van Pinxteren, D., Mueller, C., Tegen, I., Wiedensohler, A., Mueller, T., Niedermeier, N., Achterberg, E. P., Patey, M. D., Kozlova, E. A., Heimann, M., Heard, D. E., Plane, J. M. C., Mahajan, A., Oetjen, H., Ingham, T., Stone, D., Whalley, L. K., Evans, M. J., Pilling, M. J., Leigh, R. J., Monks, P. S., Karunaharan, A., Vaughan, S., Arnold, S. R., Tschritter, J., Poehler, D., Friess, U., Holla, R., Mendes, L. M., Lopez, H., Faria, B., Manning, A. J., and Wallace, D. W. R.: Seasonal characteristics of tropical marine boundary layer air measured at the Cape Verde Atmospheric Observatory, Journal of Atmospheric Chemistry, 67, 87-140, 10.1007/s10874-011-9206-1, 2010.
Carpenter, L. J., MacDonald, S. M., Shaw, M. D., Kumar, R., Saunders, R. W., Parthipan, R., Wilson, J., and Plane, J. M. C.: Atmospheric iodine levels influenced by sea surface emissions of inorganic iodine, Nature Geoscience, 6, 108-111, 10.1038/ngeo1687, 2013.
Carslaw, D. C.: On the changing seasonal cycles and trends of ozone at Mace Head, Ireland, Atmos. Chem. Phys, 5, 3441-3450, 2005.
Carslaw, D. C., Beevers, S. D., Tate, J. E., Westmoreland, E. J., and Williams, M. L.: Recent evidence concerning higher NO(x) emissions from passenger cars and light duty vehicles, Atmospheric Environment, 45, 7053-7063, 10.1016/j.atmosenv.2011.09.063, 2011.
Carter, W. P. L., and Seinfeld, J. H.: Winter ozone formation and VOC incremental reactivities in the Upper Green River Basin of Wyoming, Atmospheric Environment, 50, 255-266, 10.1016/j.atmosenv.2011.12.025, 2012.
Carvalho, A., Monteiro, A., Flannigan, M., Solman, S., Miranda, A. I., and Borrego, C.: Forest fires in a changing climate and their impacts on air quality, Atmospheric Environment, 45, 5545-5553, 10.1016/j.atmosenv.2011.05.010, 2011.

Caulton, D. R., Shepson, P. B., Santoro, R. L., Sparks, J. P., Howarth, R. W., Ingraffea, A. R., Cambaliza, M. O. L., Sweeney, C., Karion, A., Davis, K. J., Stirm, B. H., Montzka, S. A., and Miller, B. R.: Toward a better understanding and quantification of methane emissions from shale gas development, Proc. Natl. Acad. Sci. U. S. A., 111, 6237-6242, 10.1073/pnas.1316546111, 2014.
Chakraborty, T., Beig, G., Dentener, F. J., and Wild, O.: Atmospheric transport of ozone between Southern and Eastern Asia, The Science of the total environment, 523, 28-39, 10.1016/j.scitotenv.2015.03.066, 2015.
Chameides, W. L., and Walker, J. C. G.: A photochemical theory for tropospheric ozone, J. Geophys. Res., 78, 8751-8760, 1973.
Chang, H. M., Chang, L. F. W., and Jeng, F. T.: Interfacial transfer resistances of ozone dry deposition over agricultural soil of Tainan County, Taiwan, Environmental Engineering Science, 19, 133-141, 2002.
Chang, W., Heikes, B. G., and Lee, M.: Ozone deposition to the sea surface: chemical enhancement and wind speed dependence, Atmospheric Environment, 38, 1053-1059, 2004.
Chatfield, R., and Harrison, H.: Ozone in the remote troposphere - mixing versus photochemistry, Journal of Geophysical Research-Oceans and Atmospheres, 81, 421-423, 10.1029/JC081i003p00421, 1976.
Chelani, A. B.: Persistence analysis of extreme CO, NO_2 and O_3 concentrations in ambient air of Delhi, Atmospheric Research, 108, 128-134, 10.1016/j.atmosres.2012.02.001, 2012.
Chevallier, F., Fortems, A., Bousquet, P., Pison, I., Szopa, S., Devaux, M., and Hauglustaine, D. A.: African CO emissions between years 2000 and 2006 as estimated from MOPITT observations, Biogeosciences, 6, 103-111, 2009.
Choi, K. C., Lee, J. J., Bae, C. H., Kim, C. H., Kim, S., Chang, L. S., Ban, S. J., Lee, S. J., Kim, J., and Woo, J. H.: Assessment of transboundary ozone contribution toward South Korea using multiple source-receptor modeling techniques, Atmospheric Environment, 92, 118-129, 10.1016/j.atmosenv.2014.03.055, 2014.
Choi, Y., Wang, Y., Zeng, T., Martin, R. V., Kurosu, T. P., and Chance, K.: Evidence of lightning NOx and convective transport of pollutants in satellite observations over North America, Geophys. Res. Lett., 32, L02805, 2005.
Chou, C., Wu, T. C., and Tan, P. H.: Changes in gross moist stability in the tropics under global warming, Climate Dynamics, 41, 2481-2496, 10.1007/s00382-013-1703-2, 2013.
Cifuentes, L., Borja-Aburto, V. H., Gouveia, N., Thurston, G., and Davis, D. L.: Assessing the health benefits of urban air pollution reductions associated with climate change mitigation (2000-2020): Santiago, Sao Paulo, Mexico City, and New York City, Environmental Health Perspectives, 109, 419-425, 10.2307/3434790, 2001.
Clifton, O. E., Fiore, A. M., Correa, G., Horowitz, L. W., and Naik, V.: Twenty-first century reversal of the surface ozone seasonal cycle over the northeastern United States, Geophysical Research Letters, 41, 7343-7350, 10.1002/2014gl061378, 2014.
Coe, H., Gallagher, M. W., Choularton, T. W., and Dore, C.: Canopy scale measurements of stomatal and cuticular o3 uptake by sitka spruce, Atmospheric Environment, 29, 1413-1423, 1995.
Colette, A., Granier, C., Hodnebrog, O., Jakobs, H., Maurizi, A., Nyiri, A., Bessagnet, B., D'Angiola, A., D'Isidoro, M., Gauss, M., Meleux, F., Memmesheimer, M., Mieville, A., Rouil, L., Russo, F., Solberg, S., Stordal, F., and Tampieri, F.: Air quality trends in Europe over the past decade: a first multi- model assessment, Atmospheric Chemistry and Physics, 11, 11657-11678, 10.5194/acp-11-11657-2011, 2011.
Colette, A., Granier, C., Hodnebrog, O., Jakobs, H., Maurizi, A., Nyiri, A., Rao, S., Amann, M., Bessagnet, B., D'Angiola, A., Gauss, M., Heyes, C., Klimont, Z., Meleux, F., Memmesheimer, M., Mieville, A., Rouïl, L., Russo, F., Schucht, S., Simpson, D., Stordal, F., Tampieri, F., and Vrac, M.: Future air quality in Europe: a multi-model assessment of projected exposure to ozone, Atmos. Chem. Phys., 12, 10613-10630, 2012.

Colette, A., Bessagnet, B., Vautard, R., Szopa, S., Rao, S., Schucht, S., Klimont, Z., Menut, L., Clain, G., Meleux, F., Curci, G., and Rouïl, L.: European atmosphere in 2050, a regional air quality and climate perspective under CMIP5 scenarios, Atmos. Chem. Phys., 13, 7451-7471, 2013.
Colette, A., Bessagnet, B., Meleux, F., Terrenoire, E., and Rouïl, L.: Frontiers in air quality modelling, Geosci. Model Dev., 7, 203-210, 10.5194/gmd-7-203-2014, 2014.
Collins, W. J., Sitch, S., and Boucher, O.: How vegetation impacts affect climate metrics for ozone precursors, Journal of Geophysical Research-Atmospheres, 115, 10.1029/2010jd014187, 2010.
Collins, W. J., Fry, M. M., Yu, H., Fuglestvedt, J. S., Shindell, D. T., and West, J. J.: Global and regional temperature-change potentials for near-term climate forcers, Atmospheric Chemistry and Physics, 13, 2471-2485, 10.5194/acp-13-2471-2013, 2013.
Cook, P. A., Savage, N. H., Turquety, S., Carver, G. D., O'Connor, F. M., Heckel, A., D., S., Whalley, L. K., Parker, A. E., Schlager , H., Singh, H. B., Avery, M. A., Sachse, G. W., Brune, W., Richter, A., Burrows, J. P., Purvis, R., Lewis, A. C., Reeves, C. E., Monks, P. S., Levine, J. S., and Pyle, D. M.: Forest fire plumes over the North Atlantic: p-TOMCAT model simulations with aircraft and satellite measurements from the ITOP/ICARTT campaign, J. Geophys. Res., 112, D10S43, doi:10.1029/2006JD007563., 2007.
Cooper, O. R., Trainer, M., Thompson, A. M., Oltmans, S. J., Tarasick, D. W., Witte, J. C., Stohl, A., Eckhardt, S., Lelieveld, J., Newchurch, M. J., Johnson, B. J., Portmann, R. W., Kalnajs, L., Dubey, M. K., Leblanc, T., McDermid, I. S., Forbes, G., Wolfe, D., Carey-Smith, T., Morris, G. A., Lefer, B., Rappengluck, B., Joseph, E., Schmidlin, F., Meagher, J., Fehsenfeld, F. C., Keating, T. J., Van Curen, R. A., and Minschwaner, K.: Evidence for a recurring eastern North America upper tropospheric ozone maximum during summer, Journal of Geophysical Research-Atmospheres, 112, 10.1029/2007jd008710, 2007.
Cooper, O. R., Eckhardt, S., Crawford, J. H., Brown, C. C., Cohen, R. C., Bertram, T. H., Wooldridge, P., Perring, A., Brune, W. H., Ren, X., Brunner, D., and Baughcum, S. L.: Summertime buildup and decay of lightning NOx and aged thunderstorm outflow above North America, Journal of Geophysical Research-Atmospheres, 114, 10.1029/2008jd010293, 2009.
Cooper, O. R., Parrish, D. D., Ziemke, J., Balashov, N. V., Cupeiro, M., Galbally, I. E., Gilge, S., Horowitz, L., Jensen, N. R., Lamarque, J. F., Naik, V., Oltmans, S. J., Schwab, J., Shindell, D. T., Thompson, A. M., Thouret, V., Wang, Y., and Zbinden, R. M.: Global distribution and trends of tropospheric ozone: An observation-based review, Elem. Sci. Anth., 2, 000029, 10.12952/journal.elementa.000029, 2014.
Corbett, J. J., Lack, D. A., Winebrake, J. J., Harder, S., Silberman, J. A., and Gold, M.: Arctic shipping emissions inventories and future scenarios, Atmospheric Chemistry and Physics, 10, 9689-9704, 10.5194/acp-10-9689-2010, 2010.
Council, C. o. t. S. o. I. T. o. A. P. N. R.: Global Sources of Local Pollution:An Assessment of Long-Range Transport of Key Air Pollutants to and from the United States, The National Academies Press, 2009a.
Council, N. R.: Global Sources of Local pollution: An Assessment of Long-Range Transport of Key Air Pollutants to and from the United States, The National Academies Press, 2009b.
Cox, P., Delao, A., Komorniczak, A., and Weller, R.: The California Almanac of Emissions and Air Quality, California Air Resources Board, 2009.
Coyle, M.: The Gaseous Exchange of Ozone

at Terrestrial Surfaces: Non-stomatal Deposition to Grassland, School of Geosciences, Faculty of Science and Engineering, The University of Edinburgh, Edinburgh, 270 pp., 2005.
Coyle, M., Nemitz, E., Storeton-West, R., Fowler, D., and Cape, J. N.: Measurements of ozone deposition to a potato canopy, Agric. For. Meteorol., 149, 655-666, 10.1016/j.agrformet.2008.10.020, 2009.
Crawford-Brown, D., Barker, T., Anger, A., and Dessens, O.: Ozone and PM related health co-benefits of climate change policies in Mexico, Environ. Sci. Policy, 17, 33-40, 10.1016/j.envsci.2011.12.006, 2012.
Criegee, R.: Die Umlagerung der Dekalin-peroxydester als Folge von kationischem Sauerstoff, Justus Liebigs Annalen der Chemie, 560, 127-135, 10.1002/jlac.19485600106, 1948.

Cristofanelli, P., Bracci, A., Sprenger, M., Marinoni, A., Bonafè, U., Calzolari, F., Duchi, R., Laj, P., Pichon, J. M., Roccato, F., Venzac, H., Vuillermoz, E., and Bonasoni, P.: Tropospheric ozone variations at the Nepal Climate Observatory-Pyramid (Himalayas, 5079 m a.s.l.) and influence of deep stratospheric intrusion events, Atmos. Chem. Phys., 10, 6537-6549, 10.5194/acp-10-6537-2010, 2010.
Crounse, J. D., Paulot, F., Kjaergaard, H. G., and Wennberg, P. O.: Peroxy radical isomerization in the oxidation of isoprene, Physical Chemistry Chemical Physics, 13, 13607-13613, 2011.
Crutzen, P. J.: Photochemical reactions initiated by and influencing ozone in the unpolluted troposphere, Tellus, 26, 47-57, 1973.
Cuevas, E., Gonzalez, Y., Rodriguez, S., Guerra, J. C., Gomez-Pelaez, A. J., Alonso-Perez, S., Bustos, J., and Milford, C.: Assessment of atmospheric processes driving ozone variations in the subtropical North Atlantic free troposphere, Atmospheric Chemistry and Physics, 13, 1973-1998, 10.5194/acp-13-1973-2013, 2013.
Cui, H. Y., Su, J. W., Wei, J. N., Hu, Y. J., and Ge, F.: Elevated O_3 enhances the attraction of whitefly-infested tomato plants to Encarsia formosa, Sci Rep, 4, 10.1038/srep05350, 2014.
Cuvelier, C., Thunis, P., Vautard, R., Amann, M., Bessagnet, B., Bedogni, M., Berkowicz, R., Brandt, J., Brocheton, F., Builtjes, P., Coppalle, A., Denby, B., G., D., Graf, A., Hellmuth, O., Honoré, C., Hodzic, A., Jonson, J., Kerschbaumer, A., de Leeuw, F., Minguzzi, E., Moussiopoulos, N., Pertot, C., Pirovano, G., Rouil, L., Schaap, M., Stern, R., Tarrason, L., Vignati, E., Volta, M., White, L., Wind, P., and Zuber, A.: CityDelta: A model intercomparison to explore the impact of emission reductions in 2010 in European cities, Atmos. Environ., 41, 189-207, doi:10.1016/j.atmosenv.2006.07.036, 2007.
Dalsoren, S. B., Samset, B. H., Myhre, G., Corbett, J. J., Minjares, R., Lack, D., and Fuglestvedt, J. S.: Environmental impacts of shipping in 2030 with a particular focus on the Arctic region, Atmospheric Chemistry and Physics, 13, 1941-1955, 10.5194/acp-13-1941-2013, 2013.
Dalsøren, S. B., Eide, M. S., Myhre, G., Endresen, Ø., Isaksen, I. S. A., and Fuglestvedt, J. S.: Impacts of the Large Increase in International Ship Traffic 2000–2007 on Tropospheric Ozone and Methane, Environ. Sci. Technol., 44, 2482-2489, 10.1021/es902628e, 2010.
Danielsen, E. F.: Stratospheirc-tropospheirc exchange based on radioactivity, ozone and potential vorticity, J. Atmos. Sci., 25, 502-518, 1968.
Davison, B., Brunner, A., Ammann, C., Spirig, C., Jocher, M., and Neftel, A.: Cut-induced VOC emissions from agricultural grasslands, Plant Biol., 10, 76-85, 10.1055/s-2007-965043, 2008.
de Fatima, A. M., Fornaro, A., Dias de, F. E., Mazzoli, C. R., Martins, L. D., Boian, C., Oliveira, M. G. L., Peres, J., Carbone, S., Alvala, P., and Leme, N. P.: Ozone sounding in the Metropolitan Area of Sao Paulo, Brazil: Wet and dry season campaigns of 2006, Atmospheric Environment, 61, 627-640, 10.1016/j.atmosenv.2012.07.083, 2012.
de Ruyter de Wildt, M., Eskes, H., and Boersma, K. F.: The global economic cycle and satellite-derived NO_2 trends over shipping lanes, Geophys. Res. Lett., 39, L01802, 10.1029/2011gl049541, 2012.
Defra: Air Quality Statistics in the UK 1987-2012, Defra, London, 2013.
Dempsey, F.: Observations of stratospheric O_3 intrusions in air quality monitoring data in Ontario, Canada, Atmospheric Environment, 98, 111-122, http://dx.doi.org/10.1016/j.atmosenv.2014.08.024, 2014.
Derwent, R., Beevers, S., Chemel, C., Cooke, S., Francis, X., Fraser, A., Heal, M. R., Kitwiroon, N., Lingard, J., Redington, A., Sokhi, R., and Vieno, M.: Analysis of UK and European NOx and VOC emission scenarios in the Defra model intercomparison exercise, Atmospheric Environment, 94, 249-257, 10.1016/j.atmosenv.2014.05.036, 2014.
Derwent, R. G., Collins, W. J., Johnson, C. E., and Stevenson, D. S.: Transient behaviour of tropospheric ozone precursors in a global 3-D CTM and their indirect greenhouse effects, Climatic Change, 49, 463-487, 10.1023/a:1010648913655, 2001.
Derwent, R. G., Simmonds, P. G., O'Doherty, S., Stevenson, D. S., Collins, W. J., Sanderson, M. G., Johnson, C. E., Dentener, F., Cofala, J., Mechler, R., and Amann, M.: External influences on Europe's air quality: Baseline methane, carbon monoxide and ozone from 1990 to 2030 at Mace Head, Ireland, Atmospheric Environment, 40, 844-855, 10.1016/j.atmosenv.2005.09.077, 2006.

Derwent, R. G., Witham, C. S., Utembe, S. R., Jenkin, M. E., and Passant, N. R.: Ozone in Central England: the impact of 20 years of precursor emission controls in Europe, Environ. Sci. Policy, 13, 195-204, 10.1016/j.envsci.2010.02.001, 2010.
Derwent, R. G., and Hjellbrekke, A.-G.: Air Pollution by Ozone Across Europe, Urban Air Quality in Europe, edited by: Viana, M., Springer, 2013.
Di Carlo, P., Brune, W. H., Martinez, M., Harder, H., Lesher, R., Ren, X. R., Thornberry, T., Carroll, M. A., Young, V., Shepson, P. B., Riemer, D., Apel, E., and Campbell, C.: Missing OH reactivity in a forest: Evidence for unknown reactive biogenic VOCs, Science, 304, 722-725, 2004.
Dibble, T. S.: Failures and limitations of quantum chemistry for two key problems in the atmospheric chemistry of peroxy radicals, Atmospheric Environment, 42, 5837-5848, 2008.
Dix, B., Baidara, S., Bresch, J. F., Hall, S. R., Schmidt, K. S., Wang, S., and Volkamer, R.: Detection of iodine monoxide in the tropical free troposphere, Proc. Natl. Acad. Sci. U. S. A., 110, 2035-2040, 10.1073/pnas.1212386110, 2013.
Doche, C., Dufour, G., Foret, G., Eremenko, M., Cuesta, J., Beekmann, M., and Kalabokas, P.: Summertime tropospheric-ozone variability over the Mediterranean basin observed with IASI, Atmos. Chem. Phys., 14, 10589-10600, 10.5194/acp-14-10589-2014, 2014.
Doherty, R. M., Stevenson, D. S., Johnson, C. E., Collins, W. J., and Sanderson, M. G.: Tropospheric ozone and El Nino-Southern Oscillation: Influence of atmospheric dynamics, biomass burning emissions, and future climate change, Journal of Geophysical Research-Atmospheres, 111, 10.1029/2005jd006849, 2006.
Doherty, R. M., Wild, O., Shindell, D. T., Zeng, G., MacKenzie, I. A., Collins, W. J., Fiore, A. M., Stevenson, D. S., Dentener, F. J., Schultz, M. G., Hess, P., Derwent, R. G., and Keating, T. J.: Impacts of climate change on surface ozone and intercontinental ozone pollution: A multi-model study, Journal of Geophysical Research: Atmospheres, 118, 3744-3763, 10.1002/jgrd.50266, 2013.
Droge, R., Kuenen, J. J. P., Pulles, M. P. J., and Heslinga, D. C.: The revised EMEP/EEA Guidebook compared to the country specific inventory system in the Netherlands, Atmospheric Environment, 44, 3503-3510, 10.1016/j.atmosenv.2010.06.020, 2010.
Duncan, B. N., Martin, R. V., Staudt, A. C., Yevich, R., and Logan, J. A.: Interannual and seasonal variability of biomass burning emissions constrained by satellite observations, Journal of Geophysical Research-Atmospheres, 108, 10.1029/2002jd002378, 2003.
Duncan, B. N., Prados, A. I., Lamsal, L. N., Liu, Y., Streets, D. G., Gupta, P., Hilsenrath, E., Kahn, R. A., Nielsen, J. E., Beyersdorf, A. J., Burton, S. P., Fiore, A. M., Fishman, J., Henze, D. K., Hostetler, C. A., Krotkov, N. A., Lee, P., Lin, M. Y., Pawson, S., Pfister, G., Pickering, K. E., Pierce, R. B., Yoshida, Y., and Ziemba, L. D.: Satellite data of atmospheric pollution for US air quality applications: Examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid, Atmospheric Environment, 94, 647-662, 10.1016/j.atmosenv.2014.05.061, 2014.
Dunker, A. M., Koo, B., and Yarwood, G.: Sensitivity of atmospheric models to rate terms within complex chemical mechanisms, Atmospheric Environment, 98, 224-230, http://dx.doi.org/10.1016/j.atmosenv.2014.08.074, 2014.
Eckhardt, S., Stohl, A., Beirle, S., Spichtinger, N., James, P., Forster, C., Junker, C., Wagner, T., Platt, U., and Jennings, S. G.: The North Atlantic Oscillation controls air pollution transport to the Arctic, Atmospheric Chemistry and Physics, 3, 1769-1778, 2003.
Edwards, P. M., Young, C. J., Aikin, K., deGouw, J., Dube, W. P., Geiger, F., Gilman, J., Helmig, D., Holloway, J. S., Kercher, J., Lerner, B., Martin, R., McLaren, R., Parrish, D. D., Peischl, J., Roberts, J. M., Ryerson, T. B., Thornton, J., Warneke, C., Williams, E. J., and Brown, S. S.: Ozone photochemistry in an oil and natural gas extraction region during winter: simulations of a snow-free season in the Uintah Basin, Utah, Atmospheric Chemistry and Physics, 13, 8955-8971, 10.5194/acp-13-8955-2013, 2013.
Edwards, P. M., Brown, S. S., Roberts, J. M., Ahmadov, R., Banta, R. M., deGouw, J. A., Dube, W. P., Field, R. A., Flynn, J. H., Gilman, J. B., Graus, M., Helmig, D., Koss, A., Langford, A. O., Lefer, B. L., Lerner, B. M., Li, R., Li, S.-M., McKeen, S. A., Murphy, S. M., Parrish, D. D., Senff, C. J., Soltis, J., Stutz, J., Sweeney, C., Thompson, C. R., Trainer, M. K., Tsai, C., Veres, P. R., Washenfelder, R. A., Warneke,

C., Wild, R. J., Young, C. J., Yuan, B., and Zamora, R.: High winter ozone pollution from carbonyl photolysis in an oil and gas basin, Nature, advance online publication, 10.1038/nature13767, 2014.
EEA: Air Pollution in Europe 1990-2004, European Environment Agency: Copenhagen, 2007.
EEA: Assessment of ground-level ozone in EEA member countries, with a focus on long-term trends, 2009.
EEA: Air quality in Europe — 2011 report, EEA, 80, 2011.
Ehhalt, D. H.: Photooxidation of trace gases in the troposphere, Physical Chemistry Chemical Physics, 1, 5401-5408, 1999.
Elansky, N. F., Mokhov, II, Belikov, I. B., Berezina, E. V., Elokhov, A. S., Ivanov, V. A., Pankratova, N. V., Postylyakov, O. V., Safronov, A. N., Skorokhod, A. I., and Shumskii, R. A.: Gaseous admixtures in the atmosphere over Moscow during the 2010 summer, Izv. Atmos. Ocean. Phys., 47, 672-681, 10.1134/s000143381106003x, 2011.
Elbern, H., Strunk, A., Schmidt, H., and Talagrand, O.: Emission rate and chemical state estimation by 4-dimensional variational inversion, Atmospheric Chemistry and Physics, 7, 3749-3769, 2007.
Elguindi, N., Clark, H., Ordonez, C., Thouret, V., Flemming, J., Stein, O., Huijnen, V., Moinat, P., Inness, A., Peuch, V. H., Stohl, A., Turquety, S., Athier, G., Cammas, J. P., and Schultz, M.: Current status of the ability of the GEMS/MACC models to reproduce the tropospheric CO vertical distribution as measured by MOZAIC, Geosci. Model Dev., 3, 501-518, 10.5194/gmd-3-501-2010, 2010.
Emberson, L. D., Ashmore, M. R., Cambridge, H. M., Simpson, D., and Tuovinen, J. P.: Modelling stomatal ozone flux across Europe, Environmental Pollution, 109, 403-413, 10.1016/s0269-7491(00)00043-9, 2000.
Emmons, L. K., Hess, P., Klonecki, A., Tie, X., Horowitz, L., Lamarque, J. F., Kinnison, D., Brasseur, G., Atlas, E., Browell, E., Cantrell, C., Eisele, F., Mauldin, R. L., Merrill, J., Ridley, B., and Shetter, R.: Budget of tropospheric ozone during TOPSE from two chemical transport models, Journal of Geophysical Research-Atmospheres, 108, 10.1029/2002jd002665, 2003.
Emmons, L. K., Arnold, S. R., Monks, S., Huijnen, V., Tilmes, S., Law, K. S., Thomas, J. L., Raut, J.-C., Bouarar, I., Turquety, S., Long, Y., Duncan, B., Steenrod, S., Strode, S., Flemming, J., Mao, J., Langner, J., Thompson, A. M., Tarasick, D., Apel, E. C., Blake, D. R., Cohen, R. C., Dibb, J., Diskin, G. S., Fried, A., Hall, S. R., Huey, L. G., Weinheimer, A. J., Wisthaler, A., Mikoviny, T., Nowak, J., Peischl, J., Roberts, J. M., Ryerson, T., Warneke, C., and Helmig, D.: The POLARCAT Model Intercomparison Project (POLMIP): Overview and evaluation with observations Atmos. Chem. Phys. Discuss., 2014.
EPA: Assessment of the impacts of global change on regional U.S. air quality: a synthesis of climate change impacts on ground-level ozone, National Center for Environmental Assessment Washington DC, 2009.
U.S. Environmental Protection Agency (2014), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012: http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf and http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHGInventory-2014-Annexes.pdf., 2014.
Erisman, J. W., Vanpul, A., and Wyers, P.: Parameterrizaton of surface-resistance for the quantification of atmospheric deposition of acidifying pollutants and ozone, Atmospheric Environment, 28, 2595-2607, 10.1016/1352-2310(94)90433-2, 1994.
Erisman, J. W., Galloway, J. N., Seitzinger, S., Bleeker, A., Dise, N. B., Petrescu, A. M. R., Leach, A. M., and de Vries, W.: Consequences of human modification of the global nitrogen cycle, Philos. Trans. R. Soc. B-Biol. Sci., 368, 10.1098/rstb.2013.0116, 2013.
Escudero, M., Lozano, A., Hierro, J., Valle, J. d., and Mantilla, E.: Urban influence on increasing ozone concentrations in a characteristic Mediterranean agglomeration, Atmospheric Environment, 99, 322-332, http://dx.doi.org/10.1016/j.atmosenv.2014.09.061, 2014.
Ewing, S. A., Christensen, J. N., Brown, S. T., Vancuren, R. A., Cliff, S. S., and Depaolo, D. J.: Pb Isotopes as an Indicator of the Asian Contribution to Particulate Air Pollution in Urban California, Environ. Sci. Technol., 44, 8911-8916, 10.1021/es101450t, 2010.

Eyring, V., Isaksen, I. S. A., Berntsen, T., Collins, W. J., Corbett, J. J., Endresen, Ø., Grainger, R. G., Moldanova, J., Schlager, H., and Stevenson, D. S.: Assessment of Transport Impacts on Climate and Ozone: Shipping. , Atmos. Environ., 44, 4735-4771 2010.

Fabian, P., and Pruchniewicz, P. G.: Meridional distribution of ozone in the troposphere and its seasonal variations, J. Geophys. Res. , 82, 2063-2073, 1977.

Fares, S., Weber, R., Park, J.-H., Gentner, D., Karlik, J., and Goldstein, A. H.: Ozone deposition to an orange orchard: Partitioning between stomatal and non-stomatal sinks, Environmental Pollution, 169, 258-266, 10.1016/j.envpol.2012.01.030, 2012.

Fares, S., Matteucci, G., Mugnozza, G. S., Morani, A., Calfapietra, C., Salvatori, E., Fusaro, L., Manes, F., and Loreto, F.: Testing of models of stomatal ozone fluxes with field measurements in a mixed Mediterranean forest, Atmospheric Environment, 67, 242-251, 10.1016/j.atmosenv.2012.11.007, 2013a.

Fares, S., Matteucci, G., Scarascia Mugnozza, G., Morani, A., Calfapietra, C., Salvatori, E., Fusaro, L., Manes, F., and Loreto, F.: Testing of models of stomatal ozone fluxes with field measurements in a mixed Mediterranean forest, Atmospheric Environment, 67, 242-251, http://dx.doi.org/10.1016/j.atmosenv.2012.11.007, 2013b.

Farquhar, G. D., Schulze, E. D., and Kuppers, M.: Response to humidity by stomata of Nicotiana-Gluaca L and Corylus-Avellana L are consisutent with the optimization of carbon-dioxide uptake with repect to water-loss, Aust. J. Plant Physiol., 7, 315-327, 1980.

Felzer, B., Cronin, T., Reilly, J. M., and Wang, X.: Impact of ozone on trees and crops, Comptes Rendus Geoscience, 339, 784-798, 2007.

Field, R. A., Soltis, J., and Murphy, S.: Air quality concerns of unconventional oil and natural gas production, Environ. Sci.-Process Impacts, 16, 954-969, 10.1039/c4em00081a, 2014.

Finlayson-Pitts, B. J.: Halogens in the Troposphere, Analytical Chemistry, 82, 770-776, 10.1021/ac901478p, 2010.

Finley, B. D., and Saltzman, E. S.: Observations of Cl_2, Br_2, and I_2 in coastal marine air, Journal of Geophysical Research-Atmospheres, 113, 10.1029/2008jd010269, 2008.

Finney, D. L., Doherty, R. M., Wild, O., Huntrieser, H., Pumphrey, H. C., and Blyth, A. M.: Using cloud ice flux to parametrise large-scale lightning, Atmos. Chem. Phys. Discuss., 14, 17817-17856, 10.5194/acpd-14-17817-2014, 2014.

Fiore, A. M., Jacob, D. J., Bey, I., Yantosca, R. M., Field, B. D., Fusco, A. C., and Wilkinson, J. G.: Background ozone over the United States in summer: Origin, trend, and contribution to pollution episodes, Journal of Geophysical Research-Atmospheres, 107, 4275

10.1029/2001jd000982, 2002.

Fiore, A. M., West, J. J., Horowitz, L. W., Naik, V., and Schwarzkopf, M. D.: Characterizing the tropospheric ozone response to methane emission controls and the benefits to climate and air quality, Journal of Geophysical Research-Atmospheres, 113, 10.1029/2007jd009162, 2008.

Fiore, A. M., Dentener, F. J., Wild, O., Cuvelier, C., Schultz, M. G., Hess, P., Textor, C., Schulz, M., Doherty, R. M., Horowitz, L. W., MacKenzie, I. A., Sanderson, M. G., Shindell, D. T., Stevenson, D. S., Szopa, S., Van Dingenen, R., Zeng, G., Atherton, C., Bergmann, D., Bey, I., Carmichael, G., Collins, W. J., Duncan, B. N., Faluvegi, G., Folberth, G., Gauss, M., Gong, S., Hauglustaine, D., Holloway, T., Isaksen, I. S. A., Jacob, D. J., Jonson, J. E., Kaminski, J. W., Keating, T. J., Lupu, A., Marmer, E., Montanaro, V., Park, R. J., Pitari, G., Pringle, K. J., Pyle, J. A., Schroeder, S., Vivanco, M. G., Wind, P., Wojcik, G., Wu, S., and Zuber, A.: Multimodel estimates of intercontinental source-receptor relationships for ozone pollution, Journal of Geophysical Research-Atmospheres, 114, D04301, 10.1029/2008jd010816, 2009.

Fiore, A. M., Levy, H., and Jaffe, D. A.: North American isoprene influence on intercontinental ozone pollution, Atmospheric Chemistry and Physics, 11, 1697-1710, 10.5194/acp-11-1697-2011, 2011.

Fiore, A. M., Naik, V., Spracklen, D. V., Steiner, A., Unger, N., Prather, M., Bergmann, D., Cameron-Smith, P. J., Cionni, I., Collins, W. J., Dalsoren, S., Eyring, V., Folberth, G. A., Ginoux, P., Horowitz, L. W., Josse, B., Lamarque, J.-F., MacKenzie, I. A., Nagashima, T., O'Connor, F. M., Righi, M., Rumbold, S.

7113 T., Shindell, D. T., Skeie, R. B., Sudo, K., Szopa, S., Takemura, T., and Zeng, G.: Global air quality and
7114 climate, Chemical Society Reviews, 41, 6663-6683, 2012a.
7115 Fiore, A. M., Naik, V., Spracklen, D. V., Steiner, A., Unger, N., Prather, M., Bergmann, D., Cameron-
7116 Smith, P. J., Cionni, I., Collins, W. J., Dalsoren, S., Eyring, V., Folberth, G. A., Ginoux, P., Horowitz, L.
7117 W., Josse, B., Lamarque, J. F., MacKenzie, I. A., Nagashima, T., O'Connor, F. M., Righi, M., Rumbold, S.
7118 T., Shindell, D. T., Skeie, R. B., Sudo, K., Szopa, S., Takemura, T., and Zeng, G.: Global air quality and
7119 climate, Chemical Society Reviews, 41, 6663-6683, 10.1039/c2cs35095e, 2012b.
7120 Fiore, A. M., Oberman, J. T., Lin, M. Y., Zhang, L., Clifton, O. E., Jacob, D. J., Naik, V., Horowitz, L. W.,
7121 Pinto, J. P., and Milly, G. P.: Estimating North American background ozone in U.S. surface air with two
7122 independent global models: Variability, uncertainties, and recommendations, Atmospheric
7123 Environment, 96, 284-300, http://dx.doi.org/10.1016/j.atmosenv.2014.07.045, 2014.
7124 Fiscus, E. L., Fitzgarrald, L. B., and Burkey, K. O.: Crop responses to ozone: uptake, modes of action,
7125 carbon assimilation and partitioning, Plant, Cell and Environment, 28, 997-1011, 2005.
7126 Fishman, J., Watson, C. E., Larsen, J. C., and Logan, J. A.: Distribution of Tropospheric Ozone
7127 Determined from Satellite Data, Journal of Geophysical Research-Atmospheres, 95, 3599-3617, 1990.
7128 Fishman, J., Belina, K. M., and Encarnación, C. H.: The St. Louis Ozone Gardens: Visualizing the Impact
7129 of a Changing Atmosphere, Bulletin of the American Meteorological Society, 95, 1171-1176,
7130 10.1175/bams-d-13-00009.1, 2014.
7131 Foret, G., Eremenko, M., Cuesta, J., Sellitto, P., Barré, J., Gaubert, B., Coman, A., Dufour, G., Liu, X.,
7132 Joly, M., Doche, C., and Beekmann, M.: Ozone pollution: What can we see from space? A case study,
7133 Journal of Geophysical Research: Atmospheres, 119, 2013JD021340, 10.1002/2013jd021340, 2014.
7134 Fortems-Cheiney, A., Chevallier, F., Pison, I., Bousquet, P., Szopa, S., Deeter, M. N., and Clerbaux, C.:
7135 Ten years of CO emissions as seen from Measurements of Pollution in the Troposphere (MOPITT),
7136 Journal of Geophysical Research-Atmospheres, 116, 10.1029/2010jd014416, 2011.
7137 Fowler, D., Flechard, C., Cape, J. N., Storeton-West, R. L., and Coyle, M.: Measurements of ozone
7138 deposition to vegetation quantifying the flux, the stomatal and non-stomatal components, Water Air
7139 Soil Pollut., 130, 63-74, 10.1023/a:1012243317471, 2001.
7140 Fowler, D., Pilegaard, K., Sutton, M. A., Ambus, P., Raivonen, M., Duyzer, J., Simpson, D., Fagerli, H.,
7141 Fuzzi, S., Schjoerring, J. K., Granier, C., Neftel, A., Isaksen, I. S. A., Laj, P., Maione, M., Monks, P. S.,
7142 Burkhardt, J., Daemmgen, U., Neirynck, J., Personne, E., Wichink-Kruit, R., Butterbach-Bahl, K.,
7143 Flechard, C., Tuovinen, J. P., Coyle, M., Gerosa, G., Loubet, B., Altimir, N., Gruenhage, L., Ammann, C.,
7144 Cieslik, S., Paoletti, E., Mikkelsen, T. N., Ro-Poulsen, H., Cellier, P., Cape, J. N., Horvath, L., Loreto, F.,
7145 Niinemets, U., Palmer, P. I., Rinne, J., Misztal, P., Nemitz, E., Nilsson, D., Pryor, S., Gallagher, M. W.,
7146 Vesala, T., Skiba, U., Brueggemann, N., Zechmeister-Boltenstern, S., Williams, J., O'Dowd, C., Facchini,
7147 M. C., de Leeuw, G., Flossman, A., Chaumerliac, N., and Erisman, J. W.: Atmospheric composition
7148 change: Ecosystems-Atmosphere interactions, Atmospheric Environment, 43, 5193-5267,
7149 10.1016/j.atmosenv.2009.07.068, 2009.
7150 Fowler, D., Brunkreef, B., Fuzzi, S., Monks, P. S., Sutton, M. A., Brasseur, G. P., Friedrich, R., Passante,
7151 L. G., and J.M.Jimenez-Mingo: Research Findings in support of the EU Air Quality Review, Publications
7152 office of the European Union, Luxembourg, 2013a.
7153 Fowler, D., Coyle, M., Skiba, U., Sutton, M. A., Cape, J. N., Reis, S., Sheppard, L. J., Jenkins, A.,
7154 Grizzetti, B., Galloway, J. N., Vitousek, P., Leach, A., Bouwman, A. F., Butterbach-Bahl, K., Dentener,
7155 F., Stevenson, D., Amann, M., and Voss, M.: The global nitrogen cycle in the twenty-first century,
7156 Philos. Trans. R. Soc. B-Biol. Sci., 368, 10.1098/rstb.2013.0164, 2013b.
7157 Fowler, D., Steadman, C., Stevenson, D., Coyle, M., Rees, B., Skiba, U. M., Sutton, M., Cape, J. N.,
7158 Dore, T., Simpson, D., Zaehle, S., Stocker, B., Rinaldi, M., Facchini, C., Flechard, C., Nemitz, E., Twigg,
7159 M., Erisman, J. W., and Galloway, J.: Effects of global changes during the 21st century on the N cycle,
7160 Atmos Chem Phys Discuss, 15, 1747-1868, doi:10.5194/acpd-15-1747-2015, 2015.
7161 Francis, X. V., Chemel, C., Sokhi, R. S., Norton, E. G., Ricketts, H. M. A., and Fisher, B. E. A.:
7162 Mechanisms responsible for the build-up of ozone over South East England during the August 2003
7163 heatwave, Atmospheric Environment, 45, 6880-6890, 10.1016/j.atmosenv.2011.04.035, 2011.

Freitas, S. R., Longo, K. M., Chatfield, R. B., Latham, D., Silva Dias, M. A. F., Andreae, M. O., Prins, E., Gielow, R., and Carvalho Jr, J. A.: the sub-grid scale plume rise of vegetation fires in low resolution atmospheric transport models, Atmos. Chem. Phys., 7, 3385-3398, 2007.
Fromm, M., Lindsey, D. T., Servranckx, R., Yue, G., Trickl, T., Sica, R., Doucet, P., and Godin-Beekmann, S. E.: The untold story of pyrocumulonimbus, Bulletin of the American Meteorological Society, 91, 1193-1209, 10.1175/2010bams3004.1, 2010.
Frost, G. J., Ellison, G. B., and Vaida, V.: Organic peroxyl radical photolysis in the near-infrared: Effects on tropospheric chemistry, The Journal of Physical Chemistry A, 103, 10169-10178, 1999.
Frost, G. J., Falke, S. R., Granier, C., Keating, T., Lamarque, J. F., Melamed, M. L., Middleton, P., Petron, G., and Smith, S. J.: New Directions: Toward a community emissions approach, Atmospheric Environment, 51, 333-334, 10.1016/j.atmosenv.2012.01.055, 2012.
Fry, M. M., Naik, V., West, J. J., Schwarzkopf, M. D., Fiore, A. M., Collins, W. J., Dentener, F. J., Shindell, D. T., Atherton, C., Bergmann, D., Duncan, B. N., Hess, P., MacKenzie, I. A., Marmer, E., Schultz, M. G., Szopa, S., Wild, O., and Zeng, G.: The influence of ozone precursor emissions from four world regions on tropospheric composition and radiative climate forcing, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2011jd017134, 2012.
Fuentes, J. D., Gillespie, T. J., Denhartog, G., and Neumann, H. H.: Ozone Deposition onto a Deciduous Forest During Dry and Wet Conditions, Agricultural and Forest Meteorology, 62, 1-18, 1992.
Fuglestvedt, J. S., Shine, K. P., Berntsen, T., Cook, J., Lee, D. S., Stenke, A., Skeie, R. B., Velders, G. J. M., and Waitz, I. A.: Transport impacts on atmosphere and climate: Metrics, Atmospheric Environment, 44, 4648-4677, 10.1016/j.atmosenv.2009.04.044, 2010.
Fuhrer, J.: Ozone risk for crops and pastures in present and future climates, Naturwissenschaften, 96, 173-194, 10.1007/s00114-008-0468-7, 2009.
Fuzzi, S., Baltensperger, U., Carslaw, K., Decesari, S., Gon, H. D. V. d., Facchini, M. C., Fowler, D., Koren, I., Langford, B., Lohmann, U., Nemitz, E., Pandis, S., Riipinen, I., Rudich, Y., Schaap, M., Slowik, J., Spracklen, D. V., Vignati, E., Wild, M., Williams, M., and Gilardoni, S.: Particulate matter, air quality and climate: lessons learned and future needs., Atmos. Chem. Phys. Discus., 15, 521-744, doi:10.5194/acpd-15-521-2015, 2015.
Gallagher, M. W., Beswick, K. M., and Coe, H.: Ozone deposition to coastal waters, Quarterly Journal of the Royal Meteorological Society, 127, 539-558, 2001.
Galloway, J. N., Aber, J. D., Erisman, J. W., Seitzinger, S. P., Howarth, R. W., Cowling, E. B., and Cosby, B. J.: The nitrogen cascade, Bioscience, 53, 341-356, 10.1641/0006-3568(2003)053[0341:tnc]2.0.co;2, 2003.
Galloway, J. N., Dentener, F. J., Capone, D. G., Boyer, E. W., Howarth, R. W., Seitzinger, S. P., Asner, G. P., Cleveland, C. C., Green, P. A., Holland, E. A., Karl, D. M., Michaels, A. F., Porter, J. H., Townsend, A. R., and Vorosmarty, C. J.: Nitrogen cycles: past, present, and future, Biogeochemistry, 70, 153-226, 10.1007/s10533-004-0370-0, 2004.
Ganzeveld, L., Helmig, D., Fairall, C. W., Hare, J., and Pozzer, A.: Atmosphere-ocean ozone exchange: A global modeling study of biogeochemical, atmospheric, and waterside turbulence dependencies, Global Biogeochemical Cycles, 23, 10.1029/2008gb003301, 2009.
Garg, A., Shukla, P. R., and Kapshe, M.: The sectoral trends of multigas emissions inventory of India, Atmospheric Environment, 40, 4608-4620, 10.1016/j.atmosenv.2006.03.045, 2006.
Garny, H., Grewe, V., Dameris, M., Bodeker, G. E., and Stenke, A.: Attribution of ozone changes to dynamical and chemical processes in CCMs and CTMs, Geosci. Model Dev., 4, 271-286, 10.5194/gmd-4-271-2011, 2011.
Gaubert, B., Coman, A., Foret, G., Meleux, F., Ung, A., Rouil, L., Ionescu, A., Candau, Y., and Beekmann, M.: Regional scale ozone data assimilation using an ensemble Kalman filter and the CHIMERE chemical transport model, Geosci. Model Dev., 7, 283-302, 10.5194/gmd-7-283-2014, 2014.
Gauss, M., Myhre, G., Isaksen, I. S. A., Grewe, V., Pitari, G., Wild, O., Collins, W. J., Dentener, F. J., Ellingsen, K., Gohar, L. K., Hauglustaine, D. A., Iachetti, D., Lamarque, F., Mancini, E., Mickley, L. J., Prather, M. J., Pyle, J. A., Sanderson, M. G., Shine, K. P., Stevenson, D. S., Sudo, K., Szopa, S., and

Zeng, G.: Radiative forcing since preindustrial times due to ozone changes in the troposphere and the lower stratosphere. , Atmos. Chem. Phys., 6, 575-599, 2006.
Gerosa, G., Vitale, M., Finco, A., Manes, F., Denti, A. B., and Cieslik, S.: Ozone uptake by an evergreen Mediterranean Forest (Quercus ilex) in Italy. Part I: Micrometeorological flux measurements and flux partitioning, Atmospheric Environment, 39, 3255-3266, 2005.
Gerosa, G., Finco, A., Mereu, S., Vitale, M., Manes, F., and Denti, A. B.: Comparison of seasonal variations of ozone exposure and fluxes in a Mediterranean Holm oak forest between the exceptionally dry 2003 and the following year, Environmental Pollution, 157, 1737-1744, 10.1016/j.envpol.2007.11.025, 2009.
Ghude, S. D., Jain, S. L., Arya, B. C., Beig, G., Ahammed, Y. N., Kumar, A., and Tyagi, B.: Ozone in ambient air at a tropical megacity, Delhi: characteristics, trends and cumulative ozone exposure indices, Journal of Atmospheric Chemistry, 60, 237-252, 10.1007/s10874-009-9119-4, 2008.
Ghude, S. D., Jena, C., Chate, D. M., Beig, G., Pfister, G. G., Kumar, R., and Ramanathan, V.: Reductions in India's crop yield due to ozone, Geophysical Research Letters, 41, 2014GL060930, 10.1002/2014gl060930, 2014.
Giglio, L., and Kendall, J. D.: Commentary on "Improving the seasonal cycle and interannual variations of biomass burning aerosol sources" by Generoso et al, Atmospheric Chemistry and Physics, 4, 585-587, 2004.
Gilman, J. B., Lerner, B. M., Kuster, W. C., and de Gouw, J. A.: Source Signature of Volatile Organic Compounds from Oil and Natural Gas Operations in Northeastern Colorado, Environ. Sci. Technol., 47, 1297-1305, 10.1021/es304119a, 2013.
Glotfelty, T., Zhang, Y., Karamchandani, P., and Streets, D. G.: Will the role of intercontinental transport change in a changing climate?, Atm. Chem. Phys., 14, 9379-9402, 2014.
Goldstein, A. H., and Galbally, I. E.: Known and Unexplored Organic Constituents in the Earth's Atmosphere, Environ. Sci. Technol., 1 March, 1515-1521, 2007.
Granat, L., and Richter, A.: Dry Deposition to Pine of Sulfur-Dioxide and Ozone at Low Concentration, Atmospheric Environment, 29, 1677-1683, 1995.
Granier, C., Artaxo, P., and Reeves, C. E.: Emissions of Atmospheric Trace compounds, Kluwer, 545 pp., 2004.
Granier, C., Niemeier, U., Jungclaus, J. H., Emmons, L., Hess, P., Lamarque, J. F., Walters, S., and Brasseur, G. P.: Ozone pollution from future ship traffic in the Arctic northern passages, Geophysical Research Letters, 33, 10.1029/2006gl026180, 2006.
Granier, C., Bessagnet, B., Bond, T., D'Angiola, A., van der Gon, H. D., Frost, G. J., Heil, A., Kaiser, J. W., Kinne, S., Klimont, Z., Kloster, S., Lamarque, J. F., Liousse, C., Masui, T., Meleux, F., Mieville, A., Ohara, T., Raut, J. C., Riahi, K., Schultz, M. G., Smith, S. J., Thompson, A., van Aardenne, J., van der Werf, G. R., and van Vuuren, D. P.: Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980-2010 period, Climatic Change, 109, 163-190, 10.1007/s10584-011-0154-1, 2011.
Grannas, A. M., Jones, A. E., Dibb, J. E., Ammann, M., Anastasio, C., Beine, H. J., Bergin, M., Bottenheim, J., Boxe, C. S., Carver, G., Chen, G., Crawford, J., Dominé, F., Frey, M. M., Guzmán, M. I., Heard, D. E., Helmig, D., Hoffmann, M. R., Honrath, R. E., Huey, L. G., Hutterli, M. A., Jacobi, H.-W., Klán, P., Lefer, B., McConnell, J., Plane, J., Sander, R., Savarino, J., Shepson, P. B., Simpson, W. R., Sodeau, J. R., von Glasow, R., Weller, R., Wolff, E. W., and Zhu, T.: An overview of snow photochemistry: evidence, mechanisms and impacts, Atmos. Chem. Phys., 7, 4329-4373, 2007.
Grantz, D. A., Zhang, X. J., Massman, W. J., Denhartog, G., Neumann, H. H., and Pederson, J. R.: Effects of stomatal conductance and surface wetness on ozone deposition in field-grown grape, Atmospheric Environment, 29, 3189-3198, 1995.
Grantz, D. A., Zhang, X. J., Massman, W. J., Delany, A., and Pederson, J. R.: Ozone deposition to a cotton (Gossypium hirsutum L) field: stomatal and surface wetness effects during the California Ozone Deposition Experiment, Agric. For. Meteorol., 85, 19-31, 10.1016/s0168-1923(96)02396-9, 1997.

Grewe, V.: Impact of lightning on air chemistry and climate, in:, in: Lightning principles, Instruments and applications: Review of modern lightning research edited by: Betz, H. D., Schumann, U., and Laroche, P., Springer-Verlag Berlin Germany, 690, 2008.
Grewe, V., Dahlmann, K., Matthes, S., and Steinbrecht, W.: Attributing ozone to NOx emissions: Implications for climate mitigation measures, Atmospheric Environment, 59, 102-107, 10.1016/j.atmosenv.2012.05.002, 2012a.
Grewe, V., Dahlmann, K., Matthes, S., and Steinbrecht, W.: Attributing ozone to NOx emissions: Implications for climate mitigation measures, Atmos Environ, 59, 102-107, 10.1016/j.atmosenv.2012.05.002, 2012b.
Grontoft, T.: Measurements and modelling of the ozone deposition velocity to concrete tiles, including the effect of diffusion, Atmospheric Environment, 38, 49-58, 2004.
Grossmann, K., Friess, U., Peters, E., Wittrock, F., Lampel, J., Yilmaz, S., Tschritter, J., Sommariva, R., von Glasow, R., Quack, B., Krueger, K., Pfeilsticker, K., and Platt, U.: Iodine monoxide in the Western Pacific marine boundary layer, Atmospheric Chemistry and Physics, 13, 3363-3378, 10.5194/acp-13-3363-2013, 2013.
Grünhage, L., Pleijel, H., Mills, G., Bender, J., Danielsson, H., Lehmann, Y., Castell, J. F., and Bethenod, O.: Updated stomatal flux and flux-effect models for wheat for quantifying effects of ozone on grain yield, grain mass and protein yield, Environmental Pollution, 165, 147-157, 10.1016/j.envpol.2012.02.026, 2012.
Gryparis, A., Forsberg, B., Katsouyanni, K., Analitis, A., Touloumi, G., Schwartz, J., Samoli, E., Medina, S., Anderson, H. R., Niciu, E. M., Wichmann, H.-E., Kriz, B., Kosnik, M., Skorkovsky, J., Vonk, J. M., and Dortbudak, Z.: Acute effects of ozone on mortality from the "Air Pollution and Health: A European Approach " Project, Am. J. Respir. Crit. Care Med., 170, 1080-1087., 2004.
Guenther, A., Hewitt, C., Erickson, D., Fall, R., Geron, C., Graedel, T., Harley, P., Klinger, L., Lerdau, M., McKay, W., Pierce, T., Scholes, R., Steinbrecher, R., Tallamraju, R., Taylor, J., and Zimmerman, P.: A global model of natural volatile organic compound emissions, J. Geophys. Res., 100, 8873-8892, 1995.
Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P. I., and Geron, C.: Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature., Atmos. Chem. Phys., 6, 3181-3210, 2006.
Guenther, A. B., Zimmerman, P. R., Harley, P. C., Monson, R. K., and Fall, R.: ISOPRENE AND MONOTERPENE EMISSION RATE VARIABILITY - MODEL EVALUATIONS AND SENSITIVITY ANALYSES, Journal of Geophysical Research-Atmospheres, 98, 12609-12617, 10.1029/93jd00527, 1993.
Guenther, A. B., Zimmerman, P. R., Harley, P. C., Monson, R. K., and Fall, R.: Isoprene and monoterpene emission ratevariability-model evaluations and sensitivity analyses, J. Geophys. Res., 98, 12609-12617, 2003.
Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., and Wang, X.: The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions, Geosci. Model Dev., 5, 1471-1492, 10.5194/gmd-5-1471-2012, 2012.
Guerreiro, C. B. B., Foltescu, V., and de Leeuw, F.: Air quality status and trends in Europe, Atmospheric Environment, 98, 376-384, http://dx.doi.org/10.1016/j.atmosenv.2014.09.017, 2014.
Guttikunda, S. K., Tang, Y., Carmichael, G. R., Kurata, G., Pan, L., Streets, D. G., Woo, J. H., Thongboonchoo, N., and Fried, A.: Impacts of Asian megacity emissions on regional air quality during spring 2001 J. Geophys. Res., 110, D20301, doi:10.1029/2004JD004921, 2005.
Haagen-Smit, A. J.: Chemistry and Physiology of Los Angeles Smog, Indust. Eng. Chem., 44, 1342, 1952.
Hand, E.: China blamed for U.S. ozone, Science, 345, 1233-1233, 2014.
Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, M., Bauer, S., Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Kelley, M., Kiang, N., Koch, D., Lean, J., Lerner, J., Lo, K., Menon, S., Miller, R., Minnis, P., Novakov, T., Oinas, V., Perlwitz, J., Perlwitz, J., Rind, D., Romanou, A.,

Shindell, D., Stone, P., Sun, S., Tausnev, N., Thresher, D., Wielicki, B., Wong, T., Yao, M., and Zhang, S.: Efficacy of climate forcings, Journal of Geophysical Research-Atmospheres, 110, 10.1029/2005jd005776, 2005.
Hao, W. M., and Liu, M. H.: Spatial and temporal distribution of tropical biomass burning, Global Biogeochemical Cycles, 8, 495-504, 1994.
Hardacre, C., Wild, O., and Emberson, L.: An evaluation of ozone dry deposition in global scale chemistry climate models, Atmos. Chem. Phys. Discuss., 14, 22793-22836, 10.5194/acpd-14-22793-2014, 2014.
Hardacre, C. J., Palmer, P. I., Baumanns, K., Rounsevell, M., and Murray-Rust, D.: Probabilistic estimation of future emissions of isoprene and surface oxidant chemistry associated with land-use change in response to growing food needs, Atmospheric Chemistry and Physics, 13, 5451-5472, 10.5194/acp-13-5451-2013, 2013.
Hartley, W. N.: On the absorption spectrum of ozone, J.Chem.Soc., 39, 1881.
Hauglustaine, D. A., and Brasseur, G. P.: Evolution of tropospheric ozone under anthropogenic activities and associated radiative forcing of climate, Journal of Geophysical Research-Atmospheres, 106, 32337-32360, 10.1029/2001jd900175, 2001.
Hauglustaine, D. A., and Koffi, B.: Boundary layer ozone pollution caused by future aircraft emissions, Geophysical Research Letters, 39, L13808, 10.1029/2012gl052008, 2012.
Hayes, F., Jones, M. L. M., Mills, G., and Ashmore, M.: Meta-analysis of the relative sensitivity of semi-natural vegetation species to ozone, Environmental Pollution, 146, 754-762, 10.1016/j.envpol.2006.06.011, 2007.
Heal, M. R., Heaviside, C., Doherty, R. M., Vieno, M., Stevenson, D. S., and Vardoulakis, S.: Health burdens of surface ozone in the UK for a range of future scenarios, Environ. Int., 61, 36-44, http://dx.doi.org/10.1016/j.envint.2013.09.010, 2013a.
Heal, M. R., Heaviside, C., Doherty, R. M., Vieno, M., Stevenson, D. S., and Vardoulakis, S.: Health burdens of surface ozone in the UK for a range of future scenarios, Environ. Int., 61, 36-44, 10.1016/j.envint.2013.09.010, 2013b.
Heard, D. E., and Pilling, M. J.: Measurement of OH and HO_2 in the Troposphere, Chemical Reviews, 103, 5163-5198, 2003.
Hedegaard, G. B., Brandt, J., Christensen, J. H., Frohn, L. M., Geels, C., Hansen, K. M., and Stendel, M.: Impacts of climate change on air pollution levels in the Northern Hemisphere with special focus on Europe and the Arctic, Atmospheric Chemistry and Physics, 8, 3337-3367, 2008.
Hedegaard, G. B., Christensen, J. H., and Brandt, J.: The relative importance of impacts from climate change vs. emissions change on air pollution levels in the 21st century, Atmos. Chem. Phys., 13, 3569-3585, 2013a.
Hedegaard, G. B., Christensen, J. H., and Brandt, J.: The relative importance of impacts from climate change vs. emissions change on air pollution levels in the 21st century, Atmospheric Chemistry and Physics, 13, 3569-3585, 10.5194/acp-13-3569-2013, 2013b.
Hegglin, M. I., and Shepherd, T. G.: Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux, Nature Geosci, 2, 687-691, http://www.nature.com/ngeo/journal/v2/n10/suppinfo/ngeo604_S1.html, 2009.
Held, I. M., and Soden, B. J.: Robust responses of the hydrological cycle to global warming, Journal of Climate, 19, 5686-5699, 10.1175/jcli3990.1, 2006.
Helmig, D., Oltmans, S., Carlson, D., Lamarque, J.-F., Jones, A. E., Labuschagne, C., Anlauf, K., and Hayden, K.: A review of surface ozone in the polar regions, Atmos. Environ., 41, 5138-5161, doi:10.1016/j.atmosenv.2006.09.053., 2007.
Helmig, D., Johnson, B., Oltmans, S. J., Neff, W., Eisele, F., and Davis, D. D.: Elevated ozone in the boundary-layer at South Pole, Atmospheric Environment, 42, 2788-2803, doi:10.1016/j.atmosenv.2006.12.032, 2008a.
Helmig, D., Johnson, B. J., Warshawsky, M., Morse, T., Neff, W. D., Eisele, F., and Davis, D. D.: Nitric oxide in the boundary-layer at South Pole during the Antarctic Tropospheric Chemistry Investigation (ANTCI), Atmospheric Environment, 42, 2817-2830, 2008b.

7371 Hess, P., Kinnison, D., and Tang, Q.: Ensemble simulations of the role of the stratosphere in the
7372 attribution of tropospheric ozone variability, Atmos. Chem. Phys. Discuss., 14, 20461-20520, 2014.
7373 Hess, P. G., and Zbinden, R.: Stratospheric impact on tropospheric ozone variability and trends: 1990-
7374 2009, Atmospheric Chemistry and Physics, 13, 649-674, 10.5194/acp-13-649-2013, 2013.
7375 Hewitt, C. N., MacKenzie, A. R., Di Carlo, P., Di Marco, C. F., Dorsey, J. R., Evans, M., Fowler, D.,
7376 Gallagher, M. W., Hopkins, J. R., Jones, C. E., Langford, B., Lee, J. D., Lewis, A. C., Lim, S. F., McQuaid,
7377 J., Misztal, P., Moller, S. J., Monks, P. S., Nemitz, E., Oram, D. E., Owen, S. M., Phillips, G. J., Pugh, T. A.
7378 M., Pyle, J. A., Reeves, C. E., Ryder, J., Siong, J., Skiba, U., and Stewart, D. J.: Nitrogen management is
7379 essential to prevent tropical oil palm plantations from causing ground-level ozone pollution, Proc.
7380 Natl. Acad. Sci. U. S. A., 106, 18447-18451, 10.1073/pnas.0907541106, 2009.
7381 Hewitt, C. N., Ashworth, K., Boynard, A., Guenther, A., Langford, B., MacKenzie, A. R., Misztal, P. K.,
7382 Nemitz, E., Owen, S. M., Possell, M., Pugh, T. A. M., Ryan, A. C., and Wild, O.: Ground-level ozone
7383 influenced by circadian control of isoprene emissions, Nature Geoscience, 4, 671-674,
7384 10.1038/ngeo1271, 2011.
7385 Hirdman, D., Burkhart, J. F., Sodemann, H., Eckhardt, S., Jefferson, A., Quinn, P. K., Sharma, S., Strom,
7386 J., and Stohl, A.: Long-term trends of black carbon and sulphate aerosol in the Arctic: changes in
7387 atmospheric transport and source region emissions, Atmospheric Chemistry and Physics, 10, 9351-
7388 9368, 10.5194/acp-10-9351-2010, 2010.
7389 Hodnebrog, O., Stordal, F., and Berntsen, T. K.: Does the resolution of megacity emissions impact
7390 large scale ozone?, Atmospheric Environment, 45, 6852-6862, 10.1016/j.atmosenv.2011.01.012,
7391 2011.
7392 Hogg, A., Uddling, J., Ellsworth, D., Carroll, M. A., Pressley, S., Lamb, B., and Vogel, C.: Stomatal and
7393 non-stomatal fluxes of ozone to a northern mixed hardwood forest, Tellus Series B-Chemical and
7394 Physical Meteorology, 59, 514-525, 10.1111/j.1600-0889.2007.00269.x, 2007.
7395 Hooghiemstra, P. B., Krol, M. C., Bergamaschi, P., de Laat, A. T. J., van der Werf, G. R., Novelli, P. C.,
7396 Deeter, M. N., Aben, I., and Rockmann, T.: Comparing optimized CO emission estimates using
7397 MOPITT or NOAA surface network observations, Journal of Geophysical Research-Atmospheres, 117,
7398 10.1029/2011jd017043, 2012.
7399 Horowitz, L. W., Fiore, A. M., Milly, G. P., Cohen, R. C., Perring, A., Wooldridge, P. J., Hess, P. G.,
7400 Emmons, L. K., and Lamarque, J. F.: Observational constraints on the chemistry of isoprene nitrates
7401 over the eastern United States, Journal of Geophysical Research-Atmospheres, 112,
7402 10.1029/2006jd007747, 2007.
7403 Hov, O., Schmidbauer, N., and Oehme, M.: Light-hydrocarbons in the Norwegian Arctic, Atmospheric
7404 Environment, 23, 2471-2482, 10.1016/0004-6981(89)90258-8, 1989.
7405 Hsu, A., Reuben, A., Shindell, D., de Sherbinin, A., and Levy, M.: Toward the next generation of air
7406 quality monitoring indicators, Atmospheric Environment, 80, 561-570,
7407 http://dx.doi.org/10.1016/j.atmosenv.2013.07.036, 2013.
7408 HTAP: Hemispheric Transport of Air Pollution, UNECE, Geneva 2010.
7409 Huang, K., Fu, J. S., Hsu, N. C., Gao, Y., Dong, X. Y., Tsay, S. C., and Lam, Y. F.: Impact assessment of
7410 biomass burning on air quality in Southeast and East Asia during BASE-ASIA, Atmospheric
7411 Environment, 78, 291-302, 10.1016/j.atmosenv.2012.03.048, 2013.
7412 Hudman, R. C., Jacob, D. J., Cooper, O. R., Evans, M. J., Heald, C. L., Park, R. J., Fehsenfeld, F. C.,
7413 Flocke, F., Holloway, J., Hübler, G., Kita, K., Koike, M., Kondo , Y., Neuman, A., Nowak, J., Oltmans, S.,
7414 Parrish, D., Roberts, J. M., and Ryerson, T. B.: Ozone production in transpacific Asian pollution plumes
7415 and implications for ozone air quality in California, J. Geophys. Res., 109, D23S10,
7416 doi:10.1029/2004JD004974, 2004.
7417 Hudman, R. C., Murray, L. T., Jacob, D. J., Turquety, S., Wu, S., Millet, D. B., Avery, M., Goldstein, A.
7418 H., and Holloway, J.: North American influence on tropospheric ozone and the effects of recent
7419 emission reductions: Constraints from ICARTT observations, Journal of Geophysical Research-
7420 Atmospheres, 114, D07302, 10.1029/2008jd010126, 2009.
7421 Hughes, K., Lightfoot, P., and Pilling, M.: Direct measurements of the peroxy—hydroperoxy radical
7422 isomerisation, a key step in hydrocarbon combustion, Chemical physics letters, 191, 581-586, 1992.

Huo, H., Yao, Z. L., Zhang, Y. Z., Shen, X. B., Zhang, Q., Ding, Y., and He, K. B.: On-board measurements of emissions from light-duty gasoline vehicles in three mega-cities of China, Atmospheric Environment, 49, 371-377, 10.1016/j.atmosenv.2011.11.005, 2012.
Im, U., and Kanakidou, M.: Impacts of East Mediterranean megacity emissions on air quality, Atmospheric Chemistry and Physics, 12, 6335-6355, 10.5194/acp-12-6335-2012, 2012.
Inness, A., Baier, F., Benedetti, A., Bouarar, I., Chabrillat, S., Clark, H., Clerbaux, C., Coheur, P., Engelen, R. J., Errera, Q., Flemming, J., George, M., Granier, C., Hadji-Lazaro, J., Huijnen, V., Hurtmans, D., Jones, L., Kaiser, J. W., Kapsomenakis, J., Lefever, K., Leitao, J., Razinger, M., Richter, A., Schultz, M. G., Simmons, A. J., Suttie, M., Stein, O., Thepaut, J. N., Thouret, V., Vrekoussis, M., Zerefos, C., and Team, M.: The MACC reanalysis: an 8 yr data set of atmospheric composition, Atmospheric Chemistry and Physics, 13, 4073-4109, 10.5194/acp-13-4073-2013, 2013.
IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 1, Historical Overview of Climate change, in: Intergovernmental Panel on Climate Change Climate change : The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Cambridge University Press, Cambridge, 79-131, 2007.
IPCC: Climate Change 2013 – The Physical Science Basis, Cambridge University Press, Cambridge, 1552 pp., 2013.
Isaksen, I., Berntsen, T., Dalsøren, S., Eleftheratos, K., Orsolini, Y., Rognerud, B., Stordal, F., Søvde, O., Zerefos, C., and Holmes, C.: Atmospheric Ozone and Methane in a Changing Climate, Atmosphere, 5, 518-535, 2014.
Isaksen, I. S. A., Granier, C., Myhre, G., Berntsen, T. K., Dalsoren, S. B., Gauss, M., Klimont, Z., Benestad, R., Bousquet, P., Collins, W., Cox, T., Eyring, V., Fowler, D., Fuzzi, S., Jockel, P., Laj, P., Lohmann, U., Maione, M., Monks, P., Prevot, A. S. H., Raes, F., Richter, A., Rognerud, B., Schulz, M., Shindell, D., Stevenson, D. S., Storelvmo, T., Wang, W. C., van Weele, M., Wild, M., and Wuebbles, D.: Atmospheric composition change: Climate-Chemistry interactions, Atmospheric Environment, 43, 5138-5192, 10.1016/j.atmosenv.2009.08.003, 2009.
Ito, A., Sillman, S., and Penner, J. E.: Global chemical transport model study of ozone response to changes in chemical kinetics and biogenic volatile organic compounds emissions due to increasing temperatures: Sensitivities to isoprene nitrate chemistry and grid resolution, Journal of Geophysical Research-Atmospheres, 114, 10.1029/2008jd011254, 2009.
Jacob, D. J., Heikes, B. G., Fan, S. M., Logan, J. A., Mauzerall, D. L., Bradshaw, J. D., Singh, H. B., Gregory, G. L., Talbot, R. W., Blake, D. R., and Sachse, G. W.: Origin of ozone and NOx in the tropical troposphere: A photochemical analysis of aircraft observations over the South Atlantic basin, Journal of Geophysical Research-Atmospheres, 101, 24235-24250, 10.1029/96jd00336, 1996.
Jacob, D. J., Logan, J. A., and Murti, P. P.: Effect of rising Asian emissions on surface ozone in the United States, Geophys. Res. Lett., 26, 2175- 2178., 1999.
Jacob, D. J., and Winner, D. A.: Effect of climate change on air quality, Atmospheric Environment, 43, 51-63, 10.1016/j.atmosenv.2008.09.051, 2009.
Jacob, D. J., Crawford, J. H., Maring, H., Clarke, A. D., Dibb, J. E., Emmons, L. K., Ferrare, R. A., Hostetler, C. A., Russell, P. B., Singh, H. B., Thompson, A. M., Shaw, G. E., McCauley, E., Pederson, J. R., and Fisher, J. A.: The Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) mission: design, execution, and first results, Atmospheric Chemistry and Physics, 10, 5191-5212, 10.5194/acp-10-5191-2010, 2010.
Jacobson, M. Z., and Streets, D. G.: Influence of future anthropogenic emissions on climate, natural emissions, and air quality, Journal of Geophysical Research-Atmospheres, 114, 10.1029/2008jd011476, 2009.
Jaffe, D., and et al.: Transport of Asian air pollution to North America., Geophys. Res. Lett., 26, 711 - 714., 1999.
Jaffe, D. A., and Wigder, N. L.: Ozone production from wildfires: A critical review, Atmospheric Environment, 51, 1-10, 10.1016/j.atmosenv.2011.11.063, 2012.

Janssens-Maenhout, G., Petrescu, A., Muntean, M., and Blujdeau, V.: Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements, Greenhouse gas measurement and management, JRC, Ispra, Italy, 132-133, 2011.
Janssens-Maenhout, G., Dentener, F., Van Aardenne, J., Monni, S., Pagliari, V., Orlandini, L., Klimont, Z., Kurokawa, J., Akimoto, H., Ohara, T., Wankmueller, R., Battye, B., Grano, D., Zuber, A., and Keating, T.: EDGAR-HTAP: a Harmonized Gridded Air Pollution Emission Dataset Based on National Inventories, European Commission Publications Office, Ispra, Italy, 2012.
Jenkin, M. E., and Clemitshaw, K. C.: Ozone and other secondary photochemical pollutants: chemical processes governing their formation in the planetary boundary layer, Atmos. Environ,, 34, 2499-2527, 2000.
Jenkin, M. E.: Trends in ozone concentration distributions in the UK since 1990: Local, regional and global influences, Atmospheric Environment, 42, 5434-5445, 10.1016/j.atmosenv.2008.02.036, 2008.
Jerrett, M., Burnett, R. T., Pope, C. A., Ito, K., Thurston, G., Krewski, D., Shi, Y. L., Calle, E., and Thun, M.: Long-Term Ozone Exposure and Mortality, N. Engl. J. Med., 360, 1085-1095, 10.1056/NEJMoa0803894, 2009.
Jones, A. E., Anderson, P. S., Wolff, E. W., Roscoe, H. K., Marshall, G. J., Richter, A., Brough, N., and Colwell, S. R.: Vertical structure of Antarctic tropospheric ozone depletion events: characteristics and broader implications, Atmospheric Chemistry and Physics, 10, 7775-7794, 10.5194/acp-10-7775-2010, 2010a.
Jones, C. E., Hornsby, K. E., Sommariva, R., Dunk, R. M., Von Glasow, R., McFiggans, G., and Carpenter, L. J.: Quantifying the contribution of marine organic gases to atmospheric iodine, Geophysical Research Letters, 37, 10.1029/2010gl043990, 2010b.
Jonquieres, I., Marenco, A., Maalej, A., and Rohrer, F.: Study of ozone formation and transatlantic transport from biomass burning emissions over West Africa during the airborne Tropospheric Ozone Campaigns TROPOZ I and TROPOZ II, Journal of Geophysical Research-Atmospheres, 103, 19059-19073, 10.1029/98jd00819, 1998.
Jonson, J. E., Simpson, D., Fagerli, H., and Solberg, S.: Can we explain the trends in European ozone levels?, Atmos. Chem. Phys., 313, 51- 66., 2006.
Jonson, J. E., Tarrason, L., Klein, H., Vestreng, V., Cofala, J., and Whall, C.: Effects of ship emissions on European ground-level ozone in 2020, Int. J. Remote Sens., 30, 4099-4110, 10.1080/01431160902821858, 2009.
Junge, C. E.: Global ozone budget and exchange between and stratosphere and troposphere, Tellus, 14, 363-377, 1962.
Kaiser, J. W., Heil, A., Andreae, M. O., Benedetti, A., Chubarova, N., Jones, L., Morcrette, J. J., Razinger, M., Schultz, M. G., Suttie, M., and van der Werf, G. R.: Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power, Biogeosciences, 9, 527-554, 10.5194/bg-9-527-2012, 2012.
Kaiser, J. W., Andela, N., Heil, A., Leeuwen, T. T. v., Werf, G. R. v. d., Wooster, M. J., Remy, S., and Schultz, M. G.: Assessment of the Global Fire Assimilation System (GFASv1), http://gmes-atmosphere.eu, 2013.
Kalabokas, P. D., Cammas, J. P., Thouret, V., Volz-Thomas, A., Boulanger, D., and Repapis, C. C.: Examination of the atmospheric conditions associated with high and low summer ozone levels in the lower troposphere over the eastern Mediterranean, Atmospheric Chemistry and Physics, 13, 10339-10352, 10.5194/acp-13-10339-2013, 2013.
Kang, M., Kanno, C. M., Reid, M. C., Zhang, X., Mauzerall, D. L., Celia, M. A., Chen, Y., and Onstott, T. C.: Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania, Proceedings of the National Academy of Sciences, 111, 18173-18177, 10.1073/pnas.1408315111, 2014.
Kargbo, D. M., Wilhelm, R. G., and Campbell, D. J.: Natural Gas Plays in the Marcellus Shale: Challenges and Potential Opportunities, Environ. Sci. Technol., 44, 5679, 2010.
Karion, A., Sweeney, C., Petron, G., Frost, G., Hardesty, R. M., Kofler, J., Miller, B. R., Newberger, T., Wolter, S., Banta, R., Brewer, A., Dlugokencky, E., Lang, P., Montzka, S. A., Schnell, R., Tans, P.,

Trainer, M., Zamora, R., and Conley, S.: Methane emissions estimate from airborne measurements over a western United States natural gas field, Geophysical Research Letters, 40, 4393-4397, 10.1002/grl.50811, 2013.
Karlsson, P., Braun, S., Broadmeadow, M., Elvira, S., Emberson, L., Gimeno, B. S., Le Thiec, D., Novak, K., Oksanen, E., Schaub, M., Uddling, J., and Wilkinson, M.: Risk assessments for forest trees: The performance of the ozone flux versus the AOT concepts, Environmental Pollution, 146, 608-616, 10.1016/j.envpol.2006.06.012, 2007.
Karnosky, D. F., Skelly, J. M., Percy, K. E., and Chappelka, A. H.: Perspectives regarding 50 years of research on effects of tropospheric ozone air pollution on US forests, Environmental Pollution, 147, 489-506, 10.1016/j.envpol.2006.08.043, 2007.
Katragkou, E., Zanis, P., Kioutsioukis, I., Tegoulias, I., Melas, D., Krueger, B. C., and Coppola, E.: Future climate change impacts on summer surface ozone from regional climate-air quality simulations over Europe, Journal of Geophysical Research-Atmospheres, 116, 10.1029/2011jd015899, 2011.
Katzenstein, A. S., Doezema, L. A., Simpson, I. J., Blake, D. R., and Rowland, F. S.: Extensive regional atmospheric hydrocarbon pollution in the southwestern United States, Proceedings of the National Academy of Sciences, 100, 11975-11979, 10.1073/pnas.1635258100, 2003.
Kawase, H., Nagashima, T., Sudo, K., and Nozawa, T.: Future changes in tropospheric ozone under Representative Concentration Pathways (RCPs), Geophysical Research Letters, 38, 10.1029/2010gl046402, 2011.
Keenan, T. F., and Niinemets, U.: Circadian control of global isoprene emissions, Nature Geoscience, 5, 435-435, 10.1038/ngeo1500, 2012.
Keene, W. C., Long, M. S., Pszenny, A. A. P., Sander, R., Maben, J. R., Wall, A. J., O'Halloran, T. L., Kerkweg, A., Fischer, E. V., and Schrems, O.: Latitudinal variation in the multiphase chemical processing of inorganic halogens and related species over the eastern North and South Atlantic Oceans, Atmospheric Chemistry and Physics, 9, 7361-7385, 2009.
Kemball-Cook, S., Bar-Ilan, A., Grant, J., Parker, L., Jung, J. G., Santamaria, W., Mathews, J., and Yarwood, G.: Ozone Impacts of Natural Gas Development in the Haynesville Shale, Environ. Sci. Technol., 44, 9357-9363, 10.1021/es1021137, 2010.
Kercher, J. P., Riedel, T. P., and Thornton, J. A.: Chlorine activation by N_2O_5: simultaneous, in situ detection of $ClNO_2$ and N_2O_5 by chemical ionization mass spectrometry, Atmos. Meas. Tech., 2, 193-204, 2009.
Khoder, M. I.: Diurnal, seasonal and weekdays-weekends variations of ground level ozone concentrations in an urban area in greater Cairo, Environmental Monitoring and Assessment, 149, 349-362, 10.1007/s10661-008-0208-7, 2009.
Kim, C. S., Alexis, N. E., Rappold, A. G., Kehrl, H., Hazucha, M. J., Lay, J. C., Schmitt, M. T., Case, M., Devlin, R. B., Peden, D. B., and Diaz-Sanchez, D.: Lung Function and Inflammatory Responses in Healthy Young Adults Exposed to 0.06 ppm Ozone for 6.6 Hours, American Journal of Respiratory and Critical Care Medicine, 183, 1215-1221, 10.1164/rccm.201011-1813OC, 2011.
Kim, S., VandenBoer, T. C., Young, C. J., Riedel, T. P., Thornton, J. A., Swarthout, B., Sive, B., Lerner, B., Gilman, J. B., Warneke, C., Roberts, J. M., Guenther, A., Wagner, N. L., Dubé, W. P., Williams, E., and Brown, S. S.: The primary and recycling sources of OH during the NACHTT-2011 campaign: HONO as an important OH primary source in the wintertime, Journal of Geophysical Research: Atmospheres, 119, 2013JD019784, 10.1002/2013jd019784, 2014.
Kim, S. W., Heckel, A., Frost, G. J., Richter, A., Gleason, J., Burrows, J. P., McKeen, S., Hsie, E. Y., Granier, C., and Trainer, M.: NO_2 columns in the western United States observed from space and simulated by a regional chemistry model and their implications for NOx emissions, Journal of Geophysical Research-Atmospheres, 114, 29, 10.1029/2008jd011343, 2009.
Kinney, P. L.: Climate Change, Air Quality, and Human Health, Am. J. Prev. Med., 35, 459-467, 10.1016/j.amepre.2008.08.025, 2008.
Kley, D., Geiss, H., and Mohnen, V. A.: Tropospheric ozone at elevated sites and precursor emissions in the United-States and Europe, Atmospheric Environment, 28, 149-158, 10.1016/1352-2310(94)90030-2, 1994.

Klimont, Z., Kupiainen, K., Heyes, C., Cofala, J., Rafaj, P., Höglund-Isaksson, L., Borken, J., Schöpp, W., Winiwarter, W., Purohit, P., Bertok, I., and Sander R.: ECLIPSE V4a: Global emission data set developed with the GAINS model for the period 2005 to 2050 Key features and principal data sources 2013a.
Klimont, Z., Smith, S. J., and Cofala, J.: The last decade of global anthropogenic sulfur dioxide: 2000-2011 emissions, Environmental Research Letters, 8, 10.1088/1748-9326/8/1/014003, 2013b.
Kline, N. D., and Miller, T. A.: Observation of the electronic transition of C_6-C_{10} peroxy radicals, Chemical Physics Letters, 601, 149-154, 2014.
Kloster, S., Mahowald, N. M., Randerson, J. T., Thornton, P. E., Hoffman, F. M., Levis, S., Lawrence, P. J., Feddema, J. J., Oleson, K. W., and Lawrence, D. M.: Fire dynamics during the 20th century simulated by the Community Land Model, Biogeosciences, 7, 1877-1902, 10.5194/bg-7-1877-2010, 2010.
Knorr, W., Lehsten, V., and Arneth, A.: Determinants and predictability of global wildfire emissions, Atmospheric Chemistry and Physics, 12, 6845-6861, 10.5194/acp-12-6845-2012, 2012.
Kondo, Y., Takegawa, N., Matsui, H., Miyakawa, T., Koike, M., Miyazaki, Y., Kanaya, Y., Mochida, M., Kuwata, M., Morino, Y., and Shiraiwa, M.: Formation and Transport of Aerosols in Tokyo in Relation to Their Physical and Chemical Properties: A Review, J Meteorol Soc Jpn, 88, 597-624, 10.2151/jmsj.2010-401, 2010.
Koo, J. H., Wang, Y., Kurosu, T. P., Chance, K., Rozanov, A., Richter, A., Oltmans, S. J., Thompson, A. M., Hair, J. W., Fenn, M. A., Weinheimer, A. J., Ryerson, T. B., Solberg, S., Huey, L. G., Liao, J., Dibb, J. E., Neuman, J. A., Nowak, J. B., Pierce, R. B., Natarajan, M., and Al-Saadi, J.: Characteristics of tropospheric ozone depletion events in the Arctic spring: analysis of the ARCTAS, ARCPAC, and ARCIONS measurements and satellite BrO observations, Atmospheric Chemistry and Physics, 12, 9909-9922, 10.5194/acp-12-9909-2012, 2012.
Kopacz, M., Jacob, D. J., Fisher, J. A., Logan, J. A., Zhang, L., Megretskaia, I. A., Yantosca, R. M., Singh, K., Henze, D. K., Burrows, J. P., Buchwitz, M., Khlystova, I., McMillan, W. W., Gille, J. C., Edwards, D. P., Eldering, A., Thouret, V., and Nedelec, P.: Global estimates of CO sources with high resolution by adjoint inversion of multiple satellite datasets (MOPITT, AIRS, SCIAMACHY, TES), Atmospheric Chemistry and Physics, 10, 855-876, 2010.
Kort, E. A., Frankenberg, C., Costigan, K. R., Lindenmaier, R., Dubey, M. K., and Wunch, D.: Four corners: The largest US methane anomaly viewed from space, Geophysical Research Letters, 41, 2014GL061503, 10.1002/2014gl061503, 2014.
Koumoutsaris, S., Bey, I., Generoso, S., and Thouret, V.: Influence of El Nino-Southern Oscillation on the interannual variability of tropospheric ozone in the northern midlatitudes, Journal of Geophysical Research-Atmospheres, 113, 10.1029/2007jd009753, 2008.
Krewski, D., Jerrett, M., Burnett, R. T., Ma, R., Hughes, E., Shi, Y., Turner, M. C., Pope, C. A., Thurston, G., Calle, E. E., and Thun, M. J.: Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality, Health Effects Institute, Boston, 2009.
Krupa, S. V., and Manning, W. J.: Atmospheric ozone: formation and effects on vegetation, Environ. Pollut., 50, 101-137, 1988.
Kuenen, J., Gon, J. H. D. v. d., Visschedijk, A., and Brugh., H. v. d.: High resolution European emission inventory for the years 2003 – 2007, TNO, Utrecht, 2011.
Kuenen, J. J. P., Visschedijk, A. J. H., Jozwicka, M., and Denier van der Gon, H. A. C.: TNO-MACC_II emission inventory: a multi-year (2003–2009) consistent high-resolution European emission inventory for air quality modelling, Atmos. Chem. Phys. Discuss., 14, 5837-5869, 10.5194/acpd-14-5837-2014, 2014.
Kukkonen, J., Olsson, T., Schultz, D. M., Baklanov, A., Klein, T., Miranda, A. I., Monteiro, A., Hirtl, M., Tarvainen, V., Boy, M., Peuch, V. H., Poupkou, A., Kioutsioukis, I., Finardi, S., Sofiev, M., Sokhi, R., Lehtinen, K. E. J., Karatzas, K., San José, R., Astitha, M., Kallos, G., Schaap, M., Reimer, E., Jakobs, H., and Eben, K.: A review of operational, regional-scale, chemical weather forecasting models in Europe, Atmos. Chem. Phys., 12, 1-87, 10.5194/acp-12-1-2012, 2012.

7629 Kumar, P., and Imam, B.: Footprints of air pollution and changing environment on the sustainability
7630 of built infrastructure, Science of the Total Environment, 444, 85-101,
7631 10.1016/j.scitotenv.2012.11.056, 2013.
7632 Kurokawa, J., Ohara, T., Morikawa, T., Hanayama, S., Janssens-Maenhout, G., Fukui, T., Kawashima,
7633 K., and Akimoto, H.: Emissions of air pollutants and greenhouse gases over Asian regions during
7634 2000-2008: Regional Emission inventory in ASia (REAS) version 2, Atmospheric Chemistry and Physics,
7635 13, 11019-11058, 10.5194/acp-13-11019-2013, 2013a.
7636 Kurokawa, J., Ohara, T., Morikawa, T., Hanayama, S., Janssens-Maenhout, G., Fukui, T., Kawashima,
7637 K., and Akimoto, H.: Emissions of air pollutants and greenhouse gases over Asian regions during
7638 2000–2008: Regional Emission inventory in ASia (REAS) version 2, Atmos. Chem. Phys., 13, 11019-
7639 11058, 10.5194/acp-13-11019-2013, 2013b.
7640 Kurpius, M., and Goldstein, A. H.: Gas-phase chemistry dominates O3 loss to a forest, implying a
7641 source of aerosols and hydroxyl radicals to the atmosphere, Geophys. Res. Lett., 30, 1371,
7642 doi:10.1029/2002GL016785, 2003.
7643 Kvalevåg, M. M., and Myhre, G.: The effect of carbon-nitrogen coupling on the reduced land carbon
7644 sink caused by tropospheric ozone, Geophysical Research Letters, n/a-n/a, 10.1002/grl.50572, 2013.
7645 Kwak, K. H., and Baik, J. J.: Diurnal variation of NOx and ozone exchange between a street canyon and
7646 the overlying air, Atmospheric Environment, 86, 120-128, 10.1016/j.atmosenv.2013.12.029, 2014.
7647 Lahoz, W. A., Peuch, V. H., Orphal, J., Attié, J. L., Chance, K., Liu, X., Edwards, D., Elbern, H., Flaud, J.
7648 M., Claeyman, M., and Amraoui, L. E.: Monitoring Air Quality from Space: The Case for the
7649 Geostationary Platform, Bulletin of the American Meteorological Society, 93, 221-233,
7650 10.1175/bams-d-11-00045.1, 2011.
7651 Laj, P., Klausen, J., Bilde, M., Plass-Duelmer, C., Pappalardo, G., Clerbaux, C., Baltensperger, U.,
7652 Hjorth, J., Simpson, D., Reimann, S., Coheur, P. F., Richter, A., De Maziere, M., Rudich, Y., McFiggans,
7653 G., Torseth, K., Wiedensohler, A., Morin, S., Schulz, M., Allan, J. D., Attie, J. L., Barnes, I., Birmili, W.,
7654 Cammas, J. P., Dommen, J., Dorn, H. P., Fowler, D., Fuzzi, S., Glasius, M., Granier, C., Hermann, M.,
7655 Isaksen, I. S. A., Kinne, S., Koren, I., Madonna, F., Maione, M., Massling, A., Moehler, O., Mona, L.,
7656 Monks, P. S., Muller, D., Muller, T., Orphal, J., Peuch, V. H., Stratmann, F., Tanre, D., Tyndall, G., Riziq,
7657 A. A., Van Roozendael, M., Villani, P., Wehner, B., Wex, H., and Zardini, A. A.: Measuring atmospheric
7658 composition change, Atmospheric Environment, 43, 5351-5414, 10.1016/j.atmosenv.2009.08.020,
7659 2009.
7660 Lamarque, J. F., Hess, P., Emmons, L., Buja, L., Washington, W., and Granier, C.: Tropospheric ozone
7661 evolution between 1890 and 1990, Journal of Geophysical Research-Atmospheres, 110,
7662 10.1029/2004jd005537, 2005.
7663 Lamarque, J. F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville,
7664 A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R.,
7665 Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P.: Historical
7666 (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols:
7667 methodology and application, Atmospheric Chemistry and Physics, 10, 7017-7039, 10.5194/acp-10-
7668 7017-2010, 2010.
7669 Lamsal, L. N., Martin, R. V., Padmanabhan, A., van Donkelaar, A., Zhang, Q., Sioris, C. E., Chance, K.,
7670 Kurosu, T. P., and Newchurch, M. J.: Application of satellite observations for timely updates to global
7671 anthropogenic NOx emission inventories, Geophys. Res. Lett., 38, L05810, 10.1029/2010gl046476,
7672 2011.
7673 Langner, J., Engardt, M., and Andersson, C.: European summer surface ozone 1990-2100,
7674 Atmospheric Chemistry and Physics, 12, 10097-10105, 10.5194/acp-12-10097-2012, 2012a.
7675 Langner, J., Engardt, M., Baklanov, A., Christensen, J. H., Gauss, M., Geels, C., Hedegaard, G. B.,
7676 Nuterman, R., Simpson, D., Soares, J., Sofiev, M., Wind, P., and Zakey, A.: A multi-model study of
7677 impacts of climate change on surface ozone in Europe, Atmos. Chem. Phys., 12, 10423-10440, 2012b.
7678 Langner, J., Engardt, M., Baklanov, A., Christensen, J. H., Gauss, M., Geels, C., Hedegaard, G. B.,
7679 Nuterman, R., Simpson, D., Soares, J., Sofiev, M., Wind, P., and Zakey, A.: A multi-model study of

impacts of climate change on surface ozone in Europe, Atmospheric Chemistry and Physics, 12, 10423-10440, 10.5194/acp-12-10423-2012, 2012c.
Lary, D. J.: Halogens and the chemistry of the free troposphere, Atmospheric Chemistry and Physics, 5, 227-237, 2005.
Lathiere, J., Hewitt, C. N., and Beerling, D. J.: Sensitivity of isoprene emissions from the terrestrial biosphere to 20th century changes in atmospheric CO2 concentration, climate, and land use, Global Biogeochemical Cycles, 24, 10.1029/2009gb003548, 2010.
Launiainen, S., Katul, G. G., Gronholm, T., and Vesala, T.: Partitioning ozone fluxes between canopy and forest floor by measurements and a multi-layer model, Agricultural and Forest Meteorology, 173, 85-99, 10.1016/j.agrformet.2012.12.009, 2013.
Law, K. S., and Stohl, A.: Arctic air pollution: Origins and impacts, Science, 315, 1537-1540, 10.1126/science.1137695, 2007.
Law, K. S., Stohl, A., Quinn, P. K., Brock, C., Burkhart, J., Paris, J.-D., Ancellet, G., Singh, H. B., Roiger, A., Schlager, H., Dibb, J., Jacob, D. J., Arnold, S. R., Pelon, J., and Thomas, J. L.: Arctic Air Pollution: New Insights From POLARCAT-I PY, Bulletin of the American Meteorological Society, 10.1175/bams-d-13-00017.1, 2014.
Lawler, M. J., Finley, B. D., Keene, W. C., Pszenny, A. A. P., Read, K. A., von Glasow, R., and Saltzman, E. S.: Pollution-enhanced reactive chlorine chemistry in the eastern tropical Atlantic boundary layer, Geophysical Research Letters, 36, 10.1029/2008gl036666, 2009.
Lawler, M. J., Sander, R., Carpenter, L. J., Lee, J. D., von Glasow, R., Sommariva, R., and Saltzman, E. S.: HOCl and Cl_2 observations in marine air, Atmospheric Chemistry and Physics, 11, 7617-7628, 10.5194/acp-11-7617-2011, 2011.
Lawler, M. J., Mahajan, A. S., Saiz-Lopez, A., and Saltzman, E. S.: Observations of I_2 at a remote marine site, Atmospheric Chemistry and Physics, 14, 2669-2678, 10.5194/acp-14-2669-2014, 2014.
Lawrence, M. G., and Lelieveld, J.: Atmospheric pollutant outflow from southern Asia: a review, Atmospheric Chemistry and Physics, 10, 11017-11096, 10.5194/acp-10-11017-2010, 2010.
Lee, J. D., Lewis, A. C., Monks, P. S., Jacob, M., Hamilton, J. F., Hopkins, J. R., Watson, N. M., Saxton, J. E., Ennis, C., Carpenter, L. J., Carslaw, N., Fleming, Z., Bandy, B. J., Oram, D. E., Penkett, S. A., Slemr, J., Norton, E., Rickard, A. R., Whalley, L. K., Heard, D. E., Bloss, W. J., Gravestock, T., Smit, S. C., Stanton, J., Pilling, M. J., and Jenkin, M. E.: Ozone photochemistry and elevated isoprene during the UK heatwave of august 2003, Atmos. Environ., 40, 7598 -7613 2006.
Lee, K.-Y., Kwak, K.-H., Ryu, Y.-H., Lee, S.-H., and Baik, J.-J.: Impacts of biogenic isoprene emission on ozone air quality in the Seoul metropolitan area, Atmospheric Environment, 96, 209-219, http://dx.doi.org/10.1016/j.atmosenv.2014.07.036, 2014.
Lefohn, A. S., Hazucha, M. J., Shadwick, D., and Adams, W. C.: An alternative form and level of the human health ozone standard, Inhalation Toxicology, 22, 999-1011, Doi 10.3109/08958378.2010.505253, 2010.
Lefohn, A. S., Emery, C., Shadwick, D., Wernli, H., Jung, J., and Oltmans, S. J.: Estimates of background surface ozone concentrations in the United States based on model-derived source apportionment, Atmospheric Environment, 84, 275-288, http://dx.doi.org/10.1016/j.atmosenv.2013.11.033, 2014.
Leighton, P. A.: Photochemistry of Air Pollution, Academic Press, New York, 1961.
Lelieveld, J., and Dentener, F. J.: What controls tropospheric ozone?, Journal of Geophysical Research-Atmospheres, 105, 3531-3551, 10.1029/1999jd901011, 2000.
Lelieveld, J., Berresheim, H., Borrmann, S., Crutzen, P. J., Dentener , F. J., Fischer, H., Feichter, J., Flatau, P. J., Heland, J., Holzinger, R., Korrmann, R., Lawrence, M. G., Levin, Z., Markowicz, K. M., Mihalopoulos, N., Minikin, A., Ramanathan, V., de Reus, M., Roelofs, G. J., Scheeren, H. A., Sciare, J., Schlager , H., Schultz, M., Siegmund, P., Steil, B., Stephanou, E. G., Stier, P., Traub, M., Warneke, C., Williams, J., and Zieraus, H.: Global air pollution crossroads over the Mediterranean, Science, 298, 794-799, 2002.
Lelieveld, J., van Aardenne, J., Fischer, H., de Reus, M., Williams, J., and Winkler, P.: Increasing ozone over the Atlantic Ocean, Science, 304, 1483-1487, 2004.

7731 Lelieveld, J., Butler, T. M., Crowley, J. N., Dillon, T. J., Fischer, H., Ganzeveld, L., Lawrence, M. G.,
7732 Martinez, M., Taraborrelli, D., and Williams, J.: Atmospheric oxidation capacity sustained by a tropical
7733 forest, Nature, 452, 737-740 2008.
7734 Lelieveld, J., Hoor, P., Jockel, P., Pozzer, A., Hadjinicolaou, P., Cammas, J. P., and Beirle, S.: Severe
7735 ozone air pollution in the Persian Gulf region, Atmospheric Chemistry and Physics, 9, 1393-1406,
7736 2009.
7737 Leung, F.-Y., Logan, J. A., Park, R., Hyer, E., Kasischke, E., Streets, D., and Yuganov, L.: Impacts of
7738 enhanced biomass burning in the boreal forests in 1998 on tropospheric chemistry and the sensitivity
7739 of model results to the injection height of emissions J. Geophys. Res., 112, D10313,
7740 doi:10.1029/2006JD008132

7741 2007.
7742 Levy, H., Moxim, W. J., and Kasibhatla, P. S.: A global three-dimensional time-dependent lightning
7743 source of tropospheric NOx, Journal of Geophysical Research-Atmospheres, 101, 22911-22922,
7744 10.1029/96jd02341, 1996.
7745 Lewis, A. C., Evans, M. J., Methven, J., Watson, N. M., Lee, J. D., Hopkins, J. R., Purvis, R. M., Arnold, S.
7746 R., McQuaid, J. B., Whalley, L. K., Pilling, M. J., Heard, D. E., Monks, P. S., Parker, A. E., Reeves, C. E.,
7747 Oram, D. E., Mills, G., Bandy, B. J., Stewart, D., Coe, H., Williams, P., and Crosier, J.: Chemical
7748 composition observed over the mid-Atlantic and the detection of pollution signatures far from source
7749 regions, J. Geophys. Res., 112, D10S39, doi:10.1029/2006JD007584, 2007.
7750 Lewis, A. C., Evans, M. J., Hopkins, J. R., Punjabi, S., Read, K. A., Purvis, R. M., Andrews, S. J., Moller, S.
7751 J., Carpenter, L. J., Lee, J. D., Rickard, A. R., Palmer, P. I., and Parrington, M.: The influence of biomass
7752 burning on the global distribution of selected non-methane organic compounds, Atmospheric
7753 Chemistry and Physics, 13, 851-867, 10.5194/acp-13-851-2013, 2013.
7754 Li, M., Zhang, Q., Streets, D. G., He, K. B., Cheng, Y. F., Emmons, L. K., Huo, H., Kang, S. C., Lu, Z., Shao,
7755 M., Su, H., Yu, X., and Zhang, Y.: Mapping Asian anthropogenic emissions of non-methane volatile
7756 organic compounds to multiple chemical mechanisms, Atmospheric Chemistry and Physics, 14, 5617-
7757 5638, 10.5194/acp-14-5617-2014, 2014a.
7758 Li, X. Y., Liu, J. F., Mauzerall, D. L., Emmons, L. K., Walters, S., Horowitz, L. W., and Tao, S.: Effects of
7759 trans-Eurasian transport of air pollutants on surface ozone concentrations over Western China,
7760 Journal of Geophysical Research-Atmospheres, 119, 12338-12354, 10.1002/2014jd021936, 2014b.
7761 Liao, J., Sihler, H., Huey, L. G., Neuman, J. A., Tanner, D. J., Friess, U., Platt, U., Flocke, F. M., Orlando,
7762 J. J., Shepson, P. B., Beine, H. J., Weinheimer, A. J., Sjostedt, S. J., Nowak, J. B., Knapp, D. J., Staebler,
7763 R. M., Zheng, W., Sander, R., Hall, S. R., and Ullmann, K.: A comparison of Arctic BrO measurements
7764 by chemical ionization mass spectrometry and long path-differential optical absorption spectroscopy,
7765 Journal of Geophysical Research-Atmospheres, 116, 10.1029/2010jd014788, 2011.
7766 Liao, J., Huey, L. G., Liu, Z., Tanner, D. J., Cantrell, C. A., Orlando, J. J., Flocke, F. M., Shepson, P. B.,
7767 Weinheimer, A. J., Hall, S. R., Ullmann, K., Beine, H. J., Wang, Y., Ingall, E. D., Stephens, C. R.,
7768 Hornbrook, R. S., Apel, E. C., Riemer, D., Fried, A., Mauldin, R. L., III, Smith, J. N., Staebler, R. M.,
7769 Neuman, J. A., and Nowak, J. B.: High levels of molecular chlorine in the Arctic atmosphere, Nature
7770 Geoscience, 7, 91-94, 10.1038/ngeo2046, 2014.
7771 Lightfoot, P. D., Cox, R., Crowley, J., Destriau, M., Hayman, G., Jenkin, M., Moortgat, G., and Zabel, F.:
7772 Organic peroxy radicals: kinetics, spectroscopy and tropospheric chemistry, Atmospheric
7773 Environment. Part A. General Topics, 26, 1805-1961, 1992.
7774 Lim, S. S., Vos, T., Flaxman, A. D., Danaei, G., Shibuya, K., Adair-Rohani, H., Amann, M., Anderson, H.
7775 R., Andrews, K. G., Aryee, M., Atkinson, C., Bacchus, L. J., Bahalim, A. N., Balakrishnan, K., Balmes, J.,
7776 Barker-Collo, S., Baxter, A., Bell, M. L., Blore, J. D., Blyth, F., Bonner, C., Borges, G., Bourne, R.,
7777 Boussinesq, M., Brauer, M., Brooks, P., Bruce, N. G., Brunekreef, B., Bryan-Hancock, C., Bucello, C.,
7778 Buchbinder, R., Bull, F., Burnett, R. T., Byers, T. E., Calabria, B., Carapetis, J., Carnahan, E., Chafe, Z.,
7779 Charlson, F., Chen, H. L., Chen, J. S., Cheng, A. T. A., Child, J. C., Cohen, A., Colson, K. E., Cowie, B. C.,
7780 Darby, S., Darling, S., Davis, A., Degenhardt, L., Dentener, F., Des Jarlais, D. C., Devries, K., Dherani,
7781 M., Ding, E. L., Dorsey, E. R., Driscoll, T., Edmond, K., Ali, S. E., Engell, R. E., Erwin, P. J., Fahimi, S.,

Falder, G., Farzadfar, F., Ferrari, A., Finucane, M. M., Flaxman, S., Fowkes, F. G. R., Freedman, G., Freeman, M. K., Gakidou, E., Ghosh, S., Giovannucci, E., Gmel, G., Graham, K., Grainger, R., Grant, B., Gunnell, D., Gutierrez, H. R., Hall, W., Hoek, H. W., Hogan, A., Hosgood, H. D., Hoy, D., Hu, H., Hubbell, B. J., Hutchings, S. J., Ibeanusi, S. E., Jacklyn, G. L., Jasrasaria, R., Jonas, J. B., Kan, H. D., Kanis, J. A., Kassebaum, N., Kawakami, N., Khang, Y. H., Khatibzadeh, S., Khoo, J. P., Kok, C., Laden, F., Lalloo, R., Lan, Q., Lathlean, T., Leasher, J. L., Leigh, J., Li, Y., Lin, J. K., Lipshultz, S. E., London, S., Lozano, R., Lu, Y., Mak, J., Malekzadeh, R., Mallinger, L., Marcenes, W., March, L., Marks, R., Martin, R., McGale, P., McGrath, J., Mehta, S., Mensah, G. A., Merriman, T. R., Micha, R., Michaud, C., Mishra, V., Hanafiah, K. M., Mokdad, A. A., Morawska, L., Mozaffarian, D., Murphy, T., Naghavi, M., Neal, B., Nelson, P. K., Nolla, J. M., Norman, R., Olives, C., Omer, S. B., Orchard, J., Osborne, R., Ostro, B., Page, A., Pandey, K. D., Parry, C. D. H., Passmore, E., Patra, J., Pearce, N., Pelizzari, P. M., Petzold, M., Phillips, M. R., Pope, D., Pope, C. A., Powles, J., Rao, M., Razavi, H., Rehfuess, E. A., Rehm, J. T., Ritz, B., Rivara, F. P., Roberts, T., Robinson, C., Rodriguez-Portales, J. A., Romieu, I., Room, R., Rosenfeld, L. C., Roy, A., Rushton, L., Salomon, J. A., Sampson, U., Sanchez-Riera, L., Sanman, E., Sapkota, A., Seedat, S., Shi, P. L., Shield, K., Shivakoti, R., Singh, G. M., Sleet, D. A., Smith, E., Smith, K. R., Stapelberg, N. J. C., Steenland, K., Stockl, H., Stovner, L. J., Straif, K., Straney, L., Thurston, G. D., Tran, J. H., Van Dingenen, R., van Donkelaar, A., Veerman, J. L., Vijayakumar, L., Weintraub, R., Weissman, M. M., White, R. A., Whiteford, H., Wiersma, S. T., Wilkinson, J. D., Williams, H. C., Williams, W., Wilson, N., Woolf, A. D., Yip, P., Zielinski, J. M., Lopez, A. D., Murray, C. J. L., and Ezzati, M.: A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010, Lancet, 380, 2224-2260, 2012.

Lin, J. T., Pan, D., Davis, S. J., Zhang, Q., He, K. B., Wang, C., Streets, D. G., Wuebbles, D. J., and Guan, D. B.: China's international trade and air pollution in the United States, Proc. Natl. Acad. Sci. U. S. A., 111, 1736-1741, 10.1073/pnas.1312860111, 2014a.

Lin, M., Fiore, A. M., Cooper, O. R., Horowitz, L. W., Langford, A. O., Levy, H., II, Johnson, B. J., Naik, V., Oltmans, S. J., and Senff, C. J.: Springtime high surface ozone events over the western United States: Quantifying the role of stratospheric intrusions, J. Geophys. Res., 117, D00V22, 10.1029/2012jd018151, 2012a.

Lin, M., Horowitz, L. W., Oltmans, S. J., Fiore, A. M., and Fan, S.: Tropospheric ozone trends at Mauna Loa Observatory tied to decadal climate variability, Nature Geosci, 7, 136-143, 10.1038/ngeo2066, 2014b.

Lin, M. Y., Fiore, A. M., Horowitz, L. W., Cooper, O. R., Naik, V., Holloway, J., Johnson, B. J., Middlebrook, A. M., Oltmans, S. J., Pollack, I. B., Ryerson, T. B., Warner, J. X., Wiedinmyer, C., Wilson, J., and Wyman, B.: Transport of Asian ozone pollution into surface air over the western United States in spring, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2011jd016961, 2012b.

Liousse, C., Assamoi, E., Criqui, P., Granier, C., and Rosset, R.: Explosive growth in African combustion emissions from 2005 to 2030, Environmental Research Letters, 9, 035003, 2014.

Lipsett, M. J., Ostro, B. D., Reynolds, P., Goldberg, D., Hertz, A., Jerrett, M., Smith, D. F., Garcia, C., Chang, E. T., and Bernstein, L.: Long-Term Exposure to Air Pollution and Cardiorespiratory Disease in the California Teachers Study Cohort, American Journal of Respiratory and Critical Care Medicine, 184, 828-835, 10.1164/rccm.201012-2082OC, 2011.

Liu, G., Liu, J., Tarasick, D. W., Fioletov, V. E., Jin, J. J., Moeini, O., Liu, X., Sioris, C. E., and Osman, M.: A global tropospheric ozone climatology from trajectory-mapped ozone soundings, Atmos. Chem. Phys., 13, 10659-10675, 10.5194/acp-13-10659-2013, 2013a.

Liu, H., Wang, X. M., Pang, J. M., and He, K. B.: Feasibility and difficulties of China's new air quality standard compliance: PRD case of PM2.5 and ozone from 2010 to 2025, Atmos. Chem. Phys., 13, 12013-12027, 10.5194/acp-13-12013-2013, 2013b.

Liu, X., Chance, K., Sioris, C. E., Kurosu, T. P., Spurr, R. J. D., Martin, R. V., Fu, T. M., Logan, J. A., Jacob, D. J., Palmer, P. I., Newchurch, M. J., Megretskaia, I. A., and Chatfield, R. B.: First directly retrieved global distribution of tropospheric column ozone from GOME: Comparison with the GEOS-CHEM model, Journal of Geophysical Research-Atmospheres, 111, 10.1029/2005jd006564, 2006.

7834 Liu, Y., Shao, M., Fu, L. L., Lu, S. H., Zeng, L. M., and Tang, D. G.: Source profiles of volatile organic
7835 compounds (VOCs) measured in China: Part I, Atmospheric Environment, 42, 6247-6260,
7836 10.1016/j.atmosenv.2008.01.070, 2008.
7837 Logan, J. A.: Tropospheric ozone - seasonal behaviour, trends, and anthropogenic influence, Journal
7838 of Geophysical Research-Atmospheres, 90, 10463-10482, 1985.
7839 Logan, J. A., Staehelin, J., Megretskaia, I. A., Cammas, J. P., Thouret, V., Claude, H., De Backer, H.,
7840 Steinbacher, M., Scheel, H. E., Stubi, R., Frohlich, M., and Derwent, R.: Changes in ozone over Europe:
7841 Analysis of ozone measurements from sondes, regular aircraft (MOZAIC) and alpine surface sites,
7842 Journal of Geophysical Research-Atmospheres, 117, 10.1029/2011jd016952, 2012.
7843 Long, M. S., Keene, W. C., Easter, R. C., Sander, R., Liu, X., Kerkweg, A., and Erickson, D.: Sensitivity of
7844 tropospheric chemical composition to halogen-radical chemistry using a fully coupled size-resolved
7845 multiphase chemistry-global climate system: halogen distributions, aerosol composition, and
7846 sensitivity of climate-relevant gases, Atmospheric Chemistry and Physics, 14, 3397-3425,
7847 10.5194/acp-14-3397-2014, 2014.
7848 Lu, X. H., Jiang, H., Zhang, X. Y., Liu, J. X., Zhang, Z., Jin, J. X., Wang, Y., Xu, J. H., and Cheng, M. M.:
7849 Estimated global nitrogen deposition using NO2 column density, Int. J. Remote Sens., 34, 8893-8906,
7850 10.1080/01431161.2013.853894, 2013.
7851 Maccarone, A. T., Kirk, B. B., Hansen, C. S., Griffiths, T. M., Olsen, S., Trevitt, A. J., and Blanksby, S. J.:
7852 Direct observation of photodissociation products from phenylperoxyl radicals isolated in the gas
7853 phase, J Am Chem Soc, 135, 9010-9014, 2013.
7854 MacDonald, S. M., Martin, J. C. G., Chance, R., Warriner, S., Saiz-Lopez, A., Carpenter, L. J., and Plane,
7855 J. M. C.: A laboratory characterisation of inorganic iodine emissions from the sea surface:
7856 dependence on oceanic variables and parameterisation for global modelling, Atmospheric Chemistry
7857 and Physics, 14, 5841-5852, 10.5194/acp-14-5841-2014, 2014.
7858 MacKenzie, A. R., Langford, B., Pugh, T. A. M., Robinson, N., Misztal, P. K., Heard, D. E., Lee, J. D.,
7859 Lewis, A. C., Jones, C. E., Hopkins, J. R., Phillips, G., Monks, P. S., Karunaharan, A., Hornsby, K. E.,
7860 Nicolas-Perea, V., Coe, H., Gabey, A. M., Gallagher, M. W., Whalley, L. K., Edwards, P. M., Evans, M. J.,
7861 Stone, D., Ingham, T., Commane, R., Furneaux, K. L., McQuaid, J. B., Nemitz, E., Seng, Y. K., Fowler, D.,
7862 Pyle, J. A., and Hewitt, C. N.: The atmospheric chemistry of trace gases and particulate matter
7863 emitted by different land uses in Borneo, Philos. Trans. R. Soc. B-Biol. Sci., 366, 3177-3195,
7864 10.1098/rstb.2011.0053, 2011.
7865 Mahajan, A. S., Oetjen, H., Saiz-Lopez, A., Lee, J. D., McFiggans, G. B., and Plane, J. M. C.: Reactive
7866 iodine species in a semi-polluted environment, Geophysical Research Letters, 36,
7867 10.1029/2009gl038018, 2009.
7868 Mahajan, A. S., Shaw, M., Oetjen, H., Hornsby, K. E., Carpenter, L. J., Kaleschke, L., Tian-Kunze, X.,
7869 Lee, J. D., Moller, S. J., Edwards, P., Commane, R., Ingham, T., Heard, D. E., and Plane, J. M. C.:
7870 Evidence of reactive iodine chemistry in the Arctic boundary layer, Journal of Geophysical Research-
7871 Atmospheres, 115, 10.1029/2009jd013665, 2010.
7872 Manders, A. M. M., van Meijgaard, E., Mues, A. C., Kranenburg, R., van Ulft, L. H., and Schaap, M.:
7873 The impact of differences in large-scale circulation output from climate models on the regional
7874 modeling of ozone and PM, Atmospheric Chemistry and Physics, 12, 9441-9458, 10.5194/acp-12-
7875 9441-2012, 2012.
7876 Mao, J. Q., Paulot, F., Jacob, D. J., Cohen, R. C., Crounse, J. D., Wennberg, P. O., Keller, C. A., Hudman,
7877 R. C., Barkley, M. P., and Horowitz, L. W.: Ozone and organic nitrates over the eastern United States:
7878 Sensitivity to isoprene chemistry, Journal of Geophysical Research-Atmospheres, 118, 11256-11268,
7879 10.1002/jgrd.50817, 2013.
7880 Marais, E. A., Jacob, D. J., Wecht, K., Lerot, C., Zhang, L., Yu, K., Kurosu, T. P., Chance, K., and Sauvage,
7881 B.: Anthropogenic emissions in Nigeria and implications for atmospheric ozone pollution: A view
7882 from space, Atmospheric Environment, 99, 32-40,
7883 http://dx.doi.org/10.1016/j.atmosenv.2014.09.055, 2014.

Marenco, A., Gouget, H., Nedelec, P., Pages, J. P., and Karcher, F.: Evidence of a long-term increase in tropospehric ozone from Pic Du Midi data series - conswquences - positive radiative forcing, Journal of Geophysical Research-Atmospheres, 99, 16617-16632, 10.1029/94jd00021, 1994.
Mari, C. H., Cailley, G., Corre, L., Saunois, M., Attie, J. L., Thouret, V., and Stohl, A.: Tracing biomass burning plumes from the Southern Hemisphere during the AMMA 2006 wet season experiment, Atmospheric Chemistry and Physics, 8, 3951-3961, 2008.
Marlier, M. E., Voulgarakis, A., Shindell, D. T., Faluvegi, G., Henry, C. L., and Randerson, J. T.: The role of temporal evolution in modeling atmospheric emissions from tropical fires, Atmospheric Environment, 89, 158-168, 10.1016/j.atmosenv.2014.02.039, 2014.
Martin, M. V., Logan, J. A., Kahn, R. A., Leung, F. Y., Nelson, D. L., and Diner, D. J.: Smoke injection heights from fires in North America: analysis of 5 years of satellite observations, Atmospheric Chemistry and Physics, 10, 1491-1510, 2010.
Martin, R. V., Parrish, D. D., Ryerson, T. B., Nicks, D. K., Chance, K., Kurosu, T. P., Jacob, D. J., Sturges, E. D., Fried, A., and Wert, B. P.: Evaluation of GOME satellite measurements of tropospheric NO_2 and HCHO using regional data from aircraft campaigns in the southeastern United States, Journal of Geophysical Research-Atmospheres, 109, D24307, 2004.
Martin, R. V.: Satellite remote sensing of surface air quality, Atmospheric Environment, 42, 7823-7843, 10.1016/j.atmosenv.2008.07.018, 2008.
Martins, V., Miranda, A. I., Carvalho, A., Schaap, M., Borrego, C., and Sa, E.: Impact of forest fires on particulate matter and ozone levels during the 2003, 2004 and 2005 fire seasons in Portugal, Science of the Total Environment, 414, 53-62, 10.1016/j.scitotenv.2011.10.007, 2012.
Matyssek, R., Sandermann, H., Wieser, G., Booker, F., Cieslik, S., Musselman, R., and Ernst, D.: The challenge of making ozone risk assessment for forest trees more mechanistic, Environmental Pollution, 156, 567-582, 10.1016/j.envpol.2008.04.017, 2008.
Matyssek, R., Karnosky, D. F., Wieser, G., Percy, K., Oksanen, E., Grams, T. E. E., Kubiske, M., Hanke, D., and Pretzsch, H.: Advances in understanding ozone impact on forest trees: Messages from novel phytotron and free-air fumigation studies, Environmental Pollution, 158, 1990-2006, 10.1016/j.envpol.2009.11.033, 2010.
Mauzerall, D. L., Jacob, D. J., Fan, S. M., Bradshaw, J. D., Gregory, G. L., Sachse, G. W., and Blake, D. R.: Origin of tropospheric ozone at remote high northern latitudes in summer, Journal of Geophysical Research-Atmospheres, 101, 4175-4188, 10.1029/95jd03224, 1996.
McCarthy, M. C., Cheng, L., Crabtree, K. N., Martinez Jr, O., Nguyen, T. L., Womack, C. C., and Stanton, J. F.: The Simplest Criegee Intermediate (H_2CO-O): Isotopic Spectroscopy, Equilibrium Structure, and Possible Formation from Atmospheric Lightning, The Journal of Physical Chemistry Letters, 4, 4133-4139, 2013.
McFiggans, G.: Marine aerosols and iodine emissions, Nature, 433, E13-E13, 10.1038/nature03372, 2005.
McFiggans, G., Bale, C. S. E., Ball, S. M., Beames, J. M., Bloss, W. J., Carpenter, L. J., Dorsey, J., Dunk, R., Flynn, M. J., Furneaux, K. L., Gallagher, M. W., Heard, D. E., Hollingsworth, A. M., Hornsby, K., Ingham, T., Jones, C. E., Jones, R. L., Kramer, L. J., Langridge, J. M., Leblanc, C., LeCrane, J. P., Lee, J. D., Leigh, R. J., Longley, I., Mahajan, A. S., Monks, P. S., Oetjen, H., Orr-Ewing, A. J., Plane, J. M. C., Potin, P., Shillings, A. J. L., Thomas, F., von Glasow, R., Wada, R., Whalley, L. K., and Whitehead, J. D.: Iodine-mediated coastal particle formation: an overview of the Reactive Halogens in the Marine Boundary Layer (RHaMBLe) Roscoff coastal study, Atmospheric Chemistry and Physics, 10, 2975-2999, 10.5194/acp-10-2975-2010, 2010.
McKay, W. A., Stephens, B. A., and Dollard, G. J.: Laboratory measurements of ozone deposition to sea-water and other saline solutions, Atmospheric Environment Part A-General Topics, 26, 3105-3110, 1992.
McLinden, C. A., Olsen, S. C., Hannegan, B., Wild, O., Prather, M. J., and Sundet, J.: Stratospheric ozone in 3-D models: A simple chemistry and the cross-tropopause flux, Journal of Geophysical Research-Atmospheres, 105, 14653-14665, 10.1029/2000jd900124, 2000.

McMeeking, G. R., Bart, M., Chazette, P., Haywood, J. M., Hopkins, J. R., McQuaid, J. B., Morgan, W. T., Raut, J. C., Ryder, C. L., Savage, N., Turnbull, K., and Coe, H.: Airborne measurements of trace gases and aerosols over the London metropolitan region, Atmospheric Chemistry and Physics, 12, 5163-5187, 10.5194/acp-12-5163-2012, 2012.
McPeters, R. D., Labow, G. J., and Logan, J. A.: Ozone climatological profiles for satellite retrieval algorithms, Journal of Geophysical Research: Atmospheres, 112, D05308, 10.1029/2005jd006823, 2007.
Mead, M. I., Popoola, O. A. M., Stewart, G. B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J. J., McLeod, M. W., Hodgson, T. F., Dicks, J., Lewis, A., Cohen, J., Baron, R., Saffell, J. R., and Jones, R. L.: The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks, Atmospheric Environment, 70, 186-203, 10.1016/j.atmosenv.2012.11.060, 2013.
Meleux, F., Solmon, F., and Giorgi, F.: Increase in summer European ozone amounts due to climate change, Atmospheric Environment, 41, 7577-7587, 2007.
Melkonyan, A., and Kuttler, W.: Long-term analysis of NO, NO_2 and O_3 concentrations in North Rhine-Westphalia, Germany, Atmospheric Environment, 60, 316-326, 10.1016/j.atmosenv.2012.06.048, 2012.
Mickley, L. J., Jacob, D., and Rind, D.: Uncertainty in preindustrial abundance of tropospheric ozone: Implications for radiative forcing calculations, J. Geophys. Res., 106, 3389-3399, 2001.
Mielke, L. H., Furgeson, A., and Osthoff, H. D.: Observation of $ClNO_2$ in a Mid-Continental Urban Environment, Environ. Sci. Technol., 45, 8889-8896, 10.1021/es201955u, 2011.
Mielke, L. H., Stutz, J., Tsai, C., Hurlock, S. C., Roberts, J. M., Veres, P. R., Froyd, K. D., Hayes, P. L., Cubison, M. J., Jimenez, J. L., Washenfelder, R. A., Young, C. J., Gilman, J. B., de Gouw, J. A., Flynn, J. H., Grossberg, N., Lefer, B. L., Liu, J., Weber, R. J., and Osthoff, H. D.: Heterogeneous formation of nitryl chloride and its role as a nocturnal NOx reservoir species during CalNex-LA 2010, Journal of Geophysical Research-Atmospheres, 118, 10638-10652, 10.1002/jgrd.50783, 2013.
Mieville, A., Granier, C., Liousse, C., Guillaume, B., Mouillot, F., Lamarque, J. F., Gregoire, J. M., and Petron, G.: Emissions of gases and particles from biomass burning during the 20th century using satellite data and an historical reconstruction, Atmospheric Environment, 44, 1469-1477, 10.1016/j.atmosenv.2010.01.011, 2010.
Miller, S. M., Matross, D. M., Andrews, A. E., Millet, D. B., Longo, M., Gottlieb, E. W., Hirsch, A. I., Gerbig, C., Lin, J. C., Daube, B. C., Hudman, R. C., Dias, P. L. S., Chow, V. Y., and Wofsy, S. C.: Sources of carbon monoxide and formaldehyde in North America determined from high-resolution atmospheric data, Atmospheric Chemistry and Physics, 8, 7673-7696, 2008.
Mills, G., Buse, A., Gimeno, B., Bermejo, V., Holland, M., Emberson, L., and Pleijel, H.: A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops, Atmospheric Environment, 41, 2630-2643, 10.1016/j.atmosenv.2006.11.016, 2007a.
Mills, G., Hayes, F., Jones, M. L. M., and Cinderby, S.: Identifying ozone-sensitive communities of (semi-)natural vegetation suitable for mapping exceedance of critical levels, Environmental Pollution, 146, 736-743, 10.1016/j.envpol.2006.04.005, 2007b.
Mills, G., and Harmens, H.: Ozone pollution: A hidden threat to food security, Centre for Ecology and Hydrology, Bangor, UK., 2011.
Mills, G., Hayes, F., Simpson, D., Emberson, L., Norris, D., Harmens, H., and Buker, P.: Evidence of widespread effects of ozone on crops and (semi-)natural vegetation in Europe (1990-2006) in relation to AOT40-and flux-based risk maps, Global Change Biology, 17, 592-613, 10.1111/j.1365-2486.2010.02217.x, 2011a.
Mills, G., Pleijel, H., Braun, S., Buker, P., Bermejo, V., Calvo, E., Danielsson, H., Emberson, L., Fernandez, I. G., Grunhage, L., Harmens, H., Hayes, F., Karlsson, P. E., and Simpson, D.: New stomatal flux-based critical levels for ozone effects on vegetation, Atmospheric Environment, 45, 5064-5068, 10.1016/j.atmosenv.2011.06.009, 2011b.
Mills, G.: Mapping critical levels for vegetation of the LRTAP Convention Manual of Methodologies for Modelling and Mapping Effects of Air Pollution, 2014.

Millstein, D. E., and Harley, R. A.: Impact of climate change on photochemical air pollution in Southern California, Atmos. Chem. Phys., 9, 3745-3754, 10.5194/acp-9-3745-2009, 2009.
Molina, M. J., and Molina, L. T.: Megacities and atmospheric pollution, J. Air Waste Manage. Assoc., 54, 644-680, 2004.
Monks, P. S.: A review of the observations and origins of the spring ozone maximum, Atmospheric Environment, 34, 3545-3561, 2000.
Monks, P. S.: Gas-phase radical chemistry in the troposphere, Chemical Society Reviews, 34, 376-395, 2005.
Monks, P. S., Granier, C., Fuzzi, S., Stohl, A., Williams, M. L., Akimoto, H., Amann, M., Baklanov, A., Baltensperger, U., Bey, I., Blake, N., Blake, R. S., Carslaw, K., Cooper, O. R., Dentener, F., Fowler, D., Fragkou, E., Frost, G. J., Generoso, S., Ginoux, P., Grewe, V., Guenther, A., Hansson, H. C., Henne, S., Hjorth, J., Hofzumahaus, A., Huntrieser, H., Isaksen, I. S. A., Jenkin, M. E., Kaiser, J., Kanakidou, M., Klimont, Z., Kulmala, M., Laj, P., Lawrence, M. G., Lee, J. D., Liousse, C., Maione, M., McFiggans, G., Metzger, A., Mieville, A., Moussiopoulos, N., Orlando, J. J., O'Dowd, C. D., Palmer, P. I., Parrish, D. D., Petzold, A., Platt, U., Poeschl, U., Prevot, A. S. H., Reeves, C. E., Reimann, S., Rudich, Y., Sellegri, K., Steinbrecher, R., Simpson, D., ten Brink, H., Theloke, J., van der Werf, G. R., Vautard, R., Vestreng, V., Vlachokostas, C., and von Glasow, R.: Atmospheric composition change - global and regional air quality, Atmospheric Environment, 43, 5268-5350, 10.1016/j.atmosenv.2009.08.021, 2009.
Monks, P. S., and Bierle, S.: Applications of Tropospheric Composition Observations from Satellites, in: The Remote Sensing of Tropospheric Composition from Space, edited by: Burrows , J. P., Platt , U., and Borrell, P., Physics of Earth and Space Environments Springer, 536, 2011.
Monks, P. S.: European pollution: Investigate smog to inform policy, Nature, 509, 427-427, 10.1038/509427a

http://www.nature.com/nature/journal/v509/n7501/abs/509427a.html#supplementary-information, 2014.
Monks, S. A., Arnold, S. R., Emmons, L. K., Law, K. S., Turquety, S., Duncan, B. N., Flemming, J., Huijnen, V., Tilmes, S., Langner, J., Mao, J., Long, Y., Thomas, J. L., Steenrod, S. D., Raut, J. C., Wilson, C., Chipperfield, M. P., Schlager, H., and Ancellet, G.: Multi-model study of chemical and physical controls on transport of anthropogenic and biomass burning pollution to the Arctic, Atmos. Chem. Phys. Discuss., 14, 25281-25350, 10.5194/acpd-14-25281-2014, 2014.
Moody, J. L., Oltmans, S. J., Levy, H., and Merrill, J. T.: Transport, climatology of tropospheric ozone - Bermuda, 1988-1991, Journal of Geophysical Research-Atmospheres, 100, 7179-7194, 10.1029/94jd02830, 1995.
Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H.: Anthropogenic and Natural Radiative Forcing, Cambridge, UK, 2013.
Naddafi, K., Hassanvand, M. S., Yunesian, M., Momeniha, F., Nabizadeh, R., Faridi, S., and Gholampour, A.: Health impact assessment of air pollution in megacity of Tehran, Iran, Iran. J. Environ. Health Sci. Eng., 9, 10.1186/1735-2746-9-28, 2012.
Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T. Y., Kram, T., La Rovere, E. L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H. M., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S. J., Swart, R., van Rooijen, S., Victor, N., and Dadi, Z.: Special Report on Emissions Scenarios : a special report of Working Group III of the Intergovernmental Panel on Climate Change, Other Information: PBD: 3 Oct 2000, Cambridge University Press', New York, Medium: ED; Size: vp. pp., 2000.
Nedelec, P., Thouret, V., Brioude, J., Sauvage, B., Cammas, J. P., and Stohl, A.: Extreme CO concentrations in the upper troposphere over northeast Asia in June 2003 from the in situ MOZAIC aircraft data, Geophysical Research Letters, 32, 10.1029/2005gl023141, 2005.
Neirynck, J., Gielen, B., Janssens, I. A., and Ceulemans, R.: Insights into ozone deposition patterns from decade-long ozone flux measurements over a mixed temperate forest, J. Environ. Monit., 14, 1684-1695, 10.1039/c2em10937a, 2012.

Neu, J. L., Flury, T., Manney, G. L., Santee, M. L., Livesey, N. J., and Worden, J.: Tropospheric ozone variations governed by changes in stratospheric circulation, Nature Geoscience, 7, 340-344, 10.1038/ngeo2138, 2014.
Nisbet, E. G., Dlugokencky, E. J., and Bousquet, P.: Methane on the Rise-Again, Science, 343, 493-495, 10.1126/science.1247828, 2014.
Nowack, P. J., Abraham, N. L., Maycock, A. C., Braesicke, P., Gregory, J. M., Joshi, M. M., Osprey, A., and Pyle, J. A.: A large ozone-circulation feedback and its implications for global warming assessments, Nat. Clim. Chang., 5, 41-45, 10.1038/nclimate2451, 2015.
O'Connor, F. M., Johnson, C. E., Morgenstern, O., Abraham, N. L., Braesicke, P., Dalvi, M., Folberth, G. A., Sanderson, M. G., Telford, P. J., Voulgarakis, A., Young, P. J., Zeng, G., Collins, W. J., and Pyle, J. A.: Evaluation of the new UKCA climate-composition model – Part 2: The Troposphere, Geosci. Model Dev., 7, 41-91, 10.5194/gmd-7-41-2014, 2014.
OECD: OECD Environmental Outlook to 2050, OECD Publishing, 2012.
Ohara, T., Akimoto, H., Kurokawa, J., Horii, N., Yamaji, K., Yan, X., and Hayasaka, T.: An Asian emission inventory of anthropogenic emission sources for the period 1980–2020, Atm. Chem. Phys., 7, 4419-4444, 2007.
Ojha, N., Naja, M., Sarangi, T., Kumar, R., Bhardwaj, P., Lal, S., Venkataramani, S., Sagar, R., Kumar, A., and Chandola, H. C.: On the processes influencing the vertical distribution of ozone over the central Himalayas: Analysis of yearlong ozonesonde observations, Atmospheric Environment, 88, 201-211, http://dx.doi.org/10.1016/j.atmosenv.2014.01.031, 2014.
Olaguer, E. P.: The potential near-source ozone impacts of upstream oil and gas industry emissions, J Air Waste Manage, 62, 966-977, 10.1080/10962247.2012.688923, 2012.
Olivier, J. G. J., Van Aardenne, J. A., Dentener, F. J., Pagliari, V., Ganzeveld, L. N., and Peters, J. A. H. W.: Recent trends in global greenhouse gas emissions:regional trends 1970–2000 and spatial distributionof key sources in 2000, Environmental Sciences, 2, 81-99, 10.1080/15693430500400345, 2005.
Olsen, S. C., Brasseur, G. P., Wuebbles, D. J., Barrett, S. R. H., Dang, H., Eastham, S. D., Jacobson, M. Z., Khodayari, A., Selkirk, H., Sokolov, A., and Unger, N.: Comparison of model estimates of the effects of aviation emissions on atmospheric ozone and methane, Geophysical Research Letters, 2013GL057660, 10.1002/2013gl057660, 2013.
Olson, J. R., Crawford, J. H., Davis, D. D., Chen, G., Avery, M. A., Barrick, J. D. W., Sachse, G. W., Vay, S. A., Sandholm, S. T., Tan, D., Brune, W. H., Faloona, I. C., Heikes, B. G., Shetter, R. E., Lefer, B. L., Singh, H. B., Talbot, R. W., and Blake, D. R.: Seasonal differences in the photochemistry of the South Pacific: A comparison of observations and model results from PEM-Tropics A and B, J. Geophys. Res., 106, 32749-32766, 2001.
Oltmans, S., Schnell, R., Johnson, B., Pétron, G., Mefford, T., and Neely, R., III: Anatomy of wintertime ozone associated with oil and natural gas extraction activity in Wyoming and Utah, Elem. Sci. Anth., 2, 000024, 10.12952/journal.elementa.000024, 2014.
Oltmans, S. J., Lefohn, A. S., Harris, J. M., Galbally, I., Scheel, H. E., Bodeker, G., Brunke, E., Claude, H., Tarasick, D., Johnson, B. J., Simmonds, P., Shadwick, D., Anlauf, K., Hayden, K., Schmidlin, F., Fujimoto, T., Akagi, K., Meyer, C., Nichol, S., Davies, J., Redondas, A., and Cuevas, E.: Long term changes in tropospheric ozone. , Atmos. Environ., 40, 3156-3173., 2006.
Oltmans, S. J., Johnson, B. J., and Harris, J. M.: Springtime boundary layer ozone depletion at Barrow, Alaska: Meteorological influence, year-to-year variation, and long-term change, Journal of Geophysical Research, 117, D00R18, doi:10.1029/2011JD016889, 2012.
Oltmans, S. J., Lefohn, A. S., Shadwick, D., Harris, J. M., Scheel, H. E., Galbally, I., Tarasick, D. W., Johnson, B. J., Brunke, E. G., Claude, H., Zeng, G., Nichol, S., Schmidlin, F., Davies, J., Cuevas, E., Redondas, A., Naoe, H., Nakano, T., and Kawasato, T.: Recent tropospheric ozone changes – A pattern dominated by slow or no growth, Atmospheric Environment, 67, 331-351, http://dx.doi.org/10.1016/j.atmosenv.2012.10.057, 2013.

8087 Oman, L. D., Douglass, A. R., Ziemke, J. R., Rodriguez, J. M., Waugh, D. W., and Nielsen, J. E.: The
8088 ozone response to ENSO in Aura satellite measurements and a chemistry-climate simulation, Journal
8089 of Geophysical Research-Atmospheres, 118, 965-976, 10.1029/2012jd018546, 2013.
8090 Ordonez, C., Brunner, D., Staehelin, J., Hadjinicolaou, P., Pyle, J. A., Jonas, M., Wernli, H., and Prevot,
8091 A. S. H.: Strong influence of lowermost stratospheric ozone on lower tropospheric background ozone
8092 changes over Europe, Geophysical Research Letters, 34, L07805, 10.1029/2006gl029113, 2007.
8093 Orlando, J. J., and Tyndall, G. S.: Laboratory studies of organic peroxy radical chemistry: an overview
8094 with emphasis on recent issues of atmospheric significance, Chemical Society Reviews, 41, 6294-
8095 6317, 10.1039/c2cs35166h, 2012.
8096 Osthoff, H. D., Roberts, J. M., Ravishankara, A. R., Williams, E. J., Lerner, B. M., Sommariva, R., Bates,
8097 T. S., Coffman, D., Quinn, P. K., Dibb, J. E., Stark, H., Burkholder, J. B., Talukdar, R. K., Meagher, J.,
8098 Fehsenfeld, F. C., and Brown, S. S.: High levels of nitryl chloride in the polluted subtropical marine
8099 boundary layer, Nature Geoscience, 1, 324-328, 2008.
8100 Ouyang, B., McLeod, M. W., Jones, R. L., and Bloss, W. J.: NO_3 radical production from the reaction
8101 between the Criegee intermediate CH_2OO and NO_2, Physical Chemistry Chemical Physics, 15, 17070-
8102 17075, 10.1039/c3cp53024h, 2013.
8103 Padro, J.: Observed Characteristics of the Dry Deposition Velocity of O3 and So2 above a Wet
8104 Deciduous Forest, Science of the Total Environment, 147, 395-400, 1994.
8105 Palmer, P. I., Jacob, D. J., Fiore, A. M., Martin, R. V., Chance, K., and Kurosu, T. P.: Mapping isoprene
8106 emissions over North America using formaldehyde column observations from space, Journal of
8107 Geophysical Research-Atmospheres, 108, 2003.
8108 Palmer, P. I., Parrington, M., Lee, J. D., Lewis, A. C., Rickard, A. R., Bernath, P. F., Duck, T. J., Waugh, D.
8109 L., Tarasick, D. W., Andrews, S., Aruffo, E., Bailey, L. J., Barrett, E., Bauguitte, S. J. B., Curry, K. R., Di
8110 Carlo, P., Chisholm, L., Dan, L., Forster, G., Franklin, J. E., Gibson, M. D., Griffin, D., Helmig, D.,
8111 Hopkins, J. R., Hopper, J. T., Jenkin, M. E., Kindred, D., Kliever, J., Le Breton, M., Matthiesen, S.,
8112 Maurice, M., Moller, S., Moore, D. P., Oram, D. E., O'Shea, S. J., Owen, R. C., Pagniello, C., Pawson, S.,
8113 Percival, C. J., Pierce, J. R., Punjabi, S., Purvis, R. M., Remedios, J. J., Rotermund, K. M., Sakamoto, K.
8114 M., da Silva, A. M., Strawbridge, K. B., Strong, K., Taylor, J., Trigwell, R., Tereszchuk, K. A., Walker, K.
8115 A., Weaver, D., Whaley, C., and Young, J. C.: Quantifying the impact of BOReal forest fires on
8116 Tropospheric oxidants over the Atlantic using Aircraft and Satellites (BORTAS) experiment: design,
8117 execution and science overview, Atmospheric Chemistry and Physics, 13, 6239-6261, 10.5194/acp-
8118 13-6239-2013, 2013.
8119 Pappin, A. J., and Hakami, A.: Attainment vs Exposure: Ozone Metric Responses to Source-Specific
8120 NOx Controls Using Adjoint Sensitivity Analysis, Environ. Sci. Technol., 47, 13519-13527,
8121 10.1021/es4024145, 2013.
8122 Paris, J. D., Stohl, A., Ciais, P., Nedelec, P., Belan, B. D., Arshinov, M. Y., and Ramonet, M.: Source-
8123 receptor relationships for airborne measurements of CO2, CO and O-3 above Siberia: a cluster-based
8124 approach, Atmospheric Chemistry and Physics, 10, 1671-1687, 2010.
8125 Parrella, J. P., Jacob, D. J., Liang, Q., Zhang, Y., Mickley, L. J., Miller, B., Evans, M. J., Yang, X., Pyle, J.
8126 A., Theys, N., and Van Roozendael, M.: Tropospheric bromine chemistry: implications for present and
8127 pre-industrial ozone and mercury, Atmospheric Chemistry and Physics, 12, 6723-6740, 10.5194/acp-
8128 12-6723-2012, 2012.
8129 Parrington, M., Palmer, P. I., Henze, D. K., Tarasick, D. W., Hyer, E. J., Owen, R. C., Helmig, D.,
8130 Clerbaux, C., Bowman, K. W., Deeter, M. N., Barratt, E. M., Coheur, P.-F., Hurtmans, D., Jiang, Z.,
8131 George, M., and Worden, J. R.: The influence of boreal biomass burning emissions on the distribution
8132 of tropospheric ozone over North America and the North Atlantic during 2010, Atmos Chem Phys, 12,
8133 2077-2098, 2012.
8134 Parrington, M., Palmer, P. I., Lewis, A. C., Lee, J. D., Rickard, A. R., Di Carlo, P., Taylor, J. W., Hopkins, J.
8135 R., Punjabi, S., Oram, D. E., Forster, G., Aruffo, E., Moller, S. J., Bauguitte, S. J. B., Allan, J. D., Coe, H.,
8136 and Leigh, R. J.: Ozone photochemistry in boreal biomass burning plumes, Atmos. Chem. Phys., 13,
8137 7321-7341, 10.5194/acp-13-7321-2013, 2013.

Parrish, D. D., Millet, D. B., and Goldstein, A. H.: Increasing ozone in marine boundary layer inflow at the west coasts of North America and Europe, Atmos. Chem. Phys., 9, 1303-1323, 10.5194/acp-9-1303-2009, 2009.
Parrish, D. D., and Zhu, T.: Clean Air for Megacities, Science, 326, 674-675, 10.1126/science.1176064, 2009.
Parrish, D. D., Singh, H. B., Molina, L., and Madronich, S.: Air quality progress in North American megacities: A review, Atmospheric Environment, 45, 7015-7025, 10.1016/j.atmosenv.2011.09.039, 2011.
Parrish, D. D., Law, K. S., Staehelin, J., Derwent, R., Cooper, O. R., Tanimoto, H., Volz-Thomas, A., Gilge, S., Scheel, H. E., Steinbacher, M., and Chan, E.: Long-term changes in lower tropospheric baseline ozone concentrations at northern mid-latitudes, Atmospheric Chemistry and Physics, 12, 11485-11504, 10.5194/acp-12-11485-2012, 2012.
Parrish, D. D., Law, K. S., Staehelin, J., Derwent, R., Cooper, O. R., Tanimoto, H., Volz-Thomas, A., Gilge, S., Scheel, H. E., Steinbacher, M., and Chan, E.: Lower tropospheric ozone at northern midlatitudes: Changing seasonal cycle, Geophysical Research Letters, 40, 1631-1636, 10.1002/grl.50303, 2013.
Parrish, D. D., Lamarque, J. F., Naik, V., Horowitz, L., Shindell, D. T., Staehelin, J., Derwent, R., Cooper, O. R., Tanimoto, H., Volz-Thomas, A., Gilge, S., Scheel, H. E., Steinbacher, M., and Frohlich, M.: Long-term changes in lower tropospheric baseline ozone concentrations: Comparing chemistry-climate models and observations at northern midlatitudes, Journal of Geophysical Research-Atmospheres, 119, 5719-5736, 10.1002/2013jd021435, 2014.
Paulot, F., Crounse, J. D., Kjaergaard, H. G., Kürten, A., Clair, J. M. S., Seinfeld, J. H., and Wennberg, P. O.: Unexpected epoxide formation in the gas-phase photooxidation of isoprene, Science, 325, 730-733, 2009.
Paulot, F., Henze, D. K., and Wennberg, P. O.: Impact of the isoprene photochemical cascade on tropical ozone, Atmospheric Chemistry and Physics, 12, 1307-1325, 10.5194/acp-12-1307-2012, 2012.
Pausata, F. S. R., Pozzoli, L., Vignati, E., and Dentener, F. J.: North Atlantic Oscillation and tropospheric ozone variability in Europe: model analysis and measurements intercomparison, Atmos. Chem. Phys., 12, 6537-6376, doi:10.5194/acp-12-6357-2012, 2012.
Pechtl, S., and von Glasow, R.: Reactive chlorine in the marine boundary layer in the outflow of polluted continental air: A model study, Geophysical Research Letters, 34, 10.1029/2007gl029761, 2007.
Peeters, J., Nguyen, T. L., and Vereecken, L.: HOx radical regeneration in the oxidation of isoprene, Phys. Chem. Chem Phys., 11, 5935 - 5939, 2009.
Petron, G., Granier, C., Khattatov, B., Yudin, V., Lamarque, J. F., Emmons, L., Gille, J., and Edwards, D. P.: Monthly CO surface sources inventory based on the 2000-2001 MOPITT satellite data, Geophysical Research Letters, 31, 10.1029/2004gl020560, 2004.
Pétron, G., Frost, G., Miller, B. R., Hirsch, A. I., Montzka, S. A., Karion, A., Trainer, M., Sweeney, C., Andrews, A. E., Miller, L., Kofler, J., Bar-Ilan, A., Dlugokencky, E. J., Patrick, L., Moore, C. T., Ryerson, T. B., Siso, C., Kolodzey, W., Lang, P. M., Conway, T., Novelli, P., Masarie, K., Hall, B., Guenther, D., Kitzis, D., Miller, J., Welsh, D., Wolfe, D., Neff, W., and Tans, P.: Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study, Journal of Geophysical Research: Atmospheres, 117, D04304, 10.1029/2011jd016360, 2012.
Pfister, G., Hess, P. G., Emmons, L. K., Lamarque, J. F., Wiedinmyer, C., Edwards, D. P., Petron, G., Gille, J. C., and Sachse, G. W.: Quantifying CO emissions from the 2004 Alaskan wildfires using MOPITT CO data, Geophysical Research Letters, 32, 10.1029/2005gl022995, 2005.
Pfister, G. G., Walters, S., Lamarque, J. F., Fast, J., Barth, M. C., Wong, J., Done, J., Holland, G., and Bruyere, C. L.: Projections of future summertime ozone over the US, Journal of Geophysical Research-Atmospheres, 119, 5559-5582, 10.1002/2013jd020932, 2014.
Phillips, G. J., Tang, M. J., Thieser, J., Brickwedde, B., Schuster, G., Bohn, B., Lelieveld, J., and Crowley, J. N.: Significant concentrations of nitryl chloride observed in rural continental Europe associated

with the influence of sea salt chloride and anthropogenic emissions, Geophysical Research Letters, 39, 10.1029/2012gl051912, 2012.
Piedrahita, R., Xiang, Y., Masson, N., Ortega, J., Collier, A., Jiang, Y., Li, K., Dick, R. P., Lv, Q., Hannigan, M., and Shang, L.: The next generation of low-cost personal air quality sensors for quantitative exposure monitoring, Atmos. Meas. Tech., 7, 3325-3336, 10.5194/amt-7-3325-2014, 2014.
Pleijel, H., Karlsson, G. P., Danielsson, H., and Sellden, G.: Surface wetness enhances ozone deposition to a pasture canopy, Atmospheric Environment, 29, 3391-3393, 1995.
Pohler, D., Vogel, L., Friess, U., and Platt, U.: Observation of halogen species in the Amundsen Gulf, Arctic, by active long-path differential optical absorption spectroscopy, Proc. Natl. Acad. Sci. U. S. A., 107, 6582-6587, 10.1073/pnas.0912231107, 2010.
Pommier, M., Mc Linden, C. A., Neuman, J. A., and Nowak, J. B.: Biomass burning in Siberia as a source of BrO to the Arctic free troposphere, Atmospheric Environment, 62, 416-423, 10.1016/j.atmosenv.2012.08.070, 2012.
Porter, W. C., Barsanti, K. C., Baughman, E. C., and Rosenstiel, T. N.: Considering the Air Quality Impacts of Bioenergy Crop Production: A Case Study Involving Arundo donax, Environ. Sci. Technol., 46, 9777-9784, 10.1021/es3010841, 2012.
Prather, M., Gauss, M., Berntsen, T., Isaksen, I., Sundet, J., Bey, I., Brasseur, G., Dentener, F., Derwent, R., Stevenson, D., Grenfell, L., Hauglustaine, D., Horowitz, L., Jacob, D., Mickley, L., Lawrence, M., von Kuhlmann, R., Muller, J. F., Pitari, G., Rogers, H., Johnson, M., Pyle, J., Law, K., van Weele, M., and Wild, O.: Fresh air in the 21st century?, Geophysical Research Letters, 30, 10.1029/2002gl016285, 2003.
Prather, M. J., Zhu, X., Tang, Q., Hsu, J. N., and Neu, J. L.: An atmospheric chemist in search of the tropopause, Journal of Geophysical Research-Atmospheres, 116, 10.1029/2010jd014939, 2011.
Price, C., and Rind, D.: A simple lightning parameterization for calculating global lightning distributions, J. Geophys. Res., 97, 9919-9933, 1992.
Puentedura, O., Gil, M., Saiz-Lopez, A., Hay, T., Navarro-Comas, M., Gomez-Pelaez, A., Cuevas, E., Iglesias, J., and Gomez, L.: Iodine monoxide in the north subtropical free troposphere, Atmospheric Chemistry and Physics, 12, 4909-4921, 10.5194/acp-12-4909-2012, 2012.
Rama Gopal, K., Lingaswamy, A. P., Arafath, S. M., Balakrishnaiah, G., Pavan Kumari, S., Uma Devi, K., Siva Kumar Reddy, N., Raja Obul Reddy, K., Reddy, R. R., Abdul Azeem, P., and Lal, S.: Seasonal heterogeneity in ozone and its precursors (NOx) by in-situ and model observations on semi-arid station in Anantapur (A.P), South India, Atmospheric Environment, 84, 294-306, http://dx.doi.org/10.1016/j.atmosenv.2013.10.014, 2014.
Rasmussen, D. J., Hu, J. L., Mahmud, A., and Kleeman, M. J.: The Ozone-Climate Penalty: Past, Present, and Future, Environ. Sci. Technol., 47, 14258-14266, 10.1021/es403446m, 2013.
Read, K. A., Mahajan, A. S., Carpenter, L. J., Evans, M. J., Faria, B. V. E., Heard, D. E., Hopkins, J. R., Lee, J. D., Moller, S. J., Lewis, A. C., Mendes, L., McQuaid, J. B., Oetjen, H., Saiz-Lopez, A., Pilling, M. J., and Plane, J. M. C.: Extensive halogen-mediated ozone destruction over the tropical Atlantic Ocean, Nature, 453, 1232-1235, 2008.
Real, E., Law, K. S., Weinzierl, B., Fiebig, M., Petzold, A., Wild, O., Methven, J., Arnold, S., Stohl, A., Huntrierser, H., Roiger, A., Schlager, H., Stewart D. , Avery, M., Sachse, G., Browell, E., Ferrare, R., and Blake, D.: Processes influencing ozone levels in Alaskan forest fire plumes during long-range transport over the North Atlantic, J. Geophys. Res., 112, D10S41, doi:10.1029/2006JD007576, 2007.
Redelsperger, J. L., Thorncroft, C. D., Diedhiou, A., Lebel, T., Parker, D. J., and Polcher, J.: African monsoon multidisciplinary analysis - An international research project and field campaign, Bulletin of the American Meteorological Society, 87, 1739-1746, 10.1175/bams-87-12-1739, 2006.
Reeve, N., and Toumi, R.: Lightning activity as an indicator of climate change, Quarterly Journal of the Royal Meteorological Society, 125, 893-903, 10.1002/qj.49712555507, 1999.
Reeves, C. E., Formenti, P., Afif, C., Ancellet, G., Attie, J. L., Bechara, J., Borbon, A., Cairo, F., Coe, H., Crumeyrolle, S., Fierli, F., Flamant, C., Gomes, L., Hamburger, T., Jambert, C., Law, K. S., Mari, C., Jones, R. L., Matsuki, A., Mead, M. I., Methven, J., Mills, G. P., Minikin, A., Murphy, J. G., Nielsen, J. K., Oram, D. E., Parker, D. J., Richter, A., Schlager, H., Schwarzenboeck, A., and Thouret, V.: Chemical and

aerosol characterisation of the troposphere over West Africa during the monsoon period as part of AMMA, Atmospheric Chemistry and Physics, 10, 7575-7601, 10.5194/acp-10-7575-2010, 2010.
Reich, P. B., and Amundson, R. G.: Ambient levels of ozone reduce net photosynthesis in tree and crop species., Science, 230, 566-570., 1985.
Reidmiller, D. R., Fiore, A. M., Jaffe, D. A., Bergmann, D., Cuvelier, C., Dentener, F. J., Duncan, B. N., Folberth, G., Gauss, M., Gong, S., Hess, P., Jonson, J. E., Keating, T., Lupu, A., Marmer, E., Park, R., Schultz, M. G., Shindell, D. T., Szopa, S., Vivanco, M. G., Wild, O., and Zuber, A.: The influence of foreign vs. North American emissions on surface ozone in the US, Atmospheric Chemistry and Physics, 9, 5027-5042, 2009.
Riahi, K., Dentener, F., Gielen, D., Grubler, A., Jewell, J., Klimont, Z., Krey, V., McCollum, D., Pachauri, S., Rao, S., van Ruijven, B., van Vuuren, D. P., and Wilson, C.: Energy Pathways for Sustainable Development, in: Global Energy Assessment: Toward a Sustainable Future, edited by: Nakicenovic, N., IIASA, Laxenburg, Austria and Cambridge University Press, Cambridge, United Kingdom and New York, NY, 2012.
Riedel, T. P., Bertram, T. H., Crisp, T. A., Williams, E. J., Lerner, B. M., Vlasenko, A., Li, S.-M., Gilman, J., de Gouw, J., Bon, D. M., Wagner, N. L., Brown, S. S., and Thornton, J. A.: Nitryl Chloride and Molecular Chlorine in the Coastal Marine Boundary Layer, Environ. Sci. Technol., 46, 10463-10470, 10.1021/es204632r, 2012.
Riedel, T. P., Wagner, N. L., Dube, W. P., Middlebrook, A. M., Young, C. J., Ozturk, F., Bahreini, R., VandenBoer, T. C., Wolfe, D. E., Williams, E. J., Roberts, J. M., Brown, S. S., and Thornton, J. A.: Chlorine activation within urban or power plant plumes: Vertically resolved $ClNO_2$ and Cl_2 measurements from a tall tower in a polluted continental setting, Journal of Geophysical Research-Atmospheres, 118, 8702-8715, 10.1002/jgrd.50637, 2013.
Rodriguez, M. A., Barna, M. G., and Moore, T.: Regional Impacts of Oil and Gas Development on Ozone Formation in the Western United States, J Air Waste Manage, 59, 1111-1118, 10.3155/1047-3289.59.9.1111, 2009.
Rondon, A., Johansson, C., and Granat, L.: Dry Deposition of Nitrogen-Dioxide and Ozone to Coniferous Forests, Journal of Geophysical Research-Atmospheres, 98, 5159-5172, 1993.
Roscoe, H. K., Brough, N., Jones, A. E., Wittrock, F., Richter, A., Van Roozendael, M., and Hendrick, F.: Characterisation of vertical BrO distribution during events of enhanced tropospheric BrO in Antarctica, from combined remote and in-situ measurements, Journal of Quantitative Spectroscopy & Radiative Transfer, 138, 70-81, 10.1016/j.jqsrt.2014.01.026, 2014.
Royal Society: Ground-level ozone in the 21st century: future trends, impacts and policy implications., The Royal Society, London, 2008.
Rypdal, K., Berntsen, T., Fuglestvedt, J. S., Aunan, K., Torvanger, A., Stordal, F., Pacyna, J. M., and Nygaard, L. P.: Tropospheric ozone and aerosols in climate agreements: scientific and political challenges, Environ. Sci. Policy, 8, 29-43, 10.1016/j.envsci.2004.09.003, 2005.
Sahu, S. K., Beig, G., and Parkhi, N. S.: Emerging pattern of anthropogenic NOx emission over Indian subcontinent during 1990s and 2000s, Atmos. Pollut. Res., 3, 262-269, 10.5094/apr.2012.021, 2012.
Saide, P., Bocquet, M., Osses, A., and Gallardo, L.: Constraining surface emissions of air pollutants using inverse modelling: method intercomparison and a new two-step two-scale regularization approach, Tellus Series B-Chemical and Physical Meteorology, 63, 360-370, 10.1111/j.1600-0889.2011.00529.x, 2011.
Saiz-Lopez, A., Plane, J. M. C., Mahajan, A. S., Anderson, P. S., Bauguitte, S. J. B., Jones, A. E., Roscoe, H. K., Salmon, R. A., Bloss, W. J., Lee, J. D., and Heard, D. E.: On the vertical distribution of boundary layer halogens over coastal Antarctica: implications for O-3, HOx, NOx and the Hg lifetime, Atmospheric Chemistry and Physics, 8, 887-900, 10.5194/acp-8-887-2008, 2008.
Saiz-Lopez, A., Plane, J. M., Baker, A. R., Carpenter, L. J., von Glasow, R., Gómez Martín, J. C., McFiggans, G., and Saunders, R. W.: Atmospheric chemistry of iodine, Chemical reviews, 112, 1773-1804, 2011.
Saiz-Lopez, A., Lamarque, J. F., Kinnison, D. E., Tilmes, S., Ordonez, C., Orlando, J. J., Conley, A. J., Plane, J. M. C., Mahajan, A. S., Santos, G. S., Atlas, E. L., Blake, D. R., Sander, S. P., Schauffler, S.,

Thompson, A. M., and Brasseur, G.: Estimating the climate significance of halogen-driven ozone loss in the tropical marine troposphere, Atmospheric Chemistry and Physics, 12, 3939-3949, 10.5194/acp-12-3939-2012, 2012a.
Saiz-Lopez, A., Plane, J. M. C., Baker, A. R., Carpenter, L. J., von Glasow, R., Martin, J. C. G., McFiggans, G., and Saunders, R. W.: Atmospheric Chemistry of Iodine, Chemical Reviews, 112, 1773-1804, 10.1021/cr200029u, 2012b.
Saiz-Lopez, A., and von Glasow, R.: Reactive halogen chemistry in the troposphere, Chemical Society Reviews, 41, 6448-6472, 10.1039/c2cs35208g, 2012.
Salawitch, R. J., Canty, T., Kurosu, T., Chance, K., Liang, Q., da Silva, A., Pawson, S., Nielsen, J. E., Rodriguez, J. M., Bhartia, P. K., Liu, X., Huey, L. G., Liao, J., Stickel, R. E., Tanner, D. J., Dibb, J. E., Simpson, W. R., Donohoue, D., Weinheimer, A., Flocke, F., Knapp, D., Montzka, D., Neuman, J. A., Nowak, J. B., Ryerson, T. B., Oltmans, S., Blake, D. R., Atlas, E. L., Kinnison, D. E., Tilmes, S., Pan, L. L., Hendrick, F., Van Roozendael, M., Kreher, K., Johnston, P. V., Gao, R. S., Johnson, B., Bui, T. P., Chen, G., Pierce, R. B., Crawford, J. H., and Jacob, D. J.: A new interpretation of total column BrO during Arctic spring, Geophysical Research Letters, 37, 10.1029/2010gl043798, 2010.
Sanchez-Ccoyllo, O. R., Silva Dias, P. L., Andrade, M. D., and Freitas, S. R.: Determination of O_3, CO and PM10 transport in the metropolitan area of Sao Paulo, Brazil through synoptic-scale analysis of back trajectories, Meteorology and Atmospheric Physics, 92, 83-93, 10.1007/s00703-005-0139-6, 2006.
Sanchez, M. L., Rodriguez, R., and Lopez, A.: Ozone dry deposition in a semi-arid steppe and in a coniferous forest in southern Europe, Journal of the Air & Waste Management Association, 47, 792-799, 1997.
Sander, R., Keene, W. C., Pszenny, A. A. P., Arimoto, R., Ayers, G. P., Baboukas, E., Cainey, J. M., Crutzen, P. J., Duce, R. A., H¨onninger, G., Huebert, B. J., Maenhaut, W., Mihalopoulos, N., Turekian, V. C., and Dingenen, R. V.: Inorganic bromine compounds in the marine boundary layer: A critical review, Atmos. Chem. Phys., 3 1301 - 1336, 2003.
Sanderson, M. G., Jones, C. D., Collins, W. J., Johnson, C. E., and Derwent, R. G.: Effect of climate change on isoprene emissions and surface ozone levels, Geophysical Research Letters, 30, 10.1029/2003gl017642, 2003.
Sarwar, G., Simon, H., Bhave, P., and Yarwood, G.: Examining the impact of heterogeneous nitryl chloride production on air quality across the United States, Atmospheric Chemistry and Physics, 12, 6455-6473, 10.5194/acp-12-6455-2012, 2012.
Sauvage, B., Thouret, V., Cammas, J. P., Gheusi, F., Athier, G., and Nedelec, P.: Tropospheric ozone over Equatorial Africa: regional aspects from the MOZAIC data, Atmos. Chem. Phys., 5, 311-335, 2005.
Sauvage, B., Thouret, V., Thompson, A. M., Witte, J. C., Cammas, J. P., Nedelec, P., and Athier, G.: Enhanced view of the "tropical Atlantic ozone paradox" and "zonal wave one" from the in situ MOZAIC and SHADOZ data, J. Geophys. Res. , 111, D01301, doi:10.1029/2005JD006241, 2006.
Sauvage, B., Martin, R. V., van Donkelaar, A., and Ziemke, J. R.: Quantification of the factors controlling tropical tropospheric ozone and the South Atlantic maximum, J. Geophys. Res., 112, D11309, doi:10.1029/2006JD008008, 2007a.
Sauvage, B., Thouret, V., Cammas, J. P., Brioude, J., Nedelec, P., and Mari, C.: Meridional ozone gradients in the African upper troposphere, Geophys. Res. Lett., 34, L03817, doi:10.1029/2006GL028542, 2007b.
Saylor, R. D., and Stein, A. F.: Identifying the causes of differences in ozone production from the CB05 and CBMIV chemical mechanisms, Geosci. Model Dev., 5, 257-268, 10.5194/gmd-5-257-2012, 2012.
Schneising, O., Burrows, J. P., Dickerson, R. R., Buchwitz, M., Reuter, M., and Bovensmann, H.: Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations, Earth's Future, 2014EF000265, 10.1002/2014ef000265, 2014.
Schnell, R. C., Oltmans, S. J., Neely, R. R., Endres, M. S., Molenar, J. V., and White, A. B.: Rapid photochemical production of ozone at high concentrations in a rural site during winter, Nature Geoscience, 2, 120-122, 10.1038/ngeo415, 2009.

8346 Schönbein, C. F.: Über die Natur eigenthümlichen Grueches, welcher sich sowohl am positiven Pole
8347 einer Saüle während der Wasserelektrolys, wie auch beim Ausströmen der gewöhnlichen Elektrizität
8348 aus Spotzen entwickelt, Ann. Phys., 135, 1843.
8349 Schultz, M., Rast, S., van het Bolscher, M., Pulles, T., Brand, R., Pereira, J., Mota, B., Spessa, A.,
8350 Dalsøren, S., van Nojie, T., and Szopa, S.: Emission data sets and methodologies for estimating
8351 emissions,, Juelich, 2007a.
8352 Schultz, M. G., Backman, L., Balkanski, Y., Bjoerndalsaeter, S., Brand, R., Burrows, J. P., Dalsoeren, S.,
8353 Vasconcelos, M. d., Grodtmann, B., Hauglustaine, D. A., Heil, A., Hoelzemann, J. J., I.S.A. Isaksen,
8354 Kaurola, J., Knorr, W., Ladstaetter-Weißenmayer, A., Mota, B., Oom, D., Pacyna, J., Panasiuk, D.,
8355 Pereira, J. M. C., Pulles, T., Pyle, J., Rast, S., Richter, A., Savage, N., Schnadt, C., Schulz, M., Spessa, A.,
8356 Staehelin, J., Sundet, J. K., Szopa, S., Thonicke, K., Bolscher, M. v. h., Noije, T. v., Velthoven, P. v., Vik,
8357 A. F., and Wittrock, F.: REanalysis of the TROpospheric chemical composition over the past 40 years
8358 (RETRO) — A long-term global modeling study of tropospheric chemistry - Final Report,
8359 Jülich/Hamburg, Germany, 2007b.
8360 Schultz, M. G., Heil, A., Hoelzemann, J. J., Spessa, A., Thonicke, K., Goldammer, J., Held, A. C., and
8361 Pereira, J. M.: Global Emissions from Wildland Fires from 1960 to 2000, Global Biogeochem. Cycles,
8362 22, GB2002, doi:10.1029/2007GB003031., 2008.
8363 Schumann, U., and Huntrieser, H.: The global lightning-induced nitrogen oxides source, Atmos. Chem.
8364 and Phys., 7, 3823-3907, 2007.
8365 Seinfeld, J. H., and Pandis, S. N.: Atmospheric Chemistry and Physics: From Air Pollution to Climate
8366 Change, 2nd ed., Wiley, 2006.
8367 Sekiya, T., and Sudo, K.: Roles of transport and chemistry processes in global ozone change on
8368 interannual and multidecadal time scales, Journal of Geophysical Research-Atmospheres, 119, 4903-
8369 4921, 10.1002/2013jd020838, 2014.
8370 Sellitto, P., Dufour, G., Eremenko, M., Cuesta, J., Dauphin, P., Foret, G., Gaubert, B., Beekmann, M.,
8371 Peuch, V. H., and Flaud, J. M.: Analysis of the potential of one possible instrumental configuration of
8372 the next generation of IASI instruments to monitor lower tropospheric ozone, Atmos. Meas. Tech., 6,
8373 621-635, 10.5194/amt-6-621-2013, 2013.
8374 Sheps, L.: Absolute Ultraviolet Absorption Spectrum of a Criegee Intermediate CH2OO, The Journal of
8375 Physical Chemistry Letters, 4, 4201-4205, 2013.
8376 Shindell, D., Faluvegi, G., Lacis, A., Hansen, J., Ruedy, R., and Aguilar, E.: Role of tropospheric ozone
8377 increases in 20th-century climate change, Journal of Geophysical Research-Atmospheres, 111,
8378 10.1029/2005jd006348, 2006.
8379 Shindell, D.: Local and remote contributions to Arctic warming, Geophysical Research Letters, 34,
8380 10.1029/2007gl030221, 2007.
8381 Shindell, D., Schulz, M., Ming, Y., Takemura, T., Faluvegi, G., and Ramaswamy, V.: Spatial scales of
8382 climate response to inhomogeneous radiative forcing, Journal of Geophysical Research-Atmospheres,
8383 115, 10.1029/2010jd014108, 2010.
8384 Shindell, D., Kuylenstierna, J. C. I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.
8385 C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K.,
8386 Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, N. T. K., Milly, G.,
8387 Williams, M., Demkine, V., and Fowler, D.: Simultaneously Mitigating Near-Term Climate Change and
8388 Improving Human Health and Food Security, Science, 335, 183-189, 10.1126/science.1210026, 2012.
8389 Shindell, D. T., Faluvegi, G., Bell, N., and Schmidt, G. A.: An emissions-based view of climate forcing by
8390 methane and tropospheric ozone, Geophysical Research Letters, 32, 10.1029/2004gl021900, 2005.
8391 Shindell, D. T., Chin, M., Dentener, F., Doherty, R. M., Faluvegi, G., Fiore, A. M., Hess, P., Koch, D. M.,
8392 MacKenzie, I. A., Sanderson, M. G., Schultz, M. G., Schulz, M., Stevenson, D. S., Teich, H., Textor, C.,
8393 Wild, O., Bergmann, D. J., Bey, I., Bian, H., Cuvelier, C., Duncan, B. N., Folberth, G., Horowitz, L. W.,
8394 Jonson, J., Kaminski, J. W., Marmer, E., Park, R., Pringle, K. J., Schroeder, S., Szopa, S., Takemura, T.,
8395 Zeng, G., Keating, T. J., and Zuber, A.: A multi-model assessment of pollution transport to the Arctic,
8396 Atmospheric Chemistry and Physics, 8, 5353-5372, 2008.

Shindell, D. T., Faluvegi, G., Koch, D. M., Schmidt, G. A., Unger, N., and Bauer, S. E.: Improved Attribution of Climate Forcing to Emissions, Science, 326, 716-718, 10.1126/science.1174760, 2009.
Shindell, D. T., Lamarque, J. F., Schulz, M., Flanner, M., Jiao, C., Chin, M., Young, P. J., Lee, Y. H., Rotstayn, L., Mahowald, N., Milly, G., Faluvegi, G., Balkanski, Y., Collins, W. J., Conley, A. J., Dalsoren, S., Easter, R., Ghan, S., Horowitz, L., Liu, X., Myhre, G., Nagashima, T., Naik, V., Rumbold, S. T., Skeie, R., Sudo, K., Szopa, S., Takemura, T., Voulgarakis, A., Yoon, J. H., and Lo, F.: Radiative forcing in the ACCMIP historical and future climate simulations, Atmospheric Chemistry and Physics, 13, 2939-2974, 10.5194/acp-13-2939-2013, 2013.
Shindell, D. T.: Inhomogeneous forcing and transient climate sensitivity, Nat. Clim. Chang., 4, 274-277, 10.1038/nclimate2136, 2014.
Sicard, P., De Marco, A., Troussier, F., Renou, C., Vas, N., and Paoletti, E.: Decrease in surface ozone concentrations at Mediterranean remote sites and increase in the cities, Atmospheric Environment, 79, 705-715, 10.1016/j.atmosenv.2013.07.042, 2013.
Siegert, F., Ruecker, G., Hinrichs, A., and Hoffmann, A. A.: Increased damage from fires in logged forests during droughts caused by El Nino, Nature, 414, 437-440, 10.1038/35106547, 2001.
Silva, G. d., Graham, C., and Wang, Z.-F.: Unimolecular β–hydroxyperoxy radical decomposition with OH recycling in the photochemical oxidation of isoprene, Environ. Sci. Technol., 44, 250-256, 2009.
Silva, R. A., West, J. J., Zhang, Y., Anenberg, S. C., Lamarque, J.-F., Shindell, D. T., Collins, W. J., Dalsoren, S., Faluvegi, G., Folberth, G., Horowitz, L. W., Nagashima, T., Naik, V., Rumbold, S., Skeie, R., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Cionni, I., Doherty, R. M., Eyring, V., Josse, B., MacKenzie, I. A., Plummer, D., Righi, M., Stevenson, D. S., Strode, S., Szopa, S., and Zeng, G.: Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change, Environmental Research Letters, 8, 10.1088/1748-9326/8/3/034005, 2013.
Simmonds, P. G., Derwent, R. G., Manning, A. L., and Spain, G.: Significant growth in surface ozone at Mace Head, Ireland, 1987-2003, Atmos. Environ., 38, 4769-4778, 2004.
Simon, H., Kimura, Y., McGaughey, G., Allen, D. T., Brown, S. S., Osthoff, H. D., Roberts, J. M., Byun, D., and Lee, D.: Modeling the impact of ClNO2 on ozone formation in the Houston area, Journal of Geophysical Research-Atmospheres, 114, 10.1029/2008jd010732, 2009.
Simon, H., Kimura, Y., McGaughey, G., Allen, D. T., Brown, S. S., Coffman, D., Dibb, J., Osthoff, H. D., Quinn, P., Roberts, J. M., Yarwood, G., Kemball-Cook, S., Byun, D., and Lee, D.: Modeling heterogeneous ClNO2 formation, chloride availability, and chlorine cycling in Southeast Texas, Atmospheric Environment, 44, 5476-5488, 10.1016/j.atmosenv.2009.09.006, 2010.
Simon, H., Reff, A., Wells, B., Xing, J., and Frank, N.: Ozone Trends Across the United States over a Period of Decreasing NOx and VOC Emissions, Environ. Sci. Technol., 49, 186-195, 10.1021/es504514z, 2015.
Simpson, D., Arneth, A., Mills, G., Solberg, S., and Uddling, J.: Ozone — the persistent menace: interactions with the N cycle and climate change, Current Opinion in Environmental Sustainability, 9–10, 9-19, http://dx.doi.org/10.1016/j.cosust.2014.07.008, 2014.
Simpson, W. R., von Glasow, R., Riedel, K., Anderson, P., Ariya, P., Bottenheim, J., Burrows, J., Carpenter, L. J., Frieß, U., Goodsite, M. E., Heard, D., Hutterli, M., Jacobi, H.-W., Kaleschke, L., Neff, B., Plane, J., Platt, U., Richter, A., Roscoe, H., Sander, R., Shepson, P., Sodeau, J., Steffen, A., Wagner, A., and Wolff, E.: Halogens and their role in polar boundary-layer ozone depletion, Atmos. Chem. Phys., 7, 4375-4418, 2007.
Sindelarova, K., Granier, C., Bouarar, I., Guenther, A., Tilmes, S., Stavrakou, T., Müller, J. F., Kuhn, U., Stefani, P., and Knorr, W.: Global data set of biogenic VOC emissions calculated by the MEGAN model over the last 30 years, Atmos. Chem. Phys., 14, 9317-9341, 10.5194/acp-14-9317-2014, 2014.
Singh, H. B., Anderson, B. E., Brune, W. H., Cai, C., Cohen, R. C., Crawford, J. H., Cubison, M. J., Czech, E. P., Emmons, L., Fuelberg, H. E., Huey, G., Jacob, D. J., Jimenez, J. L., Kaduwela, A., Kondo, Y., Mao, J., Olson, J. R., Sachse, G. W., Vay, S. A., Weinheimer, A., Wennberg, P. O., Wisthaler, A., and Team, A. S.: Pollution influences on atmospheric composition and chemistry at high northern latitudes: Boreal and California forest fire emissions, Atmospheric Environment, 44, 4553-4564, 10.1016/j.atmosenv.2010.08.026, 2010.

Sinha, B., Singh Sangwan, K., Maurya, Y., Kumar, V., Sarkar, C., Chandra, B. P., and Sinha, V.: Assessment of crop yield losses in Punjab and Haryana using two years of continuous in-situ ozone measurements, Atmos. Chem. Phys. Discuss., 15, 2355-2404, 10.5194/acpd-15-2355-2015, 2015.
Sinha, V., Kumar, V., and Sarkar, C.: Chemical composition of pre-monsoon air in the Indo-Gangetic Plain measured using a new air quality facility and PTR-MS: high surface ozone and strong influence of biomass burning, Atmos. Chem. Phys., 14, 5921-5941, 10.5194/acp-14-5921-2014, 2014.
Siour, G., Colette, A., Menut, L., Bessagnet, B., Coll, I., and Meleux, F.: Bridging the scales in a eulerian air quality model to assess megacity export of pollution, Environ. Modell. Softw., 46, 271-282, 10.1016/j.envsoft.2013.04.001, 2013.
Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Global Change Biology, 9, 161-185, 10.1046/j.1365-2486.2003.00569.x, 2003.
Sitch, S., Cox, P. M., Collins, W. J., and Huntingford, C.: Indirect radiative forcing of climate change through ozone effects on the land-carbon sink, Nature, 448, 791-U794, 10.1038/nature06059, 2007.
Situ, S., Guenther, A., Wang, X., Jiang, X., Turnipseed, A., Wu, Z., Bai, J., and Wang, X.: Impacts of seasonal and regional variability in biogenic VOC emissions on surface ozone in the Pearl River delta region, China, Atmospheric Chemistry and Physics, 13, 11803-11817, 10.5194/acp-13-11803-2013, 2013.
Skeie, R. B., Berntsen, T. K., Myhre, G., Tanaka, K., Kvalevag, M. M., and Hoyle, C. R.: Anthropogenic radiative forcing time series from pre-industrial times until 2010, Atmospheric Chemistry and Physics, 11, 11827-11857, 10.5194/acp-11-11827-2011, 2011.
Smith, K. R., Jerrett, M., Anderson, H. R., Burnett, R. T., Stone, V., Derwent, R., Atkinson, R. W., Cohen, A., Shonkoff, S. B., Krewski, D., Pope, C. A., Thun, M. J., and Thurston, G.: Health and Climate Change 5 Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants, Lancet, 374, 2091-2103, 10.1016/s0140-6736(09)61716-5, 2009.
Smoydzin, L., and von Glasow, R.: Modelling chemistry over the Dead Sea: bromine and ozone chemistry, Atmospheric Chemistry and Physics, 9, 5057-5072, 2009.
Snyder, E. G., Watkins, T. H., Solomon, P. A., Thoma, E. D., Williams, R. W., Hagler, G. S. W., Shelow, D., Hindin, D. A., Kilaru, V. J., and Preuss, P. W.: The Changing Paradigm of Air Pollution Monitoring, Environ. Sci. Technol., 47, 11369-11377, 10.1021/es4022602, 2013.
Sofiev, M., Vankevich, R., Lotjonen, M., Prank, M., Petukhov, V., Ermakova, T., Koskinen, J., and Kukkonen, J.: An operational system for the assimilation of the satellite information on wild-land fires for the needs of air quality modelling and forecasting, Atmospheric Chemistry and Physics, 9, 6833-6847, 2009.
Sofiev, M., Vankevich, R., Ermakova, T., and Hakkarainen, J.: Global mapping of maximum emission heights and resulting vertical profiles of wildfire emissions, Atmospheric Chemistry and Physics, 13, 7039-7052, 10.5194/acp-13-7039-2013, 2013.
Sommariva, R., Bloss, W. J., and von Glasow, R.: Uncertainties in gas-phase atmospheric iodine chemistry, Atmospheric Environment, 57, 219-232, 10.1016/j.atmosenv.2012.04.032, 2012.
Sommariva, R., and von Glasow, R.: Multiphase Halogen Chemistry in the Tropical Atlantic Ocean, Environ. Sci. Technol., 46, 10429-10437, 10.1021/es300209f, 2012.
Sommariva, R., Blake, R. S., Cuss, R. J., Cordell, R. L., Harrington, J. F., White, I. R., and Monks, P. S.: Observations of the Release of Non-methane Hydrocarbons from Fractured Shale, Environ. Sci. Technol., 48, 8891-8896, 10.1021/es502508w, 2014.
Song, J., Lei, W., Bei, N., Zavala, M., de Foy, B., Volkamer, R., Cardenas, B., Zheng, J., Zhang, R., and Molina, L. T.: Ozone response to emission changes: a modeling study during the MCMA-2006/MILAGRO Campaign, Atmospheric Chemistry and Physics, 10, 3827-3846, 2010.
Squire, O. J., Archibald, A. T., Griffiths, P. T., Jenkin, M. E., Smith, D., and Pyle, J. A.: Influence of isoprene chemical mechanism on modelled changes in tropospheric ozone due to climate and land use over the 21st century, Atmos. Chem. Phys., 15, 5123-5143, 10.5194/acp-15-5123-2015, 2015.

Staehelin, J., Thudium, J., Buehler, R., Volzthomas, A., and Graber, W.: Trends in surface ozone concetrations at Arosa (Switzerland), Atmospheric Environment, 28, 75-87, 1994.
Staehelin, J.: Ozone Measurements and Trends (Troposphere), in: Encyclopedia of Physical Science and Technology (Third Edition), edited by: Meyers, R. A., Academic Press, New York, 539-561, 2003.
Stavrakou, T., Muller, J. F., Boersma, K. F., De Smedt, I., and van der A, R. J.: Assessing the distribution and growth rates of NOx emission sources by inverting a 10-year record of NO_2 satellite columns, Geophysical Research Letters, 35, L10801, 2008.
Stavrakou, T., Muller, J. F., De Smedt, I., Van Roozendael, M., van der Werf, G. R., Giglio, L., and Guenther, A.: Evaluating the performance of pyrogenic and biogenic emission inventories against one decade of space-based formaldehyde columns, Atmospheric Chemistry and Physics, 9, 1037-1060, 2009.
Stavrakou, T., Guenther, A., Razavi, A., Clarisse, L., Clerbaux, C., Coheur, P. F., Hurtmans, D., Karagulian, F., De Maziere, M., Vigouroux, C., Amelynck, C., Schoon, N., Laffineur, Q., Heinesch, B., Aubinet, M., Rinsland, C., and Muller, J. F.: First space-based derivation of the global atmospheric methanol emission fluxes, Atmospheric Chemistry and Physics, 11, 4873-4898, 10.5194/acp-11-4873-2011, 2011.
Stedman, J. R.: The predicted number of air pollution related deaths in the UK during the August 2003 heatwave, Atmos. Environ., 3, 1087-1090, 2004.
Stein, O., Schultz, M. G., Bouarar, I., Clark, H., Huijnen, V., Gaudel, A., George, M., and Clerbaux, C.: On the wintertime low bias of Northern Hemisphere carbon monoxide found in global model simulations, Atmos. Chem. Phys., 14, 9295-9316, 10.5194/acp-14-9295-2014, 2014.
Stella, P., Personne, E., Loubet, B., Lamaud, E., Ceschia, E., Beziat, P., Bonnefond, J. M., Irvine, M., Keravec, P., Mascher, N., and Cellier, P.: Predicting and partitioning ozone fluxes to maize crops from sowing to harvest: the Surfatm-O-3 model, Biogeosciences, 8, 2869-2886, 10.5194/bg-8-2869-2011, 2011.
Stevenson, D. S., Dentener, F. J., Schultz, M. G., Ellingsen, K., van Noije, T. P. C., Wild, O., Zeng, G., Amann, M., Atherton, C. S., Bell, N., Bergmann, D. J., Bey, I., Butler, T., Cofala, J., Collins, W. J., Derwent, R. G., Doherty, R. M., Drevet, J., Eskes, H. J., Fiore, A. M., Gauss, M., Hauglustaine, D. A., Horowitz, L. W., Isaksen, I. S. A., Krol, M. C., Lamarque, J. F., Lawrence, M. G., Montanaro, V., Muller, J. F., Pitari, G., Prather, M. J., Pyle, J. A., Rast, S., Rodriguez, J. M., Sanderson, M. G., Savage, N. H., Shindell, D. T., Strahan, S. E., Sudo, K., and Szopa, S.: Multimodel ensemble simulations of present-day and near-future tropospheric ozone, Journal of Geophysical Research-Atmospheres, 111, 10.1029/2005jd006338, 2006.
Stevenson, D. S., and Derwent, R. G.: Does the location of aircraft nitrogen oxide emissions affect their climate impact?, Geophysical Research Letters, 36, 10.1029/2009gl039422, 2009.
Stevenson, D. S., Young, P. J., Naik, V., Lamarque, J. F., Shindell, D. T., Voulgarakis, A., Skeie, R. B., Dalsoren, S. B., Myhre, G., Berntsen, T. K., Folberth, G. A., Rumbold, S. T., Collins, W. J., MacKenzie, I. A., Doherty, R. M., Zeng, G., van Noije, T. P. C., Strunk, A., Bergmann, D., Cameron-Smith, P., Plummer, D. A., Strode, S. A., Horowitz, L., Lee, Y. H., Szopa, S., Sudo, K., Nagashima, T., Josse, B., Cionni, I., Righi, M., Eyring, V., Conley, A., Bowman, K. W., Wild, O., and Archibald, A.: Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), Atmospheric Chemistry and Physics, 13, 3063-3085, 10.5194/acp-13-3063-2013, 2013.
Stjernberg, A.-C. E., Skorokhod, A., Paris, J. D., Elansky, N., Nedelec, P., and Stohl, A.: Low concentrations of near-surface ozone in Siberia, Tellus Series B-Chemical and Physical Meteorology, 64, 1-13, 10.3402/tellusb.v64i0.11607, 2012.
Stock, Z. S., Russo, M. R., Butler, T. M., Archibald, A. T., Lawrence, M. G., Telford, P. J., Abraham, N. L., and Pyle, J. A.: Modelling the impact of megacities on local, regional and global tropospheric ozone and the deposition of nitrogen species, Atmos. Chem. Phys., 13, 12215-12231, 10.5194/acp-13-12215-2013, 2013.
Stohl, A., Bonasoni, P., Cristofanelli, P., Collins, W. J., Feichter, J., Frank, A., Forster, C., Gerasopoulos, E., Gäggeler, H., James, P., Kentarchos, T., Kromp-Kalb, H., Krüger, B., Land, C., Meloen, J.,

8553 Papayannis, A., Priller, A., Seibert, P., Sprenger, M., Roelofs, G. J., Scheel, H. E., Schnabel, C.,
8554 Siegmund, P., Tobler, L., Trickl, T., Wernli, H., Wirth, V., Zanis, P., and Zerefos, C.: Stratosphere-
8555 troposphere exchange : A review, and what we have learned from STACCATO, J. Geophys. Res.,
8556 108(D12), 8516, doi :10.1029/2002JD002490, 2003.
8557 Stohl, A., and Eckhardt, S.: Intercontinental Transport of Air Pollution: An Introduction,
8558 Intercontinental Tranport of Air Pollution, The Handbook of Environmental Chemistry, Part G,
8559 Springer., Berlin Heidelberg New York, , 2004.
8560 Stone, D., Whalley, L. K., and Heard, D. E.: Tropospheric OH and HO_2 radicals: field measurements
8561 and model comparisons, Chemical Society Reviews, 41, 6348-6404, 10.1039/c2cs35140d, 2012.
8562 Stone, D., Blitz, M., Daubney, L., Howes, N. U., and Seakins, P.: Kinetics of CH_2OO reactions with SO_2,
8563 NO_2, NO, H_2O and CH_3CHO as a function of pressure, Physical Chemistry Chemical Physics, 16, 1139-
8564 1149, 2014.
8565 Streets, D. G., Canty, T., Carmichael, G. R., de Foy, B., Dickerson, R. R., Duncan, B. N., Edwards, D. P.,
8566 Haynes, J. A., Henze, D. K., Houyoux, M. R., Jacob, D. J., Krotkov, N. A., Lamsal, L. N., Liu, Y., Lu, Z.,
8567 Martin, R. V., Pfister, G. G., Pinder, R. W., Salawitch, R. J., and Wecht, K. J.: Emissions estimation from
8568 satellite retrievals: A review of current capability, Atmospheric Environment, 77, 1011-1042,
8569 http://dx.doi.org/10.1016/j.atmosenv.2013.05.051, 2013.
8570 Stuber, N., Ponater, M., and Sausen, R.: Why radiative forcing might fail as a predictor of climate
8571 change, Climate Dynamics, 24, 497-510, 10.1007/s00382-004-0497-7, 2005.
8572 Stutz, J., Ackermann, R., Fast, J. D., and Barrie, L.: Atmospheric reactive chlorine and bromine at the
8573 Great Salt Lake, Utah, Geophysical Research Letters, 29, 10.1029/2002gl014812, 2002.
8574 Su, Y.-T., Lin, H.-Y., Putikam, R., Matsui, H., Lin, M., and Lee, Y.-P.: Extremely rapid self-reaction of the
8575 simplest Criegee intermediate CH2OO and its implications in atmospheric chemistry, Nature
8576 chemistry, 2014.
8577 Suddick, E. C., Whitney, P., Townsend, A. R., and Davidson, E. A.: The role of nitrogen in climate
8578 change and the impacts of nitrogen-climate interactions in the United States: foreword to thematic
8579 issue, Biogeochemistry, 114, 1-10, 10.1007/s10533-012-9795-z, 2013.
8580 Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grenfelt, P., Grinsven, H. v., and
8581 Grizzetti, B.: The European Nitrogen Assessment: Sources, Effects and Policy Perspectives, Cambridge
8582 University Press, Cambridge, 664 pp., 2011.
8583 Szopa, S., Hauglustaine, D. A., Vautard, R., and Menut, L.: Future global tropospheric ozone changes
8584 and impact on European air quality., Geophys. Res. Lett., 33, L14805, doi:10.1029/2006GL025860,
8585 2006.
8586 Taatjes, C. A., Meloni, G., Selby, T. M., Trevitt, A. J., Osborn, D. L., Percival, C. J., and Shallcross, D. E.:
8587 Direct observation of the gas-phase Criegee intermediate (CH2OO), J Am Chem Soc, 130, 11883-
8588 11885, 2008.
8589 Taatjes, C. A., Welz, O., Eskola, A. J., Savee, J. D., Scheer, A. M., Shallcross, D. E., Rotavera, B., Lee, E.
8590 P., Dyke, J. M., Mok, D. K., Osborne, D. L., and Percival, C. J.: Direct Measurements of Conformer-
8591 Dependent Reactivity of the Criegee Intermediate CH3CHOO, Science, 340, 177-180, 2013.
8592 Taatjes, C. A., Shallcross, D. E., and Percival, C. J.: Research frontiers in the chemistry of Criegee
8593 intermediates and tropospheric ozonolysis, Physical Chemistry Chemical Physics, 16, 1704-1718,
8594 10.1039/c3cp52842a, 2014.
8595 Tagaris, E., Manomaiphiboon, K., Liao, K.-J., Leung, L. R., Woo, J.-H., He, S., Amar, P., and Russell, A.
8596 G.: Impacts of global climate change and emissions on regional ozone and fine particulate matter
8597 concentrations over the United States, Journal of Geophysical Research: Atmospheres, 112, D14312,
8598 2007.
8599 Tagaris, E., Sotiropoulou, R. E. P., Gounaris, N., Andronopoulos, S., and Vlachogiannis, D.: Impact of
8600 biogenic emissions on ozone and fine particles over Europe: Comparing effects of temperature
8601 increase and a potential anthropogenic NOx emissions abatement strategy, Atmospheric
8602 Environment, 98, 214-223, http://dx.doi.org/10.1016/j.atmosenv.2014.08.056, 2014.

8603 Tai, A. P. K., Mickley, L. J., Heald, C. L., and Wu, S. L.: Effect of CO_2 inhibition on biogenic isoprene
8604 emission: Implications for air quality under 2000 to 2050 changes in climate, vegetation, and land
8605 use, Geophysical Research Letters, 40, 3479-3483, 10.1002/grl.50650, 2013.
8606 Tai, A. P. K., Martin, M. V., and Heald, C. L.: Threat to future global food security from climate change
8607 and ozone air pollution, Nature Clim. Change, 4, 817-821, 10.1038/nclimate2317

8608 http://www.nature.com/nclimate/journal/v4/n9/abs/nclimate2317.html#supplementary-
8609 information, 2014.
8610 Tang, G., Li, X., Wang, Y., Xin, J., and Ren, X.: Surface ozone trend details and interpretations in
8611 Beijing, 2001-2006, Atmospheric Chemistry and Physics, 9, 8813-8823, 2009.
8612 Tang, H., Pang, J., Zhang, G., Takigawa, M., Liu, G., Zhu, J., and Kobayashi, K.: Mapping ozone risks for
8613 rice in China for years 2000 and 2020 with flux-based and exposure-based doses, Atmospheric
8614 Environment, 86, 74-83, http://dx.doi.org/10.1016/j.atmosenv.2013.11.078, 2014.
8615 Tang, Q., Prather, M. J., and Hsu, J.: Stratosphere-troposphere exchange ozone flux related to deep
8616 convection, Geophysical Research Letters, 38, 10.1029/2010gl046039, 2011.
8617 Tang, Q., Hess, P. G., Brown-Steiner, B., and Kinnison, D. E.: Tropospheric ozone decrease due to the
8618 Mount Pinatubo eruption: Reduced stratospheric influx, Geophysical Research Letters, 40, 5553-
8619 5558, 10.1002/2013gl056563, 2013.
8620 Tarasick, D. W., Fioletov, V. E., Wardle, D. I., Kerr, J. B., and Davies, J.: Changes in the vertical
8621 distribution of ozone over Canada from ozonesondes: 1980-2001, Journal of Geophysical Research-
8622 Atmospheres, 110, D02304, 10.1029/2004jd004643, 2005.
8623 Tarasova, O. A., Brenninkmeijer, C. A. M., Jöckel, P., Zvyagintsev, A. M., and Kuznetsov, G. I.: A
8624 climatology of surface ozone in the extra tropics: cluster analysis of observations and model results,
8625 Atmos. Chem. Phys., 7, 6099-6117, 2007.
8626 Tas, E., Peleg, M., Matveev, V., Zingler, J., and Luria, M.: Frequency and extent of bromine oxide
8627 formation over the Dead Sea, Journal of Geophysical Research-Atmospheres, 110,
8628 10.1029/2004jd005665, 2005.
8629 Teixeira, E., Fischer, G., van Velthuizen, H., van Dingenen, R., Dentener, F., Mills, G., Walter, C., and
8630 Ewert, F.: Limited potential of crop management for mitigating surface ozone impacts on global food
8631 supply, Atmospheric Environment, 45, 2569-2576, 10.1016/j.atmosenv.2011.02.002, 2011.
8632 Terao, Y., Logan, J. A., Douglass, A. R., and Stolarski, R. S.: Contribution of stratospheric ozone to the
8633 interannual variability of tropospheric ozone in the northern extratropics, Journal of Geophysical
8634 Research-Atmospheres, 113, 10.1029/2008jd009854, 2008.
8635 Terrenoire, E., Bessagnet, B., Rouïl, L., Tognet, F., Pirovano, G., Letinois, L., Colette, A., Thunis, P.,
8636 Amann, M., and Menut, L.: High resolution air quality simulation over Europe with the chemistry
8637 transport model CHIMERE, Geoscientific Model Development, submitted, 2013.
8638 Thomas, J. L., Stutz, J., Lefer, B., Huey, L. G., Toyota, K., Dibb, J. E., and von Glasow, R.: Modeling
8639 chemistry in and above snow at Summit, Greenland - Part 1: Model description and results,
8640 Atmospheric Chemistry and Physics, 11, 4899-4914, 10.5194/acp-11-4899-2011, 2011.
8641 Thomas, J. L., Dibb, J. E., Huey, L. G., Liao, J., Tanner, D., Lefer, B., von Glasow, R., and Stutz, J.:
8642 Modeling chemistry in and above snow at Summit, Greenland - Part 2: Impact of snowpack chemistry
8643 on the oxidation capacity of the boundary layer, Atmospheric Chemistry and Physics, 12, 6537-6554,
8644 10.5194/acp-12-6537-2012, 2012.
8645 Thomas, J. L., Raut, J. C., Law, K. S., Marelle, L., Ancellet, G., Ravetta, F., Fast, J. D., Pfister, G.,
8646 Emmons, L. K., Diskin, G. S., Weinheimer, A., Roiger, A., and Schlager, H.: Pollution transport from
8647 North America to Greenland during summer 2008, Atmospheric Chemistry and Physics, 13, 3825-
8648 3848, 10.5194/acp-13-3825-2013, 2013.
8649 Thompson, A. M., Pickering, K. E., McNamara, D. P., Schoeberl, M. R., Hudson, R. D., Kim, J. H.,
8650 Browell, E. V., Kirchhoff, V., and Nganga, D.: Where did tropospheric ozone over southern Africa and
8651 the tropical Atlantic come from in October 1992? Insights from TOMS, GTE TRACE A, and SAFARI
8652 1992, Journal of Geophysical Research-Atmospheres, 101, 24251-24278, 1996.

8653 Thompson, A. M., and Hudson, R. D.: Tropical tropospheric ozone (TTO) maps from Nimbus 7 and
8654 Earth Probe TOMS by the modified-residual method: Evaluation with sondes, ENSO signals, and
8655 trends from Atlantic regional time series, Journal of Geophysical Research-Atmospheres, 104, 26961-
8656 26975, 10.1029/1999jd900470, 1999.
8657 Thompson, A. M., Witte, J. C., McPeters, R. D., Oltmans, S. J., Schmidlin, F. J., Logan, J. A., Fujiwara,
8658 M., Kirchhoff, V., Posny, F., Coetzee, G. J. R., Hoegger, B., Kawakami, S., Ogawa, T., Johnson, B. J.,
8659 Vomel, H., and Labow, G.: Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998-2000
8660 tropical ozone climatology - 1. Comparison with Total Ozone Mapping Spectrometer (TOMS) and
8661 ground-based measurements, Journal of Geophysical Research-Atmospheres, 108,
8662 10.1029/2001jd000967, 2003a.
8663 Thompson, A. M., Witte, J. C., Oltmans, S. J., Schmidlin, F. J., Logan, J. A., Fujiwara, M., Kirchhoff, V.,
8664 Posny, F., Coetzee, G. J. R., Hoegger, B., Kawakami, S. J., Ogawa, T., Fortuin, J. P. F., and Kelder, H. M.:
8665 Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998-2000 tropical ozone climatology - 2.
8666 Tropospheric variability and the zonal wave-one, J. Geophys. Res., 108, PEM13.11-PEM13.21 2003b.
8667 Thompson, A. M., Witte, J. C., Oltmans, S. J., Schmidlin, F. J., Logan, J. A., Fujiwara, M., Kirchhoff, V.,
8668 Posny, F., Coetzee, G. J. R., Hoegger, B., Kawakami, S. J., Ogawa, T., Fortuin, J. P. F., and Kelder, H. M.:
8669 Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998-2000 tropical ozone climatology - 2.
8670 Tropospheric variability and the zonal wave-one, Journal of Geophysical Research-Atmospheres, 108,
8671 10.1029/2002jd002241, 2003c.
8672 Thompson, A. M., Balashov, N. V., Witte, J. C., Coetzee, J. G. R., Thouret, V., and Posny, F.:
8673 Tropospheric ozone increases over the southern Africa region: bellwether for rapid growth in
8674 Southern Hemisphere pollution?, Atmos. Chem. Phys., 14, 9855-9869, 10.5194/acp-14-9855-2014,
8675 2014.
8676 Thornton, J. A., Kercher, J. P., Riedel, T. P., Wagner, N. L., Cozic, J., Holloway, J. S., Dube, W. P., Wolfe,
8677 G. M., Quinn, P. K., Middlebrook, A. M., Alexander, B., and Brown, S. S.: A large atomic chlorine
8678 source inferred from mid-continental reactive nitrogen chemistry, Nature, 464, 271-274,
8679 10.1038/nature08905, 2010.
8680 Thouret, V., Saunois, M., Minga, A., Mariscal, A., Sauvage, B., Solete, A., Agbangla, D., Nedelec, P.,
8681 Mari, C., Reeves, C. E., and Schlager, H.: An overview of two years of ozone radio soundings over
8682 Cotonou as part of AMMA, Atmospheric Chemistry and Physics, 9, 6157-6174, 2009.
8683 Tie, X., Madronich, S., Li, G., Ying, Z., Weinheimer, A., Apel, E., and Campos, T.: Simulation of Mexico
8684 City plumes during the MIRAGE-Mex field campaign using the WRF-Chem model, Atmospheric
8685 Chemistry and Physics, 9, 4621-4638, 2009.
8686 Tie, X., Geng, F., Guenther, A., Cao, J., Greenberg, J., Zhang, R., Apel, E., Li, G., Weinheimer, A., Chen,
8687 J., and Cai, C.: Megacity impacts on regional ozone formation: observations and WRF-Chem modeling
8688 for the MIRAGE-Shanghai field campaign, Atmospheric Chemistry and Physics, 13, 5655-5669,
8689 10.5194/acp-13-5655-2013, 2013.
8690 Tohjima, Y., Kubo, M., Minejima, C., Mukai, H., Tanimoto, H., Ganshin, A., Maksyutov, S., Katsumata,
8691 K., Machida, T., and Kita, K.: Temporal changes in the emissions of CH_4 and CO from China estimated
8692 from CH_4/CO_2 and CO/CO_2 correlations observed at Hateruma Island, Atmospheric Chemistry and
8693 Physics, 14, 1663-1677, 10.5194/acp-14-1663-2014, 2014.
8694 Tosca, M. G., Randerson, J. T., Zender, C. S., Nelson, D. L., Diner, D. J., and Logan, J. A.: Dynamics of
8695 fire plumes and smoke clouds associated with peat and deforestation fires in Indonesia, Journal of
8696 Geophysical Research-Atmospheres, 116, 10.1029/2010jd015148, 2011.
8697 Tost, H., Jockel, P., and Lelieveld, J.: Lightning and convection parameterization - uncertainties
8698 in global modelling, , Atmos. Chem. Phys., 7, 4553-4568, 2007.
8699 Toumi, R., Haigh, J. D., and Law, K. S.: A tropospheric ozone-lightning climate feedback, Geophysical
8700 Research Letters, 23, 1037-1040, 10.1029/96gl00944, 1996.
8701 Tressol, M., Ordonez, C., Zbinden, R., Thouret, V., Mari, C., Nedelec, P., Cammas, J.-P., Smit, H., Patz,
8702 H.-W., and Volz-Thomas, A.: Air pollution during the 2003 European heat wave as seen by MOZAIC
8703 airliners, Atmos. Chem. Phys., 8, 2133-2150, 2008.

8704 Turquety, S., Logan, J. A., Jacob, D. J., Hudman, R. C., Leung, F. Y., Heald, C. L., Yantosca, R. M., Wu, S.
8705 L., Emmons, L. K., Edwards, D. P., and Sachse, G. W.: Inventory of boreal fire emissions for North
8706 America in 2004: the importance of peat burning and pyro-convective injection, J. Geophys. Res.,
8707 112, D12S03, doi:10.1029/2006JD007281
8708 2007.
8709 Tuzet, A., Perrier, A., Loubet, B., and Cellier, P.: Modelling ozone deposition fluxes: The relative roles
8710 of deposition and detoxification processes, Agricultural and Forest Meteorology, 151, 480-492,
8711 10.1016/j.agrformet.2010.12.004, 2011.
8712 Unger, N.: Global Climate Forcing by Criteria Air Pollutants, in: Annual Review of Environment and
8713 Resources, Vol 37, edited by: Gadgil, A., and Liverman, D. M., Annual Review of Environment and
8714 Resources, Annual Reviews, Palo Alto, 1-+, 2012.
8715 Val Martin, M., Honrath, R. E., Owen, R. C., Pfister, G., Fialho, P., and Barata, F.: Significant
8716 enhancements of nitrogen oxides, black carbon and ozone in the North Atlantic lower free
8717 troposphere resulting from North American boreal wildfires, J. Geophys. Res., 111, D23S60,
8718 doi:10.1029/2006JD007530, 2006.
8719 Val Martin, M., Heald, C. L., and Arnold, S. R.: Coupling dry deposition to vegetation phenology in the
8720 Community Earth System Model: Implications for the simulation of surface O3, Geophysical Research
8721 Letters, 41, 2988-2996, 10.1002/2014gl059651, 2014.
8722 Valks, P., Hao, N., Garcia, S. G., Loyola, D., Dameris, M., Jockel, P., and Delcloo, A.: Tropical
8723 tropospheric ozone column retrieval for GOME-2, Atmos. Meas. Tech., 7, 2513-2530, 10.5194/amt-7-
8724 2513-2014, 2014.
8725 van Aardenne, J. A., Dentener, F. J., Olivier, J. G. J., Klein Goldewijk, C. G. M., and Lelieveld, J.: A 1° x
8726 1° resolution dataset of historical anthropogenic trace gas emissions for the period 1890-1990,
8727 Global Biogeochem. Cycles, 15, 909-928, 2001.
8728 van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Kasibhatla, P. S., and Arellano Jr, A. F.:
8729 Interannual variability of global biomass burning emissions from 1997 to 2004, Atmos. Chem. Phys.,
8730 6, 3423-3441, 2006.
8731 van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C.,
8732 DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of
8733 deforestation, savanna, forest, agricultural, and peat fires (1997-2009), Atmospheric Chemistry and
8734 Physics, 10, 11707-11735, 10.5194/acp-10-11707-2010, 2010.
8735 van Loon, M., Vautard, R., Schaap, M., Bergström, R., Bessagnet, B., Brandt, J., Builtjes, P. J. H.,
8736 Christensen, J. H., Cuvelier, K., Graf, A., Jonson, J. E., Krol, M., Langner, J., Roberts, P., Rouil, L., Stern,
8737 R., Tarrasón, L., Thunis, P., Vignati, E., White, L., and Wind, P.: Evaluation of long-term ozone
8738 simulations from seven regional air quality models and their ensemble average., Atmos. Environ., 41,
8739 2083-2097, 2007.
8740 van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G., Kram, T.,
8741 Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S., and Rose, S.: The
8742 representative concentration pathways: an overview, Climatic Change, 109, 5-31, 2011.
8743 Vautard, R., Honore, C., Beekmann, M., and Rouil, L.: Simulation of ozone during August 2003 heat
8744 wave and emission control scenarios, Atmos. Environ., 39, 2957-2967, 2005.
8745 Vautard, R., Szopa, S., Beekmann, M., Menut, L., Hauglustaine, D. A., Rouil, L., and Roemer, M.: Are
8746 decadal anthropogenic emission changes in Europe consistent with surface ozone observations?,
8747 Geophys. Res. Lett., 33, L13810, doi: 10.1029/2006GL026080., 2006.
8748 Venevsky, S.: Importance of aerosols for annual lightning production at global scale, Atmos. Chem.
8749 Phys. Discuss., 14, 4303-4325, 10.5194/acpd-14-4303-2014, 2014.
8750 Vieno, M., Dore, A. J., Stevenson, D. S., Doherty, R., Heal, M. R., Reis, S., Hallsworth, S., Tarrason, L.,
8751 Wind, P., Fowler, D., Simpson, D., and Sutton, M. A.: Modelling surface ozone during the 2003 heat-
8752 wave in the UK, Atmospheric Chemistry and Physics, 10, 7963-7978, 10.5194/acp-10-7963-2010,
8753 2010.

Vijayaraghavan, K., DenBleyker, A., Ma, L., Lindhjem, C., and Yarwood, G.: Trends in on-road vehicle emissions and ambient air quality in Atlanta, Georgia, USA, from the late 1990s through 2009, J Air Waste Manage, 64, 808-816, 10.1080/10962247.2014.892039, 2014.
Vinken, G. C. M., Boersma, K. F., van Donkelaar, A., and Zhang, L.: Constraints on ship NOx emissions in Europe using GEOS-Chem and OMI satellite NO2 observations, Atmospheric Chemistry and Physics, 14, 1353-1369, 10.5194/acp-14-1353-2014, 2014.
Volz, A., and Kley, D.: Evaluation of the Montsouris Series of Ozone Measurements Made in the 19th-Century, Nature, 332, 240-242, 1988.
von Glasow, R., and Crutzen, P. J.: Model study of multiphase DMS oxidation with a focus on halogens, Atmos. Chem. Phys., 4, 589-608, 2004.
von Glasow, R.: Atmospheric chemistry in volcanic plumes, Proc. Natl. Acad. Sci. U. S. A., 107, 6594-6599, 10.1073/pnas.0913164107, 2010.
von Kuhlmann, R., Lawrence, M. G., Crutzen, P. J., and Rasch, P. J.: A model for studies of tropospheric ozone and nonmethane hydrocarbons: Model description and ozone results, Journal of Geophysical Research-Atmospheres, 108, 10.1029/2002jd002893, 2003a.
von Kuhlmann, R., Lawrence, M. G., Crutzen, P. J., and Rasch, P. J.: A model for studies of tropospheric ozone and nonmethane hydrocarbons: Model evaluation of ozone-related species, Journal of Geophysical Research-Atmospheres, 108, 10.1029/2002jd003348, 2003b.
von Schneidemesser, E., and Monks, P. S.: Air Quality and Climate - synergies and trade-offs, Environmental Science: Processes & Impacts, 15, 1315-1325, 10.1039/c3em00178d, 2013.
von Schneidemesser, E., Monks, P. S., Allan, J. D., Bruhwiler, L., Forster, P., Fowler, D., Lauer, A., Morgan, W. T., Paasonen, P., Righi, M., Sindelarova, K., and Sutton, M. A.: Chemistry and the Linkages between Air Quality and Climate Change, Chem Rev, 10.1021/acs.chemrev.5b00089, 2015.
vonSchneidemesser, E., Monks, P. S., and Plass-Duelmer, C.: Global comparison of VOC and CO observations in urban areas, Atmospheric Environment, 44, 5053-5064, 2010.
vonSchneidemesser, E., Monks, P. S., Gros, V., Gauduin, J., and Sanchez, O.: How important is biogenic isoprene in an urban environment? A study in London and Paris, Geophysical Research Letters, 38, L19804, 10.1029/2011gl048647, 2011.
Voulgarakis, A., Savage, N. H., Wild, O., Braesicke, P., Young, P. J., Carver, G. D., and Pyle, J. A.: Interannual variability of tropospheric composition: the influence of changes in emissions, meteorology and clouds, Atmospheric Chemistry and Physics, 10, 2491-2506, 2010.
Voulgarakis, A., Hadjinicolaou, P., and Pyle, J. A.: Increases in global tropospheric ozone following an El Nino event: examining stratospheric ozone variability as a potential driver, Atmos. Sci. Lett., 12, 228-232, 10.1002/asl.318, 2011.
Wagg, S., Mills, G., Hayes, F., Wilkinson, S., Cooper, D., and Davies, W. J.: Reduced soil water availability did not protect two competing grassland species from the negative effects of increasing background ozone, Environmental Pollution, 165, 91-99, 10.1016/j.envpol.2012.02.010, 2012.
Wagner, N. L., Riedel, T. P., Roberts, J. M., Thornton, J. A., Angevine, W. M., Williams, E. J., Lerner, B. M., Vlasenko, A., Li, S. M., Dube, W. P., Coffman, D. J., Bon, D. M., de Gouw, J. A., Kuster, W. C., Gilman, J. B., and Brown, S. S.: The sea breeze/land breeze circulation in Los Angeles and its influence on nitryl chloride production in this region, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2012jd017810, 2012.
Walker, T. W., Jones, D. B. A., Parrington, M., Henze, D. K., Murray, L. T., Bottenheim, J. W., Anlauf, K., Worden, J. R., Bowman, K. W., Shim, C., Singh, K., Kopacz, M., Tarasick, D. W., Davies, J., von der Gathen, P., Thompson, A. M., and Carouge, C. C.: Impacts of midlatitude precursor emissions and local photochemistry on ozone abundances in the Arctic, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2011jd016370, 2012.
Wang, S. W., Zhang, Q., Streets, D. G., He, K. B., Martin, R. V., Lamsal, L. N., Chen, D., Lei, Y., and Lu, Z.: Growth in NOx emissions from power plants in China: bottom-up estimates and satellite observations, Atmospheric Chemistry and Physics, 12, 4429-4447, 10.5194/acp-12-4429-2012, 2012.
Warneke, C., de Gouw, J. A., Holloway, J. S., Peischl, J., Ryerson, T. B., Atlas, E., Blake, D., Trainer, M., and Parrish, D. D.: Multiyear trends in volatile organic compounds in Los Angeles, California: Five

decades of decreasing emissions, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2012jd017899, 2012.
Weatherhead, E. C., Reinsel, G. C., Tiao, G. C., Meng, X. L., Choi, D. S., Cheang, W. K., Keller, T., DeLuisi, J., Wuebbles, D. J., Kerr, J. B., Miller, A. J., Oltmans, S. J., and Frederick, J. E.: Factors affecting the detection of trends: Statistical considerations and applications to environmental data, Journal of Geophysical Research-Atmospheres, 103, 17149-17161, 10.1029/98jd00995, 1998.
Weatherhead, E. C., Stevermer, A. J., and Schwartz, B. E.: Detecting environmental changes and trends, Phys. Chem. Earth, 27, 399-403, 10.1016/s1474-7065(02)00019-0, 2002.
Wei, W., Wang, S. X., Chatani, S., Klimont, Z., Cofala, J., and Hao, J. M.: Emission and speciation of non-methane volatile organic compounds from anthropogenic sources in China, Atmospheric Environment, 42, 4976-4988, 10.1016/j.atmosenv.2008.02.044, 2008.
Weiss, M., Bonnel, P., Kühlwein, J., Provenza, A., Lambrecht, U., Alessandrini, S., Carriero, M., Colombo, R., Forni, F., Lanappe, G., Le Lijour, P., Manfredi, U., Montigny, F., and Sculati, M.: Will Euro 6 reduce the NOx emissions of new diesel cars? – Insights from on-road tests with Portable Emissions Measurement Systems (PEMS), Atmospheric Environment, 62, 657-665, http://dx.doi.org/10.1016/j.atmosenv.2012.08.056, 2012.
Wells, K. C., Millet, D. B., Cady-Pereira, K. E., Shephard, M. W., Henze, D. K., Bousserez, N., Apel, E. C., de Gouw, J., Warneke, C., and Singh, H. B.: Quantifying global terrestrial methanol emissions using observations from the TES satellite sensor, Atmospheric Chemistry and Physics, 14, 2555-2570, 10.5194/acp-14-2555-2014, 2014.
Welz, O., Savee, J. D., Osborn, D. L., Vasu, S. S., Percival, C. J., Shallcross, D. E., and Taatjes, C. A.: Direct kinetic measurements of Criegee intermediate (CH_2OO) formed by reaction of CH_2I with O_2, Science, 335, 204-207, 2012.
Welz, O., Eskola, A. J., Sheps, L., Rotavera, B., Savee, J. D., Scheer, A. M., Osborn, D. L., Lowe, D., Murray Booth, A., Xiao, P., and others: Rate Coefficients of C1 and C2 Criegee Intermediate Reactions with Formic and Acetic Acid Near the Collision Limit: Direct Kinetics Measurements and Atmospheric Implications, Angewandte Chemie, 126, 4635-4638, 2014.
Wesely, M. L., Cook, D. R., and Williams, R. M.: Field measurement of small ozone fluxes to snow, wet bare soil, and lake water, Boundary-Layer Meteorology, 20, 459-471, 10.1007/bf00122295, 1981.
Wespes, C., Emmons, L., Edwards, D. P., Hannigan, J., Hurtmans, D., Saunois, M., Coheur, P. F., Clerbaux, C., Coffey, M. T., Batchelor, R. L., Lindenmaier, R., Strong, K., Weinheimer, A. J., Nowak, J. B., Ryerson, T. B., Crounse, J. D., and Wennberg, P. O.: Analysis of ozone and nitric acid in spring and summer Arctic pollution using aircraft, ground-based, satellite observations and MOZART-4 model: source attribution and partitioning, Atmospheric Chemistry and Physics, 12, 237-259, 10.5194/acp-12-237-2012, 2012.
Wexler, H., Moreland, W. B., and Weyant, W. S.: A preliminary report on ozone observations in little America, Antarctica, Monthly Weather Review, 88, 43-54, 10.1175/1520-0493(1960)088<0043:aprooo>2.0.co;2, 1960.
Whalley, L., Edwards, P., Furneaux, K., Goddard, A., Ingham, T., Evans, M., Stone, D., Hopkins, J., Jones, C. E., Karunaharan, A., and others: Quantifying the magnitude of a missing hydroxyl radical source in a tropical rainforest, Atmospheric Chemistry and Physics, 11, 7223-7233, 2011.
Whalley, L., Stone, D., and Heard, D.: New Insights into the tropospheric oxidation of Isoprene: Combining field measuremens, laboratory studies, chemical modelling and qualtum theory, in: Atmospheric and Aerosol Chemistry, edited by: McNeill, V. F., and Ariya, P. A., Topics in Current Chemistry, Springer, Berlin Heidelberg, 55-96, 2014.
Wheeler, A. J., Xu, X. H., Kulka, R., You, H. Y., Wallace, L., Mallach, G., Van Ryswyk, K., MacNeill, M., Kearney, J., Rasmussen, P. E., Dabek-Zlotorzynska, E., Wang, D., Poon, R., Williams, R., Stocco, C., Anastassopoulos, A., Miller, J. D., Dales, R., and Brook, J. R.: Windsor, Ontario Exposure Assessment Study: Design and Methods Validation of Personal, Indoor, and Outdoor Air Pollution Monitoring, J Air Waste Manage, 61, 324-338, 10.3155/1047-3289.61.3.324, 2011.
WHO: Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide, Bonn, 2003.

WHO: WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, 2005.
WHO: Review of evidence on health aspects of air pollution – REVIHAAP Project WHO Regional Office for Europe, Copenhagen, 2013.
Wiedinmyer, C., Tie, X. X., Guenther, A., Neilson, R., and Granier, C.: Future changes in biogenic isoprene emissions: How might they affect regional and global atmospheric chemistry?, Earth Interact., 10, 2006.
Wiedinmyer, C., Akagi, S. K., Yokelson, R. J., Emmons, L. K., Al-Saadi, J. A., Orlando, J. J., and Soja, A. J.: The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning, Geosci. Model Dev., 4, 625-641, 10.5194/gmd-4-625-2011, 2011.
Wilcox, L. J., Hoskins, B. J., and Shine, K. P.: A global blended tropopause based on ERA data. Part I: Climatology, Quarterly Journal of the Royal Meteorological Society, 138, 561-575, 10.1002/qj.951, 2012.
Wild, O., Prather, M. J., and Akimoto, H.: Indirect long-term global radiative cooling from NOx emissions, Geophysical Research Letters, 28, 1719-1722, 10.1029/2000gl012573, 2001.
Wild, O., Pochanart, P., and Akimoto, H.: Trans-Eurasian of ozone and its precursors, J. Geophys. Res., 109, D11302, doi:10.1029/2003JD004501, 2004.
Wild, O.: Modelling the global tropospheric ozone budget: exploring the variability in current models, Atmospheric Chemistry and Physics, 7, 2643-2660, 2007.
Wild, O., and Palmer, P. I.: How sensitive is tropospheric oxidation to anthropogenic emissions?, Geophysical Research Letters, 35, 10.1029/2008gl035718, 2008.
Wild, O., Fiore, A. M., Shindell, D. T., Doherty, R. M., Collins, W. J., Dentener, F. J., Schultz, M. G., Gong, S., MacKenzie, I. A., Zeng, G., Hess, P., Duncan, B. N., Bergmann, D. J., Szopa, S., Jonson, J. E., Keating, T. J., and Zuber, A.: Modelling future changes in surface ozone: a parameterized approach, Atmos. Chem. Phys., 12, 2037-2054, 2012.
Wilkinson, S., and Davies, W. J.: Drought, ozone, ABA and ethylene: new insights from cell to plant to community, Plant Cell Environ, 33, 510-525, 10.1111/j.1365-3040.2009.02052.x, 2010.
Wilkinson, S., Mills, G., Illidge, R., and Davies, W. J.: How is ozone pollution reducing our food supply?, J. Exp. Bot., 63, 527-536, 10.1093/jxb/err317, 2012.
Williams, D. E., Henshaw, G. S., Bart, M., Laing, G., Wagner, J., Naisbitt, S., and Salmond, J. A.: Validation of low-cost ozone measurement instruments suitable for use in an air-quality monitoring network, Meas Sci Technol, 24, 10.1088/0957-0233/24/6/065803, 2013.
Williams, E. R.: Lightning and climate: A review, Atmospheric Research, 76, 272-287, 10.1016/j.atmosres.2004.11.014, 2005.
Williams, J. E., van Weele, M., van Velthoven, P. F. J., Scheele, M. P., Liousse, C., and van der Werf, G. R.: The Impact of Uncertainties in African Biomass Burning Emission Estimates on Modeling Global Air Quality, Long Range Transport and Tropospheric Chemical Lifetimes, Atmosphere, 3, 132-163, 10.3390/atmos3010132, 2012.
Williams, M. L., Atkinson, R. W., Anderson, H. R., and Kelly, F. J.: Associations between daily mortality in London and combined oxidant capacity, ozone and nitrogen dioxide, Air Qual Atmos Health, DOI 10.1007/s11869-014-0249-8, 2014.
Wilson, R. C., Fleming, Z. L., Monks, P. S., Clain, G., Henne, S., Konovalov, I. B., Szopa, S., and Menut, L.: Have primary emission reduction measures reduced ozone across Europe? An analysis of European rural background ozone trends 1996–2005, Atmos. Chem. Phys., 12, 437-454, 2012.
Wittig, V. E., Ainsworth, E. A., Naidu, S. L., Karnosky, D. F., and Long, S. P.: Quantifying the impact of current and future tropospheric ozone on tree biomass, growth, physiology and biochemistry: a quantitative meta-analysis, Global Change Biology, 15, 396-424, 10.1111/j.1365-2486.2008.01774.x, 2009.
Wu, S., Mickley, L. J., Leibensperger, E. M., Jacob, D. J., Rind, D., and Streets, D. G.: Effects of 2000–2050 global change on ozone air quality in the United States, Journal of Geophysical Research: Atmospheres, 113, n/a-n/a, 2008.

Wu, S. L., Mickley, L. J., Jacob, D. J., Logan, J. A., Yantosca, R. M., and Rind, D.: Why are there large differences between models in global budgets of tropospheric ozone?, Journal of Geophysical Research-Atmospheres, 112, 10.1029/2006jd007801, 2007.
Yang, X., Cox, R. A., Warwick, N. J., Pyle, J. A., Carver, G. D., O'Connor, F. M., and Savage, N. H.: Tropospheric bromine chemistry and its impacts on ozone, J. Geophys. Res., 110, D23 311, 10.1029/2005JD006 244, 2005.
Young, C. J., Washenfelder, R. A., Edwards, P. M., Parrish, D. D., Gilman, J. B., Kuster, W. C., Mielke, L. H., Osthoff, H. D., Tsai, C., Pikelnaya, O., Stutz, J., Veres, P. R., Roberts, J. M., Griffith, S., Dusanter, S., Stevens, P. S., Flynn, J., Grossberg, N., Lefer, B., Holloway, J. S., Peischl, J., Ryerson, T. B., Atlas, E. L., Blake, D. R., and Brown, S. S.: Chlorine as a primary radical: evaluation of methods to understand its role in initiation of oxidative cycles, Atmospheric Chemistry and Physics, 14, 3427-3440, 10.5194/acp-14-3427-2014, 2014.
Young, P. J., Archibald, A. T., Bowman, K. W., Lamarque, J. F., Naik, V., Stevenson, D. S., Tilmes, S., Voulgarakis, A., Wild, O., Bergmann, D., Cameron-Smith, P., Cionni, I., Collins, W. J., Dalsoren, S. B., Doherty, R. M., Eyring, V., Faluvegi, G., Horowitz, L. W., Josse, B., Lee, Y. H., MacKenzie, I. A., Nagashima, T., Plummer, D. A., Righi, M., Rumbold, S. T., Skeie, R. B., Shindell, D. T., Strode, S. A., Sudo, K., Szopa, S., and Zeng, G.: Pre-industrial to end 21st century projections of tropospheric ozone from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), Atmospheric Chemistry and Physics, 13, 2063-2090, 10.5194/acp-13-2063-2013, 2013.
Yu, X., Yuan, Z., Fung, J. C. H., Xue, J., Li, Y., Zheng, J., and Lau, A. K. H.: Ozone changes in response to the heavy-duty diesel truck control in the Pearl River Delta, Atmospheric Environment, 88, 269-274, http://dx.doi.org/10.1016/j.atmosenv.2013.11.022, 2014.
Yu, Y., Sokhi, R. S., Kitwiroon, N., Middleton, D. R., and Fisher, B.: Performance characteristics of MM5-SMOKE-CMAQ for a summer photochemical episode in southeast England, United Kingdom, Atmospheric Environment, 42, 4870-4883, 10.1016/j.atmosenv.2008.02,051, 2008.
Yuan, T. L., Remer, L. A., Bian, H. S., Ziemke, J. R., Albrecht, R., Pickering, K. E., Oreopoulos, L., Goodman, S. J., Yu, H. B., and Allen, D. J.: Aerosol indirect effect on tropospheric ozone via lightning, Journal of Geophysical Research-Atmospheres, 117, 10.1029/2012jd017723, 2012.
Yue, X., and Unger, N.: Ozone vegetation damage effects on gross primary productivity in the United States, Atmos Chem Phys, 14, 9137-9153, 2014.
Zanis, P., Trickl, T., Stohl, A., Wernli, H., Cooper, O., Zerefos, C., Gaeggleler, H., Priller, A., Schnabel, C., Scheel, H. E., Kanter, H. J., Tobler, L., Kubik, P. W., Cristofanelli, P., Forster, C., James, P., Gerasopoulos, E., Delcloo, A., Papayannis, A., and Claude, H.: Forecast, observation and modeling of a deep stratospheric intrusion event over Europe Atmos. Chem. Phys., 3, 763-777, 2003.
Zanis, P., Hadjinicolaou, P., Pozzer, A., Tyrlis, E., Dafka, S., Mihalopoulos, N., and Lelieveld, J.: Summertime free-tropospheric ozone pool over the eastern Mediterranean/Middle East, Atmospheric Chemistry and Physics, 14, 115-132, 10.5194/acp-14-115-2014, 2014.
Zanobetti, A., and Schwartz, J.: Ozone and Survival in Four Cohorts with Potentially Predisposing Diseases, American Journal of Respiratory and Critical Care Medicine, 184, 836-841, 10.1164/rccm.201102-0227OC, 2011.
Zare, A., Christensen, J. H., Gross, A., Irannejad, P., Glasius, M., and Brandt, J.: Quantifying the contributions of natural emissions to ozone and total fine PM concentrations in the Northern Hemisphere, Atmos. Chem. Phys., 14, 2735-2756, 10.5194/acp-14-2735-2014, 2014.
Zeng, G., and Pyle, J. A.: Influence of El Nino Southern Oscillation on stratosphere/troposphere exchange and the global tropospheric ozone budget, Geophysical Research Letters, 32, 10.1029/2004gl021353, 2005.
Zhang, L., Jacob, D. J., Yue, X., Downey, N. V., Wood, D. A., and Blewitt, D.: Sources contributing to background surface ozone in the US Intermountain West, Atmospheric Chemistry and Physics, 14, 5295-5309, 10.5194/acp-14-5295-2014, 2014.
Zhang, L. M., Brook, J. R., and Vet, R.: On ozone dry deposition - with emphasis on non-stomatal uptake and wet canopies, Atmospheric Environment, 36, 4787-4799, 2002.

Zhang, Q., Streets, D. G., He, K., Wang, Y., Richter, A., Burrows, J. P., Uno, I., Jang, C. J., Chen, D., Yao, Z., and Lei, Y.: NOx emission trends for China, 1995-2004: The view from the ground and the view from space, Journal of Geophysical Research-Atmospheres, 112, D22306, 2007.
Zhao, Y., Nielsen, C. P., Lei, Y., McElroy, M. B., and Hao, J.: Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China, Atmospheric Chemistry and Physics, 11, 2295-2308, 10.5194/acp-11-2295-2011, 2011.
Zhao, Y., Zhang, J., and Nielsen, C. P.: The effects of recent control policies on trends in emissions of anthropogenic atmospheric pollutants and CO_2 in China, Atmospheric Chemistry and Physics, 13, 487-508, 10.5194/acp-13-487-2013, 2013.
Zhong, J., Cai, X. M., and Bloss, W. J.: Modelling segregation effects of heterogeneous emissions on ozone levels in idealised urban street canyons: Using photochemical box models, Environmental Pollution, 188, 132-143, 10.1016/j.envpol.2014.02.001, 2014.
Zhou, W., Cohan, D. S., and Henderson, B. H.: Slower ozone production in Houston, Texas following emission reductions: evidence from Texas Air Quality Studies in 2000 and 2006, Atmos. Chem. Phys., 14, 2777-2788, 10.5194/acp-14-2777-2014, 2014.
Zhu, T., Melamed, M., Parrish, D., Gauss, M., Klenner, L. G., Lawrence, M., Konare, A., and Liousse, C.: Impacts of Megacities on Air Pollution and Climate, WMO, Geneva, 2012.
Ziemke, J. R., and Chandra, S.: La Nina and El Nino-induced variabilities of ozone in the tropical lower atmosphere during 1970-2001, Geophysical Research Letters, 30, 10.1029/2002gl016387, 2003.
Ziemke, J. R., Chandra, S., Duncan, B. N., Froidevaux, L., Bhartia, P. K., Levelt, P. F., and Waters, J. W.: Tropospheric ozone determined from aura OMI and MLS: Evaluation of measurements and comparison with the Global Modeling Initiative's Chemical Transport Model, Journal of Geophysical Research-Atmospheres, 111, D19303, 2006.
Ziemke, J. R., Chandra, S., Oman, L. D., and Bhartia, P. K.: A new ENSO index derived from satellite measurements of column ozone, Atmospheric Chemistry and Physics, 10, 3711–3721, 2010.
Zingler, J., and Platt, U.: Iodine oxide in the Dead Sea Valley: Evidence for inorganic sources of boundary layer IO, Journal of Geophysical Research-Atmospheres, 110, 10.1029/2004jd004993, 2005.
Zlatev, Z., Christensen, J., and Hov, O.: A Eulerian air-pollution model for Europe with nonlinear chemistry, Journal of Atmospheric Chemistry, 15, 1-37, 10.1007/bf00053607, 1992.
Zoogman, P., Jacob, D. J., Chance, K., Worden, H. M., Edwards, D. P., and Zhang, L.: Improved monitoring of surface ozone by joint assimilation of geostationary satellite observations of ozone and CO, Atmospheric Environment, 84, 254-261, 10.1016/j.atmosenv.2013.11.048, 2014.
Zvyagintsev, A. M., Blum, O. B., Glazkova, A. A., Kotel'nikov, S. N., Kuznetsova, I. N., Lapchenko, V. A., Lezina, E. A., Miller, E. A., Milyaev, V. A., Popikov, A. P., Semutnikova, E. G., Tarasova, O. A., and Shalygina, I. Y.: Air pollution over European Russia and Ukraine under the hot summer conditions of 2010, Izv. Atmos. Ocean. Phys., 47, 699-707, 10.1134/s0001433811060168, 2011.