

Anonymous Referee #1

This is an important and useful paper which provides an up-to-date assessment of stratospheric ozone trends and their uncertainties. The paper provides a fairly concise summary of the results in an easy-to-find location - rather than having them in a large report. It is well written. I think the paper can be published as is, though I do have some minor comments that the authors should consider.

We thank the referee for the kind and helpful comments.

1) Abstract. The abstract is a bit long, which is ok for this style of paper, but I think it misses two points: (a) It should make clear that the +ve trend in O3 since 1998 is not necessarily recovery from EESC. The reader is left with the implication that the decrease in EESC explains 'all' of the change in the O3 trend. (b) The update of these results compared to WMO (2014) - that the upper stratospheric increase may not be significant - is an important result, I think, and is worth noting here.

It is a long abstract. A few minor changes have been made, and the two additional points suggested by the reviewer have been included.

2) P8570. Line 13. The Lambert et al paper is not available (not even submitted yet?), so that was not much help.

The preparation of the Lambert et al paper has taken longer than expected. The text referring to it has been amended and now additionally refers to the Hubert et al (2015) paper currently in ACPD. Lambert et al is still expected to be submitted, so we would like to leave a reference to it in the text.

3) P8570. Line 25. Why is "recovery" in quotation marks. This is a possibly confusing and subtle issue for some so (as in the abstract) you should say what you mean by recovery.

The quotation marks have been removed since the reference to EESC is already there.

4) P8570. Line 29. Do you mean 'a' trend?

Yes. Change made

5) P8578. Line 6. Not clear to mean what you mean by 'shape'. (Could be a vertical profile).

We have changed it to 'temporal evolution'.

6) P8578. Line 13. Change 'losses' to 'depletion' (or decreases). (Loss is the chemical process which is always occurring and balanced by production...).

We have changed 'losses' to 'decreases'.

7) P8578. Line 16. Does 'insignificant' mean 'small' or 'not significant' (statistically)?

'Statistically insignificant trends' is now used.

8) P8583. Line 25. *I can see that you would want to reference the SPARC report for the methodology but I think there is a clear difference between combining observations of the same real quantity (O₃) from different platforms, and estimates of a derived quantity using very different indirect methods and also models, which have no link to reality. I would suggest that you note this.*

There is a clear difference, but the mathematical similarities are striking. We have included the following: “In this study, we combine trends calculated from merged sets of observations of the same real quantity (O₃) from different platforms, so the comparison is not 100%. However the similarities in the amount of rigorous knowledge of the uncertainties are such that we have adopted the same methodologies...” at p8584, line 25.

9) P8586. Lines 15-19. *‘We hope...real scientific value’. These sentences should be rephrased. Is this just a wild hope, or is there reason to think that this work could be done? Change ‘real’ to something like ‘considerable’ - it makes it sound like the other work in this field has not been of any value.*

We have changed it to “Considerable benefits would be gained if the SAGE I record could be revised to be consistent with the SAGE II record without having to use the altitude correction from Wang et al. (1996), as it would lead to better knowledge of the changes in ozone in the lower stratosphere in this early period.”

10) P8587. Line 23. *‘related to individual...’*

Done.

Anonymous Referee #2

This paper presents an analysis of global stratospheric ozone trends from data reevaluated by a number of groups as part of the SI2N initiative. It is well-written and generally well-presented. There are no major issues, but I find a number of minor ones.

Thank you. The comments given below were helpful and have improved the quality of the manuscript.

Detailed comments:

Page 8568, line 18: A “hint of a trend”?

We spent some time on the phrasing of this sentence. Quantifying the uncertainty is a major part of this study, and this sentence would be written differently depending on which uncertainty estimate is used. We would prefer to stay with this wording in the absence of a better suggestion.

Page 8571, Section 2.1: It would be helpful if the merged datasets (GOZCARDS, SWOOSH) were defined here. GOZCARDS is defined in Section 3.1.2, but only for the pre-1998 period, and I cannot find SWOOSH described at all.

We have revised section 3 and now have a third section describing the merged data sets.

Page 8576: Equation 1: The large number of fitting parameters (~30) in the model is alarming. What checks have the authors made to be sure that their fits are robust, with all those degrees of freedom? QBO_orthog is not defined.

First it should be noted that the apparently large number of fitting parameters results from the expansion of some of the regression model fit coefficients in the Fourier series to account for seasonality. So, it is not the case that there are ~30 independent basis functions in the regression model fit. Standard practice in regression modeling is that there should be at least twice as many data points as fit coefficients in the regression model and this requirement has been applied throughout our analysis. When fitting the model to monthly mean data from 1979 to 2012 there are 408 data points which significantly exceeds this criterion. Previous studies that have applied the same regression model to diagnose trends in ozone have demonstrated that the resultant fits are robust and that there is no danger of over-fitting. In this study, for shorter periods with fewer data, the number of basis functions is reduced with a resultant reduction in the number of fit coefficients. Visual inspection of selected fits to the data ensures that there is no over-fitting.

We have added a sentence to the manuscript that explains the QBO orthogonal function.

Page 8576, line 18: What is a “simple linear trend”? The term seems to suggest a simple linear regression to the data without the 30-odd adjustable coefficients of Equation 1. However, I expect you mean a linear trend derived using Equation 1, but with free endpoints. In that case I suggest “single linear trend”, or “unconstrained linear trend”.

We agree and have changed it to ‘single linear trend’.

Equation 2: Why is an AR(2) model used? How exactly is Equation 2 applied?

In making the decision to use an AR(2) model we did test the effects of an AR(1) model in determining the uncertainty on the fit coefficients. We found that the regression model fit coefficient uncertainties could be under-estimated when using an AR(1) model and so, to be as robust as possible in our estimates of the trend uncertainties, we felt it prudent to use an AR(2) model consistent with what has been done in other previous applications of regression analyses to derive trends (Reinsel et al., 1994; Bodeker et al., 1998; Fioletov et al., 2003).

Page 8578, line 27: The phrase “care needs to be taken when comparing them”, used here and elsewhere, is a vague phrase that doesn’t really say anything. The issue is one of representativeness: these geographically sparse data may (no matter how much care is taken) yield trends that are different from the zonal mean.

We have made this point clearer.

Page 8581, lines 11-13: The error bars here on the ozonesonde data are quite a bit larger than one would expect from weekly data at just a single site, so presumably something other than simple atmospheric variability (representativeness error?) has been included. This statement should be

expanded to explain what the large uncertainties really reflect. Moreover, in Figures 2, 4 and 6, the uncertainties for ozonesondes appear to be for the most part larger than the Umkehr, FTIR, microwave or lidar uncertainties, which seems quite inconsistent with the fact that there are far more ozonesonde sites. Something is funny here...

The reviewer is correct. We have removed that statement and added a couple of sentences explaining the difficulties associated with comparing the trend uncertainties calculated for the ground-based records.

Figure 6: On the other hand, this figure is so small I could be reading those error bars incorrectly. Please make the little tiny plots at least as big as the little plots in Figures 2, 4, 7 and 8.

We agree and will make sure this happens in the final version.

Page 8581, Section 3.2: The discussion of Figure 5 is unsatisfying; perhaps "...is hard to be confident about the significance of this feature..." is meant to be typical British understatement? GOZCARDS and SWOOSH have (apparently statistically significant) trends in opposite directions below 40 hPa, and above 10 hPa the trends show little coherence between datasets. SAGE-GOMOS trends at the poles look seriously wonky.

We are not trying to hide the obvious disagreements between the various records – indeed dealing with them is fundamental to the main thrust of the paper and to SI2N as a whole. This particular phrasing was chosen because (a) it is true, and (b) the main conclusion we want to draw is that whichever record you look at, there has been a clear change from the negative period in the earlier period. We discuss the differences in some detail in the second paragraph, but in general there are other papers which do a more thorough comparison (e.g., Tummon et al., and the more recent intercomparison paper by Hubert et al., both in the special issue). For these reasons we would prefer not to change the text.

We are sorry the reviewer finds this example of British understatement is unsatisfying but we note that it is not in the class of Watson and Crick's "This structure has novel features which are of considerable biological interest".

Page 8582, line 12: Again, please define "simple linear trend".

We agree and have changed it to 'single linear trend'.

Page 8582, line 13: Is there a rationale for using a PWLT in the troposphere? Do you include QBO, solar cycle, etc., there too?

We are not trying to present an analysis of the troposphere, and so the reviewer is entirely correct to say the PWLT model is not appropriate there. We choose 10 km as a lower bound so that the trends presented are largely representative of the stratosphere. This is reasonable in mid-latitudes, but not in the tropics. Little emphasis is put on the lower altitude trends, and we have now removed any confusing references to the troposphere.

Past changes in the Vertical Distribution of Ozone, Part III:

Analysis and Interpretation of Trends

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22
23 **Abstract**

24 Trends in the vertical distribution of ozone are reported and compared for a number of new and
25 recently revised datasets. The amount of ozone-depleting compounds in the stratosphere (as
26 measured by Equivalent Effective Stratospheric Chlorine - EESC) maximised in the second half of
27 the 1990s. We examine the periods before and after the peak to see if any change in trend is
28 discernible in the ozone record that might be attributable to a change in EESC trend, though no

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1 | attribution is attempted. Prior to 1998, trends in the upper stratosphere (~45 km, 4 hPa) are found to
2 | be -5 to -10 % per decade at mid-latitudes and closer to -5 % per decade in the tropics. No trends
3 | are found in the mid-stratosphere (28 km, 30 hPa). Negative trends are seen in the lower
4 | stratosphere at mid-latitudes in both hemispheres and in the deep tropics. However it is hard to be
5 | categorical about the trends in the lower stratosphere for three reasons: (i) there are fewer
6 | measurements; (ii) the data quality is poorer, and (iii) the measurements in the 1990s are perturbed
7 | by aerosols from the Mt Pinatubo eruption in 1991. These findings are similar to those reported
8 | previously even though the measurements for the main satellite and ground-based records have
9 | been revised.

10 | There is no sign of a continued negative trend in the upper stratosphere since 1998: instead there is
11 | a hint of an average positive trend of ~2 % per decade in mid-latitudes and ~3% per decade in the
12 | tropics. The significance of these upward trends is investigated using different assumptions of the
13 | independence of the trend estimates found from different datasets. The averaged upward trends are
14 | significant if the trends derived from various datasets are assumed to be independent (as in WMO,
15 | 2014), but are generally not significant if the trends are not independent. This arises because many
16 | of the underlying measurement records are used in more than one merged dataset. At this point it is
17 | not possible to say which assumption is best. Including an estimate of the drift of the overall ozone
18 | observing system decreases the significance of the trends. The significance will become clearer as
19 | (i) more years are added to the observational record; (ii) further improvements are made to the
20 | historic ozone record (e.g. through algorithm development); and (iii) the data merging techniques
21 | are refined, particularly through a more rigorous treatment of uncertainties.

22 | 1 Background

23 | The successful implementation of the Montreal Protocol with its Adjustments and Amendments has
24 | led to reductions in stratospheric chlorine and bromine amounts since the late 1990s (WMO, 2011).
25 | These reductions are expected to result in less chemical depletion of ozone and so lead to increased
26 | stratospheric ozone amounts. To date, no signal of a positive response of ozone directly attributable
27 | to declining halogen levels has been unambiguously identified in the ozone record because it is hard
28 | to separate the effects of changes in chemistry and transport (e.g. WMO, 2011; WMO, 2015;
29 | Hadjinicolaou et al., 2005; Mahieu et al., 2014). There are two main reasons for this: interannual
30 | variability in ozone amounts and changes in ozone due to the changing climate. A confounding
31 | factor has been the lack of a near-global, self-consistent set of vertically resolved ozone
32 | observations.

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1 Near-global measurements of the ozone profile using satellite instruments have been made
2 continuously since 1979, a period in which the coverage achieved by ground-based instruments has
3 increased enormously. However, since 1998 when the first SPARC/IO3C/GAW report was
4 published (Harris et al, 1998), no thorough assessment of the quality of all the measurements has
5 been made in terms of their suitability for studies of long-term changes. Until 2005, when the
6 SAGE II and HALOE satellite instruments ceased operation, this did not present a major problem
7 when assessing changes in the ozone profile as the SAGE and HALOE instruments provided
8 internally consistent and quasi-independent records. Few studies extending the observational record
9 after 2005 were published in time for consideration in WMO (2011), though several instrument
10 records up to 2005 were compared thoroughly (Terao and Logan, 2007). Updates were available for
11 the ground-based instruments in the Network for the Detection of Atmospheric Composition
12 Change (NDACC) (Steinbrecht et al., 2009) and for selected satellite instruments (Jones et al.,
13 2009). This situation occurred despite the fact that many more instruments were making ozone
14 profile measurements, including those on the Envisat and Aura satellites (Tegtmeier et al., 2013;
15 Hassler et al., 2014).

16 Stratosphere-troposphere Processes And their Role in Climate (SPARC), the International Ozone
17 Commission (IO3C), the ozone focus area of the Integrated Global Atmospheric Chemistry
18 Observations (IGACO-O3) and NDACC therefore supported the SPARC/IO3C/IGACO-
19 O3/NDACC (SI2N) initiative with the aim of updating knowledge of changes in the vertical
20 distribution of ozone. In addition three synthesis papers are being prepared. The first, Hassler et al
21 (2014) summarises the wide range of available measurements of the ozone profile, highlights how
22 they contribute to our general understanding of its long-term evolution, and provides a 'bottom-up'
23 view of the potential data quality and state of the retrieval algorithms. The second, Lambert et al. (in
24 preparation) contains a thorough comparison of the various data sets and assesses the consistency
25 between them, building on the work of Hubert et al. (2015). This third synthesis paper discusses the
26 long-term changes calculated from the data sets and compares these changes with those found in
27 other studies.

28 Section 2 (Methodology) summarises the sources of the datasets, relying heavily on Hassler et al.
29 (2014) and the other SI2N papers and highlights the important features to consider when calculating
30 long-term changes. It also contains a description of the statistical approach used, including how the
31 uncertainties in the trend estimates are calculated. Section 3 (Analysis) describes and discusses the
32 results of the trend calculations performed in this study. Three periods are considered: (i) 1979-

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1 1990, a period prior to the eruption of Mt Pinatubo in which the stratosphere was relatively free of
2 aerosols; (ii) 1979-1997, a period of increasing equivalent effective stratospheric chlorine (EESC);
3 and (iii) 1998-2012, the early years of the ozone recovery from decreasing EESC. In addition to
4 these main periods, a number of additional issues are investigated including the dependence of the
5 calculated trends on the end dates chosen, and ways of averaging ozone trends from a number of
6 data sets. In section 4, we discuss and summarise the results. Overall, the aim is to determine the
7 degree to which a trend can be detected given the uncertainties resulting from the various
8 measurements, the statistical analysis, and the relatively short recent record since 1998. Best
9 estimates of the trends and their uncertainties are given based on all the available evidence.

10 2 Methodology

11 2.1 Datasets

12 The datasets used in this study are from the individual instruments described in Hassler et al (2014)
13 and the merged datasets described in Tummon et al. (2015). An assessment of the quality of the
14 datasets based on measurement comparisons is given in Lambert et al. (2015) and references therein
15 with additional information in Tegtmeier et al. (2013). Individual references are given below when
16 referring to specific datasets. Unless otherwise stated, the measurements used in the analyses
17 presented here were obtained through the URLs given in Table 1d in Hassler et al. (2014) and Table
18 7 in Tummon et al. (2015). No additional selection of published data is made based on quality
19 assessment beyond that provided by the instrument teams. The measurements used here have
20 different spatial resolutions. This study aims at providing a global overview of the observed
21 changes and what the associated uncertainties are. It does not look at the spatial structure in much
22 detail – for example issues associated with finer scale structures in the vertical profile which are
23 observable by some instruments are not addressed.

24 2.1.1 Measurements prior to 1997

25 Prior to 1997 only 4 instrument records are suitable for trend analysis: the SAGE and SBUV
26 satellite records and the ground-based ozonesondes and Umkehr measurements. Earlier versions of
27 these data sets were analysed in the SPARC/IO3C/GAW Report (Harris et al., 1998), and all have
28 recently been improved. SAGE I made 33 months of ozone measurements from February 1979 to
29 October 1981, a period in which stratospheric aerosol loading was exceptionally low. SAGE II
30 started making ozone measurements in October 1984, after a 3-year gap, when stratospheric aerosol
31 loading was still relatively high following the eruption of El Chichón in early 1982. SAGE II

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version 7.0 is used here (Damadeo et al., 2013). The lack of an overlap period causes uncertainties in the relative calibration of the two sets of measurements; these are exacerbated by the uncertainty in the reference altitude for each SAGE I measurement. The ad hoc, latitude-dependent correction for this error (Wang et al., 1996) removes this systematic error source above an altitude of approximately 20 km. Ozone trends are reported here for the SAGE I/II time series.

The SBUV instrument on the Nimbus 7 satellite made measurements from October 1978 to June 1990, with the SBUV/2 series of instruments starting in 1985 (McPeters et al., 2013). The SBUV instrument was subject to little orbital drift and its data are thought to be of higher quality than the SBUV/2 instruments that immediately followed it (Frith et al., 2014). Accordingly we look at trends through June 1990 (Section 3.1.1). This approach additionally avoids any impact of the Mt Pinatubo eruption (June 1991) on either stratospheric ozone or on the quality of the ozone measurements. Section 3.1.2 shows results of trends computed over the full period of EESC increase, from 1979-97.

The ozonesonde data were taken from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) (<http://www.woudc.org>), the [Southern Hemisphere ADditional OZonesondes \(SHADOZ\)](#) network (Thompson et al., 2007), NILU's Atmospheric Database for Interactive Retrieval (NADIR) (<http://www.nilu.no/nadir/>) and the Network for the Detection of Atmospheric Composition Change (NDACC) (<http://www.ndsc.ncep.noaa.gov/>). The standard operating procedures to be used for NDACC ozonesonde operation are those agreed upon after the JOSIE 1996, 1998, and 2000 experiments (Smit et al., 2007) and the BESOS experiment (Deshler et al., 2008).

The following procedure for data selection and averaging of ozone soundings was applied:

- (a) Integrated ozone columns are calculated for each 1 km layer from the ground to 30 km.
- (b) Data are withdrawn if there is a gap in measurements of more than 500 m in the ozone profile data.
- (c) Data are retained if at least 25 integrated layers can be calculated in the ozone profile.
- (d) To be included in the trend analysis, there must be at least two "successful" ozone profiles available during one month for the particular station under consideration.

A total of 40 non-polar stations have been used in the analysis presented here. Once the preceding criteria have been applied, the stations are far from evenly distributed and in particular, there are

relatively few stations with data for the early part of the record. For example, only one record (Lauder, New Zealand) was used for the southern mid-latitudes in the analysis up to 1997.

High quality up-to-date Umkehr measurements with records beginning prior to 1997 are available for several stations. Among these are four northern mid-latitude stations (Arosa, Switzerland starting in 1956; Tateno, Japan in 1957; Boulder, USA in 1978; Haute Provence, France in 1984), one tropical station (Mauna Loa, USA in 1984), and one southern mid-latitude station (Lauder, New Zealand in 1987). For our pre-1997 analysis, the records from the four northern mid-latitude stations are considered as a latitude band average. Of the other Umkehr records archived at the WOUDC, some are of poor quality or do not cover most of the 1979-2010 period. High levels of volcanic aerosol loading in the stratosphere can create errors in the retrieved profiles. Therefore, about two years of data are removed after the eruptions of El Chichon (1982) and Mt. Pinatubo (1991). Regular calibration of the Dobson and Brewer instruments, which are used to make the Umkehr measurements, guarantee a stable time series. Occasionally, Dobson instruments are replaced introducing potential steps in the record. In these cases, careful homogenization is required with validation against other measurements (Miyagawa et al, 2009; Zanis et al, 2006). All the data sets mentioned above have undergone major revisions since Harris et al. (1998), and an updated comparison is timely.

As before, measurements at high vertical resolution are provided by ozonesondes at a few locations and by SAGE near-globally, with greater confidence in the SAGE I measurements at altitudes above 20 km. Measurements at lower vertical resolution are provided by the Umkehr approach at a few locations and by SBUV near-globally.

2.1.2 Measurements since 1998

Section 3.2 describes our analyses of the period since 1998. Many more datasets exist for this period from both satellite and ground-based instruments (Figure 2 in Hassler et al., 2014).

The number and geographic coverage of ozonesonde and Umkehr instruments making measurements is much greater than in the earlier period (although there are unfortunately signs of this reversing). In addition the coverage of other instrument types (microwave, lidar, FTIR) in NDACC has increased over this time, and these measurements can be used for ozone trend studies as well as for comparisons with satellite measurements and verification of their long-term stability (Hubert et al., 2015; Nair et al., 2012, 2013; Steinbrecht et al., 2009, Vigouroux et al., 2014).

1 However the most striking change in this period has been in the number of satellite instruments
2 making measurements of the vertical distribution of ozone for the majority of this time and so
3 useful for trend studies (Hassler et al., 2014 and references therein): the SMR and OSIRIS
4 instruments operational on the Odin satellite since 2001; the GOMOS, MIPAS, and SCIAMACHY
5 instruments on Envisat from 2002-2012; the MLS instrument on Aura and the MAESTRO and
6 ACE-FTS instruments on SCISAT since 2004.

7 Once the recent data sets are mature, this should lead to a better overall knowledge of the changes
8 in ozone over this period. However, significant uncertainties and differences still exist (Tegtmeier et
9 al., 2013; Lambert et al., 2015), and so care is needed to identify robust conclusions about the
10 trends. These problems are likely less important for ground-based records where quality assurance
11 and control procedures can be applied through the major networks (Nair et al., 2012).

13 2.1.3 Merged data sets: 1979-2012

14 To estimate trends for the whole period (1979–2012), datasets are required which combine
15 measurements from two or more instruments. Issues that arise when merging datasets and which
16 can contribute to uncertainty include individual instrument uncertainty (precision and offset),
17 potential drift, changes in sampling and changes in measurement technique, all of which can vary
18 with latitude, altitude, time of year, etc.

19 The SBUV series of instruments has produced a continuous record over the 1979-2012 period,
20 albeit with uncertainties in trends resulting from inter-instrument differences (Frith et al., 2014).

21 Two merged data sets using the reprocessed SBUV v8.6 measurements (McPeters et al., 2013) are
22 available: v8.6 SBUV MOD (Frith et al., 2014) and SBUV Merged Cohesive (Wild and Long,
23 2015). The two data sets differ somewhat in the combination of instruments used and the averaging
24 carried out, with the SBUV Merged Cohesive data set using data from single instruments which are
25 then bias-corrected to produce a continuous record (Wild and Long, 2015). In contrast, the v8.6
26 SBUV MOD data set is constructed using the average of all available data for a particular period
27 (Frith et al., 2014).

28 The two solar occultation instruments, SAGE II and HALOE, ceased operation in 2005 so trends
29 calculated past that date require an extension of their record with measurements from other
30 instruments. Several data sets exist that extend the SAGE II record past 2005: GOZCARDS (Global
31 OZone Chemistry And Related trace gas Data records for the Stratosphere; Froidevaux et al., 2015),

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Deleted: Once the recent data sets are mature, this should lead to a better overall knowledge of the changes in ozone over this period. However, significant uncertainties and differences still exist (Tegtmeier et al., 2013; Lambert et al., 2015), and so care is needed to identify robust conclusions about the trends. These problems are likely less important for ground-based records where quality assurance and control procedures can be applied through the major networks (Nair et al., 2012). The SBUV series of instruments has produced a continuous record over the whole period, albeit with uncertainties in trends resulting from the inter-instrument differences (Frith et al., 2014). The two solar occultation instruments, SAGE II and HALOE, ceased operation in 2005 so trends calculated past that date require an extension of their record with measurements from other instruments. The number and geographic coverage of ozonesonde and Umkehr instruments making measurements is much greater than in the earlier period (although there are unfortunately signs of this reversing). In addition the coverage of other instrument types (microwave, lidar, FTIR) in NDACC has increased over this time, and these measurements can be used for ozone trend studies as well as for comparisons with satellite measurements and verification of their long-term stability (Hubert et al., 2015; Nair et al., 2012, 2013; Steinbrecht et al., 2009, Vigouroux et al., 2014).

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SWOOSH (Stratospheric Water and OzOne Satellite Homogenized; Davis et al., 2015), SAGE-GOMOS (Kyrölä et al., 2013), and SAGE-OSIRIS (Bourassa et al., 2014). The former two data sets combine observations from several instruments: GOZCARDS extending the record back to 1979 using SAGE I, as well as combining SAGE II, HALOE, MLS, and ACE-FTS; SWOOSH merges SAGE II, SAGE III, MLS, and HALOE. The SAGE-GOMOS and SAGE-OSIRIS data sets used here extend the SAGE II record with just a single instrument – GOMOS or OSIRIS. Detailed information about the merging techniques used to construct each data set can be found in the individual references.

Each measurement system has different vertical and spatial resolutions, with some expressed as a function of pressure and others as a function of altitude. The gridded data sets were latitudinally weighted and averaged into three latitude bands: 35°-60°S, 20°S-20°N; and 35°-60°N. The original vertical gridding was kept for the altitude based datasets (i.e. every 1 km spacing), as well as the pressure level data sets. When combining trend results from individual systems to estimate the overall trend, we convert to a common vertical coordinate and degrade to a common vertical scale (see Section 3.3 for details).

2.2 Statistical analysis

We apply a multiple linear regression model to all data sets using the updated version (Hassler et al., 2013) of the statistical model described in Bodeker et al. (1998) and used in Tummon et al. (2015). The core regression model includes an offset term (to describe the average annual ozone amount) and basis functions to describe ozone changes due to the seasonal variation, QBO (quasi-biennial oscillation), solar cycle, ENSO (El Nino Southern Oscillation), and a proxy for the effect of the Mt Pinatubo aerosol on ozone. The orthogonal QBO basis function is a synthetically created time series orthogonal to the monthly mean 50 hPa Singapore zonal wind that allows for a time lag at different latitudes and altitudes.

$$\Omega_t = A_{(NA=4)} + B_{(NB=2)} \cdot t + C_{(NC=2)} \cdot t_{(t=0 \text{ for } t < \text{inflection point})} +$$

$$\begin{aligned}
& D_{(ND=2)} \cdot QBO(t) + \\
& E_{(NE=2)} \cdot QBO_{orthog}(t) + \\
& F_{(NF=0)} \cdot Solar(t) + \\
& G_{(NG=0)} \cdot Pinatubo(t) + \\
& H_{(NH=0)} \cdot ENSO(t) +
\end{aligned}$$

$$R(t) \quad (1)$$

where Ω_t is the ozone concentration for a particular month t for a particular data set; A-H are the model coefficients corresponding to an offset term (to account for the mean annual cycle in ozone), linear trends, and basis functions used; while $R(t)$ represents the residuals (difference between the measured and modeled ozone values). The subscript on each term A-H indicates how many Fourier pairs the term was expanded into to account for the seasonal dependence of the ozone anomalies on the basis functions (Bodeker et al., 1998); for example NB = 2 indicates two Fourier pairs (two sine, two cosine). The number of coefficients used was about 30.

Two types of trend model were used. First, for the main set of analyses from 1979-1997 and 1998-2012, a piecewise linear trend (PWLTL) model was used with separate linear trends calculated for each period with the two lines forced to meet at the end of 1997, the point of inflection. The trends in the two periods are therefore linked. Second, a single linear trend was used for the analyses of data from 1979-1990 (Section 3.1.1), for the SAGE I/II analysis (Section 3.1.2) and for some data sets that were only analysed for 1998-2012 (latter part of Section 3.2). A comparison of a PWLTL model with a model including two unlinked linear trends found the differences to be generally small. This is also discussed further in Section 3.2.

An autoregressive model is applied to the residuals $R(t)$ following equation 2:

$$R(t) = \epsilon_1(t)R(t-1) + \epsilon_2(t)R(t-2) + e_t \quad (2)$$

where ϵ_1 and ϵ_2 are the model coefficients and e_t represents the independent random errors with zero mean and variances that are allowed to change from month to month (see Reinsel et al., 1994).

The basis functions used represent: the QBO, specified as monthly mean 50 hPa Singapore zonal wind and a synthetic basis function orthogonal to this to allow for a time-lag at different latitudes and altitudes; ENSO (El Niño-Southern Oscillation), using the monthly mean Southern Oscillation Index as proxy; the solar cycle, based on monthly mean F10.7 solar flux data from NOAA's

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1 National Geophysical Data Center; and a proxy for ozone perturbations forced by aerosols from the
2 Mt Pinatubo volcanic eruption based on a synthetic time series representing the approximate
3 temporal evolution of stratospheric aerosol concentrations following the eruption (see Bodeker et al.
4 (1998) for further details). Uncertainties in the trend estimates are thus based on the noise in the
5 residual time series and are given as 2 sigma limits in this paper unless stated otherwise. Non-
6 random effects are discussed later.

7 The estimated magnitude of the Mt Pinatubo effect should be treated with caution as most of the
8 data sets analysed here filter data that could be affected by additional aerosol in the stratosphere
9 after the eruption. Most of the analysed data sets have gaps in their time series, and so the calculated
10 signal is thus a mix of the true signal and the impact of removing data in this period. While we
11 argue that this gives greater confidence in the calculated trends, other analyses would be more
12 appropriate for an examination of the effect of Mt Pinatubo on ozone. The same model was used in
13 Tummon et al. (2015). In that work, where the main aim was comparing trends from different
14 datasets, a minimum data coverage was required as part of the averaging protocol. Here, where the
15 main aim is to provide the best estimate of trends from a given data set, all available data are used
16 and so no minimum data coverage is imposed. The main difference is in areas where the data
17 coverage is poorer such as the tropics.

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18 3 Analysis and Interpretation

19 The aim of the analysis is to identify the changes that can be detected in the decadal trends on either
20 side of the peak in EESC when halogen-catalysed ozone loss is expected to have maximised.
21 Accordingly we split the ozone record into two periods: before 1997, and from 1998 on. Within
22 these two periods, the main issues in looking at decadal trends are the quality and particularly the
23 stability of the available instruments' measurements, the way in which any merging is achieved, and
24 the length of the record. In section 3.3, we examine different methods of propagating uncertainties
25 when combining the individual trends to produce best estimates. We do not use EESC as a proxy
26 for ozone loss as that would mean the temporal evolution of the ozone change was pre-determined
27 (Kuttippurath et al., 2015).

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3.1 Ozone trends prior to 1997

3.1.1 1979-1990

Figure 1 shows the trends from 1979 to 1990 for (a) the SBUV instrument on the Nimbus 7 satellite, and (b) the combined SAGE I/II records. The overall patterns as a function of latitude and altitude are in good agreement given the differences in vertical resolution and geographic coverage between the instruments. Decreases of 10-15 % per decade are seen in the upper stratosphere (~5 hPa, 42 km) in both datasets. These are statistically significant at all latitudes and are large at high latitudes in each hemisphere. Larger trends are seen in the combined SAGE record. Statistically insignificant trends are seen in the tropical middle stratosphere. The trends again become larger at lower altitudes in the mid-latitude lower stratosphere. This is particularly true in the SAGE I/II measurements for which trends down to 20 km can be considered reliable and which additionally have higher vertical resolution.

Figure 2 shows ozone trends from 1979-1990 as a function of altitude for 3 latitude bands: 35°-60°S, 20°S-20°N; and 35°-60°N. Four data sets are used: Nimbus 7 SBUV, SAGE I/II, Umkehr, and ozonesondes. Separate plots are shown for SBUV and Umkehr (pressure coordinate, coarse altitude resolution), and SAGE and ozonesondes (geometric altitude, fine altitude resolution). Approximate altitudes/pressures are shown on the right hand axis to facilitate comparison. Only a few high quality datasets exist for ozonesondes and Umkehr in this period. These geographically sparse records are unlikely to be representative of the latitude band, and so care needs to be taken when comparing the ozonesonde and Umkehr zonal mean trends with those from the two satellite datasets. The SAGE I/II coverage is also limited in the tropics, especially at certain times of year.

Overall there is good agreement in the trends derived from the two satellite records in the upper stratosphere given the 95 % confidence limits of 2-3 %. Looking more closely, the SAGE trends tend to be more negative than the SBUV trends in both northern and southern mid-latitudes. This is consistent with the observed stratospheric cooling which causes upper stratospheric ozone trends calculated using geometric altitude as a vertical coordinate to be ~2 % per decade more negative than those calculated in pressure coordinates for 1979-2005 (McLinden et al., 2011; Pawson and Steinbrecht et al., 2014 – see below). The trends derived from the Umkehr stations in northern mid-latitudes are in good agreement with the SBUV trends. Similarly, the ozonesonde trends agree within uncertainties with the SAGE trends in the region of overlap. The increased uncertainties at lower altitudes result from the larger ozone variability in the lowermost stratosphere. While these findings are in general agreement with those reported in Harris et al. (1998) with significant trends

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in the lower and upper stratosphere, we have more confidence in them and in the estimated errors associated with them as a result of revisions of the underlying measurements.

Trends were only brought forward into the summary of the SPARC/IO3C/GAW Report (1998) for the northern mid-latitudes due to uncertainties in the underlying measurements. Here we also report trends for the tropics and for the southern mid-latitudes. In the southern mid-latitudes, the trends calculated for SBUV and SAGE are similar to each other and, in general appearance, to those in the northern mid-latitudes. Closer examination shows that the lower stratospheric trends in the southern mid-latitudes are a little smaller than in the northern hemisphere, consistent with what has been observed in total column ozone (WMO, 2011). In the upper stratosphere, there is no significant difference in the trends in the two hemispheres. There are insufficient ozonesonde and Umkehr records in the southern mid-latitudes for comparison in this period.

3.1.2 1979-1997

The trends from section 3.1.1 are now compared with those for 1979-97, a period in whose latter half stratospheric ozone was strongly influenced by the Mt Pinatubo eruption and in which a number of instruments started making measurements. In addition, the start of the period is when ozone depletion first became apparent, while 1997 was roughly when EESC maximised in the stratosphere. Figure 3 shows the trends from 1979 to 1997 for: (i) two versions of the combined SBUV instrument record based on different merging assumptions; (ii) the SAGE I and II records; and (iii) the GOZCARDS merged data set (consisting of SAGEI/II, UARS MLS and HALOE in this period, Froidevaux et al., 2015). Data sets starting in 1984, when the SAGE II record begins, are not included. Overall the main features of Figure 1 - negative trends in the upper stratosphere with larger trends at higher latitudes and large negative trends at lower altitudes - are seen in the longer records (Figure 3).

However in contrast to the panels in Figure 1, there are now noticeable differences between the three analyses shown. There is reasonable agreement between the v8.6 SBUV MOD and the SAGE I/II trends though the magnitudes of the trends are larger for SAGE I/II by up to 3 % per decade for most of the stratosphere. The differences between the two SBUV versions reflect the difficulties in tying together the records from instruments of the same type on different satellites (Frith et al., 2014; Tummon et al., 2015). The spatial distribution of the GOZCARDS trends is similar to that of v8.6 SBUV MOD, though the GOZCARDS trends are generally more negative. Figure 4 shows the ozone trends for the same satellite datasets as a function of altitude for 3 latitude bands: 35°-60°S, 20°S-20°N; and 35°-60°N. There are no major differences between these trends and those shown

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1 for 1979-1990 in Figure 2. There is also good agreement between the trends from the different data
2 sets. While Mt Pinatubo was clearly a major influence on ozone (Zerefos et al., 1994; Randel et al.,
3 1995), extending the analysis through 1997 reduces its impact on the calculated decadal trends. The
4 effect of excluding the proxy for the Mt Pinatubo eruption in the statistical analysis was tested and
5 was found to be small when compared to the trends or their associated uncertainties.

6 As in Figure 2, the trends calculated from available datasets for ozonesondes and Umkehr are
7 shown in Figure 4, though again care needs to be taken when comparing them with zonal mean
8 trends from the two satellite datasets. The spread of about +/- 3 % in the trends within the group is a
9 rough guide to the overall uncertainty in our knowledge of the ozone decrease. It is evident from
10 Figs 2 and 4 that the necessity to merge records from different instruments substantially adds to the
11 uncertainties in the trends as a result of the choices about which instruments to include and how to
12 make their records consistent (Tummon et al., 2015). Comparison of the uncertainties associated
13 with the trends from the various ground-based records is not straightforward. Each record consists
14 of measurements from a limited number of sites at any particular time. The number of sites and
15 their geographic representativeness changes through the period considered.

16 3.2 Ozone trends since 1998

17 Figure 5 shows the ozone trends calculated for 6 different merged data sets for 1998-2012 as a
18 function of latitude and altitude. There is a generally positive trend in the upper stratosphere at ~1-3
19 hPa (~40 km). Comparable latitude-altitude patterns and generally positive trends in the upper
20 stratosphere since the late 1990s/early 2000s have been reported for merged SAGE-GOMOS and
21 SAGE-OSIRIS data sets by Kyrolä et al. (2013) and Bourassa et al. (2014), respectively; for 2002
22 to 2012 SCIAMACHY data by Gebhardt et al. (2014); and for 2004 to 2012 MIPAS and Aura-MLS
23 ozone profiles by Eckert et al. (2014). Nair et al. (2013) also reported positive upper stratospheric
24 trends over northern mid-latitudes using GOZCARDS data and a combination of lidar and satellite
25 data. However there are quite a few variations in this feature between datasets (magnitude, level of
26 uncertainty, latitudinal and altitudinal extent), which means that it is hard to be confident about the
27 significance of this feature. It is, however, certainly a clear change from the negative trend seen
28 prior to 1998.

29 There are some negative trends in the tropics at altitudes ~30-35 km (~15 hPa). This feature (see
30 also Eckert et al, 2014 and Gebhardt et al., 2014) is seen in all datasets, though in most cases this is
31 not statistically significant in individual data sets. It is also obvious that there are many differences

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ozonesonde measurements.

1 in the trends calculated from the various datasets, e.g. in the shape of the trends in the upper
2 stratosphere. Some of these result from different ways of merging the data; others from differences
3 between instruments used in a merged dataset (e.g. resolution, sampling). These issues are
4 discussed further in Tummon et al. (2015). The large trends at the higher latitudes in the SAGE-
5 GOMOS record are probably a result of sampling issues (Kyrola et al., 2013; Laine et al., 2014).
6 Differences are more obvious in this period as more instruments are used, the length of the record is
7 a little shorter, and the trend signal is smaller.

8 Figure 6 shows ozone trends from 1998-2012 as a function of altitude for the same 3 latitude bands
9 (35°-60°S, 20°S-20°N; and 35°-60°N) as in Figures 2 and 4. The top two panels show the results
10 calculated using the same PWLT analysis as in Figure 4. The lowest panel contains the trends for
11 shorter time series which are calculated using a single linear trend. As a result, the ozonesondes
12 show a positive trend at lower altitudes in the mid-latitudes in both hemispheres when calculated
13 with the PWLT, but the northern mid-latitude trend becomes zero with the single linear trend
14 model. In addition, trends are shown for the ground-based lidar, microwave, and FTIR instrument
15 latitude band averages. More ground-based and ozonesonde records are available for this period
16 than for the period prior to 1997 as a result of the development of NDACC, but there are still not
17 enough to consider them truly representative of the latitude band, especially in the tropics and the
18 southern mid-latitudes. While the lack of a continued negative trend in the upper stratosphere is
19 clear, there is again a hint of a positive trend when all the records are considered. The negative trend
20 at ~30 km in the tropics is less clear than in Figure 5 where it is confined principally to the region
21 between 10°S and 10°N.

22 The uncertainties calculated for the trends should include the uncertainties resulting from
23 interannual variability, but this is inevitably less true for shorter records. We investigate the
24 importance of this using GOZCARDS data, with the resulting ozone trends shown in Figure 7.
25 These trends are calculated by using each January between 1997 and 2002 as the point of inflection
26 in the piece-wise regression. For 1979-97 the values are relatively insensitive to changing this date,
27 though there is some change for GOZCARDS in the southern mid-latitudes. The trends in the
28 second period are more sensitive to the inflection date over the mid-latitudes over both
29 hemispheres, consistent with its shorter length. For example, the magnitudes of the GOZCARDS
30 trend at 1.5 hPa in the southern hemisphere are 5 % per decade for 1997-2012 and 9 % per decade
31 for 2002-2012 (see also Gebhardt et al., 2014). A similar analysis for v8.6 SBUV MOD yields 0 %
32 per decade and 4 % per decade, respectively.

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3.3 Best estimates – combining the calculated trends

In principle the trends calculated from the various data sets can be combined to form a best estimate of the actual trend along with the appropriate uncertainty estimates. In practice it is hard to do this because the degree of independence of the various datasets is not known. If the datasets were completely independent, then a weighted mean and the uncertainty in that mean could be straightforwardly calculated using the estimates of the trends and their associated uncertainties. This approach was taken, for example, in Harris et al. (1998). However, the datasets are not completely independent – notably several use SAGE measurements in the early part of the record, and extensive comparisons of the different datasets have been made (e.g. Tegtmeier et al., 2013 and references therein) – and so there is no rigorous way of performing the weighting or propagating the uncertainties. In addition, the trends are calculated using the same regression model and data with the same underlying atmospheric variability, so imperfect regression and outliers have similar effects in all trends.

A similar conceptual problem is encountered when estimates of the lifetimes of several halocarbons are produced using a variety of methods relying to varying degrees on common underlying datasets (Appendix 2 of Chapter 6 in Ko et al., 2013). They consider two contrasting cases to produce a best estimate. In the first case, the different estimates are assumed to be independent. The central estimate is taken as the weighted mean of the various estimates of the lifetime, and the uncertainty range derived from as the weighted mean of the variances from each method, i.e. the differences between the individual mean estimates are not a factor in the variance estimate. The resulting uncertainty should be considered an underestimate of the true uncertainty and is designated the “most likely range”. This method is referred to as the sampling distribution of the weighted mean (the SWM-distribution approach). In the second case the different estimates are combined into a single distribution and the uncertainty range corresponds to the joint distribution of the individual variances around the arithmetic (unweighted) mean of the estimates, i.e. the differences in the mean trend estimates from the various satellite data sets were taken into account. The resulting range is designated the “possible range”. This method is referred to as the joint distribution approach (the J-distribution approach). The ranges for halocarbon lifetimes produced by the two approaches are quite different. For example, the best estimate for the lifetime of CFC-11 was 52 years with a “most likely” range of 43-67 years (SWM-distribution) and a “possible range” of 35-89 years (J-distribution) (Ko et al., 2013).

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1 In this study, we combine trends calculated from merged sets of observations of the same real
2 quantity (O_3) from different platforms, so the comparison is not 100%. However the similarities in
3 the amount of rigorous knowledge of the uncertainties are such that we have adopted the same
4 methodologies to combine the results of the time series modelling of the satellite datasets shown in
5 Figures 4 and 6. The resulting trends and their 95% uncertainties are shown in Figure 8. The SWM-
6 and J-distribution approaches are represented by the dark blue and red lines, respectively. The
7 underlying trend estimates from Figures 4 and 6 are shown in the thin grey lines. There is very little
8 difference in the estimated mean trends, but the uncertainties are substantially larger for the J-
9 distribution than for the SWM-distribution. In other words the possible range is noticeably larger
10 than the most likely range.

11 An additional source of uncertainty not captured in the trend analyses of the data sets is a systematic
12 drift in the overall global ozone observing satellite system. The drift can be estimated by bottom-up
13 consideration of the instruments and their long-term calibration systems (e.g., Harris et al., 1998) or
14 by comparison with a well-characterised measurement set. Here we choose the latter approach as no
15 bottom-up drift estimates exist for the merged data sets. The light blue line in Figure 8 shows the
16 effect of extending the SWM distribution approach to include drift uncertainties based on
17 comparisons of the ground-based lidar and ozonesonde observations with a number of satellite
18 datasets (Hubert et al., 2015) similar in approach to Nair et al. (2012). Here a drift uncertainty of 3
19 % (2 sigma) is included at all altitudes for the early trends (top row), while 4 % or 6 % are included
20 for the later trends in the middle or lower and upper stratosphere, respectively. (Smaller estimates
21 were tried as a sensitivity test and the overall uncertainty scaled accordingly.) The estimates,
22 applied individually to each data set, are credible because the lidars and ozonesondes are well
23 characterised and lidars in principle have a stable calibration (Werner et al., 1983; Godin et al.,
24 1989; McDermid et al., 1990). The drift-adjusted SWM trends are by definition the same as the
25 SWM trends. However the uncertainty estimates are much larger as the drift uncertainty is the
26 dominant term. Overall, the drift-adjusted SWM uncertainty estimates are comparable with those
27 derived using the J-distribution approach, with some larger and some smaller. One explanation for
28 this is that the effect of the drift uncertainties of the individual satellite datasets is included when
29 using the J-distribution since the assumption for propagation of uncertainties explicitly allows for
30 the differences in the mean values of the underlying individual estimates.

31 The best estimate ozone trends shown in Figure 8 result from trends previously shown separately
32 (in pressure or geometric altitude coordinates) in the earlier figures despite the problems associated

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1 with doing so discussed in 3.1.1. The conversion to common pressure coordinates for instruments
2 whose natural measurement coordinate is altitude was made using MERRA (Rienecker et al., 2011)
3 temperature profiles for each altitude and latitude bin. Uncertainties arising from this procedure are
4 likely mainly due to uncertainties in the MERRA reanalyses. They are not included in the
5 estimation of the ozone trend uncertainties.

6 Looking at the different approaches together, the trends seen in the upper stratosphere before 1997
7 in all 3 latitude bands are negative and statistically significant. Small positive trends are seen in the
8 period after 1998: they are significant when assuming the SWM distribution, but not when
9 assuming the J-distribution or drift-adjusted SWM distribution. The differences between the peak
10 trends in the two periods are significant for all approaches. In the lower stratosphere, the differences
11 in the trends are insignificant, with the trends in the later period being close to zero.

12 4 Discussion and summary

13 Trends are reported for a number of datasets for the periods before and after the peak in EESC in
14 1997. The findings for the period prior to 1997 are broadly similar to those reported elsewhere with
15 decreases in the upper stratosphere at all latitudes and in the lower stratosphere over mid-latitudes.
16 The values found here at 45 km for the combined SAGE I/II dataset (1979-97) are slightly larger
17 than those found elsewhere for the SAGE II dataset (Remsberg, 2014; Damadeo et al., 2014) and
18 those for the merged data sets which rely primarily on SAGE II in this period (Kyrola et al., 2013;
19 Bourassa et al., 2014; Tummon et al., 2015). There is reasonably good agreement in the lower
20 stratosphere where the trends using just SAGE II measurements, i.e. from 1984, are smaller than the
21 ones reported here starting in 1979. Considerable benefits would be gained if the SAGE I record
22 could be revised to be consistent with the SAGE II record without having to use the altitude
23 correction from Wang et al. (1996), as it would lead to better knowledge of the changes in ozone in
24 the lower stratosphere in this early period.

25 Looking at the second half of the record, it is clear that the downward trend in upper stratospheric
26 ozone has not continued and it is likely that there has been an increase since 1998. However there is
27 disagreement about both the size and the statistical significance of that increase. In particular we
28 show the sensitivity of the trends to changes in the end points of the analysed datasets and the
29 problems in defining the uncertainties in those trends. Part of the problem is caused by the relatively
30 small size of the increase (which is broadly consistent with model calculations, e.g. Fleming et al.
31 (2011); Pawson and Steinbrecht (2014)). The other part is the relatively large uncertainty which

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results from the short periods under consideration and from uncertainties introduced when merging datasets.

The earlier discussion of uncertainties (Section 3.3) involved the propagation of the uncertainties associated with the trend estimates. It is also worth noting how uncertainties associated with individual datasets are propagated when they are merged to produce a longer time series. These issues are discussed further in the comparison of merged datasets in Tummon et al (2015) as well as in the individual papers describing their production (e.g., Kyrola et al., 2013; Bourassa et al., 2014; Frith et al., 2014). Conceptually, the linking of two time series to form a single one involves a difference and uncertainty associated with their absolute calibrations and a difference in the random noise characteristics of the two time series. Each time series additionally has a drift uncertainty. Each of these terms is likely to vary as a function of time and space. In addition, sampling errors can arise when the sampling frequency changes especially when this is aliased with cycles in ozone, e.g. annually (Damadeo et al., 2014) and diurnally (Sakazaki et al., 2013; Parrish et al., 2014). All these factors serve to confuse and complicate the picture. As a general rule, however, it is clear that the fewer, more stable records that can be used, the better. This general rule will also apply in the future: for ozone trend studies, a few good, long-lasting instruments are preferable to a larger number of shorter-lived ones, though it is hard to know in advance which these are. Frith et al (2014) examined aspects of this issue for the SBUV MOD total ozone measurement series using a Monte-Carlo simulation of potential offsets and drifts. The overall impact on the trend uncertainties was therefore comprised of a term related to individual instrument uncertainties (offsets and drifts) and a term related to the natural variability of the atmosphere. The former dominated at low latitudes where total ozone variability is low, while the latter dominated at high latitudes. Similar approaches (e.g., Fioletov et al., 2006) are worth pursuing for merged data sets of vertically resolved ozone with a view to analysing the uncertainties associated with the existing data sets, as well as for learning the lessons for future measurements.

4.1 Comparison with WMO (2014)

The results presented here can be compared to those in Pawson and Steinbrecht (2014). Good agreement is found between the analyses prior to 1997. Overall, their approach is similar to the one used here, and many of the results are similar. However there are some notable differences between the two analyses most obviously in the statistical significance of the trends in the last 10-15 years. In particular they conclude that a statistically significant ozone increase has occurred since 2000 in the upper stratosphere (35-45 km) in the northern mid-latitudes (peak value of $+3.9 \pm 1.3$ % per

decade), the tropics ($+1.9 \pm 1.2$ % per decade) and southern mid-latitudes ($+3.0 \pm 1.2$ % per decade). These compare to 1.4 ± 6 , 2.7 ± 6 , and 1.8 ± 6 % per decade respectively for the drift-adjusted SWM estimates. The central values are similar (given the uncertainties), but the associated uncertainties are clearly much smaller in Pawson and Steinbrecht (2014). Possible causes of difference could arise from differences in (a) the treatment and propagation of uncertainties; (b) the selection of data; and (c) the statistical approach. These are now considered in turn.

The single most important factor affecting the uncertainty estimates is the drift estimate. Pawson and Steinbrecht (2014) use the following datasets and 2 sigma drift uncertainties: HARMOZ 2 % per decade; GOZCARDS 2 % per decade; SBUV-NASA 3 % per decade; lidar 2.0 % per decade; microwave 2.0 % per decade; Umkehr 4.0 % per decade and ozonesondes 4.0% per decade. These drift uncertainties are added in quadrature to the trend uncertainties from the regression, and the resulting individual uncertainties are used in the calculation of the weighted average trend and its uncertainty. A typical value for the uncertainty in the weighted average is thus 0.8 % per decade. In contrast in this study we use (for the satellite records only) values of the drift uncertainties in the early period 3 % per decade at all altitudes, and in the later period 4 % per decade in the middle stratosphere and 6 % per decade in the upper stratosphere (all 2 sigma). These values arise from the comparison of the satellite records with the lidar and ozonesonde data and reflect the systematic uncertainties that are common to one or more data sets. The other major difference is that the ground-based records (lidar, microwave, Umkehr and ozonesondes) are not treated as independent estimates in our study, partly because of questions as to the representativeness of the number of sites and measurements and partly because several of the sites are common to multiple instruments.

While this factor is the largest contributor to our drift-adjusted SWM estimate, it might well also be the biggest contributor to the J-distribution estimates due to the differences in the drifts from the various satellites (Hubert et al., 2015). Developing approaches to reduce the systematic drift uncertainty, e.g. by using the ground-based instruments to ground-truth the satellite instruments or by selecting satellite data more carefully will be important. For example, SAGE II is found to drift less than 1-1.5 % per decade (2 sigma), while Aura-MLS has no significant drift against the ground-based stations. Merged datasets such as SWOOSH or GOZCARDS based on these observations might be expected to provide more valid trend estimates.

Second, Pawson and Steinbrecht (2014) use a different set of measurements. For example, SBUV Merged Coherent, SWOOSH, SAGE-GOMOS and SAGE-OSIRIS were not used, while the HARMOZ data set (Sofieva et al., 2013), a weighted average of the measurements from OSIRIS,

1 SMR, SCIAMACHY, GOMOS, and MIPAS covering 2002-2012, was included. They additionally
2 include the ground-based records in their combined trends, while we choose not to because of
3 concerns about the representativeness of the trends given the small number of measurement
4 stations. Some of these selections reflect a difference in approach: Pawson and Steinbrecht (2014)
5 aim to provide the best possible estimates of recent trends and so take advantage of measurements
6 from instruments which are no longer operational, while we are analysing merged data sets since
7 they will inevitably have to be used as time goes by. This difference is probably a factor in the
8 differing uncertainty estimates with the ones presented here representing over-estimates.

9 The statistical approaches are similar in most respects, but differ in several ways. First, Pawson and
10 Steinbrecht do not allow for an annual cycle in their regression coefficients ($Nx = 0$ in Eq. 1 for
11 $x=A$ to H). This may mean that their trend uncertainty estimates from the regression are smaller
12 because fewer terms are used.

13 Second Pawson and Steinbrecht (2014) use a two-step procedure which first removes the
14 dependence of ozone on the solar cycle, QBO and ENSO based on the entire record. In the second
15 step, independent linear trends are fitted to the remaining ozone variations, which now largely
16 contain the long-term trends only. This procedure is used to remove sensitivities to the chosen point
17 of inflection and allows more freedom in choosing the trend intervals for the first and second part of
18 the record. As always, when the second period is relatively short and comparable to the length of
19 the solar cycle, the calculated trends will be susceptible to any uncertainties in the solar cycle
20 coefficient. We do not think that this different regression approach is a major factor as our central
21 estimates and the SWM uncertainties are similar to those in Pawson and Steinbrecht (2014), both
22 for the pre-1997 trends, and the post-1998 trends.

23 The periods analysed are different, with Pawson and Steinbrecht (2014) calculating trends for 2000-
24 2013 while we chose 1998-2012. Our results (Figure 7) show that the peak GOZCARDS trends are
25 1-2 % larger when calculated from 2000 than from 1998 so the different choice of period will be a
26 contributing factor to the different value of the central trend, but will not significantly impact the
27 uncertainty estimate. With comparable uncertainties, of course, larger trends such as those from
28 2000 will be more significant.

29 **4.2 Looking ahead**

30 Observed ozone trends reflect the combined effects of several forcings in the atmosphere. In
31 addition to changes in EESC, the abundances of non-CFC greenhouse gases in the atmosphere have

1 increased in recent decades. Over the coming century, greenhouse gas levels are expected to
2 continue to increase while EESC continues to decline. Increasing CO₂ cools the stratosphere [Fels
3 et al., 1980], which slows the catalytic cycles that destroy ozone [Haigh and Pyle, 1982] thereby
4 leading to an increase in ozone in the middle and upper stratosphere. In addition, climate models
5 consistently simulate a strengthening in the Brewer Dobson circulation under climate change
6 [Butchart et al., 2011]. This is particularly important in the tropical and midlatitude lower
7 stratosphere where there are strong gradients in ozone changes between 100 and 20 hPa [Zubov et
8 al., 2013]. The magnitude of these effects are of the order of a few percent per decade and are
9 strongly dependent on the scenario for future greenhouse gas emissions [Eyring et al., 2013], and on
10 the evolution of other chemically-relevant species such as methane and N₂O [Revell et al., 2012].

11 Model simulations indicate that during the rise in EESC the effects of climate change would be
12 expected to have offset a small fraction of the ODS-induced decline in middle and upper
13 stratospheric ozone [WMO, 2011]. Conversely as EESC decreases, both effects would act to
14 increase upper stratospheric ozone [Plummer et al., 2010]. However, projected changes in the
15 stratospheric circulation mean that total column ozone in the tropics may not return to pre-1980
16 levels this century [Eyring et al., 2013]. The net effect of climate change on column and profile
17 ozone amounts will therefore have a complex horizontal and vertical structure, and these changes
18 will occur concurrently with those from the expected decline in EESC. Model results indicate that
19 measurements with lower vertical resolution will be suitable in the upper stratosphere where the
20 gradients in the climate change-induced ozone changes are not too steep. However in the lower
21 stratosphere, and especially in the tropics, higher vertical resolution will be required.

22 Finally, a critical factor which will determine our ability to monitor future changes in the vertical
23 distribution of ozone is the stability and calibration of the overall system. The combined observing
24 system for total ozone is estimated to be stable to about 1 % per decade which is appropriate for the
25 size of the changes we are considering. It is not yet clear what is required for the measurements in
26 the vertical distribution of ozone, but a target of a few % per decade is plausible based on modelled
27 future changes. The results presented here suggest that this will be hard, though not impossible to
28 achieve. Certainly it is absolutely essential to minimise the drift. Success will require continued
29 work as well as continued measurements. A global view means that satellite measurements are
30 required. The need to ensure that both the quality and relative stability of the satellite instruments
31 are known requires a complementary capability for independent assessment, most likely from the
32 ground-based instruments in the NDACC and WMO-GAW observing networks. For example,

lidars have been shown to have the technical capability to provide this assessment between 20 and 40 km (Nair et al., 2012). Ozonesondes have the capability of providing measurements of suitably high quality at lower altitudes, while Umkehr, microwave, and FTIR have the potential at higher altitudes. The ground-based networks have been designed and developed with this capability in mind. It is very important to ensure that they continue to possess the same capability in a period when ozone will be affected by declining levels of halogen compounds, increasing N₂O and CH₄, as well as dynamical changes from climate change.

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Keywords: NDACC, ozone, profile, trends

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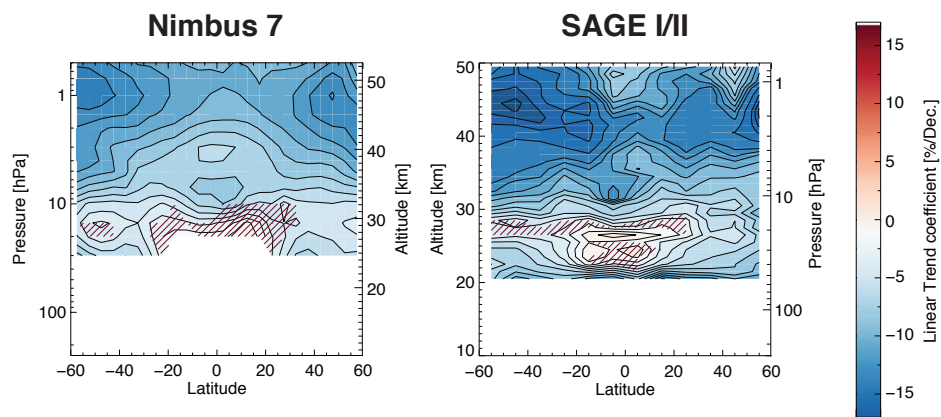
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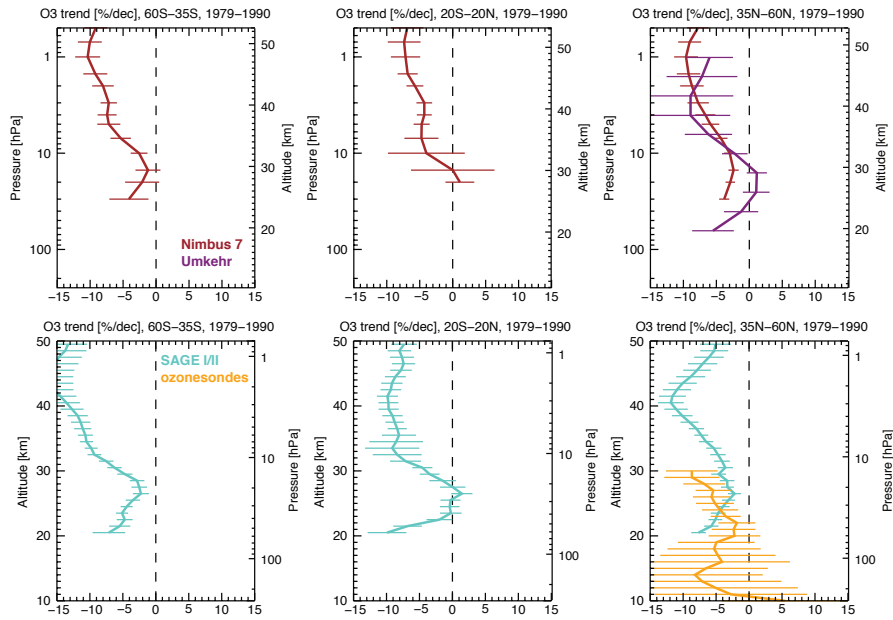
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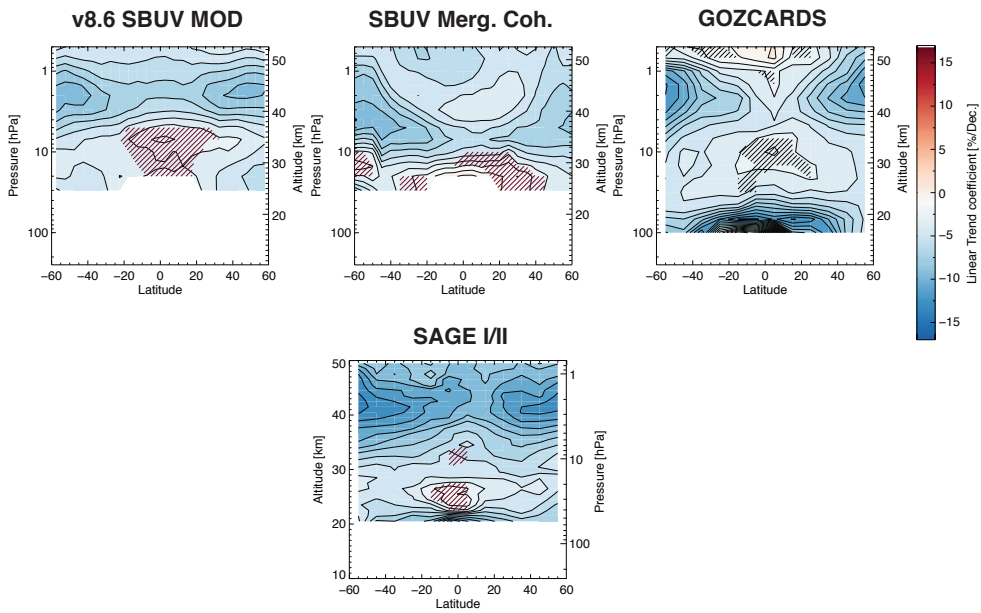


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3 Figure 1. Ozone trends derived from Nimbus 7 SBUV (Jan 1979 – June 1990) and the combined
4 SAGE I & II (Feb 1979 – June 1990) measurements. The hatched lines indicate that the trends are
5 not statistically significant at the 95% confidence level calculated using the standard deviation of
6 the residual noise.

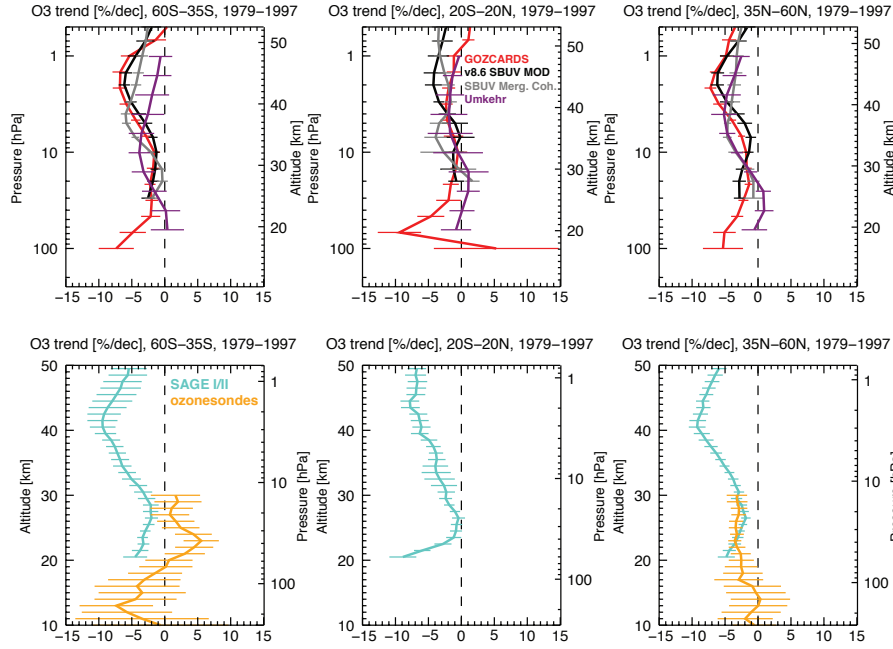


3 Figure 2. Ozone trends derived from the Nimbus 7 SBUV (brown line) and Umkehr stations (purple
4 line) (top row) , and the combined SAGE I & II satellite records (turquoise line) and ozonesondes
5 (yellow line) (bottom row). Trends for ozonesondes and Umkehr are only available at northern mid-
6 latitudes due to a paucity of measurements elsewhere. Even here, the trends are calculated from
7 only a few stations and so should be treated with caution. The error bars show the 95% confidence
8 level calculated using the standard deviation of the residual noise.



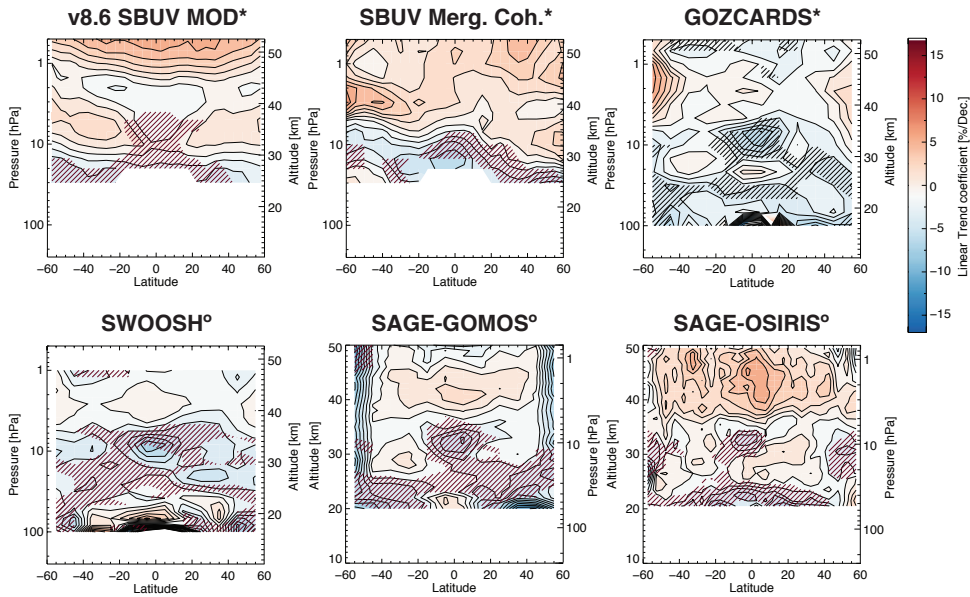
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3 Figure 3. Ozone trends for the period 1979-1997 derived from the combined SBUV records, the
4 combined SAGE I & II ozone measurements and the GOZCARDS merged data set. The hatched
5 lines indicate that the trends are not statistically significant at the 95% confidence level calculated
6 using the standard deviation of the residual noise. All trends are calculated with the PWLT model
7 except for those from the SAGE I/II record.



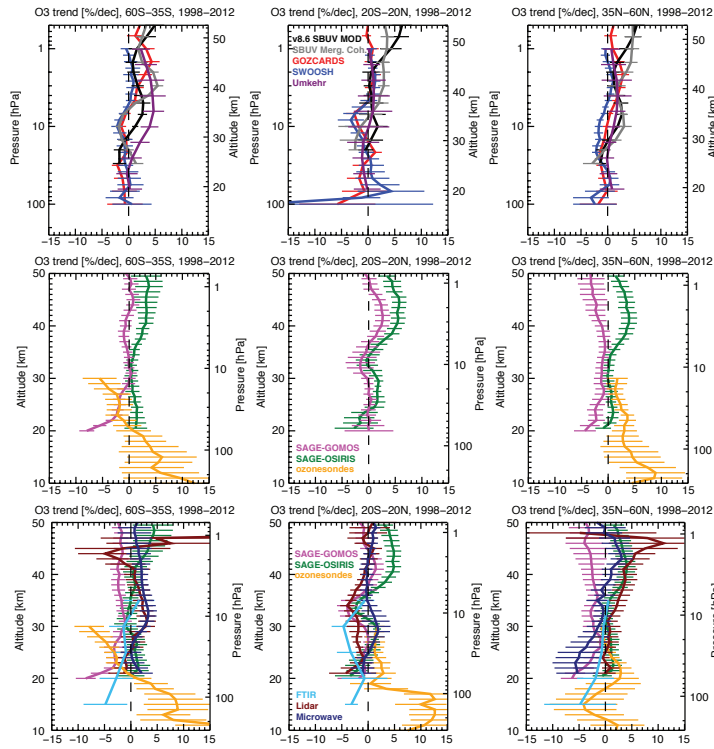
3 Figure 4. Ozone trends derived from the combined SBUV records (black and gray lines), the
 4 combined SAGE I & II ozone measurements (turquoise line), the GOZCARDS merged data (red
 5 line), ozonesondes (yellow line) and Umkehr stations (purple line). Trends for ozonesondes and
 6 Umkehr are calculated from only a few stations and so should be treated with caution. The error
 7 bars show the 95% confidence level calculated using the standard deviation of the residual noise.
 8 All trends are calculated with the PWLT model except for those from the SAGE I/II record.

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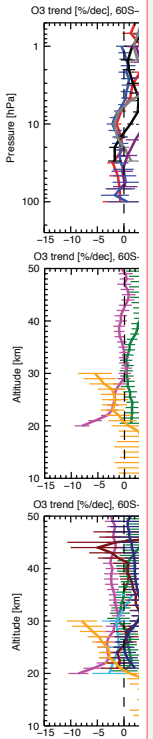
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3 Figure 5. Ozone trends for the period 1998-2012 derived from combined SBUV records, the
4 GOZCARDs, SWOOSH, SAGE-GOMOS and SAGE-OSIRIS merged data sets. The hatched lines
5 indicate that the trends are not statistically significant at the 95% confidence level calculated using
6 the standard deviation of the residual noise. Note, trends derived from GOZCARDs and the
7 combined SBUV records are based on a PWLT regression applied to the period 1979-2012
8 (indicated by a star), whereas trends from the SWOOSH, SAGE-GOMOS and SAGE-OSIRIS are
9 based on the period 1984-2012 (indicated by an open circle).



3 Figure 6. Ozone trends for the period from 1998-2012 derived from satellite and ground-based
4 datasets. The latitudinal coverage of the satellite data sets is shown in Figure 5. The trends are
5 calculated with a piecewise linear trend regression and the error bars show the 95% confidence
6 level calculated using the standard deviation of the residual noise. The ground-based trends result
7 from a small number of stations in each latitude band (see text) and so should be treated with
8 caution. Trends in the upper two rows are calculated with the PWLT model, while those in the
9 bottom row are calculated with the single linear trend model.

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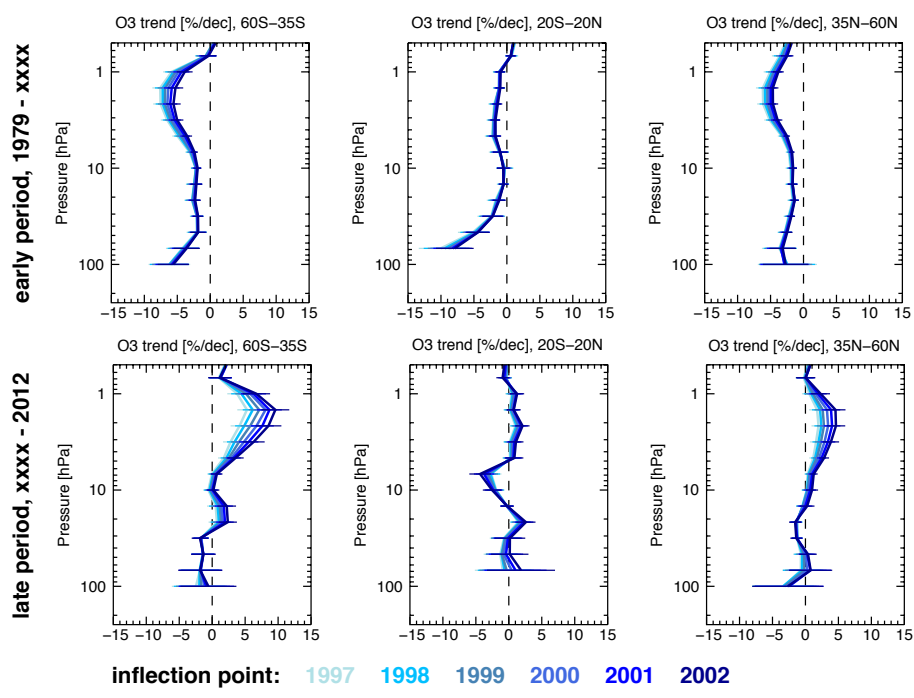
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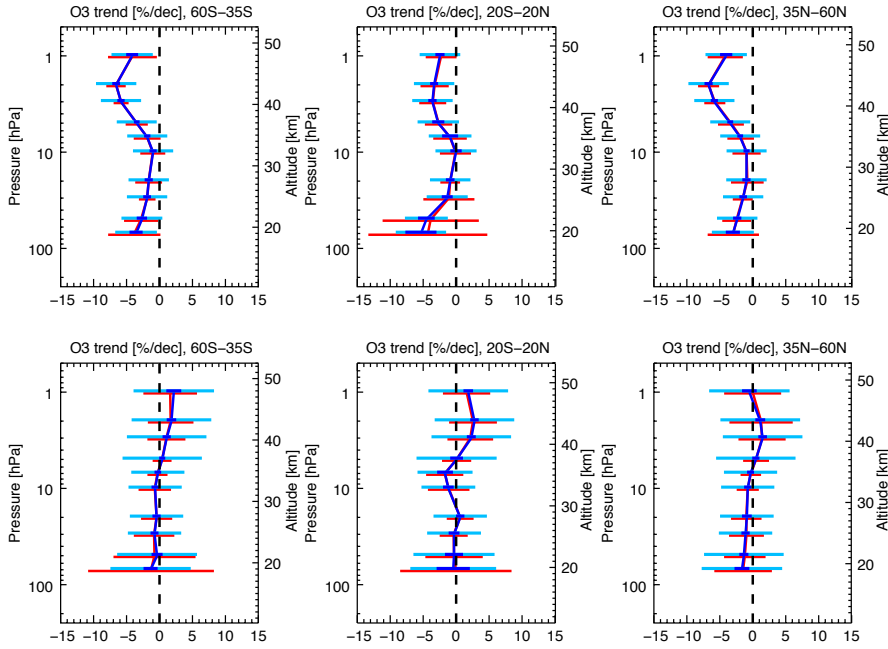
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3 Figure 7. Ozone trends derived from the GOZCARDS data set calculated using a piecewise linear
4 trend regression. The different lines show the effect of changing the point of inflection (i.e. where
5 the first trend finishes and the second trend starts) in 12 month steps from January 1997 to January
6 2002. The error bars show the 95% confidence level calculated using the standard deviation of the
7 residual noise.



3 Figure 8. Ozone trends derived from combining the satellite trend estimates shown in Figures 4 and
 4 6 for the periods before 1998 (top row) and after 1998 (bottom row). The pre-1998 trends are
 5 calculated from the trends for 1979-1997 for the two SBUV records and GOZCARDS together with
 6 1984-1997 trends for SAGE-OSIRIS, SAGE-GOMOS and SWOOSH. The post-1998 trends are
 7 calculated from all the satellite data sets analysed here. The error bars show the 95% confidence
 8 level calculated in three ways. The thick blue lines show the central estimates and their associated
 9 most likely range for the ozone trends found by propagating the individual trend errors assuming
 10 the SWM-distribution. The light blue line, based on the same analyses, additionally includes a term
 11 for the possible drift of the overall observing system (Hubert et al., 2015). The thick red lines show
 12 the possible range for the ozone trends calculated assuming the J-distribution. See text and Ko et al.
 13 (2013) for more details. The conversion to a common pressure scale of trends derived from
 14 instruments whose natural measurement coordinate is altitude was made using MERRA
 15 temperature profiles.

Once the recent data sets are mature, this should lead to a better overall knowledge of the changes in ozone over this period. However, significant uncertainties and differences still exist (Tegtmeier et al., 2013; Lambert et al., 2015), and so care is needed to identify robust conclusions about the trends. These problems are likely less important for ground-based records where quality assurance and control procedures can be applied through the major networks (Nair et al., 2012). The SBUV series of instruments has produced a continuous record over the whole period, albeit with uncertainties in trends resulting from the inter-instrument differences (Frith et al., 2014). The two solar occultation instruments, SAGE II and HALOE, ceased operation in 2005 so trends calculated past that date require an extension of their record with measurements from other instruments. The number and geographic coverage of ozonesonde and Umkehr instruments making measurements is much greater than in the earlier period (although there are unfortunately signs of this reversing). In addition the coverage of other instrument types (microwave, lidar, FTIR) in NDACC has increased over this time, and these measurements can be used for ozone trend studies as well as for comparisons with satellite measurements and verification of their long-term stability (Hubert et al., 2015; Nair et al., 2012, 2013; Steinbrecht et al., 2009, Vigouroux et al., 2014).

However the most striking change in this period has been in the number of satellite instruments making measurements of the vertical distribution of ozone for the majority of this time and so useful for trend studies (Hassler et al., 2014 and references therein): the SMR and OSIRIS instruments operational on the Odin satellite since 2001; the GOMOS, MIPAS, and SCIAMACHY instruments on Envisat from 2002-2012; the MLS instrument on Aura and the MAESTRO and ACE-FTS instruments on SCISAT since 2004.

Each measurement system has different vertical and spatial resolutions, with some expressed as a function of pressure and others as a function of altitude. The gridded data sets were latitudinally weighted and averaged into three latitude bands: 35°-60°S, 20°S-20°N; and 35°-60°N. The original vertical gridding was kept for the altitude based datasets (i.e. every 1 km spacing), as well as the pressure level data sets. When combining trend results from individual systems to estimate the overall trend, we convert

to a common vertical coordinate and degrade to a common vertical scale (see Section 3.3 for details).

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