

1. It would be useful to discuss how model-dependent the large ozone sensitivity to uncertainty in the $\text{NO}_2 + \text{OH}$ reaction rate may be. Previous studies comparing GEOS-Chem with ARCTAS observations have shown that the model displays a large overprediction of HNO_3 and a large under-prediction of PAN in the Arctic troposphere (Figs. 18 & 16 Emmons et al., (2015); Figs. 3 and 4 Arnold et al., 2015). To what extent is the sensitivity to the HNO_3 production rate a reflection of the propensity for GEOS-Chem to produce large amounts of HNO_3 ? i.e. is the sink for NO_2 through formation of HNO_3 (and therefore sensitivity to uncertainty in its rate) realistic? Does this version of the model include the NO_y chemistry updates from Fischer et al., (2014) which greatly improved the simulation of NO_y chemistry in GEOS-Chem? The authors should include some reference to these past studies comparing GEOS-Chem with ARCTAS data and other models in the discussion, and comment on how the model Arctic NO_y budget compares with observations and implications for the inferred sensitivity to the kinetic uncertainties.

Response: In our model runs we likewise see similar over-prediction of HNO_3 and under-prediction of PAN in our domain. As noted, this isn't a novel result with GEOS-Chem but should be mentioned for those readers unfamiliar with the model. We've edited the manuscript to make note of this (P10 L10-15). Even with this HNO_3 overprediction, I'm hesitant to see it as GEOS-Chem specific result with other implementations of this method to box models in other regions finding similar sensitivity (Chen et al. 2012).

The model version used in this study (v9-02) implements many of the Fischer et al. updates such as the implementation of the Paulot isoprene oxidation scheme, updating various rate coefficients, and increasing the deposition flux of PAN. Not all of the updates suggested by Fischer et al. have been included in the standard code as of yet but are slated to be included in v11-2 http://wiki.seas.harvard.edu/geos-chem/index.php/GEOS-Chem_v11-02.

2) The large response to soil NO_x emissions is a surprising and novel result, and also warrants further discussion. Given the high vertical stability of the Arctic troposphere, there is strong isolation of the free mid / upper troposphere from emissions and processes in high latitude / Arctic boundary layer, and air tends to be transported into the mid/upper troposphere from lower latitudes (e.g. Stohl, 2006, Wespes et al., 2012). Therefore ozone sensitivity at altitudes in the mid and upper troposphere is presumably driven by response to uncertainty in soil NO_x emissions from lower latitudes, and its impacts on ozone chemistry during uplift and long-range transport into the Arctic? It would be useful to expand on this in the manuscript, such that the reader has a better idea of what drives this sensitivity. A factor 3 uncertainty is assumed for these emissions based on Jaegle et al., (2005). Is this the most appropriate and recent reference for framing this uncertainty? Given the importance of this uncertainty for ozone in the N American Arctic, it would be helpful to discuss more widely estimates of the reliability (uncertainty in) the soil emissions if other studies are available and how robust the factor 3 estimate may be.

Response: Over much of our Arctic domain in the summer, soils along with biomass burning are the primary emissions sources of NO_x in the model because of the lack of major anthropogenic sources. The stability of the Arctic atmosphere brought up in the Stohl and Wespes et al. papers is more of an issue for the winter and spring periods in which the thermal inversion is stronger. In the case of the Stohl paper, the greatest summertime sensitivity to midlatitude transport was further north than almost all the flights in ARCTAS-B. Also, in our results the sensitivity to soil NO_x was most pronounced in the summertime, not the spring when this higher altitude transportation from the mid-latitudes is more important over the Arctic domain. You are correct that advection from the midlatitudes into the mid-high troposphere is an important consideration in this domain, especially for the springtime. This point was made noting the sensitivity to Asian and USA emissions P10 L20-24. Bringing up specifically the dynamic reasons for this sensitivity is a good idea and is now made more explicitly (P10 L 24).

As far as the chosen uncertainty range, you are correct in there being some uncertainty to our chosen uncertainties. In the case of soil NO_x , there has been some more recent efforts made with satellite data such as Vinken et al. (2014) to reduce this uncertainty. However, as they note in citing Schumann and Huntrieser (2007), there is still a large variability in these estimates (4-15 TgN yr⁻¹). This large range of estimates carries over to biomass burning emissions as well (6-12 TgN yr⁻¹) (also Schumann and Huntrieser, 2007 as cited by Vinken et al., 2014). With this, a factor of 3 uncertainty may be slightly on the high side, but not unreasonable in our opinion. In tests we also varied the uncertainty of all the factors to $\sigma/2$ and 2σ in

addition to the 1σ analyzed in this study and found almost exactly the same qualitative results (quantitatively the sensitivity indices values varied a few percent) giving us confidence in these results for a variety of different uncertainty ranges.

Changes: Add reference to the Vinken et al. and Schumann and Huntrieser papers P4 L10-13.

- 5 3) *To what extent is the large HO_x response to gamma HO_2 a reflection of the large uncertainty range implemented (factor 3)? It would be useful to show what actual range of gamma values this corresponds to. The authors show that the ensemble members with lower gamma values best match profile observations of HO_2 . How do these gamma HO_2 values compare with those used in previous GEOS-Chem studies? What are the implications for model comparisons with high latitude CO values, which in previous studies have been improved by implementing different formulations of aerosol uptake of HO_2 (e.g. Mao et al., 2013)? How does the choice of product (H_2O_2 or H_2O) affect comparisons with CO and ozone? It would be useful to discuss this, since underestimation of CO at high latitudes in CTMs is a persistent problem (e.g. Emmons et al., 2015).*

Response: Certainly the high uncertainty in Gamma HO_2 contributes to the high sensitivity. This high uncertainty is both evident in the JPL evaluation and in the wide range of treatment and values historically used in GEOS-Chem (P5 L10-17). Also, as we noted in the response to the previous point (# 2), in tests varying the uncertainty ranges, we found very similar results.

- 20 We described on Page 7 how we constructed the distributions in Section 2.2.1 ("Uncertainties"). As the perturbations followed a lognormal distribution, listing a range of values may not be most useful to the readers as the high and low values would be in the tails of the distribution and not indicative of the vast majority values used in the study. Excluding the upper and lower 5% of the distribution, the values roughly range from 0.04 to 1 which is within the range of values historically used in GEOS-Chem. We touched on the range of gamma values in (P12 L26, P13 L26) describing what values of gamma HO_2 provided the closest match to observed summertime HO_2 profiles.

- 25 As for CO, when the modeled HO_2 uptake produces H_2O_2 instead of H_2O , we find CO mixing ratios to be decreased throughout the vertical profile on the order of 10ppb for both spring and summer. Thus, this change exasperates the under-prediction of modeled CO with the uptake product of gamma HO_2 being H_2O_2 rather than H_2O . As you note, models tend to underestimate CO in the high latitudes. While this is the case for the Arctic spring, in the summer we found the model to over-estimate CO by around a factor of 2 in the lowest 2km of the troposphere before shifting to under-prediction above 4km (Figs S1 & S2). As for ozone, we found very modest differences between these two scenarios as evidenced by the blue dashed lines in (Figs 2 & 6).

- 30 Changes: For readers interested in CO profiles and how the aerosol uptake product of HO_2 affects CO profiles we've created figures for both spring and summer in a new supplement (S1, S2).

- 35 4) *It should be made clear in the abstract and the methodology that this analysis only provides information on drivers of model response to uncertainties in air masses sampled during ARCTAS. It cannot be assumed that this is representative of the whole Arctic unless this can be shown explicitly. Figure 2 shows a good spread of aircraft observations across altitudes, but the flights still only sample the N American Arctic on specific days, when there are certain specific air mass origins.*

Response: This is a good point. While when writing the paper we thought readers would understand the geographic limitation of the study area, but it is probably best to make it clearer as suggested.

- 40 Changes: In the abstract instead of "period", "flight tracks" is substituted (P1 L6). Also P8 L30-31 changed to "providing a fairly representative view of the Arctic troposphere over this domain for the times corresponding to these flights."

Specific / minor comments

- 45 Page 1, Line 1: "oxidation capability" change to "oxidation capacity"

Changed as suggested

Page 1, Line 19/20: "Increasing oil and gas exploration and extraction, coupled with summertime shipping lanes through the region will make air pollution worse". This statement needs a reference.

Changes: Added a citation to Granier et al. 2006.

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Page 2, line 5: ".. model shortcomings are usually attributed to errors in the chemical reaction rates, emissions, or meteorology (e.g., Wild and Prather, 2006)". The cited study is specifically about effects of model resolution? Please cite examples to back up the specific reasons you list.

10 Changes: The Wild and Prather paper made this point (section 3, paragraph 13). In lieu of this general point, we've added citations to some papers dealing with each of these three specifically (meteorology, emissions, chemistry) Kinnison et al. 2007 for meteorology, Fischer et al 2014/Jaegle et al. for emissions, Chen et al., 1997 for chemical reaction rates.

Page 2, Line 10: Omit semi-colon.

15

Changed as suggested

Page 2, line 13: "two more input factors" should be "two or more input factors"?

20 Correct. Changed as suggested.

Page 4, line 3: Better phrased as: "We note in the following section exceptions to this. . ."

Changed as suggested

25

Page 4, line 10: The Jaegle et al., (2005) reference is cited for estimating uncertainty in biomass burning emissions. The GFED 3 emissions are used, so is there a more recent and appropriate estimate of uncertainty specifically for these emissions? I am not suggesting re-running the ensemble, but again (as with soil NO_x - see point above) framing the choice of factor 3 uncertainty against any other estimates would be helpful.

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See comments for general point 2

Page 8, Line 11: OH interferences being negligible in Arctic free troposphere. Probably correct in general, but what about in biomass plumes during ARCTAS-B?

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When excluding OH measurements taken within smoke plumes (HCN > 1000 ppt), the mixing ratios differ less than 10% in nearly all the vertical bins. This is similar to what was noted in the paper with HO₂ where there is a similarly small effect. This difference doesn't change the conclusions of the paper.

40 Page 8, Sec. 2.4: The detail on the specific GEOS-Chem code for aircraft flight track interpolation seems unnecessary. Instead just describe what this does.

Scaled back a bit P8 L18-25 and removed the last sentence in that section.

45 Page 8, line 26: I am not sure you can claim that the flights give a "representative view of the Arctic troposphere". See my general point (4) above.

Response to general point 4 should cover this.

Page 8, line 27: You shouldn't refer to Fig. 6 before you have referred to Figs. 3,4,5. Consider re-ordering / re-numbering the figures.

5 The order of the figures seems to be in a good, logical order as currently ordered so the reference to these figures has been removed here. The new sentence was already edited for general point 4.

Page 11, line 17: Should be "are shown in Figure 7".

10 Correct. Changed as suggested

15 *Page 13, line 7-9: Mischaracterisation of advection from mid-latitudes effect on ozone. Has this been discussed in the main paper text? Previous multi-model studies have also shown low profile springtime ozone in the Arctic in GEOS-Chem, but no similar underestimation of ozone in other models driven by GEOS-5 meteorological data (e.g. Emmons et al., 2015, Figs. 16 & 17). It therefore seems unlikely to be related to advection errors. Please expand this discussion in light of this past work.*

20 Response: Thank you for bringing this recent literature to our attention. After considering some of the NO_x profiles, the ozone conclusions have been refocused in a different direction and mention the POLMIP results.

Changes: Moved discussion of Alvarado paper and its comparison to the POLMIP results into Section 3.2.2 (P11, L10-14)

1. *Number of parameters chosen: The authors state in the conclusions that 52 parameters have been explored. In Table 1 I count 51. Have I missed something? Can the authors please check this.*

5

There were 52 factors included in the HDMR analysis and 51 in the table. EPA NH₃ should have been included in the table and has now been added. Thank you for finding this discrepancy.

2) *Model resolution: The current simulations have all been performed at 4° x 5° horizontal resolution with the justification that the authors found only small differences (~10%) using higher resolution model simulations (2° x 2.5°). These latter higher resolution simulations still strike me as being very low resolution. Do the authors expect the same sensitivity to hold at say 0.5° x 0.5°? I ask as I have seen more and more simulations with GEOS-Chem at these sorts of high resolutions and so I think transferring the knowledge gained here to those studies is important.*

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Response: We would have preferred to run this analysis at the finest possible resolution but are limited by computational resources. The comparison to the 2° x 2.5° was intended more to illustrate how sensitive the modeled results are to changes in resolution. This comparison between 4° x 5° and 2° x 2.5° has been used in previous GEOS-Chem studies (eg., Fiore et al., 2002, Fischer et al., 2014). The expectation is that most of the findings of this paper would be applicable to other model resolution choices considering the small differences between the two resolutions we tested. While finer resolution (like 0.5° x 0.5°) studies are becoming more popular with GEOS-Chem, these studies are limited to a few regions?E Asia, Europe, and North America. In the case of the North American domain, the nested grid doesn't cover the ARCTAS domain.

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3) *Meteorological uncertainty in the model: This is out of interest, but how different is the uncertainty between the average monthly fields between GEOS-4 and GEOS-5 compared to the standard deviation of the meteorological parameters generated from the re-gridding from the native GOES-5 grid to the GEOS-Chem grid?*

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Response: By averaging over the month, some of the day-to-day and some of the spatial differences are muted between the resolution choices. From some back of the envelope calculations between the 2° x 2.5° and 4° x 5° resolution meteorological fields, we find differences less than those between meteorological models with the greatest differences coming around the edges of mountainous regions and the edge of the Antarctic continent. Going even finer to the native resolution would presumably further increase these differences to being around the same or perhaps greater than the differences between the GEOS-4 & 5 models.

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4) *The role of organic radicals: It's interesting to see that the uncertainty in isoprene emissions pops up as having an effect on ozone and HO₂. I was wondering if the authors considered the uncertainty in the organic peroxy radical reactions associated with isoprene?*

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Response: All the chemical reactions in the GEOS-Chem chemical mechanism were included in the Morris Method pre-screen test including those involving organic peroxy radicals. The isoprene peroxy radical reactions did not make the cut to be included in the HDMR analysis but some of the methane ones did as shown in Table 1.

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5) *NO_x: There is very little mention of the role of NO_x in the manuscript and I'm surprised that the authors did not include NO_x in the analysis and results. Clearly NO_x plays an important role in coupling HO_x and I would like to see how the current study impacts the NO_x partitioning. I think that this is something that many others would also benefit from seeing and I would suggest adding some plots to at least show the impact of the ensemble of simulations on the NO_x profiles.*

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Response: NO_x profiles were not originally included in the paper for a couple of reasons. First, this analysis didn't change the model treatment of NO_x (except for the perturbations to emissions and chemical rates) making most of that analysis a rehash of previous research. Secondly, a few different NO_x emissions inventories were perturbed in the analysis leading to a

large variability in their modeled concentrations between model runs, especially near the surface where the emissions sources are. As you note though, readers would be interested in the seeing at least the NO_x profiles. To address this, we have created a small supplement showing the median NO_x and CO profiles for both the spring and summer flights.

5 Changes: We've made plots showing NO, NO₂, and CO profiles for both ARCTAS A and B in a supplementary file (Figures S1 and S2).

6) *Normalised sensitivities: It's not clear to me if the reason that HO₂ uptake is the most sensitive parameter is owing to the fact that it has the greatest uncertainty? Can the authors comment on the use of the method in distinguishing/determining normalised sensitivities?*

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Response: As far as the HO₂ uptake uncertainty, please refer to my response to referee # 1, general point # 3.

The HDMR method is not necessarily used to determine normalized sensitivities, however one could infer a qualitative sense of this comparing those factors in the pie charts to their respective sensitivities listed in Table 1. We touched on this in a peripheral sense noting the sensitivity of the oxidants to both the chemical kinetic rates (which have much lower uncertainties) and emission inventories (P3, L20-24). Due to the non-linearity of the chemical system, I have reservations with creating "normalized" sensitivity indices armed with the sensitivity indices and uncertainty factors though.

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Technical corrections:

20 *Page 2 line 4: I don't think Wu et al., 2007 is a great reference for making this point. A better reference would be a multi model intercomparison study like one of the ACCMIP or HTAP papers.*

Response: That's a good suggestion to use a multi model inter-comparison paper to make this general point. Instead of the ACCMIP or HTAP papers, we've edited this reference to the POLMIP paper as it's also Arctic focused.

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Changed the reference to Emmons et al., 2015

Page 9 line 13: ppb should be ppt I think.

Correct. Changed as suggested

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Page 9 line 22: Need to define HO_x earlier in the text.

HO_x was defined on Page 2, Line1. No changes

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Page 10 line 10: ppb should be ppt I think.

Correct. Changed as suggested

Global sensitivity analysis of the GEOS-Chem chemical transport model: Ozone and hydrogen oxides during ARCTAS (2008)

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Abstract. Developing predictive capability for future atmospheric oxidation ~~capability~~capacity requires a detailed analysis of model uncertainties and sensitivity of the modeled oxidation capacity to model input variables. Using oxidant mixing ratios modeled by the GEOS-Chem chemical transport model and measured on the NASA DC8 aircraft, uncertainty and global sensitivity analyses were performed on the GEOS-Chem chemical transport model for the modeled oxidants hydroxyl (OH), hydroperoxyl (HO₂), and ozone (O₃). The sensitivity of modeled OH, HO₂, and ozone to modeled inputs perturbed simultaneously within their respective uncertainties were found for the ~~period~~flight tracks of NASA's Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) A & B campaigns (2008) in the North American Arctic. For the spring deployment (ARCTAS-A), ozone ~~is~~was most sensitive to the photolysis rate of NO₂, the NO₂ + OH reaction rate, and various emissions, including methyl bromoform (CHBr₃). OH and HO₂ were overwhelmingly sensitive to aerosol particle uptake of HO₂ with this one factor contributing upwards of 75 % of the uncertainty in HO₂. For the summer deployment (ARCTAS-B), ozone was most sensitive to emissions factors, such as soil ~~NO_x~~NO_x and isoprene. OH and HO₂ were most sensitive to biomass emissions and aerosol particle uptake of HO₂. With modeled HO₂ showing a factor of 2 underestimation compared to measurements in the lowest 2 kilometers of the troposphere, lower uptake rates ($\gamma_{HO_2} < 0.040, 0.055$), regardless of whether or not the product of the uptake is H₂O or H₂O₂, produced better agreement between modeled and measured HO₂.

1 Introduction

With rising temperatures, shrinking sea ice, and expanding emissions into the atmosphere from increased human development and biomass burning, the Arctic is experiencing rapid changes felt nowhere else on the globe. While the region is largely undeveloped, anthropogenic air pollution from Northern Hemisphere population centers in East Asia, Europe, and North America is regularly advected into the Arctic atmosphere, contributing to the "Arctic haze" (e.g., Barrie et al., 1981). Increasing oil and gas exploration and extraction, coupled with summertime shipping lanes through the region will make air pollution worse (Granier et al., 2006). A better understanding of atmospheric oxidation chemistry is needed in order to provide a scientific basis for a sound mitigation strategy to combat this likely deteriorating air quality.

Atmospheric oxidants are at the forefront of any air chemistry study because the lifetimes of most gaseous and particulate species are determined through oxidant reactions. The primary atmospheric oxidizers of interest are the hydroxyl radical (OH), the hydroperoxyl radical (HO₂), collectively referred to as HO_x (HO_x ≡ OH + HO₂), and ozone (O₃) (Levy, 1971). Ozone, OH, and HO₂ are coupled in a cycle in which ozone photolysis leads to the creation of OH, which then cycles with volatile organic compounds to create HO₂, which then can react with nitric oxide (NO) to ultimately produce ozone and recycle OH. While this cycle appears to be well known and documented, models still fail in describing atmospheric composition (e.g., Wu et al., 2007)(e.g., Emmons et al., 2015). These model shortcomings are usually attributed to errors in the chemical reaction rates, emissions, or meteorology (e.g., Wild and Prather, 2006)(e.g., Chen et al., 1997; Fischer et al., 2014; Jaeglé et al., 2005; Kinn

A useful tool for examining and attributing sources to these model shortcomings is sensitivity and uncertainty analyses. In performing sensitivity analyses, there are two basic approaches: local and global. Local sensitivity analysis involves varying model inputs one at a time around a given point in input space while holding all other model inputs constant. This method assumes at least locally linear input–output relationships. Global sensitivity analyses ; on the other hand, involve the simultaneous perturbation of all the model inputs allowing for the interactions between inputs to be analyzed as well (Rabitz and Aliş, 1999). Global sensitivity analysis does not assume that the input and output have a linear local relationship and in fact can test the sensitivity of the output factors to the co-variation of two or more input factors. Global sensitivity analysis is preferred over local sensitivity analysis for complex models (Saltelli et al., 2008) and applies well to global chemical transport models (CTMs), such as the GEOS-Chem (Goddard Earth Observing System-Chemistry) model used in this study, that can have non-linear interactions in the chemical kinetics, emissions, and meteorology.

Previous sensitivity studies using GEOS-Chem tended to use local sensitivity methods despite the known non-linearity of the underlying chemical processes and subsequent interactions with meteorological and emissions factors. To combat these non-linearities, a common strategy in sensitivity studies involves the perturbation of model factors across a smaller sample of the input space (e.g., Fiore et al., 2009; Wu et al., 2009). While useful in ascertaining sensitivities for individual factors, this method cannot provide a complete picture of the modeled uncertainty as the entire input space is not sampled. In other sensitivity studies GEOS-Chem has been analyzed for its sensitivity to meteorological models and factors (e.g., Wu et al., 2007; Heald et al., 2010) and both biogenic (Fiore et al., 2005; Mao et al., 2013b) and anthropogenic emissions (e.g., Fiore et al., 2002; Martin et al., 2003; Auvray and Bey, 2005; Jaeglé et al., 2005; Guerova et al., 2006). While helpful, these local sensitivity studies were limited to perturbing a small set of similar input factors so it is possible that some important input factors or interactions may have been missed.

This study covers National Aeronautics and Space Administration’s (USA) (NASA’s) Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) campaign (2008) (Jacob et al., 2010). The impetus of the campaign was to better understand the complex interactions between atmospheric composition, the environment, and climate in the North American Arctic and was split into three sub-campaigns, ARCTAS-A (spring), ARCTAS-CARB (California—not included in this study), and ARCTAS-B (summer). ARCTAS-A sought to better understand the chemical processes during the polar sunrise when anthropogenic pollution is at its annual maximum and halogen chemistry is active and was based in Fairbanks, Alaska (USA), Iqaluit, Nunavut (Canada), and Thule, Greenland. A point of emphasis of ARCTAS-B was characterizing the effects

of biomass burning emissions from the forest fires ubiquitous during the Arctic summer and examining the chemistry within smoke plumes of varying age (Jacob et al., 2010). ARCTAS-B was based in Cold Lake, Alberta (Canada) and Thule, Greenland.

This study is different from previous sensitivity studies involving CTMs, specifically GEOS-Chem, because the quantity and diversity of perturbed inputs are greater. Through a global sensitivity analysis, we identify and quantify the sources of uncertainty for atmospheric oxidants and explore how these factors explain model–measurement differences. Presented here is a global sensitivity analysis of a global CTM allowing for the assessment of model uncertainties and determining the sensitivities of model outputs to chemistry, emissions, and meteorology input factors.

2 Methods

2.1 GEOS-Chem

The chemical transport model used for this study is GEOS-Chem. GEOS-Chem has been a valuable tool in understanding global air chemistry since its introduction into the literature (Bey et al., 2001) and is currently used by scores of institutions around the world for a wide ranging set of air chemical applications. This study uses the standard GEOS-Chem CTM (v9-02). For computational expediency, the model runs use a regridded horizontal resolution of $4^\circ \times 5^\circ$ and 47 hybrid vertical layers. While previous CTM studies have shown that coarse resolution elevates OH concentrations and ozone production rates, the error from resolution typically pales in comparison to those errors arising from chemistry, meteorology, and emissions (Wild and Prather, 2006). In our case, we found small differences (usually $< 10\%$) for ARCTAS-A and B between mean vertical profiles of ozone, OH, and HO_2 using either $4^\circ \times 5^\circ$ or $2^\circ \times 2.5^\circ$ resolutions and thus using the coarser resolution is adequate for this study. The following sections briefly describe the meteorology, emissions, and chemistry components of the model.

2.1.1 Meteorology

GEOS-Chem is driven by the Global Modeling and Assimilation Office's (GMAO) GEOS-5 (Goddard Earth Observing System) meteorological model. GEOS-5 has a native resolution of $0.5^\circ \times 0.666^\circ$ with 72 hybrid eta levels but is regridded to $4^\circ \times 5^\circ$ with 47 hybrid vertical levels for input into GEOS-Chem. There are about 60 GEOS-5 meteorological fields handled by GEOS-Chem. Mixing depths and surface meteorological fields, such as soil wetness, heat fluxes, and albedo have a 3 hour temporal resolution. In contrast, 3D fields, such as u and v wind components and temperature, have ~~6-hour~~ 6-hour temporal resolution (Bey et al., 2001). Transport is handled by the semi-Lagrangian TPCORE algorithm (Lin and Rood, 1996).

Due to the lack of published uncertainties associated with the GEOS-5 meteorological data, we defined our meteorological uncertainties as the average monthly standard deviation of the difference between GEOS-5 and GEOS-4 meteorological fields for 2005, a year of overlap between the models. For relative and specific humidity, an uncertainty of 5%, similar to Heald et al. (2010), was assumed. Cloud mass flux uncertainty was inferred from differences between GEOS-5, a single column model, and a cloud resolving model and set at a factor of 1.5 (Ott et al., 2009).

2.1.2 Emissions

GEOS-Chem includes emissions from a variety of anthropogenic, biogenic, and other emissions sources. For this study, the default emissions were generally used. We note in the following section ~~these exceptions~~ exceptions to this and a more detailed description of the various emissions inventories.

5 For biogenic emissions, this study used the default MEGAN 2.1 (Model of Emissions and Gases and Aerosols from Nature). Out of the 9-nine species provided by MEGAN, isoprene emissions are dominant, accounting for about half of the biogenic volatile organic compound (VOC) emissions in GEOS-Chem. We assume a factor of 2 uncertainty for isoprene emissions (Guenther et al., 2012). Biomass emissions, a point of emphasis in the ARCTAS-B campaign, were supplied via the Global Fire Emissions Database 3 (GFED-3) (van der Werf et al., 2010). GFED-3 emissions were calculated every three hours. For both
10 biomass and soil NO_x emissions we assume a factor of 3 uncertainty (Jaeglé et al., 2005). With biomass and soil emissions inventories having a large spread in estimates (e.g. Schumann and Huntrieser, 2007; Vinken et al., 2014) this relatively high uncertainty is not unreasonable.

For anthropogenic volatile organic compound (VOC) emissions, the model uses a combination of REanalysis of the Tropospheric chemical composition (RETRO), Emission Database for Global Atmospheric Research (EDGAR), and regional
15 emissions inventories. RETRO was developed by The Netherlands Organization for Applied Research (TNO). GEOS-Chem 9-02 uses 12 VOC species from RETRO (Reinhart and Millet, 2011). EDGAR v4.1 emissions (Olivier et al., 1996) are the default model for NO_x ($\text{NO}_x \equiv \text{NO} + \text{NO}_2$), CO, and SO_x ($\text{SO}_x \equiv \text{SO}_2 + \text{SO}_4^{2-}$) in GEOS-Chem. It has a resolution of $1^\circ \times 1^\circ$ and is available on a yearly basis. For many parts of the world, especially the developed world, this study used the default regional emissions datasets that overwrote the RETRO or EDGAR fields.

20 Lightning NO_x is emitted through the scheme developed by Price and Rind (1992) in which lightning frequency is parameterized based on cloud height and land cover type. In this scheme, continental flash frequencies are higher than marine storms due to stronger storm updrafts observed over land. GEOS-Chem assumes a global total of 6 Tg N yr^{-1} as per Martin et al. (2007) and Sauvage et al. (2007). For this study, the lightning NO_x emissions were rescaled to 6.3 Tg N yr^{-1} with an assumed uncertainty of $\sim 25\%$ consistent with more recent literature (Miyazaki et al., 2014). This uncertainty may be higher (Liaskos
25 et al., 2015) but is not a major consideration in this domain given the low lightning frequency in the Arctic.

An important factor for any study of ozone is the stratospheric-tropospheric exchange (STE) of ozone. In GEOS-Chem, it is typically parameterized by the Linoz scheme (McLinden et al., 2000). To allow constant scaling of STE ozone, this study used instead the Synoz algorithm, which exchanges 500 TG yr^{-1} of ozone through the tropopause (McLinden et al., 2000). The assumed uncertainty for this STE ozone is a factor of 2.

30 2.1.3 Chemistry

The standard chemical scheme in GEOS-Chem has more than 230 kinetic reactions. This study uses the Sparse-Matrix Vectorized Gear Code (SMVGEAR) chemical solver (Jacobson and Turco, 1994). These rates are updated periodically and are generally supplied by the Jet Propulsion Laboratory (JPL) (Sander et al., 2011), the International Union of Pure and Applied

Chemistry (IUPAC) (Atkinson et al., 2007), or other recent literature. Uncertainties for chemical rate coefficients came from JPL (Sander et al., 2011). The standard photolysis scheme has 55 different reactions and uses the FAST-J algorithm (Wild et al., 2000) to calculate photolysis rates throughout the troposphere. Uncertainties for photolysis rates came from JPL's combined cross sectional and quantum yield uncertainties (Sander et al., 2011).

5 2.1.4 Heterogeneous chemistry

A major point of emphasis in this study is the effect of the treatment of heterogeneous chemistry in the model, especially the aerosol particle uptake of HO₂ (referred to as gamma HO₂). Gamma HO₂ is defined as the fraction of HO₂ consumed per collision with aerosol particles. Until recent work by Mao et al. (2013a) that proposed catalytic reactions involving copper and iron ions in aqueous aerosols, it was assumed aerosol uptake of HO₂ would eventually lead to H₂O₂ production (e.g.,
10 Jacob, 1986). While H₂O formation is a terminal sink for HO_x, H₂O₂ can be photolyzed and return HO_x radicals back into the atmosphere. GEOS-Chem has had an inconsistent history in the treatment of HO₂ aerosol uptake with both the rate and product of this reaction. Originally GEOS-Chem set $\gamma_{HO_2} = 0.1$ producing H₂O₂ (Jacob, 2000) then HO₂ uptake was eliminated from the model to better match tropical results (Sauvage et al., 2007) before the later implementation of Thornton et al.'s 2008 mechanism. On the upper end of values for gamma HO₂, some studies have used $\gamma_{HO_2} = 1.0$ (Emmons et al., 2015). In the
15 version of the model used in this study, HO₂ heterogeneous aerosol uptake is parameterized by $\gamma_{HO_2} = 0.2$ (Jacob, 2000) yielding H₂O, a terminal reaction for HO₂ (Mao et al., 2013a) . Uncertainties for heterogeneous chemical factors came from JPL (Sander et al., 2011).

2.2 Global sensitivity analysis

The global sensitivity analysis method used in this study is the Random Sampling-High Dimensional Model Representation
20 (RS-HDMR) (Li et al., 2001; Rabitz and Aliş, 1999). RS-HDMR is an approach to the HDMR method in which the inputs are randomly sampled from their uncertainty distributions. This study employed a slight variation of the RS-HDMR method in which, in lieu of randomly sampling the input space, it is sampled using a Sobol Sequence (Sobol, 1976), a quasi-random number sequence. Using this sequence allows for more efficient sampling of the input space and quicker convergence of the RS-HDMR metamodel solution (Feil et al., 2009), an important advantage with the high computational costs associated with
25 chemical transport models. The HDMR method describes the model output as an expansion in terms of the input factors.

$$f(x) = f_0 + \sum_{i=1}^n f_i(x_i) + \sum_{1 \leq i < j \leq n} f_{ij}(x_i, x_j) + \dots + f_{12\dots n}(x_1, \dots, x_n) \quad (1)$$

Here f_0 is the zeroth order component, a constant equivalent to the mean (Eq. 2), f_i is the first order effect corresponding to the independent effect of the input x_i on the output (Eq. 3), f_{ij} corresponding to the second order effect on the output of inputs x_i and x_j working cooperatively (Eq. 4), on down to the n^{th} order effect on the output by all the inputs working cooperatively

(Rabitz and Aliş, 1999).

$$f_0 \approx \frac{1}{N} \sum_{s=1}^N f(x^s) \quad (2)$$

$$f_i \approx \sum_{r=1}^{k_i} \alpha_r^i \varphi_r^i(x_i) \quad (3)$$

5

$$f_{ij}(x_i, x_j) \approx \sum_{p=1}^{l_i} \sum_{q=1}^{l_j} \beta_{pq}^{ij} \varphi_p^i(x_i) \varphi_q^j(x_j) \quad (4)$$

Here φ represents orthonormal polynomials, k_i , l_i , and l_j represent the orders of the polynomials, α and β are constant coefficients.

When using the RS-HDMR approach, the component functions representing the different ordered effects are orthogonal to one another. Because of this property, the total variance can be decomposed into a sum of variances of each component function (e.g., Li et al., 2010; Chen and Brune, 2012). For example:

$$V(f(x)) = \sum_{i=1}^n V(f_i(x_i)) + \sum_{1 \leq i < j \leq n} V(f_{ij}(x_i, x_j)) + \dots + V(f_{12\dots n}(x_1, \dots, x_n)) \quad (5)$$

Where $V(f_i(x_i))$ represents the variance of the first order effect due to the input x_i and so forth. It is important to note that $f_i(x_i)$ (Eq. 3) is not necessarily best described by a first order polynomial. From this expansion of the variance, the sensitivity indices of each component can be found by normalizing Eq. (5) by the total variance. Should $\sum S_i \approx 1$, first order effects dominate and individual second order effects do not need to be calculated.

$$S_i = \frac{V(f_i(x_i))}{V(f(x))} \quad (6)$$

$$S_{ij} = \frac{V(f_{ij}(x_i, x_j))}{V(f(x))} \quad (7)$$

Due to the relatively long run time and the large number of inputs that go into the GEOS-Chem model, a Morris Method sensitivity test (Morris, 1991) for the Arctic domain was completed before starting the RS-HDMR study. The Morris Method, also known as the Elementary Effects method, is a computationally inexpensive method to qualitatively determine which model factors have effects that are negligible, linear, or non-linear and has been used in conjunction with many previous HDMR studies (e.g., Ziehn et al., 2009; Chen et al., 2012; Lu et al., 2013). As suggested by Saltelli et al. (2008), we employed 10 trajectories and 4 discrete levels within the uncertainty distributions for sampling. Initially, 465 different model inputs were perturbed. In the name of computational expediency, the number of perturbed inputs was reduced to approximately the 25 % most important factors for the remaining 8 trajectories. As the Morris Method tests were used to prescreen factors for inclusion

into the RS-HDMR tests, this initial cull after two trajectories did not influence the factors chosen at the conclusion of the Morris Method test.

After the Morris Method tests were completed, we selected the 50 most influential factors for HO₂, OH, and ozone concentrations-mixing ratios for the spatial domain corresponding to the ARCTAS mission. This limiting the analysis to 50 factors is in line with (Ziehn and Tomlin, 2008b); however, they note that this pre-screening process may not be necessary if thresholds are implemented in constructing the HDMR metamodel to exclude unimportant factors. In addition to the 50 most influential factors, regional Canadian NO_x emissions from the Criteria Air Contaminant (CAC) inventory, and methyl bromoform emissions were also included in our HDMR analysis. Methyl bromoform emissions were included in the HDMR tests due to the importance of halogen chemistry in Arctic (e.g., Simpson et al., 2007). All the factors included in the RS-HDMR analysis are listed in Table 1.

2.2.1 Uncertainties

After determining the factors to include in the HDMR test, the next step was to create the distributions from which to sample. Uncertainties for all the factors are listed in Table 1. Lognormal distributions were used for all distributions, except those for temperature, soil wetness, relative humidity, and cloud fraction for which normal distributions were used. Standard deviations for the lognormal uncertainty distributions were determined by $\sigma = f - 1$, where f is the published uncertainty factor and σ is the standard deviation of the distribution to be sampled, similar to Stewart and Thompson (1996). To ensure ~95 % of the quasi-random samples would be within the published uncertainty bounds and reflecting the 2σ range JPL uses to incorporate chemical kinetic data and inferred from emissions uncertainties, these standard deviations were then halved before creating the distributions.

With the uncertainty distributions created, a Sobol Sequence (discarding the first 512 sets of values as spin up) was created to quasi-randomly sample these distributions and perturb the model. To ensure model perturbations had time to spread and reach a new global equilibrium, a 9 month spin-up period was employed before the first flights in April 2008. The ensemble was limited to 512 model runs. While previous implementations of the RS-HDMR to box models used thousands of runs (e.g., Chen and Brune, 2012), recent use of the method with a land surface model shows reliable results with as few as 256 runs (Lu et al., 2013). Likewise, we found little difference in results between 512 and 256 model runs, but have included all 512 in this study.

2.2.2 Calculation of sensitivity indices

Graphical User Interface-HDMR (GUI-HDMR) was used to calculate all the sensitivity measures and analyze the input-output behavior of the model (Ziehn and Tomlin, 2009). This MATLAB software package is freely available through <http://www.gui-hdmr.de>. For use within the software, the values of the inputs were rescaled according to their respective percentiles within the uncertainty distributions. We employed the correlation method provided in the GUI-HDMR software (Kalos and Whitlock, 1986; Li et al., 2003), a variance reduction method. In using the correlation method, the construction of the RS-HDMR expansion becomes an iterative process using an analytical reference function. With this method, as noted in (Li et al., 2003),

the accuracy of the RS-HDMR expansion increases without a corresponding increase in ensemble size, a valuable advantage considering the expensive nature of running CTMs.

2.3 Measurements

For comparison to the model, we also used measurements collected aboard the NASA DC8 ~~airplane~~aircraft. OH and HO₂ measurements came from Pennsylvania State University's Airborne Tropospheric Hydrogen Oxides Sensor (ATHOS) (Faloona et al., 2004). ATHOS uses Laser Induced Fluorescence (LIF) to measure HO_x mixing ratios. The National Center for Atmospheric Research's (USA) (NCAR) Selected-Ion Chemical Ionization Mass Spectrometer (SI-CIMS) and Peroxy Radical Chemical Ionization Mass Spectrometer (PeRCIMS) also measured OH and HO₂ respectively aboard the DC8. Comparisons between the methods showed good agreement during the campaign (Ren et al., 2012). For the purposes of our analysis, only ATHOS measurements are considered. Ozone observations aboard the DC8 were measured by NCAR using the chemiluminescence method (Weinheimer et al., 1994).

Since ARCTAS, interferences have been found in the measurements of both OH (Mao et al., 2012) and HO₂ (Fuchs et al., 2011). The OH interference can be anywhere from 20 % to 300 % of the actual ambient OH, while the HO₂ interference is typically less than a factor of two. Both interferences require the presence of alkenes or aromatics and so are limited to planetary boundary layer environments in which these volatile organic compounds are common. Interferences in the free troposphere and over much of the Arctic will be negligible.

2.4 Data manipulation

To ~~compare aircraft observations to~~directly compare the model ensemble ~~, the Planeflight option within GEOS-Chem was used. The Planeflight option allows for modeled values to be output at one minute to the aircraft observations, modeled results were output in one-minute~~ intervals along the DC8 flight track using the Planeflight option within GEOS-Chem. To match the modeled flight track, we averaged the aircraft observation data over one minute intervals and excluded observations from the stratosphere. For our flight-by-flight HDMR analyses, average mixing ratios along the flight track as the output of interest in GUI-HDMR were used. For vertical profiles, modeled and measured flight track data were binned and averaged in one kilometer increments, excluding the transit flights (flights 3, 11, 16, and 24). While it is a concern that the modeled representation of the flight tracks may misrepresent spatially or temporally synoptic or mesoscale features important to the abundances of the studied species, these differences likely are small when averaged over each flight, and especially when averaged across all modeled flights.

~~At this time, Planeflight offers the most consistent method for model-measurement comparison.~~

3 Results

Given the seasonal differences between Arctic spring and summer in both meteorology and emissions, and the differences between the mission objectives between ARCTAS-A and ARCTAS-B, the results are separated by their respective season.

During both ARCTAS-A and ARCTAS-B, the NASA DC8 sampled the troposphere at a variety of heights ranging from near surface to the lower reaches of the stratosphere providing a [fairly representative view of the Arctic troposphere as seen in the bar graphs in Figs. 2 and 6. over this domain for the times corresponding to these flights.](#)

3.1 ARCTAS-A (Spring 2008)

5 3.1.1 Uncertainty analysis

Across the modeled ensemble, ozone has relatively low uncertainty (6.8 %, 1σ confidence) reflecting the low ozone production rates within the domain during ARCTAS-A (Fig. 1). In contrast to ozone, we found both OH and HO₂ to have much higher uncertainty across the model ensemble with OH and HO₂ both having 1σ uncertainties of around 27 %. Figure 2 shows this uncertainty spread vertically. For ARCTAS-A, uncertainties and sensitivities were generally uniform with altitude across the
10 model ensemble for ozone and HO_x.

3.1.2 Vertical profiles

Figure 2 shows mean vertical profiles binned per kilometer for the spring deployment (Fig. 1). Ozone was consistently under-predicted by the model at all altitudes except near the surface and showed little variation across the ensemble in modeled ozone. [This profile roughly follows what was observed with the NO₂ profiles with NO₂ being underpredicted by the model except for near the surface \(Figure S1\).](#) The lack of significant ~~in-situ~~ [in situ](#) ozone production in April over the domain could partially explain the small variation in modeled mixing ratios among ensemble members. Similar to Mao et al. (2010), OH mixing ratios were low, in the tenths of one ~~ppb~~ [ppt](#) and showed a consistent model underestimation for the lower and middle troposphere with better agreement above ~ 6 km, although the limit of detection for the OH measurement is $\sim 10^5$ cm⁻³. Across the model
15 ensemble there is general agreement between measured and modeled HO₂ within the vertical column as measured values are mostly within the first standard deviation of modeled results. This is different from Mao et al. (2010) in which GEOS-Chem showed a consistent overestimation of HO₂. Above 7 km, modeled HO₂ is higher than measured, by upwards of a factor of 2, similar to Mao et al. (2010). These results are consistent with improvement in modeled characterization of HO₂ aerosol particle uptake as aerosol concentrations are highest in the lowest few kilometers of the atmosphere and very low in the upper
20 reaches of the troposphere.

25 3.1.3 Sensitivity analysis

Figure 3 shows the first order results of the HDMR analysis for the average tropospheric mixing ratios along selected flight tracks for ozone, OH, and HO₂. For HO_x and ozone, the sensitivities are, with a minor few exceptions, altitude independent. The first order sensitivity index for all factors are represented and are color coded by their respective category as defined in Table 1. In this sense, first order effects describe each factor's individual contribution to the ensemble variance. The RS-HDMR
30 component functions for each factor are not necessarily linear, and are in fact often best represented by 2^{nd} degree and higher polynomials. GUI-HDMR calculates the optimal order for each HDMR polynomial using a least squares method (Ziehn and

Tomlin, 2008a). The missing portion of the pie graph represents second and higher order sensitivities. While all flights are not presented here, the three flights in Fig. 3 cover the geographic spread of the domain and are representative of the results seen among other spring flights.

Ozone: Overall, the sum of all the first order effects was usually below 0.90 meaning that first order effects explain close to 90 % of the observed variance. To calculate meaningful second order terms will require substantially more model runs.

For each spring flight, the photolysis of NO_2 was the most influential factor for modeled ozone with sensitivity indices ranging from around 0.09 to 0.11 (mean 0.10). It is not surprising NO_2 photolysis is a sensitive factor considering the photolysis of NO_2 leads directly to ozone production; however, it is somewhat surprising given its rather low uncertainty (20 %) and the limited ozone production in the Arctic spring. Other most influential factors are the $\text{NO}_2 + \text{OH}$ reaction (mean $S_i = 0.083$), soil NO_x emissions (0.047), temperature (0.056), and methyl bromoform emissions (0.072). Sensitivity of ozone to methyl bromoform emissions is expected due to bromine compounds' ability to catalytically destroy ozone, especially early in the Arctic spring when sunlight returns allowing for halogen photochemistry to commence (e.g., Barrie et al., 1988). Tropospheric ozone depletion events arising via catalytically destructive halogen reactions were observed during the ARCTAS-A campaign, mainly below 1 km (Koo et al., 2012). The misrepresentation of nitrogen reservoirs (NO_y), specifically the overprediction of HNO_3 (nitric acid) and underprediction of PAN (peroxyacetyl nitrate), has been a long-standing issue within GEOS-Chem (e.g., Alvarado et al., 2010; Fischer et al., 2014) so it is unsurprising we find GEOS-Chem to be sensitive to the $\text{NO}_2 + \text{OH}$ reaction rate. However, with previous implementations of the RS-HDMR method to box models showing similar sensitivity to this reaction (Chen and Brune, 2012; Chen et al., 2012), it does not appear to be a model specific result.

OH: OH mixing ratios were very low, in the tenths of one ppb ppt . These low mixing ratios are expected considering the low sun angles in April over the Arctic and was noted in prior ARCTAS studies (Mao et al., 2010). Unlike ozone, $\sum S_i \approx 0.90$ for most modeled flights meaning first order effects describe the vast majority of the model uncertainty. For all the flights, aerosol particle uptake of HO_2 (gamma HO_2) was the most influential factor having S_i values ranging from 0.37 and 0.58 (mean $S_i = 0.49$). Temperature (0.071), biomass CO (0.058) also routinely had S_i values above 0.05. Among emissions, Asian and biomass NO_x and CO contributed the most to the uncertainty. The influence of Asian emissions during ARCTAS-A has been noted previously (Jacob et al., 2010) and highlights the sensitivity of the Arctic region to the advection of anthropogenic pollution, especially during the winter and spring when the thermal inversion and vertical stratification of the air in the Arctic troposphere is most pronounced (Stohl, 2006).

HO_2 : As with OH, HO_2 mixing ratios were also low, and first order effects dominated in the RS-HDMR metamodel with $\sum S_i$ values ranging from 0.94 to 0.98. Of the first order effects, gamma HO_2 was dominant, with S_i values ranging from 0.60 to 0.76 (mean $S_i = 0.71$). This suggests that around 71 % of the uncertainty associated with modeled HO_2 is due to uncertainties in gamma HO_2 . Temperature was the only other factor regularly having a sensitivity index greater than 0.05 (mean $S_i = 0.10$).

Aerosol particle uptake of HO_2 has been found in previous studies to be of particular importance in the Arctic (Martin et al., 2003; Mao et al., 2010). With low NO_x concentrations and temperatures, the HO_2 lifetime in the Arctic spring is especially long when compared to the midlatitudes or tropics. Without terminating reactions with other NO_x or HO_x radicals, uptake by aerosols becomes a dominant loss of HO_2 .

Providing a broad view of the sensitivity results from ARCTAS-A, Fig. 4 shows the same analysis as Fig. 3 but averaged across all flights and summed by factor category as defined in Table 1. While ozone is most sensitive to emissions, chemical factors from kinetics and photolysis rates also contribute a large portion to the uncertainty. OH and HO₂ are overwhelmingly sensitive to heterogeneous chemistry, particularly gamma HO₂ as seen in Fig. 3.

5 3.2 ARCTAS-B (Summer 2008)

3.2.1 Uncertainty analysis

Compared to ARCTAS-A, ozone in ARCTAS-B (Fig. 5) saw much higher uncertainty across the model ensemble (12 %, 1 σ confidence) compared to the spring (6.8 %). This is reflective of the more photochemically active summertime in contrast to the spring. Like the spring, OH and HO₂ uncertainties were similar to the spring with OH and HO₂ uncertainties being 25 % and 24 % (1 σ confidence) respectively across the model ensemble.

3.2.2 Vertical profiles

Figure 6 shows the vertical profiles observed in ARCTAS-B for ozone, OH, and HO₂. As [found in our ARCTAS-A results \(Fig. 2\) and](#) also reported by Alvarado et al. (2010), we found GEOS-Chem to under-predict ozone for the middle troposphere by 10–20 ppb. [Previously, Alvarado et al. posited mischaracterization of advection from the midlatitudes as a possible source of this error; however, not all chemical transport models run by GEOS-5 meteorology show this bias \(Emmons et al., 2015\). Other possible sources of error may come from mischaracterized chemistry or under-represented stratospheric transport.](#) OH mixing ratios, as in ARCTAS-A, were low. Although well predicted by the model above 3 km, OH was over-predicted below 3 km by around a factor of 2. HO₂ saw the greatest model–measurement disagreement with the model under-predicting HO₂ by over a factor of 2 below 2 km. This modeled underestimation of HO₂ is noteworthy considering HO₂ overestimation is much more common in air chemistry models (e.g., Mao et al., 2013a). Even when excluding measurements taken within smoke plumes as defined by HCN > 1000 pptv, this underestimation decreases only by about 1 pptv for the lower 2 km and remains about a factor of 2. The simultaneous overestimate of OH and underestimate HO₂ suggests the model is partitioning HO_x incorrectly and may be missing or underrepresenting OH reactions that would cycle OH to HO₂. Another possible explanation for a portion of this overestimation of HO₂ could be organic peroxy radical (RO₂) interference artificially elevating HO₂ measurements (Fuchs et al., 2011), but this would likely not account for the factor of 2 underestimation.

3.2.3 Sensitivity analysis

First order RS-HDMM sensitivity indices for tropospheric average ozone, OH, and HO₂ for along the path of flights 17, 19, and 22 (Fig. 5) ~~is~~ [are](#) shown in Figure 7. Figure 8 provides a broad view of the sensitivities calculated across all the ARCTAS-B flights binned by category as shown in Table 1. With a few exceptions, $\sum S_i \approx 0.90$ for all flight averaged ozone, OH, and HO₂ meaning first order effects explain around 90 % of the model uncertainty with higher order input interactions responsible for

the remaining uncertainty. Compared to ARCTAS-A, emissions are more influential across the board, especially from soils, biomass, and isoprene. Like ARCTAS-A, ARCTAS-B sensitivities were largely altitude independent.

Ozone: For modeled ozone, mixing ratios were most sensitive to soil NO_x emissions with average S_i across the flights around 0.181, isoprene emissions (mean $S_i = 0.081$), biomass CO and NO_x emissions (mean $S_i = 0.069, 0.089$ respectively),
5 the $\text{NO}_2 + \text{OH}$ reaction rate (mean $S_i = 0.075$), and NO_2 photolysis (mean $S_i = 0.054$). The greater sensitivity to emissions in the summer compared to spring is almost certainly a result of biomass, soil, and isoprene emissions being much greater in Arctic summer than spring. These higher emissions coupled with higher sun angles allows for ozone production in the Arctic summer, unlike the very slow production in spring. Also, there is relatively low sensitivity to anthropogenic emissions, reflecting the remoteness of this domain and its relative pristine condition.

10 OH: Soil and biomass NO_x emissions (mean S_i across flights is 0.095 and 0.105 respectively), biomass CO emissions (mean $S_i = 0.220$), and gamma HO_2 (mean $S_i = 0.137$) are most influential for OH. As normal OH production requires the photolysis of ozone, OH being sensitive to the same emissions as ozone is expected. OH is sensitive to gamma HO_2 as it represents a net sink of HO_x radicals.

HO_2 : For HO_2 , the modeled mixing ratios were most sensitive to gamma HO_2 and biomass CO and organic carbon emissions
15 with mean S_i across the flights of 0.405, 0.167, and 0.094 respectively. This is qualitatively similar to the results from the spring, only the dominance of gamma HO_2 on the total variance in modeled HO_2 is lessened, but still prominent (mean $S_i = 0.405$ in summer as opposed to 0.712 in spring). It is noteworthy that even with reduced HO_2 lifetimes in the Arctic summer compared to spring, HO_2 still had such high sensitivity to gamma HO_2 .

Fig. 8 shows an overview of the sensitivity results from ARCTAS-B averaged among all flights and summed by factor
20 category as defined in Table 1. As found during ARCTAS-A (Fig. 4), ozone is most sensitive to emissions with chemical factors from kinetics and photolysis rates also contributing a large portion of the uncertainty. In contrast to the spring, OH and HO_2 are most sensitive to emissions factors in the summer; however, heterogeneous chemistry, especially gamma HO_2 , provides a large slice of the uncertainty as also noted in the spring (Fig. 4). In the case of summer HO_2 , gamma HO_2 contributes individually almost as much as the sum of all emissions factors to the model uncertainty.

25 To probe this disagreement between modeled and measured HO_2 at lower altitudes seen in Fig. 6, we examined ensemble members with the best agreement between modeled and measured HO_2 profiles. The ensemble members that matched the measured profile best had especially low gamma HO_2 values. Figure 9 shows a comparison between the entire ensemble and ensemble members with gamma HO_2 values in the lowest 10 percentile of the uncertainty distribution ($\gamma_{\text{HO}_2} < 0.040, 0.055$). This model-measurement disagreement was not observed among all flights in the ARCTAS-B campaign. In fact, areas with lower
30 aerosol abundances such as the northernmost flights, 22 and 23, showed general agreement between modeled and measured HO_2 profiles (Fig. 10). Likewise, above 4 km, the model performs very well in replicating the observed HO_2 profile. Given its overwhelming importance in the RS-HDMR analysis, mischaracterization of gamma HO_2 is a likely cause.

One possible cause of this disagreement is that HO_2 aerosol particle uptake is leading to the formation of H_2O_2 instead of H_2O . Figure 11 shows the modeled and measured H_2O_2 profile for the ARCTAS-A and B flights. When altering the model for
35 gamma HO_2 to produce H_2O_2 instead of H_2O ($\gamma_{\text{HO}_2} \Rightarrow 0.5 \text{H}_2\text{O}_2$) (blue lines in vertical profiles in Figs. 2, 6, and 11, S1, and

S2), modeled HO₂ increased throughout the vertical column by between 0.25 and 0.75 ppt in the summer (Fig. 6) and between 0.5 and 1 ppt in the spring (Fig. 2). In this same model run, H₂O₂ increased upwards of a factor of 3, especially in the lowest 2 km taking modeled values a factor of 2 or greater higher than measurements (Fig. 11). It is noted that there was a large spread in H₂O₂ within the ensemble and a large uncertainty in the measured values (50 % + 150 ppbv). In the same test, we also find CO mixing ratios to decrease around 10 ppb when gamma HO₂ produces H₂O₂ instead of H₂O (Fig. S1 and S2) As Arctic CO tends to be underestimated by chemical transport models (Fisher et al., 2010; Shindell et al., 2006), this decrease widens the model-measurement gap. While the difference in modeled HO₂ between model runs having gamma HO₂'s product being either H₂O or H₂O₂ is important during the spring when HO₂ mixing ratios are lower, as Mao et al. (2010) and Figure 2 show, this difference is less significant during the summer when HO₂ concentrations-mixing ratios are higher (Fig. 6). The difference between these model scenarios cannot be responsible for the difference between the observed and modeled mixing ratios in the lowest 2 km (~7 to 8 ppt). This small effect suggests that, especially in the Arctic summer, concentrating on better characterization of the rate may be more important than the product for improving the agreement between measured and modeled HO_x.

4 Conclusions

We have applied a RS-HDMR sensitivity analysis to a 3D chemical transport model. First order sensitivity indices for the 52 perturbed model inputs have been calculated and shown in Figs. 3, 4, 7, and 8. For OH and HO₂, we find general agreement between modeled and measured values when uncertainties in the measurements and uncertainties in model input factors are taken into account as evidenced by the overlap between the vertical model and measurement profiles (Figs. 2 and 6) with the notable exception of summertime HO₂. In contrast, vertically binned modeled and measured ozone mixing ratios do not show as much overlap, especially in spring. ~~Mischaracterization of advection from the midlatitudes as posited by Alvarado et al. (2010) is a possible source of this error, especially given the importance of isoprene and Asian and North American anthropogenic emissions in the Arctic spring. Other possible sources of error may come from mischaracterized chemistry or under-represented stratospheric transport. for reasons that remain unclear.~~ Modeled ozone was most sensitive to various emissions sources, especially soil NO_x and isoprene, and chemical factors, such as j[NO₂] and k[NO₂]+[OH]. Model sensitivities for OH and HO₂ were dominated by aerosol particle uptake of HO₂, especially in the spring with a combination of biomass and soil emissions being also important, particularly in summer. While the sensitivity of oxidants to emissions is expected considering the high uncertainty in emissions inventories (factors of 2 to 3), it is noteworthy that chemical kinetic and photolysis rates also were responsible for a considerable portion of uncertainty even with their much lower published uncertainties, 20 % and 30 % for j[NO₂] and k[NO₂]+[OH] respectively for example. This highlights the value in not only more certain emissions inventories but also more certain chemical kinetics rates.

HO₂ aerosol particle uptake remains the dominant source of uncertainty in our analysis for HO_x. From our ensemble, the best model-measurement agreement came with lower gamma HO₂ values ($\gamma_{HO_2} < 0.040,055$) than currently implemented in GEOS-Chem regardless of the uptake product. Much attention has been given to determining the product of the aerosol particle

uptake of HO₂, and whether or not or in which instances H₂O₂ or H₂O is produced. We find there is not a large difference in modeled HO₂ between these two possibilities, especially in Arctic summer. In contrast, H₂O₂ is very sensitive to the product of the aerosol particle uptake of HO₂ with H₂O₂ increasing upwards of a factor of 3 when the product is H₂O₂ instead of H₂O (Fig. 11). Recent studies have expanded this question of HO₂ uptake products from aqueous aerosols to smaller cloud droplets (Whalley et al., 2015). In particular, the analysis of Whalley et al. showed the Arctic region being especially sensitive to changes in HO₂ uptake compared to the midlatitudes and tropics due to longer HO₂ lifetimes in the Arctic. As shown in our results, this study also finds HO_x in the Arctic region to be particularly sensitive to gamma HO₂. Because the Arctic is unique in its relatively low HO_x mixing ratios and long HO_x lifetimes compared to the midlatitudes and tropics, future research will be needed to determine whether or not gamma HO₂ is as important globally as it is in the Arctic and whether or not aerosol particle uptake rates need to be reduced in GEOS-Chem.

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Table 1. Factors included in RS-HDMR analysis and their respective uncertainties. OC is organic carbon, ALK₄ is lumped ≥ 4 C alkanes, MP is methylhydroperoxide, and MO₂ is methylperoxy radical. Uncertainties are expressed as multiplicative factors, except as noted in meteorological factors.

| Factor | Uncertainty [#] | Factor | Uncertainty [#] |
|--|--------------------------|-------------------------------------|--------------------------|
| Emissions | | Photolysis | |
| Biomass CO, NH ₃ , NO _x , OC | 3.0 ^a | j [BrNO ₃] | 1.4 ^d |
| Soil NO _x | | j [BrO] | 1.4 ^d |
| CAC (Canada) NO _x | 2.0 | j [H ₂ O ₂] | 1.3 ^d |
| Methyl Bromoform (CHBr ₃) | | j [HNO ₃] | 1.3 ^d |
| EDGAR NO _x | | j [HOBr] | 2.0 ^d |
| EMEP (European) NO _x | | j [MP] | 1.5 ^d |
| EPA (USA) ALK ₄ , CO, NH ₃ , NO _x | | j [NO ₂] | 1.2 ^d |
| Streets (E. Asian) CO, NH ₃ , NO _x , SO ₂ | | j [O ₃] | 1.2 ^d |
| Ship NO _x | | Meteorology | |
| Strat-Trop Exchange O ₃ | | Cloud fraction | 8.5 % ^e |
| Isoprene | 2.0 ^b | Cloud mass flux | 1.5 ^f |
| Lightning NO _x | 1.25 ^c | Relative Humidity | 5 % ^g |
| Kinetics | | Soil Wetness | 8.8 % ^e |
| k [BrO] [HO ₂] | 1.15 / 1.2 ^{*d} | Specific Humidity | 5 % ^g |
| k [BrO] [NO ₂] | 1.2 ^d | Temperature | 1.8K ^e |
| k [HNO ₃] [OH] | 1.2 ^d | Heterogeneous | |
| k [HO ₂] [HO ₂] | 1.15 / 1.2 ^{*d} | Gamma HO ₂ | 3.0 ^d |
| k [HO ₂] [NO] | 1.15 ^d | Gamma HOBr | 3.0 ^d |
| k [MO ₂] [HO ₂] | 1.3 ^d | Gamma N ₂ O ₅ | 1.4 ^d |
| k [MP] [OH] | 1.4 ^d | Gamma NO ₂ | 3.0 ^d |
| k [NO ₂] [OH] | 1.3 ^d | Henry's Law HOBr | 10.0 ^d |
| k [O ₃] [HO ₂] | 1.15 ^d | | |
| k [O ₃] [NO] | 1.1 ^d | | |
| k [O ₃] [NO ₂] | 1.15 ^d | | |
| k [OH] [CH ₄] | 1.1 ^d | | |

at 1 σ uncertainty confidence; * high pressure limit / low pressure limit uncertainties; ^a Jaeglé et al. (2005); ^b Guenther et al. (2012); ^c Miyazaki et al. (2014); ^d Sander et al. (2011); ^e GEOS5-GEOS4; ^f Ott et al. (2009); ^g Heald et al. (2010)

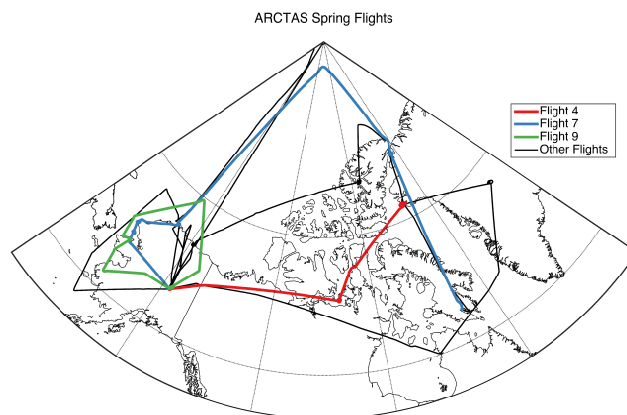


Figure 1. Map of ARCTAS-A flights over the North American Arctic. Highlighted flights correspond to flight data results analyzed in Fig. 3

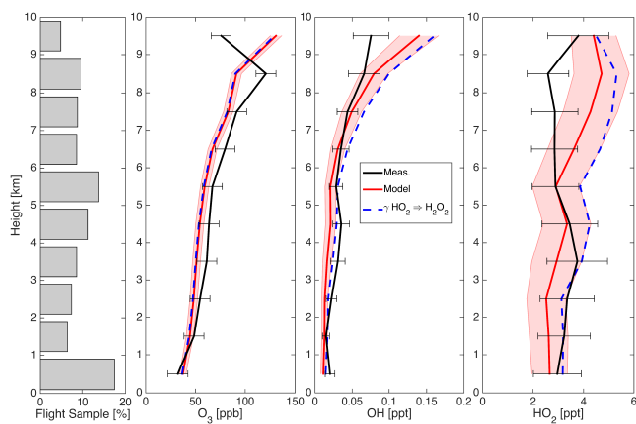


Figure 2. Vertical profiles of mean modeled (red) and measured (black) ozone, OH, and HO₂ for ARCTAS-A flight data binned by kilometer. Gray bar graph shows percent of flight data within each vertical bin. Shaded regions represent 1 σ of model ensemble; error bars on measurements are uncertainty at 1 σ confidence. Blue line represents gamma HO₂ producing H₂O₂ rather than H₂O.

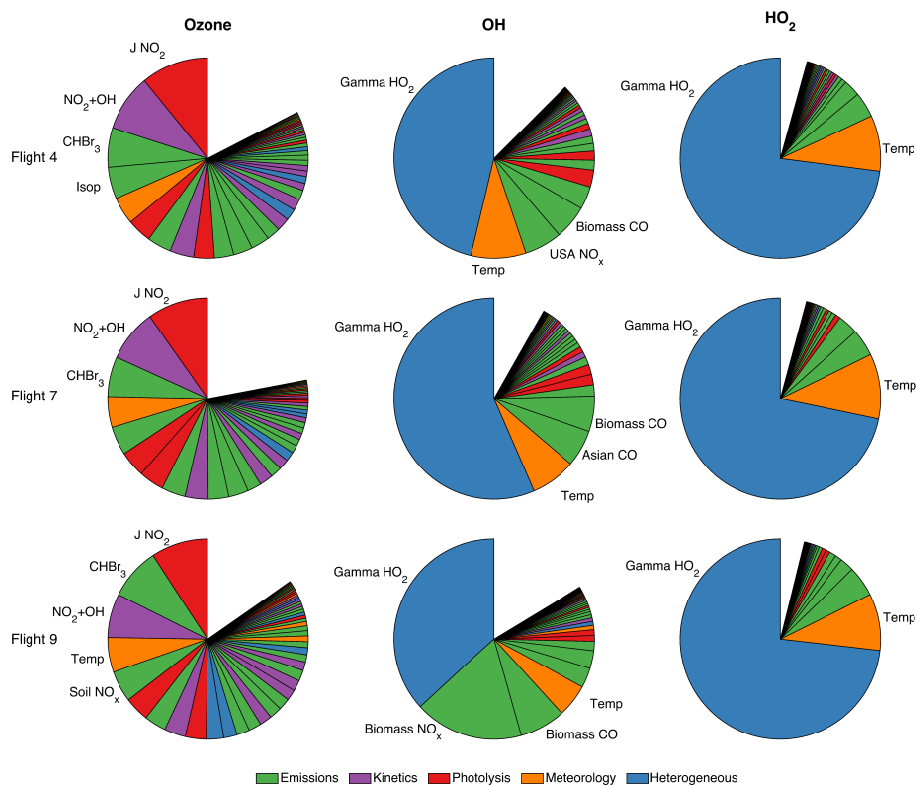


Figure 3. First order sensitivity indices for average flight track O_3 , OH, and HO_2 for ARCTAS-A flights. Legend categories are defined in Table 1.

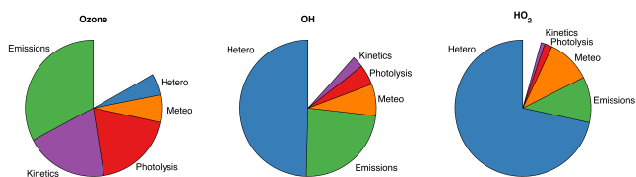


Figure 4. First order sensitivity indices for modeled O_3 , OH, and HO_2 during ARCTAS-A averaged across all flights and binned by categories defined in Table 1.

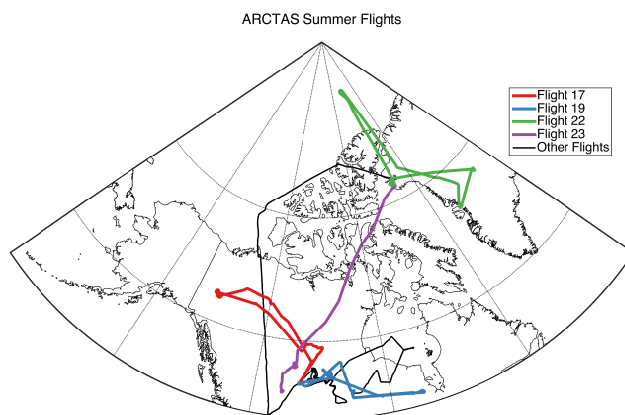


Figure 5. Map of ARCTAS-B deployment over the North American Arctic. Colored flights correspond to flight data results analyzed in Figs. 7 and 10.

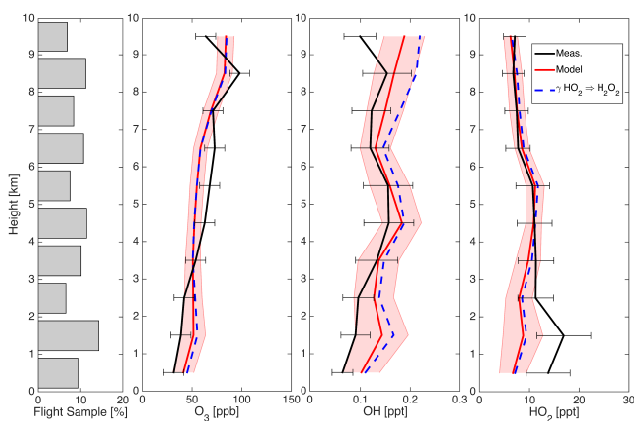


Figure 6. Vertical profiles of mean modeled (red) and measured (black) ozone, OH, and HO₂ for ARCTAS-B flight data binned by kilometer. Gray bar graph shows percent of flight data within each vertical bin. Shaded regions represent 1 σ of model ensemble; error bars on measurements are uncertainty at 1 σ confidence. Blue line represents gamma HO₂ producing H₂O₂ rather than H₂O.

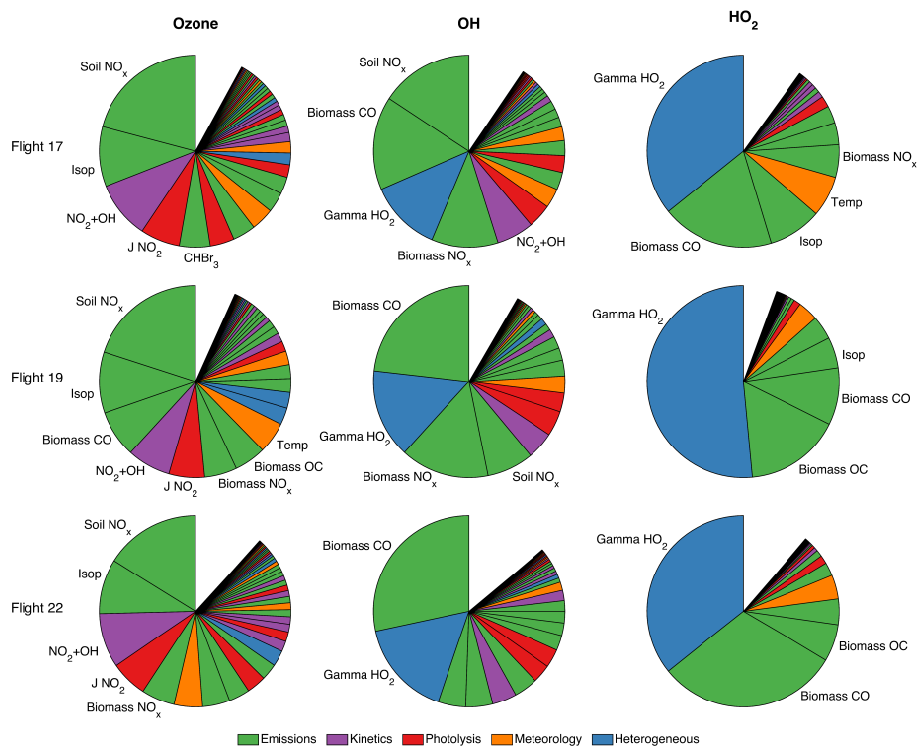


Figure 7. First order sensitivity indices for average modeled O₃, OH, and HO₂ along selected ARCTAS-B flights. Legend categories are defined in Table 1.

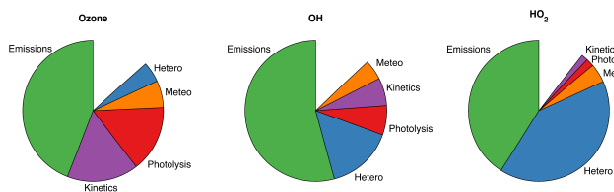


Figure 8. First order sensitivity indices for modeled O₃, OH, and HO₂ during ARCTAS-B averaged across all flights and binned by categories defined in Table 1.

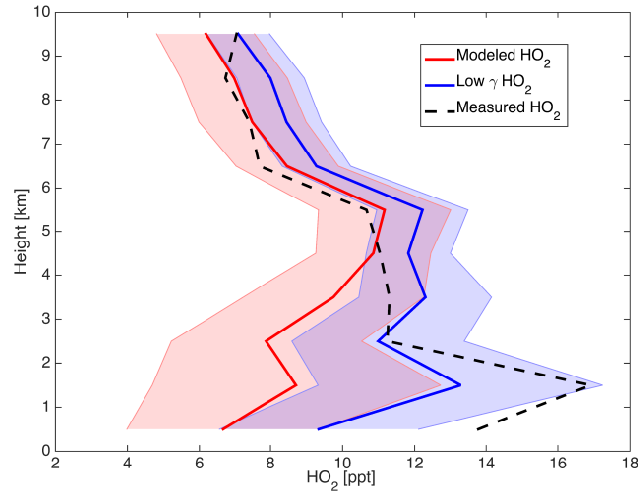


Figure 9. Vertical HO₂ profile for ARCTAS-B flights. Shaded region represents 1 σ of the model ensemble. Blue line and region represents model runs with gamma HO₂ values in the lowest 10 % of the uncertainty distribution.

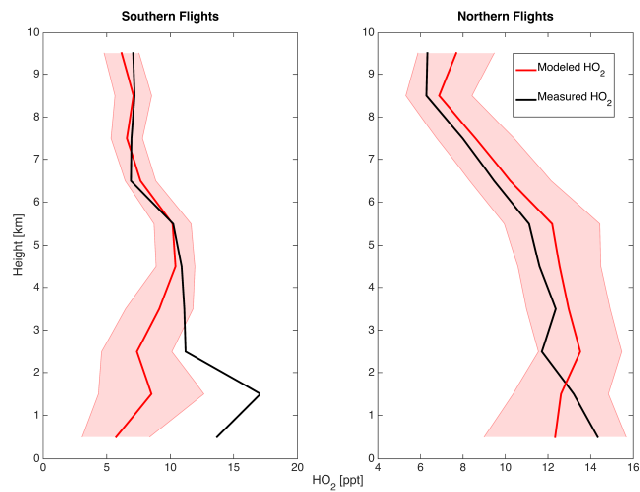


Figure 10. Modeled and measured HO₂ profiles for ARCTAS-B flights. Shaded region represents 1 σ of model ensemble. Left represents flights 17, 18, 19, 20, 21. Right represents flights 22 and 23.

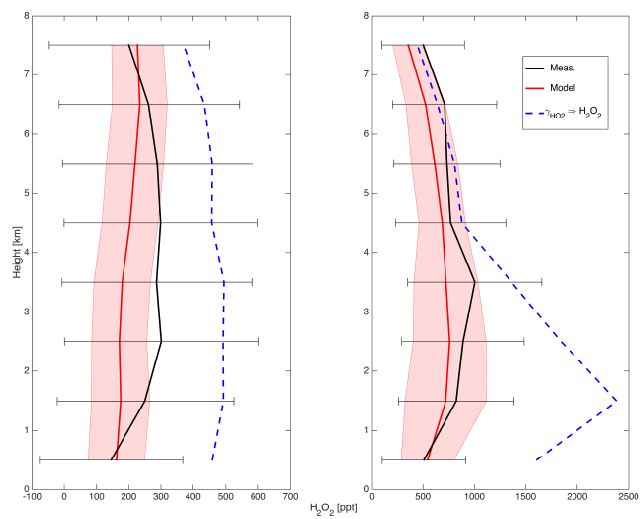


Figure 11. Vertical profile for H_2O_2 for flights during ARCTAS-A (left) and ARCTAS-B (right). Shaded region represents 1σ of model ensemble. Error bars represent measurement uncertainty. Blue lines show gamma HO_2 producing H_2O_2 rather than H_2O in the model.