The distribution of hydrogen, nitrogen, and chlorine radicals in the lower stratosphere: Implications for changes in O₃ due to emission of NOy from supersonic aircraft

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Abstract. In situ measurements of hydrogen, nitrogen, and chlorine radicals obtained in the lower stratosphere during SPADE are compared to results from a photochemical model that assimilates measurements of radical precursors and environmental conditions. Models allowing for heterogeneous hydrolysis of N₂O₅ agree well with measured concentrations of NO and ClO, but concentrations of HNO₃ and OH are underestimated by 10 to 25%, concentrations of NO₂ are overestimated by 10 to 30%, and concentrations of HCl are overestimated by a factor of 2. Discrepancies for [OH] and [HO₂] are reduced if we allow for higher yields of O¹(D) from O₃ photolysis and for heterogeneous production of HNO₂. The data suggest more efficient catalytic removal of O₃ by hydrogen and halogen radicals relative to nitrogen oxide radicals than predicted by models using recommended rates and cross sections. Increases in [O₃] in the lower stratosphere may be larger in response to inputs of NOx from supersonic aircraft than estimated by current assessment models.

Introduction

Data collected during the Stratospheric Photochemistry, Aerosols, and Dynamics Expedition (SPADE) in May 1993 offer a unique opportunity to investigate the chemistry of HO₃, NO₂, and ClO₂ radicals in the lower stratosphere. We assimilate into a photochemical model data for pressure, temperature, aerosol surface area, long-lived precursors of free radicals (O₃, H₂O, CH₄, NOy, and Cl) inferred from CCl₃F and CO₂), total column ozone, and planetary albedo obtained by the ER-2 aircraft on latitude transects from 15 to 58°N. Concentrations of radicals (OH, HO₂, NO, NO₂, ClO) and HCl are computed and compared to observations to test our understanding of key photochemical processes.

Theory and Observation

We focus on segments of two flights, to Moffett Field, CA (37.4°N) from the south on 14 May 1993 (930514) and from the north on 18 May 1993 (930518), that provided the most complete set of measurements during SPADE. Each segment began with a descent from ~50 mb to ~120 mb near noon, followed by a climb and cruise at maximum altitude (~50 mb), and a second descent and ascent near the midpoint. Fig. 1 shows measurements (used as inputs to the photochemical model) of pressure, temperature, aerosol surface area, and long-lived radical precursors.

The aerosol surface area was measured by the Focused Cavity Aerosol Spectrometer (FCAS) and the Forward Scattering Spectrometer Probe (FSSP), optical particle counters that determine the size of ambient particles with diameters between 0.1 and 0.9 μm, and diameters between 0.4 and 20 μm, respectively. The surface area estimated by the FSSP for the overlap region between the two instruments was approximately 50% larger than the area measured by the FCAS. We have adopted an estimate of aerosol surface area for the size range 0.1 to 20 μm using data from the FCAS for the overlap region. Model results are relatively insensitive to this assumption, since total surface area changes by ~20% depending on which measurement is used for the overlap region.

Measurements of [NOy] were not available for the latter portion of 930514 and were estimated from data for [N₂O₅] using the compact correlation observed between these species. Concentrations of inorganic chlorine (Cl) were computed from in situ measurements of halogenated source gases and [CO₂] [Woodbridge et al., 1994]. We adopted the mean of H₂O concentrations reported by two instruments since the ~15% systematic difference between the measurements is not understood. Other inputs to the model include measured [CH₄], [CO] estimated from its correlation with [O₃] [Murphy et al., 1993], and [C₂H₄] and concentrations of inorganic Br estimated from their correlations with [N₂O] [D. Blake, private communication, 1994; Schaufeller et al., 1993].

Concentrations of HO₂ ([OH]+[HO₂]) are sensitive to the column abundance of O₃ due to its role in regulating production of O¹(D); partitioning of NO₂ ([NO]+[NO₂]) is sensitive to planetary albedo due to photolysis of NO₂. Photolysis rates were calculated...
Figure 1. Values of pressure, temperature, aerosol surface area, and mixing ratios of O3, NOx, Clx, and H2O obtained during the return segment of ER-2 flights 930514 and 930518. Dashed lines indicate values inferred from other tracers (see text).

Figure 2. Measurements (points) of [OH], [HO2], [NO], [NO2], [ClO], and [HCl] for 930514 and 930518 compared to model simulations using rates and cross sections from DeMore et al. [1992]: neglecting all heterogeneous processes (JPL-Gas, blue dotted line); including heterogeneous hydrolysis of N2O5 and ClNO3 (JPL-Het, blue solid line); and same as JPL-Het except allowing for updated absorption cross sections for HNO3 and quantum yields of O(1D), and the heterogeneous production of HNO3 (Model B; red line). Measurements of [ClO] and [NO] (obtained every 16 and 1 second, respectively) have been smoothed using a 1 minute median filter.
NO and NO\(_2\) by nearly a factor of 2, significantly larger than the uncertainty of measurement for each gas (2\(\sigma\) measurement uncertainties, including random and systematic effects, are estimated to be 30\% for [OH], 40\% for [HO\(_2\)], 20\% for [NO], 25\% for [NO\(_2\)], 25\% for [CIO], and 20\% for [HCl]).

Calculated concentrations of radicals are within the uncertainty of measurement for OH, HO\(_2\), NO, NO\(_2\), and CIO if we allow for heterogeneous hydrolysis of N\(_2\)O\(_5\) and CINO\(_3\) (JPL-Het in Fig. 2). Hence simultaneous observations of HO\(_2\), NO\(_2\), and CIO radicals demonstrate the importance of heterogeneous reactions on sulfate aerosols (primarily hydrolysis of N\(_2\)O\(_5\)) in regulating the abundance of radicals in the lower stratosphere, consistent with previous studies using in situ measurements of [CIO] [King et al., 1991] and [NO] [Fahey et al., 1993].

Values of [OH] and [HO\(_2\)] observed during early morning and late afternoon at 37\(^\circ\)N are represented poorly by the JPL-Het model (discrepancies exceed a factor of 3 near sunrise) [Wennberg et al., 1994; Salawitch et al., 1994]. Concentrations of HO\(_2\) during mid-day are underestimated by -20\%. Concentrations of NO\(_2\) are overestimated by -25\% and [NO] is slightly underestimated, suggesting possible errors in the partitioning of NO\(_2\) [Jaeglé et al., 1994]. Differences between observed and calculated concentrations of HO\(_2\) and NO\(_2\) during mid-day suggest contributions from HO\(_2\) and halogen cycles to the removal rate of O\(_3\) in the lower stratosphere are larger than predicted by models that use recommended rates and cross sections, although these differences lie within the 2\(\sigma\) uncertainty of the measurements.

Wennberg et al. [1994] proposed heterogeneous decomposition of HNO\(_2\) as a source of HNO\(_3\) to account for the rapid rise in [OH] and [HO\(_2\)] at sunrise. This reaction would increase [HO\(_2\)] at mid-day due to reduction of the OH+HNO\(_3\) sink. Michelsen et al. [1994] suggested that photolysis of vibrationally and rotationally excited states of O\(_3\) result in quantum yields for O('D) approximately 25\% higher than values recommended by DeMore et al. [1992], leading to enhanced production of HO\(_2\) from the reaction of O('D)+H\(_2\)O. Recent measurements of the temperature-dependent absorption cross section for HNO\(_3\) reported by Burkholder et al. [1994] result in a 20\% reduction in the photolysis rate of HNO\(_3\) for a temperature of 220 K compared to models using cross sections from DeMore et al. [1992], lowering calculated [NO\(_2\)] and [HO\(_2\)], and raising [CIO].

Agreement between theory and observation for [OH] and [HO\(_2\)] is improved if we adopt absorption cross sections for HNO\(_3\) from Burkholder et al. [1993] and quantum yields for O('D) from Michelsen et al. [1994], and allow for the heterogeneous decomposition of HNO\(_3\) to form HNO\(_2\) with a reaction probability of 0.2 (Model B, Fig. 2). This model results in an excellent simulation of the diurnal variation of [OH] and [HO\(_2\)] observed at 37\(^\circ\)N [Salawitch et al., 1994].

Comparisons between observed and calculated [NO\(_2\)] and [CIO] are unable to distinguish between various heterogeneous models. Calculated values of [NO] and [NO\(_2\)] are sensitive to uncertainties in the rates of processes that regulate the ratio of NO to NO\(_2\) (including the photolysis rate of NO\(_2\)) and the ratio of NO\(_2\) to NO (including aerosol surface area, the reaction probability of hydrolysis of N\(_2\)O\(_5\), and the influence of variations in latitude of air parcels during the 2 weeks prior to measurement) [Kawa et al., 1994; R. Cohen et al., in preparation, 1994]. Comparisons between observed and calculated CIO are complicated further by uncertainties in estimating [Cl\(_2\)] and processes that regulate production and loss of CINO\(_3\) and HCl. Stimpfle et al. [1994] demonstrate that in situ [CIO] and [NO\(_2\)] are inversely correlated; therefore, errors in the simulation of NO\(_2\) will be reflected directly in the simulation for CIO. Significant refinements in atmospheric and laboratory observations are required to define the significance of the discrepancies for [NO\(_2\)] and [CIO] illustrated in Fig. 2.

Concentrations of HCl computed using all models are higher than measured values by about a factor of 2. Our study demonstrates that this discrepancy does not arise from errors in simulating HCl. The origin of this discrepancy and its implications for understanding the response of O\(_3\) in the lower stratosphere to natural and anthropogenic perturbations remain unclear.

Effects of NO\(_x\) Emitted from Aircraft on O\(_3\)

The contributions of NO\(_x\), NO\(_2\), and halogen catalytic cycles to the loss rate of O\(_3\) is shown in Fig. 3a-c. Models with hetero-
hogeneous chemistry on sulfate aerosols indicate larger contributions from HOX and halogen cycles and larger total loss rates (Fig. 3d) than models based solely on gas phase reactions (Rodriquez et al., 1991; McElroy et al., 1992).

Emission scenarios for the proposed fleet of High Speed Civil Transports (HSCT) indicate possible increases in [NOy] of 20 to 100% at ER-2 flight levels. The gas phase model predicts decreases in [O3] as [NOy] rises due to NOy-related chemistry, in contrast to models with heterogeneous chemistry that predict increases due to deactivation of the more efficient HOX and halogen cycles (Weisenstein et al., 1993). The decrease in the chemical removal rate of O3 for an increase in [NOy], for aerosol loading encountered during SPADE, is ~30% larger for Model B than for JPL-Het (Fig. 3e), reflecting increased rates for HOX and halogen cycles in Model B. Loss rates exhibit a more pronounced difference to a perturbation of [NOy] for background (non-volcanic) aerosol loading due to larger contributions from the NOy cycle in each heterogeneous model (Fig. 3f).

The region of the atmosphere accessible to the ER-2, 16 to 20 km, is characterized by slow rates for chemical removal of O3. Perturbations to [O3] at higher altitudes (20 to 30 km) by HSCT aircraft will be sensitive to chemical partitioning of radicals and to the transport of NOx emitted from aircraft. Simultaneous measurements of HOX, NOx, and ClOx radicals and long-lived precursors at these altitudes are essential for constraining future assessment models.

Conclusions

Models that include heterogeneous hydrolysis of N2O5 on sulfate aerosols provide a good description of observed concentrations of hydrogen, nitrogen, and chlorine radicals in the lower stratosphere. Nevertheless, the relative contribution to chemical removal of O3 from cycles involving HOX and halogens appears to be underestimated by models based on recommended rates and cross sections. Consequently, emission of NOy from supersonic aircraft may result in larger increases in concentrations of O3 in the lower stratosphere than predicted by current assessment models [e.g., Weisenstein et al., 1993].

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References

