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## Coupled evolution of BrO<sub>x</sub>-ClO<sub>x</sub>-HO<sub>x</sub>-NO<sub>x</sub> chemistry during bromine-catalyzed ozone depletion events in the arctic boundary layer

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[1] Extensive chemical characterization of ozone (O<sub>3</sub>) depletion events in the Arctic boundary layer during the TOPSE aircraft mission in March–May 2000 enables analysis of the coupled chemical evolution of bromine (BrO<sub>x</sub>), chlorine (ClO<sub>x</sub>), hydrogen oxide (HO<sub>x</sub>) and nitrogen oxide (NO<sub>x</sub>) radicals during these events. We project the TOPSE observations onto an O<sub>3</sub> chemical coordinate to construct a chronology of radical chemistry during O<sub>3</sub> depletion events, and we compare this chronology to results from a photochemical model simulation. Comparison of observed trends in ethyne (oxidized by Br) and ethane (oxidized by Cl) indicates that ClO<sub>x</sub> chemistry is only active during the early stage of O<sub>3</sub> depletion (O<sub>3</sub> > 10 ppbv). We attribute this result to the suppression of BrCl regeneration as O<sub>3</sub> decreases. Formaldehyde and peroxy radical concentrations decline by factors of 4 and 2 respectively during O<sub>3</sub> depletion and we explain both trends on the basis of the reaction of CH<sub>2</sub>O with Br. Observed NO<sub>x</sub> concentrations decline abruptly in the early stages of O<sub>3</sub> depletion and recover as O<sub>3</sub> drops below 10 ppbv. We attribute the initial decline to BrNO<sub>3</sub> hydrolysis in aerosol, and the subsequent recovery to suppression of BrNO<sub>3</sub> formation as O<sub>3</sub> drops. Under halogen-free conditions we find that HNO<sub>4</sub> heterogeneous chemistry could provide a major NO<sub>x</sub> sink not included in standard models. Halogen radical chemistry in the model can produce under realistic conditions an oscillatory system with a period of 3 days, which we believe is the fastest oscillation ever reported for a chemical system in the atmosphere.

*INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0317 Atmospheric Composition and Structure: Chemical kinetic and photochemical properties; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; *KEYWORDS:* Polar, ozone, boundary layer, bromine, NO<sub>x</sub>, HO<sub>x</sub>

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### 1. Introduction

[2] Events of near-total ozone (O<sub>3</sub>) depletion in Arctic spring surface air have been observed since the 1980s [Oltmans, 1981; Oltmans and Komhyr, 1986] and are known to be due to fast catalytic loss driven by unusually

high concentrations of bromine oxide radicals (BrO<sub>x</sub> ≡ Br + BrO) [Barrie et al., 1988; Hausmann and Platt, 1994]. These events are also associated with high concentrations of chlorine oxide radicals (ClO<sub>x</sub> ≡ Cl + ClO) as demonstrated by observations of differential hydrocarbon depletion [Yokouchi et al., 1994; Jobson et al., 1994]. More recently, several studies have pointed out the importance of polar snow as a source of nitrogen oxide radicals (NO<sub>x</sub> ≡ NO + NO<sub>2</sub>) and of precursors of hydrogen oxide radicals (HO<sub>x</sub> ≡ OH + peroxy radicals) during spring [Sumner and Shepson, 1999; Honrath et al., 2000; Jones et al., 2001]. Extensive chemical observations during the Tropospheric Ozone Production around the Spring Equinox (TOPSE) aircraft campaign [Atlas et al., 2003] offer the first opportunity to analyze the coupled evolution of BrO<sub>x</sub>-ClO<sub>x</sub>-NO<sub>x</sub>-HO<sub>x</sub> radical chemistry during O<sub>3</sub> depletion events in the Arctic spring. We present such an analysis here and use photochemical model calculations to place the TOPSE observations in the context of current understanding.

[3] The bromine chemistry leading to O<sub>3</sub> depletion is relatively well understood [Barrie et al., 1988; Fan and

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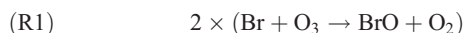
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Jacob, 1992; Hausmann and Platt, 1994; Michalowski *et al.*, 2000]. It involves the catalytic O<sub>3</sub> destruction by BrO<sub>x</sub> radicals and it requires the recycling of BrO<sub>x</sub> from its non-radical reservoirs. The main catalytic mechanism for O<sub>3</sub> depletion is



[4] The efficiency of this cycle is limited by conversion of BrO<sub>x</sub> to the non-radical reservoir HBr, which is long-lived with respect to both photolysis and reaction with OH. Production of HBr is mostly by the reaction between Br and CH<sub>2</sub>O, although reactions with other carbonyls can also be significant [Shepson *et al.*, 1996].



[5] The HBr is readily soluble and dissolves in aerosols to release bromide (Br<sup>-</sup>) in solution. Similarly, the other non-radical bromine reservoirs BrNO<sub>3</sub> (produced from NO<sub>2</sub> + BrO) and HOBr (produced from HO<sub>2</sub> + BrO) are taken up by aerosol, where BrNO<sub>3</sub> hydrolyzes to HOBr [Hanson *et al.*, 1996]. In acidic aerosols, as are observed in the Arctic spring [Sirois and Barrie, 1999], HOBr reacts with Br<sup>-</sup> to produce Br<sub>2</sub>, which escapes into the gas phase and is photolyzed:



[6] In this manner the radical bromine is regenerated, sustaining the O<sub>3</sub> loss cycle (R1–R3). Although there is now substantial evidence from field and laboratory studies to support the above mechanism, model calculations of the O<sub>3</sub> loss rate in relation to the BrO<sub>x</sub> radical supply have never been evaluated with observations. We will present such an evaluation here and examine the chemical coupling of BrO<sub>x</sub> with other radical families.

[7] A complicating factor for the NO<sub>x</sub> and HO<sub>x</sub> radical budgets in the Arctic boundary layer is the emission of NO<sub>x</sub> and CH<sub>2</sub>O from the snow surface. These emissions appear to be driven by sunlight [Sumner and Shepson, 1999; Ridley *et al.*, 2000; Honrath *et al.*, 2000; Jones *et al.*, 2001] although physical adsorption and desorption may also take place [Hutterli *et al.*, 1999, 2001]. Surface measurements at Alert in the Canadian Arctic show a pronounced diurnal cycle of NO<sub>x</sub> concentrations [Ridley *et al.*, 2000] with a noon maximum, suggesting a shorter lifetime for NO<sub>x</sub> (less than 4 hours) than would be expected from atmospheric loss by oxidation in standard models. We include the snow emissions of NO<sub>x</sub> and CH<sub>2</sub>O in our analysis and propose that heterogeneous oxidation of HNO<sub>4</sub> in aerosols provides a major sink of NO<sub>x</sub> in the Arctic boundary layer.

[8] Section 2 describes the O<sub>3</sub> depletion events observed during TOPSE with focus on the evolution of radical chemistry. We apply a photochemical model (section 3) to

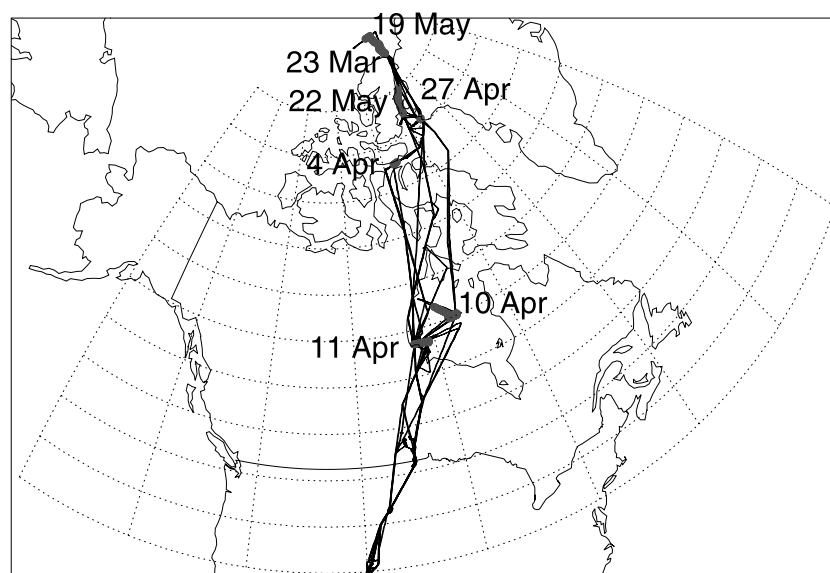
simulate the chemical development of these events and interpret the TOPSE observations (section 4). An intriguing chemical oscillation taking place in the model under certain conditions is presented in section 5. Conclusions are in section 6.

## 2. Ozone Depletion Events Observed During TOPSE

[9] The TOPSE aircraft program took place between February and May 2000 [Atlas *et al.*, 2003]. Its goal was to investigate the origin of the springtime O<sub>3</sub> maximum observed at northern extra-tropical latitudes [Monks, 2000]. The NSF C-130 aircraft flew between Boulder (Colorado), Churchill (Manitoba), and Thule (Greenland), with some flights north to 85°N over the Arctic Ocean. A total of 37 flights were carried out (see Figure 1). The aircraft carried a wide range of chemical instrumentation including measurements of O<sub>3</sub>, NO<sub>x</sub> and total reactive nitrogen oxides (NO<sub>y</sub>) [Ridley *et al.*, 2003], speciated hydrocarbons [Blake *et al.*, 2003], OH [Mauldin *et al.*, 2003], total peroxy radicals (RO<sub>2</sub>) (C. A. Cantrell *et al.*, Peroxy radical observations using CIMS during TOPSE, manuscript submitted to J. Geophys. Res., 2002), H<sub>2</sub>O<sub>2</sub> and CH<sub>3</sub>OOH [Snow *et al.*, 2003], CH<sub>2</sub>O [Fried *et al.*, 2003], peroxyacetyl nitrate (PAN) and soluble bromide [Scheuer *et al.*, 2003]. Photolysis frequencies [Shetter and Mueller, 1999] and aerosol size distributions were also measured. Individual cases of O<sub>3</sub> depletion events observed during TOPSE are discussed by Ridley *et al.* [2003].

[10] Figure 2 shows the cumulative probability distribution of O<sub>3</sub> concentrations observed in the Arctic boundary layer (below 500 m altitude and north of 50°N) during spring (March 23 to May 22) and around local noon (1100 to 1300). Most TOPSE data were collected around midday; introducing the 1100 to 1300 restriction filters out 50% of the data and makes little change to the distribution. The O<sub>3</sub> concentrations range from 0.2 to 50 ppbv; 50% of the measurements are below 23 ppbv. The accuracy of the O<sub>3</sub> measurements was 0.06 ppbv at 1 ppbv of O<sub>3</sub> [Ridley *et al.*, 2003]. For further analysis we partitioned the data into four O<sub>3</sub> bins (0 to 1 ppbv, 1 to 10 ppbv, 10 to 30 ppbv and above 30 ppbv). Table 1 gives the means and standard deviations of the ensemble of TOPSE observations in these four bins. Selection of data below 100 m rather than 500 m leads to an increased probability of low O<sub>3</sub> concentrations but little change to the concentration of species within each O<sub>3</sub> bin. We will assume in what follows that differences in composition between the four categories of air masses in Table 1 reflect different degrees of processing by halogen radical chemistry. In support of this assumption, we see in Table 1 that CO (unaffected by halogen chemistry) is uniform across all four categories.

[11] Soluble bromide concentrations observed during TOPSE are highest in the O<sub>3</sub> depleted air masses. Ethyne and ethane show differing trends as O<sub>3</sub> decreases. Whereas the ethyne concentration drops continuously with O<sub>3</sub>, the ethane concentration changes little below 10 ppbv of O<sub>3</sub>. We propose in section 4.2 that this reflects different temporal evolutions of bromine and chlorine radicals during O<sub>3</sub> depletion events. Concentrations of HO<sub>x</sub> radicals and reservoir species (OH, RO<sub>2</sub>, CH<sub>2</sub>O, H<sub>2</sub>O<sub>2</sub> and CH<sub>3</sub>OOH) all



**Figure 1.** Flight tracks during TOPSE (February–May 2000). Symbols show location of boundary layer tracks (below 500 m altitude) with  $O_3$  concentrations less than 15 ppbv. The dates during which these air masses were encountered are given.

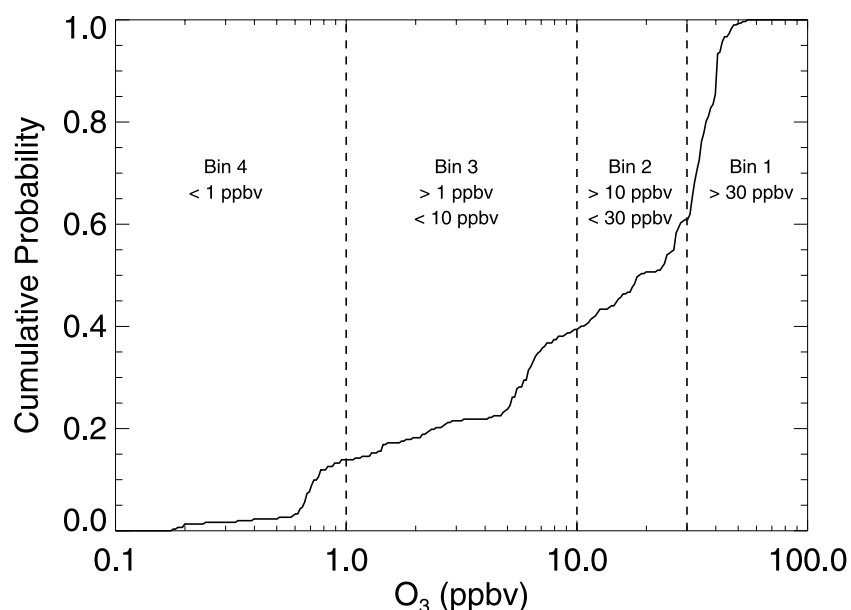
decrease with decreasing  $O_3$  concentration. A previous study of  $CH_2O$  evolution during  $O_3$  depletion events observed at Alert [Rudolph *et al.*, 1999] showed a gradual increase in  $CH_2O$  concentrations from 40 to 15 ppbv of  $O_3$  followed by a decline similar to that observed during TOPSE. The budgets of these species are discussed in section 4.3

[12] Concentrations of  $NO_x$  observed in TOPSE decrease as  $O_3$  drops below 30 ppbv but then recover as  $O_3$  drops below 10 ppbv, so that concentration under conditions of strong  $O_3$  depletion ( $O_3 < 1$  ppbv) are similar to those with little or no depletion ( $O_3 > 30$  ppbv). The initial reduction in  $NO_x$  at the onset of  $O_3$  depletion events has been seen before

[Beine *et al.*, 1997]. Concentrations of  $NO_y$  appear to increase slightly as the  $O_3$  concentration decreases and PAN concentrations shows a more substantial increase. These intriguing trends in the  $NO_y$  species are examined further in section 4.4.

### 3. Photochemical Model

[13] We apply a 0-D (box) photochemical model of the Arctic boundary layer to interpret the relationships described above and examine the coupled evolution of  $BrO_x$ - $ClO_x$ - $HO_x$ - $NO_x$  radical chemistry during  $O_3$  deple-



**Figure 2.** Cumulative probability distribution of midday (1100 to 1300 local time)  $O_3$  concentrations measured north of  $50^\circ N$  and below 500 m altitude between March 23 and May 22 during TOPSE. 252 1-minute measurements are included in the distribution. The dashed lines define the  $O_3$  bins used for analysis.

**Table 1.** Arctic Boundary Layer Observations During TOPSE<sup>a</sup>

	Bin 1	Bin 2	Bin 3	Bin 4	Background
Ozone Range (ppbv)	>30	10 – 30	1 – 10	<1	Note b
Day of year	107 ± 26	108 ± 23	107 ± 13	105 ± 9	106.7
Latitude (°N)	72 ± 9	77 ± 8	74 ± 10	67 ± 11	73
Longitude (°E)	–77 ± 12	–70 ± 11	–75 ± 10	–78 ± 12	–75
Altitude (m)	144 ± 140	96 ± 107	97 ± 104	52 ± 57	100
O <sub>3</sub> column (DU)	370 ± 42	371 ± 55	428 ± 67	470 ± 59	398
Aerosol area (10 <sup>–7</sup> cm <sup>2</sup> /cm <sup>3</sup> ) <sup>c</sup>	4.7 ± 2.5	3.8 ± 2.0	5.3 ± 1.0	4.7 ± 1.2	4.9
Aerosol volume (10 <sup>–12</sup> cm <sup>3</sup> /cm <sup>3</sup> ) <sup>c</sup>	4.2 ± 3.0	3.7 ± 3.4	4.5 ± 0.95	4.1 ± 1.3	4.4
H <sub>2</sub> O (g/kg)	1.4 ± 0.8	0.88 ± 0.54	0.76 ± 0.35	0.71 ± 0.35	1.06
O <sub>3</sub> (ppbv)	38 ± 5	22 ± 6.1	5.0 ± 2.3	0.65 ± 0.21	48
CO (ppbv)	153 ± 10	151 ± 10	156 ± 4	157 ± 3	153
CH <sub>4</sub> (ppmv)	1.84 ± 0.01	1.85 ± 0.01	1.85 ± 0.01	1.85 ± 0.01	1.84
Soluble Bromide (pptv) <sup>d</sup>	7.8 ± 5	12.9 ± 9.4	23.0 ± 8.5	23.6 ± 2.8	Note e
Ethane (pptv)	1578. ± 302	1401 ± 341	1256 ± 162	1134 ± 152	1660
Ethyne (pptv)	347 ± 143	284 ± 125	119 ± 60	42 ± 28	389
Propane (pptv)	423 ± 250	352 ± 198	234 ± 85	179 ± 62	484
n-Butane (pptv)	109 ± 90	87 ± 61	40 ± 23	26 ± 13	136
i-Butane (pptv)	64 ± 52	63 ± 36	34 ± 18	25 ± 12	73
n-Pentane (pptv)	32 ± 15	19 ± 9.3	7.2 ± 3.6	4.3 ± 1.3	48
i-Pentane (pptv)	41 ± 20	31 ± 12	11 ± 6.3	6.5 ± 2.7	62
Hexane (pptv)	10 ± 4	6.8 ± 1.6	3.8 ± 0.5	<3 <sup>f</sup>	15
OH (× 10 <sup>5</sup> cm <sup>–3</sup> )	11. ± 9	5.0 ± 3.6	2.7 ± 2.1	1.7 ± 1.4	N/A
RO <sub>2</sub> (× 10 <sup>8</sup> cm <sup>–3</sup> ) <sup>g</sup>	2.2 ± 1.2	1.9 ± 1.2	1.3 ± 0.6	1.6 ± 0.4	N/A
CH <sub>2</sub> O (pptv)	143 ± 104	137 ± 93	94 ± 89	35 ± 110	143
H <sub>2</sub> O <sub>2</sub> (pptv)	264 ± 128	183 ± 113	92 ± 41	92 ± 74	254
CH <sub>3</sub> OOH (pptv)	240 ± 123	230 ± 99	151 ± 43	131 ± 40	206
NO <sub>x</sub> (pptv)	13 ± 8	4.6 ± 7.3	5.2 ± 4.7	15.0 ± 4.8	16
NO (pptv)	5.0 ± 5.0	1.1 ± 4.6	2.9 ± 3.2	11.7 ± 4.2	7.0
NO <sub>2</sub> (pptv)	7.5 ± 4	3.4 ± 3.7	2.4 ± 2.4	3.2 ± 2.1	9.9
NO <sub>y</sub> (pptv) <sup>h</sup>	225 ± 39	200 ± 38	258 ± 16	253 ± 13	N/A
PAN (pptv)	152 ± 16	163 ± 39	212 ± 25	207 ± 10	161

<sup>a</sup>Means and standard deviations of aircraft observations made north of 50°N below 500 m altitude, from March 23 to May 22, 2000 and around local noon (1100–1300). The data are partitioned by O<sub>3</sub> concentration range (see text) to determine the chemical characteristics of O<sub>3</sub> depletion events.

<sup>b</sup>Mean concentrations of species in air masses with O<sub>3</sub> > 45 ppbv and no detected soluble bromide. These concentrations are used as initial condition for the model simulation (Section 3). Initial condition for species not measured during TOPSE are given in section 3.

<sup>c</sup>Integrated over the 0.1–3 μm aerosol size distribution.

<sup>d</sup>Soluble bromide in gas (HBr) and aerosol phase (Br<sup>–</sup>).

<sup>e</sup>Model simulations are conducted with initial bromide concentrations in the range 0–43 pptv [Sirois and Barrie, 1999].

<sup>f</sup>Below level of detection (~3 pptv).

<sup>g</sup>RO<sub>2</sub> is the sum of all peroxy radicals (HO<sub>2</sub> + organic peroxy radicals).

<sup>h</sup>NO<sub>y</sub> is the sum of all gas phase nitrogen oxide species (NO, NO<sub>2</sub>, NO<sub>3</sub>, 2 × N<sub>2</sub>O<sub>5</sub>, HNO<sub>2</sub>, HNO<sub>3</sub>, HNO<sub>4</sub>, organic nitrates).

tion events. We do not consider IO<sub>x</sub> chemistry as there is little evidence to suggest that it plays an important role in the evolution of these O<sub>3</sub> depletion events [Sander *et al.*, 1997; Martinez *et al.*, 1999]. The model does not consider the deposition or emission of halogens to or from the snow surface and thus assumes that the bromine cycling within the aerosol is the dominant bromine activation mechanism (in general agreement with Michalowski *et al.* [2000]), and that the sole source and reservoir of bromine is the aerosol.

[14] The chemistry scheme used in the model has been described before [e.g., Jaeglé *et al.*, 2000] and has been extended here to include halogen and aerosol chemistry following Michalowski *et al.* [2000]. It includes a detailed description of the oxidation of C<sub>1</sub>–C<sub>6</sub> hydrocarbons updated with recent developments [Sander *et al.*, 2000]. The rate constants for the reactions of Br with aldehydes [Ramacher *et al.*, 2000] and ethyne [Ramacher *et al.*, 2001] have been updated. Reactions of BrO with CH<sub>2</sub>O and HBr are not included, based on evidence that they are negligibly slow; even at the upper limits reported by Orlando *et al.* [2000] we find that they have little effect on the evolution of O<sub>3</sub> depletion. Photolysis frequencies

are calculated with a clear-sky radiative transfer model and are scaled to the mean midday photolysis frequencies of NO<sub>2</sub> (J(NO<sub>2</sub>)) and O<sub>3</sub> → O(<sup>1</sup>D) (J(O<sup>1</sup>D)). The J(O<sup>1</sup>D) scaling factor is applied to wavelengths less than 330 nm and the J(NO<sub>2</sub>) scaling factor to higher wavelengths. Aerosol processes in the chemical mechanism are listed in Tables 2a and 2b and include halogen radical as well as HNO<sub>4</sub> chemistry.

[15] The model is initialized on April 15 at 73°N, at local noon at 100 m altitude, with TOPSE measurements representative of background Arctic conditions unaffected by halogen chemistry (Table 1: Background). The composition of the boundary layer aerosol is derived from previous studies. We assume that the bulk of the aerosol is sulfuric acid [Barrie and Hoff, 1984]. Aerosol concentrations per volume of air of Cl<sup>–</sup> (100 ng m<sup>–3</sup>, equivalent to 1.7 × 10<sup>9</sup> cm<sup>–3</sup>) and I<sup>–</sup> (0.3 ng m<sup>–3</sup>, equivalent to 1.4 × 10<sup>6</sup> cm<sup>–3</sup>) are taken from Sirois and Barrie [1999]; we assume that 50% of total iodine reported in Sirois and Barrie [1999] is iodide [Baker *et al.*, 2001]. An aerosol pH of 0.5 is assumed from Li [1994]. An initial aerosol HNO<sub>2</sub> concentration of 8 × 10<sup>7</sup> cm<sup>–3</sup> (again referenced to volume of air) is also taken from Li [1994]. Aerosol concentrations of H<sup>+</sup>, I<sup>–</sup>, and

**Table 2a.** Aerosol Chemistry: Aqueous-Phase Reactions

Reaction	Rate Constant ((M <sup>-1</sup> ) <sup>n</sup> s <sup>-1</sup> )	Reference
HNO <sub>4</sub> + HSO <sub>3</sub> <sup>-</sup> → SO <sub>4</sub> <sup>2-</sup> + NO <sub>3</sub> <sup>-</sup> + 2 H <sup>+</sup>	1.1 × 10 <sup>7</sup> [H <sup>+</sup> ] + 3.3 × 10 <sup>5</sup>	<i>Amel et al.</i> [1996]
HNO <sub>4</sub> + HNO <sub>2</sub> → 2 NO <sub>3</sub> <sup>-</sup> + 2 H <sup>+</sup>	12	<i>Lögager and Sehested</i> [1993]
HNO <sub>4</sub> + Cl <sup>-</sup> → HOCl + NO <sub>3</sub> <sup>-</sup>	0.014	<i>Régimbal and Mozurkewich</i> [1997]
HNO <sub>4</sub> + Br <sup>-</sup> → HOBr + NO <sub>3</sub> <sup>-</sup>	0.54	<i>Régimbal and Mozurkewich</i> [1997]
HNO <sub>4</sub> + I <sup>-</sup> → HOI + NO <sub>3</sub> <sup>-</sup>	890	<i>Régimbal and Mozurkewich</i> [1997]
Br <sup>-</sup> + O <sub>3</sub> + H <sup>+</sup> → HOBr + O <sub>2</sub>	11.7	<i>Haag and Hoigné</i> [1983]
HOBr + Cl <sup>-</sup> + H <sup>+</sup> → BrCl + H <sub>2</sub> O	5.6 × 10 <sup>9</sup>	<i>Wang et al.</i> [1994]
HOBr + Br <sup>-</sup> + H <sup>+</sup> → Br <sub>2</sub> + H <sub>2</sub> O	1.6 × 10 <sup>10</sup>	<i>Beckwith et al.</i> [1996]
HOCl + Cl <sup>-</sup> + H <sup>+</sup> → Cl <sub>2</sub> + H <sub>2</sub> O	2.2 × 10 <sup>4</sup>	<i>Wang and Margerum</i> [1994]
HOCl + Br <sup>-</sup> + H <sup>+</sup> → BrCl + H <sub>2</sub> O	1.3 × 10 <sup>6</sup>	<i>Kumar and Margerum</i> [1987]
BrCl + H <sub>2</sub> O → HOBr + Cl <sup>-</sup> + H <sup>+</sup>	1.0 × 10 <sup>5</sup>	<i>Wang et al.</i> [1994]
Br <sub>2</sub> + H <sub>2</sub> O → HOBr + Br <sup>-</sup> + H <sup>+</sup>	9.7 × 10 <sup>1</sup>	<i>Beckwith et al.</i> [1996]
Cl <sub>2</sub> + H <sub>2</sub> O → HOCl + Br <sup>-</sup> + H <sup>+</sup>	2.2 × 10 <sup>1</sup>	<i>Wang and Margerum</i> [1994]
BrCl + Br <sup>-</sup> → Br <sub>2</sub> Cl <sup>-</sup>	5 × 10 <sup>9</sup>	Note a
Br <sub>2</sub> + Cl <sup>-</sup> → Br <sub>2</sub> Cl <sup>-</sup>	5 × 10 <sup>9</sup>	Note a
BrCl + Cl <sup>-</sup> → BrCl <sub>2</sub> <sup>-</sup>	5 × 10 <sup>9</sup>	Note a
Br <sub>2</sub> Cl <sup>-</sup> → Br <sub>2</sub> + Cl <sup>-</sup>	3.9 × 10 <sup>9</sup>	Note b
Br <sub>2</sub> Cl <sup>-</sup> → BrCl + Br <sup>-</sup>	2.8 × 10 <sup>8</sup>	Note b
BrCl <sub>2</sub> <sup>-</sup> → Cl <sub>2</sub> + Cl <sup>-</sup>	6.9 × 10 <sup>2</sup>	Note b
HBr → Br <sup>-</sup> + H <sup>+</sup>	0.3 <sup>c</sup>	<i>Schweitzer et al.</i> [2000]
HCl → Cl <sup>-</sup> + H <sup>+</sup>	0.3 <sup>c</sup>	<i>Schweitzer et al.</i> [2000]
BrNO <sub>3</sub> + H <sub>2</sub> O → HOBr + NO <sub>3</sub> <sup>-</sup> + H <sup>+</sup>	0.3 <sup>c</sup>	<i>Hanson et al.</i> [1996]
ClNO <sub>3</sub> + H <sub>2</sub> O → HOCl + NO <sub>3</sub> <sup>-</sup> + H <sup>+</sup>	0.002 <sup>c</sup>	<i>Robinson et al.</i> [1997]
N <sub>2</sub> O <sub>5</sub> + H <sub>2</sub> O → 2 NO <sub>3</sub> <sup>-</sup> + 2 H <sup>+</sup>	0.1 <sup>c</sup>	<i>Jacob</i> [2000]

<sup>a</sup>Assumed [*Michalowski et al.*, 2000].

<sup>b</sup>Derived from the equilibrium constant [*Wang et al.*, 1994] and the assumed forward rate constant (see footnote a).

<sup>c</sup>Reaction probabilities ( $\gamma$ ), dimensionless.

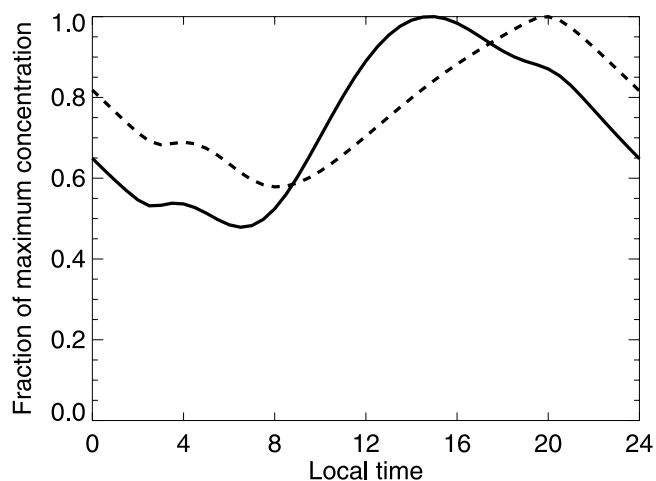
HNO<sub>2</sub> are kept constant in the simulation but the Cl<sup>-</sup> concentration is allowed to evolve. I<sup>-</sup> and HNO<sub>2</sub> are included in the model as aerosol-phase sinks of HNO<sub>4</sub> (see later) and play no further chemical role. Concentrations of CH<sub>3</sub>CHO (18 pptv) and (CH<sub>3</sub>)<sub>2</sub>CO (300 pptv) are assumed from chemical steady state with the background hydrocarbon concentrations given in Table 1.

[16] The boundary layer in our model is taken to be dynamically isolated from the free troposphere (zero flux boundary conditions at boundary layer top). This is a reasonable assumption for O<sub>3</sub> depletion events in general [*Wessel et al.*, 1998] and TOPSE in particular [*Ridley et al.*, 2003]. The surface is assumed to be snow and to provide a source or sink of nitrogen oxides, H<sub>2</sub>O<sub>2</sub>, and CH<sub>2</sub>O. The surface flux boundary conditions for these and other non-radical secondary species are chosen to reproduce observed concentrations in background air (Background: Table 1) in a steady state calculation; for that purpose the boundary layer represented by the model is assumed to be 200m deep. We

thus specify small deposition velocities for PAN, PPN and H<sub>2</sub>O<sub>2</sub> (0.004 cm s<sup>-1</sup>, 0.008 cm s<sup>-1</sup>, and 0.09 cm s<sup>-1</sup> respectively). Emission of NO<sub>x</sub> and CH<sub>2</sub>O from the snow surface is necessary to reproduce the observed concentrations with the model. We assume that these emissions vary diurnally following the photolysis of NO<sub>2</sub>. The resulting 24-hour average emissions of CH<sub>2</sub>O and NO<sub>x</sub> are 1.2 × 10<sup>9</sup> cm<sup>-2</sup> s<sup>-1</sup> and 3.6 × 10<sup>8</sup> cm<sup>2</sup> s<sup>-1</sup> respectively. Our implied CH<sub>2</sub>O emission is a factor of 4 less than that found by *Sumner and Shepson* [1999]. This is mainly due to differing assumptions for the boundary layer height in the calculation (600m in *Sumner and Shepson* [1999] and 200 m in this work). Our implied NO<sub>x</sub> emission is roughly 4 times higher than that observed by *Jones et al.* [2001] in Antarctica; such a difference could be rationalized as reflecting higher nitrate concentrations in the Arctic snow compared to the Antarctic [*Wolff et al.*, 1995]. It is in reasonable agreement (40% higher) with measurements made at Summit, Greenland during the summer of 2000 [*Honrath et al.*, 2002].

**Table 2b.** Aerosol Chemistry: Henry's Law Equilibria (H) and Mass Accommodation Coefficients ( $\alpha$ )

Species	H (M/atm) 250K	$\alpha$	References
HOBr(g) ↔ HOBr (aer)	3.0 × 10 <sup>4</sup>	0.3	H: <i>Waschewsky and Abbatt</i> [1999] $\alpha$ : <i>Allanic et al.</i> [1997]
HOCl(g) ↔ HOCl(aer)	1.8 × 10 <sup>4</sup>	0.3	H: <i>Huthwelker et al.</i> [1995] $\alpha$ : <i>Abbat and Molina</i> [1992]
Br <sub>2</sub> (g) ↔ Br <sub>2</sub> (aer)	1.0 × 10 <sup>1</sup>	0.01	H: <i>Kelley and Tartar</i> [1956] $\alpha$ : (estimated) <i>Sander and Crutzen</i> [1996]
Cl <sub>2</sub> (g) ↔ Cl <sub>2</sub> (aer)	3.7 × 10 <sup>1</sup>	0.01	H: <i>Wilhelm et al.</i> [1977] $\alpha$ : (estimated) <i>Sander and Crutzen</i> [1996]
BrCl (g) ↔ BrCl (aer)	5.6 × 10 <sup>1</sup>	0.01	H: <i>Bartlett and Margerum</i> [1999] $\alpha$ : (estimated) <i>Sander and Crutzen</i> [1996]
O <sub>3</sub> (g) ↔ O <sub>3</sub> (aer)	3.5 × 10 <sup>1</sup>	0.002	H: <i>Kosak-Channing and Helz</i> [1983] $\alpha$ : <i>Magi et al.</i> [1997]
HNO <sub>4</sub> (g) ↔ HNO <sub>4</sub> (aer)	1.2 × 10 <sup>4</sup>	0.05	H: <i>Régimbal and Mozurkewich</i> [1997] $\alpha$ : <i>Li et al.</i> [1996]



**Figure 3.** Normalized diurnal profile of  $\text{NO}_x$  ( $\text{NO} + \text{NO}_2$ ) concentration simulated in the model with heterogeneous  $\text{HNO}_4$  chemistry (solid line) and without (dashed line). Concentrations are normalized to the maximum concentration calculated over the diurnal cycle. Results are from a steady state Arctic boundary layer simulation for background conditions (Table 1) and no  $\text{BrO}_x$ - $\text{ClO}_x$  chemistry.

[17] We find that the uptake of  $\text{HNO}_4$  by aerosols and its subsequent reaction in the aerosol phase (mostly with  $\text{HNO}_2$  and  $\text{I}^-$ ) provides a significant  $\text{NO}_x$  sink in the Arctic boundary layer outside of  $\text{O}_3$  depletion episodes. It accounts in the model for 40% of the  $\text{NO}_x$  loss on a 24-hour average basis and 50% at noon. This heterogeneous  $\text{HNO}_4$  chemistry increases the amplitude of the diurnal cycle of  $\text{NO}_x$  concentrations and shifts the diurnal maximum to mid afternoon, as compared to a sensitivity simulation with no  $\text{HNO}_4$  uptake by aerosols (Figure 3). The rate of the aerosol  $\text{HNO}_4$  sink is limited by the rate of reaction in the aerosol phase, which in turn depends on the assumed concentration of reactants [Sirois and Barrie, 1999; Li, 1994]. The amplification of the diurnal cycle of  $\text{NO}_x$  concentrations due to  $\text{HNO}_4$  chemistry in our model is consistent with the Alert observations of Ridley *et al.* [2000], but the timing of the model maximum (1400 local time) is still later than observed (1200) suggesting that the lifetime of  $\text{NO}_x$  in the measurements of Ridley *et al.* [2000] may be even shorter than that calculated here.

[18] Previous studies [Warneck, 1999; Leriche *et al.*, 2000; Dentener *et al.*, 2002] have shown the importance of  $\text{HNO}_4$  in the oxidation of  $\text{S(IV)}$  in clouds. Our understanding of the role of  $\text{HNO}_4$  in the atmospheric chemistry system is limited by both a lack of field observations and uncertainties in its chemistry (for example at 250K its thermal dissociation constant is uncertain by a factor of 10 [DeMore *et al.*, 1997]).

## 4. Radical Chemistry During Ozone Depletion Events

### 4.1. Temporal Evolution and $\text{O}_3$ Chemical Coordinate

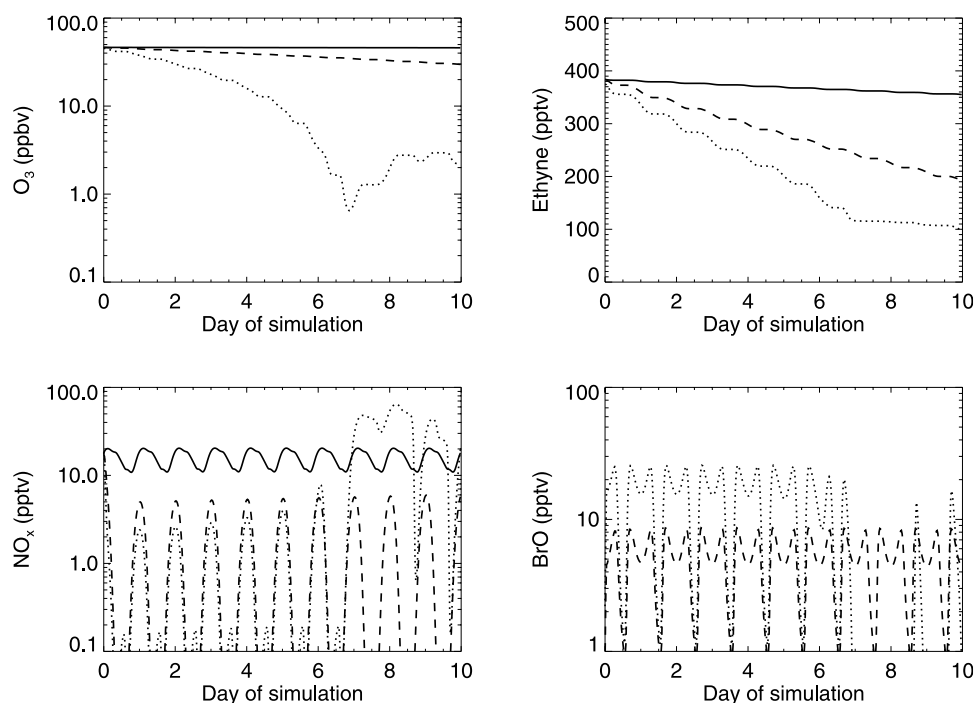
[19] Starting from the steady state background conditions described in the previous section and summarized in Table 1, the model atmosphere was perturbed instantaneously with varying levels of bromide ( $\text{Br}^-$ ) from 0.2 to 43 pptv

(range observed by Sirois and Barrie [1999]) and then allowed to evolve chemically for 10 days. The initial activation of the halogen radicals is through the reactions of  $\text{Br}^-$  and  $\text{O}_3$  [Haag and Hoigné, 1983] and  $\text{HNO}_4$  [Régimbal and Mozurkewich, 1997] to release  $\text{HOBr}$ . After this initial activation, the recycling of bromine radicals from non-radical reservoirs is controlled by  $\text{Cl}^- + \text{HOBr} + \text{H}^+ \rightarrow \text{BrCl} + \text{H}_2\text{O}$  [Wang *et al.*, 1994] and  $\text{Br}^- + \text{HOBr} + \text{H}^+ \rightarrow \text{Br}_2 + \text{H}_2\text{O}$  [Beckwith *et al.*, 1996], with the recycling of  $\text{Br}^-$  being dominated by the latter.

[20] Figure 4 shows the temporal evolution of  $\text{O}_3$ , ethyne,  $\text{NO}_x$  ( $\text{NO} + \text{NO}_2$ ) and  $\text{BrO}$  concentrations over 10 days for 3 of the cases (0, 13 and 43 pptv initial bromide). Without any bromine the model is at steady state for the radicals and their reservoirs; ethyne concentration decreases very slowly due to reaction with  $\text{OH}$ . With 13 pptv of initial bromide the  $\text{O}_3$  concentration drops slowly from 45 to 30 ppbv over the 10 days of the simulation. This is accompanied by a slow linear loss of ethyne. The  $\text{NO}_x$  concentration drops precipitously due to  $\text{BrNO}_3$  hydrolysis. The formation of  $\text{BrNO}_3$  is favored toward dawn and dusk when  $\text{Br}/\text{BrO}$  and  $\text{NO}/\text{NO}_2$  ratios are low, leading to a large diurnal cycle in the  $\text{NO}_x$  concentration. The small increases in  $\text{NO}_x$  concentrations simulated during night are due to the slow thermal decay of  $\text{PAN}$  and  $\text{HNO}_4$ . The daytime  $\text{BrO}$  concentrations remain steady at 9 pptv. If the concentration of initial bromide is increased to 43 pptv, the impact is much greater.  $\text{O}_3$  concentrations drop down to a steady state of 1–2 ppbv after 6 days. As the  $\text{O}_3$  concentration drops below 3 ppbv the bromine radical chemistry essentially shuts down, as seen in the disappearance of  $\text{BrO}$  and the leveling off of ethyne. This suppression of bromine radical chemistry is due to a change in the balance between gas-phase and aerosol-phase bromine. As the  $\text{O}_3$  concentration drops, the  $\text{NO}/\text{NO}_2$  and  $\text{Br}/\text{BrO}$  concentration ratios increase. Eventually,  $\text{HOBr}$  production by  $\text{BrO} + \text{HO}_2$  is suppressed, preventing the recycling of bromine radicals by  $\text{R5}$ . The suppression of bromine radical chemistry and the increase in the  $\text{NO}/\text{NO}_2$  ratio suppress in turn the formation of  $\text{BrNO}_3$ . The longer  $\text{NO}_x$  lifetime, together with the surface source, allows the  $\text{NO}_x$  concentration to recover.

[21] Simulations of the temporal evolution of  $\text{O}_3$  and halogen radical concentrations in the Arctic boundary layer during  $\text{O}_3$  depletion events have been reported in previous model studies [Sander *et al.*, 1997; Michalowski *et al.*, 2000]. Important new aspects here include the depletion and recovery of  $\text{NO}_x$  driven by  $\text{BrNO}_3$  hydrolysis, and the coupling of  $\text{Br}$  and  $\text{Cl}$  chemistry which affects the evolution of ethyne and alkanes differently, as discussed below. As in previous modeling studies [e.g., Sander *et al.*, 1997], we find that the  $\text{BrO}$  self reaction is the dominant mechanism for halogen-catalyzed  $\text{O}_3$  loss ( $\sim 70\%$ ), with  $\text{BrO} + \text{HO}_2$  playing a subsidiary role ( $\sim 25\%$ ). Other mechanisms ( $\text{BrO} + \text{CH}_3\text{O}_2$ ,  $\text{BrNO}_3 + \text{aerosol}$ , and  $\text{ClO} + \text{BrO}$ ) play minor roles ( $\sim 1\%$ ).

[22] It is difficult to compare this temporal evolution in the model directly with the TOPSE observations, which were not collected in a Lagrangian framework, and this has been a general problem in the evaluation of models of Arctic  $\text{O}_3$  depletion. In order to enable such a comparison, we use the  $\text{O}_3$  concentration as a proxy for chemical history and make the comparison along this chemical coordinate



**Figure 4.** Simulated evolution of O<sub>3</sub>, ethyne, NO<sub>x</sub> (NO + NO<sub>2</sub>) and BrO concentrations over 10 days with 3 different initial aerosol phase bromide concentrations (zero (continuous line), 13 pptv (dashed line) and 43 pptv (dotted line)). Initialization is at local noon.

(Figure 5) for different initial bromide concentrations. The observed relationships apparent in Figure 5 between the different species and O<sub>3</sub> concentration were previously discussed in section 2. Many of these relationships are reproduced by the model and the mechanisms leading to them can therefore be elucidated.

#### 4.2. Halogen Radicals and Hydrocarbons

[23] The TOPSE observations show a decrease of the hydrocarbon concentrations along with O<sub>3</sub> (Table 1) reflecting the presence of both Br and Cl radicals. The model reproduces the observed trends, as shown in Figure 5 for ethyne and ethane. The differing behavior of ethyne and ethane reflects different temporal evolution of Br atoms (ethyne oxidant) and Cl atoms (ethane oxidant) as the O<sub>3</sub> concentrations drop (see for example *Ramacher et al.* [1999]). Bromine chemistry continues to operate at low O<sub>3</sub> concentrations (the ethyne concentration declines at all O<sub>3</sub> concentrations) whereas chlorine chemistry is quenched below 10 ppbv of O<sub>3</sub> (ethane is not depleted further).

[24] Figure 6 describes the simulated evolution of the concentrations of halogen species as the O<sub>3</sub> concentration drops. Chlorine radical concentrations drop to near zero below 5 ppbv of O<sub>3</sub>. A number of processes contribute to this decline. The only significant source of chlorine radicals in the model is the reaction of aerosol Cl<sup>-</sup> with HOBr to produce BrCl which volatilizes and photolyses. The Cl<sup>-</sup> concentration remains essentially constant during the simulation (Figure 6) so that the production of active chlorine is limited by the availability of HOBr. As the O<sub>3</sub> concentration drops, the production of HOBr decreases (as discussed previously), reducing the production of BrCl. The production of Br<sup>-</sup> increases, so that the reaction of Br<sup>-</sup> and HOBr competes with the reaction of Cl<sup>-</sup>, further reducing the

conversion of Cl<sup>-</sup> into BrCl. The increase in Br<sup>-</sup> also increases the rate of the reaction between Br<sup>-</sup> and BrCl to produce Br<sub>2</sub>Cl<sup>-</sup>, which predominantly decomposes to Br<sub>2</sub> and Cl<sup>-</sup>.

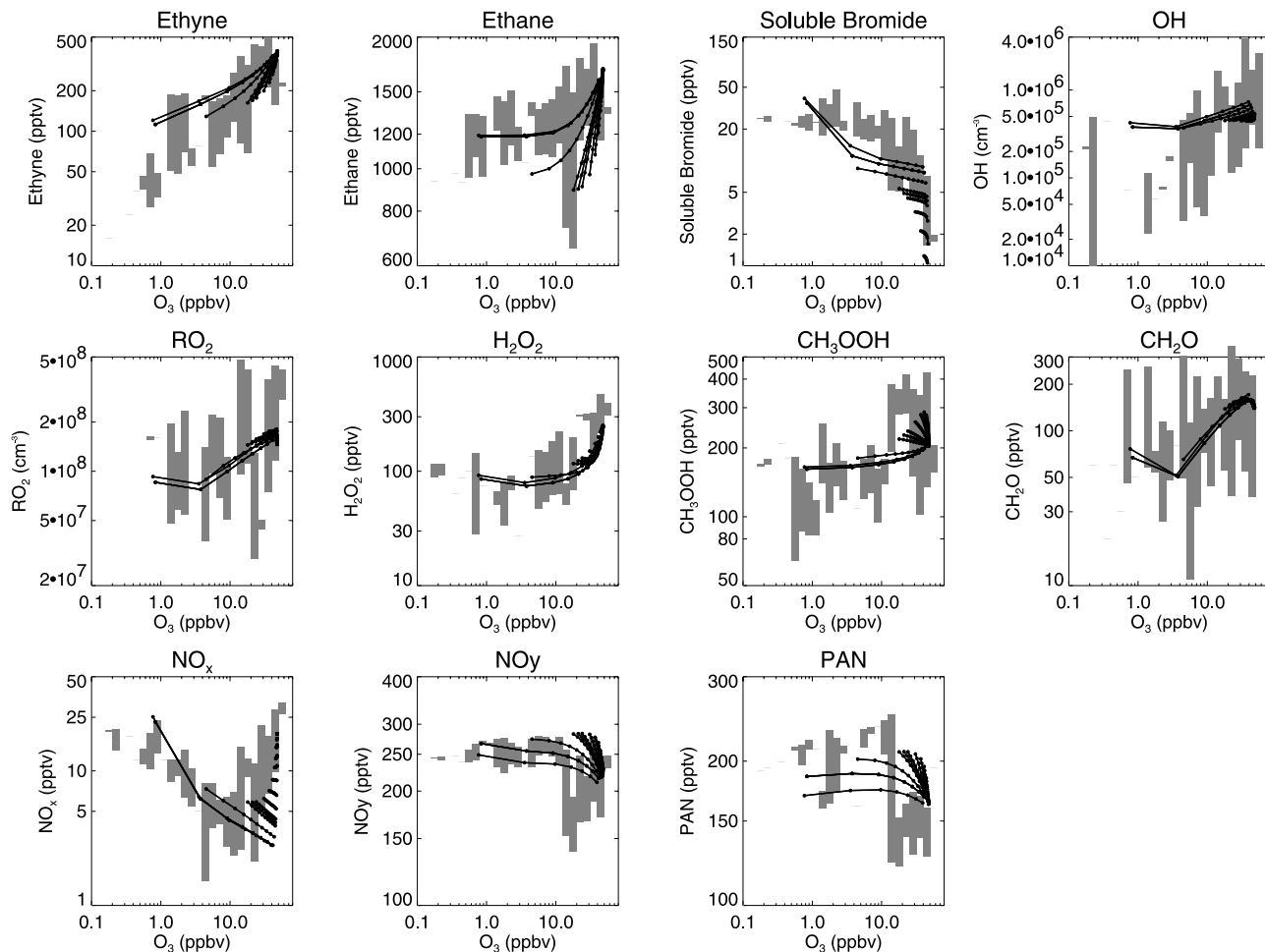
[25] In contrast to Cl, the concentration of Br atoms increases initially as O<sub>3</sub> declines, and remains relatively high even as O<sub>3</sub> drops down to 1 ppbv. The reduction in the HOBr concentration as the O<sub>3</sub> drops is to some extent compensated for by an increase in the Br<sup>-</sup> concentration, so that overall the rate of volatilization of Br<sub>2</sub> from the aerosol is maintained. Increasing Br/BrO ratio as the O<sub>3</sub> concentration declines further contributes to maintaining high Br atom concentrations.

#### 4.3. Hydrogen Oxide Radicals

[26] We find that the RO<sub>2</sub> concentration drops by a factor of 2, both in the model and in the observations, as O<sub>3</sub> concentrations decrease from background values down to 1 ppbv (Figure 5). Measured OH declines by a factor of 5 while simulated OH declines by only a factor of 2. Problems with the OH instrumentation [*Mauldin et al.*, 2003] make interpretation of the discrepancy difficult.

[27] Halogen radicals in the model drive profound changes in the HO<sub>x</sub> budget during O<sub>3</sub> depletion episodes. Without any halogens the production of HO<sub>x</sub> is mainly due to the photolysis of CH<sub>2</sub>O (~40%) with the photolysis of O<sub>3</sub> providing a smaller contribution (~20%). Most of the CH<sub>2</sub>O (60%) in the model originates from surface emission (as opposed to production from methane and higher VOC oxidation) and thus acts as a primary HO<sub>x</sub> source. The loss of HO<sub>x</sub> is mainly (~75%) through the HO<sub>2</sub> self reaction to produce H<sub>2</sub>O<sub>2</sub>. With the inclusion of halogens this balance changes substantially. The primary source of HO<sub>x</sub> becomes the reaction between Br and CH<sub>2</sub>O. HOBr





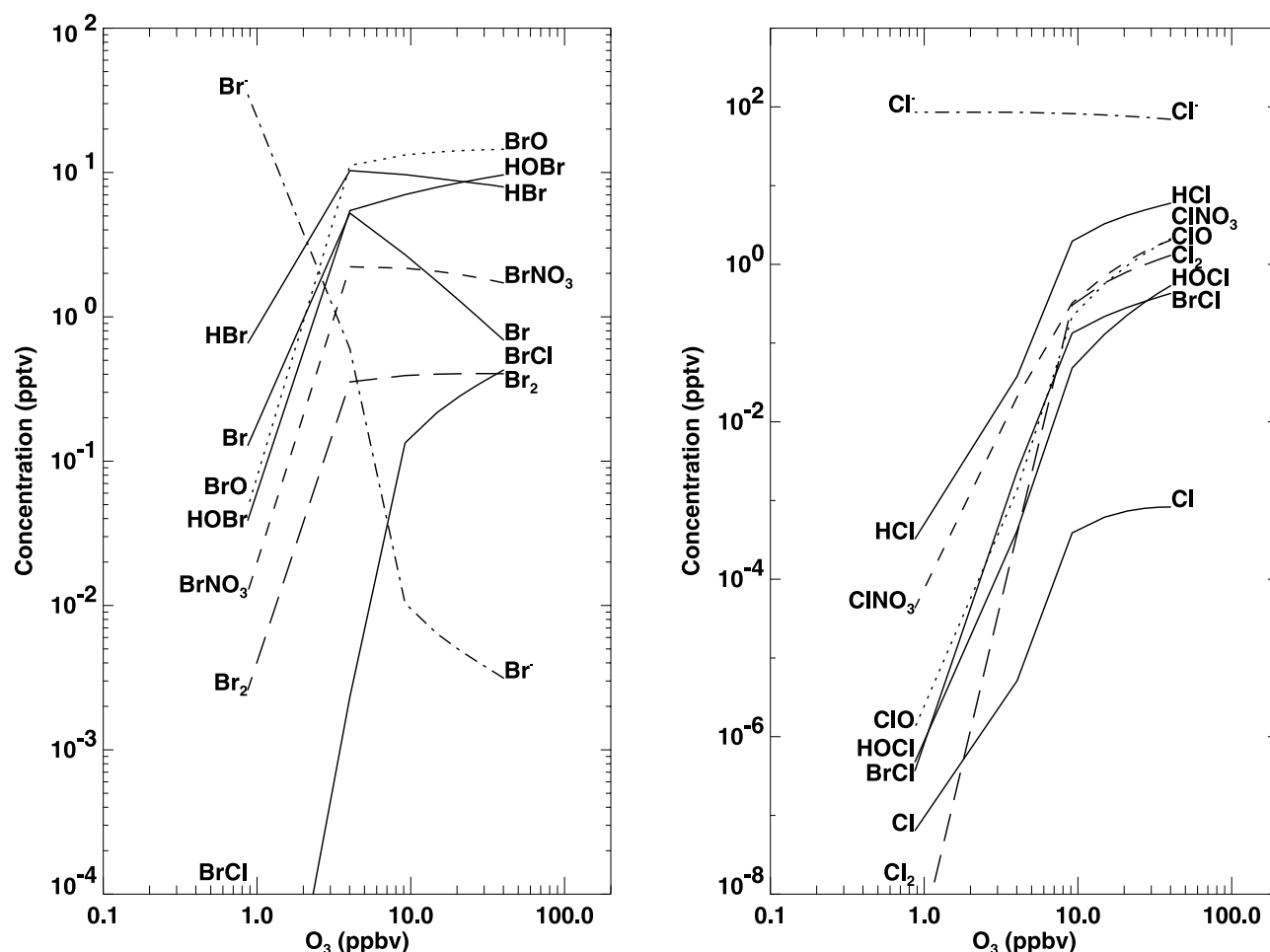
**Figure 5.** Chemical evolution during  $O_3$  depletion events in the Arctic boundary layer in spring, plotted against the  $O_3$  chemical coordinate. Aircraft measurements from TOPSE (north of  $50^\circ N$ , below 500 m altitude, March 23–May 22, 11:00–13:00 local time) are shown as grey bars ( $\pm 1$  standard deviation). Model results (section 3) are shown as lines for different initial bromide concentrations (0 to 43 pptv): the higher the initial bromide concentration, the larger the  $O_3$  loss and thus the longer the line. The model simulations were conducted for 10 days starting at noon, and noontime concentrations are shown here (symbols on lines). See Table 1 for definitions of the lumped species.

acts as a temporary reservoir for  $HO_x$ , producing OH when photolysed and consuming  $HO_2$  when produced. The uptake and subsequent destruction of HOBr in aerosols by R5 acts as a large  $HO_x$  sink. The rapid oxidation of hydrocarbons and carbonyls by Br or Cl increases the importance of organic peroxy radicals ( $CH_3O_2$  and above) in the  $HO_x$  budget.

[28] We see from the above discussion that there is strong coupling and interchange between the  $HO_x$  and  $BrO_x$  families, with major sinks of  $HO_x$  serving as sources of  $BrO_x$  and vice versa, and with HOBr serving as a reservoir for both radical families. One can consider these families together with  $ClO_x$  (which plays little role and will not be discussed further) as components of a larger radical family H/Cl/Br $O_x$ . The primary production of H/Cl/Br $O_x$  is from the photolysis of  $CH_2O$  and the primary sink is from peroxy–peroxy reactions. When H/Cl/Br $O_x$  is at steady state the photolysis of  $CH_2O$  is approximately balanced by the self reaction between  $RO_2$  radicals. Reactions involving  $BrO_x$  play little role in producing or destroying

H/Cl/Br $O_x$ . Thus, the  $RO_2$  concentration should be proportional to the square root of the  $CH_2O$  concentration regardless of the bromine chemistry. In both the model and the observations,  $CH_2O$  concentrations decline by a factor 4 as  $O_3$  is depleted (Figure 5) and the  $RO_2$  concentration responds by dropping by a factor of 2, in line with this simple analysis. The decline in  $CH_2O$  is driven by reaction with Br atoms. Thus the reaction between Br and  $CH_2O$ , rather than acting to increase  $HO_x$  concentrations, does in fact suppress them.

[29] Concentrations of  $H_2O_2$  decrease during  $O_3$  depletion events, while  $CH_3OOH$  initially increases and then decreases, both in the model and in the observations. The decline of  $H_2O_2$  is due both to the decline of total peroxy radicals ( $RO_2$ ) and to a shift in the partitioning of  $RO_2$  to favor organic peroxy radicals, as discussed above. The latter shift favors  $CH_3OOH$  production, which is further favored by the drop in  $NO_x$  concentration at the onset of  $O_3$  depletion events (the  $CH_3O_2 + HO_2$  reaction proceeds faster under low  $NO_x$  concentration due to less competition from



**Figure 6.** Modeled evolution of halogen concentrations for the simulation with 43 pptv of initial bromide, as a function of the  $O_3$  concentration.

$CH_3O_2 + NO$ ). As  $O_3$  concentrations drop below 10 ppbv, the recovery of  $NO_x$  as well as the decline in total  $RO_2$  act to decrease  $CH_3OOH$ .

#### 4.4. Nitrogen Oxide Radicals

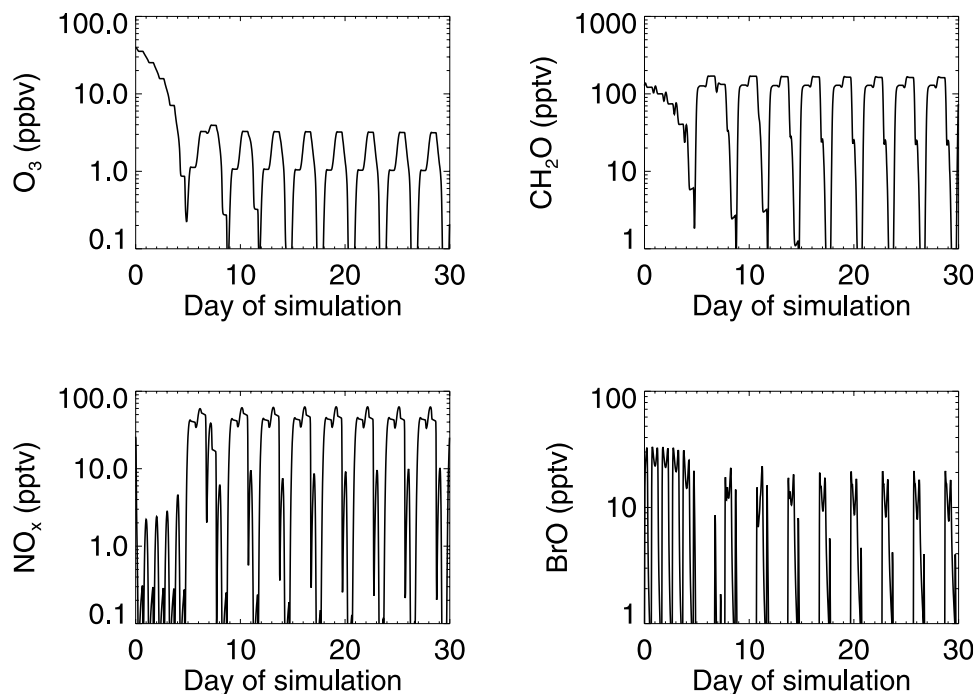
[30] As  $O_3$  concentrations decrease from 40 to 10 ppbv the measured  $NO_x$  exhibits a rapid decline from about 20 pptv to 3 pptv. As  $O_3$  is further depleted the  $NO_x$  concentration recovers, eventually reaching similar concentrations to those observed in air masses with  $O_3$  concentrations above 40 ppbv. The model reproduces this evolution as shown in Figure 5. In the model the decline and subsequent recovery in the  $NO_x$  concentration is due to a combination of  $BrNO_3$  hydrolysis and  $NO_x$  emission from the snow. When  $BrO_x$  chemistry is active and  $O_3$  concentrations are still high, formation and hydrolysis of  $BrNO_3$  ( $\nu = 0.3$ ) leads to loss of  $NO_x$ . At lower  $O_3$  concentrations,  $BrNO_3$  formation is suppressed due to increases in both the  $NO/NO_2$  and  $Br/BrO$  ratios.

[31] Both PAN and  $NO_y$  show a similar relationship with  $O_3$ , reflecting the dominant role of PAN in the composition of  $NO_y$ . The measurements show increases of PAN and  $NO_y$  during  $O_3$  depletion events, and this is reproduced by the model (Figure 5). In the model, the rise in PAN is due to the oxidation of carbonyls and hydrocarbons by Cl and Br

atoms, and is kept in check by the concurrent depletion of  $NO_x$ . The model study of *Shepson et al.* [1996] found much more rapid production of PAN during  $O_3$  depletion events because they did not include  $BrNO_3$  hydrolysis in their mechanism.

#### 5. An Oscillatory System in Bromine-Catalyzed $O_3$ Depletion

[32] The search for oscillatory solutions in atmospheric chemistry models generates sporadic interest in the literature, both for theoretical curiosity and for possible implications for atmospheric stability [*Madronich and Hess, 1994; Poppe and Lustfeld, 1996; Tinsley and Field, 2001*]. We find in our photochemical simulation for the Arctic boundary layer described above that an oscillatory system with a period of 3 days develops under low  $O_3$  conditions if the reactive uptake coefficients ( $\gamma$ ) of HBr and HOBr are increased from 0.3 to 0.8 (alternatively this can be viewed as an increase in the aerosol surface area). Figure 7 shows the evolution of  $O_3$ ,  $CH_2O$ , and  $NO_x$  and BrO concentrations under these conditions over a 30 day model simulation period with 43 pptv of initial bromide. The strong 3 day oscillation is evident. As bromine destroys  $O_3$ , the Br/BrO ratio increasingly favors HBr production over HOBr. This leads to an accumulation of



**Figure 7.** Temporal evolution of  $O_3$ ,  $CH_2O$ ,  $NO_x$  and  $BrO$  concentrations over a 30-day period for our standard simulation of  $O_3$  depletion events in the Arctic boundary layer (c.f. Figure 4) but with enhanced aerosol uptake of  $HBr$  and  $HOBr$  ( $\gamma = 0.8$ , or equivalent increase in aerosol surface area). The initial bromide concentration is 43 pptv.

$Br^-$  in the aerosol. Eventually virtually all of the model bromine resides in the aerosol (see Figure 6), suppressing  $BrO_x$  chemistry. Those species which are depleted by bromine radical chemistry, notably  $CH_2O$  and  $NO_x$ , increase in concentration, leading to  $O_3$  production. The increase in  $O_3$  concentration leads to increased  $HOBr$  concentration which in turn leads to an increased rate of recycling of bromine. This leads to net  $O_3$  destruction and thus an oscillation. This appears to be the fastest oscillation calculated by a numerical model of the troposphere. Previous studies reviewed by *Tinsley and Field* [2001] have investigated cycles which act on timescales of a few weeks or more. Measurements in the Arctic boundary layer may offer the best opportunity of observing a chemical oscillation in the real atmosphere.

## 6. Conclusions

[33] Observations from the TOPSE aircraft campaign over the Arctic in March–May 2000 provide extensive chemical characterization of  $O_3$  depletion events in the boundary layer. We used a combination of data analysis and photochemical modeling to investigate the processes controlling the coupled evolution of  $BrO_x$ - $ClO_x$ - $HO_x$ - $NO_x$  radicals and their reservoirs.

[34] Ethane and ethyne observations during TOPSE indicate that  $Cl$  radical chemistry is important only during the early stages of  $O_3$  depletion while  $Br$  radical chemistry remains active even as  $O_3$  drops below 1 ppbv. We reproduce these results in our model. As the  $O_3$  concentration decreases below 5 ppb, accumulation of  $Br^-$  in the aerosol leads  $Br_2$  production to compete with  $BrCl$  production as a sink of  $HOBr$  leading to a reduction in the rate of

$Cl$  radical production. Also, the reaction between aerosol phase  $BrCl$  and  $Br^-$  to produce  $Br_2Cl^-$  further inhibits the release of  $BrCl$ . These two processes lead to a marked reduction in  $Cl$  chemistry below 10 ppbv of  $O_3$ .

[35] Measured total peroxy radical concentrations ( $RO_2$ ) drop by a factor of 2 during  $O_3$  depletion events, a trend well reproduced by our model. During these events there are strong interchanges between  $HO_x$  and  $BrO_x$  radicals, and  $HOBr$  serves as a major reservoir for both. We define a generalized  $H/Cl/BrO_x$  radical family to account for this coupling. Production of this family is mostly from the photolysis of  $CH_2O$  emitted from the snow, and loss is mostly by the self reactions of peroxy radicals. Thus, at steady state the  $RO_2$  concentration is proportional to the square root of the  $CH_2O$  concentration. Measured and simulated  $CH_2O$  concentrations drop by a factor of 4 during  $O_3$  depletion events due to reaction with  $Br$  atoms, explaining the observed decrease in  $RO_2$  concentrations.

[36] Observed  $NO_x$  concentrations show a marked decline during the early stages of  $O_3$  depletion with subsequent recovery as the  $O_3$  concentration drops below 10 ppbv. We reproduce this feature and ascribe the initial  $NO_x$  depletion to  $BrNO_3$  hydrolysis. As the  $O_3$  concentration continues to drop, both the  $Br/BrO$  and  $NO/NO_2$  ratios increase which leads to a reduction in the  $BrNO_3$  concentration and thus the magnitude of the  $NO_x$  sink. The emission of  $NO_x$  from the snow then leads to a recovery in the  $NO_x$  concentration. The magnitude of this recovery is obviously dependent upon the strength of the surface source and thus may vary geographically and seasonally.

[37] Outside of  $O_3$  depletion episodes, our model calculations suggest that aerosol phase reactions of  $HNO_4$  with

$\text{HNO}_2$  and  $\text{I}^-$  could represent a substantial sink for  $\text{NO}_x$ . There is an obvious need for  $\text{HNO}_4$  measurements in the Arctic boundary layer and for better characterization of  $\text{HNO}_4$  chemistry.

[38] Our photochemical model simulation for the Arctic boundary layer shows a large-amplitude oscillation for  $\text{O}_3$  with a period of 3 days under certain realistic conditions with high bromine. The period of the oscillation is much shorter than previously reported oscillations in tropospheric chemistry mechanisms. Although it could be nothing more than a theoretical curiosity, since external forcing (such as from transport) is likely to disrupt it, it may because of its short period afford an opportunity for observing an oscillation in the real atmosphere.

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