An overview of ISCAT 2000

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Abstract

The Investigation of Sulfur Chemistry in the Antarctic Troposphere (ISCAT) took place over the timer period of 15 November to 31 December in the year 2000. The study location was the Amundsen Scott Station in Antarctica. ISCAT 2000 defines the second phase of a program designed to explore tropospheric chemistry in Antarctica. As in 1998, the 2000 ISCAT study revealed a strong oxidizing environment at South Pole (SP). During the 2000 investigation, however, the suite of measurements was greatly expanded. These new measurements established the recycling of reactive nitrogen as a critical component of this unique environment. This paper first presents the historical background leading up to the ISCAT 2000 observations; then it focuses on providing a summary of the year 2000 results and contrasts these with those recorded during 1998. Important developments made during the 2000 study included the recording of SP data for several species being emitted from the snowpack. These included NO, H_2O_2 and CH_2O. In this context, eddy-diffusion flux measurements provided the first quantitative estimates of the SP NO and NO_x snow-to-atmosphere fluxes. This study also revealed that HNO_3 and HO_2NO_2 were major sink species for HO_x and NO_x radicals. And, it identified the critical factors responsible for SP NO levels exceeding those at other polar sites by nearly an order of magnitude.

Finally, it reports on the levels of gas phase sulfur species and provides evidence indicating that the absence of DMS at SP is most likely due to its greatly shorten chemical lifetime in the near vicinity of the plateau. It is proposed that this is due to the influence of NO on the distribution of OH in the lower free troposphere over a region that extends well beyond the plateau itself. Details related to each of the above findings plus others can be found in the 11 accompanying Special Issue papers.

1. Introduction

1.1. Pre-ISCAT results

As stated in a 1991 symposium on Antarctic Tropospheric Chemistry, "there are many unique features of Antarctica that make it a valuable laboratory for monitoring and understanding the state of our global environment" (Bodhaine et al., 1992). Clearly, one of the most unique features of this land of ice is that it represents a giant archive of atmospheric conditions dating back nearly 500,000 years bp (Legrand and Feniet-Saigne, 1988; Legrand et al., 1991, and references therein). Thus, all major global geophysical, biological, and/or climatological events that have had a measurable impact on atmospheric composition are recorded in some form in the vast ice accumulations on this continent. However, for a species' ice signature to be of real scientific value one must have a reasonably good understanding of what the major atmospheric sources of the species are. This critical information has in some cases already been generated from past Antarctic studies. In other cases it is being produced by on-going studies such as the current one.

Sulfur is one of the elements found in ice cores that has been previously studied in the Antarctic atmosphere. In fact, some of the earliest studies involving this element have shown that it is one of the major elements to be found in aerosol samples (Shaw, 1980, 1988, and references therein). During the summer months, it is the dominant element. Because of this, sulfur has become a critical proxy species used to identify major global geophysical events such as volcanic eruptions and El Nino occurrences (e.g., Legrand and Delmas, 1987; Bergin et al., 1998; Dibb and Whitlow, 1996). However, based on results showing that most sulfur reaching the mainland is a by-product of locally released marine dimethyl sulfide (DMS), fluctuations in the levels of the oxidation products from DMS can also be used as climate proxy species (Legrand and Saigne, 1988; Legrand and Feniet-Saigne, 1991; Legrand et al., 1991; Legrand et al., 1992; Saigne et al., 1987; Mulvaney et al., 1992; Mulvaney and Wolff, 1994; Saltzman, 1994). Unfortunately, our knowledge about DMS oxidation chemistry is still quite limited. In addition, some of the

details concerning air-to-snow transfer processes for sulfur have been lacking (Bales and Wolff, 1995; Wolff and Bales, 1996; Davis et al., 1998).

Our lack of understanding of the mechanistic details about DMS oxidation can be illustrated here from a simple comparison of the sulfur oxidation products measured in aerosol samples collected at coastal sites versus those on the Antarctic plateau. Based on the known temperature dependencies for DMS oxidation via OH radicals (Hynes et al., 1986), arguments can be made that the ratio of the major products from DMS (i.e., methane sulfonate (MS) and non-sea-salt sulfate (NSS)) should be quite different for these two environments. The kinetic data, in fact, would suggest that the lower the average temperature the larger should be the value of this MS/NSS ratio. However, in spite of the much lower average temperature at the plateau, one typically finds that coastal values during the summer months are 3–10 times higher than those taken on the plateau (e.g., Saigne and Legrand, 1987; Prospero et al., 1991, Berresheim, 1987; Wagenbach, 1996; Arimoto et al., 2001, Legrand and Pasteur, 1998). Quite interestingly, the typical average plateau value for this ratio of 0.06 is a value that is consistently found for the tropical marine boundary layer (MBL) (Davis et al., 2003, and references therein). Even more confounding are observations at some coastal sites showing that at certain times the value of this ratio abruptly changes during the summer months, but with no corresponding temperature change (e.g., Prospero et al., 1991).

An earlier Georgia Tech/NCAR field initiative called Sulfur Chemistry in the Antarctic Troposphere Experiment (SCATE) provided considerable insight as related to the above observations. This program was focused on studying sulfur chemistry at Palmer Station on the Antarctic coast. Although this field study led to considerable speculation about the specifics concerning DMS oxidation, the larger picture emerging from it revealed that an estimated half of the total available surface released DMS (near Palmer) underwent oxidation at high altitudes. Evidence supporting this conclusion was found in the form of direct measurements of the intermediate DMS oxidation product, dimethylsulfoxide (DMSO) (Berresheim et al., 1998). Laboratory kinetic studies have shown that under low temperature

conditions the dominant initial DMS oxidation product is DMSO (Barnes et al., 1996; Sørensen et al., 1996; Hynes et al., 1986). However, during SCATE, the levels of this species, as well as the byproduct from the further oxidation of DMSO (e.g., dimethyl sulfone ($DMSO_2$)), were found to be highly variable, at times changing by factors of 10 or more over a period of just a few hours. Quite significant also was the finding that given the measured levels of DMS and hydroxyl radical (OH), it was not possible to explain the observed high concentrations of DMSO (Davis et al., 1998). Further analysis, in fact, revealed that these abrupt increases in DMSO correlated with air parcels descending from higher altitudes, e.g., depressed dew points and aerosol levels with elevated O_3 levels (Davis et al., 1998). Legrand et al. (2001) in a study at Dumont Urville found somewhat similar results, observing sudden unpredictable elevated levels of DMSO and $DMSO_2$.

The SCATE study was also revealing in that it strongly suggested that a very large fraction of the DMSO that was returned to the MBL was rather efficiently converted into MS via heterogeneous processes involving sea-salt aerosols (Jefferson et al., 1998). Collectively, these results led to the tentative conclusion that the low MS/NSS ratio found on the plateau most likely was a result of the high-altitude oxidation of the intermediate, DMSO. Specifically, it required that DMSO be further oxidized under conditions involving very low temperatures and very low sea-salt levels (D. Davis, paper in preparation). As discussed by Arimoto et al. (2001), an examination of the MS/NSS ratio at different polar sites reveals that it is the MS level, not NSS that undergoes major shifts in concentration. As noted above, within the MBL DMSO predominantly disappears via heterogeneous reactions involving sea-salt to form MS; while at higher altitudes, free of sea-salt, the dominant reaction of DMSO can involve reaction with OH, leading to SO_2 formation and subsequently to NSS (D. Davis, paper in preparation).

Based on the above hypothesis, a new research initiative was formulated which focused on making detailed observations of sulfur species at the South Pole (SP). The argument put forward for this new sampling strategy was as follows. During those time periods when coastal marine air moved rapidly inland and reached the SP in 2–3 days, considerable amounts of un-reacted DMS would be delivered to the SP site. Under these conditions, the SP setting could thus provide an excellent opportunity to monitor the entire chemical evolution of DMS under very low temperature and salt-free conditions.

The resulting new sulfur chemistry initiative, Investigation of Sulfur Chemistry in Antarctica Troposphere (ISCAT) focused on two major objectives: (1) assessing the relative importance of the atmospheric chemical, physical, and meteorological factors responsible for defining gas and aerosol phase sulfur speciation at SP; and (2) evaluating the role of H_2SO_4, MSA, H_2O, NH_3, and temperature in the formation and growth of new particles under SP conditions. A secondary ISCAT objective involved examining the key factors modulating the atmospheric oxidizing power (e.g., OH levels) at SP. Recall, it is the level of OH that controls the rate of oxidation of any DMS transported to SP.

1.2. ISCAT 1998 results

Among the major findings from ISCAT 1998 was the observation that DMS levels were typically at or below the detection limit of our instrumentation, e.g., <2 pptv. These low values of DMS were reflected in the equally low values observed for the oxidation products MSA and H_2SO_4 (Mauldin et al., 2001). Even so, the ISCAT 1998 sulfur aerosol results demonstrated for the first time that the value of the airborne aerosol MS/NSS ratio (i.e., 0.07) was indistinguishable (within the uncertainties of the analyses) from the average value typically cited for near surface ice cores from the plateau (Arimoto et al., 2001). Thus, these results would suggest that what actually reaches the plateau in the form of aerosol is what gets deposited. It is likely then that this ratio is the end result of pre-plateau chemical/dynamical processes that take place during transport.

The reason for the very low DMS levels at SP will be addressed later in the text as well as in two of the accompanying papers in this Special Issue. Taken at face value, however, they suggest that either our original estimate of the transport time for DMS from the coast to SP was too short or that the average oxidation rate via OH was much faster than first calculated.

Without question, the most surprising finding during the 1998 study was observing the photodenitrification of surface snow as the major source of atmospheric NO_x at SP (Davis et al., 2001). In this regard, it is noteworthy that similar findings were also independently recorded at Alert, Canada (Ridley et al., 2000), at Summit, Greenland (Honrath et al., 1999) and at Neumayer on the coast of Antarctica (Jones et al., 2000). What makes the 1998 ISCAT NO results so exceptional is the magnitude of the NO concentration. As summarized in Davis et al., 2004, the median 1998 level of 225 pptv is nearly a factor of 10 greater than at other polar sites, including those recorded at two coastal Antarctica locations. One of the major chemical consequences resulting from such high levels of NO is its impact on the levels of OH (Davis et al., 2001). Reflecting this fact, the ISCAT 1998 data resulted in an estimated 24 h average value for OH of $\sim 2 \times 10^6$ mol cm^{-3}. This places the oxidizing power of near surface air at SP as equal to or slightly exceeding that of the tropical marine BL (Mauldin et al., 2001). (Note, the latter environment has traditionally been viewed as having one of the highest average OH levels

for a remote site.) This level is nearly 10 times larger than any previous model prediction for this region. However, all previous predictions have been based on NO levels similar to that measured at Palmer Station during the SCATE program, e.g., $\leqslant 5$ pptv (Chen et al., 2001).

2. ISCAT 2000 site location and instrumental techniques

Given the cited $NO_x/HO_x/O_3$ and DMS/sulfur surprises of ISCAT 1998, there was a major reconfiguring of the ISCAT 2000 field study. Its new focus was shifted to NO_x/HO_x science issues. Key objectives included: (1) establishing the chemical characteristics of the SP snowpack (e.g., NO_3-levels) relative to the surrounding terrain; (2) assessing the magnitude of the NO_x emission flux; (3) evaluating the possible contributions of other snowpack trace gas emissions (e.g., CH_2O, H_2O_2, and HONO) on the budgets of HO_x and NO_x; (4) reassessing the factors responsible for the large day to day shifts observed in NO_x levels; (5) evaluating the major sinks for NO_x and HO_x (e.g., HNO_3, HO_2NO_2); and (6) exploring the relationship between synoptic conditions and the efficiency with which gas phase sulfur species get transported to SP.

In addition to the new objectives for ISCAT 2000 cited above, there was also the important task of contrasting the results from the 1998 ISCAT study with those from 2000. As covered in the 11 papers in this Special Issue, significant differences were found between the two. This paper notes these differences, and the accompanying 11 papers will examine in greater detail some of the reasons behind the differences.

2.1. Site location

The major sampling site during ISCAT 2000 was the Atmospheric Research Observatory (ARO) building at SP. More limited sampling took place on the SP MET tower and from several surface sites, most of which were relatively close to the ARO building (e.g., 50 m). The farthest distance at which sampling occurred was a snow pit ~ 12 km from ARO. As noted in earlier ISCAT papers (Davis et al., 2001 and adjoining papers), the ARO building at SP is positioned at the apex of what is known as the "clean air sector". This sector is nominally defined as 0–120°. It is therefore upwind of the main SP dome and all power generating facilities. Equally important, the dominant wind direction (80–90%) falls within this sector. Thus, it encompasses the major flow coming off of the polar plateau (labeled downslope flow). The latter defines the coldest/driest air that can be sampled at SP. By contrast, wind directions in the range 330–180° have been labeled as upslope flow and typically lead to an inflow of warm/moist air of marine origin. The chemical differences in these air masses is amplified on in three papers in the ISCAT 2000 Special Issue (e.g., see Davis et al., 2004; Swanson et al., 2004; Arimoto et al., 2004a, b).

2.2. Instrumental techniques

Virtually all of the measurements recorded during the 1998 campaign were repeated during ISCAT 2000. Many new measurements, however, were added in 2000. Table 1 provides a summary of the ISCAT 2000 measurements. Included here are the principle investigator, the instrument's sensitivity, and what years it was used. Further details concerning each technique can be found either in the individual ISCAT papers appearing in this Special Issue or in the Special ISCAT Section of Geophysical Research Letters Vol #19 in October of 2001.

3. Overview of meteorological observations

3.1. Average and median meteorological conditions during ISCAT 1998 versus ISCAT 2000

In the text that follows, the ISCAT 1998 and 2000 studies are both examined individually and contrasted. As seen in Table 2, some of the seasonal MET trends in 1998 are what one might expect, given the intensity of the seasonal changes at SP. The temperature, for example, undergoes a major increase from late November to early December but then levels out. A similar trend is also seen in the dew point. In contrast, the median value for atmospheric barometric pressure is nearly constant from the middle of November to the middle of December, then increases during the last half of December. The wind speed, on the other hand, shows the reverse trend, systematically decreasing across the entire sampling time period. By contrast, the trend in the temperature gradient, as measured as the difference between 22 and 1.6 m on the MET tower (ΔT), shows almost no trend during the 1998 sampling season, all values lying within $0.3°$ and positive.

The ISCAT 2000 MET data reveals some significant deviations from those recorded in 1998. However, one trend that was similar in both years was wind speed. As in 1998 a systematic decrease is evident in the 2000 data from the last half of November to the last half of December. The 1998 temperature and dew point data, on the other hand, are seen as systematically lower than those in 2000. In November the difference was nearly $5°$, but by the end of December it had decreased to only $1°$. The 2000 ΔT values go from small positive values in late November and the first-half of December to small negative values in late December, again quite different from the trend that one sees in the ISCAT 1998 data. Barometric pressure levels during the 2000 field study

Table 1
ISCAT 2000 atmospheric measurements

Compound	Investigator	Technique	Sensitivity	Meas. 1998
HNO_3	Huey	SICIMS	5 pptv	New 2000
	Dibb	Mist chamber/IC	1 pptv	New 2000
HO_2NO_2	Huey	SICIMS	5 pptv	New 2000
SO_2	Bandy	CIMS	1–2 pptv	New 2000
	Huey	CIMS	(a)	New 2000
CH_2O	Hutterli	Scrubber/Fluorescence Spectroscopy	30 pptv	New 2000/ Collaborative
HONO	Dibb	Mist chamber/IC	1 pptv	New 2000
H_2O_2	Hutterli	Scrubber/Fluorescence Spectroscopy	50 pptv	New 2000/ collaborative
OH	Eisele	SICIMS	1×10^5 mol cm^{-3}	Yes
HO_2/RO_2	Eisele	SICIMS	5×10^5 mol cm^{-3}	New 2000
H_2SO_4	Eisele	SICIMS	1×10^5 mol cm^{-3}	Yes
MSA	Eisele	SICIMS	1×10^5 mol cm^{-3}	Yes
NMHC and Halocarbons	Blake	Grab sample/GC and GC/MS	0.05–5 pptv	Yes
DMS	Blake	Grab sample/GC/MS	1 pptv	Yes
	Bandy	CIMS	1–10 pptv	Yes
DMS	Bingemer	Goldwool/ Fluorescence	1–2 pptv	Yes
Actinic flux	Shetter	Spectroradiometer	N/A	Yes
NO	Davis/Buhr	Chemiluminescence	2 pptv	Yes
HCO_2H and CH_3CO_2H	Dibb	Mist chamber/IC	1 pptv	New 2000
Aerosol size and number	McMurry	CNC, UFCNC, OPS	0.01 cm^{-3}	Yes
O_3, Temp, DP, Pressure, wind, speed/ direction, Col. O_3, Solar Irradiance	CMDL-South Pole Station	Multiple Techniques Irradiance-Biospherical Inst.	Suitable for South Pole	Yes collaborative
NO Flux	Oncley/Davis	Sonic anemometers/ Chemiluminescence		New 2000
Aerosol ion comp. and gas phase HNO_3	Arimoto	IC	30 ng m^{-3}	Yes
Aerosol elemental composition	Arimoto	ICP-MS, AAS, Gamma Spectrometer	30 ng m^{-3}	Yes
Measurements in the snow made during ISCAT 2000				
NO	Davis	Chemiluminescence	2 pptv	New 2000
NO_2	Huey	SICIMS	100 pptv?	New 2000
CH_2O, H_2O_2	Hutterli	Scrubber/Fluorescence	40 pptv	New 2000
Snow ion composition	Dibb	IC	Variable	New 2000

also differed somewhat from 1998 as revealed in Table 2 in the form of median values for each 15 day sampling time-period. Although the differences in several of the individual MET variables appear to be quite modest between the two sampling years, as discussed below they seem to reflect rather major differences in the synoptic conditions for the two years.

3.2. Brief synoptic overview

A common meteorological condition on the Antarctic plateau involves cold continental surface air flowing past the SP after several days of residence on the plateau itself. Even so, the presence of a pressure gradient about one or more low-pressure centers, usually over the Ross Sea/Shelf or the Weddell Sea, can induce warmer "extra-continental" air to flow over the SP from western hemispheric directions. This warm inflow can occur several times in November, but influences only a few days in December and January. During ISCAT 2000, there was also observed an inflow of "extra-Antarctic" air (i.e., air beyond the Antarctic Convergence-60°S) associated with a high-pressure ridge that developed during the break-up of the polar vortex. These three

Table 2
Median and mean MET parameters for ISCAT 1998 and 2000

	Nov. 15–30				Dec. 1–15				Dec. 15–31			
	1998		2000		1998		2000		1998		2000	
	Avg.	Med.	Avg.	Med.	Avg.	Med.	Avg.	Med.	Avg.	Med.	Avg.	Med.
WS (m s^{-1})	6.4±2.4	5.9	6.1±1.7	6.17	4.7±1.8	4.3	4.6±1.6	4.9	3.2±1.3	3.2	3.7±1.5	3.74
P (mb)	681±4	679.8	690±5	690	680±7	679	692±2	692	686±4	688	691±5	692
T(2) (°C)	−33.3±3.6	−33.8	−29.6±2.8	−29.1	−28.2±2.4	−29.0	−27.0±1.1	−27.1	−28.8±2.4	−29.1	−27.7±1.7	−27.6
T(22) (°C)	−32.9±3.4	−33.5	−29.2±2.7	−28.5	−28.1±2.4	−29.0	−26.7±1.1	−26.6	−28.5±2.2	−28.8	−27.7±1.4	−27.6
ΔT (°C)	0.4±0.4	0.3	0.4±0.5	0.2	0.1±0.2	0.1	0.3±0.3	0.3	0.3±0.5	0.2	0.0±0.5	−0.1
T$_d$ (°C)	−36.4±4.0	−37.2	−33.1±2.9	−32.6	−31.3±2.4	−32.0	−30.4±1.0	−30.4	−31.4±2.4	−31.8	−31.2±1.8	−31.0

different types of circulation can lead to significant shifts in the concentration of several trace gases as well as aerosol species. Such shifts in concentration are the subject of several of the papers presented in this Special Issue of ISCAT 2000.

In general, it is quite common in Antarctica to find that the continent is encircled by low-pressure centers with the surface barometric pressure being even lower along the Antarctic coast. The heights of the standard pressure levels are also typically lower over Antarctica than at sub-Antarctic latitudes. Here, and in subsequent papers in this Special ISCAT Issue, we have used the standard 500 hPa pressure level for our tropospheric analysis as it is the lowest continuous pressure level over the continent as previously noted by Turner and Pendlebury (2001). The 5160 m contour height associated with the 500 hPa pressure level usually encircles Antarctica during summer and is a convenient way to define what constitutes "Antarctic air". Climatologically, the 500 hPa height increases over Antarctica in November, reaches a maximum in late November, and steadies, or diminishes after the filling of the polar vortex.

During ISCAT 98, the 500 hPa height was at a maximum during the period 30 November–3 December, corresponding to a strong inflow or filling of the polar vortex. Following this, the 500 hPa height immediately diminished above both McMurdo and SP stations, consistent with the climatically prevalent tropospheric low pressure over these locations and the low-pressure center over the Ross Sea/Ice Shelf. The chronology of the 500 hPa level observed during ISCAT 2000 had a similar maximum with the filling of the vortex in early December, but the high pressure remained over the continent through mid-December. In fact, the 500 hPa height observed at McMurdo suggests that the "Ross Low" was very weak or absent during December and that the 500 hPa height above SP remained greater than 5160 m up to mid-December, being only slightly less above McMurdo. This is all consistent with there being a tropospheric high-pressure system over the Polar Plateau.

The 500 hPa height differences are reflected in the different surface flows actually experienced during the two ISCAT field studies. Several inflows of extra-continental air occurred during December 98, associated with circulation about a low-pressure system above the Ross Ice Shelf. The extremely vigorous extra-Antarctic inflow that occurred during late-November 2000 was followed by nearly 15 days of stagnation of air over the polar plateau, and weak or intermittent extra-continental inflow through the remainder of December.

Isentropic trajectories (Harris, 1992) at 500 hpa, provided by Harris (J. Harris, NOAA, private communication) were examined to provide the elapsed time of travel from the Antarctic Coast to the vicinity of the SP. The strong inflows of November 2000, passed over SP two to three days after crossing the coast. The

stagnation period which followed the filling of the polar vortex had a residence time over the snow of more than five days, and residence times up to 10 days, e.g., 4–14 December 2000, occurred at that time. Later in December 2000, occasional inflows to SP, resulting from flow around the weak low-pressure center forming over the Ross Ice Shelf, were also shown from air trajectory analysis to have much shorter residence times.

4. Overview of chemical species measurements

4.1. Average and median levels of gas phase species during ISCAT 1998 versus ISCAT 2000

As shown in Table 3 only six gas phase species were extensively measured in both years, and thus, the focus here will be on these, e.g., NO, O_3, CO, H_2SO_4, MSA, and OH. Of the six trace gases listed, it is quite apparent that NO underwent one of the largest changes between field studies. In 1998 the median value was in the 200–250 range for the month of December. In contrast, for the last half of November 2000, the median NO was 93 pptv, and dropped into the eighties during December. Extreme variations in the day to day values of NO are apparent in the very large standard deviations cited for the mean values of NO, both for 1998 and 2000.

Median O_3 levels in 1998 underwent a very modest decrease from the last half of November to the last half of December; whereas, in 2000 there was some meandering in the levels observed, with the maximum value in the median occurring in the first half of December. However, the medians for both years tended to range from 30 to 35 ppbv; and as seen in Table 3, mean values were typically within 1 ppbv of the median. One of the more interesting characteristics of the O_3 data is the rather large standard deviation cited in both the 1998 and 2000 data. As noted by Crawford et al. (2001), this large value primarily reflects the major oscillations that can occur in SP O_3 levels over the course of just a few days due to the net photochemical formation of this species. The positive excursions in O_3 above the median value typically exceed the well-documented maximum in O_3 that occurs during the Austral winter season.

The trend in median CO is similar to that for O_3 in that CO is seen decreasing from the second half of November to the last half of December. This decrease reflects the enhancement in CO's photochemical destruction as driven by its oxidation via reaction with OH. However, the difference between sampling years is seen as being quite modest with the final values in the last half of December for both studies being nearly identical. Only in the second half of November is there a significant difference in CO levels, the median value for 1998 being 3 ppbv higher than in 2000.

Table 3
Median and mean values for gas phase chemical species and photochemical parameters for ISCAT 1998 and 2000

| | Nov. 15–30 | | | | Dec. 1–15 | | | | Dec. 15–31 | | | |
| | 1998 | | 2000 | | 1998 | | 2000 | | 1998 | | 2000 | |
	Avg.	Med.	Avg.	Med.	Avg.	Med.	Avg.	Med.	Avg.	Med.	Avg.	Med.
$J(O^1D)$ $(S^{-1}) \times 10^{-6}$			5.9 ± 1.8	5.3	8.2 ± 0.5	8.16	6.7 ± 0.7	6.8	8.6 ± 1.3	8.9	8.5 ± 0.8	8.5
$J(NO_2)$ $(S^{-1}) \times 10^{-2}$			0.88 ± 0.15	0.91	1.1 ± 0.1	1.0	1.0 ± 0.1	1.1	0.95 ± 0.11	1.0	1.0 ± 0.1	1.1
NO (pptv)			102 ± 69	93.379	214 ± 84	209	95 ± 103	82.	244 ± 120	237	113 ± 102	88
O_3 (ppbv)	34.4 ± 5.3	35.1	32.2 ± 3.4	32.3	32.6 ± 5.9	32.6	35.6 ± 3.1	35.2	27.7 ± 7.0	26.1	29.3 ± 5.8	30.0
CO (ppbv)	45.1	44.2	40.1 ± 1.6	40.0	37.7		37.4 ± 2.0	37	34.5		34.3 ± 2.7	34.35
C_2H_6 (pptv)			215 ± 12	214	439 ± 186	417	181 ± 26	180	383 ± 153	376	144 ± 13.6	145
CH_2O (pptv)							109 ± 36	122			100 ± 29	105
H_2O_2 (pptv)							288 ± 129	294			231 ± 74	229
OH $(m\,cm^{-3}) \times 10^6$			2.5 ± 0.6	2.4	1.6 ± 0.4	1.4	2.6 ± 1.0	2.9	1.9 ± 1.1	1.7	2.1 ± 0.8	2.3
PO_2 $(m\,cm^{-3}) \times 10^7$											8.3 ± 2.4	8.1
HCO_2H (pptv)							70 ± 42	58			124 ± 83	85
CH_3CO_2H (pptv)							231 ± 126	215			275 ± 119	264
HONO (pptv)							8.0 ± 3.7	7			27.0 ± 7.4	28
HNO_3^- UNH (pptv)							35.3 ± 8.4	33.8			23.5 ± 11.4	19.9
HNO_3^- GT (pptv)											19.3 ± 11.4	18.2
HO_2NO_2 (pptv)											23.3 ± 10.9	23.5
DMS (pptv)					<2	<2	6.6 ± 5.3	3.3	1.7 ± 3.9	0.7	1.9 ± 1.0	1.4
SO_2 (pptv)			7.8 ± 4.6	6.5			9.9 ± 11.4	4.5			5.7 ± 4.3	2.8
H_2SO_4 $(m\,cm^{-3}) \times 10^5$			2.9 ± 1.2	2.9	2.5 ± 0.3	2.5	3.0 ± 1.3	3.0	2.5 ± 1.5	2.4	2.4 ± 1.4	2.3
MSA $(m\,cm^{-3}) \times 10^4$			5.3 ± 3.2	4.81	5.9 ± 2.8	5.6	5.9 ± 6.3	4.4	7.5 ± 12	4.6	6.9 ± 8.2	3.8

For the shorter lived species OH, H_2SO_4, and MSA, the trends within a given sampling season are very weak and lie clearly within the standard deviations cited in Table 3. In the case of H_2SO_4 and MSA, there is only a very modest difference between the 1998 and 2000 seasons, e.g., they fall well within the stated uncertainties. Only in the case of OH can one possibly make an argument that perhaps the 2000 data are systematically higher. However, given the large uncertainty assigned to the calibration of the OH SICIMS system in 1998, it is difficult to argue that a major difference exists between the two sampling seasons. As stated by Mauldin et al. (2001), what is apparent is that the oxidizing power at the SP rivals or exceeds that in the tropics (i.e., the tropical marine BL) based on both year's sampling.

4.2. Median and mean values of radiative parameters

Both the values of $J(NO_2)$ and $J(O^1D)$ are shown in Table 3 increasing as the observational period moved from mid-November to the end of December. However, the degree of change for $J(NO_2)$ is seen as quite modest, reflecting the much larger dependence of this "J" value on longer wavelength radiation. By contrast, $J(O^1D)$ is strongly dependent on low wavelength UV radiation, making it sensitive to both the solar path-length and the overhead O_3 column density. Thus, significant variations in its value can occur during the spring/summer season. This is revealed in Table 3, where it can be seen that a significant shift in the value of $J(O^1D)$ occurred over the course of the 2000 study, and a significant difference can also be seen between the 1998 and 2000 values for the same time of year due to 1998 having a lower overhead O_3 column density in early December. (For additional detail the reader is directed to Lefer et al. (2001).)

4.3. Median and mean values for aerosol species

Of the aerosol species shown in Table 4, NO_3^-, SO_4^{-2}, and MS were the three species for which data were collected in both the 1998 and 2000 studies. For both NO_3^- and SO_4^{-2} no major trend can be seen within the years 1998 or 2000 during the sampling season itself. But, this is not true for MS which in 2000 decreased by over a factor of 2 from the second half of November to the first half of December. In contrast, no significant trend is seen in the 1998 data over the month of December. By far the most important trend in these aerosol data is the difference seen when comparing the 1998 with the 2000 results. For example, the 1998 SO_4^{-2} values are typically a factor of 2 higher and MS levels are at least a factor of 4 higher. Interestingly, NO_3^- shows just the opposite trend, with 2000 levels being approximately 4 times higher than those in 1998. (For further details see Arimoto et al. (2001).

Table 4
Median and mean values for aerosol species for ISCAT 1998 and 2000

| | Nov. 15–30 | | | | Dec. 1–15 | | | | Dec. 15–31 | | | |
| | 1998 | | 2000 | | 1998 | | 2000 | | 1998 | | 2000 | |
	Avg.	Med.	Avg.	Med.	Avg.	Med.	Avg.	Med.	Avg.	Med.	Avg.	Med.
Na + (μg m^{-3})					0.047 ± 0.021	0.042			0.035 ± 0.018	0.030		
NO$_3^-$ (μg m^{-3})			0.13 ± 0.06	0.14	0.041 ± 0.018	0.045	0.16 ± 0.06	0.154	0.038 ± 0.024	0.032	0.15 ± 0.04	0.14
SO$_4^{2-}$ (μg m^{-3})			0.11 ± 0.02	0.104	0.21 ± 0.05	0.20	0.09 ± 0.02	0.09	0.22 ± 0.05	0.21	0.10 ± 0.02	0.10
MS (μg m^{-3})			6.5 ± 2.8	7.0	11.8 ± 4.7	10.4	2.6 ± 1.1	2.4	11.3 ± 4.1	11.6	4.6 ± 3.5	3.1
Be^7 (fCi m^{-3})			LOD	LOD	205 ± 90	174	LOD	LOD	157 ± 28	148.5	LOD	LOD
Pb^{210} (fCi m^{-3})			LOD	LOD	LOD	LOD	LOD	LOD	LOD	LOD	LOD	LOD
Hg (ng m^{-3})			0.19 ± 0.11	0.18			0.20 ± 0.16	0.22			0.086 ± 0.041	0.079

5. Research highlights—ISCAT special issue papers

5.1. $HO_x/NO_x/O_3$ and fast photochemistry

It is now quite apparent that the ISCAT 2000 field study has moved our understanding of SP photochemistry substantially forward relative to where we were at the end of ISCAT 1998. At the end of the1998 study, there was speculation that other HO_x sources might be present at SP (Chen et al., 2001). The H_2O_2 and CH_2O observations during ICAT 2000 have now made quite evident that this is almost certainly true (see e.g., Chen et al., 2004, Hutterli et al., 2004). For example, the new observations have shown that even though generated photochemically in the gas phase, a still larger source of these species exists in the form of emissions from the snowpack (Hutterli et al., 2004). The reporting of the first of their kind measurements of the radical species $(HO_2 + RO_2)$, has also resulted in a more rigorous testing of current photochemical mechanisms (e.g., Mauldin et al., 2004; Chen et al., 2004). A major surprise arising from the ISCAT 2000 observations was finding relatively high levels of HONO. Using the observed concentration values for this species dramatically altered the predicted levels of OH. They also lead to the conclusion that HONO emissions could be the major source of atmospheric NO_x (Dibb et al., 2004; Chen et al., 2004). This result, therefore, has raised yet a new set of questions related to possible missing sinks for HO_x and NO_x or alternatively, problems with the HONO measurement itself.

The field measurements of NO during 2000, both within the snowpack and in the atmosphere at multiple elevations, have confirmed the credibility of the 1998 observations and clearly demonstrated that the source of NO_x is emission from the snow (Davis et al., 2004). The MET tower gradient measurements of NO, in conjunction with micro-MET observations of temperature, humidity, and wind speed, have also made possible the first flux estimates of NO and NO_x from surface snow at SP (Oncley et al., 2004). These values have been used to evaluate the recycling NO_x flux for the plateau and how this process might be influencing the distribution of near surface nitrate levels across the plateau (Davis et al., 2004). And finally, the detailed analysis of both the ISCAT 1998 and 2000 NO observations have been quite revealing in establishing the uniqueness of the SP site relative to other polar sites as related to NO_x levels. In particular, the fact that NO levels are nearly an order of magnitude higher at SP than at all other polar sites can now be understood in terms of the differences in 5 critical factors (e.g., see Davis et al., 2004).

Closely related to the above NO_x chemistry developments are the first of their kind SP measurements of HNO_3 and HO_2NO_2. These new measurements performed during ISCAT 2000 have convincingly demonstrated that the formation of these species define the dominate SP sinks for HO_x and NO_x (Huey et al., 2004; Slusher et al., 2002; Dibb et al., 2004). Equally interesting, and again related to the observed HO_x levels at SP and the intensity of photochemistry there, are the results involving marine emissions of the trace gases DMS, $CHBr_3$, CH_3I, and CH_3ONO_2. These trace gases are removed from the atmosphere either via their oxidation via OH or by direct photolysis. Quite interestingly, the ISCAT 2000 results have convincingly shown that due to the wide range in chemical lifetimes, in conjunction with a wide range of possible transport times, quite different mixes of gases of marine origin can routinely arrive at SP even though the species start out at the same source location (e.g., see Swanson et al., 2004).

5.2. Aerosol and sulfur results

One of the surprising results of ISCAT 1998 was finding very little evidence of DMS and of SO_2 at SP. This was also the case in the 2000 study (Swanson et al., 2004; Huey et al., 2004). The levels of H_2SO_4 and MSA measured at SP in both years also tend to confirm that the source of sulfur aerosol is not due to the condensation of locally formed H_2SO_4 and MSA (Mauldin et al., 2004; Park et al., 2004). However, the 2000 study did provide new evidence showing the coupling between SO_2 and OH and the end product H_2SO_4 (Huey et al., 2004). They also, with one possible exception, have provided evidence that conditions at SP are not, on average, favorable to the formation of new particle formation (Park et al., 2004). The one exception appears to be a case where the wind direction and low wind speed may have resulted in SP generator emissions influencing the observations at the ARO building. Quite significant as related to aerosol findings was also establishing that in both ISCAT 1998 and 2000 the median value for the ratio of MS/NSS was 0.07 (Arimoto et al., 2001). This observation has demonstrated for the first time that these two chemical species arrive at SP in approximately the same ratio as is typically found in plateau near-surface (1000 yr bp) ice cores (Saigne and Legrand, 1987). A final 2000 finding was observing for the first time at SP filterable Hg. The concentration levels found approached those reported in the Arctic; however, the chemical driving mechanism at SP appears to be quite different from that in the Arctic (Arimoto et al., 2004b).

5.3. Snow chemistry

A number of snow pits were examined during the ISCAT 2000 study in which the levels of NO_3^-, SO_4^{-2}, Cl^-, and Na^+, were analyzed for comparison with earlier studies as well as comparison with studies at other polar sites in Antarctica and in Greenland (Dibb et al., 2004). Of particular interest here was the finding

that snowpits near the ARO building at SP did not contain appreciably different levels of NO_3^- as pits dug 12 km away. The levels of this species at SP also appear to be within a factor of 2–3 of other polar sites. In addition to the aforementioned ions, snow measurements were also recorded for the soluble species CH_2O and H_2O_2 (Hutterli et al., 2004). In conjunction with gradient measurements from which flux values for these same species were estimated, ice modeling studies were carried out showing internal consistency between air and snow levels of these species (Hutterli et al., 2004).

Acknowledgements

References

Arimoto, R., Nottingham, A.S., Webb, J., Schloesslin, C.A., Davis, D.D., 2001. Non-sea salt sulfate and other aerosol constituents at the South Pole during ISCAT. Geophysical Research Letters 28, 3645–3648.

Arimoto, R., Hogan, A., Grube, P., Davies, D., Webb, J., Schloesslin, C., Sage, S., 2004a. Major ions and radio-nuclides in aerosol particles from the South Pole during ISCAT 2000, Atmospheric Environment, this issue, doi:10.1016/j.atmosenv.2004.01.049.

Arimoto, R., Schloesslin, C., Davis, D., Hogan, A., Grube, P., Fitzgerald, W., Lamborg, C., 2004b. Lead and mercury in aerosol particles from the South Pole collected during ISCAT 2000, Atmospheric Environment, this issue, doi:10.1016/j.atmosenv.2004.03.073.

Bales, R.C., Wolff, E.W., 1995. Interpreting natural climate signals in ice cores. EOS Transactions on AGU 76, 477–483.

Barnes, I., Becker, K.H., Patroescu, I., 1996. FTIR product study of the OH initiated oxidation of dimethyl sulfide: observation of carbonyl sulfide and dimethyl sulfoxide. Atmospheric Environment 30, 1805–1814.

Bergin, M.S., Russell, A.G., Milford, J.B., 1998. Effects of chemical mechanism uncertainties on the reactivity quantification of volatile organic compounds using a three-dimensional air quality model. Environmental Science and Technology 32, 694–703.

Berresheim, H., 1987. Biogenic sulfur emissions from the Subantarctic and Antarctic Oceans. Journal of Geophysical Research 92, 13245–13262.

Berresheim, H., Huey, J.W., Thorn, R.P., Eisele, F.L., Tanner, D.J., Jefferson, A., 1998. Measurements of dimethylsulfide, dimethylsulfoxide, dimethylsulfone, and aerosol ions at Palmer Station, Antarctica. Journal of Geophysical Research 103, 1629–1637.

Bodhaine, B.A., Barrie, L.A., Schnell, R.C., Shaw, G.E., Mckie, J.K., 1992. Symposium on the tropospheric chemistry of the Antarctic region. Tellus B 44, 250–251.

Chen, G., Davis, D., Crawford, J., Nowak, J.B., Eisele, F., Mauldin, R.L., Tanner, D., Buhr, M., Shetter, R., Lefer, B., Arimoto, R., Hogan, A., Blake, D., 2001. An investigation of South Pole HO_x chemistry: Comparison of model results with ISCAT observations. Geophysical Research Letters 28, 3633–3636.

Chen, G., Davis, D., Crawford, J., Maudin III, R., Eisele, F., Huey, G., et al., 2004. A reassessment of HO_x chemistry based on observation recorded during ISCAT 2000. Atmospheric Environment, this issue, doi:10.1016/j.atmosenv.2003.07.018.

Crawford, J.H., Davis, D.D., Chen, G., Buhr, M., Oltmans, S., Weller, R., Mauldin, L., Eisele, F., Shetter, R., Lefer, B., Arimoto, R., Hogan, A., 2001. Evidence for photochemical production of ozone at the South Pole surface. Geophysical Research Letters 28, 3641–3644.

Davis, D.D., Chen, G., Kasibhatla, P., Jefferson, A., Tanner, D., Eisele, F., Lenschow, D., Neff, W., Berresheim, H., 1998. DMS oxidation in the Antarctic marine boundary layer I: Comparison of model simulations with field observations for DMS, DMSO, $DMSO_2$, $H_2SO_4(g)$, MSA(g), and MSA(p). Journal of Geophysical Research 103, 1657–1678.

Davis, D., Nowak, J.B., Chen, G., Buhr, M., Arimoto, R., Hogan, A., Eisele, F., Mauldin, L., Tanner, D., Shetter, R., Lefer, B., McMurry, P., 2001. Unexpected high levels of NO observed at South Pole. Geophysical Research Letters 28, 3625–3628.

Davis, D., Chen, G., Chin, M., 2003. In: Potter, T.D., Colman, B.R. (Eds.), Atmospheric Sulfur, Handbook of Weather, Climate, and Water: Atmospheric Chemistry, Hydrology, and Societal Impacts. Wiley, New York.

Davis, D., Chen, G., Buhr, M., Crawford, J., Lenschow, D., Leffer, B., Shetter, R., Eisele, F., Mauldin, L., Hogan, A., 2004. South Pole NO_x chemistry: an assessment of factors controlling variability and absolute levels. Atmospheric Environment, this issue, doi:10.1016/j.atmosenv.2004.04.039.

Dibb, J., Whitlow, S., 1996. Recent climate anomalies and their impact on snow chemistry at South Pole, 1987–1994. Geophysical Research Letters 23, 1115–1119.

Dibb, J., Huey, G., Slusher, D., Tanner, D., 2004. Soluble reactive nitrogen oxides at South Pole during ISCAT 2000, Atmospheric Environment, this issue, doi:10.1016/j.atmosenv.2003.01.001.

Harris, J.M., 1992. An analysis of 5-day mid-tropospheric flow patterns for the South Pole-1985–1989. Tellus B 44, 409–421.

Honrath, R.E., Peterson, M.C., Guo, S., Dibb, J.E., Shepson, P.B., Campbell, B., 1999. Evidence of NO_x production within or upon ice particles in the Greenland snowpack. Geophysical Research Letters 26, 695–698.

Huey, G., Tanner, D., Slusher, D., Dibb, J., Davis, D., Chen, G., 2004. CIMS measurements of HNO_3 and SO_2 at the

South Pole during ISCAT 2000, Atmospheric Environment, this issue, doi:10.1016/j.atmosenv.2004.04.037.

Hutterli, M., McConnell, J., Chen, G., Bales, R., Davis, D., Lenschow, D., 2004. Formaldehyde and hydrogen peroxide in air, snow, and interstitial air at South Pole, Atmospheric Environment, this issue, doi:10.1016/j.atmosenv.2004.06.003.

Hynes, A.J., Wine, P.H., Semmes, D.H., 1986. Kinetics and mechanism of OH reactions with organic sulfides. Journal of Physical Chemistry 90, 4148–4156.

Jefferson, A., Tanner, D.J., Eisele, F.L., Davis, D.D., Chen, G., Crawford, J., Huey, J.W., Torres, A.L., Berresheim, H., 1998. OH photochemistry and methane sulfonic acid formation in the coastal Antarctic boundary layer. Journal of Geophysical Research 103, 1647–1656.

Jones, A.E., Weller, R., Wolff, E.W., Jacobi, H.W., 2000. Speciation and rate of photochemical NO and NO_2 production in Antarctic snow. Geophysical Research Letters 27, 345–348.

Lefer, B.L., Hall, S.R., Cinquini, L., Shetter, R.E., 2001. Photolysis frequency measurements at the South Pole during ISCAT-98. Geophysical Research Letters 28 (19), 3637–3640.

Legrand, M., Delmas, R., 1987. A 220-year continuous record of volcanic H_2SO_4 in the Antarctic ice sheet. Nature 327, 671–676.

Legrand, M., Saigne, C., 1988. Formate, acetate, and methanesulfonate measurements in Antarctic ice: Some geochemical implications. Atmospheric Environment 22, 1011–1017.

Legrand, M., Feniet-Saigne, C., 1991. Methanesulfonic acid in South Pole snow layers: A record of strong El Nino. Geophysical Research Letters 18, 187–190.

Legrand, M., Feniet-Saigne, C., Saltzman, E.S., Germain, C., Barkov, N.I., Petrov, V.N., 1991. Ice core record of oceanic emissions of dimethylsulfide during the last climatic cycle. Nature 350, 144–146.

Legrand, M., Feniet-Saigne, C., Saltzman, E.S., Germain, C., 1992. Spatial and temporal variations of methanesulfonic acid and non-seasalt sulfate in Antarctic ice. Journal of Atmospheric Chemistry 14, 245–260.

Legrand, M., Pasteur, E.C., 1998. Methane sulfonic acid to non-sea-salt sulfate ratio in coastal Antarctic aerosol and surface snow. Journal of Geophysical Research 103, 10991–11006.

Legrand, M., Sciare, J., Jourdain, B., Genthon, C., 2001. Subdaily variations of atmospheric dimethylsulfide, dimethylsulfoxide, methanesulfonate, and non-sea-salt sulfate aerosols in the atmospheric boundary layer at Dumont d'Urville (coastal Antarctica) during summer. Journal of Geophysical Research 106, 14409–14422.

Mauldin, R.L., Eisele, F.L., Tanner, D.J., Kosciuch, E., Shetter, R., Lefer, B., Hall, S.R., Nowak, J.B., Buhr, M., Chen, G., Wang, P., Davis, D., 2001. Measurements of OH, H_2SO_4, and MSA at the South Pole during ISCAT. Geophysical Research Letters 28, 3629–3632.

Mauldin III, R.L., Kosciuch, E., Henry, B., Eisele, F.L., Shetter, F., Lefer, B., et al., 2004. Measurement of OH, HO_2/RO_2, H_2SO_4, and MSA during ISCAT 2000, Atmospheric Environment, this issue, doi:10.1016/j.atmosenv.2004.06.031.

Mulvaney, R., Pasteur, E.C., Peel, D.A., 1992. The ratio of MSA to non-sea-salt sulfate in Antarctic Peninsula ice cores. Tellus B 44, 295–303.

Mulvaney, R., Wolff, E., 1994. Spatial variability of the major chemistry of the Antarctic ice sheet. Annals of Glaciology 20, 440–447.

Oncley, D., Lenschow, D., Buhr, M., Davis, D., Semmer, S., 2004. Observations of summertime NO fluxes at the South Pole using scalar similarity, Atmospheric Environment, this issue, doi:10.1016/j.atmosenv.2004.05.053.

Park, J., Sakurai, H., Vollmers, K., McMurry, P.H., 2004. Aerosol size distributions measured at the South Pole during ISCAT 2000. Atmospheric Environment, this issue, doi:10.1016/j.atmosenv.2002.12.001.

Prospero, J.M., Savoie, D.L., Saltzman, E.S., Larsen, R., 1991. Impact of oceanic sources of biogenic sulfur on sulfate aerosol concentrations at Mawson, Antarctica. Nature 350, 221–223.

Ridley, B., Walega, J., Montzka, D., Grahek, F., Atlas, E., Flocke, F., Stroud, V., Deary, J., Gallant, A., Boudries, H., Bottenheim, J., Anlauf, K., Worthy, D., Sumner, A.L., Splawn, B., Shepson, P., 2000. Is the Arctic surface layer a source and sink of NO_x in winter/spring? Journal of Atmospheric Chemistry 36, 1–22.

Saigne, C., Legrand, M., 1987. Methanesulfonic acid in Antarctic ice. Nature 330, 240–242.

Saigne, C., Kirchner, S., Legrand, M., 1987. Ion-chromatographic measurements of ammonium, fluoride, acetate, formate, and methanesulfonate ions at very low levels in Antarctic ice. Analytica Chemica Acta 203, 11–21.

Saltzman, E.S., 1994. Ocean/atmosphere cycling of dimethylsulfide: Sensitivity to climate change, NATO ARW on GBCs in polar ice.

Shaw, G.E., 1980. Optical, chemical and physical properties of aerosols over the Antarctic ice sheet. Atmospheric Enviornment 14, 911–921.

Shaw, G.E., 1988. Antarctic aerosol: A review. Review Geophysical 26, 89–112.

Slusher, D.L., Huey, L.G., Tanner, D.J., Chen, G., Davis, D.D., Buhr, M., Nowak, J.B., Eisele, F.L., Kosciuch, E., Mauldin, R.L., Lefer, B.L., Shetter, R.E., Dibb, J.E., 2002. Measurements of pernitric acid at the South Pole during ISCAT 2000. Geophysical Research Letters 29 (21), 2011 doi:10.1029/2002GL015703.

Sørensen, S., Falbe-Hansen, H., Mangoni, M., Hjorth, J., Jensen, N.R., 1996. Observation of DMSO and $CH_3S(O)OH$ from the gas phase reaction between DMS and OH. Journal of Atmospheric Chemistry 24, 299–315.

Swanson, A., Davies, D., Arimoto, R., Roberts, P., Meinardi, S., Rowland, F., Blake, D., 2004. Organic trace gases of oceanic origin observed at South Pole during ISCAT 2000, Atmospheric Environment, this issue, doi:10.1016/j.atmosenv.2004.03.072.

Turner, J., Pendlebury, S., 2001. The International Antarctic Weather Forecasting Handbook.

Wagenbach, D., 1996. Coastal Antarctica: atmospheric chemical composition and atmospheric transport, in process of chemical exchange between the atmosphere and polar snow. In: Wolff, E., Bates, R. (Eds.), NATO ASI Ser, vol. 143. Springer, New York, pp. 173–179.

Wolff, E.W., Bales, R.C. (Eds.), 1996. Processes of Chemical Exchange between the Atmosphere and Polar Snow. Springer, Berlin Heidelberg, p. 675.