Earth Science Faculty Scholarship

Earth Sciences

1999

The Weddell Sea Region: An Important Precipitation Channel to the Interior of the Antarctic Ice Sheet as Revealed by Glaciochemical Investigation of Surface Snow Along the Longest Trans-Antarctic Route

Qin Dahe

Paul Andrew Mayewski
University of Maine, paul.mayewski@maine.edu

Ren Jiawen

Xiao Cunde

Sun Junying

The Weddell Sea region: an important precipitation channel to the interior of the Antarctic ice sheet as revealed by glaciochemical investigation of surface snow along the longest trans-Antarctic route

QIN DAHE,[1] PAUL A. MAYEWSKI,[2] REN JIAWEN,[1] XIAO CUNDE,[1] SUN JUNYING[1]

[1]*Laboratory of Ice Core and Cold Regions Environment, Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, Lanzhou, Gansu 730000, China*
[2]*Climate Change Research Center, Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH 03824, U.S.A*

ABSTRACT. Glaciochemical analysis of surface snow samples, collected along a profile crossing the Antarctic ice sheet from the Larsen Ice Shelf, Antarctic Peninsula, via the Antarctic Plateau through South Pole, Vostok and Komsomolskaya to Mirny station (at the east margin of East Antarctica), shows that the Weddell Sea region is an important channel for air masses to the high plateau of the Antarctic ice sheet (>2000 m a.s.l.). This opinion is supported by the following. (1) The fluxes of sea-salt ions such as Na^+, Mg^{2+} and Cl^- display a decreasing trend from the west to the east of interior Antarctica. In general, as sea-salt aerosols are injected into the atmosphere over the Antarctic ice sheet from the Weddell Sea, large aerosols tend to decrease. For the inland plateau, few large particles of sea-salt aerosol reach the area, and the sea-salt concentration levels are low. (2) The high altitude of the East Antarctic plateau, as well as the polar cold high-pressure system, obstruct the intrusive air masses mainly from the South Indian Ocean sector. (3) For the coastal regions of the East Antarctic ice sheet, the elevation rises to 2000 m over a distance from several to several tens of km. High concentrations of sea salt exist in snow in East Antarctica but are limited to a narrow coastal zone. (4) Fluxes of calcium and non-sea-salt sulfate in snow from the interior plateau do not display an eastward-decreasing trend. Since calcium is mainly derived from crustal sources, and $nssSO_4^{2-}$ is a secondary aerosol, this again confirms that the eastward-declining tendency of sea-salt ions indicates the transfer direction of precipitation vapor.

INTRODUCTION

Glaciochemical studies of the surface layer over the Antarctic ice sheet are still relatively rare. Previous studies have shown the basic principles governing the chemical composition of impurities in snow on the Antarctic ice sheet, and have provided an understanding of their origins and historic variations (Legrand and Delmas, 1985; Legrand, 1987; Kamiyama and others, 1989; Mayewski and Legrand, 1990; Mulvaney and Wolff, 1994). Since most of the data for the above studies were collected by different methods, procedures and investigators in different years, comparing the data is not always straightforward.

The 1990 International Trans-Antarctic Expedition (ITAE) provided a rare opportunity to investigate the surface characteristics of the Antarctic ice sheet over a wide region. Mulvaney and Wolff (1994) have compiled reliable data for Na^+, NO_3^-, Cl^- and SO_4^{2-}, mostly derived from several transects from the coast towards the interior. Up to now, such data are still very scarce for the vast interior region. The sampling sites along the ITAE route represent the longest transect ever conducted through the main geographic regions of Antarctica (Fig. 1). Along the ITAE route,
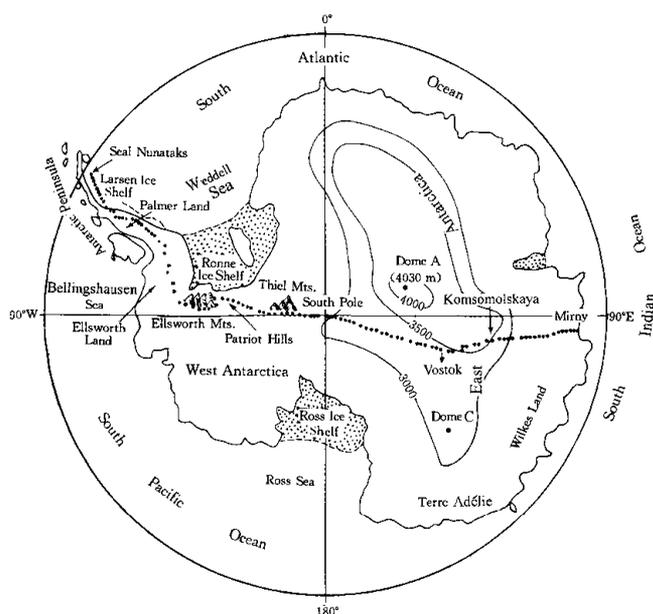

Fig. 1. Antarctic map showing the route of the 1990 ITAE and the sampling sites listed in Table 1.

surface snow samples of 25 cm depth were collected at 97 sites. These samples were analyzed for major ions (Na^+, Cl^-, Mg^{2+}, Ca^{2+}, NO_3^- and SO_4^{2-}) as well as methane-sulfonic acid (MSA). An interpretation of the distribution of NO_3^- has been published (Qin and others, 1992). This paper presents the distribution of the major ions and MSA in the surface snow along the ITAE route, in order to provide a basic interpretation of snow chemistry along the study transect. This in turn casts new light on the problem of trans-portation of air masses onto the Antarctic ice sheet.

Understanding the mean annual temperature and accu-mulation rate along the ITAE route is essential for glacio-chemical interpretation of the data collected. The mean annual temperature data at these sampling stations include (1) $-17.3°C$ measured in the firn at 9.5 m depth at station 10 on 31 August 1989; (2) temperatures measured previously at meteorological stations or in 10 m depth snow (at stations 23, 32, 52, 74, 82, 86 and 92 (Shimizu, 1964; Lorius and others, 1970; Schwerdtfeger, 1970; Barkov, 1975; Lipenkov, 1980; Jouzel and others, 1990)); (3) estimated temperatures obtained from the isothermal diagram of average annual surface tempera-ture in the interior of the East Antarctic plateau (Crary, 1963; Cameron and others, 1968); and (4) the lapse rate and the latitude effect. The elevation along the route was obtained from a large-scale contour map of Antarctica (Drewry, 1983), corrected to position records made on the traverse by G. Samers and J.-L. Etienne (personal communication, 1992).

The Larsen Ice Shelf, located on the east side of the Ant-arctic Peninsula and terminating as ice cliffs in the Weddell Sea, is in a continental climate region. This is because the Antarctic Peninsula is a natural meteorological barrier that demarcates a distinct climatic division between a maritime climate in the west and a continental climate in the east. Sampling sites 1–12 were set on the Larsen Ice Shelf. At these sites, elevations are below 100 m, annual mean tem-peratures are $-12°$ to $-14°C$ and the average accumulation rates are in the range $500–600\ kg\ m^{-2}\ a^{-1}$. Sites 13–19 are distributed over Palmer Land in the Antarctic Peninsula. Within this section of the traverse route, topography is com-plicated, with an elevation range of several hundred meters to 2000 m and the distance to the coast changing irregularly. The estimated accumulation rates are $50–400\ kg\ m^{-2}\ a^{-1}$ and the annual mean temperatures range from $-16°$ to $-22°C$.

From site 30 to the end of the traverse is the main section of the expedition route. Except for the Ellsworth Mountains, where elevation changes irregularly, the elevation increases progressively with increasing distance along the route to the highest point (site 86, 3560 m a.s.l.) and then decreases. About half of this section of the route is > 3000 m a.s.l., belonging to the interior of Antarctic Plateau. Here the climate is quite stable since it is under the control of the polar cold high-pres-sure system. The annual mean temperature is lowest $(-55°C)$ at Vostok, from where, toward both east and west, it increases $(-49°C$ at South Pole and $-27°C$ at Patriot Hills). The accu-mulation is $< 100\ kg\ m^{-2}\ a^{-1}$ at most sites within this section of the route, except at the Ellsworth Mountains. The accumu-lation and climatic data come from several different sources and are described in detail by Qin (1992). Variations in mean annual temperature, accumulation rate and altitude along the route are shown in Figure 2. The accumulation rate was largely derived from the compilation of Giovinetto and Bull (1987), but additional data were used from shallow ice cores and shallow snow pits which covered several tens of years and several years of snow accumulation, respectively (Shimi-
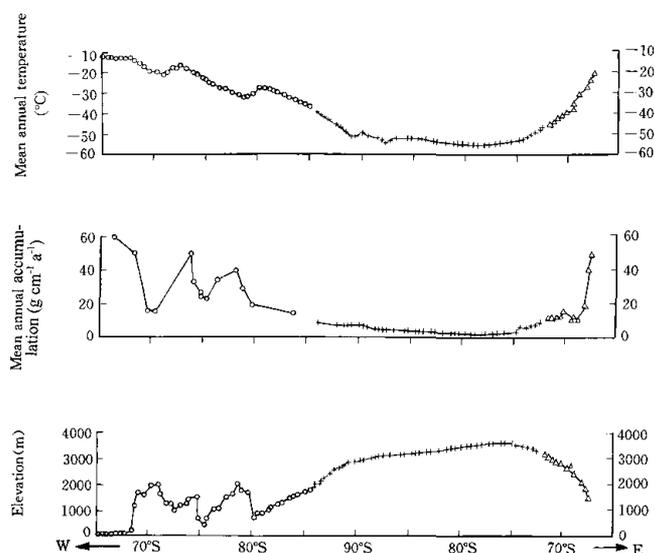

Fig. 2. Variations of mean annual temperature, snow-accumu-lation rate and altitude change along the ITAE route. The ab-scissa is the latitudes of the sampling sites.

zu, 1964; Taylor, 1965; Hamilton and O'Kelley, 1971; Kotlyakov and others, 1978; Lipenkov, 1980; Peel and Clausen, 1982; Jouzel and others, 1983).

Elements derived from the marine environment, Na^+, Cl^- and Mg^{2+}, are used in this study as a proxy for vapor transport. Non-sea-salt derived elements such as Ca^{2+} and non-sea-salt sulfate ($nssSO_4^{2-}$) are used to compare with the sea-salt distribution since they are tracers of continental source area and marine biogenic sources, respectively.

SAMPLING AND ANALYTICAL PROCEDURES

From 27 July 1989 to 3 March 1990, the ITAE succeeded in crossing the Antarctic by dog-sled. The expedition route began at Seal Nunataks ($65°05'$ S, $59°35'$ W), then traversed from the northern end of the Antarctic Peninsula via the Larsen Ice Shelf, Palmer Land, the Ellsworth Mountains ($76–81°$ S, $87°$ W), South Pole, the Area of Inaccessibility and Vostok, and ended at Mirny, a station at the margin of East Antarctica. The route covered a total distance of 5896 km and the journey took 220 days. Ninety-seven 25 cm deep samples of surface snow were collected in polyethylene bottles along the route at roughly equidistant points. Special steps were taken to keep the samples as clean as possible during sampling. The bottles were new and were washed three times using Milli-Q water to clean each bottle to main-tain blank values in the ppb range for ionic measurement of the snow samples. Washed bottles were packed in clean bags in a clean room and were opened only during sampling for a short time. Contamination was avoided by wearing gloves, cleaning the surface of the profile of the snow pits and facing in the windward direction when collecting samples.

All samples were kept frozen until processed. Concentra-tions of major anions and cations in the samples were meas-ured by Dionex 4000 ion chromatography at the Laboratoire de Glaciologie et Géophysique de l'Environnement, Grenoble, France. The detection limits and precision, respectively, were $1 \times 10^{-6} g\ g^{-1}$ and 4% for Cl^-, $0.5 \times 10^{-6} g\ g^{-1}$ and 5% for Na^+, $0.1 \times 10^{-6} g\ g^{-1}$ and 10% for Mg^{2+}, $0.5 \times 10^{-6} g\ g^{-1}$ and 50% for Ca^{2+}, and $1 \times 10^{-6} g\ g^{-1}$ and 5% for SO_4^{2-}.

RESULTS AND DISCUSSION

Analytical results for Na$^+$, Cl$^-$, Mg^{2+}, SO$_4$$^{2-}$ and Ca^{2+} in samples are presented in Table 1 along with the sampling date and location. The distance from station 1 (Seal Nunataks), elevation and mean annual accumulation rate at 65 stations have been listed previously (Qin and others, 1992). Among the major ions, Na$^+$ is usually considered to be totally derived from sea-salt aerosol. Thus it is often selected

for calculating sea-salt (ss) and non-sea-salt (nss) fractions of other ions. The calculation is important because it could provide information on sources, transportation and/or development of aerosol recorded in snow. Unfortunately, we find negative values of nssMg^{2+} when the calculation is based on Na$^+$. Since we exclude the possibility that the samples were contaminated, the explanation is believed to be (1) Na$^+$ was concentrated during the process of transportation from source region to deposition site, and /or (2) extra

Table 1. *The results of chemical analyses of some ions in 25 cm deep snow samples on the ITAE route. Unit of ion concentration is 10^{-6} g g^{-1}. The sampling date, positions and represented seasons of the snow are also listed*

Site	Date	Position	Na$^+$	Mg^{2+}	Ca^{2+}	Cl$^-$	SO$_4$$^{2-}$	Accumulation season of snow*	Site	Date	Position	Na$^+$	Mg^{2+}	Ca^{2+}	Cl$^-$	SO$_4$$^{2-}$	Accumulation season of snow*
	dd/mm/yy									dd/mm/yy							
1	27/07/89	65°05′ S 59°35′ W	271	32.7	14.5	441	54	W	54	05/12/89	87°36′ S 91°06′ W	4	0.5	1.5	23	39	M
2	28/07/89	65°10′ S 59°59′ W	–	–	–	–	–	–	55	06/12/89	87°57′ S 91°55′ W	16	1.9	2.5	61	39	M
3	29/07/89	65°17′ S 60°19′ W	–	–	–	–	–	–	56	08/12/89	88°38′ S 92°26′ W	13	1.6	3.0	50	43	M
4	30/07/89	65°27′ S 60°45′ W	–	–	–	–	–	–	57	09/12/89	89°00′ S 92°58′ W	12	1.5	2.5	52	47	M
5	01/08/89	65°35′ S 61°10′ W	457	55.1	32.5	799	132	W	58	10/12/89	89°22′ S 91°39′ W	14	1.7	1.5	41	31	M
6	02/08/89	65°42′ S 61°32′ W	–	–	–	–	–	–	59	13/12/89	90°00′ S	8	1.0	1.5	30	39	M
7	03/08/89	65°50′ S 61°57′ W	324	39.0	24.5	578	100	W	60	16/12/89	89°53′ S 114°22′ E	13	1.6	2.0	53	42	M
8	10/08/89	66°20′ S 62°36′ W	1054	127.0	48.5	1872	210	W	61	17/12/89	89°32′ S 108°18′ E	17	2.1	2.0	59	45	M
9	13/08/89	66°54′ S 63°32′ W	499	60.1	23.0	784	112	W	62	18/12/89	89°11′ S 105°35′ E	14	1.7	1.5	52	48	M
10	15/08/89	67°20′ S 64°07′ W	43	5.2	2.5	61	17	W	63	20/12/89	88°26′ S 104°27′ E	18	2.2	2.0	68	54	M
11	18/08/89	67°47′ S 64°32′ W	21	2.5	2.0	32	12	W	64	21/12/89	88°03′ S 104°35′ E	16	1.9	2.0	63	55	M
12	23/08/89	68°25′ S 65°15′ W	76	9.2	4.5	107	29	W	65	22/12/89	87°42′ S 104°39′ E	13	1.6	1.5	57	61	M
13	27/08/89	68°43′ S 65°26′ W	60	7.2	4.0	115	31	W	66	23/12/89	87°20′ S 104°25′ E	19	2.3	2.5	79	56	M
14	28/08/89	68°48′ S 65°22′ W	–	–	–	–	–	–	67	25/12/89	86°36′ S 104°57′ E	16	1.9	2.0	72	53	M
15	29/08/89	68°57′ S 65°26′ W	–	–	–	–	–	–	68	29/12/89	85°33′ S 105°40′ E	16	1.9	2.0	61	83	M
16	30/08/89	69°04′ S 65°20′ W	–	–	–	–	–	–	69	30/12/89	85°13′ S 105°49′ E	26	3.1	1.5	72	85	M
17	31/08/89	69°10′ S 65°18′ W	21	2.5	1.5	42	26	W	70	01/01/90	84°28′ S 106°17′ E	20	2.4	3.0	72	68	M
18	05/09/89	69°41′ S 65°13′ W	12	1.5	1.0	23	29	W	71	02/01/90	84°07′ S 106°17′ E	17	2.0	3.0	99	79	M
19	09/09/89	70°25′ S 64°44′ W	25	3.0	2.0	73	47	W	72	03/01/90	83°44′ S 106°24′ E	21	2.5	2.0	85	108	M
20	14/09/89	70°58′ S 64°41′ W	7	0.8	1.0	17	20	W	73	05/01/90	83°00′ S 106°12′ E	36	4.3	2.0	73	93	M
21	15/09/89	71°17′ S 65°43′ W	85	10.2	3.5	137	29	W	74	06/01/90	82°40′ S 106°19′ E	17	2.0	3.0	116	77	M
22	17/09/89	71°56′ S 65°18′ W	31	3.7	3.5	64	22	W	75	09/01/90	81°50′ S 106°28′ E	21	2.5	2.5	77	85	M
23	18/09/89	72°14′ S 65°29′ W	47	5.7	3.0	86	18	W	76	11/01/90	81°05′ S 106°26′ E	–	–	–	–	119	M
24	19/09/89	72°33′ S 65°55′ W	17	2.1	1.5	34	11	W	77	12/01/90	80°42′ S 106°12′ E	28	3.4	3.5	131	87	M
25	23/09/89	73°14′ S 66°48′ W	54	6.5	2.5	98	18	W	78	13/01/90	80°17′ S 106°14′ E	29	3.5	4.0	92	83	M
26	30/09/89	73°56′ S 67°30′ W	88	10.6	4.0	164	32	W	79	14/01/90	79°42′ S 106°04′ E	28	3.4	4.5	119	137	M
27	06/10/89	74°05′ S 69°57′ W	26	3.1	2.5	50	10	W	80	16/01/90	79°08′ S 106°08′ E	22	2.6	1.5	92	126	M
28	09/10/89	74°46′ S 72°46′ W	87	10.5	5.0	164	29	W	81	17/01/90	78°46′ S 106°41′ E	24	2.9	2.5	116	110	M
29	11/10/89	74°51′ S 75°45′ W	51	6.1	2.5	89	30	W	82	22/01/90	78°07′ S 105°47′ E	20	2.4	2.5	109	76	M
30	15/10/89	75°26′ S 78°29′ W	60	7.2	3.0	10	29	W	83	23/01/90	77°43′ S 104°47′ E	30	3.6	2.0	119	109	M
31	18/10/89	75°47′ S 81°40′ W	66	8.0	4.0	111	28	W	84	25/01/90	77°00′ S 102°55′ E	17	2.1	4.0	88	93	M
32	24/10/89	76°25′ S 85°10′ W	44	5.3	4.0	80	29	W	85	26/01/90	76°36′ S 102°00′ E	18	2.2	3.0	73	72	M
33	26/10/89	76°56′ S 86°15′ W	31	3.7	2.5	68	18	W	86	28/01/90	75°54′ S 100°31′ E	16	1.9	3.0	59	75	M
34	28/10/89	77°39′ S 87°07′ W	38	4.6	4.0	78	18	W	87	29/01/90	75°33′ S 100°31′ E	12	1.4	2.5	59	49	M
35	30/10/89	78°12′ S 87°39′ W	33	4.0	3.5	77	23	W	88	31/01/90	74°44′ S 98°41′ E	14	1.7	1.5	44	60	M
36	01/11/89	78°49′ S 87°14′ W	165	20.0	7.0	264	30	W	89	01/02/90	74°21′ S 98°00′ E	19	2.3	4.0	60	53	M
37	02/11/89	79°10′ S 86°51′ W	66	8.0	6.5	139	29	W	90	04/02/90	73°41′ S 97°26′ E	8	1.0	4.0	52	58	M
38	04/11/89	79°45′ S 85°18′ W	32	3.8	3.0	73	31	W	91	05/02/90	73°18′ S 97°09′ E	8	1.0	1.0	32	43	M
39	09/11/89	80°18′ S 81°21′ W	109	13.1	75.5	97	94	W	92	06/02/90	72°51′ S 96°59′ E	4	0.5	3.0	37	25	M
40	11/11/89	80°45′ S 81°15′ W	204	24.6	7.0	342	38	W	93	07/02/90	72°28′ S 96°45′ E	6	0.7	3.5	29	23	M
41	14/11/89	81°12′ S 82°00′ W	304	36.6	8.5	444	42	W	94	09/02/90	71°42′ S 96°17′ E	5	0.6	2.0	30	31	S
42	16/11/89	81°48′ S 82°50′ W	271	32.7	9.5	409	62	W	95	10/02/90	71°20′ S 96°01′ E	12	1.4	4.5	46	41	S
43	17/11/89	81°55′ S 83°20′ W	65	7.8	4.0	98	29	W	96	11/02/90	70°57′ S 95°54′ E	8	1.0	2.5	24	30	S
44	19/11/89	82°41′ S 84°00′ W	156	18.8	6.5	235	41	W	97	12/02/90	70°33′ S 95°43′ E	9	1.1	5.5	41	31	S
45	20/11/89	83°05′ S 84°45′ W	70	8.4	7.5	170	35	W	98	14/02/90	70°11′ S 95°35′ E	4	0.5	2.5	29	24	S
46	22/11/89	83°47′ S 87°25′ W	44	5.3	3.0	84	22	W	99	15/02/90	69°46′ S 95°22′ E	2	0.2	1.5	12	28	S
47	23/11/89	84°12′ S 88°05′ W	27	3.3	2.5	68	19	W	100	18/02/90	69°26′ S 95°07′ E	14	1.7	4.0	38	60	S
48	24/11/89	84°35′ S 88°55′ W	33	4.0	4.0	82	38	W	101	21/02/90	68°51′ S 94°37′ E	4	0.5	2.0	28	35	S
49	26/11/89	85°11′ S 88°58′ W	66	7.9	3.0	130	26	W	102	23/02/90	68°05′ S 93°50′ E	5	0.6	3.0	22	52	S
50	29/11/89	85°53′ S 88°10′ W	15	1.8	2.5	48	25	W	103	24/02/90	67°42′ S 93°39′ E	7	0.8	4.5	35	52	S
51	30/11/89	86°12′ S 88°25′ W	14	1.7	2.0	44	24	M	104	25/02/90	67°21′ S 93°26′ E	7	0.8	2.3	31	45	S
52	02/12/89	86°34′ S 88°57′ W	17	2.0	3.5	66	29	M	105	03/03/90	66°33′ S 93°00′ E	–	–	–	–	–	–
53	03/12/89	86°54′ S 90°19′ W	17	2.0	1.5	49	72	M									

* W, winter snow; S, summer snow; M, multi-year snow.

Na^+, such as crustal-origin Na^+, exists in addition to sea-salt aerosol. Mg^{2+} was therefore chosen for the calculation. The revised Na^+ concentrations are listed in Table 1.

The number of years represented by the 25 cm snow samples depends on the accumulation rate at the sampling site. Generally, it is difficult to identify annual layers in such a shallow depth, so we estimate the accumulation rate as follows.

The net accumulation rate in Antarctica usually decreases with increasing latitude from the coast to the interior. But this relationship is less reliable than that of the mean annual temperature with latitude, particularly in near-coastal regions. On the other hand, accumulation rate may exhibit high annual variability. All of these circumstances make it difficult to estimate the age of the surface snow in Antarctica. However, Giovinetto and Bull (1987) summarized recent surface mass-balance measurements over the Antarctic ice sheet. By using previous records of accumulation rate at some sites on the route (e.g. sites 25, 37, 39, 62, 64, 66, 68, as well as sites 90–104 (Shimizu, 1964; Taylor, 1965; Hamilton and others, 1971; Lipenkov, 1980, Peel and Clausen, 1982; Jouzel and others, 1983, 1990), and by interpolating values between the sites at which accumulation rate is known, the age of the surface 1 m snow along the traverse route was plotted (Qin and others, 1994).

The pattern of the mean annual accumulation rate along the ITAE route is one of high accumulation at the beginning and end of the route, and lower accumulation in the middle section (Qin and others, 1992). The highest value is $600 \text{ kg m}^{-2}\text{a}^{-1}$, and the lowest is $23 \text{ kg m}^{-2}\text{a}^{-1}$. Using a mean snow density of 400 kg m^{-3} in the regions where the accumulation rate is $<100 \text{ kg m}^{-2}\text{a}^{-1}$, a 25 cm depth snow sample may represent 1–4 annual layers (Fig. 3), and we call this multi-year snow (M in Table 1, sites 51–93). On the east side of section M (i.e. from Seal Nunataks to site 50), the surface 25 cm represents only winter snow (W in Table 1) since the accumulation rate is $>100 \text{ kg m}^{-2}\text{a}^{-1}$. On the west side of section M (i.e. from site 94 to Mirny station), it represents only summer snow (S in Table 1).

Concentrations of Cl^-, Na^+, Mg^{2+}, Ca^{2+} and $nssSO_4^{2-}$ over the ITAE route, as well as their fluxes in section M, are shown in Figure 4. It is clear that the three ions (Cl^-, Na^+, Mg^{2+}) that are mainly derived from maritime aerosols display a similar distribution pattern along the ITAE route. The concentrations of the three ions are highest at sea level on the Larsen Ice Shelf, variable but quite high in the rest of section W (i.e. West Antarctica), lower over section M (i.e. the interior plateau of Antarctica) and even lower over section S (i.e. the east margin of Antarctica). Fluxes of these three ions also show a similar pattern of distribution, decreasing from west to east over section M. Of the fluxes of the three ions, Na^+ and Mg^{2+} decrease more sharply than Cl^-.

The composition and concentration of impurities in snow over Antarctica depend largely on the sources of the air masses, the transport distance and compositional changes along the transport route.

The average altitude of the initial segment of the ITAE route in West Antarctica is relatively low. This coastal region, located adjacent to the South Atlantic, is a primary source of water vapor and provides large amounts of maritime impurities to the snow of West Antarctica. The flat open area from the Ross–Bellingshausen–Weddell Sea southward to the interior continental plateau is the most favorable region in Antarctica for water-vapor transfer to inland regions. Previous aerosol studies have revealed that air masses coming
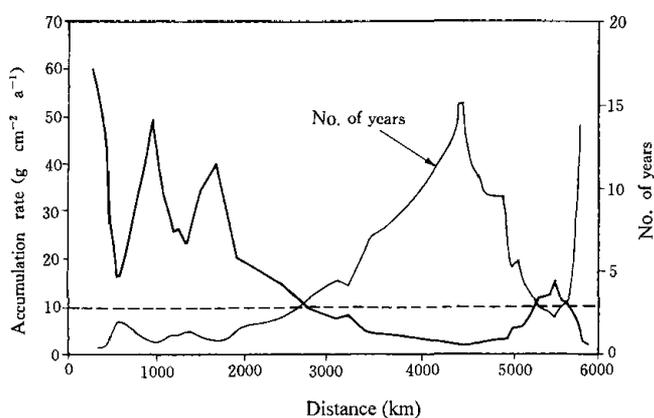

Fig. 3. Annual-layer number within 1m deep snow and annual mean accumulation rate along the ITAE traverse route.

from the mid-latitudes and the sub-Antarctic Ocean are sporadically transported towards the inland plateau and even reach South Pole (Bodhaine and others, 1986). These "sodium storms" bring large quantities of sea salt to the central ice sheet.

These events are most frequent in late winter/early spring, accompanying the breakdown of the circumpolar vortex (Shaw, 1988). Hogan and others (1990) recognized that the large quantity of maritime aerosols is associated with large-
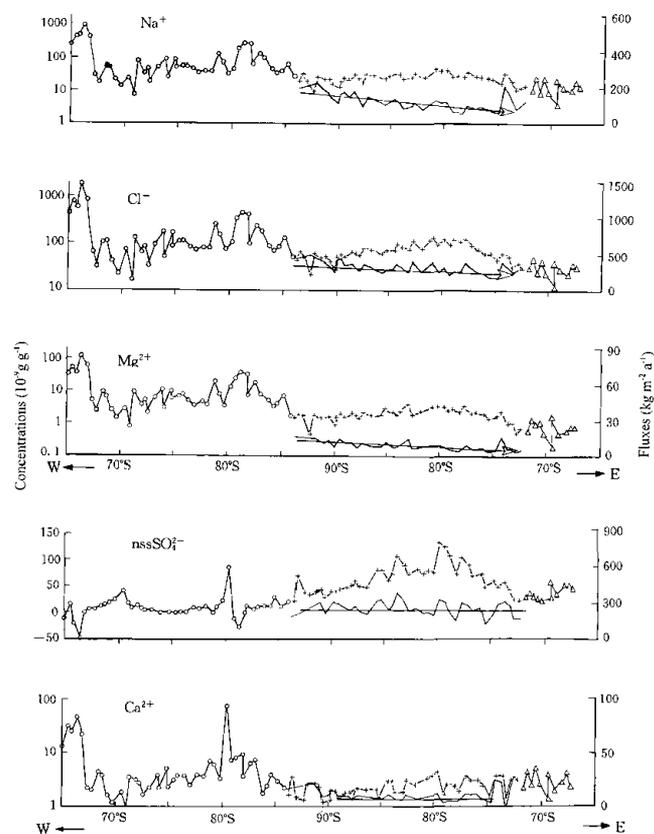

Fig. 4. Distribution of the concentrations and fluxes of Cl^-, Na^+, Mg^{2+}, Ca^{2+} and $nssSO_4^{2-}$ along the ITAE route. Circles represent the section mainly of winter snow; crosses the multi-year snow; and triangles the section mainly of summer snow. Left ordinate: the measured concentration (in exponent) of surface snow. Right ordinate: the calculated fluxes ($kg\, m^{-2}a^{-1}$) for multi-year snow only. Abscissa: the latitudes of the sampling sites.

scale increases in temperature. Meteorological evidence shows that the precipitation season over West Antarctica is mainly during October–December (Schwerdtfeger, 1984). The route of transport for these air masses towards the South Pole coincides approximately with the route of the ITAE, and the "storm events" season occurs at the same period the ITAE team passed through West Antarctica. It is therefore not surprising that the sea-salt ions (Cl^-, Na^+, Mg^{2+} and $ssSO_4^{2-}$) show high concentration in the West Antarctic segment of the route. The concentration peaks at Larsen Ice Shelf, where the elevation is close to that of sea surface.

At the other end of the ITAE route, the concentration of the sea-salt ions decreases. If the precipitation to this region is mainly derived from the adjacent ocean, i.e. the South Indian Ocean, the concentration of Cl^-, Na^+ and Mg^{2+} should increase. Apart from a very narrow strip in coastal East Antarctica, water vapor in the regions of East Antarctica above 2000 m a.s.l. has clearly not come from the South Indian Ocean. It is probably derived from the vapor channel from the Ross–Bellingshausen–Weddell Sea towards the interior, especially from the Weddell Sea direction. Evidence for this inference is as follows:

(1) The central part of the East Antarctic plateau, where the altitude is over 3000 m, is dominated by a polar cold high pressure all year round. This is an effective obstruction to air masses from the South Indian Ocean intruding up to the inland plateau.

(2) The elevation is low in the coastal regions of East Antarctica, but increases sharply inland. It rises to >2000 m a.s.l. in a distance of a few tens of km. The rapid topographic change favors the formation of orographic precipitation, and thus leads to a loss of impurities from the narrow coastal regions of East Antarctica. As noted by Delmas and Boutron (1978), deposition of coarse-sized sea-salt aerosols in Antarctic snow rapidly decreases with distance inland or elevation, and comprises only about 10% of the total sulfate deposition at inland sites in Antarctica.

(3) The fluxes of Cl^-, Na^+ and Mg^{2+} display a decreasing trend from west to east in section M of the ITAE route (Fig. 3), indicating that sea-salt aerosol is mainly derived from the direction of the Weddell Sea. During transport from the coastal ocean area towards the South Pole, large particles tend to deposit in the initial segment of the route, leading to high concentrations and fluxes of sea-salt ions, such as Cl^-, Na^+, Mg^{2+} and $ssSO_4^{2-}$. But in section M, few large particles remain in the air, and the aerosol amount largely decreases. The fluxes of the four ions decrease eastward. In fact, the interior of the Antarctic Plateau is one of the driest regions on Earth.

(4) Ca^{2+} does not show an eastward flux decreasing in the interior plateau. Except for a few high values, Ca^{2+} concentrations are very low and maintain a rather constant flux level in section M. Remote continental areas are believed to be the main sources of Ca^{2+} in snow of the East Antarctic plateau. The low values of Ca^{2+} in snow of the interior plateau represent background values for Antarctica.

High values of calcium in section W can be partly attributed to sea salt. Extremely high values are formed close to the bare rocks or mountains along the ITAE route. For instance, widespread bare bedrock and nunataks over the

Larsen Ice Shelf are responsible for the high concentrations of Ca^{2+} in this region. Also, calcium content at site 39 is 10–20 times higher than at the adjacent sites, because site 39 is located downwind from Patriot Hills.

Sources of $nssSO_4^{2-}$ are complicated. They may include crustal, volcanic and anthropogenic as well as marine biotic sources. In Figure 4, $nssSO_4^{2-}$ shows high concentrations in interior Antarctica and a constant distribution of fluxes over that segment of the route. This is quite similar to the distribution of Ca^{2+} fluxes, which implies that their distribution in the atmosphere over the high Antarctic Plateau is uniform. Because of the high altitude of this segment of the route (>3600 m a.s.l.) we suggest that the majority of Ca^{2+} and $nssSO_4^{2-}$ may be derived from the upper troposphere.

CONCLUDING REMARKS

Direct observational and instrumental records in Antarctica are relatively scarce and cover a very short history. Any study of the spatial and temporal complexity of the climate system over this isolated continent is worthwhile. Up to now, the recovery of surface snow samples and ice cores has clearly been insufficient to cover the entire Antarctic continent, and this has obstructed the interpretation of even its most recent (decades to centuries) climatic and environmental history. Fortunately, the International Trans-Antarctic Scientific Expedition (ITASE) has had as a primary aim the improvement of the coverage. Future studies across the ITASE traverse net covering the whole continent will provide more detailed information on surface snow chemistry.

ACKNOWLEDGEMENTS

REFERENCES

Barkov, N. I. 1975. Snow accumulation along the Mirny–Vostok profile, 1970–1973. *Antarct. J. U.S.*, **19**(20), 56–57.

Bodhaine, B. A., J. J. Deluisi, J. M. Harris, P. Houmere and S. Bauman. 1986. Aerosol measurements at the South Pole. *Tellus*, **38B**(3–4), 223–235.

Cameron, R. L., E. Picciotto, H. S. Kane and J. Gliozzi. 1968. Glaciology on the Queen Maud Land traverse, 1964–1965 South Pole–Pole of Relative Inaccessibility. *Ohio State Univ. Inst. Polar Stud. Rep.* 23.

Crary, A. P. 1963. Results of the United States traverses in East Antarctica, 1958–1961. *IGY Glaciol. Rep. Ser.* 7.

Delmas, R. and C. Boutron. 1978. Sulfate in Antarctic snow: spatio-temporal distribution. *Atmos. Environ.*, **12**(1–3), 723–728.

Drewry, D. J. 1983. The surface of the Antarctic ice sheet. *In* Drewry, D.J., *ed. Antarctica: glaciological and geophysical folio.* Cambridge, University of Cambridge. Scott Polar Research Institute, Sheet 2.

Giovinetto, M. B. and C. Bull. 1987. Summary and analyses of surface mass balance compilations for Antarctica, 1960–1985. *Byrd Polar Res. Cent. Rep.* 1.

Hamilton, W. L. and M. E. O'Kelley. 1971. Investigation of particulate matter in Antarctic firn. *In* Crary, A.P., *ed. Antarctic snow and ice studies II.* Washington, DC, American Geophysical Union, 355–362. (Antarctic Research Series 16.)

Hogan, A.W., W. G. Egan and J. A. Samson. 1990. Seasonal variation of some constituents of Antarctic tropospheric air. *Geophys. Res. Lett.*, **17**(12), 2365–2368.

Jouzel, J., L. Merlivat, J. R. Petit and C. Lorius. 1983. Climatic information over the last century deduced from a detailed isotopic record in the South Pole snow. *J. Geophys. Res.*, **88**(C4), 2693–2703.

Jouzel, J., J. R. Petit and D. Raynaud. 1990. Palaeoclimatic information from ice cores: the Vostok records. *Trans. R. Soc. Edinburgh, Ser. Earth Sci.*, **81**(4), 349–355.

Kamiyama, K., Y. Ageta and Y. Fujii. 1989. Atmospheric and depositional environments traced from unique chemical compositions of snow over an inland high plateau, Antarctica. *J. Geophys. Res.*, **94**(D15), 18,515–18,519.

Kotlyakov, V. M., K. S. Losev and I. A. Loseva. 1978. The ice budget of Antarctica. *Polar Geogr.*, **2**(4), 251–262.

Legrand, M. 1987. Chemistry of Antarctic snow and ice. *J. Phys.* (Paris), **48**, Colloq. C1, 77–86. (Supplément au 3.)

Legrand, M. and R. J. Delmas. 1985. Spatial and temporal variations of snow chemistry in Terre Adélie (East Antarctica). *Ann. Glaciol.*, **7**, 20–25.

Lipenkov, V.Ya. 1980. Nekotorye osobennosti nakopleniya snega na profile Mirnyy–Vostok [Features of snow accumulation at the Mirnyy–Vostok profile]. *Inform. Byull. Sov. Antarkt. Eksped.* 100, 59–60.

Lorius, C., L. Merlivat and R. Hagemann. 1970. Fluctuations of the average deuterium content of precipitation in Antarctica. *Sov. Antarct. Exped. Inf. Bull.*, **7**(6), 513–516.

Mayewski, P. A. and M. Legrand. 1990. Recent increase in nitrate concentration of Antarctic snow. *Nature*, **346**(6281), 258–260.

Mulvaney, R. and E.W. Wolff. 1994. Spatial variability of the major chemistry of the Antarctic ice sheet. *Ann. Glaciol.*, **20**, 440–447.

Peel, D. A. and H. B. Clausen. 1982. Oxygen-isotope and total beta-radioactivity measurements on 10 m ice cores from the Antarctic Peninsula. *J. Glaciol.*, **28**(98), 43–55.

Qin Dahe. 1992. [The modern climatic and environmental record in the surface snow of the Antarctic ice sheet.] (Ph.D. thesis, Chinese Academy of Sciences. Lanzhou Institute of Glaciology and Geocryology.) [In Chinese with English abstract.]

Qin Dahe, E. J. Zeller and G. A. M. Dreschhoff. 1992. The distribution of nitrate content in the surface snow of the Antarctic ice sheet along the route of the 1990 International Trans-Antarctic Expedition. *J. Geophys. Res.*, **97**(A5), 6277–6284.

Qin Dahe, J. R. Petit, J. Jouzel and M. Stievenard. 1994. Distribution of stable isotopes in surface snow along the route of the 1990 International Trans-Antarctica Expedition. *J. Glaciol.*, **40**(134), 107–118.

Schwerdtfeger, W. 1970. The climate of the Antarctic. *In* Orvig, S., *ed. Climates of the polar regions.* New York, Elsevier, 253–355.

Schwerdtfeger, W. 1984. *Weather and climate of the Antarctic.* Amsterdam, Elsevier. (Developments in Atmospheric Science 15.)

Shaw, G. E. 1988. Antarctic aerosols: a review. *Rev. Geophys.*, **26**(1), 89–112.

Shimizu, H. 1964. Glaciological studies in West Antarctica, 1960–62. *In* Mellor, M., *ed. Antarctic snow and ice studies.* Washington, DC, American Geophysical Union, 37–64. (Antarctic Research Series 2.)

Taylor, L. D. 1965. Glaciological studies on the South Pole traverse, 1962–1963. *Ohio State Univ. Inst. Polar Stud. Rep.* 17.