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Distribution of sea salt components in snow cover along the traverse route from the coast to Dome Fuji station 1000 km inland at east Dronning Maud Land, Antarctica

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ABSTRACT

We show and discuss the results of the regional distribution of Cl^- and Na^+ concentrations in snow cover along the study route from the coast to Dome Fuji station, 1000 km inland, in east Dronning Maud Land, Antarctica. The concentrations of Cl^- and Na^+ at the coast exponentially decreased with distance from the coast up to 200 km inland. Between 200–1000 km inland, the concentrations of Na^+ were nearly constant. On the other hand, the concentrations of Cl^- increased with distance beyond 750 km inland. Furthermore, the contribution factors between Cl^- and Na^+ decreased and the Cl^-/Na^+ ratio and the $nssCl^-/Cl^-$ ratio increased toward the interior of the continent. These results indicate that sea salt aerosols are transported from the coastal region toward the inland region of the Antarctic continent, and that a source of Cl^- other than sea salt exists in the inland plateau of Antarctica.

1. Introduction

Antarctic ice sheet records atmospheric deposition continuously in time and space. Therefore, vertical analyses of the ice sheet provide us with information about past climatic change (Delmas, 1992; Legrand and Mayewski, 1997) and horizontal analyses of the ice sheet provide us with knowledge regarding long-range transport of airborne materials (Kamiyama et al., 1989; Kreutz and Mayewski, 1999). However, studies on regional distribution of chemical tracers in the ice sheet with successive snow sampling are very scarce at present. The Japanese Antarctic Research Expeditions (JARE) have conducted many glaciological observations, including the Dome Fuji Project (Dome-F Coring Group, 1998) on the ice sheet in east Dronning Maud Land during recent decades. The study route from the coast to Dome Fuji station, 1000 km inland, has been established through these observations (Ageta et al., 1989; Kamiyama et al., 1996). Here we show and discuss the results of regional distribution of Cl^- and Na^+ concentrations in snow cover along the route, which were obtained by an inland expedition performed on the 40th JARE (1998–2000).

2. Samples and methods

A map of the study route is shown in Fig. 1. The traverse from the coast, S16 (69°02′S, 40°04′E, 591 m a.s.l.), to Dome Fuji station (77°19′S, 39°42′E, 3810 m a.s.l.) was carried out during the austral summer, from 27 December 1998 to 15 February 1999. In this expedition, a sample for ion analyses was taken every 10 km along the route by pushing a 100-ML pre-cleaned plastic bottle into the snow at a depth of 0–2 cm. The study route is approximately perpendicular to the prevailing

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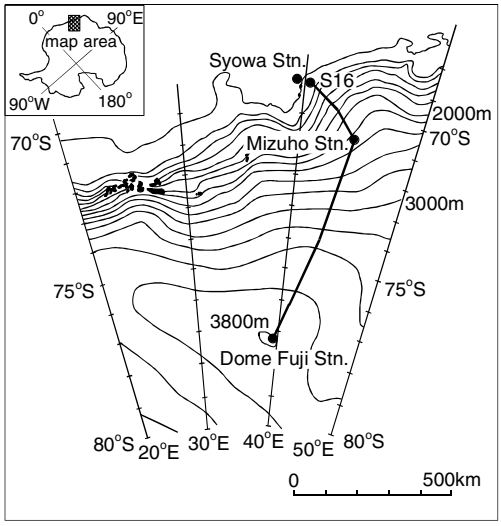

Fig. 1. Map showing the study route in East Dronning Maud Land, Antarctica.

wind direction. The sample collection was performed in the research area located to windward of the route. During the return traverse of the expedition, each sampling site was shifted 5 km further along the route than those of the outward traverse. The concentrations of Cl^- and Na^+ were measured by portable ion chromatography (TOA Electronics, IA-100) at Syowa station (69°00′S, 39°35′E, 29 m a.s.l.) immediately after the inland expedition. The coefficient of variation of this method is stated to be within 2% in the specification of the apparatus.

3. Results and discussion

The concentrations of Cl^- and Na^+ in snow cover along the study route are shown in Fig. 2. Variation of the altitude is also indicated in the figures. There were no remarkable differences between the results of outward and return traverses to and from Dome Fuji station. This implies that the temporal variation of Cl^- and Na^+ concentrations in snow were not significant during the period of the inland expedition. The concentrations of Cl^- and Na^+ at the coast were approximately 0.6 and 0.3 mg kg^{-1}, respectively. These values decreased by one order of magnitude until about 200 km inland (2.0 km a.s.l.) from S16 point. This result indicates that sea salt aerosols are transported from the coastal region toward the inland region of the Antarctic continent (Kreutz and Mayewski, 1999). Delmas (1992) suggested that sea salt deposition in polar snow is very high in coastal areas but decreases rapidly inland as a function of elevation rather than of the distance from the sea, because the Na^+ concentrations found at J9 on the Ross Ice Shelf (0.06 km a.s.l.) and at D80 in Adélie Land (2.5 km a.s.l.), both located about 430 km from the ice front, were 100 ng g^{-1} (Herron and Langway, 1979) and 20 ng g^{-1} (Legrand

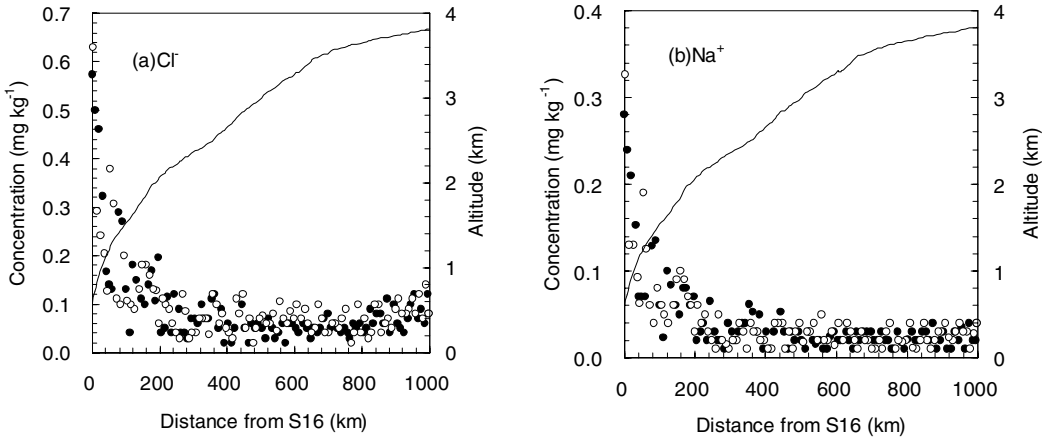

Fig. 2. Distribution of the concentrations of (a) Cl^- and (b) Na^+ in snow cover along the study route. Solid circles and open circles express the data obtained on the outward and return traverses, respectively. Variation in altitude is indicated by the solid line.

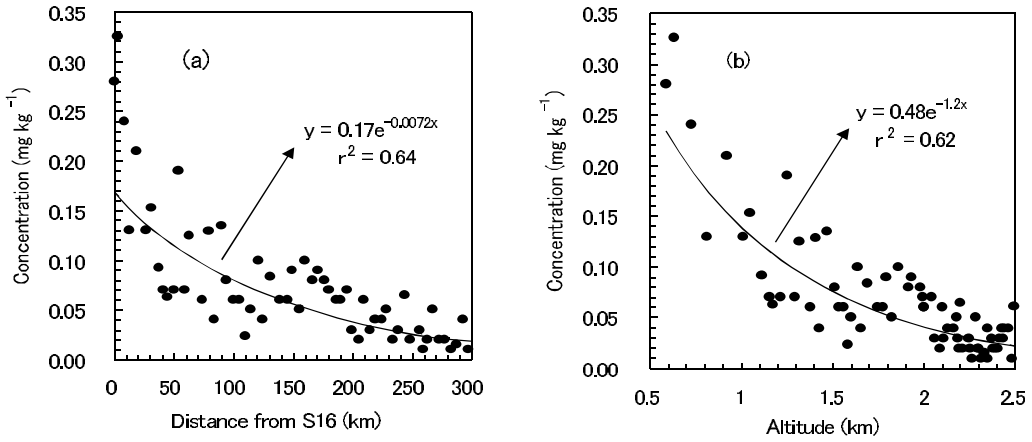

Fig. 3. Concentrations of Na^+ in snow plotted against (a) the distance from S16 and (b) the altitude. The curves in the figures are obtained by a least-squares method.

and Delmas, 1985), respectively. On the other hand, Minikin et al. (1994) found an exponential decrease of the Cl^- concentration on the Filchner–Ronne ice shelf, which is essentially flat. These findings indicate that sea salt concentrations in snow at the coast of Antarctica are dependent both on altitude and distance from the coast. In Fig. 3 the concentrations of Na^+ in snow are plotted against (a) the distance from S16 up to 300 km and (b) the altitude up to 2.5 km. Regression analyses using an exponential formula were performed on these data sets based on the assumption that sea salt aerosols in the atmosphere are removed to the ice sheet in proportion to their concentration in the atmosphere, i.e. a first-order removal process. The half-decrease distance of sea salt in the ice sheet expected from the exponential term of the equation in Fig. 3a is approximately 100 km. In the same way, from Fig. 3b we can recognize that the concentration of sea salt in the ice sheet decreases to half with increasing altitude every 0.6 km.

From 200 to 1000 km inland, the concentrations of Na^+ were nearly constant (Fig. 2b). On the other hand, the concentrations of Cl^- increased with distance beyond 750 km inland (3.6 km a.s.l.) (Fig. 2a). These results suggest that a source of Cl^- other than sea salt exists in the inland plateau of Antarctica. The study route can be divided into three sections on the basis of the characteristics of snow surface features: Section I, a coastal region (0.6–2 km a.s.l), characterized by a high frequency of small sastrugi and low frequency of dunes; Section II, a katabatic-wind region (2.0–3.6 km a.s.l.) characterized by the coexistence of small and large sastrugi, dunes and a glazed surface; and Section III, an inland plateau region (3.6–3.8 km a.s.l.) characterized by low frequencies of small sastrugi and dunes (Furukawa et al., 1996). Number of samples, the correlation coefficients (r^2) between Cl^- and Na^+, the average Cl^-/Na^+ ratios and the average $nssCl^-/Cl^-$ ratios in each section are summarized in Table 1. The concentrations of $nssCl^-$ (non-sea-salt Cl^-) were obtained as follows:

Table 1. *Sample number, the correlation coefficients between Cl^- and Na^+, the Cl^-/Na^+ and the $nssCl^-/Cl^-$ ratios in three sections of the study route*

Section	n[a]	r^{2}[b]	Cl^-/Na^{+}[c]	$nssCl^-/Cl^-$[c]
I	39	0.97	2.0 ± 0.3	0.09 ± 0.13
II	108	0.61	2.6 ± 1.0	0.22 ± 0.24
III	50	0.33	3.4 ± 1.5	0.38 ± 0.24

[a]Number of samples.
[b]Square of correlation coefficient between Cl^- and Na^+.
[c]Errors are ± 1 standard deviation.

$$[nssCl^-] = [Cl^-] - 1.8[Na^+] \quad (1)$$

where 1.8 is the Cl^-/Na^+ ratio in bulk sea water (Broecker and Peng, 1982), considering that Na^+ is the best reference element for sea salt. The correlation coefficients between Cl^- and Na^+ were 0.97 in the coastal region, 0.61 in the katabatic-wind region and 0.33 in the inland plateau, respectively. The decrease in the correlation coefficients indicates that the

correlation between the concentration of Cl^- and Na^+ is weakened toward the inland region. In the coastal region, the average value of the Cl^-/Na^+ ratio, 2.0±0.3, was close to the ratio in bulk sea water, 1.8, and the proportion of $nssCl^-$ to total Cl^- was less than 10%. On the other hand, the Cl^-/Na^+ ratio in the inland plateau region, 3.4±1.5, was approximately twice the value of the ratio in sea water, and roughly 40% of Cl^- in this section was the non-sea-salt fraction. Not only the average values of Cl^-/Na^+ and $nssCl^-/Cl^-$, but also their standard deviations, increased toward the interior of the continent. These results indicate that the intensity and instability of unknown source of Cl^- become strong toward the inland plateau. The increase in the concentration of Cl^- in the snow inland may be due to an inflow of $nssCl^-$ into the Antarctic boundary layer from the stratosphere and the upper troposphere, along with atmospheric convergent flow in the interior of the Antarctic continent (James, 1989; Parish and Bromwich, 1991). Although we cannot identify the origin of $nssCl^-$ in this study, the anthropogenic Cl^- which is injected into the upper atmosphere in the mid-latitude region and/or naturally occurring Cl^- which is produced by the chemical reaction in the Antarctic atmosphere, e.g. HCl production from sea salt aerosol as suggested by Legrand and Delmas (1988), are possibilities. Wagnon et al. (1999) clarified that volatile chemical species in the upper snow layers of the inland region suffer very serious post-depositional change. If the influence of post-depositional migration and redeposition process increases with altitude or distance from the coast, the enrichment of Cl^- in the surface snow by this phenomenon will be important to the interpretation of our results. However, Kamiyama and Watanabe (1994) reported that not only the concentrations of Cl^- and NO_3^- but also the concentration of SO_4^{2-}, non-volatile species, in the surface snow have also increased on the inland plateau of east Dronning Maud Land. Further observations of the regional distribution of the upper atmospheric tracers and the extent of post-depositional migration of the volatile species are needed to identify the source of $nssCl^-$ in the interior of Antarctica.

4. Conclusions

We have shown the regional distribution of Cl^- and Na^+ concentrations in snow cover along the study route from S16 to Dome Fuji station in east Dronning Maud Land, Antarctica, and obtained the following results.

(1) The concentrations of Cl^- and Na^+ at the coast rapidly decreased up to the point of 200 km inland (2.0 km a.s.l.). This result may be due to the fact that sea salt aerosols are transported from the coast toward the interior of the continent and are removed onto the Antarctic ice sheet.

(2) Between 200 and 1000 km inland, the concentrations of Na^+ were nearly constant. On the other hand, the concentrations of Cl^- increased with distance beyond 750 km inland. Furthermore, the correlation between Cl^- and Na^+ decreased and the Cl^-/Na^+ and the $nssCl^-/Cl^-$ ratios increased toward the interior of the continent. These results suggest that a source of Cl^- other than sea salt exists in the inland plateau of Antarctica.

(3) The concentrations of Na^+ in snow cover in the ice sheet within the coastal region decreased to half with every 100 km distance from the coast and 0.6 km altitude.

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