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Relation between surface topography and sea-salt snow chemistry from Princess Elizabeth Land, East Antarctica

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Abstract

Previous studies on variability of sea-salt records in Antarctic snow have established an unambiguous relationship with the proximity to the sea and have been directly correlated with the site specific features like elevation and distance from the coast. On the other hand, variations in Cl^-/Na^+ ratio in have been attributed with the reaction mechanisms involving atmospheric acids. In the present study, annual records of Na^+, Cl^- and SO_4^{2-} records were investigated using snow cores along a 180 km coast to inland transect in Princess Elizabeth Land, East Antarctica. Exceptionally high Na^+ concentrations varying between 1000 and 2000 $\mu g\,l^{-1}$ were observed within 50 km of the transect. Large variations in Cl^-/Na^+ ratio were observed within 50 km from the coast. A rapid increase in the elevation (0–1115 m) was noticed up to 50 km from the coast, whereas a steady elevation change (1115–2200 m) occurred between 50 and 180 km. The largest slope of the entire transect was observed (33.7 $m\,km^{-1}$) between 20 and 30 km and records from this area correspondingly revealed extensive modifications in snow sea-salt chemistry, with Cl^-/Na^+ ratios as low as 0.2. Statistical analysis showed a strong association between the slope of the ice sheet and variation of the sea-salt ions along the transect. While distance from coast accounted for some variability, the altitude by itself seem to have no significant control on the distribution of sea-salt ions. We suggest that the degree of slope of the ice sheet on the coastal regions of Antarctica could have a major influence the sea-salt chemistry.

1 Introduction

Comprehensive studies from data compiled along various traverses across the Antarctic continent has shown the association between snow chemistry and site specific features like elevation, distance from the sea and to an extent, snow accumulation (Mulvaney and Wolff, 1994; Bertler et al., 2005). Studies have also revealed that complex morphology of the snow surface (Goodwin, 1990), micro-relief features (Frezzotti et al.,

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2005) and the movement of megadunes (Frezzotti et al., 2002) due to the windborne redistribution of snow, play an important role on the snow accumulation processes in the Antarctic. The coastal region of Antarctica, where the sea-salt aerosols are at higher concentrations compared to the inland, could have a profound impact on the formation of cloud condensation nuclei and therefore on the coastal climate (Hara et al., 2005). Although a large number of studies have been carried out to understand the effect of surface physical processes on snow accumulation, very few studies have attempted to elucidate the role of these physical processes on snow chemistry in Antarctica. A thorough knowledge of all these parameters are critical, for instance, in calculating the precise mass balance of the ice sheet or understanding the past changes in the chemical composition of ice.

The major chemical constituents of the Antarctic snow and ice are sea-salt ions (Na^+, Cl^-, SO_4^{2-}, K^+, Mg^{2+} and Ca^{2+}), H_2SO_4 and HNO_3 along with minor constituents that include MSA, NH_4^+, and other organic acids (Hall and Wolff, 1998). Cl^- and Na^+ are the main constituents of sea-salt aerosols and make up the dominant component of the aerosols of coastal Antarctic atmosphere (Kerminen et al., 2000). High concentrations of H_2SO_4 due to the oxidation of marine biogenic DMS are observed in the Antarctic coasts during summer while HNO_3 is mainly derived from the stratospheric fallout (Hall and Wolff, 1998), with significant post depositional loss controlled by various factors (Röthlisberger et al., 2002). The sea-salt ions, especially Na^+ and Cl^-, involve in heterogeneous reactions with the H_2SO_4 and HNO_3 in the atmosphere with the liberation of reactive halogen species (Legrand and Delmas, 1988) given by

$$NaCl + HNO_3 \rightarrow HCl_{(g)} + NaNO_3$$
$$NaCl + H_2SO_4 \rightarrow HCl_{(g)} + NaHSO_4$$

Therefore, a significant part of variation in SO_4^{2-} and NO_3^- flux observed in snow could be due to the reactions of atmospheric acid with the sea-salt aerosol, especially Na^+ and Cl^-.

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Sea-spray from the ocean surface is considered to be a major contributor of sea-salt to the Antarctic snow in summer whereas during winter, the surface of the sea-ice contributes to the sea-salt concentration snow. As a result of differences due to fractionation in winter and summer conditions, the chemistry variability give rise to a seasonal pattern which are used to infer long term variability of atmospheric conditions (Aristarain and Delmas, 2002). Cl^-/Na^+ ratio in snow or ice is a basic parameter that is compared with that in sea-water to understand the chemical processes that occur during the transport and deposition of snow (e.g. Legrand and Delmas, 1988). Various studies have shown the changes that are associated with the Cl^-/Na^+ ratio and have related various mechanisms to it (Legrand and Delmas, 1988; Röthlisberger et al., 2003; Hara et al., 2004). Hara et al. (2004) showed that the sea-salt particles were transported long distances to the coastal (Syowa) and inland (Dome Fuji) sites and as a result, Cl^-/Na^+ ratios closer to that of the bulk sea water. Lower Cl^-/Na^+ ratios have been linked to shorter atmospheric residence times of the sea salt aerosols (Legrand and Delmas, 1988) and post depositional HCl losses in surface snow (Wagnon et al., 1999). Decreased formation of HCl in the atmosphere owing to the higher dust levels resulting in a higher Cl^-/Na^+ ratio at certain periods in the past have also been suggested from an ice core study (Röthlisberger et al., 2008).

Previous studies have therefore mainly investigated the fluctuations in Cl^-/Na^+ ratio in terms of seasonal variation of the sea-salt aerosol concentration, the availability of atmospheric acids, as well as dust concentration in the atmosphere. Hall and Wolff (1998) have shown the importance of coastal topography with open ice shelves allowing more sea-salt inland than in the region with coastal mountains. This study discusses the possibilities of a significant relationship between the coastal surface topography and the sea-salt snow chemistry using high resolution snow core data along a coast to inland transect in the Princess Elizabeth Land, East Antarctica.

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2 Sampling and methodology

In spite of having the largest glacier basin in Antarctica, Princess Elizabeth Land is one of the least studied regions in terms of seasonal and spatial variability of snow. A coast to inland snow core sampling was carried out during the austral summer of 2008–2009 at Princess Elizabeth Land in order to assess the spatial variability of snow chemistry. Studies in this region indicate that the coastal area is dominated by a steep escarpment zone influenced by katabatic winds (Allison, 1998). Also, the prevailing wind in this region blows from the direction East-North-East for a maximum number of days in a year (Ma et al., 2010). Therefore, prior to the field sampling, adequate planning was made to sample along a transect perpendicular to the elevation contours in order to study the effect of rapid elevation changes along with the wind pattern and distance from the coast (Fig. 1).

A faster way of snow core sampling method was adopted in order to achieve a high resolution on a shorter time frame along transect. This method also reduced the chances of contaminating samples than the snow pit sampling method during the field work. Beginning at 10 km from coastline (Larsemann hills), a series of one-meter snow cores were collected approximately at 10 km intervals. In the coastal section between 20 and 50 km, cores were collected at closer intervals in order to assess the spatial variability due to rapid changes in elevation. A total of 22 snow cores were collected over a distance of 180 km inland that covered an elevation up to 2200 m. Coring was carried out using a KOVACS Mark IV snow coring device with a 14 cm barrel, following clean protocols. In order to avoid contamination due to movement of the transect team, sampling was always carried out ~ 50 m upwind from landing site at each location. The cores were sealed in clean custom made LDPE (low density polyethylene) bags. All samples were transported in EPP (Expanded Poly Propylene) boxes and stored in −20 °C conditions prior to the laboratory sub-sampling at the National Centre for Antarctic and Ocean Research, Goa, India.

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Sub-sampling of snow cores at 5 cm resolution were carried out under clean conditions in a laminar-flow bench housed in the processing facility at −15 °C cold room. All sub-sampling equipment and sample containers were pre-cleaned by rinsing several times with Milli-Q water, soaking for at least 24 h, followed by rinsing with fresh Milli-Q water and drying in a laminar-flow bench. Samples were melted immediately prior to the analysis in a class 100 clean room facility. Cations were analysed using a Dionex DX-2500 with IonPac CS17 column and anions were analysed on a Dionex ICS-2000 with IonPac AS11-HC column. The detection limits were within 2 µg l^{-1} for Cl^-, SO_4^{2-} and Na^+. Reference standards and random samples were analysed routinely to estimate the analytical precision which was better than 5 % for the ions except Cl^-, which was within 10 %. Stable isotope ratios were measured using a dual inlet, Isoprime Isotope Ratio Mass Spectrometer, following standard analytical procedures (Naik et al., 2010). The external precision obtained using a laboratory standard (CDML1) on oxygen isotope analysis was ±0.05 ‰.

2.1 Snow core data seasonality

Down core variability of $\delta^{18}O$ values were used to infer the representation of annuity of snow cores along the entire transect as well as to determine seasonal and annual accumulation of the sea-salt concentrations in snow. A seasonal $\delta^{18}O$ amplitude of 4 ‰ was considered large enough to represent the temperature difference between summer and winter precipitation (Stenberg et al., 1998). The seasonal amplitude of $\delta^{18}O$ values for snow cores along the Princess Elizabeth Land transect was larger than 6 ‰ and in places where $\delta^{18}O$ records were obscured, seasonality of sea-salt chemistry were compared to determine the annual layers (Fig. 2).

2.2 Determination of slope

In order to estimate the slope between subsequent sampling points, a combination of elevation data and the distance from coast along the transect were used. Accordingly,

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slope = elevation change/distance change (between two points) (Ciciarelli, 1991). The relationship between the slope unit and degree unit of slope is given by degree of slope = arctan (slope) (Huppes and Masanobu, 2007). Slope between the sampling locations was subsequently derived in terms of m km^{-1}.

3 Results

Princess Elizabeth Land showed a marked contrast in elevation changes at coast and inland region (Fig. 1). Between 20 and 50 km (from the coast unless otherwise mentioned), the elevation showed a rapid increase from 300 to 1235 m, indicating a steep escarpment zone. The elevation after 50 km had a gradual increase from 1235 to 2109 m at 180 km. Slope variations between the coast and inland region was also prominent. The region between 20 and 50 km of the ice sheet showed an average slope of 27.1 m km^{-1}. The steepest region in the transect was between 20 and 30 km with a dramatic slope of 33.7 m km^{-1}. Meanwhile, the interior region showed a three-fold decrease in slope between 50 and 100 km (9.4 m km^{-1}) and 100 and 180 km (7.8 m km^{-1}). However, it may be noted that Frezzotti et al. (2002) has considered > 4 m km^{-1} as steep within the East Antarctic ice sheet.

The seasonal variations in concentrations of Na^+, Cl^- and SO_4^{2-} can be clearly seen from the data (Fig. 3). Na^+ and Cl^- were exceptionally high along the initial 30 km. Variations in the seasonal distribution were large and the concentrations ranged above 100 µg l^{-1} throughout the year for both Na^+ and Cl^- ions within 30 km. At 20 km, the Na^+ ranged between 100 and 1000 µg l^{-1} whereas between 20 and 30 km, an exceptionally high concentration ranging between 500 and 1500 µg l^{-1} was observed (Fig. 3a). Outliers indicating sporadic events were present at all the sampling locations, with a maximum of about 3000 µg l^{-1} Na^+ between 20 and 30 km. Similar trend was not observed in Cl^- concentration, which ranged between 100 and 1000 µg l^{-1} (Fig. 3b). High concentrations above 1000 µg l^{-1} have been recorded in snow at mean sea level conditions (Wagenbach et al., 1998). Concentrations reduced logarithmically

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from coast to inland, with Na^+ ranging between 10 and 100 µg l^{-1} and Cl^- ranging between 20 and 200 µg l^{-1} above 50 km. The SO_4^{2-} concentration showed a linear trend with large seasonal variations within 50 km and the values ranging between 25 and 250 µg l^{-1} (Fig. 3c). Little variation was observed above 50 km with the values ranging between 25 and 75 µg l^{-1}.

Annual Cl^-/Na^+ ratio were calculated from all the locations along the transect which showed a slightly lower value of 1.4 compared to that of the bulk sea water (1.81 w/w). However, data from some of the locations within 50 km from the coast revealed extremely low annual mean Cl^-/Na^+ ratios (Fig. 4a). Lowest value (0.26) was recorded from a core retrieved at 26 km at an elevation of 640 m followed by 0.33 at 23 km at an elevation of 580 m. The annual mean Cl^-/Na^+ ratios gradually increased inland till ~ 50 km with few exceptions. A mean value of 0.89 was also reported from the Lambert glacier basin area (Hur et al., 2007). The annual average Cl^-/Na^+ ratio remained closer to that of the bulk sea water ratio after 60 km.

4 Discussion

4.1 Altitudinal influence on snow chemistry

High concentrations of the order above 1000 µg l^{-1} were observed for both Na^+ and Cl^- within 50 km from the coast, which decreased logarithmically inland. Despite the differences in altitude between 20 and 30 km inland (300 and 795 m), the concentrations of Na^+ exceeded 500 µg l^{-1} throughout the year (Fig. 3a). Cl^- and SO_4^{2-} on the other hand, did not show similar variations resulting in dominance of Na^+ at specific sites within 50 km from the coast. Calculations revealed that the majority (> 85 %, data not shown) of Na^+ in snow had a marine origin and no exposed nunataks were present in the vicinity of the transect to significantly contribute to the Na^+ concentration in snow. Previous studies have shown that even at a higher altitude of James Ross Island, a maximum concentration of 350 and 240 µg l^{-1} was observed in snow for Na^+

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and Cl^- due to the proximity to the surrounding seas (Aristarain and Delmas, 2002). Studies have also shown that the moderate winds, rather than high winds regulate the concentration of the sea-salt particles in the atmosphere (Hall and Wolff, 1998). It is therefore clear from our study region that altitudinal differences by itself in the coastal regime do not play an important role in the variability of sea-salt concentrations in snow.

4.2 Cl^-/Na^+ variability and Cl^- depletion in coastal region

As a result of high Na^+ concentrations at specific locations in the coastal section, the Cl^-/Na^+ ratio reduced significantly in comparison with the bulk sea water. Past studies in surface snow from East Antarctica have suggested a post depositional loss resulting in a reduced Cl^-/Na^+ ratio at a few meters depth (Wagnon et al., 1999). Chloride depletion mechanism based on the reaction of sea-salt aerosol with atmospheric acids, leading to the formation of HCl in the gas phase has also been implicated for low Cl^-/Na^+ ratio in snow (Legrand and Delmas, 1984). In the present study, the lowest Cl^-/Na^+ values were observed specifically at sites within 50 km from the coast, all located within the steepest slopes of the coastal escarpment (Fig. 5). Largest change in the gradient (33.1 m km^{-1}) was observed between 20 and 30 km and snow samples from this section show the strongest depletion of Cl^-. Few studies with year-round measurements of sea-salt aerosols have shown that Cl^- depletion occur predominantly during the summer months in coastal Antarctica (Kerminen et al., 2000; Jourdain and Legrand, 2002). The chloride depletion events are less significant in winter owing to the reduced atmospheric acidity at this time (Jourdain and Legrand, 2002). However, it is clear from Fig. 4b, that the seasonal records showed a very low Cl^-/Na^+ ratio, which indicated Cl^- depletion events that occurred irrespective of the time of the year within 50 km from the coast. The Cl^- depletion events were strong within 50 km and the Cl^-/Na^+ ratios showed narrow temporal variations at 26, 30 and 45 km, an indication of a phenomenon that is site specific. Cl^- depletion is resulted when the acidic species, in particular H_2SO_4 in the Antarctic atmosphere, react with NaCl in sea-salt aerosols and replace Cl^- in the form of HCl gas.

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4.3 Influence of slope on Cl^- depletion

In order to understand the sea-salt modification processes in the present study, a distance vs. elevation plot was sectioned into three distinct zones based on slope of the ice sheet surface and modification of sea-salt composition in snow (Fig. 5). Considering the dominant Cl^- liberation processes due to interaction with H_2SO_4, Na-Cl-SO_4 ternary plots representing the composition of snow samples has been presented from the respective zones with the bulk seawater Cl^-/Na^+ composition represented as S. The dotted line joining the S and the SO_4^{2-} summit indicate the common phenomenon of the troposphere, i.e. sea-salt aerosol scavenging by the atmospheric H_2SO_4, leading to the liberation of volatile HCl into the atmosphere. The area between the S and the SO_4 summit also suggest the composition of sea-salt modified by the chloride depletion reactions with Cl^- loss or gain represented below or above the line, respectively (Aristarain and Delmas, 2002). Ternary plot for locations within 50 km (Fig. 5a) showed strong sea-salt fractionation resulting in a composition dominated by Na^+ between 26 and 45 km. The composition at 30 km also revealed a see-saw pattern, with points towards the SO_4 summit representing modification by H_2SO_4 during summer and the points away from it representing winter. The samples from the inland sections of the transect showed compositions with typical chloride depletion due to the H_2SO_4 fluctuations in the atmosphere (Fig. 5b, c).

Fractionation of Cl^- with respect to Na^+ at source is less likely since we do not observe significant changes in the sea-salt chemistry in the interior (> 50 km). Therefore, the possible modifications of sea-salt chemistry could occur during: (1) the transportation of sea-salt aerosols from the source; (2) dry or wet depositional phase (Kärkäs et al., 2005); (3) post depositional changes in the snow pack (Weller, 2004). Even though it is known from several studies that the H_2SO_4 or its precursors like MSA are absent in the coastal troposphere during winter (Legrand, 1997), the sea-salt modifications were predominant throughout the year in the study area, especially between 20 and 50 km. The samples retrieved from inland locations (after 50 km) display a normal

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trend in the ternary plots, with summer period samples closer to the SO_4 summit, indicating the presence of H_2SO_4 scavenging during summer. For the transformation of sea-salt particles throughout the year, an alternate mechanism is more likely to be present which drives the Cl^- depletion in coastal East Antarctica. Large Cl^- depletion in the tropics has been related to a higher relative humidity (> 75 %) in the atmosphere (Zhuang et al., 1999). Ma et al. (2010) have shown that the relative humidity increases from the coastal to interior sites, with 90 % relative humidity at LGB69, an automatic weather station site at 180 km (Fig. 1). Therefore, NaCl could deliquesce into aqueous phase resulting in the reaction with HNO_3 in winter and H_2SO_4 in summer atmosphere. Moreover, we observe a strong negative correlation ($r = -0.679$ at 0.01 confidence level) between the annual mean Cl^-/Na^+ ratios and the degree of slope between the sampling locations (Table 1). This negative correlation suggests that an effective Cl^- depletion mechanism predominantly occur along the steep slopes of the ice sheet surface resulting in lower Cl^-/Na^+ values. In order to further estimate the Cl^-/Na^+ variability explained by the slope, multiple regression was performed with slope as a predictive variable (Table 2). The slope alone accounted for 46.1 % variability of Cl^-/Na^+, whereas distance from the coast and slope combined accounted for about 67.9 % variability indicating the importance of slope in changing sea-salt chemistry in snow. Also, elevation itself has no significant control on the sea-salt chemistry in the study transect. Therefore we suggest that chloride depletion could be triggered by the steep coastal topography with existing meteorological conditions throughout the year in Princess Elizabeth Land.

The prevailing winds originated as a result of atmospheric circulation blows throughout the year from a predominant ENE direction (Fig. 1). A strong directional constancy in the prevailing wind direction is also evident at a nearby coastal station and LGB69 at 180 km, with winds accounting for 90.3 % from ENE direction (Ma et al., 2010). Acting as a barrier, the steep coastal slopes impede the prevailing winds that are rich in sea-salt aerosol. On the other hand, Ma et al. (2010) have also shown that the strongest katabatic wind occurs at LGB69 when compared with the coastal and inland region.

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The steep down slopes of the coastal escarpment experience strong katabatic wind flow (Frezzotti et al., 2005) that are adiabatically warmed and unsaturated in sea-salt aerosol (Wendler et al., 1993). A precipitous convergence of two opposing air mass with distinct temperature and moisture content at the slope break form a localised frontal wedging that would influence the deposition of sea-salt aerosol particles from the sea-salt laden prevailing winds. During the heterogeneous reactions with atmospheric acids, Cl^- in snow would preferentially be liberated to gaseous phase, transported along with finer particles and re-deposited inland (Röthlisberger et al., 2003). As a result, the Cl^-/Na^+ ratio values > 60 km are closer to that of the bulk sea water (Fig. 4). In this case, the stability of Cl^- liberation varies with the seasonal input of atmospheric acids which result in a see-saw fluctuation between SO_4^{2-} summit the bulk sea-water composition, observed in most of the locations (Fig. 5). Unlike Cl^-, Na^+ does not undergo any changes with atmospheric acids and therefore could accumulate in snow resulting in a very high concentration on the coastal escarpment. Therefore continuous deposition of Na^+ rich (Cl^- depleted) snow from the inland to the locations at coastal region (for e.g. 26 km) could also result in lower Cl^-/Na^+ ratio throughout the year. It is therefore clear from our studies that the steep coastal topography along with the interaction of different wind regimes has a direct impact on the sea-salt chemistry modification in snow.

5 Conclusions

The present study using annual snow core records along a coast to inland transect in Princess Elizabeth Land revealed large chloride depletion resulting in significantly low Cl^-/Na^+ ratios within 50 km from the coast. These sites are also characterized by a steep slope which decreased significantly inland. Strong correlation was observed between slope and the Cl^-/Na^+ ratio that suggested a predominant influence of the slope of surface on sea-salt chemistry. We suggest that the large chloride depletions within 50 km are driven by the steep slopes, where the interaction of the prevailing and

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the katabatic surface winds result in preferential deposition of coarse sea-salt aerosol that are scavenged by the atmospheric acids. A combination of seasonal measurements in snow and aerosol would reveal more insight of this mechanism on the coastal regions across Antarctica.

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Wendler, G., André, J. C., Gosink, J., and Parish, T.: Katabatic winds in Adélie coast, in: Antarctic Meteorology and Climatology: Studies Based on Automatic Weather Stations, edited by: Bromwich, D. H. and Stearns, C. R., vol. 61, American Geophysical Union, Washington, 23–46, 1993.

Zhuang, H., Chan, C. K., Fang, M., and Wexler, A. S.: Formation of nitrate and non-sea-salt sulfate on coarse particles, Atmos. Environ., 33, 4223–4233, 1999.

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Table 1. Correlation coefficients (r) between the site specific features and Na^+ and Cl^- ions. Correlations are based on annual ion concentration data.

	Distance from sea	Elevation	Slope	Cl	Na	Cl : Na
Distance from sea	1	0.965[b]	–0.426	–0.678[b]	–0.726[b]	0.712[b]
Elevation	0.965[b]	1	–0.357	–0.839[b]	–0.841[b]	0.654[b]
Slope	–0.426	–0.357	1	0.176	0.537[a]	–0.679[b]
Cl	–0.678[b]	–0.839[b]	0.176	1	0.904[b]	–0.370
Na	–0.726[b]	–0.841[b]	0.537[a]	0.904[b]	1	–0.631[a]
Cl : Na	0.712[b]	0.654[b]	–0.679[b]	–0.370	–0.631[a]	1

Values marked with [a] and [b] represent correlations that are significant at 0.05 and 0.01 levels, respectively.

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Table 2. Multiple regression model summary explaining the percentage of snow accumulation and Cl^-/Na^+ variability attributed to the physical parameters. *R* is the correlation coefficient.

Model	Cl : Na	
	R	Variance (%)
1	0.679[a]	46.1
2	0.824[b]	67.9
3	0.825[c]	68.0

[a] slope;
[b] slope and distance from sea;
[c] slope, distance from sea and elevation.

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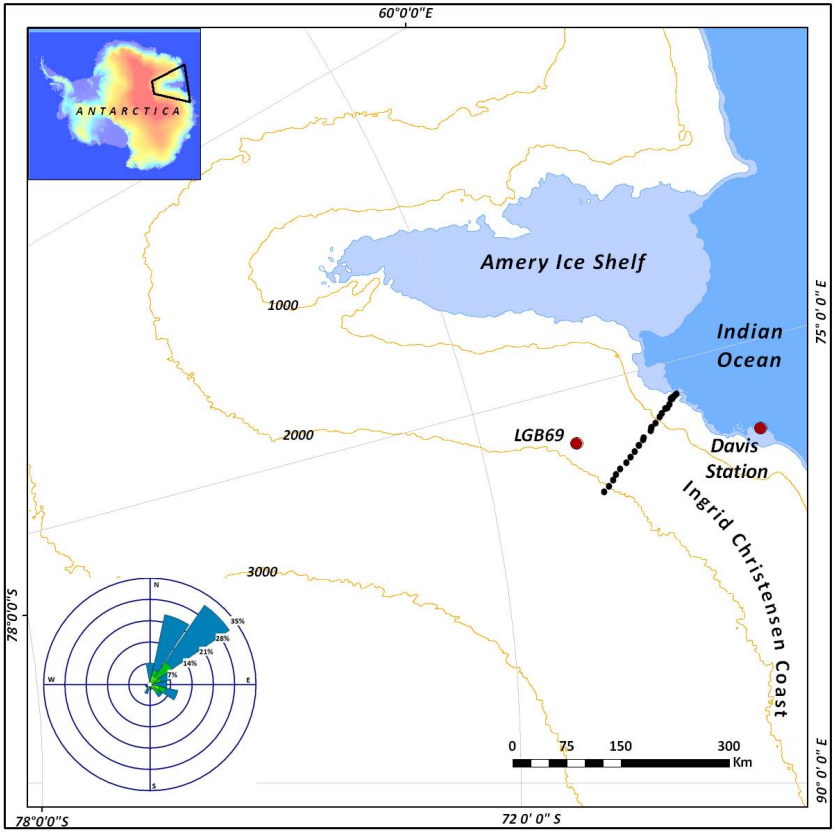

Fig. 1. Map showing the sampling locations in Princess Elizabeth Transect. Samples were collected at intervals ranging between 3 and 10 km at first 50 km from the coast. The rest of the transect inland was sampled at 10 km interval. Inset on the left bottom corner shows the wind rose chart for the year 2008 obtained from the Australian station Davis, showing prevalent wind direction from NNE–ENE throughout the year.

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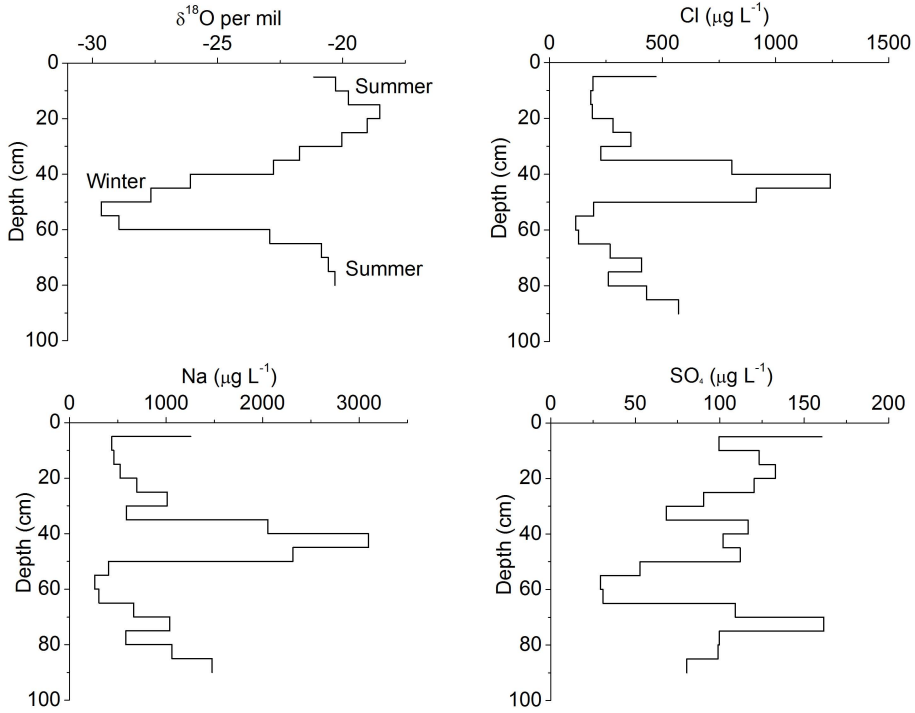

Fig. 2. Representative temporal records of $\delta^{18}O$, Cl^-, Na^+ and SO_4^{2-} at 30 km from the coast. Seasonality in $\delta^{18}O$ variability was primarily used to determine the annual accumulations within the core. Na^+, Cl^- and SO_4^{2-} records were also used to validate the $\delta^{18}O$ records.

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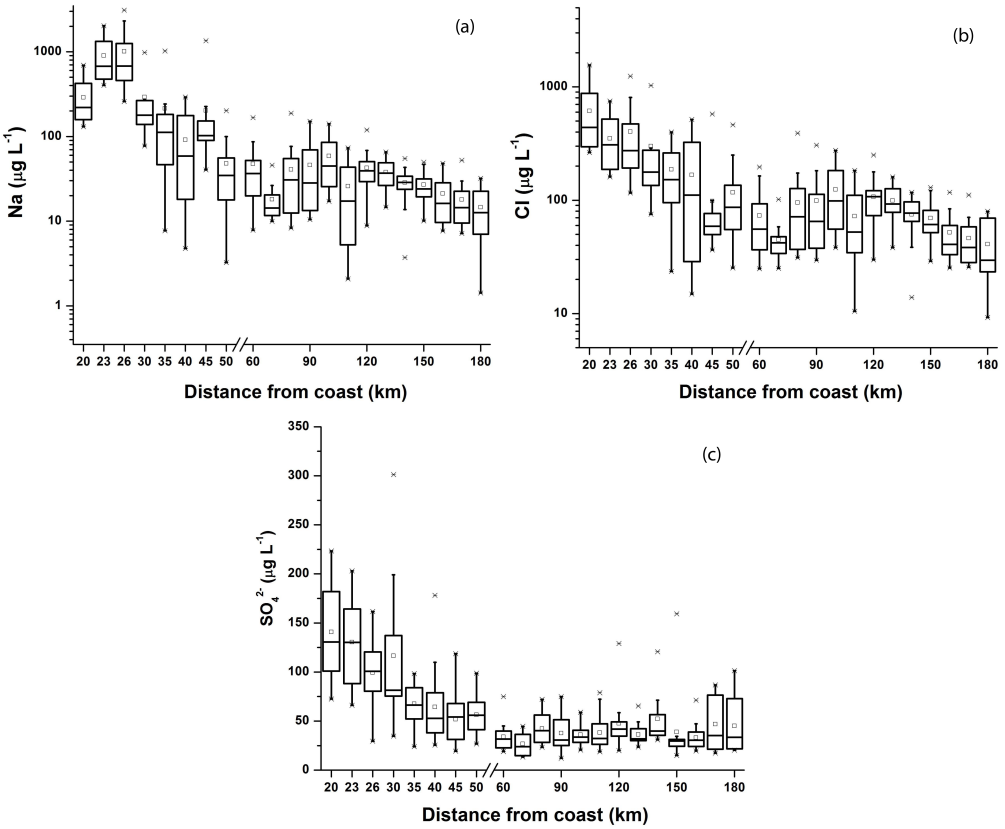

Fig. 3. Distribution and statistical variations in annual concentrations of Na^+ **(a)**, Cl^- **(b)** and SO_4^{2-} **(c)** from coast to inland. Note the logarithmic scale for concentrations in Na^+ and Cl^- plots. The whiskers (x) represent outliers, i.e. the maximum and the minimum for the year; the square inside the box shows mean value and the line inside the box represents median. Break in the x-axis show difference in sampling interval after 50 km.

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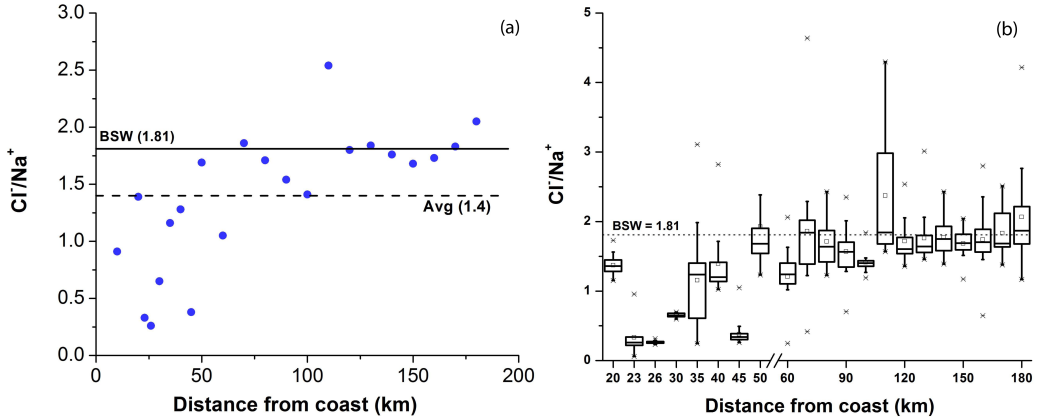

Fig. 4. (a) Plot showing the average annual Cl^-/Na^+ ratio from coast to inland. Note the strong chloride depletions within 50 km from the coast and Cl^-/Na^+ averages closer to the bulk sea water (BSW) in the interior of the transect. The dashed line is the annual average Cl^-/Na^+ ratio along the entire transect and the solid line is BSW ratio. **(b)** Plot showing seasonal variations of Cl^-/Na^+ variations from the entire transect. Please note the break in scale.

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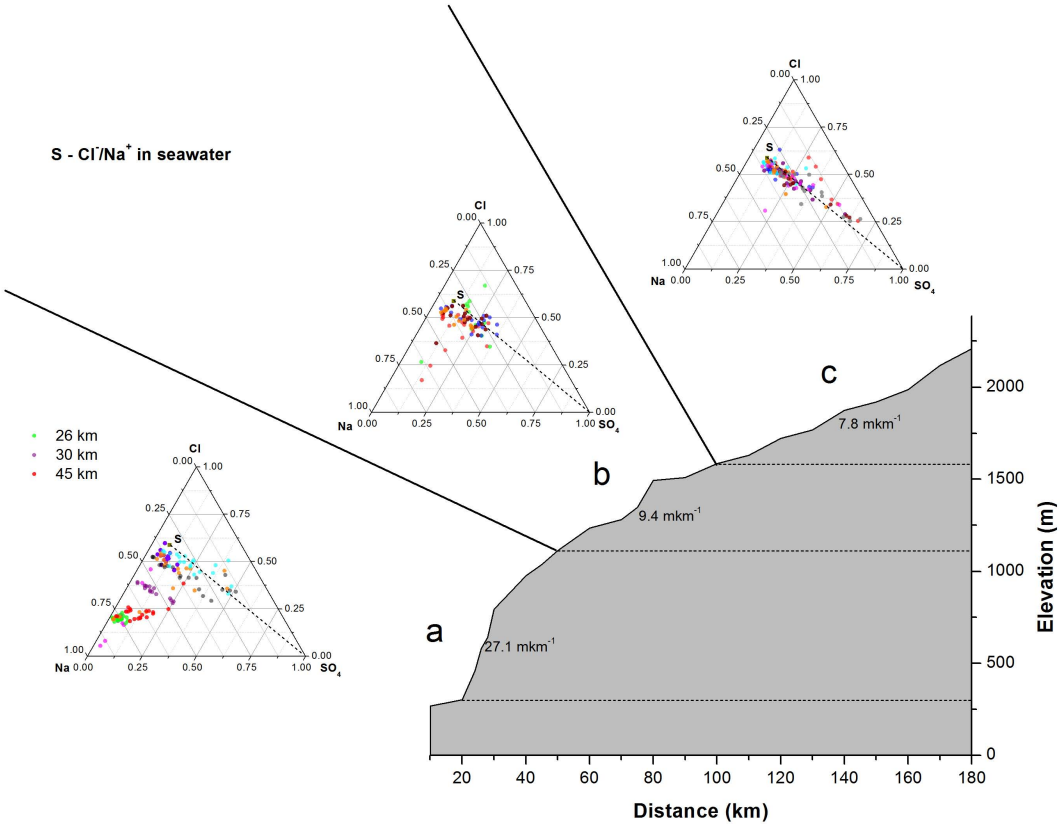

Fig. 5. Plot showing the changes in elevation and slope along the Princess Elizabeth Land transect. Sections (a–c) with ternary diagrams show the modification of sea-salt (Na^+ and Cl^-) chemistry with respect to the changes in slope. See text for more details.

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