

Reconstruction of Antarctic Climate Change Using Ice Core Proxy Records from the Coastal Dronning Maud Land, East Antarctica

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Abstract: Antarctic ice core records have provided unprecedented information on past climatic changes and forcing factors on decadal to millennial timescales. The glaciochemical and stable isotope records of a shallow ice core from the coastal Dronning Maud Land (East Antarctica) were used here to reconstruct the coastal Antarctic environmental variability during the past ~470 years. Sea salt ion data indicate a significant additional contribution of chloride ions compared to sea water values, possibly through atmospheric scavenging. The nitrate (NO_3^-) profile exhibit significant temporal shifts than that of the sulphate (SO_4^{2-}), with a major shift around 1750 AD. The changes in NO_3^- record are synchronous with the proxy record of solar activity (^{10}Be profile from a South Pole ice core), suggesting enhanced NO_3^- values during periods of reduced solar activity like the Dalton Minimum (~1790-1830 AD) and Maunder Minimum (~1640-1710 AD). The $\delta^{18}\text{O}$ records reveal that the more negative $\delta^{18}\text{O}$ values were coeval with several events of increased NO_3^- concentrations, suggesting enhanced preservation of NO_3^- during periods of reduced air temperatures. The $\delta^{18}\text{O}$ and δD records of the core also suggest significant short-term and long-term variability with more negative values indicating relatively lower air temperatures prior to 1715 AD. The $\delta^{18}\text{O}$ records also revealed a significant warming of 2.7°C for the past 470 years, with a warming of ~0.6°C per century.

Keywords: Glaciochemistry, Stable isotope, Ice core, Solar activity, Dronning Maud Land, Antarctica.

INTRODUCTION

Antarctic ice sheet is presently the largest and longest-lived ice mass on earth (Stonehouse, 2002). The cryosphere, hydrosphere and atmosphere in and around Antarctica are the closely interactive components of a complex climate system, with global, regional, as well as local influences. It is therefore obvious that in understanding global warming, Antarctica has a crucial role to play. However, the role of Antarctica within the global climate system and the spatial and temporal complexity of its climate are still poorly understood because of the limited and very short periods of observational and instrumental data on Antarctic climatic variables collected over the last few decades (Schneider et al. 2006). Recently, a continent-wide reconstruction of last 50 years revealed that the significant warming cover most of the West Antarctica (0.1°C, 10 years) and part of the East Antarctica (Steig et al. 2009). Study of ice core proxy records provided one of the most direct and accurate methods to analyse Antarctic climate change beyond the instrumental limits (Legrand and Mayewski, 1997; EPICA Community Members 2006; Mayewski et al. 2009). Ice cores from polar

regions offer continuous and highly resolved long-term records of reliable information on major atmospheric parameters like temperature, composition and trace gases. Among the various proxy variables used for the reconstruction of climate using ice cores, the stable isotope ratios of oxygen and hydrogen offer the most critical information on the past changes in temperature. Owing to the differences in saturation vapour pressure and molecular diffusivity, isotopic fractionation (HD^{16}O and H_2^{18}O relative to H_2^{16}O , the main component of water) takes place at each phase change of atmospheric water (Dansgaard, 1964). Since the heavy isotopes in precipitation decrease with the temperature of condensation, stable isotope ratios in ice cores provide quantitative proxy records of past temperature. Isotope data of ice cores have provided insight into the tropical-Antarctic teleconnections in the pre-instrumental period (Isaksson and Karlén 1994; Schneider et al. 2006; Naik et al. 2010 a, b).

Another widely used proxy parameter is the quantitative concentration of greenhouse gases like CO_2 and CH_4 occluded within the ice sheets. When the firn turns into ice,

bubbles are formed, trapping atmospheric air whose composition provides information on the trace gas content of the atmosphere at the time of ice formation. Since the snow and firn deposits are porous and continuously interact with the atmosphere, the trace gas records are reliable only after the firn-ice transition when the bubble closure takes place (Schwander and Stauffer, 1984). Reconstruction of changes in the greenhouse gas concentration and temperature through the past several glacial-interglacial cycles in deep ice cores recovered from Antarctica remarkably revealed the responsiveness of the ice sheet to changes in orbitally induced insolation patterns and the close association between atmospheric greenhouse gases and temperature (Petit et al. 1999; EPICA Community Members, 2006). The chemical composition of aerosols trapped in snow and the interpretation of these records within firn and ice in terms of composition of the past atmosphere has opened up a powerful new avenue of ice core research called glaciochemistry (Legrand and Mayewski, 1997). In combination with the temperature proxy records, these chemical records are extremely useful in examining the atmospheric forcing of climate in the past. Changes in the amount and composition of the atmospheric aerosol imprinted in the polar snow layers are related to the changes in source, transport mechanisms, atmospheric removal processes as well as the extent and seasonality of snow accumulation rates, controlled by the regional/ global climatic variations (Legrand et al. 1999). Among various glaciochemical parameters, ionic and trace metal composition were extensively studied for reconstructing the atmospheric circulation, global volcanism, dust input, sea ice extent/ concentration, oceanic productivity, air-snow biogeochemistry as well as the environmental pollution (Kreutz et al. 1997; Curran et al. 2003; Bertler et al. 2004; Thamban et al. 2006, 2010; Mayewski et al. 2009).

Although the deep ice core records from Antarctica provided excellent understanding on the past climatic changes in the context of recent warming, most of the records have a sampling resolution of few decades and focus on the large-scale climate changes during the glacial - interglacial cycles. A continental wide network of ice core records with annually resolved proxy data that focus on the past few centuries and millennia are fundamental for the study of recent climate change. The international effort in this regard was pioneered by the International Trans Antarctic Scientific Expedition (ITASE) that established calibration tools and reconstruction of climate indices and evidence for climate forcing using multiple arrays of proxies and sites based on shallow ice cores covering the past 200–1000 years (Mayewski et al. 2004, 2009; Bertler et al. 2006). The

increased focus on the annually-dated shallow ice cores has indeed improved our understanding on the recent climate variability in Antarctica and forcing mechanisms. The inherent complexities in the proxy records also necessitate the availability of a large array of well-dated firn/ice cores from the coastal regions of Antarctica. With this backdrop, India had initiated shallow ice core studies in the coastal Dronning Maud Land (DML) in East Antarctica. The early results suggested that a careful selection of core sites and a focussed study of proxy parameters would be critical for climatic interpretations of the ice cores (Nijampurkar et al. 2002; Thamban et al. 2006; Laluraj et al. 2009; Naik et al. 2010 a, b). We discuss here the results of a multi-proxy (anionic/cationic chemistry and stable oxygen isotopes) study of an ice core from the coastal Dronning Maud Land (DML) and report our understanding on the climatic/ environmental variability and forcing mechanisms during the past 470 years.

MATERIAL AND METHODS

An ice core (IND-22/B4, 70°51.3' S and 11°32.2' E, elevation 680 m) collected during the 22nd Indian Antarctic Expedition from the coastal DML region was used for the present study (Fig. 1). The drilling was carried out using an electromechanical drill system during the austral summer of 2003. The retrieved ice core samples were labelled, packed in good quality LDPE containers and subsequently shipped in -20°C deep freezer facilities. These cores were archived in frozen conditions in custom-made expanded polypropylene (EPP) insulated containers at the NCAOR cold room facility (-20°C), until further processing in the laboratory. Details on the field activities related to the ice core drilling and retrieval were reported by Chaturvedi and Singh (2008). The ice core samples were first manually decontaminated by removing a thin outer layer using contaminant-free microtome blades and subsequently sub-sampled using custom-made band-saw machines at the cold room (-15°C) processing facility. Sample preparation and analyses were performed following standard protocols. Extreme care was taken to minimize contamination during processing and subsequent analysis. Prior to the chemical analysis, samples were melted at room temperature in a Class 100 clean room. Major ions such as sodium (Na⁺), chloride (Cl⁻), nitrate (NO₃⁻) and sulphate (SO₄²⁻) and were measured with good precision (better than ±20 µg/l) in the melted snow samples using ion chromatographic techniques. A Dionex ICS-2500 reagent-free ion chromatography (RF-IC) system placed in a clean room and equipped with an automated EG50 Eluent Generator module and CD25

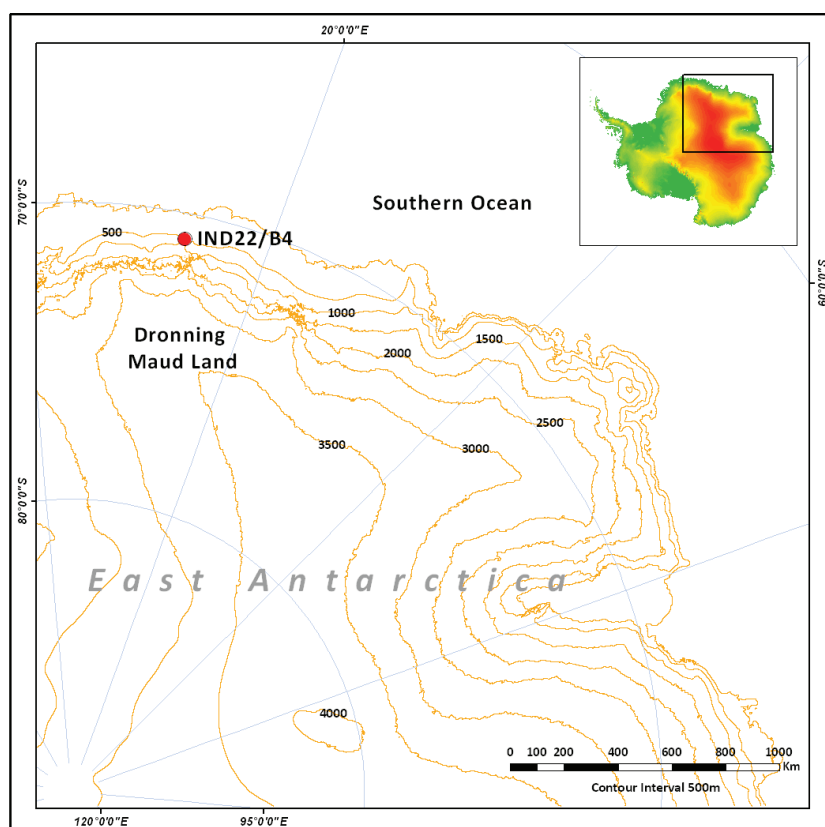


Fig.1. Study area and location of the ice core IND-22/B4 within the Dronning Maud Land.

conductivity detector was used for the study. Details of experimental setup, analytical procedures and precision are provided in Thamban et al. (2006). A total of 225 subsamples were analysed for the ~50 m length of the IND-22/B4 ice core.

Stable isotope ratios of the ice core samples were measured at NCAOR using an 'Isoprime' IRMS from GV instruments (UK). Oxygen isotope ratios ($\delta^{18}\text{O}$) were determined using the method of equilibrating the water samples with CO_2 gas following the procedure of Epstein and Mayeda (1953). For hydrogen isotope ratio (δD) analysis, the method of H_2 - H_2O equilibration using platinum catalyst was followed (Coplen et al. 1991). All measurements were made against NIST Standard Reference Material Vienna Standard Mean Ocean Water (V-SMOW) and Standard Light Antarctic Precipitation (SLAP). The isotopic composition is expressed in per mil (‰) deviation of the sample from VSMOW standard. The external precision (1σ) obtained for $\delta^{18}\text{O}$ and δD values using a laboratory standard (CDML1; Snow collected from a coastal DML site in east Antarctica) are $\pm 0.05\text{‰}$ and $\pm 0.77\text{‰}$ respectively. Chronological control of the core was achieved by volcanic markers using the non-sea-salt sulphate (nssSO_4^{2-}) records.

The detailed chronological reconstruction of the core using the aerosol events globally ascribed to some of the major volcanic eruptions, including the most prominent doublet peaks ascribed to Tambora (1815) and Unknown (1809) eruptions, have been detailed by Thamban et al. (2006). The stratigraphic model thus obtained was further confirmed by tephra records (Laluraj et al. 2009) and oxygen isotope records in the core. Accordingly, the ~50 m long ice core studied here represents the past 470 years, with an estimated chronological error of ± 3 years.

RESULTS AND DISCUSSION

Concentrations of major primary and secondary ionic species fluctuated significantly throughout the core (Fig. 2). Among the sea salt species, Na^+ content varied from 7.4 to 500.2 $\mu\text{g/l}$, with a mean value of 103 $\mu\text{g/l}$ (Fig. 2a). The Cl^- content fluctuated widely between 24.8 and 1461.2 $\mu\text{g/l}$ around a mean concentration

of 286.5 $\mu\text{g/l}$ (Fig. 2b). The down core variations in sea salt ions showed distinct seasonal to annual variability. Among the secondary ion species, the SO_4^{2-} concentration fluctuated between 16.0 and 396.1 $\mu\text{g/l}$ with a mean value of 94.6 $\mu\text{g/l}$ (Fig. 2c). The NO_3^- concentration varied between 10 and 306 $\mu\text{g/l}$ with a mean value of 107.5 $\mu\text{g/l}$ (Fig. 2d). Among the various ionic species studied, except the NO_3^- , most of the ions did not reveal significant secular variations. The NO_3^- profile showed a clear shift in concentration values around 1750 AD, with relatively high values (average 151 $\mu\text{g/l}$) prior to 1750 AD and low values (average 75 $\mu\text{g/l}$) thereafter.

The $\delta^{18}\text{O}$ and δD records revealed significant variability on an inter-annual to decadal scale with a major shift around 1710 AD. The $\delta^{18}\text{O}$ record varied between -32.2 and -21.2 per mil (mean -25.5 per mil) and the δD values varied between -256.2 and -157.9 per mil (mean -196.4 per mil) (Figs. 2e and f). The $\delta^{18}\text{O}$ and δD records showed similar down core fluctuations with excellent positive relationship ($R^2 = 0.9$; $n = 216$) between the two.

Temporal Variations in Sea Salt Components and its Fractionation

The major sea salt components in Antarctica reveal large

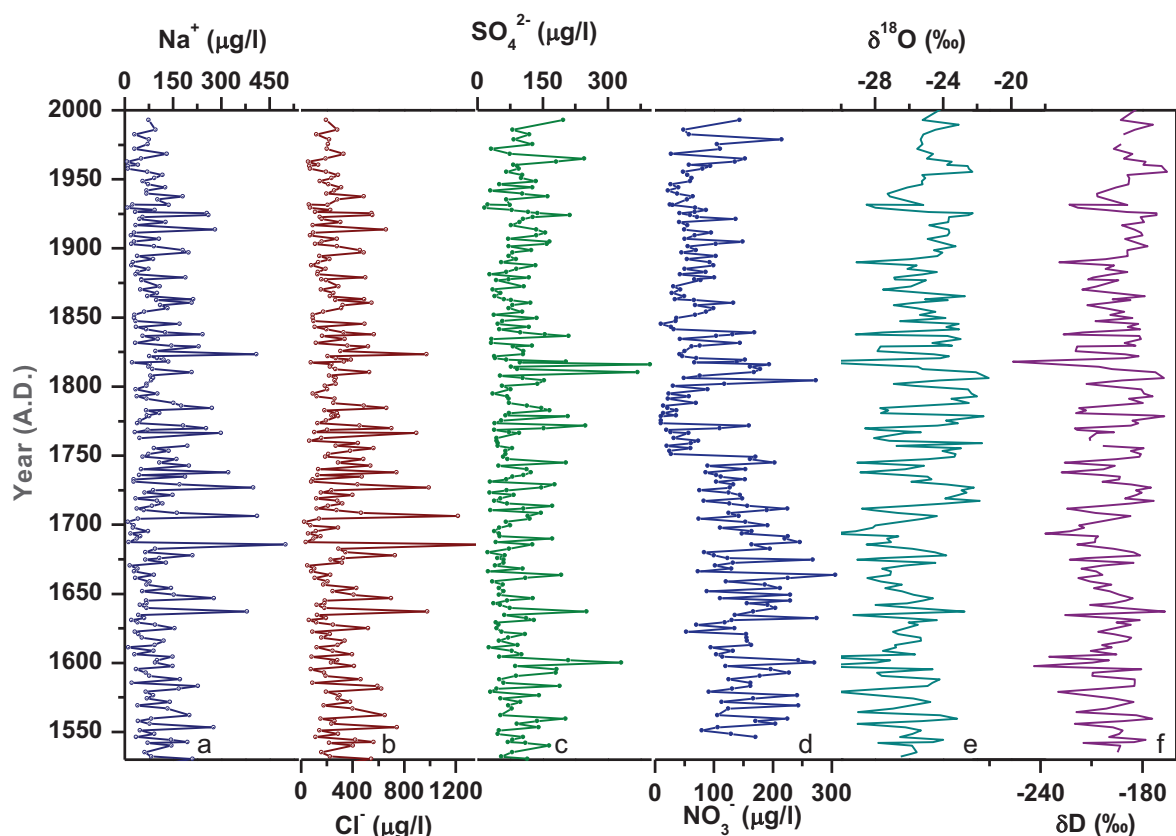


Fig.2. Glaciochemical (Na^+ , Cl^- , SO_4^{2-} , NO_3^-) and stable isotope ($\delta^{18}\text{O}$ and δD) profiles of the core IND-22/B4.

spatial and temporal variations than other components present in snow (Keene et al. 1986; Wagenbach et al. 1998; Becagli et al. 2004). Such spatial and temporal variability is influenced by factors like accumulation rates, elevation and the relative distance from sea (Hall and Wolff, 1998; Becagli et al. 2004; Benassai et al. 2005). Several studies using snow and ice records have confirmed that the concentration of Na^+ and Cl^- are directly related to the proximity of the sea (Traversi et al. 2004; Karkäs et al. 2005). The excellent positive relationship of Na^+ with Cl^- ($R^2 = 0.9$; $n = 223$) during the past nearly 470 years suggests that the sea salt aerosol remained their major source in the study region.

High-resolution glaciochemical investigations using snow records from the study region revealed that the sea salt species (Na^+ and Cl^-) peaked during summer compared to the winter periods (Mahalinganathan and others, unpublished data). Similar observations were also made at the James Ross Island in Antarctic Peninsula (Aristarain and Delmas, 2002). Since the sea-ice extent significantly expands during winter, the increased distance from the open sea would lead to deposition of coarser salt particles over sea-ice and ice shelf region before reaching the site. It is thus

suggested that the increased accumulation of sea salt ions in the study area during summer could be caused by the dry deposition of coarse particles during periods of open sea conditions.

Among various ions, Na^+ is the most conservative proxy for the sea spray compared to Cl^- in the coastal Antarctica (Traversi et al. 2004). In order to understand the temporal variability of the relative fractionations among these sea salt ions at the core site, the Cl^-/Na^+ ratios were calculated (Fig. 3a). Based on the major ion composition of sea water (Chester, 2003), the reference Cl^-/Na^+ ratio should be 1.81(w/w), if no significant fractionation takes place. However, the calculated Cl^-/Na^+ ratios in the core revealed wider fluctuations with an average ratio of 3.1, suggesting additional sources of Cl^- existed throughout the past nearly 470 years. The Cl^-/Na^+ ratios were very high (up to 13) at certain intervals in the core and are not synchronous with the non-sea-salt SO_4^{2-} anomalies in the core (Fig.3b; details of nss- SO_4^{2-} estimation is given in the following section). The enhanced Cl^-/Na^+ values in the core are thus unrelated to the input from volcanic aerosol deposition and in many cases are associated with exceptionally low Na^+ content and associated high error. Relatively higher Cl^-/Na^+ ratios in

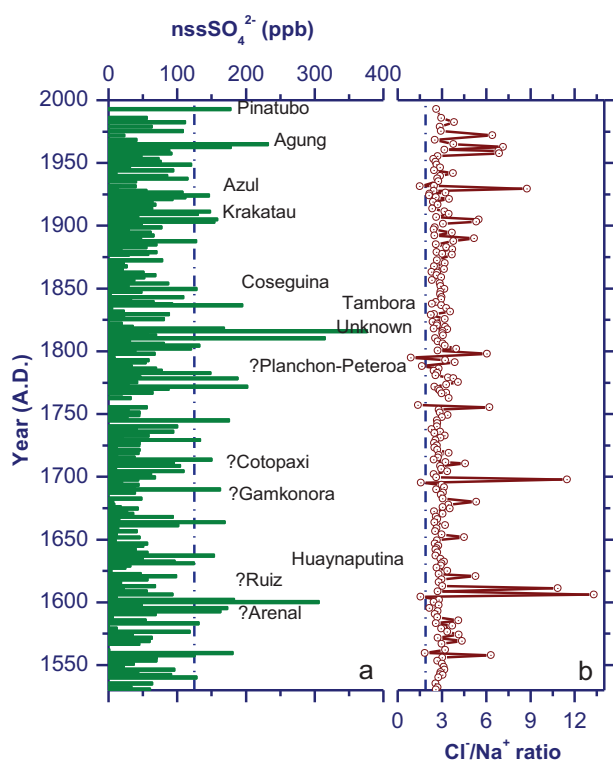


Fig.3. The estimated non-sea-salt sulphate (nssSO_4^{2-}) and Cl^-/Na^+ profiles of the core IND-22/B4. The vertical dashed line on nssSO_4^{2-} record is the upper limit defined for the background values and that on the Cl^-/Na^+ profile is the seawater Cl^-/Na^+ ratio (1.8).

the coastal Antarctic snow were attributed to scavenging of gaseous HCl present in the air, and/or fractionation of sea salt particles during more intense circulation (Udisti et al. 1999; Benassai et al. 2005; Thamban et al. 2006). It is obvious that the exchange reaction between marine NaCl and atmospheric H_2SO_4 ($\text{H}_2\text{SO}_4 + 2\text{NaCl} \rightarrow \text{Na}_2\text{SO}_4 + 2\text{HCl}$) could readily generate HCl. The HCl thus formed could be selectively deposited in the Antarctic snow, effectively increasing the Cl^-/Na^+ ratios of snow.

A ternary diagram depicting the major sea salt species (Na^+ , Cl^- and SO_4^{2-}) data of IND-22/B4 core revealed useful information on the fractionation affecting the sea salt (Fig. 4). In this diagram, the reference composition of sea water (Chester, 2003) is denoted by a filled circle and a dashed line connecting the sea water value to the SO_4^{2-} end-member is the theoretical line of sea salt composition with increasing SO_4^{2-} fractionation. The ionic concentrations of the IND-22/B4 ice core samples revealed a systematic offset from the theoretical line with many points lying above the line, suggesting an additional contribution of Cl^- at the core site throughout the past 470 years. Such a pattern supports scavenging of gaseous HCl present in the air by snow. It is also possible that the soil dust from ice-free areas as well as

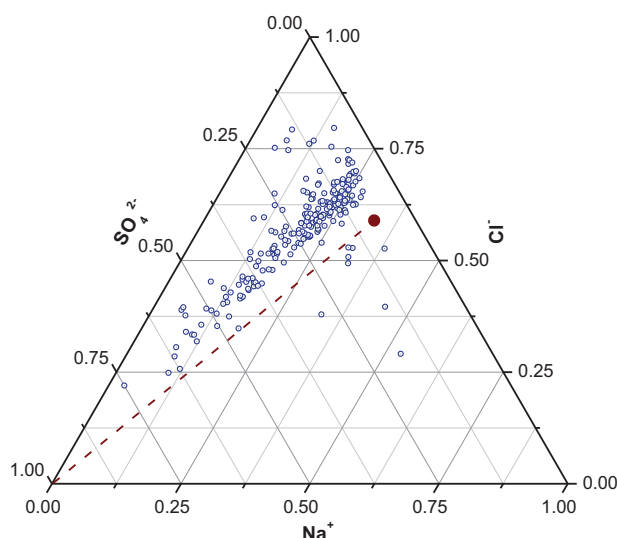


Fig.4. Ternary plot of Na^+ , Cl^- and SO_4^{2-} . In this diagram, the reference composition of sea water (Chester, 2003) is denoted by a filled circle and a dashed line connecting the sea water value to the SO_4^{2-} end-member is the theoretical line of sea salt composition with increasing SO_4^{2-} fractionation.

the nunataks in the vicinity of the study region might have contributed some Cl^- to the snow, leading to the increased Cl^-/Na^+ ratios.

Sulphate Records as Proxies of Global Volcanism

The important sources for SO_4^{2-} in Antarctic atmosphere include the sea salt spray, marine biological processes as well as the volcanic aerosols (Legrand and Mayewski, 1997). Of these, the sea salt SO_4^{2-} is well-defined in the coastal Antarctica and can be estimated using a conservative sea salt marker like Na^+ (Traversi et al. 2004). The non-sea-salt SO_4^{2-} (nss-SO_4^{2-}) component from the total SO_4^{2-} concentration can be estimated using Na^+ as reference species:

$$(\text{nss-SO}_4^{2-}) = (\text{SO}_4^{2-}) - 0.252 (\text{Na}^+),$$

where 0.252 is the $\text{SO}_4^{2-}/\text{Na}^+$ ratio in sea water (Chester, 2003), SO_4^{2-} and Na^+ are the concentrations of these ions in the ice core.

On a seasonal to annual basis, the biogenic contribution dominates the budget of nss-SO_4^{2-} in coastal Antarctica and originate from the enhanced biological activity in the surrounding seas during the austral summer (Bates et al. 1992). Previous studies have shown that such “background” nss-SO_4^{2-} have remained nearly constant during the entire Holocene (Legrand, 1995). This background nss-SO_4^{2-} can be quantified either by adding the average value of the sulphate record as well as its standard deviation (Delmas

et al. 1992), or by using a robust-spline smoothing of the raw nss-SO₄²⁻ (Zeilinski et al. 1994). Using the former method, the nss-SO₄²⁻ background of the present record is estimated to be of the order of 125 µg/l (Fig. 3b). This value is similar to the robust and sensitive estimation for the several shallow ice cores from the EPICA site of inland Dronning Maud Land (Traufetter et al. 2004). Accordingly, the nss-SO₄²⁻ concentrations above the estimated background profile of the present core are interpreted as directly related to the volcanic eruptions in the past.

The nss-SO₄²⁻ profile revealed significant fluctuations (Fig.3a) that are comparable to the several significant volcanic events that are globally recorded as well as proxy data from Antarctica and elsewhere (Thamban et al. 2006; and references therein). The most important volcanic eruptions identified from the nss-SO₄²⁻ records include: the 1991 eruption of Mount Pinatubo (Philippines; 15°N); the 1963 Agung eruption (Indonesia; 8°S); the 1932 eruption of Cerro Azul (Chile; 36°S); the 1883 Krakatau (Indonesia; 6°S); the 1835 Coseguina (Nicaragua; 13°N) eruption; the dual peaks of 1815 Tambora (Indonesia; 8°S) eruption and the older unknown 1809 eruption; the 1641 Mt Parker (Philippines; 6.1°N) eruption; the 1600 Huaynaputina (Peru; 16.6 °S) eruption; the 1595 eruption of Ruiz (Colombia; 4.9°N) and some other volcanic events that are less recognizable (Fig.3b). Many of these inferred major volcanic events seem to be originated from the tropical regions (Thamban et al. 2006). A bipolar comparison of nss-SO₄²⁻ profiles during the past millennium using ice cores from Antarctica and Greenland had demonstrated a strong interhemispheric correlation of the several prominent volcanic events (Langway et al. 1995). When the nss-SO₄²⁻ record of the IND-22/B4 core was compared with records from the Greenland and Antarctica, it revealed the presence of SO₄²⁻ depositions attributed to the Krakatau (1883), Tambora (1815), Unknown (1809) and Huaynaputina (1600) events in all records.

Globally, volcanic plumes consist of both gaseous and solid (tephra) components. While the gaseous aerosols injected to the stratosphere effectively reach both hemispheres, the fine fraction of the tephra material may also travel long distances, depending on the intensity of the eruptions and the circulation pattern (Palais et al. 1992). Presence of tephra in the Antarctic ice cores provide the physical evidence of volcanic events and are useful to understand the origin and transport mechanism involved in the distribution of such particles in Antarctica. SEM-EDS study of the accreted particles in IND-22/B4 core revealed the presence of different types of particles and confirmed the presence of volcanic tephra particles during intervals of

enhanced nss-SO₄²⁻. Detailed SEM study of tephra from intervals of two well-recorded volcanic eruptions of Agung (1963) and Krakatau (1883) also revealed presence of a plethora of microbial cells (clusters and isolated) of different shapes (cocci and rods) and sizes (micron and sub-micron) adhered to the surfaces of tephra (Laluraj et al. 2009).

Nitrate Records and Implications on Solar Forcing of the Antarctic Environment

The nitrogen ions deposited in polar ice as nitrates and nitric acids serves as a good indicator of the nitrogen cycle in the atmosphere. In spite of the numerous studies using the NO₃⁻ data in the polar snow/ice, the process of accumulation of nitrogen in polar ice is still not fully understood because of the multitude of sources and complex depositional processes (Röthlisberger et al. 2000; Wolff et al. 2008). Understanding the various processes influencing the production, accumulation and post-depositional preservation of NO₃⁻ in ice core records are vital to resolve the environmental signals contained in ice.

The nitrate (NO₃⁻) profile of the IND 22/B4 core revealed a major shift at ~1750 AD with relatively high values (average 151 µg/l) prior to 1750 AD and low values (average 75 µg/l) thereafter (Fig. 5a). Such a shift is not evident in any other ions like Na⁺, Cl⁻ and SO₄²⁻ (Fig. 2). Among various environmental factors, temperature has a potential influence on the NO₃⁻ concentration, with an increased NO₃⁻ preservation in snow at low temperatures (Wolff and Mulvaney, 2000). In order to examine the influence of temporal changes in atmospheric temperature on the NO₃⁻ preservation, the NO₃⁻ profile of IND-22/B4 was compared with the δ¹⁸O record of the core (Fig.5c). Earlier studies have shown that the δ¹⁸O record of firm/ice cores are found to correlate well with the records of local surface air temperature data from the coastal Dronning Maud Land (Marshall et al. 2009; Naik et al. 2010 b). Comparison of NO₃⁻ and δ¹⁸O profiles of the core revealed that major negative spikes of δ¹⁸O were synchronous with the NO₃⁻ peaks (Fig. 5), indicating a close relationship between the two. However, the marked shift in NO₃⁻ record at ~1750 AD lagged the change δ¹⁸O record by more than 20 years, indicating that while the local temperature could influence the NO₃⁻ preservation, other factors are important in interpreting the NO₃⁻ profile. Detailed studies on the air to snow transfer rates are required to examine the influence of temperature on nitrate preservation.

Studies using firm/ice cores have shown that the solar activity significantly influenced the temporal variability of NO₃⁻ concentration in Antarctica (Zeller and Parker, 1981; Dreschhoff et al. 1993; Palmer, 2001; Mayewski et al. 2005).

Changes in the production rate would also be indicative of changing influences on the source strength. The rate of accumulation of new odd nitrogen (the sum of all oxidised forms of nitrogen) in ice mainly depends on the production rate of nitrogen oxide molecules in the atmosphere through the reactions of O_2 and N_2 by solar and geomagnetic charged particles that are modulated by the solar activity (Zeller and Parker, 1981; Palmer, 2001). In order to understand the association between solar variability and the NO_3^- proxy in coastal Antarctica, we compared the NO_3^- record of IND-22/B4 to a ^{10}Be record from a South Pole ice core that had been extensively used as a proxy record of solar irradiance (Raisbeck et al. 1990; Bard et al. 2000). Since magnetic fields of the solar wind deflect primary flux of charged cosmic particles, increased solar activity leads to a reduction of cosmogenic nuclide (e.g., ^{10}Be and ^{14}C) production in the earth's atmosphere and vice versa (Beer et al. 1990; Bard et al. 2000). Therefore, temporal records of ^{10}Be would be

similar at least regionally and is considered to be a reliable indicator for solar activity as well as production of odd nitrogen.

The NO_3^- profile of IND-22/B4 core revealed good similarity with the ^{10}Be record of the South Pole ice core (Fig. 5a,b). Several major peaks in the NO_3^- record correspond well with the peaks in ^{10}Be record, with a marked shift around 1750 AD. Major periods of reduced solar activity like Dalton Minimum (~1790-1830 AD) and Maunder Minimum (~1640-1710 AD) were characterised by relatively enhanced NO_3^- concentration in the ice core, similar to the enhanced ^{10}Be concentration in the South Pole ice core (Fig. 5). A similar variability in NO_3^- and ^{10}Be records suggests that the NO_3^- concentrations in Antarctic ice cores is mainly controlled by changes in its production rate in the upper atmosphere. The nitrate ions are generated in the upper atmosphere following chain reactions with nitric oxide that would be then captured by aerosols and get

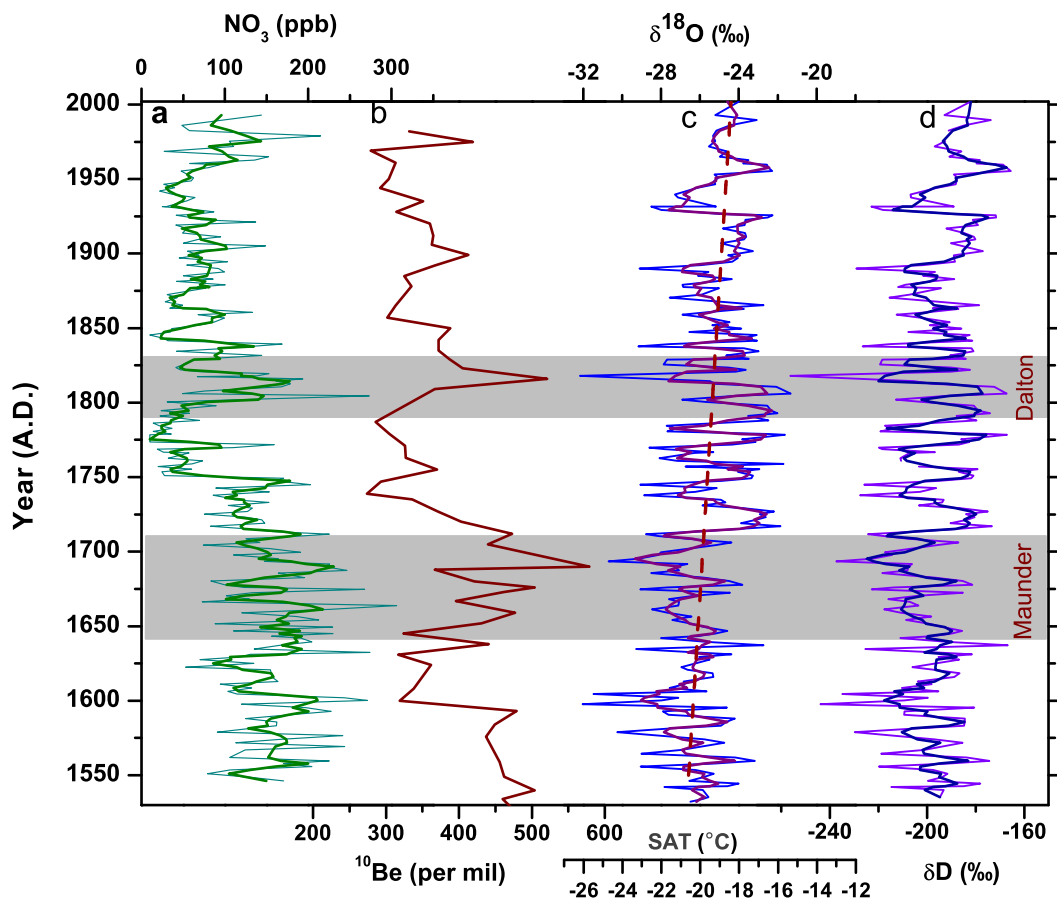


Fig.5. Profiles of nitrate (NO_3^-) and stable isotopes ($\delta^{18}O$ and δD) in the ice core IND-22/B4 along with the South Pole ^{10}Be proxy data by Bard et al. (2000). The smoothed records of NO_3^- , $\delta^{18}O$ and δD are obtained by a 3 point running average. The estimated surface air temperature (SAT) record of the core is also plotted in the $\delta^{18}O$ record and the dashed line represents long term warming trend in the SAT data. The shaded region represents the well known periods of reduced solar activity within the time frame of the core.

deposited in the polar ice, together with nitrate from tropospheric sources. Additionally, local factors like temperature would modulate the deposition and post-depositional preservation of NO_3^- in Antarctic snow deposits.

The $\delta^{18}\text{O}$ Records of Temperature Variability and the Recent Warming

The $\delta^{18}\text{O}$ and δD profiles of the core showed large interannual to decadal variability (Fig. 5). The $\delta^{18}\text{O}$ values varied between -21.2 and -32.2‰, with the amplitude and variability comparable to similar studies from the region (Nijampurkar et al. 2002; Anschutz et al. 2007). The $\delta^{18}\text{O}$ values were significantly more negative during 1550-1715 AD, suggesting cooler temperatures during this period. This interval is coeval with the so called "Little Ice Age" (LIA) widely depicted in the northern hemisphere and elsewhere. Many researchers consider the LIA a global event and demonstrated the existence of this cool interval in Antarctic proxy records (Kreutz et al. 1997; Stenni et al. 2002). However, the timing and signatures of LIA in Antarctica is debated (Bradley and Jones, 1993; Bard et al. 2000). Another important question is how this fits in to the proposed anti-phased warming ("bipolar seesaw") in the Antarctic region during the northern hemisphere LIA (Broecker et al. 2000).

Since a strong spatial relationship exists between the average local surface temperature and isotopic composition of local precipitation, $\delta^{18}\text{O}$ composition of polar snow had been used as a valuable temperature proxy (Dansgaard, 1964). The $\delta^{18}\text{O}$ records in the polar ice cores have often been used to determine the mean annual surface air temperatures (SAT) at the site of precipitation using the $\delta^{18}\text{O}$ -T relation (spatial slope). Within the DML region, spatial variations in oxygen isotopes had been used to determine the empirical relationship between the SAT and the $\delta^{18}\text{O}$ content in snow (Isaksson and Karlén, 1994). Although the relation between $\delta^{18}\text{O}$ and temperature are not completely known at the study site, an effort was made to deduce an empirical relationship using the available information. Estimation of $\delta^{18}\text{O}$ -T slope using data from central DML region (grid of 71°S to 76°S and 5°E to 15°E) based on the regional study of Masson-Delmotte et al. (2008), provided a spatial $\delta^{18}\text{O}$ -T slope of 1.31‰/°C for this region (Naik et al. 2010b). Using the $\delta^{18}\text{O}$ -T spatial slope of 1.31‰/°C, the $\delta^{18}\text{O}$ data of the IND-24/B4 ice core were converted to temperature, which gives an average temperature of -19.3°C (Fig. 5c). The SAT record thus generated clearly revealed an inter-annual to decadal variability with a long-term positive trend (Fig. 5c). The estimated warming of 2.7°C for the past 470 years is

significant with a warming of 0.6°C per century. Steig et al. (2009) reported a significant continent-wide warming during the past 50 years at the rate of 0.1°C/decade, with significant warming in the West Antarctica, compared to the East Antarctica. Records from the coastal DML region (East Antarctica) also supports enhanced warming with a reconstructed warming of 0.12‰/decade for the period 1920-1999 at S100 site (Divine et al. 2009) and 0.10‰/decade for the period 1905-2005 at IND-25/B5 site (Naik et al. 2010b). Considering the much longer duration (~470 years) of the present study, it is obvious that the warming in the coastal DML region is real and was extended at least the past few centuries. Comparison of $\delta^{18}\text{O}$ and δD records with the ^{10}Be profile of South Pole ice core (Fig. 5) suggest that periods of reduced solar activity like the Dalton Minimum (~1790-1830 AD) and Maunder Minimum (~1640-1710 AD) were characterised by relatively depleted $\delta^{18}\text{O}$ and δD , indicating relatively lower air temperatures during these periods. Climatic reconstructions using a variety of records have indeed suggested solar forcing on the global climate system in addition to other natural and anthropogenic factors (Lean et al. 1995; Bard et al. 2000; Beer et al. 2000; Mayewski et al. 2005). A possible mechanism for the solar modulation of the southern hemisphere climate system is through the dynamical coupling between the troposphere and stratosphere during the late spring/winter (Kuroda et al. 2007). Accordingly, enhanced solar activity would enhance the ultraviolet and ozone production that would lead to stronger troposphere-stratosphere coupling through a strong interaction between the planetary waves and radiation. The present study in association with multiple ice records from Antarctica as well as the proxy records of solar variability suggest a possible influence of solar forcing on the Antarctic climate change during the past few centuries.

CONCLUSIONS

Temporal records of ionic concentrations and stable isotope ratios in ice cores from coastal Antarctica provide excellent proxies of recent Antarctic variability and factors influencing the changes. Study of IND-24/B4 ice core from coastal Dronning Maud Land revealed significant fractionation in sea salt ions with much higher Cl^-/Na^+ ratios compared to the seawater, suggesting an additional contribution of Cl^- by scavenging of gaseous HCl present in the air by snow throughout the past 470 years. While the nss-SO_4^{2-} record showed fluctuations coeval with the major volcanic events, the NO_3^- profile of the core suggested large fluctuations with a significant shift at ~1750 AD.

Comparison of NO_3^- and ^{10}Be data of the South Pole ice core suggested that temporal changes in NO_3^- are controlled by fluctuations in solar activity in the past. The NO_3^- record also revealed good similarity with the $\delta^{18}\text{O}$ records, suggesting enhanced preservation of NO_3^- in snow during periods of reduced temperatures. The estimated surface air temperature at the core site revealed a significant warming

of 2.7°C with a warming of $\sim 0.6^\circ\text{C}$ per century for the past 470 years.

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