Clim. Past Discuss., 9, 1841–1867, 2013
www.clim-past-discuss.net/9/1841/2013/
doi:10.5194/cpd-9-1841-2013

Climate of the Past Discussions
Open Access

Dust and associated trace element fluxes in a firn core from the coastal East Antarctica and its linkages with the Southern Hemisphere climate variability over the last ∼ 50 yr

C. M. Laluraj, M. Thamban, and K. Satheesan

National Centre for Antarctic and Ocean Research, Headland Sada, Goa-403804, India

Received: 18 March 2013 – Accepted: 31 March 2013 – Published: 5 April 2013

Correspondence to: C. M. Laluraj (lalucm@ncaor.org)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

High-resolution records of dust and trace element fluxes were studied in a firn core from the coastal Dronning Maud Land (cDML) in East Antarctica to identify the influence of climate variability on accumulation of these components over the past ~ 50 yr. A doubling of dust deposition was observed since 1985, coinciding with a shift in the Southern Annular Mode (SAM) index to positive values and associated increase in the wind speed. Back-trajectories showed that an increase in dust deposition is associated with the air parcels originating from north-west of the site, possibly indicating its origin from the Patagonian region. Our results suggest that while multiple processes could have influenced the increased dust formation, shift in SAM had a dominant influence on its transport. It is observed that since the 1985s the strength of easterlies increased significantly over the cDML region, which could sink air and dust material to the region that were brought by the westerlies through mass compensation. The correlation between the dust flux and $\delta^{18}O$ records further suggest that enhanced dust flux in the firn core occurred during periods of colder atmospheric temperature, which reduced the moisture content and increased dust fall. Interestingly, the timing and amplitude of the insoluble dust peaks matched remarkably well with the fluxes of Ba, Cr, Cu, and Zn confirming that dust was the main carrier/source of atmospheric trace elements to East Antarctica during the recent past.

1 Introduction

The ice sheets of Antarctica holding fingerprints of past climatic perturbations, store not only information about changes in temperature, precipitation and ion chemistry, but also the changes in the composition of dust fallout (Petit et al., 1999; Stauffer, 1999; Laluraj et al., 2011; Delmonte et al., 2008). The dust particles of the atmosphere containing various elements are ultimately trapped in the ice, providing historical information on changes in the atmospheric composition and climate (Delmonte et al., 2008; Laluraj et al., 2009). Studies on Antarctic ice cores have revealed increased dust flux during the last glacial maximum with respect to the Holocene due to increased terrestrial aridity and vigorous atmospheric disturbances (Petit et al., 1999). Similar studies have indicated that the influences of atmospheric events on the Antarctic ice are controlled by the source, quality and scavenging property of the dust particles. The concentration of insoluble dusts in snow depends on the inter-continental origin, which is related to the prevailing environmental conditions, volcanic inputs, snow accumulation rate, transport mechanisms and atmospheric cleansing (Laluraj et al., 2009; Petit et al., 1999). The dust depositions in polar regions are generally associated with: (i) atmospheric disturbances causing transport and settling of dust (COHMAP Members, 1988), (ii) weak hydrological cycle and reduced scavenging by precipitation leading to efficient transport of dust (Yung et al., 1996), and (iii) expanded dust source region following reduced soil moisture and vegetation (Joussaume, 1990; Delmonte et al., 2008).

The mineral dust archived in the east Antarctic ice is mainly aeolian in nature, originating from the Southern Hemisphere (Basile et al., 1997; Delmonte et al., 2010). The short-term and long-term variations of its concentration and size reflect several characteristics like soil properties at the source, meteorological conditions, hydrological cycle, removal processes, atmospheric disturbance and snow accumulation rate (Yung et al., 1996). Antarctic ice core and source data strongly suggest that Patagonia was an important source of dust in the East Antarctica, as the westerly winds favored its transfer to Antarctica during cold periods in the past (Basile et al., 1997; Delmonte et al., 2008). However, there are studies contradicting this, claiming the origin of dust in East Antarctica to be from Australia (Gaudichet et al., 1992; Revel-Rolland et al., 2006).

Southern Annular Mode (SAM) is a major climate mode in the Southern Hemisphere. A positive SAM is associated with decrease in the temperature over Antarctica and an increase in the westerly winds in the main belt of subpolar regionsd (Thompson and Wallace, 2000; Marshall, 2002). Accordingly, the dust deposition rates on the Antarctic ice sheets might have changed in the past due to shift in SAM (Thompson and Wallace,

CPD
9, 1841–1867, 2013

2000; Delmonte et al., 2008). The geochemical components accumulated in the ice deposits are therefore, good indicators of the past changes in their emissions by natural or anthropogenic processes, which would be influenced by climate change and have significant ecological consequences (Boutron, 1995). Geochemical fractions trapped in the ice can also provide information on the soil response to changing climate, extraterrestrial particles falling on polar region and anthropogenic activities at other continents. While dust profiles provide proxy records of long-term climate variability in ice core records, high-resolution studies are necessary to quantify the effect of short-term drastic perturbations on the transport of impurities into the Antarctic environment. A recent study of aluminosilicate dust fall in an ice core from Antarctic Peninsula revealed that the dust deposition nearly doubled during the 20th century, coincident with widespread desertification in Patagonia and northern Argentina (McConnell et al., 2007). However, there are no high resolution firn core studies in East Antarctica depicting the recent dust deposition and associated changes in geochemical composition. With this background, we investigated the changes in the dust flux and associated geochemical components during the past ~ 50 yr in a high resolution firn core record from the coastal Dronning Maud Land (cDML) in East Antarctica. Our study attempts to understand the magnitude of recent variability in dust flux and to identify the processes involved in the supply, transport and deposition of dust and associated chemical components that have significant implications on the recent Antarctic climate changes.

2 Material and methods

A 65 m firn/ice core (IND-25/B5) collected from the coast of central Dronning Maud Land (cDML, Lat. 71°20′ S Long. 11°35′ E, elevation: ~ 1300 m) was used for the present study (Fig. 1). Details of the field and laboratory processing work conducted on the core are detailed by Naik et al. (2010). With an objective to evaluate the dust and chemical components in response to recent climate change as evidenced from instrumental records, the top ~ 30 m of the firn core was studied with high resolution

CPD
9, 1841–1867, 2013
Dust and elements archived in Antarctica
C. M. Laluraj et al.

sampling (12–14 samples per year). Prior to the sub-sampling, the firn core was decontaminated manually by skimming of the outer layer in a Class 100 laminar bench. Further to avoid contamination, only the inner part of the core was used for the trace metal analyses. Chronological control on the core was obtained by multiple methods: (i) annual layer determination from the summer peaks in $\delta^{18}O$; (ii) using the of $nssSO_4^{2-}$ (non-sea salt sulphate) markers of volcanic eruptions; and (iii) atomic bomb markers (Naik et al., 2010).

The core samples were melted in a Class 100 clean room before conducting the particle size and chemical analyses. A Multisizer IV (Beckman Coulter) Coulter Counter with 50 µm orifice installed in a class 100 clean room was used to measure dust particles of size between 1 and 25 µm diameter (400 channels). For the Coulter Counter (CC) analysis, an electrolyte (NaCl) was pumped to the sample through a small orifice and the electrical conductance was measured. The detailed procedures used in the study are described elsewhere (Wu et al., 2009). Size calibration was achieved using certified standards of latex particles and for each measurements, 0.5 mL of sample was repeated for three times. Continuous analysis of Laboratory blanks showed an analytical precision of ±1 ppb. For dust estimation, a microparticle density of 2.6 $g\,cm^{-3}$ was assumed (Wu et al., 2009).

Trace metal analysis was carried out using a X7 series ICP-MS with Collision Cell Technology (ThermoFisher Scientific, UK). Samples were kept for melting in a Class 10 clean bench. All ICP-MS samples were acidified by 1 % ultra-pure HNO_3 and kept at −20 °C for approximately 12 h. Samples were brought to room temperature approximately 6 h prior to analysis. The elements selected for the present study were Ba, Cr, Zn and Cu. The ICP-MS running conditions consisted a RF power of 1400 W and a nebulizer gas flow of 1 $mL\,min^{-1}$. All apparatuses coming in contact with the samples were soaked overnight in 10 % HNO_3 and thoroughly rinsed with deionised water and dried. Only 18.2 MΩ deionised water (Milli-Q Element A10, Millipore) and ultra pure HNO_3 were used for the entire analysis. The instrument detection limits were; Ba 0.05 $\mu g\,L^{-1}$, Cr 0.05 $\mu g\,L^{-1}$, Zn 0.03 $\mu g\,L^{-1}$ and Cu 0.06 $\mu g\,L^{-1}$. The procedural blank prepared in

CPD
9, 1841–1867, 2013
Dust and elements archived in Antarctica
C. M. Laluraj et al.

ultrapure water was below the detection limit. The ICP-MS system was calibrated daily with five standards in the range expected for the sample concentrations. Calibration was accomplished by using standard solutions prepared from multi elemental standards of Inorganic Ventures, USA. Standard Reference Material of NIST 1640 natural water with appropriate dilution was used for estimating the analytical precision and was found to be in excellent agreement. Repeated analysis of acidified samples provided the analytical repeatability within 5–10 %. The concentrations were in excellent agreement with the certified values for all elements. Internal standard Rhodium was spiked in all the calibration standards and samples to monitor the long-term drift.

Annual accumulation rates at the core site were calculated based on the summer peaks in $\delta^{18}O$ record and density of snow at respective section. Density of snow was estimated using weight and volume of the individual core sections The annual accumulation rate of the present firn core was ranged between 154 to 456 $kg\,m^{-2}\,yr^{-1}$ with standard deviation of 83.5 $kg\,m^{-2}\,yr^{-1}$ (Fig. 2d). The average accumulation rate of the present core (286 $kg\,m^{-2}\,yr^{-1}$) is comparable with earlier studies from DML region (e.g. Giovinetto and Zwally, 2000). For quantitative comparison, firn core dust and trace elemental concentrations were converted to annual flux, computed by multiplying the concentration with the water equivalent accumulation rates. The dust and metal flux data were filtered using a Fourier transform low pass filter after interpolating the data to equispaced points. Additional datasets employed in this study are the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (NNR) data (Kalnay et al., 1996) for the period 1960–2005, and the Southern Annular Mode index for the period 1960–2005. Southern Annular Mode (SAM) is defined as the difference in the normalized monthly zonal mean sea level pressure between 40° S and 70° S (Nan and Li, 2003). NNR data set provides excellent quality reanalyses for this region (Simmonds et al., 2003). In order to find the source of the air parcels in the lower atmosphere, three dimensional back-trajectories were also used, which were produced using the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2013) using NNR. We used only the

NNR data from 1979 in order to maintain the consistency. The data prior to 1979 may be having some bias since very few data over Antarctica were used in the assimilation. We also compared the surface wind data available from the European Centre Medium Range Forecast (ECMWF, ERA-Interim) with the NNR surface wind data during 1979–2006 and are showing similar trends with comparable amplitude. The surface wind data plotted in Fig. 1a and b is taken from ERA-Interim for the period 1979–1984 and 1985–2006 respectively. The trajectories were initialized from 1000 m above the surface because they minimize disturbance from underlying topography while being sufficiently close to the terrain to be dynamically linked to the surface wind field (Sinclair et al., 2010). A number of back-trajectories were obtained which were clustered to combine similar trajectories. Cluster analysis is a statistical method that identifies homogeneous groups of members within large data sets. Cluster analysis accounts for variations in transport speed and direction simultaneously yielding groups of trajectories which have similar length and curvature (Stohl, 1998). In order to identify the change in depositional trends and seasonal variations prior and after 1985, we computed representative back-trajectories for the summer and winter months for two years prior and after 1985.

3 Results and discussion

3.1 Variability in dust and trace metal fluxes at the coastal Droning Maud Land

Dust flux in the fine fraction (1–6 µm) and total fraction (1–25 µm) of the IND-25/B4 core showed large variations over the last five decades (Fig. 2a, b). Though the fine fraction contributed 91.9 % of the concentration number (CN), it constituted only inner fraction of the total dust fall. This indicates that the fine fraction representing a small amount of concentration mass (CM) has a larger CN. This is in agreement with the Junge distribution law, which states that even though the number of dust particle decreases exponentially with increasing diameter, larger particles mostly contributes to the total mass (Wu et al., 2009). This is further evidenced by the increased dust flux (4.61 µg cm^{-2} yr^{-1} and 17.67 µg cm^{-2} yr^{-1} for 1–6 µm and 1–25 µm particles, respectively) after 1985 compared to its lower flux (2.14 µg cm^{-2} yr^{-1} and 8.63 µg cm^{-2} yr^{-1} for 1–6 µm and 1–25 µm) prior to it (Table 1). Thus, the dust fall over the cDML region have doubled since 1985. Over the past 5 decades, the δ^{18}O levels have fluctuated widely in ice cores (−22.54 to −36.74, average −30.15; Fig. 2c), in accordance with an increase in the surface air temperature from −27.9 °C to −21.8 °C (Naik et al., 2010). The negative incursions in δ^{18}O profiles coinciding with enhanced dust fluxes (Fig. 2a–c), indicates an inverse correlation between the surface air temperature and aeolian accumulation ($r = -0.42$; $n = 454$; $p > 0.0001$). A colder climate could considerably enhance the dust fall due to atmospheric turbulence that carry them over large distances (Yung et al., 1996). The dry air during austral winter can lead to violent storms to increase the Aeolian (Genthon, 1992), which are transported over the hemisphere before being deposited on the Antarctic ice sheet. It was demonstrated that weathering and erosion play an important role in the dust production in South America (Gaiero, 2007; Sugden et al., 2009) and its transport to Antarctica (Krinner and Genthon, 2003). Thus, the dust deposited in Antarctica was originally coming from the South America following short hydrological cycles (Lambert et al., 2008). The dry aerosol also could avoid their removal and enable a longer residence time in the atmosphere (Yung et al., 1996). Prospero et al. (2002) have shown that high dust production over four regions in South America, namely (1) Bolivian Altiplano, an elevated basin centered around 15° S, (2) the Atacama Desert in Chile, between 20 and 30° S (3) western Argentina (32° S) and (4) Patagonia, between 35°–50° S are characterized by dry sandy desert. Recently it was demonstrated that dust fall was high in Antarctica during glacial periods (Delmonte et al., 2008), and it was also reported that significant changes in dust flux also occurred over the last 100 yr (McConnell et al., 2007; Marino et al., 2008; Lambert et al., 2008), with the Patagonian desert and Australia being the major sources of dust to Antarctica (Revel-Rolland et al., 2006; Marino et al., 2008). In addition, the recent doubling of dust input to Antarctica is coincident with the environmental changes in the South America, especially in response to the widespread deforestation (McConnell et al., 2007).

In order to understand the linkage between the enhanced dust and transported geochemical impurities in the study site from other continents in recent decades, we examined the concentrations of major geochemical components in the core. Down core profiles of the trace metal fluxes of Ba, Cr, Cu and Zn with in IND-25/B5 core are shown in the Fig. 3 and their statistical distribution prior and after 1985 are shown in Table 1. Among the various geochemical components, Zn was the dominant element and Cr the lowest in the order Zn > Cu > Ba > Cr (Fig. 3). Within the Antarctic snow/ice, Cr and Ba are generally considered as crustal elements, while Zn and Cu are attributed to sea spray and/or soil dust. Ba concentration in the recent times in Antarctic snow was higher than "natural" levels following an increased dust fall, which is attributed to the influence of climate change caused by deforestation (Vallelonga et al., 2002). Boutron et al. (1990) observed that the Antarctic troposphere contains elevated levels of Zn from wind-blown dust from crustal rock and soil. Comparison between the dust and geochemical fluxes of IND 25/B5 core revealed similar variability (Figs. 2a, b and 3). The dust/trace metal flux reveals seasonality with a maximum in the winter (Figs. 2a, b and 3). The increased metal flux in the core after 1980s is likely a result from factors relating to its transport history, such as its specific trajectory and residence time, or the concentration of dust particles and/or metal pollutants in the atmosphere at the time of its transport. The significant correlation between metal fluxes to dust accumulation suggests that increased dust has critical role in their distributions. Pearson's correlation coefficients suggest a strong association (significant at 99 % level; $p = 0.0001$) among the geochemical components and the total fraction dust flux. A strong correlation of dust flux with Ba and Cr flux ($r = 0.61$ and $r = 0.40$; $n = 454$) is due to the crustal origin of these elements. Similarly, positive correlations were found between dust with other elements ($r = 0.33$ with Zn, $r = 0.31$ with Cu; $n = 454$). Such relationships emphasize that these elements have a common origin and/ or responds to the environmental changes similarly. Additionally, strong positive correlations between Ba

CPD
9, 1841–1867, 2013

and Cr and with other elemental fluxes clearly indicate a common source or scavenging of these elements by aeolian dust.

Studies showed that mineral dust serve as a vector for pollution transport (Jaffe et al., 1999; Han et al., 2004). The scavenging of chemical components by dust depends on the type, composition and concentration of pollutants and dust particles, moisture content, transport trajectories and their residence time in the atmosphere (Erel et al., 2006; Fujiwara et al., 2006). Recent studies of mineral dust, which can scavenge pollutants from the atmosphere, show that dust can serve as a medium for pollution transport (Jaffe et al., 1999; Han et al., 2004). The correlation between geochemical and dust fluxes confirms that trace metals are transported along with dust as well as through precipitation of which, the former one is a major environmental concern. Our study suggests that the trace metal concentration in the firn records is linked to dust flux and in turn, to wind strength and trajectory. Stronger transport or shorter trajectory can reduce the mineralogical fractionation and lead to deposition of large particles over the East Antarctic (Delmonte et al., 2002). As evidenced from the records, there is a two-fold increase in the geochemical fluxes at the firn core site since 1985 (Table 1). Considering the similar variations in dust and tracemetal fluxes viz-á-viz the apparent variability in surface air temperature (based on δ^{18}O record) and zonal wind strength, it is suggested that all these processes are closely linked through a climatic shift in the Southern Hemisphere.

3.2 The recent increase in dust flux to East Antarctica and its relation to SAM

In order to study the origin of the dust and trace metals in the present core and their seasonality, back-trajectories were constructed for 10 days using the HYSPLIT model for two representative years of low and high dust fluxes. We selected the one month each of the two periods for computing the back-trajectories; summers of 1983 and 1998 and winters of 1982 and 1998. These periods were chosen since they are in the same phase of El-Nino Southern Oscillation (ENSO) and since ENSO has a known linkage with Southern Hemisphere climatic variability (L'Heureux and Thompson, 2006).

CPD
9, 1841–1867, 2013

Figure 4a shows the back-trajectories computed in January 1983. Most of the time, sources of the air parcels coming to the location were from the Antarctic continent itself. Compared to this, for August 1982 representing the winter season, some of the trajectories are pointing towards the Southern Ocean and Antarctic Peninsula (Fig. 4b). Figure 4c, d shows the trajectories for January 1998 and August 1998, respectively. In January 1998, few air parcels reaching the site are from the interior Antarctica while few others points towards the Southern Ocean. In winter, most of the parcels are coming from the oceanic regions traveling long distance from the western sector of the South Atlantic. Apparently, the enhanced dust influx in recent period originates from Patagonian region. Further, the source of the air parcels in winter is outside the Antarctic continent while in summer, it is from the interior or nearby oceanic regions. This explains the increased dust during winter.

While the source of seasonal variation in the dust can be interpreted as above, the mechanism for the doubling of the dust/trace metals after 1985 is also needs to be explained. The SAM is characterized by a large-scale alternation of atmospheric masses between the mid and high latitudes (Thompson and Wallace, 2000). This is manifested as meridional shifts by the subpolar westerly winds (Hartmann and Lo, 1998). The SAM also contributes to major circulation in the Antarctica on different time scales (Marshall, 2002). It is observed that there is a positive shift in the SAM since the 1960s, consistent with strengthening of the circumpolar vortex and the southern westerlies (Marshall, 2002, 2003). Shifts in the winds and SAM can substantially alter the circulation pattern and aerosol transport to the Antarctica (Hall and Visbeck, 2002; Marshall, 2003; Oke and England, 2004). The dust and trace metal flux distribution was found to be closely linked with climate variation with high values during the positive SAM and low values during negative SAM periods. It suggests that there is a critical climate condition beyond which, the deposition of dust and geochemical components in the firn core increases considerably.

The dust flux estimated at the IND-25/B5 firn core site showed good similarity with the SAM records with enhanced dust flux after 1985 coinciding with positive SAM

CPD
9, 1841–1867, 2013

(Table 1, Fig. 2a, b, d). A possibility could be the changes in the source characteristics from Patagonia or Australia (Delmonte et al., 2002, 2004; Revel-Rolland et al., 2006; Lambert et al., 2008). A more well known mechanism could be that the positive SAM after 1985s could have strengthened the winds and dust particles which were transported to the East Antarctic (Gabrielli et al., 2005). Thus the increased dust flux as found in cDML core could be due to an increase in the intensity of westerly winds modulated by the positive SAM. Thus, the aerosols over the Antarctic region may be actually transported from mid latitudes (Lambert et al., 1990). Since the tropospheric aerosol transport is negligible during summer (Polian et al., 1986), the low summer dust accumulation in firn core substantiates the seasonal behavior in the cDML (Fig. 2d). The increase in the cyclone depth and the positive SAM index persistent after 1985s was attributed to the warming of the atmosphere over the Antarctic Peninsula (Thompson and Wallace, 2000). Thus positive SAM could lead to stronger cyclones over southern latitudes (Pezza et al., 2008). This is accompanied by warming of the troposphere over the tropics leading to increased gradients in winds over the mid latitude (Pezza et al., 2008). It is thus evident that the aeolian dust reaching the East Antarctic plateau during modern and past times is transported through the mid-to-high troposphere from the Southern Hemisphere land mass. Over the past few decades, the gradient in the meridional pressure following a positive SAM seems to have strengthened the circumpolar vortex and the westerlies surrounding Antarctica (Marshall, 2002).

Dust reaching the East Antarctica is usually wind-borne from the Southern Hemisphere landmasses and transported through the mid-to-high troposphere (Delmonte et al., 2008). Increased wind intensities could also allow more dust to be entrained and carried to remote areas like Antarctica (COHMAP Members, 1988). Within the cDML, the wind regime is dominated by polar easterlies that are intrinsically related to the Southern Hemisphere westerlies (Thompson and Wallace, 2000). While examining the wind pattern of the present study region obtained from NCEP/NCAR reanalysis data, it is evident that there was a continuous increase in the easterly winds from 1960 onwards. However, the gradient of zonal wind strength substantially increased

CPD
9, 1841–1867, 2013

after 1985 (Fig. 2f). The wind speed increased from 5.1–6.7 $m s^{-1}$ during 1960–1985 to 6.7–9.8 $m s^{-1}$ during 1985–2006 (Fig. 2f). When SAM index increases, the Antarctic continent becomes more insulated from mid-latitudes resulting in colder conditions and greater frequency of katabatic winds. Katabatic winds flow off the continent which due to the effect of Coriolis force gets deflected to the west. Thus we can expect the easterlies to increase when the SAM-index increases (Fig. 2e, f). Such a substantial change in zonal wind strength could be implicated for the doubling of dust deposition in the cDML region after 1985. The strong winds over Patagonia lead to low pressure over the Pacific–Atlantic Oceans, whereas the dust plumes move according to the relative position of these low pressure systems (Labraga, 1994; Li et al., 2008). These westerlies (cyclonic structure) can elevate the air masses and aerosols to the upper troposphere by taking large quantities of loose surficial sediments and dust from Patagonia (Iriondo, 2000). Through mass compensation, the enhanced polar easterlies (surface anticyclones; Fig. 2f) could sink the air masses and deposit the dust material over the coastal East Antarctica. This could be the reason for the increased dust deposition in the coastal cDML region since 1985. This mechanism has been explained with the help of the schematic of the circulation in the atmosphere over Southern Hemisphere after 1985 in Fig. 5.

Previous studies using tracers of crustal origin such as ^{222}Rn and aluminum microparticles (Evangelista and Pereira, 2002), Pb, Ba and In (Burn-Nunes et al., 2011) have found cyclones originating from 60° S to be a major factor in transporting warm aerosols, mineral dust and pollutants to Antarctica. Simmonds et al. (2003) used trajectories to explain the atmospheric transport from Southern Hemisphere continents towards Antarctica. During the migration of cyclones, the vorticity accelerates the meridional winds to drive aerosol particles to the south (Law et al., 1992). This is further supported by dust plumes observed over the South Atlantic and Southern Ocean by remote sensing (Gasso et al., 2010). The atmospheric transport of dust microparticles from Patagonia to Antarctica is attributed to the combined effect of longer residence time of dry aerosols and the expansion of South American desert (Lambert et al.,

CPD
9, 1841–1867, 2013
Dust and elements archived in Antarctica
C. M. Laluraj et al.

2008). The mid-to-Subantarctic zones are experiencing enhanced Westerlies and cyclones. This provides a favorable condition for mineral dust delivery to the Antarctica. Sr/Nd isotope studies in East Antarctica (Basile et al., 1997; Delmonte et al., 2010) and atmospheric circulation models (Lunt and Valdes, 2002) have also identified Patagonian deserts in South America as a major dust source. Ice core studies also supported that Patagonia is the principal source of dust in the East Antarctica ice and that the enhanced westerlies supported its transport during glacial intervals over the last 800 ka (Basile et al., 1997; Delmonte et al., 2008). Interpretations of dust deposits in Antarctic ice cores have been connected to atmospheric transport strength and source availability of dust in the surrounding continents (Basile et al., 1997; Li et al., 2008). At least two recent ice coring projects conducted in West Antarctica revealed the impact of the increasing westerlies on dust dispersion and deposition on to the Antarctic ice sheet (Li et al., 2008). It also has been demonstrated that Subantarctic cyclones are very efficient systems at transporting particulate materials to the Antarctic continent (Law et al., 1992), and their effectiveness in dust dispersion is related to their energy and radius (Evangelista and Pereira, 2002).

Studies have shown that due to global warming and associated deforestation, which was further amplified by the land use changes, the availability of dust in the Patagonia region has increased during the recent decades (Tegen et al., 1996; McConnell et al., 2007). We propose that increased dust availability in Patagonia and enhanced westerlies since 1980s can be attributed for the doubling of dust flux at the core site in cDML during the recent decades. The westerlies around the Antarctica oscillates semi-annually. The westerlies also have a southward component, giving them a cyclonic nature. These cyclonic vorticity will enhance the convergence along these belts which will help in the upward mass transport. Patagonia, which is abundant with dusts and aerosols, lies in these belts. The rising air masses in these regions will carry the dust and aerosols upward. While these southeast winds transport dusts upward, the permanent anticyclone over Antarctica induces downward transport of air masses which will compensate for the upward transport along the westerlies. The upward limb of the polar cell lies along the westerly belts while the downward limb lies over the anticyclonic regions of the Antarctica. It is evident from Fig. 1 that not only the westerly wind speed has increased after 1985 but also the direction of the wind has become more southward which would have strengthen the upward air mass transport and consequently increase in the uptake of dusts and aerosols. Correspondingly, the divergence over Antarctica is also increased as evidenced from the increase in the easterly wind speed (Fig. 2f).

It is proposed that when a critical pressure gradient was reached between mid and high latitudes due to a shift towards positive SAM, it caused enhancement of westerlies, allowing increased amounts of dust and associated geochemical components to be transported to the East Antarctica. Wind-blown dust from Patagonia appears to be the main natural source of metals in the East Antarctica, as supported by the excellent statistical relationships between them. While a possibility of land use changes/deforestation in the source region cannot be completely ruled out, the strong correlations with the climatic parameters modulated by the SAM suggests a predominant control of SAM in the temporal distribution of dust and geochemical fluxes at the coastal East Antarctica. The fluxes of dust/metal in Antarctic ice appear to be controlled by wind strength and their trajectory.

4 Conclusions

The present study shows that during the last ~ 50 yr, the dust deposition increased by two-fold since 1985 in the coastal Dronning Maud Land (cDML) of East Antarctica. A strong negative correlation between δ^{18}O records and dust flux suggests that enhanced dust flux in the firn occurred during the austral winters. Back-trajectory studies suggested that the seasonal increase in the dust deposition is associated with a transport of air from the north and west of cDML, possibly originating from the Patagonia region. Further, the chemical fluxes of Ba, Cr, Cu and Zn at the core site were found to be closely associated with the dust flux, confirming that these chemical components are transported/scavenged by the aeolian dust. These results corroborate that the tracemetal accumulation in the firn cores of Antarctica are closely linked to the aeolian depositions. Comparison with major climatic parameters in this region confirms that the increase in the dust and metal accumulations in the Antarctic snow were influenced by a positive shift in the Southern Annular Mode.

Acknowledgements. We thank the Director, NCAOR for the encouragement and the Ministry of Earth Sciences, Government of India for the financial support. We are grateful to B. L. Redkar and Sunaina Wadeker, Ice Core Laboratory, NCAOR, Goa for their help in the laboratory analysis This is NCAOR contribution No. xx/2013.

References

Basile, I., Grousset, F. E., Revel, M., Petit, J. R., Biscaye, P. E., and Barkov, N. I.: Patagonian origin of glacial dust deposited in East Antarctica (Vostok and Dome C) during glacial stages 2, 4 and 6, Earth Planet. Sc. Lett., 146, 573–589, 1997. 1843, 1854

Boutron, C. F.: Historical reconstruction of the earth's past atmospheric environment from Greenland and Antarctic snow and ice cores, Environ. Rev., 3, 1–28, 1995. 1844

Boutron, C. F., Patterson, C. C., and Barkov, N. I.: The occurrence of zinc in Antarctic ancient ice and recent snow, Earth Planet. Sc. Lett., 101, 248–259, 1990. 1849

Burn-Nunes, L. J., Vallelonga, P., Loss, R. D., Burton, G. R., Moy, A., Curran, M., Hong, S., Smith, A. M., Edwards, R., Morgan, V. I., and Rosman, K. J.: Seasonal variability in the input of lead, barium and indium to Law Dome, Antarctica, Geochim. Cosmochim. Ac., 75, 1–20, 2011. 1853

COHMAP Members: Climatic changes of the last 18 000 yr: observations and model simulations, Science, 241, 1043–1052, 1988. 1843, 1852

Delmonte, B., Petit, J. R., and Maggi, V.: Glacial to Holocene implications of the new 27 000 yr dust record from the EPICA Dome C (East Antarctica) ice core, Clim. Dynam., 18, 647–660, 2002. 1850, 1852

Delmonte, B., Petit, J. R., Andersen, K. K., Basile-Doelsch, I., Maggi, V., and Lipenkov, V. Y.: Dust size evidence for opposite regional atmospheric circulation changes over East Antarctica during the last climatic transition, Clim. Dynam., 23, 427–438, 2004. 1852

Delmonte, B., Andersson, P. S., Hansson, M., Schöberg, H., Petit, J. R., Basile-Doelsch, I., and Maggi, V.: Aeolian dust in East Antarctica (EPICA-Dome C and Vostok): provenance during glacial ages over the last 800 kyr, Geophys. Res. Lett., 35, L07703, doi:10.1029/2008GL033382, 2008. 1842, 1843, 1844, 1848, 1852, 1854

Delmonte, B., Andersson, P. S., Schöberg, H., Hansson, M., Petit, J. R., Delmas, R., Gaiero, D. M., Maggi, V., and Frezzotti, M.: Geographic provenance of aeolian dust in East Antarctica during Pleistocene glaciations: preliminary results from Talos Dome and comparison with east Antarctic and new Andean ice core data, Quaternary Sci. Rev., 29, 256–264, 2010. 1843, 1854

Draxler, R. R. and Rolph, G. D.: HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website, available at: http://ready.arl.noaa.gov/HYSPLIT.php (last access: 18 March 2013), NOAA Air Resources Laboratory, Silver Spring, MD, 2013. 1846

Erel, Y., Dayan, U., Rabi, R., Rudich, Y., and Stein, M.: Trans boundary transport of pollutants by atmospheric mineral dust, Environ. Sci. Technol., 40, 2996–3005, 2006. 1850

Evangelista, H. and Pereira, E.: Radon flux at King George Island, Antarctic Peninsula, J. Environ. Radioactiv., 61, 283–304, 2002. 1853, 1854

Fujiwara, F., Dos Santos, M., Marrero, J., Polla, G., Gomez, D., Dawidowski, L., and Smichowski, P.: Fractionation of eleven elements by chemical bonding from airborne particulate matter collected in an industrial city in Argentina, J. Environ. Monit., 8, 913–922, 2006. 1850

Gabrielli, P., Barbante, C., Boutron, C., Cozzi, G., Gaspari, V., Planchon, F., Ferrari, C., Turetta, C., Hong, S., and Cescon, P.: Variations in atmospheric trace elements in Dome C (East Antarctica) ice over the last two climatic cycles, Atmos. Environ., 39, 6420–6429, 2005. 1852

Gaiero, D. M.: Dust provenance in Antarctic ice during glacial periods: calibrating the dust emission record of southern South America, AGU Fall Meeting Abstracts, 10–14 December 2007, San Francisco, CA, USA, Abstract No. PP31E-03, 2007. 1848

Gasso, S., Grassian, V. H., and Miller, R. L.: Interactions between mineral dust, climate, and ocean ecosystems, Elements, 6, 247–252, 2010. 1853

Gaudichet, A., de Angelis, M., Joussaume, S., Petit, J. R., Korotkevich, Y. S., and Petrov, V. N.: Comments on the origin of dust in East Antarctica for present and ice age conditions, J. Atmos. Chem., 14, 129–142, 1992. 1843

Genthon, C.: Simulations of desert dust and sea-salt aerosols in Antarctica with a general circulation model of the atmosphere, Tellus B, 44, 371–389, 1992. 1848
Giovinetto, M. B. and Zwally, H. J.: Spatial distribution of net surface accumulation on the Antarctic ice sheet, Ann. Glaciol., 31, 171–178, 2000. 1846
Hall, A. and Visbeck, M.: Synchronous variability in the Southern Hemisphere atmosphere, sea ice, and ocean resulting from the annular mode, J. Climate, 15, 3043–3057, 2002. 1851
Han, J. S., Moon, K. J., Ahn, J. Y., Hong, Y. D., Kim, Y. J., Ryu, S. Y., Cliff, S. S., and Cahill, T. A.: Characteristics of ion components and trace elements of fine particles at Gosan, Korea in spring time from 2001 to 2002, Environ. Monit. Assess., 92, 73–93, doi:10.1023/B:EMAS.0000014510.21563.50, 2004. 1850
Hartmann, D. L. and Lo, F.: Wave-driven zonal flow vacillation in the Southern Hemisphere, J. Atmos. Sci., 55, 1303–1315, 1998. 1851
Iriondo, M.: Patagonian dust in Antarctica, Quaternary Int., 68, 83–86, 2000. 1853
Jaffe, D., Anderson, T., Covert, D., Kotchenruther, R., Trost, B., Danielson, J., Simpson, W., Berntsen, T., Karlsdottir, S., Blake, D., Harris, J., Carmichael, G., and Uno, I.: Transport of Asian air pollution to North America, Geophys. Res. Lett., 26, 711–714, 1999. 1850
Joussaume, S.: Three-dimensional simulations of the atmospheric cycle of desert dust particles using a general circulation model, J. Geophys. Res., 95, 1909–1941, 1990. 1843
Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, B., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-year reanalysis project, B. Am. Meteorol. Soc., 77, 437–472, 1996. 1846
Krinner, G. and Genthon, C.: Tropospheric transport of continental tracers towards Antarctica under varying climatic conditions, Tellus B, 55, 54–70, 2003. 1848
Labraga, J. C.: Extreme winds in the Pampa del Castillo Plateau, Patagonia, Argentina, with reference to wind farm settlement, J. Appl. Meteorol., 33, 85–95, 1994. 1853
Laluraj, C., Krishnan, K., Thamban, M., Mohan, R., Naik, S., D'Souza, W., Ravindra, R., and Chaturvedi, A.: Origin and characterisation of microparticles in an ice core from the central Dronning Maud Land, east Antarctica, Environ. Monit. Assess., 149, 377–383, doi:10.1007/s10661-008-0212-y, 2009. 1842, 1843
Laluraj, C., Thamban, M., Naik, S., Redkar, B., Chaturvedi, A., and Ravindra, R.: Nitrate records of a shallow ice core from East Antarctica: atmospheric processes, preservation and climatic implications, Holocene, 21, 351–356, 2011. 1842

CPD
9, 1841–1867, 2013

Lambert, F., Delmonte, B., Petit, J. R., Bigler, M., Kaufmann, P. R., Hutterli, M. A., Stocker, T. F., Ruth, U., Steffensen, J. P., and Maggi, V.: Dust-climate couplings over the past 800 000 yr from the EPICA Dome C ice core, Nature, 452, 616–619, 2008. 1848, 1852, 1853

Lambert, G., Ardouin, B., and Sanak, J.: Atmospheric transport of trace elements toward Antarctica, Tellus B, 42, 76–82, 1990. 1852

Law, R., Simmonds, I., and Budd, W. F.: Application of an atmospheric tracer model to high southern latitudes, Tellus B, 44, 358–370, 1992. 1853, 1854

L'Heureux, M. L. and Thompson, D. W. J.: Observed relationships between the El Niño Southern Oscillation and the extratropical zonal-mean circulation, J. Climate, 19, 276–287, 2006. 1850

Li, F., Ginoux, P., and Ramaswamy, V.: Distribution, transport, and deposition of mineral dust in the Southern Ocean and Antarctica: contribution of major sources, J. Geophys. Res.-Atmos., 113, D10207, doi:10.1029/2007JD009190, 2008. 1853, 1854

Lunt, D. J. and Valdes, P. J.: Dust deposition and provenance at the Last Glacial Maximum and present day, Geophys. Res. Lett., 29, 2085, doi:10.1029/2002GL015656, 2002. 1854

Marino, F., Castellano, E., Ceccato, D., De Deckker, P., Delmonte, B., Ghermandi, G., Maggi, V., Petit, J. R., Revel-Rolland, M., and Udisti, R.: Defining the geochemical composition of the EPICA Dome C ice core dust during the last glacial-interglacial cycle, Geochem. Geophy. Geosy., 9, Q10018, doi:10.1029/2008GC002023, 2008. 1848

Marshall, G. J.: Trends in Antarctic geopotential height and temperature: a comparison between radiosonde and NCEP-NCAR reanalysis data, J. Climate, 15, 659–674, 2002. 1843, 1851, 1852

Marshall, G. J.: Trends in the southern annular mode from observations and reanalyses, J. Climate, 16, 4134–4143, 2003. 1851

McConnell, J. R., Aristarain, A. J., Banta, J. R., Edwards, P. R., and Simões, J. C.: 20th-Century doubling in dust archived in an Antarctic Peninsula ice core parallels climate change and desertification in South America, P. Natl. Acad. Sci. USA, 104, 5743–5748, 2007. 1844, 1848, 1849, 1854

Naik, S. S., Thamban, M., Laluraj, C. M., Redkar, B. L., and Chaturvedi, A.: A century of climate variability in central Dronning Maud Land, East Antarctica, and its relation to southern annular mode and El Niño-Southern Oscillation, J. Geophys. Res., 115, D16102, doi:10.1029/2009JD013268, 2010.

CPD
9, 1841–1867, 2013

Nan, S. and Li, J.: The relationship between the summer precipitation in the Yangtze River valley and the boreal spring Southern Hemisphere annular mode, Geophys. Res. Lett., 30, 2266, doi:10.1029/2003GL018381, 2003. 1844, 1848

Oke, P. R. and England, M. H.: Oceanic response to changes in the latitude of the Southern Hemisphere subpolar westerly winds, J. Climate, 17, 1040–1054, 2004. 1846

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., and Stievenard, M.: Climate and atmospheric history of the past 420 000 yr from the Vostok ice core, Antarctica, Nature, 399, 429–436, 1999. 1851

Pezza, A. B., Durrant, T., Simmonds, I., and Smith, I.: Southern Hemisphere synoptic behavior in extreme phases of SAM, ENSO, sea ice extent, and southern Australia rainfall, J. Climate, 21, 5566–5584, doi:10.1175/2008JCLI2128.1, 2008. 1842, 1843

Polian, G., Lambert, G., Ardouin, B., and Jegou, A.: Long-range transport of continental radon in subantarctic and antarctic areas, Tellus B, 38, 178–189, doi:10.1111/j.1600-0889.1986.tb00185.x, 1986. 1852

Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S. E., and Gill, T. E.: Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, Rev. Geophys., 40, 2.1–2.31, doi:10.1029/2000RG000095, 2002. 1852

Revel-Rolland, M., de Deckker, P., Delmonte, B., Hesse, P. P., Magee, J. W., Basile-Doelsch, I., Grousset, F., and Bosch, D.: Eastern Australia: a possible source of dust in East Antarctica interglacial ice, Earth Planet. Sc. Lett., 249, 1–13, 2006. 1848

Simmonds, I., Keay, K., and Lim, E.-P.: Synoptic activity in the seas around Antarctica, Mon. Weather Rev., 131, 272–288, doi:10.1175/1520-0493(2003)131<0272:SAITSA>2.0.CO;2, 2003. 1843, 1848, 1852

Stauffer, B.: Cornucopia of ice core results, Nature, 399, 412–413, 1999. 1846, 1853

Stohl, A.: Computation, accuracy and applications of trajectories – a review and bibliography, Atmos. Environ., 32, 947–966, 1998. 1842

Sugden, D. E., McCulloch, R. D., Bory, A. J.-M., and Hein, A. S.: Influence of Patagonian glaciers on Antarctic dust deposition during the last glacial period, Nat. Geosci., 2, 281–285, 2009. 1847

CPD

9, 1841–1867, 2013

Tegen, I., Lacis, A. A., and Fung, I.: The influence on climate forcing of mineral aerosols from disturbed soils, Nature, 380, 419–422, 1996. 1848
Thompson, D. W. J. and Wallace, J. M.: Annular modes in the extratropical circulation, Part 1: Month-to-month variability, J. Climate, 13, 1000–1016, 2000. 1854
Vallelonga, P., van de Velde, K., Candelone, J.-P., Morgan, V. I., Boutron, C. F., and Rosman, K. J. R.: The lead pollution history of Law Dome, Antarctica, from isotopic measurements on ice cores: 1500 AD to 1989 AD, Earth Planet. Sc. Lett., 204, 291–306, 2002. 1843, 1851, 1852
Wu, G., Yao, T., Xu, B., Tian, L., Zhang, C., and Zhang, X.: Volume-size distribution of microparticles in ice cores from the Tibetan Plateau, J. Glaciol., 55, 859–868, 2009. 1849
Yung, Y. L., Lee, T., Wang, C.-H., and Shieh, Y.-T.: Dust: a diagnostic of the hydrologic cycle during the Last Glacial Maximum, Science, 271, 962–963, 1996. 1845, 1848
1843, 1848

Table 1. Statistical representation of trace metals fluxes, dust fluxes and $\delta^{18}O$ before and prior to 1985 along the ice core. All the units are in $\mu g\,cm^{-2}\,yr^{-1}$ except for $\delta^{18}O$ (per mil).

Period	statistics	Ba	Zn	Cu	Cr	Fine fraction 1–6 µM	Total fraction 1–25 µM	$\delta^{18}O$
After 1985	Average	0.031	0.207	0.037	0.005	4.65	17.67	–29.84
	Max.	0.119	1.501	0.187	0.016	30.7	89.35	–35.49
	Min.	0.010	0.029	0.002	0.001	0.36	0.71	–22.54
Before 1985	Average	0.015	0.103	0.014	0.003	2.14	8.63	–30.42
	Max.	0.036	0.752	0.077	0.010	23.58	61.89	–36.74
	Min.	0.003	0.016	0.002	0.001	0.31	0.76	–25.25

CPD
9, 1841–1867, 2013

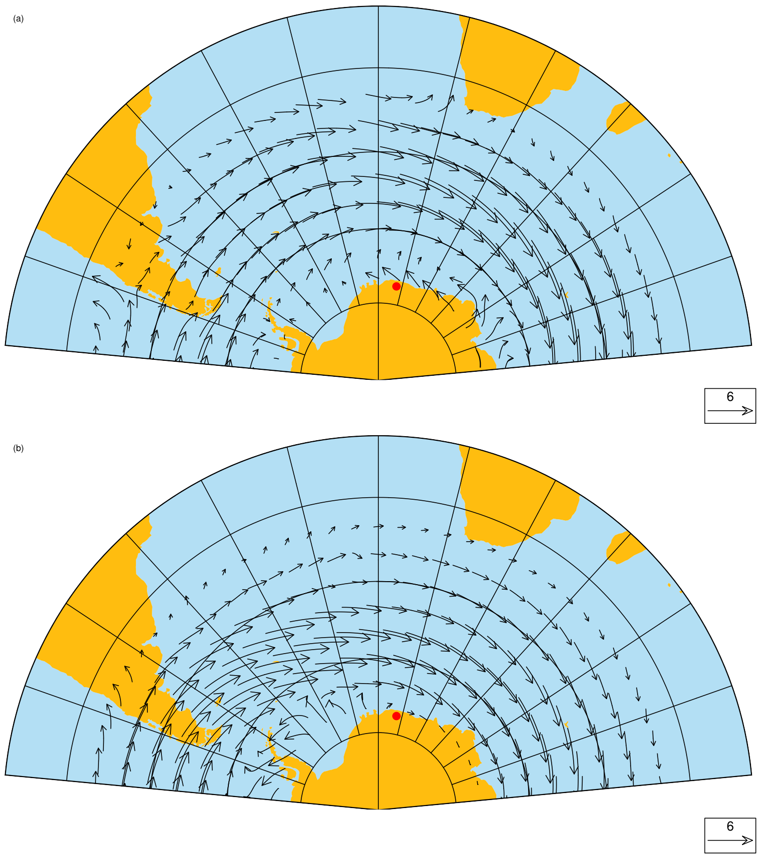

Fig. 1. Average surface wind vectors over Southern Hemisphere **(a)** during 1979–1984 and **(b)** 1985–2006. The location of IND-25/B5 ice core within Dronning Maud Land is marked by a red circle. The size of the reference wind vector shown in the box is 6 m s^{-1}.

CPD
9, 1841–1867, 2013

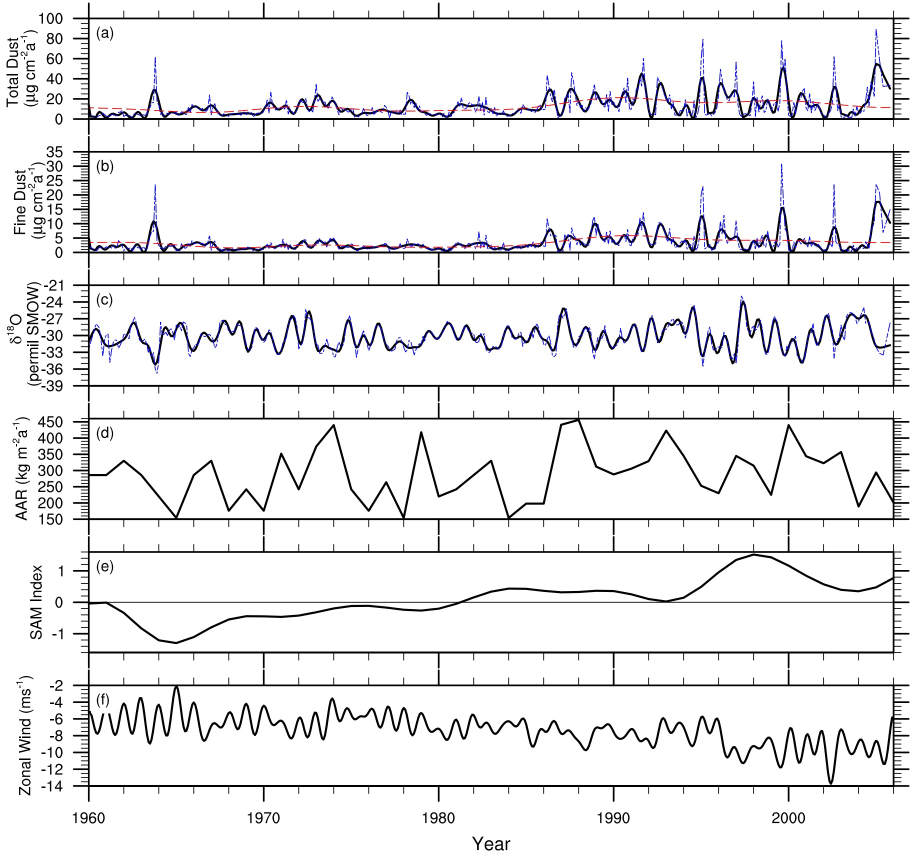

Fig. 2. High-resolution records of **(a)** total dust flux (1–25 µm), **(b)** fine dust flux (1–6 µm), **(c)** oxygen isotope ratio (δ^{18}O), and **(d)** annual accumulation rate (AAR) of the IND-25/B5 ice core. The blue dashed lines are the raw data, thick blue lines represent the low pass filtered data, and dashed red lines represent averaged data. The **(e)** SAM index and **(f)** zonal wind strength at the site are also given for the past ∼ 50 yr.

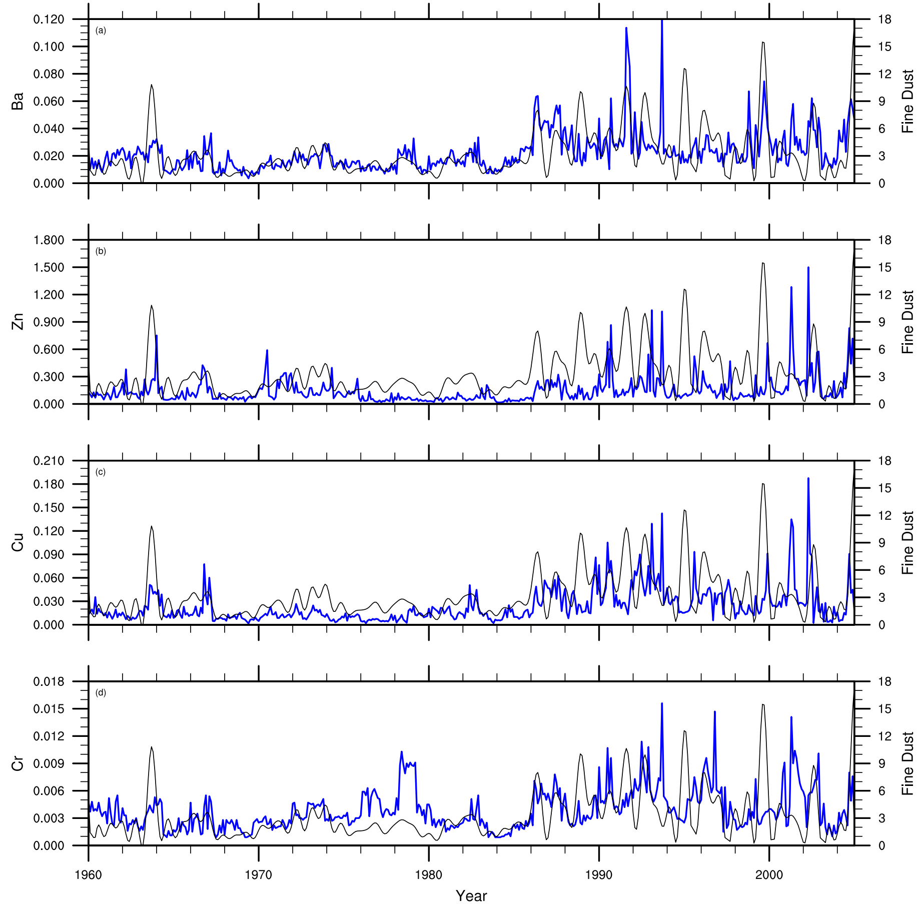

Fig. 3. High-resolution flux records of **(a)** Barium, **(b)** Zinc, **(c)** Copper and **(d)** Chromium in the IND-25/B5 ice core. The black line in the background represents the low pass filterd data of fine fraction dust (right axis). All the units are in $\mu g\,cm^{-2}\,yr^{-1}$.

CPD
9, 1841–1867, 2013

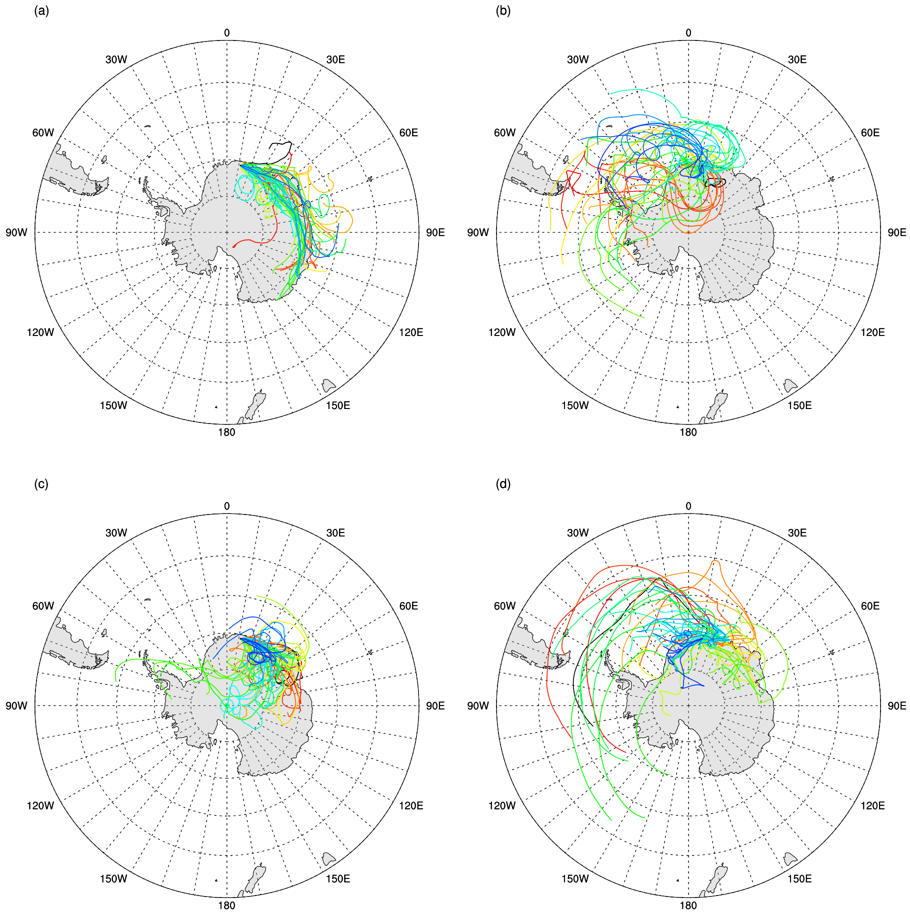

Fig. 4. Clustered back-trajectories at study site representing the summer and winter seasons during **(a)** January 1983, **(b)** August 1982, **(c)** January 1998 and **(d)** August 1998.

CPD
9, 1841–1867, 2013

Dust and elements archived in Antarctica

C. M. Laluraj et al.

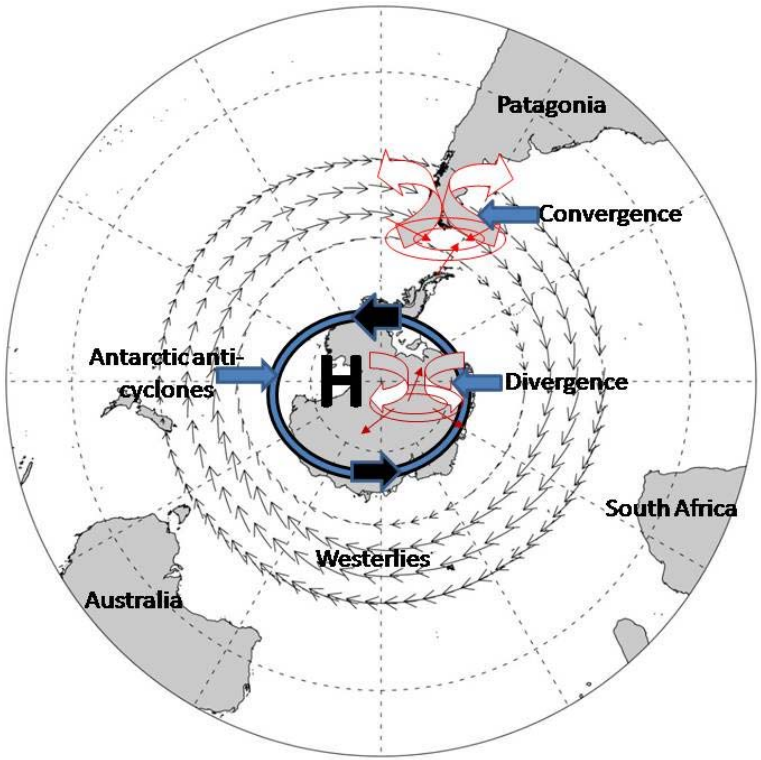

Fig. 5. Schematic representation for the proposed physical processes of dust deposition in Antarctica. The increase in cyclonic activities due to the strengthening of westerlies would elevate the dust to the upper levels from Patagonia. The enhanced polar easterlies (surface anticyclones) along the coast and the continent of Antarctica could sink the air masses and deposit dust material over east Antarctica from the upper levels.

CPD
9, 1841–1867, 2013