Enhanced Dust Influx to South Atlantic Sector of Antarctica During the Late-20th Century: Causes and Contribution to Radiative Forcing

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Abstract Atmospheric dust influences global climate and ocean biogeochemistry. Here we present a high-resolution ice core dust record (1905–2005 CE) from coastal Dronning Maud Land (71°20′S, 11°35′E), East Antarctica, to understand dust flux variability, its causes, and potential contribution to radiative forcing during the 20th century in the South Atlantic sector of East Antarctica (SASA). The dust flux profile (sum of 1–25 μm size fractions) reveals three stepwise increase during 1905–1929, 1930–1979, and 1980–2005 CE time with an average of 0.83, 4.7, and 12.88 mg·m⁻²·year⁻¹, respectively. Our investigation for such dramatic dust flux increase reveals that the increased aridity and favorable wind conditions over Southern South America (SSA), a potential dust source to Antarctica, caused increase in dust production and transport during the late 20th century. The dust flux variability in Southern Hemisphere is concomitant with in-phase relationship between El-Niño Southern Oscillation and Pacific Decadal Oscillations, which influenced the spatial distribution of global wet-dry phase (precipitation pattern). Further, shifting of Southern Annular Mode to positive phase made wind conditions more conducive for long-range dust transport from SSA to coastal Dronning Maud Land region. To the best of our knowledge, this is the first report of past radiative forcing estimates for Antarctica using ice core dust record into a radiative transfer model. Our estimates of radiative forcing corresponding to the enhanced dust flux yield nearly 30% increase in aerosol forcing during the late 20th century. This has resulted 40% decrease in atmospheric cooling rate, which contributed to net atmospheric warming over SASA.

Plain Language Summary Atmospheric dust plays an important role in global climate variability through the changes in radiative forcing. Like other parts of Antarctica, the coastal Dronning Maud Land (cDML) in East Antarctica is vulnerable to such changes in radiative balance. However, causative factors for the dust deposition and impact of dust originated radiative forcing on this region remain unknown due to lack of long-term records of dust-derived radiative forcing estimates. Toward this, we have undertaken a systematic ice core-based study from cDML region to reconstruct past records of dust influx, its potential sources, causative factors for the dust production in the Southern Hemispheric continents, and understanding its role on the radiative forcing during the 20th century (1905–2005). Our radiative forcing estimates corresponding to approximately four fold increase in dust influx in the late 20th century indicate an increase in atmospheric warming. The present study would help to better understand the long-term Antarctic climate variability by providing radiative forcing input to the climate models and to improve our current knowledge about the role of dust in contributing to Southern Hemisphere warming during the 20th century.

1. Introduction

Mineral dust and aerosols play an important role in controlling atmospheric radiative forcing and thereby climate variability (IPCC, 2013; Kok et al., 2018). Dust is known as one of the major suppliers of nutrients to global ocean and support phytoplankton productivity and drawdown of atmospheric CO₂, which have important implications on global climate change (Hooper et al., 2019; Johnson et al., 2011; Martin, 1990). In order to understand past climate variability and changes in the Southern Hemisphere (SH), several studies have been carried out on Antarctic ice core dust records (Delmonte et al., 2002; Delmonte et al., 2013; Delmonte et al., 2019; Laluraj et al., 2014; McConnell et al., 2007; Wegner et al., 2015). However, most of them mainly focused on the causative factors for dust deposition and dust flux variability but not on the quantitative estimates of radiative forcing that might contribute to Antarctic climate variability. Major
of dust originates from semiarid regions and world’s deserts, which influences global climate by changing the radiative balance of our planet (Jeong et al., 2016). The quantitative estimate of radiative forcing contributing to recent global climate change is poorly constrained (IPCC, 2013; Potenza et al., 2016; Tegen & Lacis, 1996). In order to understand the role of dust and its contribution to radiative forcing during the recent past, we mainly depend on either modeling or paleo-dust records. The estimates of past radiative forcing based on models are often associated with large uncertainties (Miller et al., 2004; Potenza et al., 2016; Tegen & Lacis, 1996). Therefore, high-resolution dust records together with radiative transfer model could serve a better constrain on past radiative forcing and its role on the past climate variability. In addition, such ice core dust records from Antarctica would help to understand changes in dust source regions (Hooper & Marx, 2018) and atmospheric transport processes (Li et al., 2010) that carry dust particles from SH landmasses to Antarctica.

Dronning Maud Land (DML) situated in the East Antarctica, extending from approximately 30°W to 50°E, is a region of major wind passage between western and eastern part of Antarctica (Li et al., 2008). There are few studies on modern dust transportation over DML region based on both model-derived air trajectories (Li et al., 2008; Neff & Bertler, 2015) and observational studies (Krinner et al., 2010; Laluraj et al., 2014). Additionally, few ice core-based dust concentration records and studies on dust sources were recently reported from central Dronning Maud Land (cDML), East Antarctica Plateau (Delmonte et al., 2019; Laluraj et al., 2014; Laluraj et al., 2009; Wegner et al., 2015). However, there is dearth of observational studies on dust production, transport, and its impact on radiative balance of atmosphere over the South Atlantic sector of Antarctica (SASA) during the 20th century. Hence, we have undertaken a high-resolution study on ice core dust records to assess the changes in dust production from the potential dust source regions and its mobilization to SASA during the 20th century. Toward this, we examine a high-resolution ice core dust concentration and flux records (1905–2005 CE). This study provides information about the potential dust source regions as well as the factors that favored its production over the source regions and transport to DML on the time scales ranging from seasonal to annual during the last century. Further, we have quantified its impact in terms of changes in radiative forcing corresponding to dust flux variability and changes during the last century over the SASA using a radiative transfer model.

2. Materials and Methods

An ice core of 65 m long (IND-25/B5) retrieved from the cDML region (71°20’S, 11°35’E, elevation: 1,300 m) during the 2006–2007 is used for this study (Figures 1a and 1b). The details of the ice coring, processing in laboratory, method for chronology determination, and stable water isotopes analysis were published elsewhere (Naik et al., 2010; Rahaman et al., 2016). Ice core chronologies were established using annual layer counting of summer and winter peaks in the water isotopes ($\delta^{18}$O and $\delta^{2}H$) method as the main dating tool in combination with nssSO$_4^{2-}$ (nonsea salt sulfate) markers of volcanic eruptions and Tritium atomic bomb markers (1963 bomb radioactivity). Uncertainty on the chronology of the core is ±2 years (Naik et al., 2010). With an objective to evaluate dust flux variability in response to recent climate change in SH, the ice core record was examined in high temporal resolution (on an average 12–14 samples per year). The density of the core samples at respective section along with age-depth summer peaks in $\delta^{18}$O record (1905–2005) was used to calculate annual snow accumulation rates. The top 30 m of the present core (IND-25/B5) record of dust and trace metal was studied earlier to understand the geochemical origin of dust (Laluraj et al., 2014). Details of the dust concentration measurements were discussed in the earlier publication (Laluraj et al., 2014). Briefly, dust concentrations were measured using a Multisizer IV Coulter Counter setup in discrete samples of inner part of the ice core with 5 cm resolution by shaving and cutting the surface ice layer in a clean room following the standard methods (Laluraj et al., 2014). The detailed methodology was described elsewhere (Delmonte et al., 2002; Steffensen, 1997). Three replicate measurements were carried out for each sample with a 50 μm aperture (400 channels), which measures insoluble particles between 1 and 25 μm. Calibration was done using certified standards of latex particles. The analytical precision based on several repeat measurements of samples was better than 5%. The dust flux was computed by multiplying dust concentration with the water equivalent snow accumulation rate for each year.
In order to understand possible dust sources reaching to the ice core site, 9-day forward trajectory analysis was performed using HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler & Rolph, 2011). The forward trajectories were calculated from two prominent dust-emitting hot spots in the SSA region (suggested by Li et al., 2010), the North Patagonia (44°S, 67°W), and San Julian’s Great Depression (49°S, 69°W). The trajectories were initialized at 1,000 m above the surface to minimize disturbances from underlying topography (Sinclair et al., 2010). Further, we computed the trajectories of summer (February) and winter (August) periods for the years 1991, 1993, and 2001, when dust activity was high and considered them as dust events in Patagonia as reported by Gassó and Torres (2019).

A MATLAB program (REDFIT; Schulz & Mudelsee, 2002) was used to perform power spectrum analysis of a dust time series and to identify the significant periods against the red noise background from a first-order autoregressive (AR1) process. The spectrum of an irregularly spaced time series was determined without the need for interpolation by means of the Lomb-Scargle Fourier transform. This MATLAB code was used to determine the significant periodicities against the red noise. The wavelet transform was used to analyze dust time series that contain nonstationary power at various frequency bands. We used Morlet wavelet to decompose the time series into time-frequency space that enable us to identify the modes of variability and how they vary with time (Grinsted et al., 2004). For analysis of the covariance of two time series, we used cross wavelet, which highlights the common highest power in two time series (Grinsted et al., 2004). Statistical significance was estimated against red noise.

### 2.1. Radiative Forcing Calculations Using Model

Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model (Ricchiazzi et al., 1998) was used to estimate aerosol radiative forcing (ARF) and heating/cooling rates corresponding to the prominent changes in our dust records. ARF at the surface (2 m height), in the atmosphere (up to 100 km), and at top of atmosphere (100 km) was calculated. The SBDART model solves plane-parallel radiative transfer in clear and cloudy sky conditions within the Earth’s atmosphere (Ricchiazzi et al., 1998). Shortwave (SW; 0.25–4.0 μm) and longwave (LW; 4.0–40.0 μm) fluxes were computed using the SBDART model. This model requires the spectral aerosol optical properties (aerosol optical depth [AOD], single scattering albedo [SSA],...
and asymmetry parameter \([\text{AP}, g]\), and additional inputs such as surface reflectance, atmospheric profiles of temperature, pressure, water vapor, and ozone to calculate the fluxes.

ARF at the top of the atmosphere (TOA) and surface (SFC) was estimated from the change between the net flux (down minus up) with and without aerosols as expressed

\[
ARF_{\text{TOA,SFC}} = NetFlux_{\text{with aerosol TOA,SFC}} - NetFlux_{\text{without aerosol TOA,SFC}}. \tag{1}
\]

The difference between the ARF at TOA and surface is defined as the atmospheric ARF (ATM) and expressed as

\[
ARF_{\text{ATM}} = ARF_{\text{TOA}} - ARF_{\text{SFC}}. \tag{2}
\]

The spectral aerosol optical properties in SW and LW ranges are required to calculate the radiative flux using the SBDART model. Therefore, spectral aerosol optical properties were estimated using optical properties of aerosols and clouds (OPACs) model (Hess et al., 1998). The aerosol optical properties mainly depend on the number size distribution and refractive indices of aerosol species. In the OPAC model, aerosols are assumed to follow lognormal size distribution in the size range of 0.005 to 20 (and >20) \(\mu m\). The objective of the simulations is to investigate the radiative impacts of dust deposition changes on Earth-atmosphere radiative balance over Antarctica. The AOD was estimated for the three periods of 20th century (1905–1930, 1930–1980, and 1980–2005) corresponding to the significant changes in our ice core dust record. The ice dust record was obtained from the actual measured dust concentration in the ice core. Therefore, the measured averaged dust concentrations from the present ice core were used as input to OPAC model. The other aerosols such as sea salt and sulfate concentrations for Antarctic region were taken from OPAC database (Hess et al., 1998). Only the dust concentrations were changed as per measurements in different time periods, while the concentrations of the other two aerosols (sulfate and sea salt) were kept constant (Table S1 in the supporting information). Therefore, the only variable parameter here is dust concentration data, which was obtained from our ice core. In the OPAC model, aerosol size distribution is assumed to follow lognormal distribution in the size range of 0.005 to 20 (and >20) \(\mu m\). Mineral dust in the nucleation, accumulation, and coarse modes is described by mode radius of 0.07, 0.39, and 1.90 \(\mu m\), respectively (Hess et al., 1998). In the present study, we have considered the coarse mode dust while calculating the spectral aerosol optical properties. For coarse mode dust, OPAC considers the size ranges between 0.005 and 60 \(\mu m\) with mode radius \((r_m)\) 1.9 \(\mu m\) and the width of the distribution \((\sigma)\) 2.15. The size distribution of dust particle is shown in Figure S1.

Dust behaves as a moderate absorber and also acts as a scatter in SW (0.25 to 2.5 \(\mu m\)) range, while it is highly absorbing for higher wavelength range (>7 \(\mu m\)). SSA (ratio of scattering to extinction [scattering + absorbing] coefficients) shows that the coarse mode dust is higher absorbing in SW and becomes more scattering in long wave range (Figure S2). The number concentrations of dust particles in the size range 1–25 \(\mu m\) were considered while estimating optical properties and radiative forcing. The simulations were performed on annual scale corresponding to our annual dust flux estimates. Annual mean ARF was estimated in SW (0.25–4.0 \(\mu m\)) and LW (4.0–40.0 \(\mu m\)) regimes at SFC, in the ATM and TOA.

In radiative flux simulations, the annual mean atmospheric profiles of temperature, pressure, ozone, and water vapor were obtained from radiosonde measurements and ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis data (Vignon et al., 2019). The atmospheric model was developed using the vertical profiles of temperature, pressure, water vapor, density, and ozone density profiles of 37 vertical levels; in that, 23 levels are within 10 km height, as aerosols are mostly confined within 10 km height. Surface reflectance for snow was considered during the simulations. Spectral values of snow surface reflectance were utilized in the model (Ricchiazzi et al., 1998). The value of reflectance is 0.97 in UV and visible range; however, it decreases in IR range (Figure S3).

In order to validate our model estimates, we have compared the model solar irradiances \((W \ m^{-2})\) with the observed irradiances over the Japanese SYOWA station \((60.0^\circ S, 39.58^\circ E)\), located in DML (Järvinen & Leppäranta, 2013). This shows a strong positive \((r^2 = 0.99, at 99\% significance level)\) correlation (Figure S4). The radiation trapped (or removed) within (from) the atmosphere (atmospheric forcing) is further used in the following equation 3 (Liou, 2002) to estimate the radiative heating (or cooling) rate \((K \ day^{-1})\).
Dust records of (a) particle counts of Figure 2. – 10 μm, coarse (5 μm), and bulk fractions (10–25 μm), and bulk fractions (10–25 μm) from the IND-25/B5 ice core.

where $\frac{\partial T}{\partial t}$ is the heating (or cooling) rate (K day$^{-1}$), $g$ is the acceleration due to gravity, $C_p$ is the specific heat capacity of air at constant pressure, and $P$ is the atmospheric pressure. $\frac{\partial T}{\partial t}$ provides heating rate, if it is positive (+) and cooling rate, if negative (−).

The accuracy of model estimated radiative forcing depends on aerosol types and environmental properties, including their dependencies on wavelength, and associated uncertainties in these values. The sources of uncertainty in aerosol direct radiative forcing are AOD, SSA, AP, solar geometry, and surface reflectance. The AOD (measure of total columnar aerosol burden) contributes substantially to total uncertainty in the radiative forcing. The SSA, which is the measure of scattering properties of aerosols, is the largest contributor to the total uncertainty in radiative forcing. The AP, which describes the angular distribution of scattered light, has lesser importance to accuracy in calculating forcing than AOD and SSA. The radiative fluxes calculated by SBDART model were found within 2% of direct and diffuse irradiance measurements (Michalsky et al., 2006). The total uncertainty in the forcing is derived from the propagation of the uncertainties associated with the input parameters such as AOD, SSA, AP, solar geometry, and surface reflectance. The total uncertainty in the modeled ARF was found to vary with different inputs parameters mentioned above. The total uncertainties in radiative forcing were higher for lower radiative fluxes (McComiskey et al., 2008). The uncertainty in the estimation of ARF was found to be <15% by taking into account the uncertainties associated with the aerosol parameters (AOD, SSA, and AP), solar geometry, surface properties, and the radiative flux estimates (Srivastava et al., 2011).

3. Results and Discussion

3.1. Size Fraction Variability of Dust Over SASA

Dust concentration measured over large ranges of grain size (1–25 μm) shows significant variations in dust size fractions during the 20th century (Figure 1c). Several studies reveal that the particles size >10 μm can remain in the atmosphere up to several weeks and thus can be transported thousands of kilometers from source regions (Maring et al., 2003; van der Does et al., 2016). The particles sizes of 1–5 μm are referred as “fine fraction,” 5–10 μm as “coarse fraction,” and particle size above 10 μm as “bulk fraction” as defined in the previous coastal ice core studies (Delmonte et al., 2013, and references therein). The fine fractions were high in number, and the numbers decrease with increasing diameter size (Figure 2). This follows Junge distribution law; the number of dust particle decreases exponentially with increasing diameter; however, larger particles mostly contribute to the total mass (Wu et al., 2009). The numbers of particles of coarse fraction (5–10 μm) and bulk fraction (10–25 μm) were much less compared to fine fraction (average 1,170 Nm$^{-1}$ fine fraction, 85 Nm$^{-1}$ coarse fraction, and 6 Nm$^{-1}$ of bulk fraction). The fine fraction contributes up to ~93% of the total number fraction (1–25 μm) of dust deposited, of which 75% of fine fraction particles are of 1–2 μm diameter in size. Several studies have also documented the presence of large particles (>62.5 μm) that have been transported to a great distance from the sources (>10,000 km) through the atmosphere (Betzer et al., 1998; Middleton et al., 2001; Ram & Gayley, 1991).

The dust concentration of 1–25 μm record shows large variability and ranges from 0.10 to 133.01 μg kg$^{-1}$ (1905–2005 CE) with an average of 19.73 μg kg$^{-1}$ (Figure 1c). Since, the ice core dust concentration data could be significantly affected by snow accumulation and post depositional secondary processes (Li et al., 2010); dust flux is a better representative of the dust record from Antarctic ice cores. The snow density increases gradually from 0.42 to 0.79 g cm$^{-3}$ with an average of 0.61 g cm$^{-3}$ (Figure 3a). The annual snow
The total dust record does not show any concomitant trend with snow accumulation rates (Figure 3b), and total dust concentration does not show any significant correlation with snow accumulation rate (Figure 3b; $r = 0.02, n = 100$), and hence, the possibility of any secondary processes that might alter dust flux record can be ruled out (Koffman et al., 2014). Further, snow accumulation rates and density do not show any significant correlation with dust records indicating that dust data was free from any kind of analytical artifacts. Changes in dust concentration and flux profiles show a similar trend during the same periods (Figures 1c and 1d). This indicates that the postdepositional processes and changes in snow accumulation do not alter the dust record in the present study site. Similar pattern observed in both concentration and flux records clearly indicates that changes in mass concentration drive observed variability in total dust flux (Figures 1c and 1d). The total dust flux of the above concentration ranges from 0.05 to 57.7 mg·m$^{-2}$·year$^{-1}$ (mean 5.8 mg·m$^{-2}$·year$^{-1}$) during 1905–2005 CE (Figure 1d). The observed dust values are comparable with the available dust records from various sectors of Antarctica ranging from the Holocene to the last millennium provided in Table 1, and core locations are represented in Figure 1b. Meanwhile, considering the paucity of high-resolution (subannual) ice core records during the 20th century, we have used only ice core record from Antarctic Peninsula (McConnell et al., 2007) for the comparison due to their common dust origin as discussed later. A high-resolution ice core dust record from the James Ross Island, Antarctic Peninsula (Figures 1b and 4b), has also reported an average total dust concentration of 21 mg·m$^{-2}$·year$^{-1}$ during the 1905–1991 CE (McConnell et al., 2007). These results of dust records show that the estimated dust records from present ice cores are comparable to the reported values from other coastal ice cores from different parts of Antarctica during the Holocene (Table 1). However, the presence of coarse and bulk fraction particles observed in the ice core may indicate local inputs from ice-free areas and nunataks related to the prevailing wind pattern as suggested by earlier study in a nearby location (Laluraj et al., 2009). Similarly, the presence of larger particles (>5 μm diameter) may indicate possible short-range transport from proximal sources within Antarctica as suggested by other studies from coastal and low elevated ice core sites from different part of Antarctica (Albani et al., 2012; Bory et al., 2010; Delmonte et al., 2019; Wegner et al., 2012; Winton et al., 2016). Therefore, presence of coarse particles in the bulk fractions (>5 μm diameter particles) in the present ice core (IND-25/B5) also indicates proximal dust sources in Antarctica. In addition, based on the similarities in radiogenic isotopes composition (Sr and Nd) of ice core dust and the rocks present in the DML regions, Delmonte et al. (2019) suggested proximal dust sources during the late Holocene. However, the observed higher number contributions of fine dust particles (especially particles <5 μm) in the IND-25/B5 ice core indicate long-range transport of dust particles from potential dust sources from other continents to the present study region.

Closer look on the total fraction (1–25 μm) dust flux profile reveals three steps increase during the last century with an average of 0.83 mg·m$^{-2}$·year$^{-1}$ (1905–1929 CE), 4.7 mg·m$^{-2}$·year$^{-1}$ (1930–1979 CE), and 12.88 mg·m$^{-2}$·year$^{-1}$ (1980–2005 CE), with an overall average of 5.8 mg·m$^{-2}$·year$^{-1}$ during the 20th century (Figure 4a). The increased emission of atmospheric dust due to increasing aridity and unconsolidated soil was a global trend after 1930s (Donald, 1979). A comparison with a similar ice core dust record obtained from the James Ross Island (Antarctica Peninsula) for the 20th century (McConnell et al., 2007) showed an average of 14.9 mg·m$^{-2}$·year$^{-1}$ (1905–1929 CE), 20.9 mg·m$^{-2}$·year$^{-1}$ (1930–1979 CE), and 32.1 mg·m$^{-2}$·year$^{-1}$ (1980-1991 CE) with an average of 20.8 mg·m$^{-2}$·year$^{-1}$ during the last century (Figure 4b). The average dust flux of the James Ross Island ice core is higher than the IND-25/B5.
ice core. This could be due to close proximity of the James Ross Island to the potential dust source regions of the Southern South American (SSA) deserts (especially Patagonia region) and also its geographical position (lower latitude than cDML). However, similar pattern with stepwise increase of dust flux during the three time periods of 20th century (Figures 4a and 4b) seems to suggest similar dust source and common causative factors for the enhanced dust in flux over two distinct regions in Antarctica. A recent satellite-and station-based study by Gassó and Torres (2019) suggested an increase in dust activity by 35% over arid regions of SSA during recent decades, especially in the Patagonia region (Figure 4a). In addition, Earth’s surface experienced enormous transition in land use and land cover (LULC), including conversion of wild lands to agricultural lands resulted semiarid and arid landscapes, which are highly sensitive to wind erosion during the mid-20th Centuries (Hooper & Marx, 2018). Studies based on comparison of trace metals composition between Patagonian sediments and from the IND-25/B5 ice core (Laluraj et al., 2014), forward and backward wind trajectories analysis (Mahalinganathan & Thamban, 2016), and modeling based studies and satellite observations (Gassó et al., 2010; Johnson et al., 2011; Li et al., 2008) have suggested that Southern South America is a dominant dust source region of dust transport to Antarctic Peninsula and DML regions. However, few studies contradict these results and are in favor of the interpretation that dust contribution comes from the Australian and other continental dust sources (Albani et al., 2012; Revel-Rolland et al., 2006). The interior of the Australia continent characterized by arid condition due to the low precipitation could be a potential dust source regions and contribute to East Antarctica during the Holocene (Albani et al., 2012Revel-Rolland et al., 2006). Therefore, in order to decipher dust sources and to understand possible causative factors for the dust flux increase, we have investigated wind trajectory, the main driver of dust transport, and climatological conditions over the nearby continents in the SH in the following section.

### 3.2. Possible Dust Sources to SASA

The enhanced dust flux during the last three decades in Antarctica (after 1980 CE) require further investigations, as this period coincides with recent warming recorded across major continents (PAGES 2k Consortium, 2013). In order to decipher dust sources, forward wind trajectory analysis for winter and summer seasons of high dust deposition years (1991, 1993, and 2001 CE) between 1980 and 2005 period were

<table>
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<tr>
<th>Ice core</th>
<th>Location</th>
<th>Period</th>
<th>Concentration (µg kg⁻¹)</th>
<th>Flux (mg m⁻² year⁻¹)</th>
<th>Particle counts (Nml⁻¹)</th>
<th>Particle size (µm)</th>
<th>Reference</th>
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<td>Total dust</td>
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<td>D4 (ITASE)</td>
<td>75°35'S, 135°49'E</td>
<td>1420–1700 (CE)</td>
<td>9 ± 4</td>
<td>0.19 ± 0.13</td>
<td>1–5</td>
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<td>D4 (ITASE)</td>
<td>75°35'S, 135°49'E</td>
<td>1420–1700 (CE)</td>
<td>3 ± 2</td>
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<td>1–5</td>
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performed (Figures 5a–5f). This study indicates SSA as dust source for these two regions (Figure 5). Most of the air traceries show sources of the air parcels coming to the SASA region, and apparently, the enhanced dust influx during the recent decades originates from the SSA region. The observational and satellite-based studies also show a consistent picture of the dust transport from the Patagonia desert to

Figure 4. Dust flux records of (a) IND-25/B5 ice core from central Dronning Maud Land (South Atlantic sector of Antarctica); number of dust days record over southern South America (after Gassó & Torres, 2019) is shown in red color and (b) James Ross Island (JRI) ice core (Antarctica peninsula). Both records show three major stepwise increases during the last century. Dashed line indicates average dust flux, and gray band indicates standard deviation. To understand the factors for dust production in dust source regions and its transport to Antarctica during period 1980–2005 CE when dust flux was maximum, mean composite anomaly maps (January 1948–2005 CE minus 1948–1980 CE) are given of the influencing factors like (c) temperature, (d) relative humidity, (e) wind speed, and (f) precipitation. Data source is 20th century ERA reanalysis. The record of number of dust days over southern South America is taken from Gassó and Torres (2019).
Southern Atlantic and East Antarctica during the recent decades (Gassó & Stein, 2007; Gassó et al., 2010), which also pointing toward the transport of dust from SSA to present ice core location in the cDML region. SSA dust is transported primarily through the atmospheric boundary layer and dominates over half of the SH comprises of the Atlantic and Indian sectors of the SH (Li et al., 2010), thus making a dominant dust source for DML.

A significant periodicity of \(~3.5\) year is observed in both the dust flux and Southern Annular Mode (SAM) records (Figures 6a and 6c), indicating possible role of SAM on dust flux changes. Since the 1980s, the

**Figure 5.** Clustered 9-day forward wind trajectories from Patagonia region are shown for the summer (February) and winter (August) seasons for Years 1991, 1993, and 2001. These years have been reported as years of higher dust events/activity (Gassó & Torres, 2019).
SAM has shifted to positive mode (i.e., increasingly low pressure over Antarctica), characterized by a strengthening polar vortex and intensification of the westerlies (Figures 7a and 7b). The SSA in particular comes entirely under the influence of the westerly wind dynamics favorable for long-range dust transport toward Antarctica (Laluraj et al., 2014; Li et al., 2008). The wind trajectories show favorable pattern for the dust transport from SSA to SASA associated with shifting of SAM from negative to positive mode during the last three decades (Figure 5). Based on forward and backward wind trajectory analysis, Mahalinganathan and Thamban (2016) suggested that >65% of dust-laden air parcels in summer and >40% trajectories in winter in DML region were originated from SSA. In addition, the particle volume distribution of fine and coarse fractions against SAM index shows a concomitant increase in dust volume record of all size fractions with strengthening of SAM index (Figure S5). We find that the fine and coarse dust particles show a clear increase in volume of both fractions after 1980s is associated with shifting of SAM index from negative to positive especially after 1980s (Figures S5 and 7a). We infer that the increased fine and coarse particle deposition in SASA since 1980s is consistent with the observed strengthening in SH westerlies and associated shift in wind direction southward during the end of 20th century (Figure 7b). In addition, a recent study using correlations with reanalysis zonal wind speed to calibrate the dust record over the period 1979–2002 evidenced that the coarse dust particle fraction in WAIS Divide ice core is driven by variability in southern westerly wind intensity via cyclonic storm activity in the Amundsen-Bellingshausen Sea region (Koffman et al., 2014). Hence, we suggest that the increased dust deposition in DML region could be due to the prevailing stronger westerlies after 1980s; the eastward transport of high wind carries dust over a long distance from the SSA dust sources (Figure 5). The dust source regions in South America is also characterized by low-pressure systems accompanied by enhanced westerlies Karoly and Vincent (1998) that could transport these fine particles to the Antarctic continent. Further, unfavorable wind conditions over Australia (Figure 7b) for dust transport to DML region and longer geographical distance, the possibility of significant dust supply from Australia to present core site during the recent past (since 1980s) is ruled out (Li et al., 2008).

3.3. Climatological Conditions Favoring the Dust Production Over SSA

To understand the major factors influencing dust production and its transport to Antarctica, we have compared the period of higher dust flux (1980 to 2005 CE) with the mean composite anomaly maps
(January 1948–2005 minus 1948–1979) of the factors such as temperature, relative humidity (RH), soil moisture, wind speed, and precipitation (Figures 4c–4f). These maps clearly reveal positive anomaly in mean annual temperature and surface wind whereas negative anomaly in mean annual RH and soil moisture over the SSA. These evidences clearly indicate that the climatic conditions became more conducive for the dust production as well as transport to Antarctica during the late 20th century compared to that of earlier periods. To understand the relative role of individual factors for the higher dust fluxes, we have compared dust flux record with the possible factors that influenced dust productions in potential dust source regions such as temperature, RH, soil moisture, zonal wind velocity (U wind), and wind speed over the SSA. The correlation matrix (Table 2) highlights the relationship between the dust flux record and the causative factors. The dust flux shows significant negative correlations (at 95% significance level) with RH ($r = -0.59; n = 21$), soil moisture ($r = -0.47; n = 21$) and positive correlation with wind speed ($r = 0.45; n = 21$); however, temperature does not show significant correlations ($r = -0.13, n = 21$). These correlations indicate that, out of these factors, RH and soil moisture are the primary factors, controlled by precipitation played a greater role in dust production than the temperature over the source regions.

South American precipitation response to ENSO is fairly known (Andreoli & Kayano, 2005; Schneider & Gies, 2004); the strong El Niño reduced precipitation by about 15% over the SSA (Kayano & Andreoli, 2007), which resulted in lower soil moisture content. Therefore, reduced soil moisture can lower the interparticle force and thereby reduce the particle size and increase their emission to atmosphere (Ravi et al., 2006). Therefore, increased wind speed is expected to enhance the soil erosion, where humidity is lower (Ravi et al., 2004; Ravi & D’Odorico, 2005), particularly in the arid-semiarid regions of SSA, and these large bare surface areas produce dust during frequent dust storms (Gassó & Torres, 2019; Kavan et al., 2017). Kavan et al. (2018) evidenced that once the wind speed exceeds threshold velocity of 10 m s$^{-1}$, it can lift the mineral particles even higher than 10 μm diameter sizes. The SSA also experienced a high warming trend from 1979 to 2006 and extremely windy, which made these arid and semiarid regions of Patagonia to highly evaporative conditions (Falvey & Garreaud, 2009; Garreaud et al., 2009), which made majority of Patagonia’s glaciers to retreat after 1950s (Lopez et al., 2010). Further, it has been also suggested that widespread deforestation in SSA (Aagesen, 2002) could increase the dust production (McConnell et al., 2007). Deforestation together with changes in land use pattern due to agriculture practices might have increased the soil erosion in SSA (Garreaud et al., 2017) leading to increase dust fluxes to the Antarctic continent (McConnell et al., 2007). It was also suggested that climate change and desertification during the late 20th century caused more dust export to the West Antarctica (McConnell et al., 2007). The satellite and ground-based observations of dust data of the major arid regions from SSA also confirmed the increased dust activity since 1978 CE (Gassó & Torres, 2019). The increased dust activity over the Patagonia region after 1965 CE (Gassó & Torres, 2019) showed a similar trend with the increased dust flux record observed in the present core (Figure 4a). The dust activity days were increased in the beginning of 20th century (1965–1970) from an average of seven number of dust days (NDD)/month to 54 NDD/month during the end of the 20th century (Gassó & Torres, 2019). The close observation of dust deposited in the IND-B5/25 ice core and the dust production at the Patagonia region (Figure 4a) showed a concomitant trend in peaking of dust production at source region (Patagonia), and dust deposited in the ice core site is clearly indicating their dependency in production and deposition of dust in their respective
Table 2
Correlation Matrix of Dust Flux Versus Records Meteorological Parameters Over SSA

<table>
<thead>
<tr>
<th>Variables</th>
<th>Dust flux</th>
<th>Temperature</th>
<th>Soil moisture</th>
<th>Relative humidity</th>
<th>U wind</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust flux</td>
<td>1</td>
<td>-0.134</td>
<td>-0.467</td>
<td>-0.585</td>
<td>-0.145</td>
<td>0.450</td>
</tr>
<tr>
<td>Temperature</td>
<td>-0.134</td>
<td>1</td>
<td>0.228</td>
<td>0.279</td>
<td>0.223</td>
<td>-0.133</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>-0.467</td>
<td>0.218</td>
<td>1</td>
<td>0.943</td>
<td>0.013</td>
<td>-0.152</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>-0.585</td>
<td>0.279</td>
<td>0.943</td>
<td>1</td>
<td>-0.006</td>
<td>-0.216</td>
</tr>
<tr>
<td>U wind</td>
<td>-0.145</td>
<td>0.223</td>
<td>0.013</td>
<td>-0.006</td>
<td>1</td>
<td>-0.336</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.450</td>
<td>-0.133</td>
<td>-0.152</td>
<td>-0.216</td>
<td>-0.336</td>
<td>1</td>
</tr>
</tbody>
</table>

Note. Data of the annual meteorological parameters were taken from Reanalysis ERA Interim over southern South America (SSA). Values highlighted in bold represent significant correlations (n = 21, p < 0.05).
band, and in case of PDO, it shows significant periodicities at 2- to 4-year and 16- to 32-year bands (Figures 8a and 8b). Wavelet coherency analysis of SOI and PDO time series demonstrates phase relationship between them; antiphase at 16- to 32-year band during 1940–2005 CE and at 4- to 16-year band during 1980–2005 CE (Figure 8c). Stepwise increase in dust flux profile during 1940–1980 CE and 1980–2005 CE coincides with the periods when SOI and PDO were in antiphase (Figure 8c), consistent with the earlier proposition by Wang et al. (2014). Gassó and Torres (2019) also observed an increase in dust events over arid regions of SSA during the last 50 years. The above lines of evidence suggest the meteorological condition and the change in ENSO and PDO phase relationship influenced the dust production over SSA during the late 20th century.

3.4. Impact of Enhanced Dust Influx on Radiative Forcing Over SSA

To estimate the ARF corresponding to the major periods of enhanced dust fluxes, we have employed Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model (discussed in section 2). The SBDART model has been widely used for radiative transfer calculations over different locations like, Asia (Srivastava et al., 2011), Southern Great Plains (Gautier & Landsfeld, 1997), East Antarctic (Hudson et al., 2010), and oceanic regions (Kedia et al., 2010). The ARF depends on aerosol optical properties such as spectral AOD, SSA, and AP. The optical properties were further used in SBDART to estimate radiative forcing. The midvisible (0.5 μm) AODs estimated from the OPAC model were found to vary between 0.05 to 0.15, which are consistent with the reported values from elsewhere in Antarctica (0.07 to 0.12) (Taori et al., 2018). The higher AODs values (0.158 to 0.164; Wei et al., 2019) have been reported for SSA region, compared to Antarctica. The OPAC estimated SSA (at 0.5 μm) was in the range of 0.98 to 0.99, and asymmetry parameter (at 0.5 μm) was in range of 0.78 to 0.79. The estimated AODs were within the uncertainty limit of model and observations. The SW, LW, and total ARF outputs at surface (2 m height), in the atmosphere (0–100 km height) and at the TOA (above 100 km height) during three major dust stages (1905–1930 CE, 1930–1980 CE, and 1980–2005 CE), revealed that the SW ARF at the surface level shows cooling (Figure 9). This could be due to a decrease in ground reaching radiation due to scattering and absorption of radiation by enhanced dust loading. Within the atmosphere (0–100 km), the SW forcing flips its sign from negative (−0.14 ± 0.02 W m⁻²) during 1930–1980 to positive (0.03 ± 0.004 W m⁻²) in 1980–2005, as there is more absorbing and scattering of the radiation due to enhanced dust, which results warming in the atmosphere during the 20th century. At TOA (above 100 km), more radiations are backscattered due to an increase in dust and contribute to the increase in aerosol forcing. The LW ARF shows warming due to absorbing nature of dust in LW regime. In total (SW + LW) ARF, at surface, it does not exhibit significant change because the radiation absorbed by the snow surface is further reflected back to atmosphere. Interestingly, the total aerosol forcing in the atmosphere was increased by nearly 30–40%, suggesting an increased warming due to absorption and scattering of radiation from 1905–1930 to 1980–2005 CE. Such increase in ARF due to increase in dust flux could cause atmospheric warming and thereby impact on other climatic parameters over the Antarctica. The dust radiative forcing at TOA over the East Antarctica region increased from −0.6 W m⁻² during 1905–1930 to −0.45 W m⁻² during 1980–2005 CE (Figure 9c). Global climate model estimated, average dust radiative forcing at the top of atmosphere with respect to preindustrial era was reported to be −0.4 W m⁻² (Mahowald et al., 2006), whereas Miller et al. (2004) reported global net forcing −0.18 W m⁻² at TOA and −1.64 W m⁻² at surface during...
the recent time. In addition, to compare our data with others in different regions, we have provided various RF estimates from other studies over Arctic, Antarctic, and Global regions (Table S2). The AOD and radiative forcing values estimated in the present study are within the range and lower than those in reported values. The radiation trapped (or removed) within (from) the atmosphere (atmospheric forcing) is further used to quantify radiative heating (or cooling) rate (K day\(^{-1}\)) corresponding to the changes in the radiative forcing (see section 2). The estimated atmospheric radiative cooling rate corresponding to the dust during 1905–1930 CE was \(-0.01 \pm 0.003\) K day\(^{-1}\) (\(-3.8 \pm 0.2\) K year\(^{-1}\)), which reduced to \(-0.006 \pm 0.001\) K day\(^{-1}\) (\(-2.3 \pm 0.1\) K year\(^{-1}\)) during 1980–2005 CE (Figure S6). This reduction in atmospheric cooling rate by \(-40\%\) contributed to atmospheric warming during the late 20th century. The surface air temperature reconstructed based on \(\delta^{18}O\) record from the IND-B5/B5 ice core has shown a significant warming of 1 °C during the 20th century (Figure S6; Naik et al., 2010). Though temperature variability in the cDML region has been largely explained in terms of SAM‐ENSO phase relation and their teleconnections (Naik et al., 2010), however, the long-term increase in 1 °C temperature could be attributed to the changes in the dust derived radiative forcing as one of the forcing factors. The estimated increases in atmospheric dust flux and associated aerosol forcing have enormous implications in terms of Earth’s radiation budget, global sea level change, and ocean biogeochemistry.

4. Summary of Main Findings and Implication

Compared to other parts of Antarctica, coastal DML has a far less body of knowledge about dust deposition and its impact on radiative forcing in the modern times. The present study is an attempt to fill this gap by providing a high-resolution dust record of IND-B5/25 ice core (1905–2005 CE) from coastal DML East Antarctica (cDML) and first attempt of quantitative estimates of past radiative forcing corresponding to the dust flux variability in the SASA using a radiative transfer model. Our finding of dust flux increase during the late 20th century has important implications for Southern Ocean biogeochemistry. The following findings were established:

1. The dust record reveals three stepwise increases during 1905–1929, 1930–1979, and 1980–2005 CE: almost several-fold increase in dust deposition flux in the late 20th century compared to beginning of the century.
2. Enhanced dust flux reveals that an increased aridity over the Southern South America (i.e., Patagonia) due to changes in ENSO and PDO phase relationship resulted in amplifying global wet-dry phase extremes during the late 20th century. Further, favorable wind conditions (strengthen of wind speed and direction of westerlies) due to shifting of the SAM from negative to positive phase after the 1980s caused more efficient long-range transport for Southern South America to cDML.
3. The radiative forcing corresponding to the dust flux increase during the late 20th century has resulted in 40% decrease in atmospheric cooling rate and ultimately contributed to a net atmospheric warming over SASA. This dust derived radiative forcing increase could be one of the factors attributed to ~1 °C temperature increase in the East Antarctica as shown \(\delta^{18}O\) record of the present ice core.
4. Though the present study focused primarily on the impact of dust on radiative forcing, however, our finding of several fold increase in the dust deposition in the Southern Ocean could impact on the productivity and carbon cycle. This could be a scope of future investigation.

Data Availability Statement

The ice core dust data used in this study are publicly available at NCPOR polar data center (http://npdc.ncaor.gov.in/npdc). SOI Index and PDO Index data used in this study are publically available online (from
References


