

Dust deposition in Antarctica: a modelling study

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Dust deposition in Antarctica in glacial and interglacial climate conditions: a modelling study

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Abstract

The mineral dust cycle responds to climate variations and plays an important role in the climate system by affecting the radiative balance of the atmosphere and modifying biogeochemistry. Polar ice cores provide a unique information about deposition of aeolian dust particles transported over long distance. These cores are a paleoclimate proxy archive of climate variability thousands of years ago. The current study is a first attempt to simulate past interglacial dust cycles with a global aerosol-climate model ECHAM5-HAM. The results are used to explain the dust deposition changes in Antarctica in terms of quantitative contribution of different processes, such as emission, atmospheric transport and precipitation, which will help to interpret paleodata from Antarctic ice cores. The investigated periods include four interglacial time-slices such as the pre-industrial control (CTRL), mid-Holocene (6000 yr BP), last glacial inception (115 000 yr BP) and Eemian (126 000 yr BP). One glacial time interval, which is Last Glacial Maximum (LGM) (21 000 yr BP) was simulated as well as to be a reference test for the model. Results suggest an increase of mineral dust deposition globally, and in Antarctica, in the past interglacial periods relative to the pre-industrial CTRL simulation. Approximately two thirds of the increase in the mid-Holocene and Eemian is attributed to enhanced Southern Hemisphere dust emissions. Slightly strengthened transport efficiency causes the remaining one third of the increase in dust deposition. The moderate change of dust deposition in Antarctica in the last glacial inception period is caused by the slightly stronger poleward atmospheric transport efficiency compared to the pre-industrial. Maximum dust deposition in Antarctica was simulated for the glacial period. LGM dust deposition in Antarctica is substantially increased due to 2.6 times higher Southern Hemisphere dust emissions, two times stronger atmospheric transport towards Antarctica, and 30 % weaker precipitation over the Southern Ocean. The model is able to reproduce the order of magnitude of dust deposition globally and in Antarctica for the pre-industrial and LGM climates.

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1 Introduction

Desert dust suspended in the atmosphere plays an important role in the climate system. Dust affects climate by changing the radiative balance of the atmosphere through the absorption and scattering of incoming solar and outgoing terrestrial radiation (e.g. Sokolik et al., 2001; Tegen, 2003; Balkanski et al., 2007). Additionally mineral dust may impact climate by modifying cloud properties, acting as cloud condensation nuclei (Twohy et al., 2009; Karydis et al., 2011) or ice nuclei (DeMott, 2003; Liu et al., 2012; Kuebbeler et al., 2014). The atmospheric supply of desert dust is the major source of iron in the open ocean, which is an essential micronutrient for phytoplankton growth and therefore may influence the ocean uptake of atmospheric CO₂ (e.g. Martin et al., 1990; Jickells et al., 2005; Wolff et al., 2006; Mahowald et al., 2008). Mineral dust can also act as fertilizer for tropical forests over long time periods (e.g. Okin et al., 2004). In addition, dust can impact atmospheric chemistry via heterogeneous reactions and changes in photolysis rates (e.g. Dentener et al., 1996). Moreover, global aerosol modelling studies suggest that dust is one of the main contributors to the global aerosol burden (Textor et al., 2006).

The main mechanisms controlling dust emissions are vegetation cover, aridity, land surface/soil characteristics, wind speed, precipitation and topographical features. Therefore mineral dust is very sensitive to climate change which has been evidenced by many observational studies (e.g. Kohfeld and Harrison, 2001). Polar ice cores represent unique geological archives of the deposition of aeolian dust particles transported over long distance from desert regions to the polar ice sheets where dust particles are well preserved (Delmonte et al., 2002). Ice core records indicate up to 25 times higher dust deposition rates at high latitudes during glacial than interglacial periods (e.g. Petit et al., 1990, 1999; EPICA Community Members, 2004, 2006). However considering interglacial periods only, some variabilities of dust also can be noticed (e.g. from the high resolution records in EPICA Community Members, 2006).

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Paleodust records provide mostly local information. Modelling studies help to assess global dust emission and deposition as well as the atmospheric transport. In addition, they help to examine the relative contribution of possible factors to dust deposition changes that is useful for interpretation of proxy data.

5 Simulations of the dust cycle for paleoclimate conditions can give additional insight into past climates, and they also represent a critical test for the models under different climate scenarios, since these simulations can be validated against independent paleo data. One additional aspect is that the simulation of the marine carbon cycle of past time-slices requires adequate dust deposition values as input information for the
10 climate models, which can be derived from model simulations.

Taking into account the impact of different orbital parameters and boundary conditions, four interglacial time-slices, as well as one glacial period, were performed and investigated. The control simulation (CTRL) represents the pre-industrial (interglacial) period. Other interglacial time-slices are the mid-Holocene (6000 yr BP), last glacial
15 inception (115 000 yr BP) and Eemian (126 000 yr BP). The glacial time interval is the Last Glacial Maximum (LGM) (21 000 yr BP). The dust cycle during past interglacial time intervals has not been the subject of many studies (transient EMIC simulation in Bauer and Ganopolski, 2010). Thus, no broad data sets of dust deposition exist. For the LGM however, a good precompiled observational based data set on dust deposition is
20 known (DIRTMAP, Kohfeld and Harrison, 2001) and this time-slice has been simulated in several other studies (e.g. Andersen et al., 1998; Werner et al., 2002; Mahowald et al., 1999, 2006; Li et al., 2010; Albani et al., 2012). Thus, in our study we can use results for the LGM simulation as a reference test for the model.

25 This study is a first attempt to simulate past interglacial dust cycles. The main goals are to analyze the response of the dust cycle to different interglacial (pre-industrial, 6 kyr, 115 kyr and 126 kyr) and glacial (21 kyr) climate conditions and to estimate the quantitative contribution of different processes, such as emission, atmospheric transport and precipitation to dust deposition changes in Antarctica. This is useful for interpretation of the paleo data from Antarctic ice cores. Other important additional aspect

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order to compensate for a slight underestimation of vegetation cover fraction by the LPJ-GUESS model and assuming that even in autumn and winter time, when grass is drying up and leaves are shed, the roots still suppress the emission of soil particles. The basins with pronounced topographic variations are especially favourable for dust mobilization and were taken into account following Ginoux et al. (2001). These areas are called preferential dust source areas and contain large amounts of sediments which are accumulated essentially in the valleys and depressions, and are predominantly silt sized. The setup followed the Paleoclimate Modelling Intercomparison Project (PMIP2) protocol (<http://pmip2.lsce.ipsl.fr/>, Braconnot et al., 2007). For all interglacial time periods current topography and ice sheets were used. For defining the orographic changes in the LGM, the 5 min data set of reconstructed ice sheet topography from PMIP2 (Peltier, 2004), aggregated to a T31 grid was used.

Orbital parameters and greenhouse gas concentrations for the Holocene and LGM simulations were prescribed following the PMIP2 protocol (Table 1). For the time slices 115 kyr and 126 kyr insolation was changed accordingly, greenhouse gas concentrations were kept at pre-industrial level. Monthly mean sea surface temperature (SST), sea ice concentration and surface background albedo for each time-slices were obtained from the long-term simulation with the coupled atmosphere ocean dynamical vegetation model ECHAM5/MPIOM/LPJ (Mikolajewicz et al., 2007). Sea surface temperatures were corrected for the systematic error of the coupled run by adding the SST differences between observed and simulated SSTs for the pre-industrial period (similar to Arpe et al., 2011). SST's thus prescribed for the paleo time-slice simulations are, on a global average, lower by -0.07°C in 6 kyr, by -0.08°C in 115 kyr, by -0.13°C in 126 kyr and by -2.7°C in the LGM compared to the pre-industrial SST. In this study the results from 20 yr time-slice simulations after 5 yr of spin up have been analyzed.

3 Model results for the pre-industrial climate conditions

First of all we estimated the model ability with prescribed pre-industrial modelled vegetation map to reproduce modern dust deposition flux (Fig. 2). Dust deposition records include ice core measurements, expressed as deposition fluxes and marine sediment core records and represent averages for the Holocene period or shorter periods within that interval. The data are derived from “Dust Indicators and Records of Terrestrial and Marine Palaeoenvironments” data base (DIRTMAP, Kohfeld and Harrison, 2001).

The model is able to reproduce the general patterns and capture the large range of five orders of magnitude of the observed dust deposition flux within an order of magnitude (Fig. 2). The correlation coefficient of the natural logarithm of the observed and modelled values is 0.78. The model underestimates dust deposition in the Arabian Sea which is most likely due to an underestimation of the source on the Arabian peninsula. The model also tends to underestimate the magnitude of dust deposition off the east coast of Asia, but the geographical location of the plume appears to be consistent with the data available from this region. In the polar regions a discrepancy between the simulated and available observed dust deposition occurs in the northern high-latitudes in Greenland, where the model overestimates the observed values by a factor of about 3–10. A similar bias is also reported in other modelling study by Mahowald et al. (1999). Some difficulties arise in validating the model for the Southern Hemisphere due to lack of datasets in these latitudes. In Antarctica the model overestimates observed values by a factor of about 2–3 due to the overestimation of the Australian dust source, as well as due to too high wet deposition in the Antarctica interior. At the same time, the model underestimates the dust deposition in the Weddell Sea close to Antarctica, which was also reported in other global modelling studies (e.g. Huneus et al., 2011).

Simulated seasonal cycle of dust deposition in different sites in Antarctica shows general agreement with the observations. Observations at James Ross Island station show a maximum dust deposition in late austral winter (McConnell et al., 2007), which is close to the simulated spring maximum at that site. Similarly, the simulated maxi-

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mum dust deposition at the Berkner Island site is in spring, while observations show a spring/summer maximum (Bory et al., 2010). The recorded annual cycle of dust deposition at Law Dome shows spring and autumn maximum (Burn-Nunes et al., 2011). In our simulation dust deposition at Law Dome shows a maximum during spring and summer seasons.

The global mean dust emission for the pre-industrial control simulation is 1540 Tg yr^{-1} . This value is in fairly good agreement with the total dust emissions generated by the pre-industrial model runs within the aerosol model intercomparison project (AeroCom), which lie between 1570 and 1700 Tg yr^{-1} (<http://aerocom.met.no>). Dust emissions from the Southern Hemisphere contribute less than 10% to the global emissions, but are the main sources of dust deposited in Antarctica. Simulated dust emissions from Australia amount to 60 Tg yr^{-1} , which is in the range of 15 different models with modern climate conditions within the AeroCom project (Huneeus et al., 2011). Dust mobilization from South America is rather small and lies close to the low end of the AeroCom model simulations. The South African source is also weak and underestimated compared to other models.

Simulated dust emissions from Australia start to increase in October and reach their maximum in November–December, showing equally high emissions in SON and DJF (not shown). This is in general agreement with satellite observations, suggesting the start of Australian dust mobilization is in September–October and its maximum is in December–February (Prospero, 2002). Observations over southern Africa show maximum emissions in August–October, while the modelled maximum emissions are shifted to November–January. The modelled seasonal cycle of South American dust emissions is in general agreement with observations and shows maximum activity in October–November.

The dominant sink process of mineral dust in Antarctica is wet deposition, which is in agreement with observational based estimates made for coastal sites in Antarctica (e.g. Wolff et al., 1998). However, the model overestimates wet deposition in the interior of Antarctica, similar to other modelling study by Albani et al. (2012). Observations in

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genic dust sources in the LGM simulation, one of which is located in South America, Pampas region (Mahowald et al., 2006).

For both 6 kyr and 126 kyr, Australian emissions are higher by a factor of 1.8 compared to the CTRL simulation. Most of the increase in 126 kyr is caused by an enlarged source area extent (by about factor of 1.8) as a consequence of dry austral summers. In 6 kyr and 115 kyr the Australian dust source area extent is reduced by almost one half of the source area in CTRL. The increase of Australian emissions in 6 kyr is related to more frequent high wind speed and low soil wetness in the western part of Australia. In 115 kyr, regionally dry soil in combination with an almost unchanged distribution of wind speed compared to CTRL results in emissions similar to CTRL. According to the simulations, the dust source areas and emissions in South America are quite persistent through all interglacial time-slices, except for a large increase of emissions in 6 kyr. This is due to very strong dust emissions from one particular grid box (Fig. 3, 6 kyr, ~ 35° S, 65° W) with higher wind speed and lower soil wetness relative to other grid boxes. The dust emissions from the south African source are stable in considered time-slice simulations, consistent with the frequency of high wind speed.

The main increase in Southern Hemisphere emissions is found in the LGM due to the significantly strengthened South American dust source. This is caused by both an extended dust source area and a much higher probability of high wind speed over the additional source area, which is formed in the LGM. Furthermore increased emissions are also related to regionally reduced soil wetness and particularly dry soil in the “new” source areas in the south of Patagonia region. Emissions from the Australian dust source are slightly increased in the LGM with respect to the pre-industrial time-slice. This results from an enlarged dust source area extent and regionally lower soil wetness, while the probability of high wind speed over Australian sources is almost similar to that in the CTRL run.

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4.3 Dust deposition with focus on Antarctica

The increase of global dust mobilization in paleoclimate conditions, which was discussed previously, is reflected in enhanced dust deposition compared to the pre-industrial period (Fig. 4). In all time-slice simulations, sedimentation and wet deposition are the main global loss processes of mineral dust accounting each for more than 40 % of the total dust removal, except for 126 kyr. In 126 kyr the relative contribution of sedimentation to the total sink is weaker, due to increased tropical monsoonal activity and consequently wet deposition close to the main dust source regions in Asia and the Sahara. Wet deposition is slightly reduced in relative strength in the LGM compared to CTRL due to the drier climate conditions. Dry deposition is also a significant sink process, accounting for 14 ± 1 % of dust removal.

Simulated dust deposition over Antarctica is higher by a factor of 3.8 in 6 kyr, by a factor of 2.7 in 126 kyr and slightly larger in 115 kyr with respect to CTRL. The maximum dust deposition is found in the LGM showing a 10-fold increase which is similar to the other modelling study (Albani et al., 2012). Model results suggest wet deposition as the dominant process responsible for diminishing dust over the Antarctic continent for considered time-slice simulations, although the relative contribution to the total sink is slightly weakened in the LGM.

Regarding the seasonality of dust concentration in Antarctic ice, the model results suggest the maximum in austral spring (SON) for all interglacial time-slices. However, for the LGM the geographical patterns of seasonal maximum dust concentration in ice are more complicated and depend on the region (not shown).

In the next section the modelled dust deposition in the LGM and past interglacial time-slices are compared with observations.

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4.5.1 Atmospheric transport efficiency

One of the possibilities to describe the atmospheric transport is by means of air mass trajectories. The air mass trajectories from the Southern Hemisphere dust sources to Antarctica were calculated. To calculate trajectories, 6 hourly data of the meridional, zonal and vertical components of wind from 20 years of simulation were used. Trajectories were calculated once per day. We considered trajectories originating over the Southern Hemisphere dust sources at pressure levels of 800 hPa and 500 hPa and reaching Antarctica within 10 days. The three-dimensional passive tracer trajectories were calculated based on bilinearly interpolated velocities. According to Krinner et al. (2010), there are two types of tropospheric tracer transport towards the interior of the Antarctic continent: fast, low-level advection enhanced by cyclonic systems off the Antarctic coast and advection via mass convergence in the middle troposphere above Antarctica. The 500 hPa and 800 hPa pressure levels therefore have been chosen in order to analyze the atmospheric dust transport in the low and middle troposphere. In order to examine atmospheric transport alone, without the influence of the dust source extent which is different in all the simulations, the number of trajectories for each time-slice was normalized with respect to the dust source area extent. An example of trajectories for austral spring originating over the Southern Hemisphere dust sources at 500 hPa and reaching Antarctica for the CTRL simulation is shown in Fig. 8.

For the interglacial time-slice simulations, the number of trajectories originating over the Southern Hemisphere dust sources at the height of 800 hPa and reaching Antarctica is about 10 % of the total number of trajectories originating over the Southern Hemisphere dust sources; and the number of trajectories originating at the height of 500 hPa and reaching Antarctica is about 3.5–5 %. The increased meridional temperature gradient at the LGM leads to more efficient poleward transport (Petit et al., 1999) and the number of trajectories reaching Antarctica is higher (13 % for 800 hPa and 7.3 % for 500 hPa) compared to the interglacial time-slices. Another feature of the glacial period is a weaker seasonality of poleward transport compared to the interglacial time-slices

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70° S in contrast with our trajectories that originate above the Southern Hemisphere dust sources ($\sim 20\text{--}50^\circ$ S) at the height of 500 hPa.

In order to understand which mechanism is responsible for the poleward transport change, dust flux for different climate conditions at 500 hPa was calculated by using monthly mean (not shown) and 6 hourly data (Fig. 9). Dust flux calculated with monthly mean data shows that the mean transport at high southern latitudes is dominated by zonal circulation and very similar for all time-slices. However, dust flux calculated by using 6 hourly data shows an increase of meridional contribution and significant changes in the dust transport patterns towards Antarctica between different time-slices due to synoptic variability. Thus, the transport pathway change in different time-slices is due to synoptic variability. The relative contribution of dust transport at $40\text{--}70^\circ$ N due to synoptic variability to the mean (total) meridional transport is about 70–90 % in interglacial time-slices and nearly 100 % in the LGM.

Contribution of different sources to the number of trajectories reaching Antarctica in the pre-industrial time period (and 115 kyr) suggests slightly more trajectories originating over a single unit of South American dust source than over Australia. Analysis for 6 kyr and 126 kyr shows slightly higher number of Australian trajectories rather than South American trajectories. Delmonte et al. (2007) suggested a mixture of Australian and South American dust as most probable sources for dust deposition in Antarctica in Holocene and Eemian. But they notice that this hypothesis needs further investigation. At the LGM the number of trajectories originated over South American dust source is significantly higher (almost double) compared to pre-industrial, whereas Australian trajectories are just slightly enhanced. Observations suggested a dominant southern South American provenance of dust deposited in Antarctica for the glacial period (e.g. Grousset et al., 1992; Basile et al., 1997; Delmonte et al., 2010a).

Multiplying the Southern Hemisphere dust emissions with the number of trajectories leading to Antarctica defines a quantity, which we call potential dust transport (in arbitrary units) (Fig. 7d). This gives some idea about both, how much dust is emitted and

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how often dust is transported to Antarctica. However these factors alone cannot explain the modelled dust deposition changes (Fig. 7b).

4.5.2 Precipitation

Precipitation is an important process as it is one of the removal mechanisms for atmospheric particles on the transportation pathway. Interglacial time-slices show just a moderate change in precipitation over the ocean south of 40° S, while LGM precipitation is about 30 % less compared to the pre-industrial time-slice (Figs. 10 and 7e). This favours the increase of dust deposition in Antarctica in glacial periods. Moreover, LGM precipitation over Antarctica is approximately one half of pre-industrial precipitation, which alone leads to about doubling of the dust concentration in ice (not shown).

Seasonal influence of precipitation can be seen in MAM (Fig. 7e). Relatively strong dust transport efficiency is affected by seasonal maximum precipitation (over the ocean south of 40° S), which results in seasonal minimum deposition in Antarctica (Fig. 7b). This is valid for all interglacial time-slices. In the LGM, the seasonality of dust deposition over Antarctica in MAM and JJA is affected by precipitation in a different way. This probably results from an increased fraction of snowfall, compared to rain in the LGM over the Southern Ocean, and different scavenging efficiency coefficients for snow and liquid in the model. According to Stier et al. (2005), liquid precipitation removes aerosol more efficiently than snow.

5 Summary and conclusions

This study presents the first attempt to simulate past interglacial dust cycles with a global aerosol-climate model. The work aims to investigate the variations of dust deposition in Antarctica in terms of quantitative contribution of different processes, such as dust emission, atmospheric transport and precipitation in order to help interpret paleo records of dust from Antarctic ice cores. The four interglacial time periods ana-

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lyzed include the pre-industrial control (CTRL), mid-Holocene (6000 yr BP), last glacial inception (115 000 yr BP) and Eemian (126 000 yr BP) simulations. One glacial time interval, which is Last Glacial Maximum (LGM) (21 000 yr BP), was simulated as well, as a reference test for the model.

5 The model is able to capture the large range of five orders of magnitude of the observed dust deposition flux within an order of magnitude for pre-industrial and LGM climate conditions. Underestimation of glacial values in Eastern Antarctica can most likely be attributed to the comparable weak source in southern South America. Including glaciogenic dust sources in the Pampas region (Mahowald et al., 2006) would
10 enhance the South American dust source and could improve the agreement with observations. The increase of spatial model resolution could be important for a better representation of the southern South American dust source as well. Records from Antarctic ice cores for interglacial time periods indicate slightly higher dust concentration in the ice compared to pre-industrial values. Simulations show general agreement
15 with the measurements, with exceptions for the overestimated 6 kyr to pre-industrial ratios. For a complete comparison more observational records would be needed.

Our results suggest the increase of dust deposition in Antarctica for all considered time-slices relative to the pre-industrial period. In the mid-Holocene, dust deposition is increased by a factor of 3.8, and in the Eemian by a factor of 2.7. Approximately two
20 thirds of the increase in both periods is attributed to enhanced Southern Hemisphere dust emissions. Slightly strengthened transport efficiency due to southward deflection of the transport pathway causes the remaining one third of the increase in dust deposition. Compared to pre-industrial conditions, more intensive poleward transport at 115 kyr together with almost similar Southern Hemisphere emissions results in only slightly enhanced dust deposition in Antarctica. The highest dust deposition in Antarctica
25 is simulated for the LGM, showing a 10.2-fold increase compared to CTRL. This results from a combination of 2.6 times higher Southern Hemisphere dust emissions, two times stronger transport and 30 % weaker precipitation over the Southern Ocean. Our finding supports suggestion of other studies (e.g., Krinner et al., 2010; Krinner and

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Genthon, 2003) towards more intensive atmospheric poleward transport during glacial period.

Similar to Krinner et al. (2010) who analyzed model results for LGM and present day, our results show that poleward atmospheric transport is more vigorous in JJA and MAM for all simulated time periods. This implies that seasonality of atmospheric transport towards Antarctica and Southern Hemisphere dust emissions (with a peak in SON and DJF) are in general out of phase.

Based on trajectories and source strength simple analyses we support earlier idea of Revel-Rolland (2006) that Australia is possible the dominant source of dust in Antarctica in 6 kyr and 126 kyr and we suggest mixture of South American and Australian sources for dust deposition in Antarctica in pre-industrial and 115 kyr.

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Table 1. Orbital parameters and greenhouse gas concentrations for the CTRL, 6 kyr, 21 kyr, 115 kyr, 126 kyr simulations derived from the PMIP2 protocol.

	CTRL	6 kyr	21 kyr	115 kyr	126 kyr
eccentricity	0.016724	0.018682	0.018994	0.041421	0.03971
obliquity, [°]	23.446	24.105	22.949	22.404	23.928
day of perihelion	282.04	180.87	294.42	290.88	111.24
CO ₂ , [ppm]	280	280	185	280	280
CH ₄ , [ppm]	0.76	0.65	0.35	0.76	0.76
N ₂ O, [ppm]	0.27	0.27	0.20	0.27	0.27

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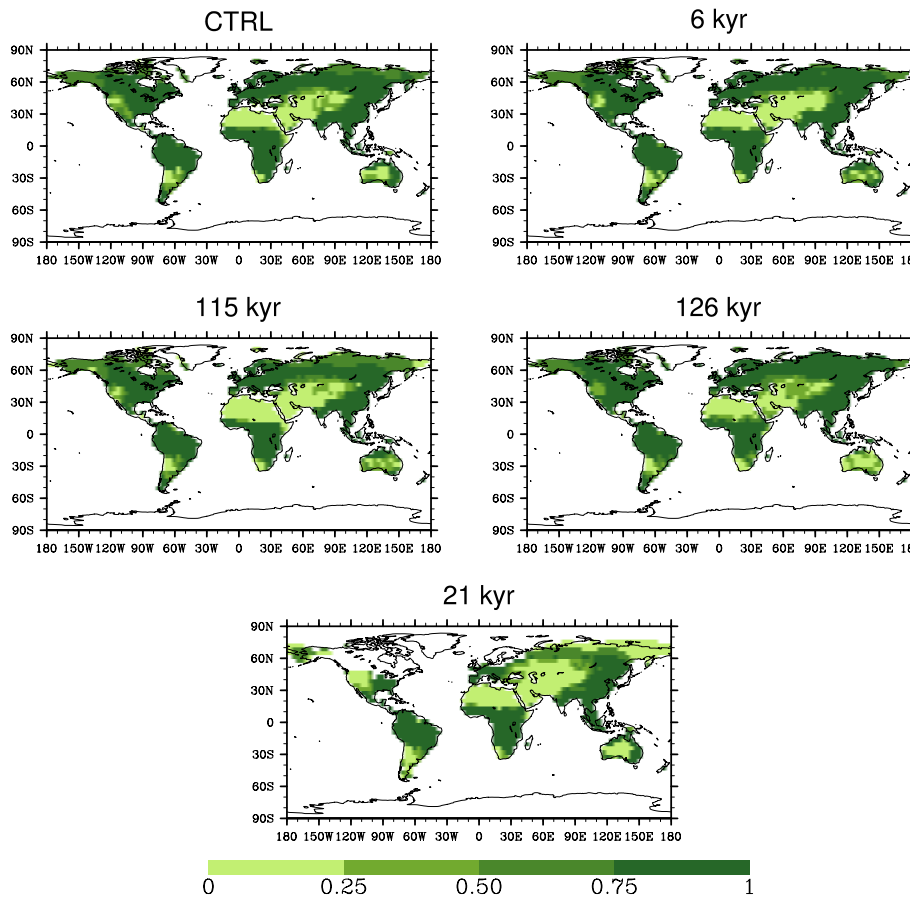


Figure 1. Annual maximum vegetation cover fraction obtained from the LPJ-GUESS model for the CTRL, 6 kyr, 115 kyr, 126 kyr and LGM time periods. The regions with annual maximum vegetation cover less than or equal to 25 % (light green color) are defined as the potential dust source regions.

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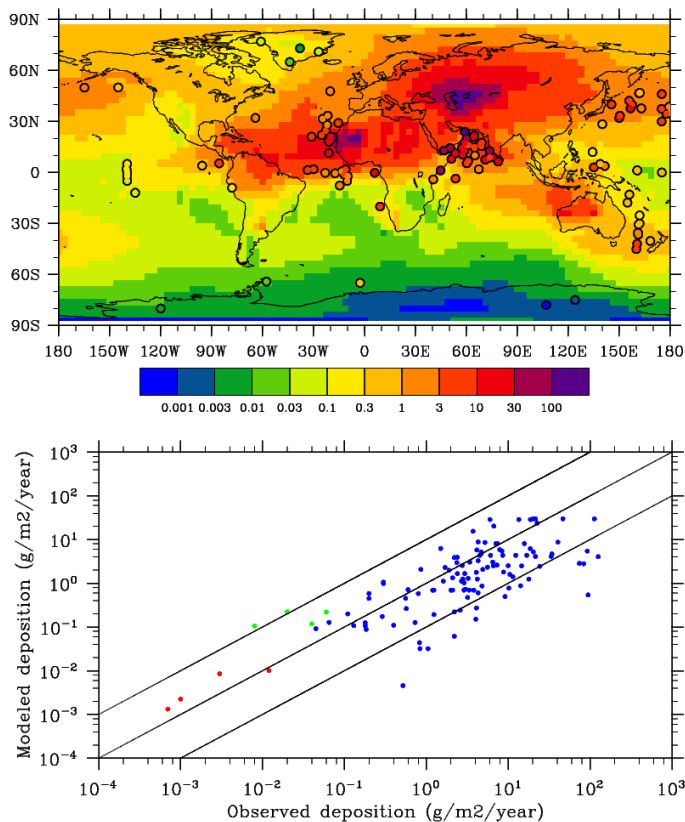


Figure 2. Simulated dust deposition flux [$\text{g m}^{-2} \text{yr}^{-1}$] for the pre-industrial time-slice compared with dust deposition data compiled from ice cores, marine sediment traps and marine sediment cores [$\text{g m}^{-2} \text{yr}^{-1}$] (circles) and a scatter plot between the model and observations. The red color indicates Antarctica, green indicates Greenland and blue indicates other locations.

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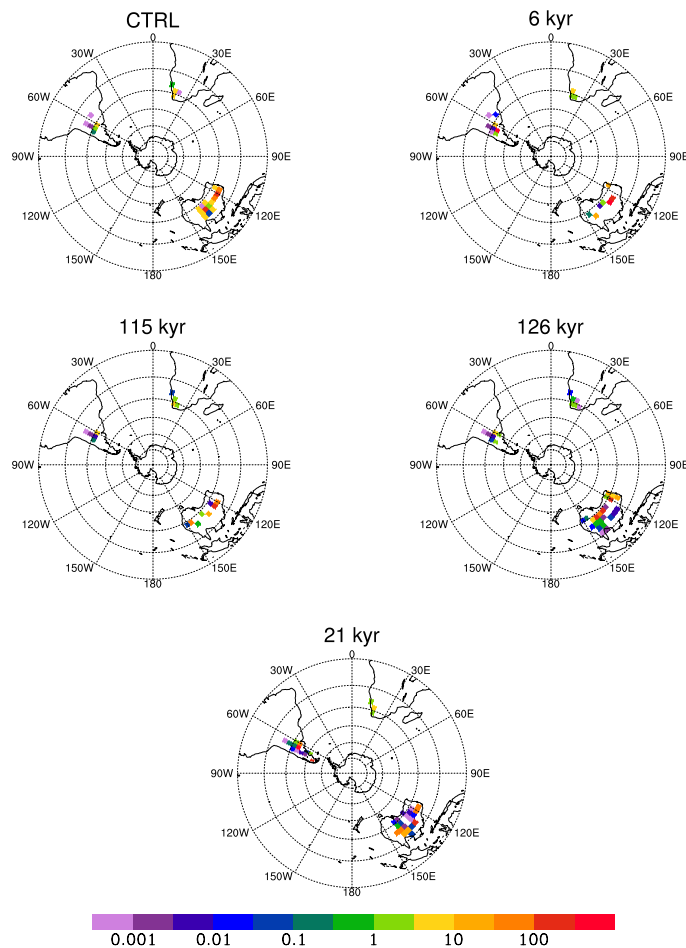


Figure 3. Mean Southern Hemisphere dust emission flux for the CTRL, 6 kyr, 115 kyr, 126 kyr and LGM simulations, [$\text{g m}^{-2} \text{yr}^{-1}$].

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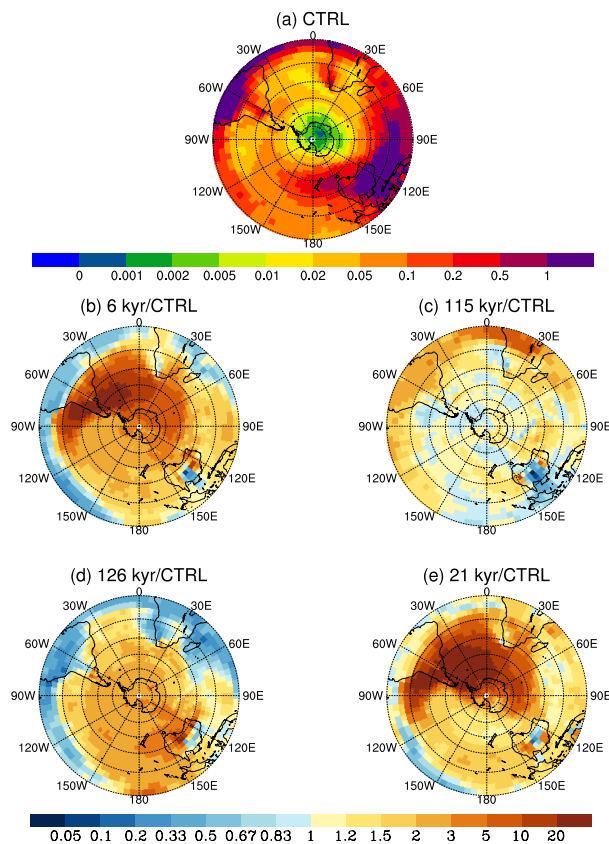


Figure 4. Annual average dust deposition flux [$\text{g m}^{-2} \text{yr}^{-1}$] for the Southern Hemisphere for the CTRL pre-industrial simulation (a). Ratio of dust deposition flux for the interglacial and glacial time-slices with respect to the CTRL pre-industrial simulation (b–e).

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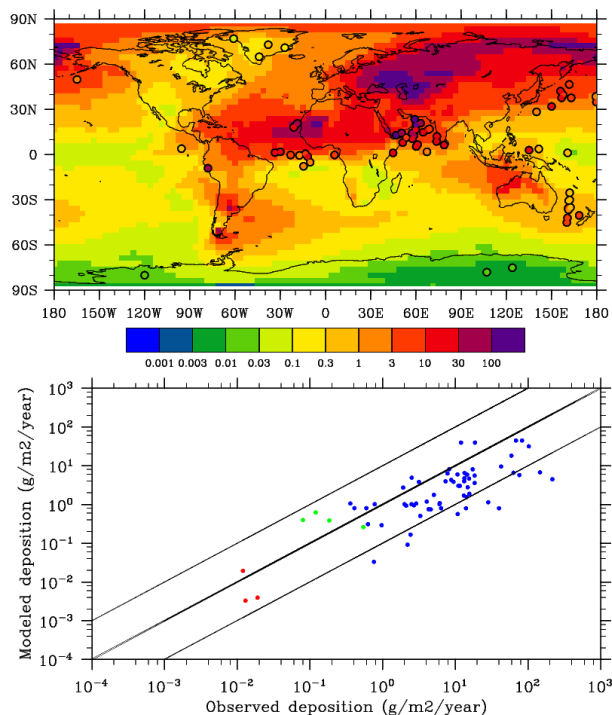


Figure 5. Simulated dust deposition flux [$\text{g m}^{-2} \text{yr}^{-1}$] for the LGM time-slice compared with dust deposition data compiled from ice cores, marine sediment traps and marine sediment cores [$\text{g m}^{-2} \text{yr}^{-1}$] (circles) and a scatterplot between the model and observations. The red color indicates Antarctica, green indicates Greenland and blue indicates other locations.

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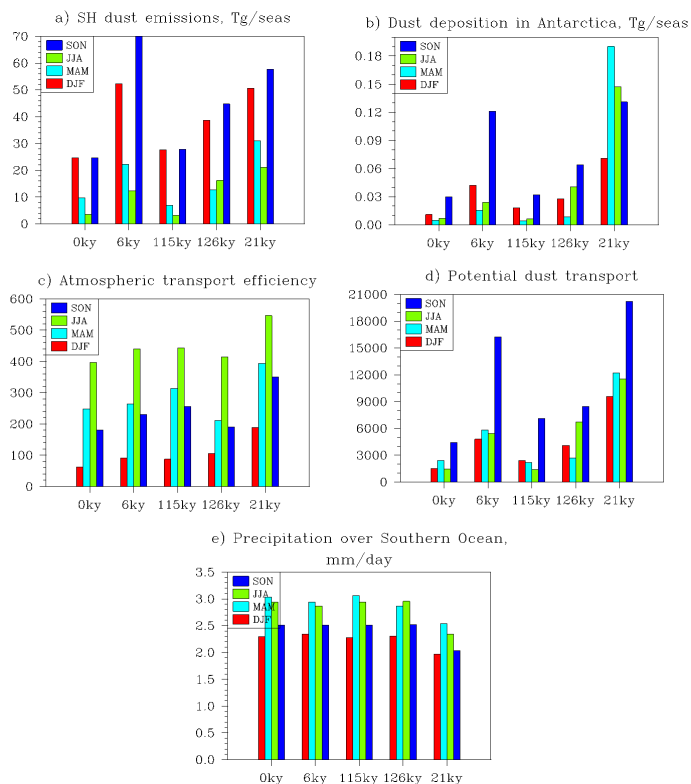


Figure 7. (a) Southern Hemisphere dust emission [Tg season^{-1}], (b) dust deposition in Antarctica [Tg season^{-1}], (c) atmospheric transport efficiency [trajectories season^{-1}], (d) potential dust transport [arbitrary units], (e) precipitation over the ocean south of 40°S [mm day^{-1}] for the interglacial and glacial simulations. Atmospheric transport efficiency is the number of trajectories originated at 500 hPa and 800 hPa (combined) from a single dust source grid box per season and reached Antarctica within 10 days.

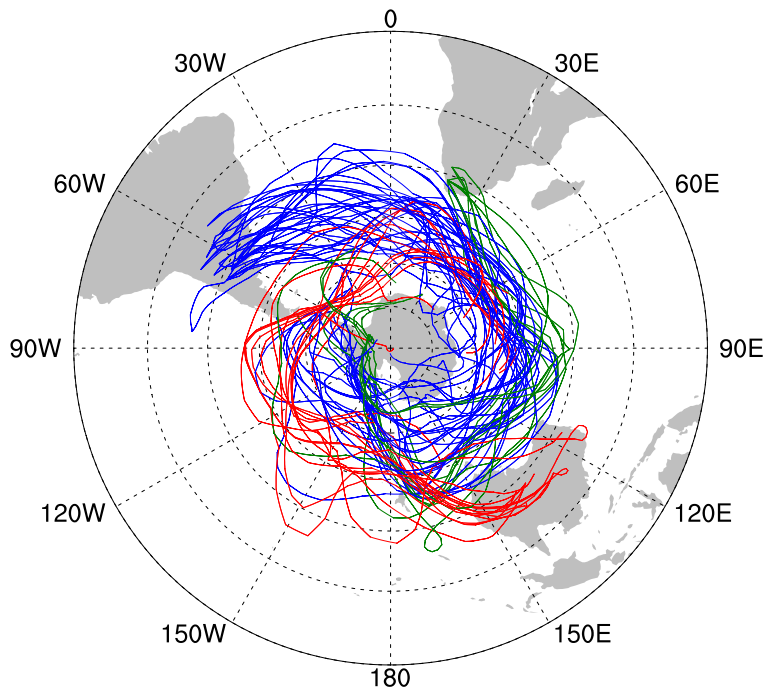


Figure 8. Ten day forward trajectories of air masses on 500 hPa originating over the South American (blue color), south African (green color) and Australian (red color) dust sources that reached Antarctica. Trajectories are shown for the CTRL simulation, austral spring season (SON). Note that only every 10th trajectory is plotted.

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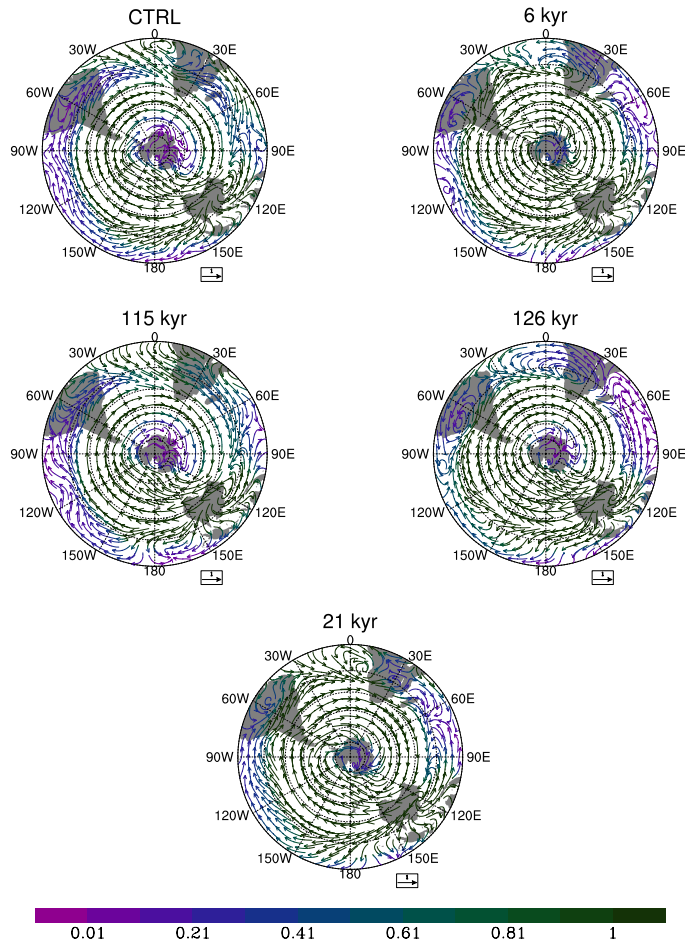


Figure 9. Dust transport on 500 hPa calculated by using 6 hourly data, September, October, November (SON).

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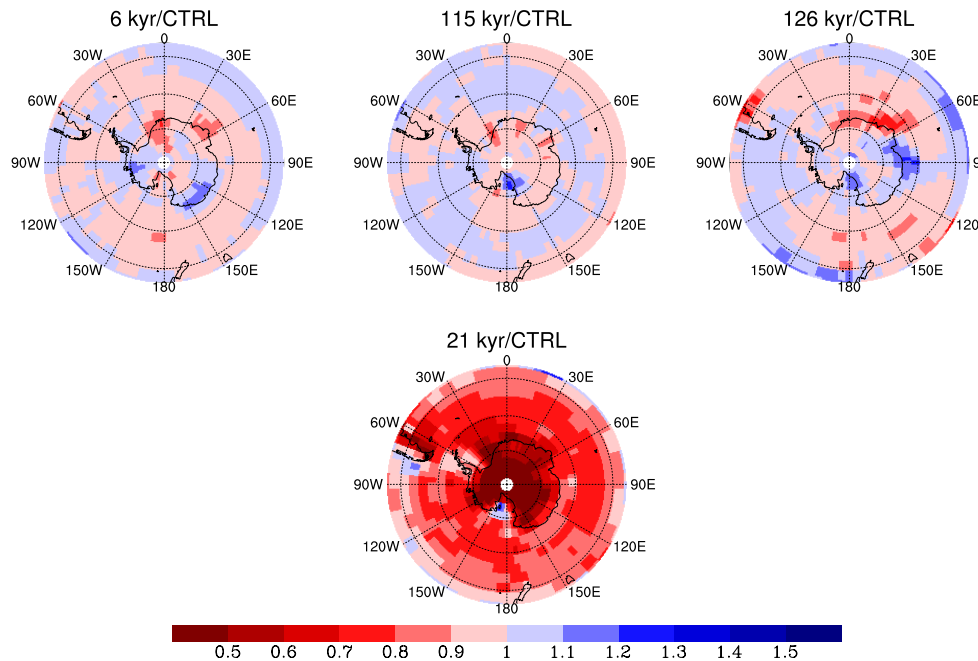
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Figure 10. Paleo to pre-industrial ratios of annual mean precipitation.