[1]N.Sudarchikova [1]U.Mikolajewicz [1]C.Timmreck [2]D.O'Donnell [3,*]G.Schurgers [4]D.Sein [5]K.Zhang
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Reply to the comments on "Modelling of mineral dust for interglacial and glacial climate conditions with focus on Antarctica"

Max-Planck-Institute for Meteorology, Hamburg, Germany

Finnish Meteorological Institute, Helsinki, Finland

Department of Physical Geography and Ecosystem Science, Lund University, Sweden

Alfred-Wegener-Institute, Bremerhaven, Germany

Pacific Northwest National Laboratory, Richland, WA

now at: Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark

Correspondence to: N. Sudarchikova (natalia.sudarchikova@mpimet.mpg.com)

We thank both reviewers for reviewing our manuscript and providing constructive suggestions for improving text and figures. The comments by Reviewer are shown in quotation marks and in italic. Our answers are in normal font. Revised text is indicated by number of page and line.

1 Response to Reviewer 1

"This paper attempts to simulate the dust cycle in Antarctica by using the global aerosol-climate model ECHAM5-HAM. I have several concerns about the approach adopted, in particular because the model aims to extrapolate the physics that hold for tropical regions to the Antarctic domain, without paying attention to the specificity of the dust cycle in Antarctica."

We disagree with this assertion. ECHAM5 is a global model that implements a discretization of the governing equations of atmospheric motion, which contain no regional specificity, together with a comprehensive suite of parametrizations applicable to all conditions from the surface to the stratosphere at all latitudes. See Roeckner et al. (2003) for a full description of the ECHAM5 model. The aerosol module HAM (Stier et al., 2005) simulates the full aerosol life cycle: emission, atmospheric transport, and sink processes, namely wet deposition by rain and snow, sedimentation and dry deposition. Dust emissions are calculated online based on the physical characteristics of the surface, vegetation cover, soil moisture, snow cover and wind speed. These schemes are also global in scope and contain no latitude-specific adaptations.

"I will focus here on some major weak points. First, when dealing with dust reaching the remote, high-elevation Antarctic sites such as Dome C and Vostok cited in the text, one has to consider that the altitude of dust transport is well above the levels where most washing out occurs: decay of 222Rn of continental origin suggests a transport duration as long as 3 to 4 weeks. This should be comparable to the time of transport of dust to inner sites, while the authors suggest a much shorter time of about 10 days. Such a short transport time is reasonable only for marine aerosol. Therefore, a first important critic is related to the duration of fine particles transport from the source areas to the interior of Antarctica."

The time duration of 10 days for atmospheric transport from Southern Hemisphere dust sources to Antarctic continent is similar to the lifetime of mass-less radioactive tracers transported over a similar route and distance in Krinner et. al., (2010). Krinner and Genthon (2003) also shown that the simulated tracer age ranges from 5 to 9 days (figure 8 therein). Reijmer et al., (2002) used a method based on 5 days backward trajectories from 5 Antarctic sites (EDC, EDML, Vostok, Byrd and DML05) to source regions of moisture which lie between 60 and 50°S.

We do not agree that 10 days distance is only reasonable for the marine aerosol. Long- range transport of aerosol takes place with the characteristic speed of free tropospheric winds (about 10 m/s), which corresponds to a distance from source of the order of 8000 km within 10 days. This is sufficient for dust transport from the source regions to Antarctica. The residence time of particles in the atmosphere may be longer than that, depending (as the Reviewer points out) on the exposure of the particles to wet deposition and on the height to which the particles are transported. In the analysis, we used trajectory levels of 500 hPa and 800 hPa, which are subject to wet removal, so that an assumption of longer residence times is not warranted. Also, when comparing model results with observations taken at high-altitude sites, coarse model orography, which can severely limit the models ability to reproduce actual surface conditions at such sites, should be taken into account.

The most important sink processes of atmospheric aerosol are wet deposition and sedimentation, which are not applicable for 222Rn, and the sink process of 222Rn is radioactive decay, which is not applicable to aerosol. 222Rn is thus not a reliable guide to aerosol-related quantities (such as lifetime).

In general, our concept is to apply a similar method of trajectory analysis to all time slices in order to capture relative changes between different paleo periods.

"A second issue concerns LGM climate: the dust source productivity increased during LGM with respect to Holocene of a factor 3 to 5, as documented by Martinez-Garcia et al., 2009, 2014, Lamy et al., 2014, Jaccard et al., 2013. These authors all provide

evidence for an LGM/Holocene dust source change that is in this order of magnitude, and it is not clear how/if the authors have taken this literature into account."

Dust emissions, in our study, are calculated by the model taking into account vegetation, soil characteristics and wind speed. Based on this information the model gives 2.6 times higher emissions from the SH dust sources at LGM compared to current climate (page 21), which is close to the low end of mentioned by the Reviewer data.

"When considering a change in snow accumulation rate in Antarctica of a factor 2 between LGM and Holocene, the remaining factor (about 5) that is missing to explain the 30-to-50 fold increase registered in Antarctic ice cores during LGM can be attributed to transport efficiency, and to a longer lifetime of dust in the atmosphere during the last glacial period (as suggested also by Petit Delmonte 2009). In this work it is not clear how/if the authors have considered an increase of dust residence time in the atmosphere related to the reduced atmospheric water vapor."

The influence of the hydrological cycle is addressed in section 4.5.2, where we note that precipitation over the Southern Ocean is 30% weaker in the LGM compared to the preindustrial. We do accept that this provides no direct quantitative information on the dust flux to Antarctica and will improve this in the revised paper.

Page 13, lines 10-12: The relative contribution of dry deposition in Antarctica at LGM is increased, but the model still overestimates wet deposition in that region.

"Other points that are equally important include the use of a mass mean radius of 1.75 micron, that is obviously too coarse with respect to dust in central Antarctica (mass mean radii around 1 micron), and another size bin that seems a bit small for mineral dust."

In our model the aerosol size distribution is represented using the modal method, not the bin method (or sectional method). For the dust emissions we use two modes: accumulation mode with $0.05 < r$ (µm) ≤ 0.5 and coarse mode with $0.5 < r$ (µm) (Stier et al., 2005). The two modes cover the whole size range of 0.05um to 10um. We accept that the paper should be clear that the stated mass-median radii of 0.37 µm and 1.75 µm are the emitted particle sizes from dust sources, not the predicted size after various aerosol microphysical processes (for example, coagulation). The model has no prescribed particle size for such particles. Also, aerosol sink processes in the model are size-dependent, so that these emission radii are not of relevance for comparison with observations. This will be clarified in the revised manuscript.

Page 6, line 1-3: Emitted dust aerosol is represented by two modes, accumulation mode (with $0.05 < r$ (µm) ≤ 0.5) and coarse mode (with $0.5 < r$ (µm) with mass-median radii of 0.37 (µm) and 1.75 (µm) and standard deviations of 1.59 and 2.00, respectively.

*"Further, the authors seem to ignore literature on Antarctic dust between 2001 and 2014, and they use DIRTMAP as reference for observations. Dust flux to plateau sites (Dome C area) in preindustrial times is around 0.2*10(-3) mg/m2 per year (Delmonte et al., 2013), that is much lower than the Holocene mean at Dome C and Vostok (0.4*10(-3) mg/m2 per year, Delmonte et al., 2005). Today, DIRTMAP values that are taken as reference for the observations are considered too high and cannot be used for comparison. A direct consequence of this is that the model overestimates observations of a factor that is much higher than the one stated in this paper."*

We restricted to our comparisons to paleorecords from particular cores that cover all investigated time-slices. Now we will compare the modeled results with available measurements even if they cover only some of considering time-slices. DIRTMAP database is widely used in the global model comparison, for example in Mahowald et al., 2006, 2011, Albani et al., 2011 etc. We know of no paper that recommends not to use this database. We agree that additional data are needed for more complete comparison. In particular in Antarctica we will add more data, e.g. TALDICE dataset (Schupbach et. al., 2013).

Talos Dome ice core is added to the comparison (Page 14, line 21-22).

"Normalization to CTRL values is reasonable, but: -The 3.8 increase in dust flux (wrt CTRL) at 6 kyrs BP seems very large for central Antarctica and there is no clear evidence for this in Holocene data from Vostok and Dome C (Delmonte et al., 2005) - or you have a reference for this?"

An additional adjustment to the 6 kyr case was applied and the simulation was repeated.

Page 7, lines 14-20: We applied additional adjustment to the mid-Holocene case due to too high emissions from one particular grid box in South American source and as a consequence overestimated dust deposition in Antarctica. Thus, in order to get reasonable results and better agreement with observations, we suppressed emissions from this grid box and repeated the simulation. Also the vegetation cover in this grid box is almost 25 % which is close to the limit for the definition of potential dust source regions. Hereafter in the text we will refer to this simulation as 6 kyr.

Results from the new simulation are in better agreement with observations (Page 15, lines 2-4 and Figure 7, right).

"-LGM dust flux as clearly admitted, is underes- timated. In EPICA Dome C the LGM/Holocene flux ratio is aroung 22-23 while the LGM/preindustrial flux ratio would be up to 45! Probably the lack of glaciogenic dust sources accounts for this discrepancy only in part, but a role is probably played by min- eral aerosol residence time in the atmosphere. As far as the simulation does not re- produce properly observations dur-

ing LGM it seems not clear why the authors decided to extend the simulations to older, climate periods where the dust cycle in Antarctica is less well known. On the whole, the simulation presented does not take into ac- count some important constraints for the dust cycle in Antarctica it seems necessary to deeply revise this approach."

Although our model does not perfectly match to the data retrieved from ice core mea- surements, the simulation for LGM is comparable to the results from other modeling studies. LGM global dust emissions are similar to other modeling studies: Werner et al., 2002, Mahowald et al., 2006, Li et al.,2010. LGM dust deposition over Antarctica in our study is in agreement with study by Albany et al., 2011 and higher compared to modeled results from Li et al., 2010 and Werner et al., 2002. In addition, dust deposition data retrieved from ice cores have their own uncertainty, which should also be considered when using these data to constrain the model. As a first attempt to simulate the past interglacial periods, we think it is acceptable to use a model that is comparable to currently available GCMs for paleo-climate studies. One should also bear in mind that a model grid cell covers an area of thousands of square kilometers, and the limitations that this places on comparisons with measurements taken at a single point.

2 Response to Reviewer 2

"Sudarchikova et al present a model study on dust deposition in Antarctica based on a global aerosol-climate model ECHAM5-HAM. It is a first attempt to simulate past interglacial dust cycles by investigating different interglacial (pre-industrial, 6, 115, and 126 kyr BP) and glacial (21 kyr BP) climate conditions. The main goals are to estimate the quantitative contribution of different processes such as dust emission, atmospheric transport and precipitation as well as deposition changes in Antarcitca. The subject of the paper is within the scope of Climate of the Past. However, before this manuscript can be published major revisions to the manuscript should be performed by the authors

according to the comments listed below.
The title of the paper suggests that the results of the model study are limited to dust depostition in Antarctica. However, a substantial part of the results and discussion (and figures) include global results (e.g. p 3722 lines 8-20, p 3724 lines 9-20, p 3726 lines 1-11). I suggest to either restrict the results and discussion to Antarctica, or change the title and main focus of the paper. Since Antarctica is a particular location in terms of atmospheric circulation, and dust sources for Antarctica are southern South America, South Africa and Australia, and, thus, independent from other source regions than those mentioned here, this can be done easily."

We agree with this suggestion. Possible change in title: Modelling of mineral dust for interglacial and glacial climate conditions with focus on Antarctica.

We think that it is still useful for readers in the modelling community to provide informa- tion about where our model lies in the spectrum of available models with respect to, for example, dust emission, so global totals and AeroCom comparisons will be retained. Specific information about measurements outside Antarctica will be removed.

Page 8, lines 21-25 are removed.

"P3718, L1: Paleodust records provide mostly local information. I strongly disagree. This would be the case if there were only local, i.e. Antarctic sources active for the dust records in Antarctic ice cores. However, there is a set of (East) Antarctic ice cores (EDML, EDC, Vostok, TALDICE,. . .) with which the entire region ¿50 S can be investigated in terms of source regions/strength, transport effects etc. Thus, the entire dynamics of the high southern latitudes can be investigated, providing climate information far beyond a local scale."

We agree that this sentence can be misleading. The sentence has been revised.

Page 4, lines 3-8: For interpretation of paleodust records, a combination of measurements and modelling results can be a fruitful approach. Paleodust records can provide information about the amount, geochemical features and spatial variability of dust in source and deposition regions. The modelling approach is needed for more complete picture involving variations in atmospheric transport of dust and for coverage of places with lack of data.

"P3718, line18. no broad data sets of dust deposition exist. Please clarify that this refers to model simulation data sets. There are quite a few observational data sets from Antarctica available (see comment further down)."

Here we wanted to emphasize the lack of observational data covering all investigated interglacial periods. The sentence has been changed.

Page 4, lines 20-23: The dust cycle during past interglacial time intervals has not been the subject of many modelling studies (transient EMIC simulation in Bauer and Ganopolski, 2010). Also global dust records covering these periods are rare.

"The model overestimates dust deposition flux in Antarctica by a factor of 2-3, according to the authors due to an overestimation of accumulation in Antarctica and thus wet deposition. The authors even say that a result of the pre-industrial simulation the dominant sink process of mineral dust in Antarctica is wet deposition (p 3723, line 26). Please clarify that this is a result of the model study and not an observation. The way this sentence is written this is not entirely clear. On p 3726, lines 15-18 this is written satisfactorily. However, its not clarified here that again, this is based on an overestimated accumulation (especially for the LGM period we know that dry deposi- tion is by far the most important deposition process). Please quantify this model bias (as has been done for the pre-industrial period) such that it can be compared to the pre-industrial results."

Following the reviewers comment, the two sentences have been revised:

Page 10, lines 8-20: In the model simulation wet deposition is the dominant sink process of dust over Antarctica, which is similar to the modelling study of Albany et al., 2012. However, observations in high-latitude polar regions at inland sites suggest dry deposition as the dominant sink process (e.g. Legrand and Mayewski, 1997, De Angelis et al., 1997) and wet deposition can be a major sink process for the coastal Antarctic sites (Wolff et al., 1998). Modelled snow accumulation in Antarctic sites, and thus processes responsible for wet deposition, are overestimated by a factor of about 1.5–2.5.

Page 13, lines 10-14: The relative contribution of dry deposition in Antarctica at LGM is increased, but the model still overestimates wet deposition in that region. Modelled glacial snow accumulation in Antarctic sites is higher compared to observations by a factor of about 1.2–2, which is similar to the overestimation of precipitation in the pre-industrial period.

"Sect 4.4.1: It is mentioned that the model is in good agreement with west Antarctic observations but underestimates dust deposition on the East Antarctic plateau. However in fig 5 there is only one observation shown from west Antarctica and only two observations for East Antarctica. In order to have a more robust comparison between model and observations I suggest to increase the number of observations, i.e. add as many ice core records as possible (again, the paper is focused on Antarctica. With only three observations a reasonable model evaluation cannot be performed.) Why is EDML not included in this section (whereas it is included in sect 4.4.2)? Or is it just not indicated in Fig.5?. Additional literature which could be used as references for glacial/interglacial dust deposition changes are Fischer et al, 2007, Rev. Geophys, Fischer et al. 2007 Earth Planet. Sci. Lett., and Schpbach et al. 2013, Clim. Past. There, also dust (nssCa, resp.) data from Talos Dome can be found which could be

included in the comparison, especially also for sect. 4.4.2 where the authors mention the scarce availability of dust records. There is also the Dome Fuji ice core covering all investigated periods (Watanabe et al 1999, Annals of Glaciology, or maybe even more recent publications). For West Antarctica, there also might be more data available (WAIS Divide, Byrd,. . .). Even the authors acknowledge that more observational records are needed for a complete comparison (conclusions p3733, line16)."

We restricted our comparison to paleorecords from particular cores that cover all investigated time-slices. The point of Reviewer is well taken and we will compare the modeled results with available measurements even if they cover only some of considered time-slices.

Talos Dome ice core data are added for the comparison (Page 14, line 21-22).
Data from Dome Fuji are not available online. Requested data are only possible to get after providing the coauthorship to the owners of the data.

"Sect. 4.4.2: Here the authors suddenly switch from dust deposition flux (as used previously) to dust mass concentration (also in Fig. 6). I suggest to use flux consistently throughout the entire manuscript, since this is a better measure of atmospheric dust in Antarctica than the concentration of dust in the ice. Are the model results shown in Fig 6 dust deposition fluxes or modelled dust concentration in the ice? Be careful not to mix the two parameters."

The model results which are shown in mentioned by Reviewer figure are dust concentration (calculated as dust deposition rate divided by precipitation). We agree with the suggestion to use dust flux for the paper (Fig. 7 in the manuscript).

"P 3728, lines 12-14: The authors claim that very strong Australian emissions in the 6kyr and 126 kyr simulations cause an overestimation of the dust deposition at EDC.

However, when looking at Fig. 8 I cannot see a single trajectory coming from Australia reach EDC. The only trajectories shown in Fig.8 reaching EDC are originating from South America. I acknowledge that the trajectories are based on modern meteorological data and, thus, it cannot be ruled out that the picture might be different for trajectories 6 kyr ago. Nevertheless, I would not expect such trajectories to be completely different from the modern ones. So, how can a change in Australian source strength have an effect on EDC, if the Australian air parcels never reach EDC? Might there be an additional effect being responsible for the overestimation of dust deposition at EDC for the mentioned two time slices?"

The Reviewer is correct, trajectories are quite similar for all interglacial time slices. In Figure 9 (in the manuscript) we show every 2nd trajectory from each separate SH dust source originated at both, 500 hPa and 800 hPa. From this figure we can see that some trajectories from Australian source reached EDC within 10 days, especially in the low atmosphere. Based on our model results, the dust source strength in 6 kyr and 126 kyr in Australia was almost doubled compared to CTRL and stronger than the South American source. Thus we think it is possible that even a limited numbers of trajectories from the very strong source in Australia can bring a sufficient amount of dust particles to Antarctica.

The influence of increased Australian emission source to dust deposition in Antarctica and EDC site particularly can be seen in fig.1 (for example, for CTRL and 126 kyr).

"The authors have done reasonable air mass trajectory calculations to analyse the atmospheric transport and to calculate the potential dust transport. This is a nice piece of work. However, the presentation of the results of these air mass trajectories in Fig. 8 are very sketchy. Maybe the figure could be improved by plotting the mean trajectory from each starting point, instead of the arbitrarily chosen every 10th trajectory. This might reduce the number of individual lines of the plot and simultaneously strengthen

the message of the figure."

We improved the presentation of trajectories by showing every 2nd trajectory from each source separately for both, 500 hPa and 800 hPa (Fig. 9 in the manuscript). Showing the mean trajectory will be misleading, because trajectories ending in different points in Antarctica and calculating the mean ending point will not give correct information.

"Figure 4: The ratio of dust deposition at EDC and Vostok between the 6kyr time slice to CTRL is higher than between 21kyr and CTRL. Thus, from this figure I learn that dust deposition at these two locations was higher 6 kyr ago than 21 kyr ago, which is completely against any knowledge we have about dust in Antarctica. Something went wrong with the model here. Please clarify why this is the case or correct if it is wrong."

We applied additional adjustment to the 6 kyr case and repeted the simulation.

Page 7, lines 14-20: We applied additional adjustment to the mid-Holocene case due to too high emissions from one particular grid box in South American source and as a consequence overestimated dust deposition in Antarctica. Thus, in order to get reasonable results and better agreement with observations, we suppressed emissions from this grid box and repeated the simulation. Also the vegetation cover in this grid box is almost 25 % which is close to the limit for the definition of potential dust source regions. Hereafter in the text we will refer to this simulation as 6 kyr.

Resultes from this simulation are in better agreement with observations (Page 15, line 2-4).

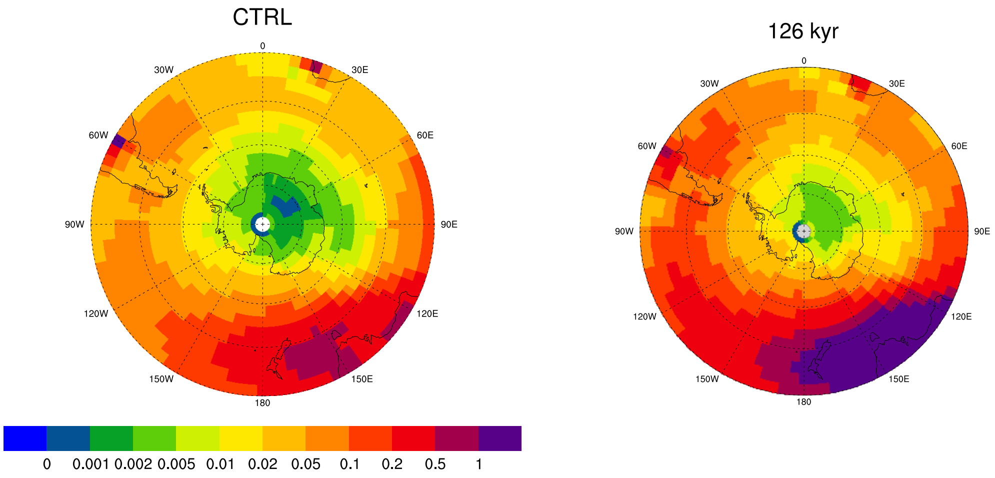

Fig. 1. Annual average dust deposition $[\mu g/m2]$ in the Southern Hemisphere for the pre-industrial and 126 kyr time-slices

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[1]N.Sudarchikova [1]U.Mikolajewicz [1]C.Timmreck [2]D.O'Donnell [3,*]G.Schurgers [4]D.Sein [5]K.Zhang
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~~Dust deposition in Antarctica in glacial and~~ Modelling of mineral dust for interglacial and glacial climate conditions ~~: a modelling study~~ with focus on Antarctica

Max-Planck-Institute for Meteorology, Hamburg, Germany

Finnish Meteorological Institute, Helsinki, Finland

Department of Physical Geography and Ecosystem Science, Lund University, Sweden

Alfred-Wegener-Institute, Bremerhaven, Germany

Pacific Northwest National Laboratory, Richland, WA

now at: Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark

Correspondence to: N. Sudarchikova (natalia.sudarchikova@mpimet.mpg.com)

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~~ the 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.

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 CO_2 (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 periods than in interglacial periods (e.g. Petit et al., 1990, 1999; EPICA Community Members, 2004, 2006). However considering interglacial periods only, some variabilities variability of dust also can be noticed (e.g. from the high resolution records in EPICA Community Members, 2006).

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 For interpretation of paleodust records, a combination of measurements and modelling results can be a fruitful approach. Paleodust records can provide information about the amount, geochemical features and spatial variability of dust in source and deposition regions. The modelling approach is needed for more complete picture involving variations in atmospheric transport of dust and for coverage of places with lack of data.

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 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 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 modelling studies (transient EMIC simulation in Bauer and Ganopolski, 2010). Thus, no broad data sets of dust deposition existAlso global dust records covering these periods are rare. For the LGM however, a - good precompiled observational based data set on dust deposition is 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.

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, 115and 126) and glacial (21kyr) glacial 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 of the study is to evaluate the model ability to reproduce the dust cycle under different climate condition by comparing our results with observations and other modelling studies (if where available).

In the following sections, we first describe the modelling approach used in the study (Sect. 2). The ability of the model to reproduce the observed dust cycle in pre-industrial period is shown examined in Sect. 3. Model results and discussion for paleoclimate conditions are the subjects of Sect. 4, in which global and Southern Hemisphere dust emissions are analyzed (Sects. 4.1 and 4.2). Section 4.3 shows the simulated dust deposition with focus on Antarctica for different paleo periods. Comparison of modelled and observed dust deposition fluxes for past interglacial and glacial climate conditions is discussed in Sect. 4.4. The contribution of different processes to dust deposition in Antarctica with emphasis on atmospheric transport efficiency and precipitation is analyzed in Sect. 4.5. Section 5 concludes the main findings of this study.

2 Methods

2.1 Model description

The global aerosol-climate model ECHAM5-HAM (Stier et al., 2005) is used in the current study. The model resolution we use is T31L19, which corresponds to a horizontal resolution of approximately $3.75^{\circ} \times 3.75^{\circ}$ and 19 vertical hybrid sigma-pressure levels in the atmosphere (see Table 4 in Roeckner et al. (2006) for details). The aerosol species treated in the model are mineral dust, sulfate, black carbon, organic carbon and sea salt. We focus here on the analysis of the mineral dust cycle. For a detailed description of the model as well as other aerosol species, see Stier et al. (2005). ~~Dust~~ Emitted dust aerosol is represented by two ~~classes, accumulation and coarse modes~~ modes, accumulation mode (with $0.05 < r$ (μm) ≤ 0.5) and coarse mode (with $0.5 < r$ (μm)) with mass-median radii of 0.37 (μm) and 1.75 (μm) and standard deviations of 1.59 and 2.00, respectively. Prognostic variables are aerosol mass and aerosol particle number concentrations for each mode. Emission of mineral dust is calculated online, based on the scheme of Tegen et al. (2002). Dust source regions are arid and semi-arid areas with sparse or no vegetation. The strength of the aeolian emissions depends on surface wind velocity, soil moisture and texture, and snow cover (e.g. Marticorena and Bergametti, 1995; Mahowald et al., 2005). Emissions can take place, when the wind speed reaches a certain threshold friction velocity (Marticorena and Bergametti, 1995). For wind speeds that exceed this threshold, the dust flux is calculated following Tegen et al. (2002). Several soil types (Zobler, 1986) are used in the model. Each soil type is represented by different percentage of soil populations which are characterized by different particle size distribution. Influence of the soil moisture of each soil type on the wind erosion threshold is defined according to Fecan et al. (1999). Aerosol transport is calculated according to Stier et al. (2005).

Sink processes of dust are dry deposition, sedimentation and wet deposition. In this study new changes in wet deposition scheme have been introduced following Verheggen et al. (2007). Scavenging parameter for the mixed and liquid phase clouds parameterization was changed due to a decrease of activated fraction of aerosol particles with increasing cloud ice mass fraction and with decreasing temperature from 0 to $-25\,^{\circ}$C.

2.2 Experimental setup

Vegetation plays an important role in dust modelling because its distribution determines the areas that are potential dust source regions. Present-day and paleoclimatic vegetation conditions were obtained from simulations with the dynamic vegetation model LPJ-GUESS (Smith et al., 2001).

The vegetation model LPJ-GUESS was forced with monthly mean temperature, precipitation and shortwave radiation, obtained from paleoclimate simulations with a coupled climate model (Mikolajewicz et al., 2007), and uses a T31 spatial resolution. The potential dust source regions are defined as regions with annual maximum grass and shrub cover fraction less than or equal to 25 % (modified from Tegen et al., 2002) and shown as light green areas in Fig. 1. The maximum of vegetation cover was used in 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. We applied additional adjustment to the mid-Holocene case due to too high emissions from one particular grid box in South American source and as a consequence overestimated dust deposition in Antarctica. Thus, in order to get reasonable results and better agreement with observations, we suppressed emissions from this grid box and repeated the simulation. Also the vegetation cover in this grid box is almost 25 % which is close to the limit for the definition of potential dust source regions. Hereafter in the text we will refer to this simulation as 6 kyr.

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 $-0.07\,^{\circ}\mathrm{C}$ in 6 kyr, by $-0.08\,^{\circ}\mathrm{C}$ in 115 kyr, by $-0.13\,^{\circ}\mathrm{C}$ in 126 kyr and by $-2.7\,^{\circ}\mathrm{C}$ 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~~ ability of the model, using a 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~~ the 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. Huneeus et al., 2011).

~~Simulated~~ The 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 maximum 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 $\mathrm{Tg\,yr^{-1}}$. 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 $\mathrm{Tg\,yr^{-1}}$ (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 $\mathrm{Tg\,yr^{-1}}$, 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~~

In the model simulation wet deposition is the dominant sink process of ~~mineral dust in Antarcticais wet deposition~~dust over Antarctica, which is ~~in agreement with observational based estimates made for coastal sites in Antarctica . However, the model overestimates wet deposition in the interior of Antarctica, similar to other modelling study by~~ similar to the modelling study of Albani et al. (2012). ~~Observations~~ However, observations in high-latitude polar regions at inland sites suggest dry deposition as the dominant sink process (e.g. Legrand and Mayewski, 1997; De Angelis et al., 1997) ~~. Comparison of modelled and observed~~ and wet deposition can be a major sink process for the coastal Antarctic sites (e.g. Wolff et al., 1998). Modelled snow accumulation in ~~the Antarctic interior sitesshows that the model overestimates precipitation over the Antarctic inland by a~~ Antarctic sites, and thus processes responsible for wet deposition, are overestimated by a factor of about 1.5–2.5~~which is the cause for the high contribution of wet deposition~~.

In the next section we will discuss paleo time-slice simulations relative to pre-industrial results.

4 Model results and discussion for paleoclimate conditions

4.1 Global dust emissions

Global dust emissions are higher by 27 %, 23 % and 55 % for 6 kyr, 115 kyr and 126 kyr respectively and by a factor of 2 for the LGM compared to the CTRL simulation (Table 2). The changes are mainly due to strengthening of the Northern Hemisphere dust sources. In 126 kyr (less pronounced in 6 kyr) the increase of total emissions is mainly attributed to the Ustyurt Plateau source (Central Asia). In 115 kyr the increase of emissions is largest in Sahara due to the weakening of African summer monsoons and as a consequence an extension of the Saharan dust source . Simulated (Fig. 1). The simulated enlargement of emissions in the glacial period is consistent with other modelling studies (e.g. Werner et al., 2002). Mahowald et al. (2006) reported an increase in LGM dust emissions from 2.2 times current climate to 3.3 after including the glaciogenic dust sources (generated by continental ice sheets) in the LGM simulation.

4.2 Southern Hemisphere dust emissions

Southern Hemisphere dust emissions are dominated by the Australian dust source in all interglacial simulations (Fig. 3). In the LGM, the southern South American dust source is of equal importance to the Australian one. Note that we did not include glaciogenic dust sources in the LGM simulation, one of which is located in South America, Pampas region (Mahowald et al., 2006).

For both Australian emissions in 6 kyr and 126 kyr , Australian emissions are higher are higher compared to the CTRL simulation by a factor of 1.9 and 1.8 compared to the CTRL simulationrespectively. 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~~ drier soil combined with an almost unchanged ~~distribution of wind speed compared to CTRL results in emissions similar to~~ wind speed distribution effectively cancels out the effect of the reduced source area previously noted, resulting in an emission flux similar to that in 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. This is due to very strong dust emissions from one particular grid box (Fig. 3, 6, ~ 35 S, 65W) 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.

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 $14 \pm 1\,\%$ of dust removal.

Simulated dust deposition over Antarctica is higher by a factor of ~~3.8~~ 2.8 and 2.7 in 6 kyr ~~, by a factor of 2.7 in~~ and 126 kyr respectively, 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~~The relative contribution of dry deposition in Antarctica at LGM is increased, but the model still overestimates wet deposition in that region. Modelled glacial snow accumulation in Antarctic sites is higher compared to observations by a factor of about 1.2–2, which is similar to the overestimation of precipitation in the pre-industrial period.

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.

4.4 Model results versus observations: dust deposition in paleoclimate conditions

4.4.1 Last Glacial Maximum

To compare model results with observations the DIRTMAP database (Kohfeld and Harrison, 2001) was used. The absolute magnitude of the observed (circles) and modelled LGM dust deposition rates are shown in Fig. 5 (top). Both dust deposition records and modelled data at the LGM show deposition fluxes that are generally higher than in the current climate. A scatter plot of the observed versus modelled dust fluxes (Fig. 5, bottom) for the LGM shows that the model is able to capture the high- and low-deposition regions. The correlation coefficient of the natural logarithm of the observed and modelled values for the LGM is 0.81. The model overestimates observed deposition flux on the coasts of Greenland and slightly underestimates it at an inland site. The model is in good agreement with observations in western Antarcticafrom Byrd station (western Antarctica). On the East Antarctic Plateau the model underestimates LGM dust deposition by a factor of about 4–5.

Observational studies indicate uniform South American origin of LGM dust on the East Antarctic plateau. This would suggest that the model underestimates the LGM dust source in South America.

4.4.2 Interglacial time periods

There are not many data sets of dust records existing which cover the considered time periods. Moreover comparison of the model results against observations for 6 kyr period is a nontrivial task because many of the available records represent the average for the Holocene (0–10 kyr) and assume that these data represent the current climate. However some continuous measurements from ice cores and marine cores can be found in the literature. To compare modelled results with observations for the past interglacial periods the ice core records in Antarctica were used. These are Vostok (78°28′ S, 106°50′ E) (Petit et al., 1999), EPICA Dome C (EDC, 75°06′ S, 123°21′ E) and (Lambert et al., 2012), EPICA Dronning Maud Land (EDML, 75°00′ S, 00°04′ E) (A. Wegner, personal communication, 2010) . Locations of the sites and Talos Dome ice core (TALDICE, 72°70′ S, 159°11′ E) (Schupbach et al., 2013). The sites locations are shown in Fig. ?? (right)6.

The records of dust mass concentration from the ice coresdeposition flux, as mean values for the intervals 6 ± 1 kyr, 115 ± 1 kyr and 126 ± 1 kyr relative to the values averaged for the period 0–4.5 kyr (or shorter period within this interval) from corresponding ice cores, are shown in Fig. ?? (left)7. The observations show a general increase of dust ~~concentration in the ice~~ deposition for the past interglacial intervals compared to pre-industrial values, with maximal increase in 126 kyr. The model results are ~~in general agreement with the observations, with exceptions for overestimated~~ close to the observed values in some cases, but can differ by a factor of up to 3 in others. Overestimated 6 kyr to pre-industrial ratios ~~which~~ are likely due to too high emissions from ~~the South American and Australian sources~~Australian source in 6 kyr. The underestimation in Vostok in 115 kyr and 126 kyr could be a consequence of the underestimated South American dust source. Very strong emissions from the Australian source in 6 kyr and 126 kyr causes an overestimation of the dust deposition at EDC site in these time slices.

4.5 Contribution of different processes to dust deposition in Antarctica

As mentioned before, dust deposition in Antarctica is nonlinearly related to a number of factors such as Southern Hemisphere dust emissions, atmospheric transport and the hydrological cycle. Figure 8a demonstrates that simulated Southern Hemisphere dust emissions with a seasonal maximum in austral summer (DJF) and spring (SON) under interglacial and glacial climate conditions can only partly explain the relative amount and seasonality of dust deposition in Antarctica (Fig. 8b). The main focus of this section is to analyze the contribution of the aforementioned processes to dust deposition in Antarctica in different climate conditions by using a modelling approach. With this goal, an analysis method has been developed that describes emission of dust in the Southern Hemisphere, its poleward transport, loss due to precipitation over the ocean south of 40° S and final deposition in Antarctica (Fig. 8). Using this method we made an attempt to qualitatively explain seasonal variations of dust deposition between time-slices as well as differences between time-slices.

4.5.1 Atmospheric transport efficiency

One of the possibilities to describe ~~the~~ atmospheric transport is by means of air mass trajectories. ~~The air~~ 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~~ that originated over the Southern Hemisphere dust sources at the pressure levels of 800 hPa and 500 hPa and ~~reaching~~ reached 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~~ have therefore 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~~ South American, Australian and South African dust sources at 500 hPa and ~~reaching Antarctica~~ 800 hPa and reaching Antarctica within 10 days for the CTRL simulation is shown in Fig. ~~??~~9.

~~For~~ Based on the number of trajectories that reach Antarctica, we derived transport efficiency. Our simulations show that low level transport from Australia is more efficient than from South America. In 500 hPa, the picture is opposite, trajectories that originate over South America are more frequent than those originating over Australia. This is similar for all considered interglacial time slices. Delmonte et al. (2007) suggested a mixture of Australian and South American dust as the most probable sources for dust deposition in Antarctica in the Holocene and Eemian. However they note that this hypothesis needs further investigation. At the LGM, both, low- and middle atmosphere transport from South America is more efficient than from Australia.

In general, 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 (Fig. 8c). The poleward atmospheric transport for all considered time-slices is more active in austral winter (JJA) and minimal in summer (DJF) (Fig. 8c), similar to the results from Krinner et al. (2010), who compared model results for LGM and present day. This implies that seasonality of Southern Hemisphere dust mobilization and atmospheric transport towards Antarctica are out of phase.

Regarding dust deposition in Antarctica, the transport strength is most important for the seasons with largest Southern Hemisphere dust emissions (SON and DJF). Analysis shows a slight increase of poleward transport in the corresponding seasons in 6 kyr and 126 kyr. The increase is attributed to the southward deflection of the transport pathway over the Weddell Sea in 6 kyr and over the Ross Sea region in 126 kyr (Fig. 10). Our results suggest slightly more active atmospheric transport in 115 kyr compared to other interglacial time-slices which is in agreement with the modelling study by Krinner and Genthon (2003) for present and 115 kyr. According to our model results this can be explained by somewhat enhanced cyclonic activity in most of the seasons (not shown). This seems to be consistent with the ice core data (Petit et al., 1999; Wolff et al., 2006) which show an increase of sea salt concentration at 115 kyr, as an indicator of greater cyclonic activity at over the open ocean (Petit and Delmonte, 2009). The slight strengthening of the atmospheric transport in 115 kyr results only in a moderate increase of dust concentration in Antarctica compared to pre-industrial according to the model.

The poleward transport for both, the low- and middle atmosphere is found to be more efficient at the LGM (by about factor of 2 compared to pre-industrial), in particular in austral summer. The strengthened low-level transport is consistent with findings from Krinner and Genthon (2003) who indicated a more frequent fast low-level tracer advection towards Antarctica as a consequence of the more vigorous meridional eddy transport and of the increased vertical atmospheric stability during the LGM. However, contrary to our study, they suggested a lower fraction of tracers advected via the upper-level pathways in the LGM than in present. A possible reason for this disagreement could be related to different trajectory analysis. Krinner and Genthon (2003) considered the tracers originating above 400 hPa over the Southern Ocean between 50 and 70° S in contrast with our trajectories that originate above the Southern Hemisphere dust sources (~ 20–50° 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. 10). 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 40–70° 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) suggests slightly more trajectories originating over a single unit of South American dust source then over Australia. Analysis for 6and 126shows slightly higher number of Australian trajectories rather then South

American trajectories. 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 .

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. 8d). This gives some idea about both, how much dust is emitted and how often dust is transported to Antarctica. However these factors alone cannot explain the modelled dust deposition changes (Fig. 8b).

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 weaker compared to the pre-industrial time-slice (Figs. 11 and 8e). This favours the increase of dust deposition in Antarctica in glacial periods. Moreover, LGM precipitation over Antarctica is approximately one half of half the pre-industrial precipitation, which alone leads to about doubling of the dust concentration in ice (not shown).

Seasonal The seasonal influence of precipitation can be seen in MAM (Fig. 8e). 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. 8b). 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 analyzed 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.

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 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~~ deposition flux compared to pre-industrial values. ~~Simulations show general agreement with the measurements, with exceptions for the overestimated 6to pre-industrial ratios. For a complete comparison more observational records would be needed~~The model results are close to the observed values in some cases, but can differ by a factor of up to 3 in others. The model is very sensitive to vegetation cover and thus it is the main source of uncertainties in our study.

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 , and Eemian dust deposition is increased by a factor of 3.8, and in the Eemian by a factor of 2.8 and 2.7 respectively. Approximately two 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 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 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 DJF 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 that Australia is possible the dominant source of dust in Antarctica in 6and 126and we suggest mixture of South American and Australian sources for dust deposition in Antarctica in pre-industrial and 115.

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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_2O, [ppm]	0.27	0.27	0.20	0.27	0.27

Table 2. Global mass budget for different climate conditions.

	CTRL	6 kyr	115 kyr	126 kyr	LGM
Emissions, [Tg yr^{-1}]					
Total	1540	~~1951~~ 1961	1898	2385	3106
NH	1478	~~1795~~ 1845	1834	2273	946
SH	62	~~157~~ 117	65	112	160
Australia	60	~~109~~ 115	63	110	84
Southern America	1	~~47~~ 1.1	1.2	1.2	75
Southern Africa	1.2	~~1.1~~ 0.9	1.1	0.8	1.6
Deposition, [Tg yr^{-1}]					
Total dep.	1539	~~1952~~ 1959	1896	2376	3119
Wet dep.	643	~~811~~ 828	790	1123	1293
Dry dep.	214	~~302~~ 296	239	363	456
Sedimentation	682	~~839~~ 835	867	890	1370
Deposition in Antarctica, [Tg yr^{-1}]					
Total dep.	0.053	~~0.202~~ 0.150	0.061	0.141	0.540

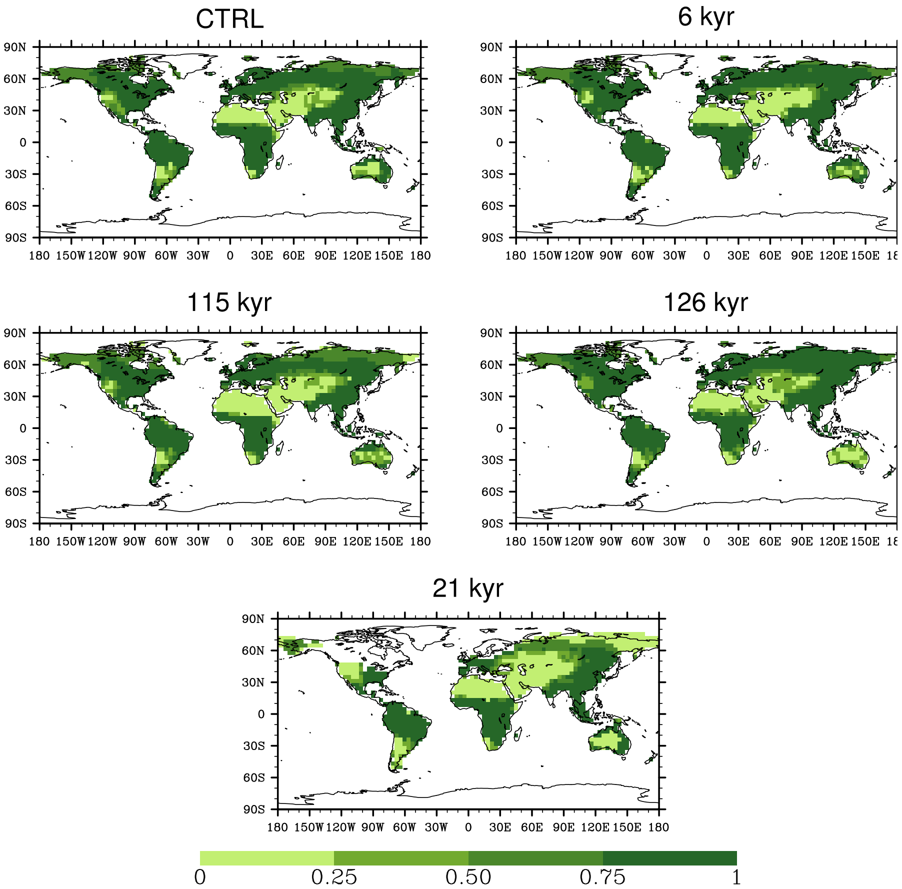

Fig. 1. Annual maximum vegetation cover fraction obtained from the LPJ-GUESS model for the CTRL, 6 kyr, 115 kyr, 126 kyr and LGM time periods. The regions with annual maximum vegetation cover less than or equal to 25 % (light green color) are defined as the potential dust source regions.

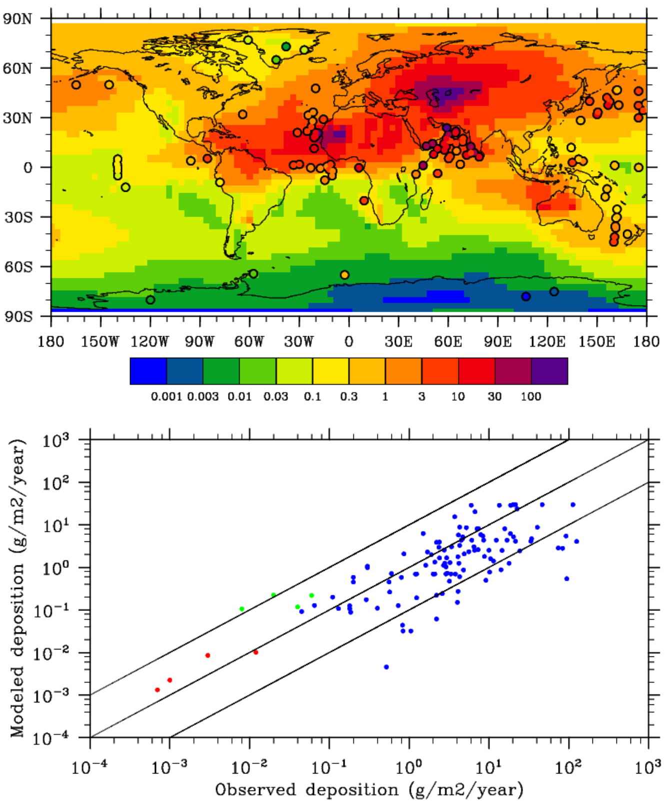

Fig. 2. Simulated dust deposition flux [$g\,m^{-2}yr^{-1}$] for the pre-industrial time-slice compared with dust deposition data compiled from ice cores, marine sediment traps and marine sediment cores [$g\,m^{-2}yr^{-1}$] (circles) and a scatter plot between the model and observations. The red color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

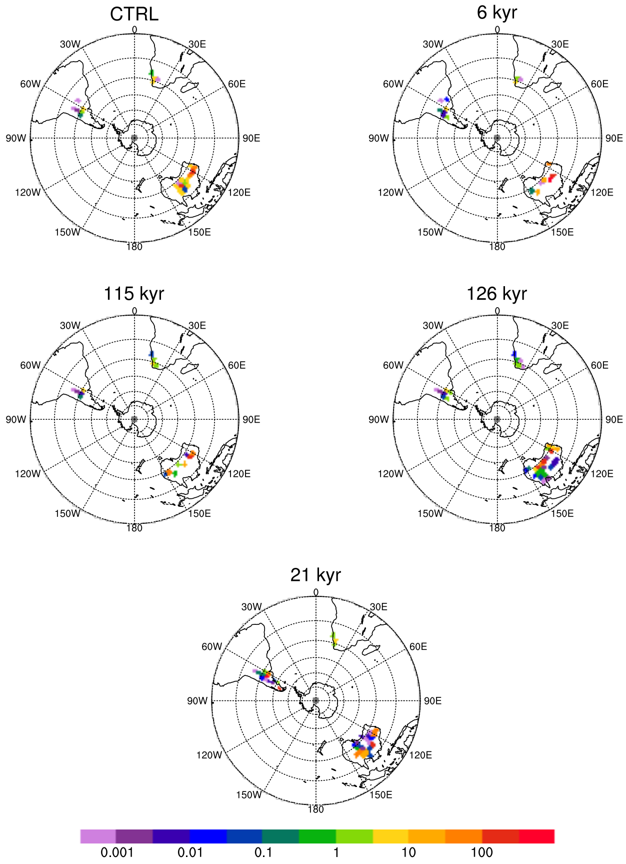

Fig. 3. Mean Southern Hemisphere dust emission flux for the CTRL, 6 kyr, 115 kyr, 126 kyr and LGM simulations, [$g\,m^{-2}\,yr^{-1}$].

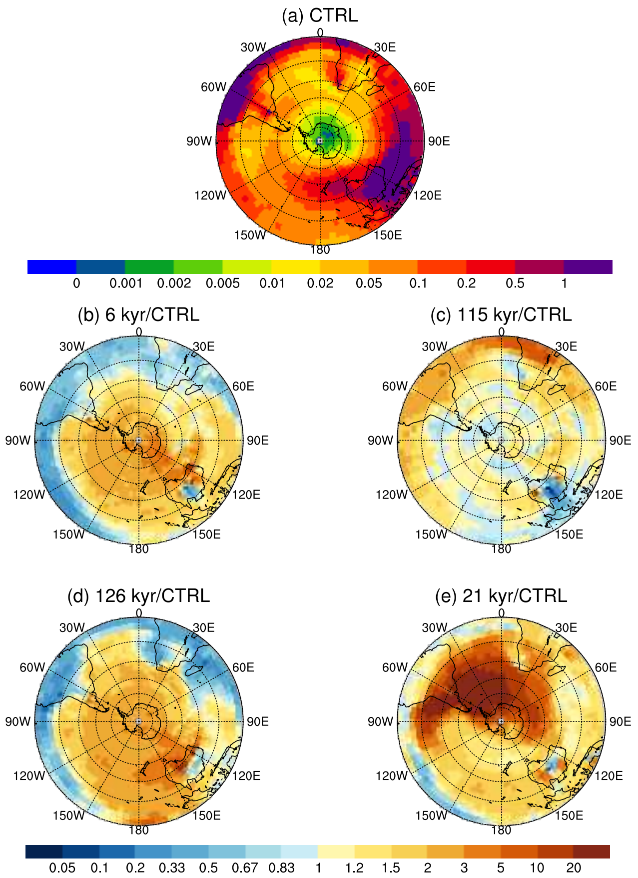

Fig. 4. Annual average dust deposition flux [$g\,m^{-2}\,yr^{-1}$] for the Southern Hemisphere for the CTRL pre-industrial simulation **(a)**. Ratio of dust deposition flux for the interglacial and glacial time-slices with respect to the CTRL pre-industrial simulation **(b–e)**.

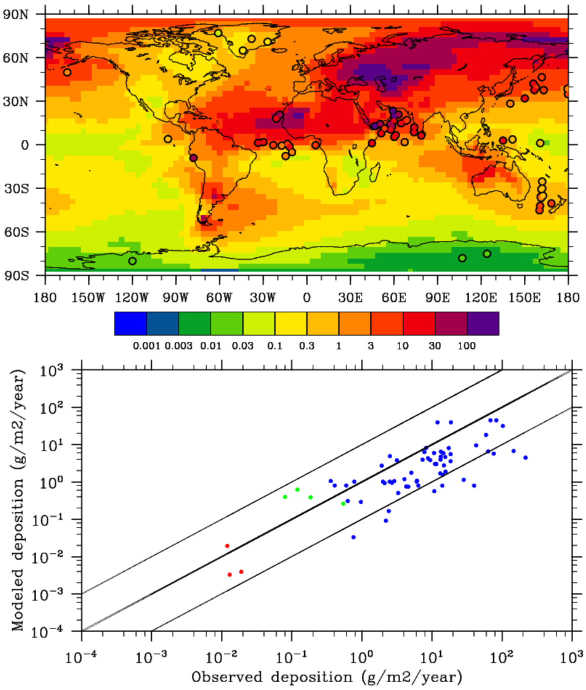

Fig. 5. Simulated dust deposition flux [$\mathrm{g\,m^{-2}yr^{-1}}$] for the LGM time-slice compared with dust deposition data compiled from ice cores, marine sediment traps and marine sediment cores [$\mathrm{g\,m^{-2}yr^{-1}}$] (circles) and a scatterplot between the model and observations. The red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

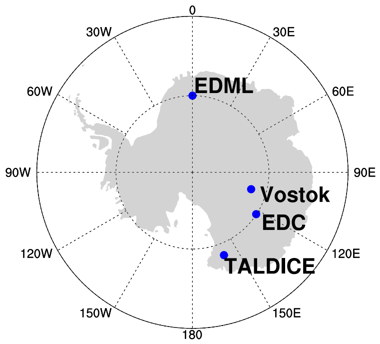

Fig. 6. ~~The ratios of dust mass concentration in the Antarctic ice for model simulations (light colors) and observations (dark colors) for 6, 115and 126with respect to pre-industrial period (left). Dust records from Vostok (shown in blue) and EDC (shown in green) ice cores were obtained by using Coulter counter. Data from EDML (shown in brown) were calculated using laser sensor.~~ Locations of the ice ~~cores~~ core sites in Antarctica~~(right)~~.

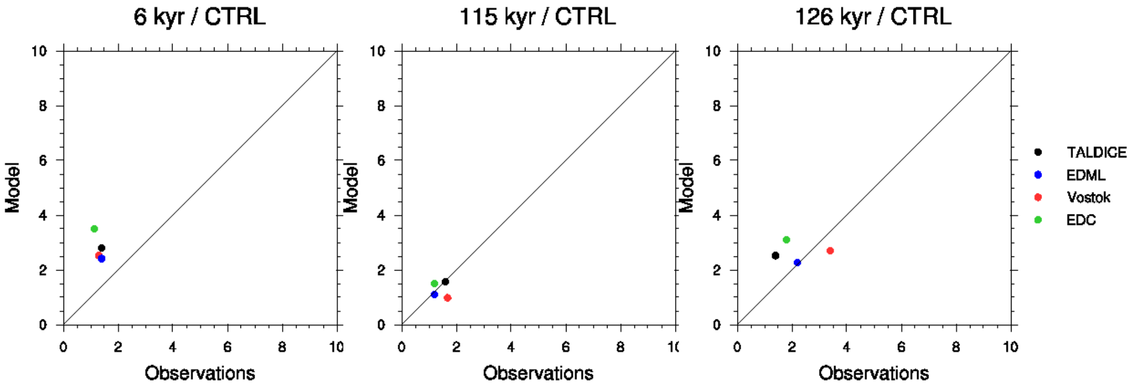

Fig. 7. Dust deposition flux ratios of 6 kyr (left), 115 kyr (central) and 126 kyr (right) to pre-industrial period from observations and model simulations. Ratios are compared for four Antarctic cites, EDC (green), Vostok (red), EDML (blue) and TALDICE (black).

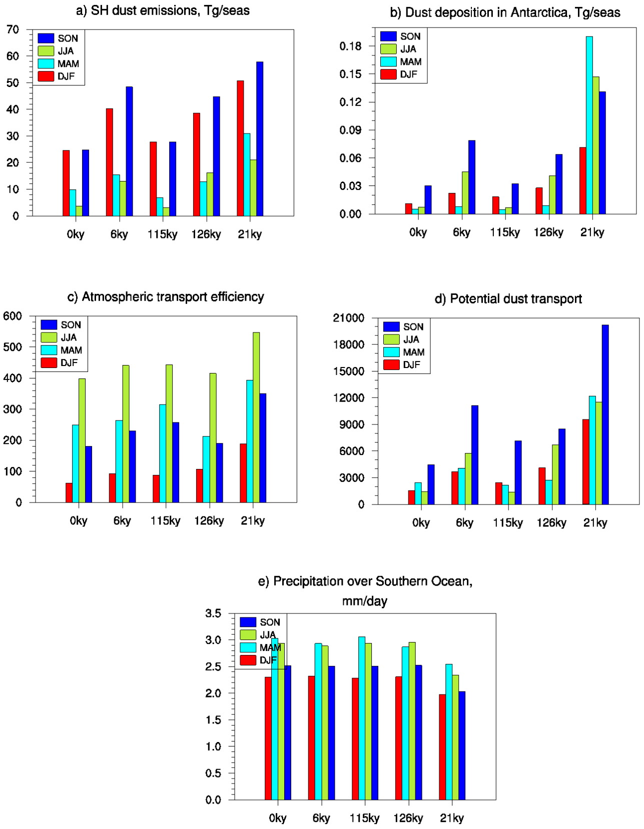

Fig. 8. **(a)** Southern Hemisphere dust emission [Tg season^{-1}], **(b)** dust deposition in Antarctica [Tg season^{-1}], **(c)** atmospheric transport efficiency [trajectories season^{-1}], **(d)** potential dust transport [arbitrary units], **(e)** precipitation over the ocean south of 40° S [mm 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.

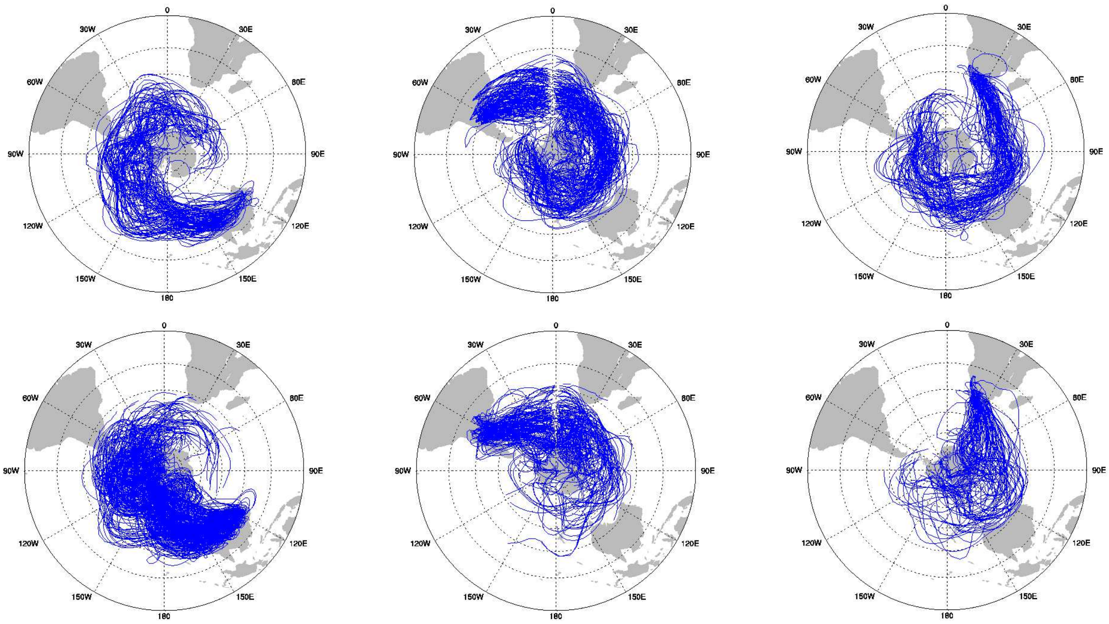

Fig. 9. Ten day forward trajectories of air masses ~~on~~ originated at 500 hPa ~~originating~~ (top) and 800 hPa (bottom). Trajectories originated over the ~~South American~~ Australian (~~blue color~~left), ~~south African~~ South American (~~green color~~central) and ~~Australian~~ south African (~~red color~~right) dust sources ~~that~~ and reached Antarctica withim 10 days. Trajectories are shown for the CTRL simulation, austral spring season (SON). Note that only every ~~10th~~ 2nd trajectory is plotted.

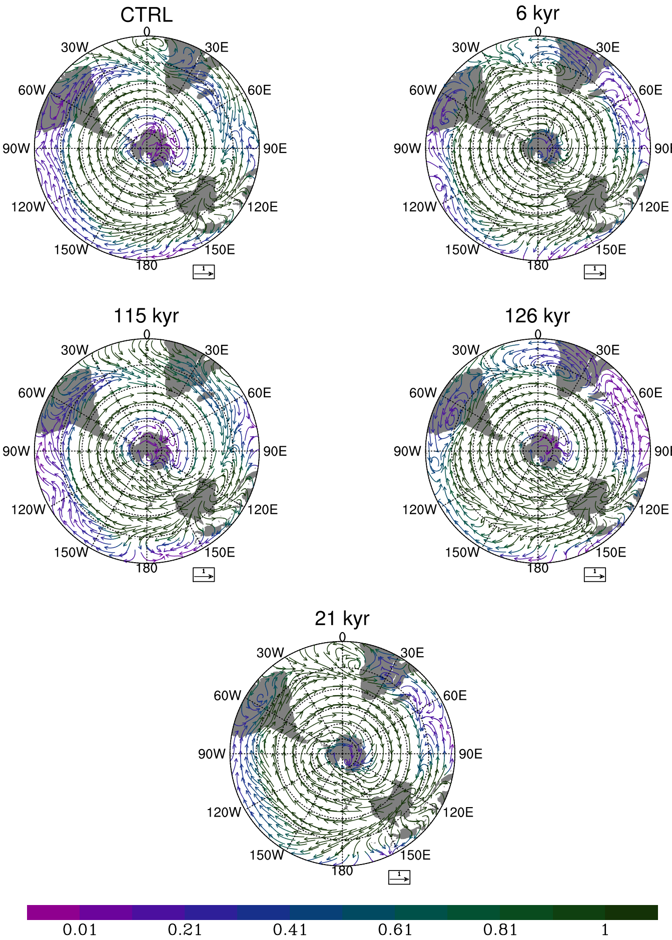

Fig. 10. Dust transport on 500 hPa calculated by using 6 hourly data, September, October, November (SON).

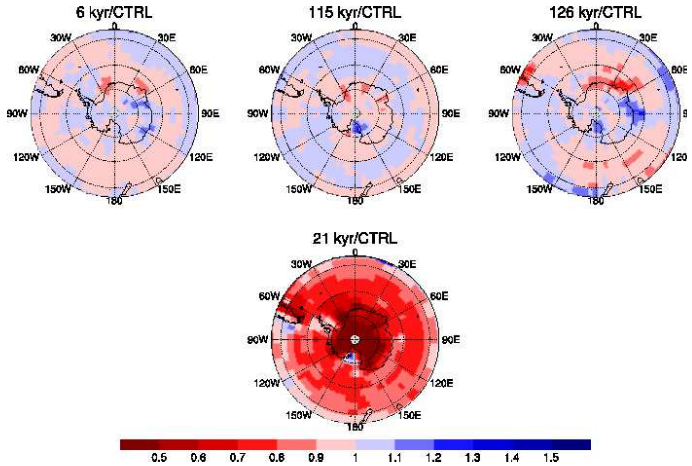

Fig. 11. Paleo to pre-industrial ratios of annual mean precipitation.