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Toward understanding the dust deposition in Antarctica during the Last Glacial Maximum: Sensitivity studies on plausible causes

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[1] Understanding the plausible causes for the observed high dust concentrations in Antarctic ice cores during the Last Glacial Maximum (LGM) is crucial for interpreting the Antarctic dust records in the past climates and could provide insights into dust variability in future climates. Using the Geophysical Fluid Dynamics Laboratory (GFDL) General Circulation Models, we conduct an investigation into the various factors modulating dust emission, transport, and deposition, with a view toward an improved quantification of the LGM dust enhancements in the Antarctic ice cores. The model simulations show that the expansion of source areas and changes in the Antarctic ice accumulation rates together can account for most of the observed increase of dust concentrations in the Vostok, Dome C, and Taylor Dome cores, but there is an overestimate of the LGM/present ratio in the case of the Byrd core. The source expansion due to the lowering of sea level yields a factor of 2–3 higher contribution than that due to the reduction of continental vegetation. The changes in other climate parameters (e.g., SH precipitation change) are estimated to be relatively less important within the context of this sensitivity study, while the model-simulated LGM surface winds yield a 20%–30% reduction rather than an increase in dust deposition in Antarctica. This research yields insights toward a fundamental understanding of the causes for the significant enhancement of the dust deposition in the Antarctic ice cores during the LGM.

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1. Introduction

[2] Mineral dust is presently one of the most abundant aerosols in the Earth's atmosphere, and its abundance was observed to be orders of magnitude higher during past glacial periods. On the basis of the dust records in ice cores, *Petit et al.* [1999] have shown that dust concentration varies nearly synchronously with temperature and atmospheric CO_2. This would suggest that dust could be a good proxy of climate change. However, it has proved to be difficult to satisfactorily explain the much greater abundance of dust during the Last Glacial Maximum (LGM, ~21,000 years BP) compared to the present.

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[3] Early studies suggested that increase of dust concentration in glacial periods was due to an expansion of dust source areas, either by desertification or exposed continental shelves [*Grousset et al.*, 1992; *de Angelis et al.*, 1992]. But later, it was suggested that dynamical factors, such as stronger circulation, were important [*Werner et al.*, 2002]. Other studies have pointed out that low precipitation during glacial period would significantly increase the dust lifetime [*Yung et al.*, 1996]. One reason for the different conclusions is that, with the exception of relatively few modeling studies [e.g., *Genthon*, 1992; *Mahowald et al.*, 1999], there has been a lack of a comprehensive description of the dust cycle in the SH. The dust cycle (emission, transport and deposition) in SH is intrinsically related to the abundance of dust in ice cores. In a previous work focusing on dust transport to Antarctica, *Li et al.* [2008] quantified the contributions from the major continental sources. They showed that dust in East Antarctica is from South America, specifically Patagonia, while dust in West Antarctica is predominantly from Australia. *Li et al.* [2010] further focused on the transport pathways of the Patagonian dust to Antarctica and the corresponding meteorological conditions giving rise to the dust transport. They found that the frequency and amount of dust

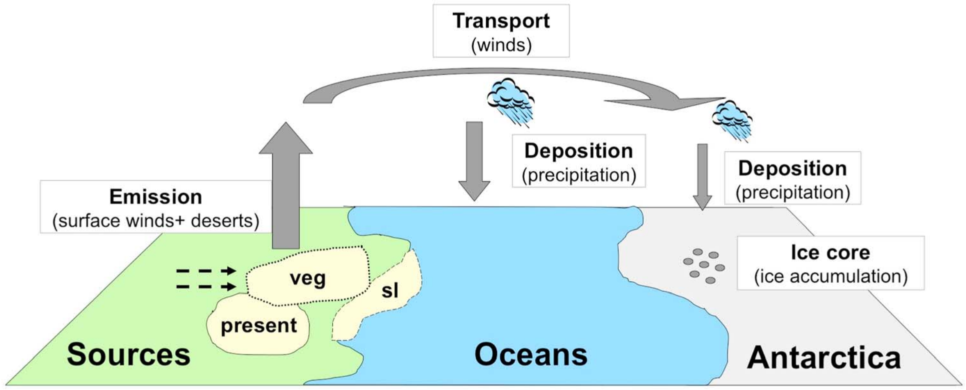

Figure 1. The journey of mineral dust from sources to Antarctic ice cores, including emission, transport, and deposition processes. Factors that affect these processes are indicated in the parentheses. "Present" denotes the present-day dust sources. "veg" and "sl" indicate additional sources due to the vegetation reduction and the lowing of the sea level during the LGM, respectively. The dashed arrows illustrate the surface winds near the dust sources.

transport to Antarctica originating from Patagonia depend on the source locations and transport pathways. They identified two main transport pathways, which depend on the position and strength of the high-pressure system over the Southern Atlantic Ocean. Their study would suggest that changes in source location and atmospheric dynamics would be key factors to understanding the dust variability in the Antarctic ice cores. However, their study did not examine the relationship between these factors and ice core measurements, which is the subject of the present study.

[4] The journey of mineral dust particles from their source to the Antarctic location of the ice cores is schematically illustrated in Figure 1. Changes of vegetation cover and sea level during LGM would affect the area acting as dust sources and, correspondingly, the dust emission. The emission of dust is also dependent on changes in surface winds. Circulation also influences the distance of dust transport, and precipitation plays an important role in regulating the deposition process. These changes together determine the changes in the amount of dust reaching Antarctica. The dust concentration in the ice cores mentioned above would depend on the amount of dust removed from the atmosphere by local precipitation and the ice accumulation rate.

[5] Previous hypotheses have focused on some of these above aspects and have therein argued for various factors being responsible for the high LGM dust concentrations. These factors are (1) enlarged dust source area during the LGM due to the reduction of continental vegetation [*Mahowald et al.*, 1999]; (2) lowering of the sea level and greater exposure of the continental shelves [*Grousset et al.*, 1992]; (3) enhancement of surface wind intensities which initiates more dust emission [*Werner et al.*, 2002] and increase in the amount of dust transported [*COHMAP Members*, 1988]; and (4) weaker precipitation during the LGM, which induces a lower wet deposition and thus results in a longer dust lifetime [*Fischer et al.*, 2007]. These are elaborated below.

[6] First, the increase of the dust fluxes in Antarctic ice cores during the LGM has been interpreted in terms of the source expansion by most studies [*Grousset et al.*, 1992; *Fischer et al.*, 2007]. Early general circulation model studies that did not consider the source expansion greatly underestimated the amount of dust deposited in Antarctica during the LGM [*Genthon*, 1992; *Tegen and Rind*, 2000]. *Anderson et al.* [1998] and *Mahowald et al.* [1999] considered the change of vegetation in their studies and obtained a considerable increase of dust deposition in the polar regions during the LGM. However, these studies did not include the additional source due to the exposed continental shelves associated with lower sea level during glacial periods. Previous estimates [e.g., *Fairbanks*, 1989], *Peltier* [1994] indicated that the sea level could be at least a hundred meters lower during the LGM. Continental shelf regions are usually dry and could be transformed into significant dust sources [*Fischer* et al., 2007]. *Grousset et al.* [1992] estimated that such dust sources would have doubled the source area in South America. However, whether this increase actually translated into more dust transported to East Antarctica is still speculative. *de Angelis et al.* [1992] suggested that ~50% of the dust in the East Antarctica ice sheet during the LGM originated from the exposed continental shelf areas. Other isotopic analyses [e.g., *Basile et al.*, 1997] have shown that the contribution from continental shelves to the dust in Dome C and Vostok ice is small, but *Delmonte et al.* [2007] further suggested that the continental shelves cannot be excluded for those studies.

[7] Second, the surface wind stress is thought to have strengthened by about 25% during the LGM [*Shin et al.*, 2003], but the character of the differences remains unclear. The strengthening of the surface winds could have influenced the dust transport to Antarctica first by increasing the emission rate, which depends on the cubic power of the surface wind speed (equation (1)), and second by enhancing the long range transport [*COHMAP Members*, 1988; *Bay et al.*, 2010]. *Werner et al.* [2002] stated that 65% of the increase in dust emissions during the LGM is caused by the increase in surface wind speed, while only 35% was due to the expansion of the dust sources. They used an interactive vegetation scheme but challenged the conclusion of *Mahowald et al.* [1999], who suggested that most of the increase was from the source expansion. Regarding the enhancement of atmospheric circulation, there has been no direct evidence on how much it could increase the amount of dust deposited in Antarctica during the LGM. Instead,

Toggweiler et al. [2006] and *Kim and Lee* [2009] argued that the westerlies over the Southern Ocean seem to be weaker and/or shift to low latitudes in cooler climates, and this shift has been seen in other PMIP2 LGM simulations [*Rojas et al.*, 2008]. The contradictions in the literature concerning GCM-simulated LGM circulation patterns over the Southern Ocean make it hard to estimate the overall dynamical effect on dust transport to Antarctica. This issue is further complicated by the fact that the transport is more likely related to the synoptic conditions prevailing during the LGM over the Southern Oceans as shown in the work of *Li et al.* [2010].

[8] The third primary hypothesis for the high dust deposition in Antarctic ice cores is less precipitation during the LGM. The reduced precipitation can be expected to increase the lifetime of dust and thus to increase the amount transported to Antarctica [*Hansson*, 1994]. *Shin et al.* [2003] indicated that the decrease of precipitation over the Southern Ocean during the LGM could be up to 0.5 mm/d relative to present-day values [*Ganopolski et al.*, 1998]. *Yung et al.* [1996] simulated an increase of atmospheric dust lifetime by a factor of 2–3 over Antarctica by reducing the washout rate, but most studies have reported that the global average atmospheric lifetime of dust due to wet deposition has not changed significantly [*Fischer et al.*, 2007]. A similar conclusion was reached by the model studies of *Mahowald et al.* [1999], who obtained a ~20% reduction of dust lifetime in LGM.

[9] Despite all the above attempts to explain the high dust concentration in Antarctic ice cores during the LGM, there is no comprehensive analysis evaluating the relative contributions from each of these processes, particularly through global model sensitivity studies. This study compares the model-simulated contributions of each of the above factors with the observed increase of dust abundance in four ice cores in Antarctica. Section 2 presents the model description and experimental design. In section 3, the effects from source expansion (3.1), circulation (3.2), and precipitation changes (3.3) are evaluated using sensitivity experiments. We then present our conclusions in section 4.

2. Model Description and Experiment Design

2.1. Model Configuration

[10] For this study, dust distribution is simulated with the GFDL Atmospheric Model AM2 [*GFDL GAMDT*, 2004] in a version including online dust and involving nudging of meteorological fields with National Centers for Environmental Prediction (NCEP) reanalysis (this version is henceforth labeled AM2.1n). The model has been fully described in the work of *Li et al.* [2008, 2010]. For all experiments, the simulations cover 20 years (1986–2005). A null concentration of dust is imposed as initial condition, and the first year is discarded as part of the model spin-up.

[11] The major difference from the previous work [*Li et al.*, 2008, 2010] is in the "present-day" vegetation map used to simulate dust emission. The dust emission flux F_p (μg s^{-1} m^{-2}) is calculated as follows,

$$\begin{array}{l} F_p = CSs_p u_{10m}^2 (u_{10m} - u_t) \quad \text{if} \quad u_{10m} > u_t \\ F_p = 0 \text{ otherwise}, \end{array} \qquad (1)$$

where C is a dimensional factor (μg s^2 m^{-5}), S is the source function determined empirically and based on topographical map over bare grounds [*Ginoux et al.*, 2001], u_{10m} (m s^{-1}) is the horizontal wind speed at 10 m, u_t (m s^{-1}) is the threshold velocity for dust emission, and s_p is the fraction of each size class.

[12] The vegetation data set previously used to locate area with bare grounds was based on satellite data [*DeFries and Townshend*, 1994] and fixed in time. This has the major disadvantage that change of bare ground with climate is not taken into account. Since we want to use a consistent method of classification of vegetation for both present-day and LGM simulations, we choose the vegetation maps compiled by *Adams and Faure* [1997] (for present climate) and *Ray and Adams* [2001] (for the LGM). These two maps are compiled with the same vegetation classification through the Quaternary Environments Network [*Adams and Faure*, 1997], based mostly on plant fossil and other proxy data. Although these two maps are a preliminary and broad-scale reconstruction, they enable a direct and consistent comparison of the present-day and LGM dust sources.

[13] Figures 2a and 2b show the distribution of different desert types defined by the two vegetation maps. In equation (1), the parameter S is a function of the fraction of bare grounds per model grid cell, which may vary between desert types. To attribute a value for a specific type of desert, we compare for present-day and over each desert type the value attributed at that location by *Ginoux et al.* [2001]. The overall locations and size of the deserts are comparable between the two. The exception is Australia, where the desert area is substantially smaller in the *Adams and Faure* [1997] data set. This smaller area results in an underestimation of present-day Australian emission (~1/3 of the Australian emission obtained in the work *Li et al.* [2008, 2010]), which may create a low bias of Australian dust in Antarctic ice cores for the present climate (discussed later).

2.2. LGM Data

[14] In this study, several LGM climate parameters affecting dust distribution (precipitation, winds, and surface wind speed) are taken from the LGM simulations performed with the GFDL coupled atmosphere-ocean model. The GCM for the LGM conditions is constructed based on the GFDL CM2.1 model [*Delworth et al.*, 2006; Delworth and Zeng, personal communication, 2009]. It has the same atmospheric model resolution and physics as in AM2.1n. The boundary conditions and atmospheric composition are altered to be consistent with the known forcings during the LGM. These include orbital parameters (eccentricity = 0.018994 and obliquity = 22.949°) and greenhouse gas concentrations (CO_2 = 185 ppm, CH_4 = 350 ppb, and N_2O = 200 ppb). The LGM boundary forcings are specified based on the PMIP2 protocol (http://pmip2.lsce.ipsl.fr). The ice sheet topography is based on ICE-5G model, provided by *Peltier* [2004]. Early in the spin-up of the CM2.1 LGM simulation, the salinity in the world ocean is uniformly and instantaneously raised by 1 practical salinity unit (PSU) to account for the impact of freshwater tied up as land ice. The model starts from modern conditions and is run for a total of 2500 years to allow time for the model to adjust to the new

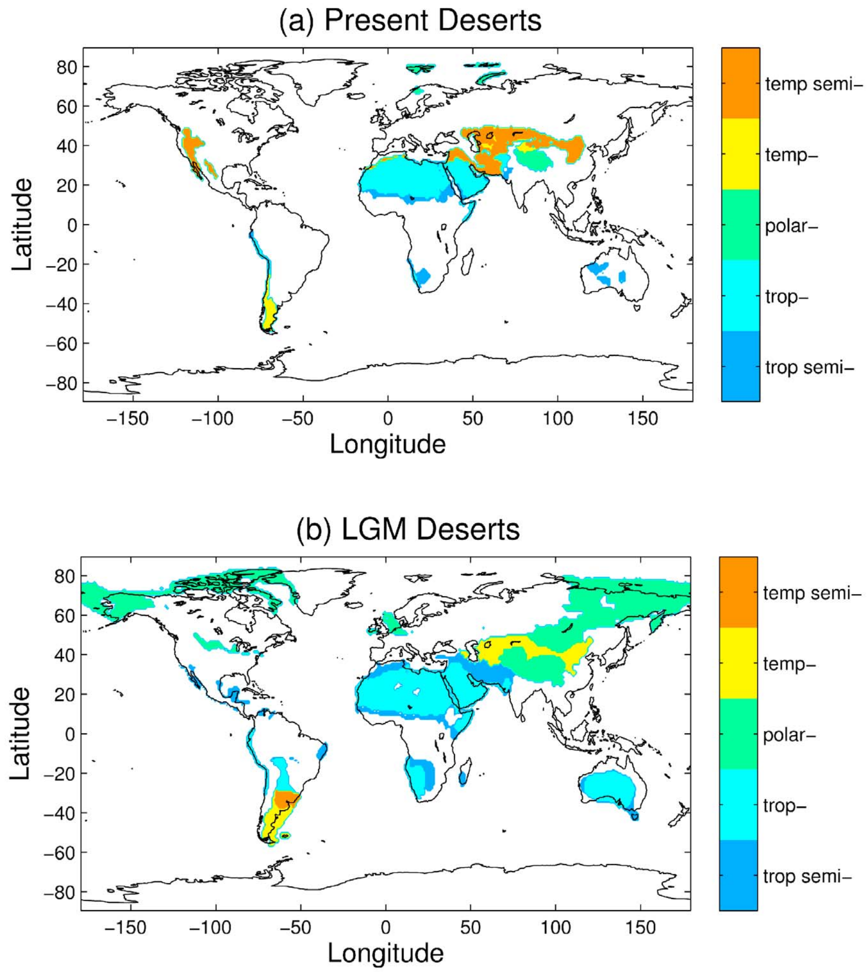

Figure 2. (a) The present-day desert classification [*Adams and Faure*, 1997]. (b) The LGM desert classification [*Ray and Adams*, 2001]. The two vegetation maps are compiled with the same vegetation classification, and only the deserts are shown: temperate semidesert (temp semi-), temperate desert (temp-), polar and alpine desert (polar-), tropical extreme desert (trop-), and tropical semidesert (trop semi-).

forcings. The last 20 years of integration are used for the applications in the present study.

2.3. Ice Accumulation Rate

[15] The dust concentration in the ice cores is given in units of mass of dust per mass of ice (g g^{-1}) [e.g., *Petit et al.*, 1999]. To allow comparison with the ice core data, the simulated total dust deposition flux (kg m^{-2} yr^{-1}) to Antarctic ice is converted to concentration using the following formula,

$$\text{Concentration} = \frac{\text{total deposition flux}}{\text{ice accumulation rate}}. \tag{2}$$

In this study, the ice accumulation rate (kg m^{-2} yr^{-1}) for present-day and LGM is equal to the accumulated snowfall calculated by CM2.1 for present-day and LGM conditions, respectively. The total dust deposition consists of dry and wet deposition, and dry deposition dominates in inland Antarctica (section 3.3.2).

[16] Table 1 shows the simulated and observed [*Lorius*, 1989] ice accumulation rates at four Antarctic ice cores viz., Vostok (78°S, 107°E), Dome C (75°S, 123°E), Taylor Dome (77°S, 158°E), and Byrd (80°S, 120°W). The simulated present-day ice accumulation rates are underestimated by ~30% at Vostok and Dome C and overestimated by ~45% at Byrd. Previous studies estimated that the LGM ice accumulation rate was 25% [*Fischer et al.*, 2007] to 50% [*Lorius*, 1989] of the present-day rates over Antarctica. The simulated

Table 1. The Simulated and Observed Ice Accumulation Rates (kg m^{-2} yr^{-1}) at Four Antarctic Ice Cores[a]

Precipitation		Vostok	Dome C	Taylor Dome	Byrd
Present	model	16.1	22.5	47.4	233.5
	observations	23	34	–	160
LGM	model	3.6	8.1	20.4	104.8
	¼–½ of present	4.0–8.1	5.6–11.2	11.9–23.7	58.4–116.8

[a]The present-day observations are obtained from *Lorius* [1989]. The LGM precipitations estimates follow *Fischer et al.* [2007] (25% of the present-day values) and *Lorius* [1989] (50% of the present-day rates).

Table 2. LGM Sensitivity Experiments Related to the Different Source Components Considered in This Study

Source Components	Sensitivity Experiments
Present-day source	"Sp"
Source due to vegetation reduction	"Sveg"-"Sp"
Source due to lower sea level	"Ssl"-"Sp"
LGM source	"SLGM" (overall effect of the above three components)

LGM ice accumulation rates are generally within this range. Although there are uncertainties in the simulation of precipitation during the LGM [*Gates et al.*, 1996], the values in Table 1 provide a reasonable basis for comparing the model-derived concentration with the Antarctic ice core records.

2.4. Design of the Sensitivity Experiments

[17] The hypotheses proposed to explain high dust concentration in Antarctica during the LGM, and described in section 1 are (1) source area increase due to reduction in continental vegetation cover; (2) source area increase due to lowering of the sea level; (3) change of dust emission due to surface wind speed; (4) stronger general circulation leading to enhancement in transport; and (5) weaker precipitation over the Southern Ocean resulting in weaker dust removal and consequently more transport to Antarctica. We also consider the changes in local precipitation, which directly affects the ice accumulation rates and thus the concentration in the ice cores.

[18] In order to evaluate the above processes, we perform sensitivity experiments by replacing the corresponding parameters in the control experiment. These sensitivity experiments are as follows:

[19] 1. Control experiment "Sp." The control experiment is the AM2.1n simulation covering the period 1986–2005. It represents the dust cycle under present-day climatic conditions with present-day vegetation [*Adams and Faure*, 1997] and present-day sea level.

[20] 2. Experiment "Sveg." In this experiment, we replace the present-day vegetation of the control experiment with the LGM vegetation [*Ray and Adams*, 2001]. All the other parameters remain unchanged from present-day conditions including sea level. This experiment targets the individual contribution of increased desertification during the LGM. The increase of dust source due to the LGM vegetation reduction is thus equal to "Sveg" minus "Sp" (Table 2).

[21] 3. Experiment "Ssl." This experiment is similar to "Sp" except for that the sea level corresponds to LGM, allowing us to quantify the effect of the lower sea level during the LGM (Table 2). A large area of continental shelves was exposed to wind erosion due to this sea level change and thus served as potential dust sources. The vegetation cover types on these continental shelves are also adapted from *Ray and Adams* [2001], but elsewhere are taken from the present-day conditions. The increase of dust source due to the lower sea level is thus equal to "Ssl" minus "Sp" (Table 2).

[22] 4. Experiment "SLGM." This experiment is also based on "Sp" except that the vegetation and sea level correspond to LGM conditions. This experiment is equal to the combined effects of "Sp," ("Sveg"-"Sp"), and ("Ssl"-"Sp") (Table 2).

[23] 5. Experiment "Cemis." This experiment is similar to "Sp," but the emission scheme is driven by the LGM 10 m wind speed ($u_{10\mathrm{m}}$) (refer equation (1)) to investigate its effects in explaining the increase of dust concentration in Antarctic ice cores.

[24] 6. Experiment "Ptrans." This experiment is similar to "Sp" but the scavenging of dust particles below-cloud is reduced. The below-cloud scavenging coefficient (Γ) is proportional to the precipitation flux,

$$\Gamma = -\frac{3}{4}\left(\frac{P_{\mathrm{rain}} \times \alpha_{\mathrm{rain}}}{R_{\mathrm{rain}} \times \rho_{\mathrm{H2O}}} + \frac{P_{\mathrm{snow}} \times \alpha_{\mathrm{snow}}}{R_{\mathrm{snow}} \times \rho_{\mathrm{snow}}}\right), \tag{3}$$

where P_{rain} and P_{snow} are the precipitation fluxes (kg m^{-2} s^{-1}) as defined in the model, α is the efficiency with which aerosols are collected by raindrop and snow, with α_{rain} = 0.001 and α_{snow} = 0.001. Thus, instead of directly reducing the rain and snow flux for the desired objective, we reduce the scavenging efficiency factors by 50%, which yields the largest possible (in this study) precipitation reduction over Southern Ocean during the LGM. This has the effect of scaling down the wet removal of dust in an attempt to mimic LGM conditions. Although this is a crude approximation, it avoids the need to run interactively a LGM dust simulation with a fully coupled atmosphere-ocean GCM. Nevertheless, it does provide insights into the zeroth-order sensitivity. We run the model for 20 years and analyze how the dust deposition is changed due to this LGM-prescribed versus present-day dust removal efficiency.

[25] For all experiments, we use the precipitation from the LGM simulations by the GFDL CM2.1 model (refer section 2.2) to estimate the ice accumulation rate (due to precipitation) and thus the local removal of dust. This yields the LGM concentration in the ice cores (refer equation (2)).

[26] The effects of some of the processes discussed in section 1 cannot be quantified through a sensitivity experiment in the model framework used for the analysis here, such as the singular effect of the changes in general circulation. This is because the change in the wind fields will also change the climatological fields such as precipitation and surface winds. As shown in the work of *Li et al.* [2010], the transport of dust is determined by the synoptic conditions over the Southern Ocean. Information on this aspect is crucial for a more in-depth analysis of the LGM conditions, which are currently unavailable from the CM2.1 simulations. This complexity is beyond the scope of current study. However, we do compare the present and LGM wind fields to qualitatively evaluate if mean wind flows can play a significant role in the dust deposition changes in Antarctica between present-day and LGM.

3. Results

[27] Figure 3a shows the control simulation "Sp" with the dust emission corresponding to present-day vegetation cover, sea level, and climatic conditions. We only show the emission in the SH sources, since it is the SH dust sources that contribute to most of (>90%) of the dust deposited in Antarctica [*Li et al.*, 2008]. The total emission in the three SH continents is 104 Tg yr^{-1}, with 52 Tg yr^{-1} from South America, 29 Tg yr^{-1} from Australia, and 23 Tg yr^{-1} from South Africa (Table 4). Compared with the

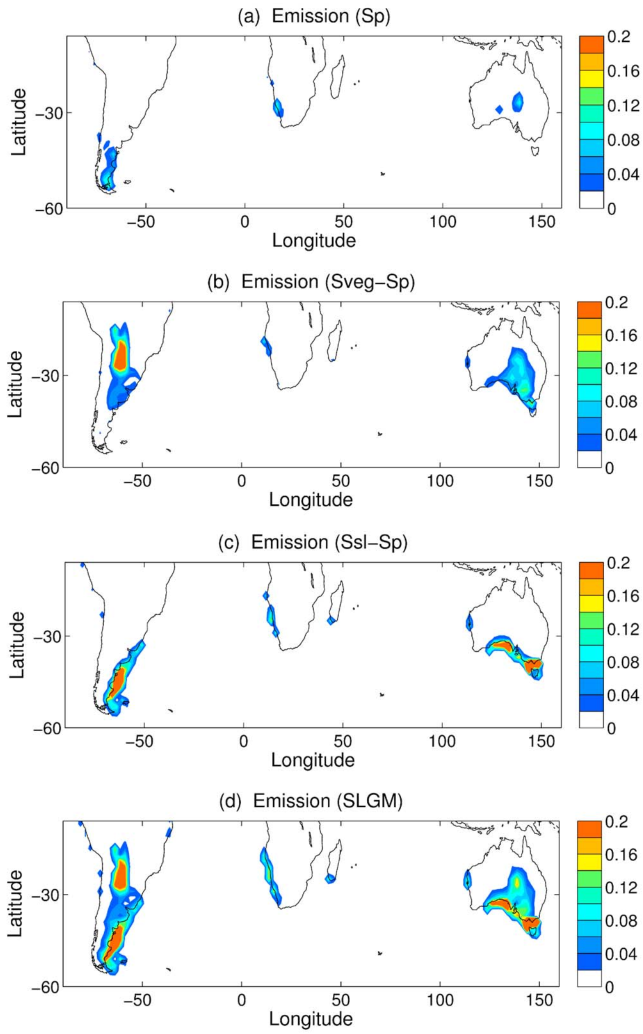

Figure 3. Dust emission (kg m^{-2} yr^{-1}) in the SH from (a) present-day sources (control run "Sp"), (b) increase in the source due to LGM vegetation reduction ("Sveg-Sp"), (c) increase in the source due to the lowering of the sea level ("Ssl-Sp"), and (d) total LGM sources (SLGM).

previous estimates (Table 1) using a satellite-based vegetation map [*Defries and Townshend*, 1994], the dust emissions are comparable in South America and South Africa, but significantly lower in Australia (~1/4 of the previous estimate). This is due to the lower estimation of the desert area in Australia with the *Ray and Adams* [2001] vegetation map.

[28] The present-day dust concentration from the control run is shown in Table 3 with the observed present-day values from the ice core records at Vostok, Dome C, and Byrd cores and the present-day dust deposition flux at Taylor Dome. The control experiment essentially got the order of magnitudes right compared with observations, although there are still significant biases. The experiment overestimates the values in Vostok, Dome C, and Taylor Dome by a factor of 2–3, compared with the observations, but underestimates the dust concentration at Byrd by a factor of 3, very likely attributable to the underestimates of the dust source area in the present-day vegetation mask [*Adams and Faure*, 1997].

Table 3. Present-Day Dust Concentrations and Fluxes at the Four Antarctic Ice Cores[a]

	Vostok	Dome C	Taylor Dome	Byrd
Model	75	49	1.6	6
Observations	30 (±14)	21 (±13)	0.5–0.7 (1)	19 (2)

[a]The units are ng g^{-1} for the dust concentrations at Vostok, Dome C, and Byrd, and kgm^{-2}yr^{-1} for the dust deposition flux at Taylor Dome. The observed concentrations at Vostok and Dome C are calculated using the data from *Petit et al.* [1999] and *Lambert et al.* [2008], respectively. The present-day dust concentrations at the above two cores are estimated from the most recent 5000 years with observational data coverage. The LGM is taken as ~22,000 to 19,000 years B.P. [*Yokoyama et al.*, 2000]. The values at the two other cores are from (1) *Morse et al.* [2000] and (2) *Cragin et al.* [1977].

3.1. Source Effects

[29] In this section, we analyze the experiments "Sveg," "Ssl," and "SLGM" (Table 2) to quantify the effects of the source expansion during the LGM.

3.1.1. Experiment "Sveg"

[30] During the LGM, most of the tropics and subtropics were arid, as suggested by paleoenvironmental data [*Kohfeld and Harrison*, 2001]. Figure 3b shows the accompanying enhancement in the dust production in the SH. Compared with the control run (Figure 3a), there is a substantial source expansion on all three SH continents during the LGM. In South America, the source area is doubled with a large addition of dust sources west of the Altiplano region. The emission due to the reduction of continental vegetation is ~4.9 times of the present-day South American emission (Table 4), much higher than the 100% glacial increase in Patagonian dust emissions modeled by *Andersen et al.* [1998]. Australian dust emission increased by about a factor of 6.2. The Australian dust source features an expansion of the source area in the Lake Eyre Basin in addition to the Murray-Darling Basin. South Africa also has a slight increase of dust emission (~70% of present-day emission). These emission increases cannot be directly translated into the dust deposition in Antarctica, since different sources contribute differently to the dust deposition in specific region in Antarctica [*Li et al.*, 2008] (Figure 4).

Table 4. The Dust Emission (Tg yr^{-1}) in the Sensitivity Experiments Concerning the Sources[a]

	Global	SH	SAM	AUS	SAF
Sp (control)	1205	104	52	29	23
Sveg-Sp	759(0.63)	450(4.34)	254(4.88)	180(6.21)	17(0.74)
Ssl-Sp	937(0.78)	460(4.42)	198(3.80)	225(7.72)	38(1.65)
SLGM	2885(2.39)	1011(9.72)	502(9.65)	431(14.89)	78(3.39)

[a]Global, global sources; SH, Southern Hemisphere; SAM, South America; AUS, Australia; SAF, South Africa. The numbers in the parentheses are the ratios of dust emission for the LGM relative to present-day. "Sp," "Sveg-Sp," and "Ssl-Sp" denote present-day source, the source increase due to vegetation reduction, and the source increase due to sea level change, respectively (Table 2). "SLGM" denotes the total increase in the dust source in LGM relative to present-day (see also Table 2).

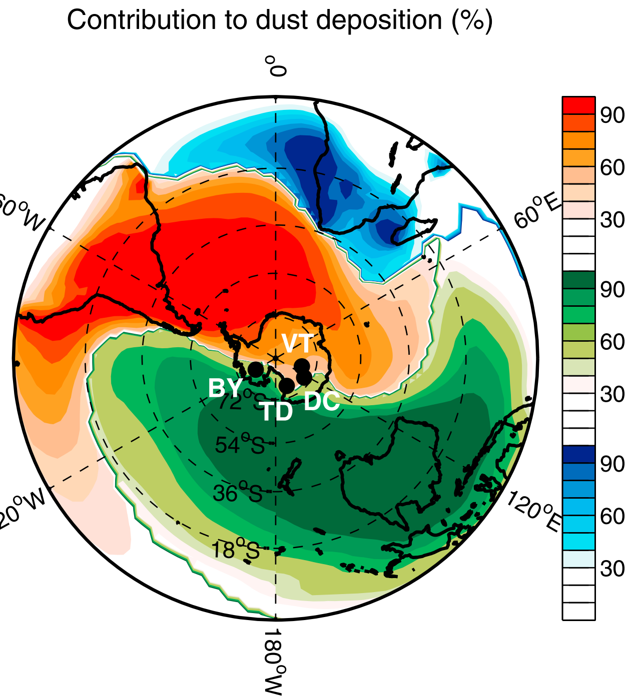

Figure 4. Relative contribution (%) from the three SH sources to dust deposition in the high-latitude SH, with LGM dust sources. The red, blue, and green shadings represent the contributions from South America, South Africa, and Australia, respectively. Four well-known Antarctic ice core sites are also shown: VT (Vostok: 78°S, 107°E), DC (Dome C: 75°S, 124°E), TD (Taylor Dome: 77°S, 158°E), and BY (Byrd Station: 80°S, 120°W).

[31] *Andersen et al.* [1998] modeled an increase in dust deposition in the Antarctic ice sheet by a factor of 1.4, compared to the present-day value, primarily due to the reduced vegetation cover in Patagonia region and SH low-latitude sources. In our simulation, the source expansion over land results in a 60% increase of dust deposition globally and 80% increase in Antarctica under present-day climate conditions. This source expansion also induces an increase of 50% in the global dust optical depth (DOD) and 2.2 times in the Antarctic DOD (Table 5).

3.1.2. Experiment "Ssl"

[32] As described in section 2, experiment "Ssl" uses a LGM sea level of 120 m lower than the present-day value [*Peltier*, 1994]. Compared to the control run, the source area increases by 89% (in South America), 63% (in Australia), and 33% (in South Africa) due to the exposed continental shelves in these three continents (Figure 3c). However, the emission becomes relatively stronger in the continental shelf regions due to the low elevation, more arid land cover, and stronger surface winds (Table 4). In South America, the lower sea level almost completely exposes the broad Argentine continental shelf, rich in Patagonian and Andean-derived sediments, to the strong westerly winds. This yields ~3.8 times more dust emission for the whole continent than during the present-day. The Australian emission is also greatly enhanced, by about 7.7 times, due to the exposed continental shelf south of its present-day south coastline (note that, as pointed out earlier, there is an underestimation of present dust source in the control run). The South African dust emission was also higher during the LGM, but its magnitude is much smaller than that from the other two continents. The increases of global dust deposition and dust optical depth due to the lower sea level (by 80%) are comparable to those due to reduced vegetation cover, but the increases are much higher in Antarctica (Table 5). This is because exposed continental shelves are mostly in the southern parts of South American and Australian continents (Figure 3). They are much closer to Antarctica compared to the increase in the source area arising due to the vegetation change (mostly inland of South America and Australia). Thus, it takes less time and is relatively easier for the dust from these continental shelf sources to be transported to Antarctica.

3.1.3. Experiment "SLGM"

[33] *Mahowald et al.* [1999] simulated a twofold global expansion of desert area in the LGM by allowing vegetation to vary on the land, leading to 3 times higher global dust emission. Our simulation, with both vegetation reduction and sea level change, indicates a smaller global source area expansion (1.5 times the present-day value) and emission enhancement (2.4 times the present-day value). However, the LGM source expansion in this experiment is much more significant in the three SH continents (Figure 3d), which are the principal contributors for the dust deposition in Antarctica [*Li et al.*, 2008]. The SH source area (~15×10^{12} m^2) is a factor of 3.8 times the present source area. For the dust emission in the SH, South Africa has an overall increase of a factor of 3.4. The increase of Australian emission is a factor of 14.9 compared with present-day emission (note that the present-day vegetation underestimates the dust source in Australia in the control run). South American source expansion is approximately a factor of 3, and this yields a factor of 9.7 increase in the dust emission. The increase has a slightly larger contribution from vegetation reduction than the lower sea level (Table 4). This LGM source expansion induces a 6.3 times higher dust deposition and 6.7 times higher DOD over Antarctica (Table 5).

Table 5. The LGM/Present Ratios of Dust Deposition (Tg yr^{-1}) and Dust Optical Depth for the Antarctica and Global Mean[a]

	Antarctica			Global		
Ratio (LGM/Current)	Sveg-Sp	Ssl-Sp	SLGM	Sveg-Sp	Ssl-Sp	SLGM
Deposition	0.9(0.08)	4.4(0.36)	6.3(0.52)	0.6(302)	0.8(372)	2.4(1157)
DOD	2.2(0.0009)	3.5(0.0012)	6.7(0.0026)	0.5(0.008)	0.5(0.008)	2.0(0.032)

[a]The absolute values are in parentheses. "Sveg-Sp," "Ssl-Sp," and "SLGM" denote the contribution from the source increase due to vegetation reduction, due to sea level change, and the total LGM source, respectively. DOD, dust optical depth.

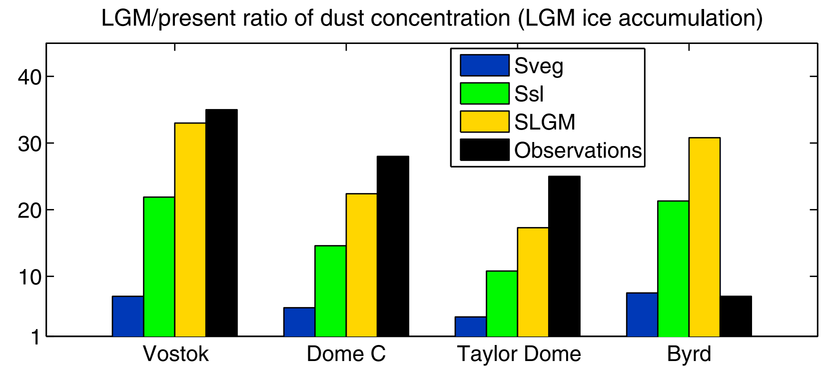

Figure 5. The LGM/present ratios of dust concentrations in the four ice cores: Vostok, Dome C, Taylor Dome, and Byrd. The dust concentration is converted from the simulated flux using the LGM ice accumulation rate (obtained from the model-simulated LGM precipitation). The colors indicate the ratios from the various experiments. Blue, the source increase due to the reduction of continental vegetation ("Sveg-Sp"); green, the source increases from sea level change ("Ssl-Sp"); yellow, total LGM sources ("SLGM"); and black, ratios inferred from observations (Table 6).

[34] The LGM source expansion (Figure 3d) also leads to a shift in the contributions from the individual sources to the dust deposition in Antarctica relative to present-day conditions. Most isotopic studies, based on a limited number of samples collected in present-day deserts, show that dust in East Antarctica originated essentially from Patagonia during the LGM [*Basile et al.*, 1997; *Delmonte et al.*, 2004; *McConnell et al.*, 2007]. Some other analyses have argued that the origin of dust in East Antarctica may change with climate and that a significant amount of the dust deposited at Vostok during the LGM could have come from Australia [*Gaudichet et al.*, 1992; *Revel-Rolland et al.*, 2006; *Mahowald et al.*, 1999]. *Li et al.* [2008] showed that South America and Australia each contribute to about half of the dust deposition in Antarctica under current climate conditions. Our sensitivity experiments indicate that the LGM source expansion results in an increase of South America's contribution to the East Antarctic dust deposition (Figure 4).

[35] The simulated present-day concentrations, shown previously in Table 3, are of the same order of magnitude, but slightly higher than the observed values for present-day climate, except for Byrd where the dust concentration is a factor of 3 smaller. Figure 4 shows the fractional contribution from the individual continental sources to the dust deposition in the SH under current climate conditions, but with LGM dust sources (experiment "SLGM"), as obtained by tagging the individual sources. With the LGM source expansion, South American dust becomes more dominant generally in the Antarctic continent for dust deposition (57%), compared with Australia (40%). Contributions from South Africa and the Northern Hemisphere are negligible (~1%). The Vostok dust deposition has a clear South American origin (60%), but with a significant contribution from Australia (38%). At Dome C and Taylor Dome, the contributions are comparable, with slightly greater values from South America. For instance, at Dome C, the simulations yield a slightly bigger contribution from South America (52%) than Australia (45%). Note that *Grousset et al.* [1992], comparing $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of Dome C with the individual continental sources, argued for a clear Patagonian origin. Australia dominates the dust deposition at Byrd (71%) in West Antarctica. However, as mentioned earlier, the model may have underestimated the dust source in Australia during the LGM and consequently underestimated the dust concentration in the ice cores strongly influenced by this source, such as Byrd Station (Table 3 and Figure 4). The underestimation of the present-day dust source area in Australia and an overestimation of ice accumulation rate (Table 1) are consistent with the low dust concentration simulated for the Byrd core.

[36] The changes of dust concentration in the Antarctic ice cores could reflect the long-term climate change. Figure 5 shows the LGM/current rates of dust deposition rate and concentrations in the four Antarctic ice cores marked in Figure 4. The simulated dust deposition rate is converted to dust concentration in Antarctica ice using equation (2) (section 2.3 and Table 1). This conversion provides the most direct comparison with the concentrations in the Antarctic ice core records. This also includes the effect of ice accumulation changes, which is discussed later (section 3.3.3). The LGM/current ratios of dust deposition, concentration, and precipitation at these four sites are all listed in Table 6.

[37] At Vostok, the observed LGM/current ratio of dust concentration is 35 (Figure 5). Without accounting for the ice accumulation change, their model predicts a factor of 7.4 increase in the amount of dust in the Vostok ice core, with a 1.6 times increase from vegetation reduction and a factor of 4.9 increase due to sea level change. When the change of LGM ice accumulation rate is accounted for, the simulated ratio reaches ~33, which appears to explain almost all the observed concentration increase in LGM (33 versus 35). Thus, in this study, the total LGM source expansion is estimated to contribute to most of the increase of the amount of dust in Vostok core. It should be noted that the 33 times increase of dust concentration during the LGM could be a little too high due to the low simulated LGM ice accumulation rate (~22% of present value) at Vostok (refer section 3.3.3).

[38] At Dome C, the simulated concentration increase is 22.4, which explains about 80% of the observed ratio (28 times larger) [*Lambert et al.*, 2008, Figure 5.1].

Table 6. Present-Day and LGM Values of Dust Deposition, Precipitation, and Dust Concentration in the Four Antarctic Ice Cores: Vostok, Dome C, Taylor Dome, and Byrd and LGM/Present Ratios of Dust Concentrations in the Above Ice Cores[a]

		Vostok				Dome C				Taylor Dome				Byrd			
		Sp	Sveg-Sp	Ssl-Sp	SLGM	Sp	Sveg-Sp	Ssl-Sp	SLGM	Sp	Sveg-Sp	Ssl-Sp	SLGM	Sp	Sveg-Sp	Ssl-Sp	SLGM
	Deposition, Precipitation, and Concentration in Present-Day and LGM																
Present	Deposition(kg m^{-2} yr^{-1} × 10^{-6})	1.2	1.9	5.9	8.9	1.1	2.1	5.8	8.9	1.6	2.7	7.5	11.6	1.3	4.7	13.6	19.4
	Precipitation(kg m^{-2} yr^{-1})	16.1				22.5				47.4				233.5			
	Concentration(ng g^{-1})	**75**	118	366	553	**49**	93	258	396	**34**	57	158	245	**6**	20	58	83
LGM	Precipitation(kg m^{-2} yr^{-1})	3.6				8.1				20.4				104.8			
	Concentration (ng g^{-1})	333	528	1639	**2472**	136	259	716	**1099**	78	132	368	**589**	12	45	128	**185**
	Ratio of Dust Concentration (LGM/Present)																
Present-day(present accumulation)		–	1.6	4.9	7.4	–	1.9	5.3	8.1	–	1.7	4.6	7.2	–	3.3	9.7	13.8
LGM(LGM accumulation)		–	7.0	21.9	**33.0**	–	5.3	14.6	**22.4**	–	3.9	10.8	**17.3**	–	7.5	21.3	**30.8**
LGM (low end)(1/2 present accumulation)		–	3.2	9.8	14.8	–	3.8	10.6	16.2	–	3.4	9.2	14.4	–	6.6	19.4	27.6
LGM (high end)(1/4 present accumulation)		–	6.4	19.6	29.6	–	7.6	21.2	32.4	–	6.8	18.4	28.8	–	13.2	38.8	55.3
LGM(observations)		–	–	–	**35**	–	–	–	**28**	–	–	–	**25**[1]	–	–	–	**7**[2]

[a]"Sp," "Sveg-Sp," "Ssl-Sp," and "SLGM" denote the contribution from the present-day source, source increase due to vegetation reduction, source increase due to sea level change, and the total LGM source, respectively. The observation ratios for Vostok, Dome C, Talyor Dome, Byrd cores are from *Petit et al.* [1999], *Lambert et al.* [2008], *Rothlisberger et al.* [2002], and *Cragin et al.* [1977], respectively. The dust concentrations are also calculated from two additional sensitivity experiments, in which the modeled present-day ice accumulation rates are scaled down by 1/2 [*Fischer et al.*, 2007] and 1/4 [*Lorius*, 1989]. These are shown to provide an approximate range of the effects due to the changes of ice accumulation rates during LGM.

Rothlisberger et al. [2002] reported a higher increase (~50 times) based on measurement of calcium, which was used as a proxy for dust. We used the ratio from *Lambert et al.* [2008] since the relationship between dust and calcium may not always be linear. The LGM lower sea level contributes to most of the increase (14.6 times), with the reduced vegetation (5.3 times) being a secondary factor.

[39] The simulated LGM increase of dust deposition in Taylor Dome is a factor of 17.3, smaller than Dome C, but with approximately similar relative contributions from LGM reduced vegetation (3.9 times) and lower sea level (10.8 times). The total LGM expansion accounts for 2/3 of the observed increase in Taylor Dome (25).

[40] Byrd station has a clear Australian dust origin (Figure 4), and the model significantly overestimates the LGM increase at this site: the simulated LGM/present ratio is ~31, while the observed ratio is 7. This is likely due to the underestimation of the present-day Australian sources in the vegetation map [*Adams and Faure*, 1997], as the Australian dust emission in the control run is 1/3 of the emission in Chapter 3 using a satellite based vegetation map [*DeFries and Townshend*, 1994].

[41] Taking the ice accumulation changes during LGM into consideration, the overall LGM source expansion can explain most (~70%–90%) of the increase of dust concentration in the three ice cores, e.g., Vostok, Dome and Taylor Dome. The source expansion itself very likely accounts for most of increase of the amount of dust deposited to the Antarctic ice sheets. This is in agreement with previous studies [e.g., *Fischer et al.*, 2007], but we find here that the contribution of source expansion is more significant than the

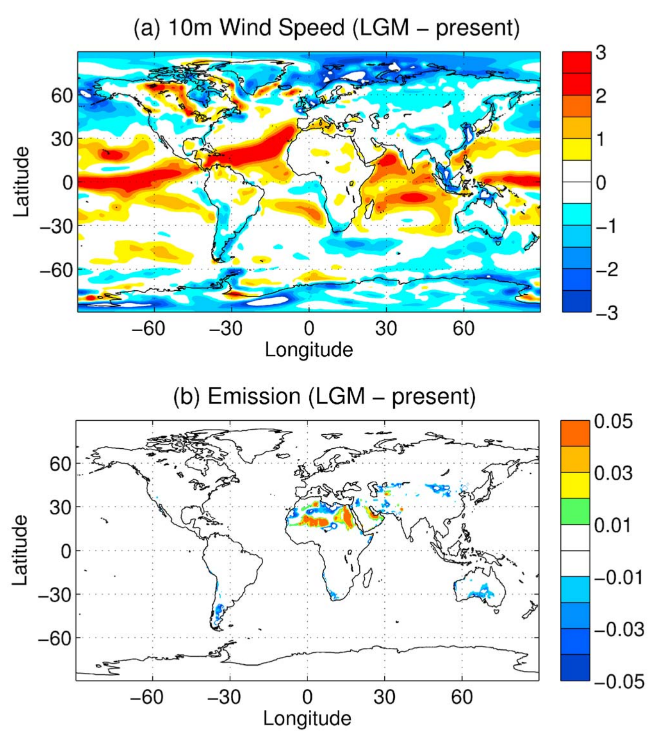

Figure 6. (a) The LGM-minus-present difference of the annual mean 10 m wind speed (m s^{-1}). (b) The LGM-minus-present difference of the global dust emission (kg m^{-2} yr^{-1}).

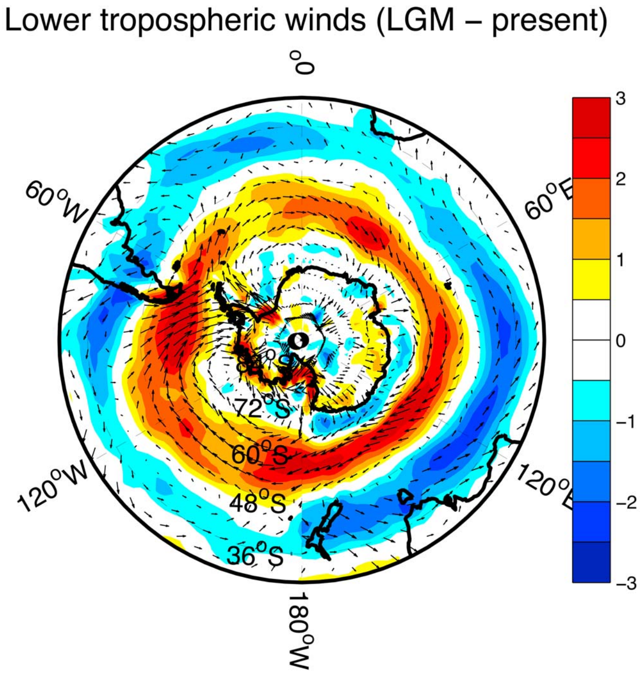

Figure 7. The difference in the lower troposphere winds (averaged below 500 mb) between LGM and present-day climates. The color shading and the arrows indicate the LGM-minus-present difference of the wind speed and horizontal wind vectors, respectively. The arrow length indicates the wind speed in m s^{-1}.

earlier estimates. These sensitivity experiments are among the first attempts to separate the influence of source expansion from that of the other parameters. We conclude that the lower sea level, by exposing a large area of continental shelves for dust production, is more important for the source expansion during the LGM.

3.2. Circulation Effects

3.2.1. Experiment "Cemis"

[42] In experiment "Cemis," the LGM dust emission is obtained using the simulated LGM 10 m wind speed, and Figure 6 shows the LGM minus control run ("Sp") difference in the mean wind speed (Figure 6a) and dust emission (Figure 6b).

[43] The 10 m winds in the LGM simulation were stronger in the tropical to midlatitude region, especially over the oceans, but weaker in the extratropics (Figure 6a). The global dust emission is 1229 Tg yr^{-1} during the LGM in experiment "Cemis," slightly larger than that in the control run, 1205 Tg yr^{-1}, as listed in Table 4. The emission in the three SH continents is significantly reduced during the LGM, 72 Tg yr^{-1} compared to the present-day SH emission, 104 $Tgyr^{-1}$, as listed in Table 4. The reductions are significant in all the three continental sources, and the resulting dust emissions during the LGM were only ~30%, ~42%, and 38% of the present-day values for South American, Australia, and South Africa, respectively. This is opposite to the increase due to source area expansion discussed in section 3.1. Referring to their individual contributions in Figure 4, the dust deposition in Antarctica ice cores is ~40%–60% smaller than the present-day values due to the contribution of the surface wind speed changes and assuming all other factors remain the same. The effects of surface winds on dust emission therefore do not enhance the amount of dust deposited to Antarctic ice, but instead yield a reduction.

3.2.2. Circulation Effects on Transport

[44] The enhancement of atmospheric circulation during the LGM has been suggested as a plausible reason for the major increase of dust in the Antarctic ice cores [*COHMAP Members*, 1988; *Grousset et al.*, 1992]. Unfortunately, a sensitivity study using a coupled atmosphere-ocean model is beyond the scope of this study. Instead, we examine the general characteristics of the LGM wind fields in mid-high latitude SH to provide a qualitative evaluation concerning the importance of this factor for the increase of dust deposition in Antarctic ice. The present-day winds used are from the GFDL GCM CM2.1 "present-day" simulations [*Delworth et al.*, 2006], to be consistent with the LGM winds simulated by the same model using LGM forcings (section 2.2).

[45] Figure 7 shows the difference in the lower tropospheric winds (averaged below 500 mb) between LGM and present-day climates. This layer is where the dust from South America and Australia is mainly transported to Antarctica [*Li et al.*, 2008]. The change in wind directions are indicated by the wind vectors in Figure 7, which denotes the LGM minus present-day difference of horizontal winds. The lower tropospheric wind speed appears to increase by 1–3 ms^{-1} (~10%–30%) over the Southern Ocean (50°S–70°S). It is in agreement with *Shin et al.* [2003], but different from other PMIP2 LGM simulations [*Rojas et al.*, 2008]. The dust from the three SH continents would be transported predominantly eastward as in the present-day [*Li et al.*, 2008]. Therefore, the change of wind directions in the regions downwind (east) of the three SH continents would have more important implications for the dust transport to Antarctica. There are northward horizontal anomalies downwind (east) of all the source regions: Patagonia, Australia, and South Africa. This would not favor further southward dust transport, and thus should reduce the amount of the dust transport to East Antarctica ice cores, e.g., Vostok, Dome C, and Taylor Dome cores. Note that there is a big increase of southward winds west of Drake Passage, close to the source region. This could change the present-day dust transport pathways to West Antarctica and might be expected to enhance the dust deposition in the Byrd ice core.

3.3. Precipitation Effects

[46] Precipitation could affect the dust concentrations in Antarctic ice cores through three different processes: (a) the precipitation in SH, particularly over the Southern Ocean where the Antarctica-bound dust is mostly removed during transport; this can influence the removal of dust from the atmosphere and hence determine the amount of dust transported to Antarctica (experiment "Ptrans"); (b) the change of Antarctic local precipitation could affect the amount of dust deposited into the ice sheets during the LGM; and (c) the precipitation over Antarctica determines the ice accumulation rate, which is used to calculate the dust concentration in the ice cores from the total (dry + wet) dust deposition flux. These three processes are discussed below.

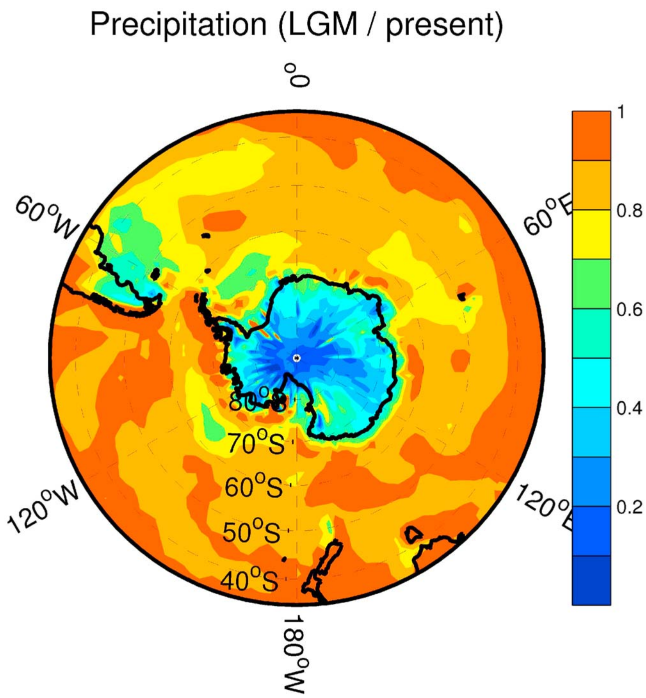

Figure 8. The LGM/present ratio of simulated precipitation in the mid-high latitude SH.

3.3.1. Experiment "Ptrans"

[47] The precipitation flux affects the removal of atmospheric dust through the washout deposition parameterized in equation (3). The washout wet deposition is proportional to the product of precipitation flux and the scavenging efficiency α.

[48] As shown in Figure 8, the simulated precipitation during the LGM is 80%–90% of the present precipitation over the Southern Ocean. Therefore, on the basis of these estimates, the reduction of wet removal is at most 20% and should result in relative small increase of dust transported to Antarctica. Although this factor could be significant, it should not explain a factor of 10 or more increase of dust during the LGM.

[49] We perform an additional sensitivity experiment "Ptrans" to mimic the reduction of wet deposition by scaling down the scavenging efficiency α by 50%, which is the largest possible precipitation reduction over Southern Ocean during the LGM (Figure 8). This results in a 50% reduction of wet deposition everywhere. Since the precipitation reduction during the LGM is 10%–20% over the Southern Ocean and larger than 50% in Antarctica, the 50% reduction will lead to more dust transport to Antarctica and thus more dust deposited onto the Antarctic ice sheet.

[50] Figure 9 shows the change in the dust deposition during the LGM relative to the present deposition (LGM/present) using the "Ptrans" and "Sp" simulations. Near the source regions, the dust deposition is slightly less, but it gets larger in remote regions such as Antarctica. Even though the scaling down of the scavenging efficiency by 50% could lead to more dust transport to Antarctica and more local dust deposition, the increase of dust deposition is less than 8% in inland Antarctica (equivalent to 20%–30% in terms of the dust concentration in ice cores). For this simulation, the dust deposition in the four ice cores is slightly higher during the LGM: Vostok (+6%), Dome C (+6%), Taylor Dome (+6%), and Byrd Station (+8%). The uncertainties associated with these values may be larger since we use here a simplification by uniformly scaling down the wet deposition. However, such a small enhancement of dust deposition, in a crude sense, indicates that the weaker precipitation during the LGM is far from being the main factor explaining the 10–100 times higher dust concentration in Antarctic ice cores.

3.3.2. Local Deposition

[51] Figure 8 shows that precipitation is significantly reduced during the LGM than for present over the entire Antarctica. This local precipitation reduction during the LGM will reduce the amount of local dust deposition by wet removal and correspondingly induce a decrease of the dust concentration via wet deposition process in the ice cores. This is opposite to the large increase observed in the ice core records.

[52] Furthermore, in Antarctica, wet deposition appears to be less important than dry deposition, for both present-day and LGM (Figure 10). In the control simulation, wet deposition contributes to less than 50% of the total deposition over the entire Antarctic continent. The percentages are 19%, 25%, 43%, and 39% at Vostok, Dome C, Taylor Dome and Byrd, respectively. Therefore, the role of local wet deposition is limited over Antarctica, and the precipitation changes during the LGM probably did not significantly modulate the dust concentration in Antarctica.

3.3.3. Local Ice Accumulation Rate

[53] The dust concentration in the Antarctic ice cores is calculated using the ice accumulation rates (equation (2)), which is approximately equal to and assumed here to be the local precipitation rate in Antarctica (section 2.3).

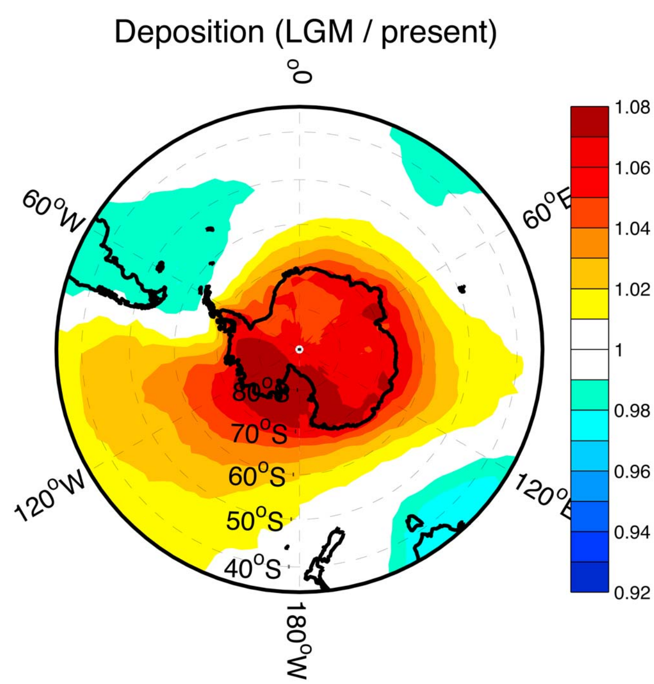

Figure 9. The LGM/present ratio of dust deposition in the sensitivity experiment "Ptrans," obtained by scaling down the scavenging efficiency in wet deposition scheme by 50%.

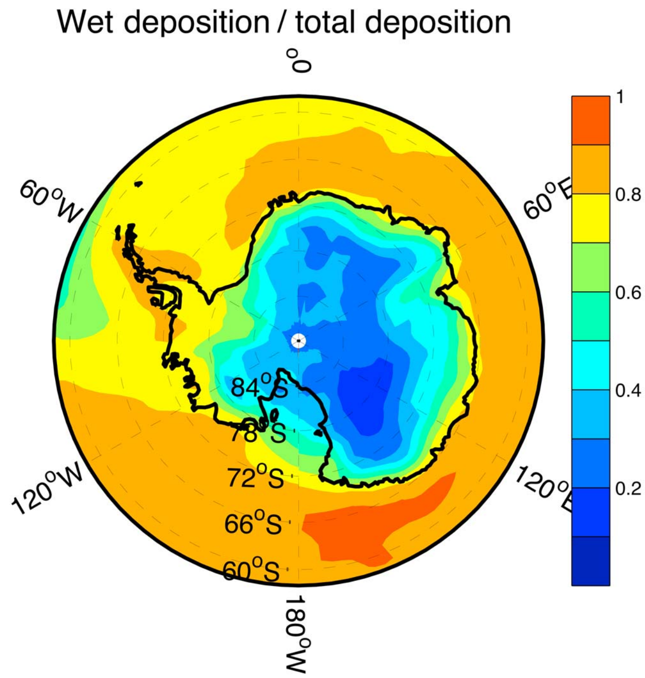

Figure 10. The contribution of wet deposition to the total deposition in present-day SH (wet deposition/total deposition).

[54] Figure 8 shows that the precipitation during LGM was lower by about 50% over Antarctica (also in Table 1). This is in reasonable agreement with previous estimates: 25% [*Fischer et al.*, 2007] to 50% [*Lorius*, 1989]. Any change of dust deposition flux will need to be multiplied by a factor of 2–4 to obtain the corresponding dust concentrations in the LGM. The simulated LGM ice accumulation rate (~22% of present value) at Vostok is at the low end of the previous estimates [e.g., *Lemieux-Dudon et al.*, 2010] and thus could result in an overestimation of the dust concentration during the LGM. As shown in Table 6, the overall LGM source expansion induces a factor of 7–8 increase in the dust deposition fluxes to the Vostok, Dome C, and Taylor Dome cores. Combined with the LGM ice accumulation reductions, the source expansion contributes to 33, 22, and 17 times increase of dust concentrations in Vostok, Dome C, and Taylor Dome cores, respectively. These two factors can explain most of the observed increase of dust concentration in these ice cores.

4. Conclusions

[55] We investigate in this study the processes that could cause the high dust accumulations in Antarctic ice cores during the LGM and test the different hypotheses to determine the principal causality. Five specific sensitivity experiments are performed using the GFDL AM2.1n and CM2.1 models to estimate the relative importance of the source characteristics, circulation, and Antarctic precipitation on the accumulation of mineral dust in Antarctic ice cores. The modeling and application strategy employed here differs significantly from the previous modeling studies of LGM dust transports [e.g., *Andersen et al.*, 1998; *Mahowald et al.*, 1999]. This study, to the best of our knowledge, is the first to evaluate the contributions due to each of the above processes by performing separate experiments in the context of a global general circulation model. This study also discusses the LGM precipitation effects through three separate processes: on the dust removal over the Southern Ocean, the local dust deposition, and the ice accumulation rates over Antarctica. The principal results are as follows:

[56] 1. Source expansion, due to the reduction in the continental vegetation and lowering of the sea level, contributes to most of the increase of dust transport to Antarctica during the LGM. The lowering of the sea level, by exposing large areas of continental shelves for dust production, is more important than the reduction in the continental vegetation.

[57] 2. Source expansion and Antarctic ice accumulation rate changes (see also the last bullet point) during the LGM can together account for most of the observed increase of dust concentration in the three ice cores (Vostok, Dome C, and Talyor Dome).

[58] 3. The surface winds induce a significant reduction in the dust emission over the three continental sources in the SH during the LGM. This, by itself, would lead to a decrease of dust deposition in Antarctica relative to the present, instead of an enhancement as observed in the ice core records. This would also affect the degree of agreement between the observed and model-based increases of dust concentration illustrated in Figure 5.

[59] 4. The increase of lower tropospheric wind speed is small (~10%–30%) over the Southern Ocean, and the horizontal wind anomalies are mostly northward at the downwind (east) regions of the SH source regions during the LGM. There does not seem to be favorable circumstances for enhanced dust transport to Antarctica, especially to East Antarctica (Vostok, Dome, and Taylor Dome cores). There could be an increase of dust transport to West Antarctica (e.g., Byrd core) due to the southward wind anomaly west of Drake Passage.

[60] 5. Reduced precipitation in the Southern Ocean and Antarctica during the LGM, mimicked here by alteration of the wet deposition coefficient involved in the wet removal of the atmospheric dust, induces only a slight increase of dust deposition in Antarctic ice cores, by less than 10%, even if a relatively large precipitation reduction (50%) from the present values is assumed. The local precipitation reduction also reduces the amount of dust deposited through wet deposition to Antarctic ice cores during the LGM.

[61] 6. The reduced precipitation during LGM also implies that the ice accumulation rate is reduced which, in turn, means that, for the same total (dry + wet) deposition flux, this factor by itself would represent an enhancement of the LGM/present ratio of the dust concentration in the ice cores.

[62] Source expansion is broadly regarded as an important reason for the high atmospheric dust loading during the LGM by most of the earlier studies [e.g., *Rothlisberger et al.*, 2002]. However, these studies have also argued for other hypotheses such as surface winds and precipitation [*Fischer et al.*, 2007]. This study argues that the changes in circulation and precipitation during the LGM do not appear to be as important as the source expansion in affecting the amount of dust deposited to Antarctic ice cores, while the Antarctic ice accumulation changes are essential in explaining the dust concentrations. The lowering of the sea level is more

important than the reduction in the continental vegetation for the source expansion effects. This contrasts with the conclusion of *Basile et al.* [1997], who argued that an increase in continental dust source area is more important to explain the ice core data than exposed shelf areas from isotopic analysis. *Delmonte et al.* [2007], however, further argued that the continental shelf cannot be excluded based on isotopic analysis of *Basile et al.* [1997].

[63] *Chylek et al.* [2001] hypothesized that the narrowing of Hadley circulation during the LGM could expose more tropical dust source area to southward circulation and lead to a factor of 2–3 increase of dust deposition in Antarctica. However, *Shin et al.* [2003] argued that the present-day annual mean Hadley circulation is similar to that during the LGM. The stronger meridional sea surface temperature gradient during the LGM may have strengthened the Hadley circulation and increased midlatitude precipitation, which would likely have reduced dust transport to Antarctica. Such disagreement shows the uncertainties concerning the atmospheric circulation during the LGM. This aspect has not been studied extensively in our sensitivity experiments but should be explored in future research.

[64] Another uncertainty is associated with the vegetation mask used in the model's dust emission scheme. The vegetation mask used in the control simulation for present-day conditions [*Adams and Faure*, 1997] shows a much smaller dust source area in Australia than the satellite-based vegetation map [*Defries and Townshend*, 1994]. The corresponding emission using *Adams and Faure* [1997] vegetation map is ~30 Tg yr^{-1}, which is 1/4 of the emission (~120 Tg yr^{-1}) using the map from *Defries and Townshend* [1994]. This results in a substantial underestimation of the dust deposition in the ice in West Antarctica (an order of magnitude less than the observed present-day dust concentration at the Byrd ice core location).

[65] It should also be noted that our LGM simulations have essentially been sensitivity studies, which have used simple, diagnostic strategies to represent particular aspects of the climate change from the present to LGM conditions. They should not be considered as comprehensive LGM simulations. We have explored the most basic processes involving the dust enhancements during the LGM, but not the factors governing the time dependence of dust nor its variability during the LGM.

[66] To improve upon the quantification of dust obtained here and to further understand the role of mineral dust in the past climate, there is a compelling need to address the following issues in future studies:

[67] 1. The development of a pair of vegetation maps consistent for both present-day and LGM, with specific attention to the SH sources, is crucial in future studies of the dust deposition in Antarctic ice cores. A more extensive emission characterization of Australian dust sources is strongly needed, together with a further investigation of the transport pathway of the Australian dust to Antarctica. These are essential to evaluate the uncertainties in the relative contributions by the Australian and South American dust to the West Antarctica ice core locations.

[68] 2. The dry and wet deposition processes of mineral dust are difficult to parameterize, especially in a global GCM model. The dry deposition depends upon the individual properties of the turbulent transfer, the aerodynamic and surface resistances, as well as the size and shape of the particles. A realistic description of wet deposition process requires knowledge of the microphysics of condensation and precipitation, and the microphysics of the aerosols. As the models use several approximations, especially in the microphysical aspects, there exist uncertainties in simulating the net outcome of the interactions. Improvement of these parameterizations and their validation would enable an improved quantification of the deposition of dust in the SH. Other than the parameterizations themselves, a better constraint on precipitation flux in the SH, especially for high latitude regions, would yield a more precise estimate of the rainout rate of the atmospheric dust.

[69] 3. GCM simulations with a more comprehensive treatment of LGM dust are needed to more thoroughly understand the dust deposition during the LGM and the associated long-term climate changes. The simulations should include the sea level change, as indicated in Chapter 5, and the vegetation classification. LGM simulations, in which the dust is interactive with climate, would be useful to understand the large potential effect of dust in glacial periods when its loading was high. Using these with an online dust module would be useful to investigate directly the dust-atmosphere interactions, as opposed to the diagnostic methodology adopted in this study. Treatment of dust as an interactive tracer in the coupled model would also allow the radiative effects of dust to be fed back into the simulated climate change, which could have additional interesting implications for the SH circulation and dust deposition in the Antarctica.

[70] 4. Theoretical studies and in situ observations have shown that dust deposition to the oceans provides nutrients (i.e., iron) and thus acts as a fertilizing agent for ocean phytoplankton in regions with iron deficit such as the Southern Ocean [e.g., *Watson et al.*, 2000; *Fan et al.*, 2006]. Consequently, the change of the Southern Ocean biogeochemical cycle induced by dust deposition could modulate the CO_2 flux between the ocean and atmosphere and further contribute to the change of atmospheric CO_2 and climate [*Martin*, 1990]. *Marinov et al.* [2006] added another perspective to this by emphasizing that not all regions of the Southern Ocean are the same. Therefore, it would be necessary to incorporate complete dust cycles into the corresponding studies of the past climates to understand these mechanisms. This could provide insights for the understanding of the long-term climate variability and the changes from LGM to present.

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