The role of dust in glacial–interglacial cycles

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Abstract

In this work, the possible climate effects of variations in dust flux during the last six glacial cycles (575–0 ka before present (BP)) are investigated. While most past studies investigated the role of dust in equilibrium or in relatively short transient experiments, in the present study, we conduct million-year simulations using a two-dimensional model. Our results show that accounting for increases in atmospheric dust strongly affects the mean annual surface temperature, and more importantly affects the evolution of the ice sheets. We found a similar cooling trend as previous studies due to the direct radiative forcing by dust. We also found that the effect of dust on snow albedo has a significant impact on the speed of ice-sheet retreat. Furthermore, we found that dust radiative forcing emphasizes the asymmetry of the glacial cycles, especially in the cycles that were symmetric in the reference simulation, a finding that could only be observed with multi-glacial cycle simulations.

1. Introduction

Earth’s climate undergoes variations on a wide range of time scales. For the last few million years or so, the 100,000-year (100 ka) cycle has been the most pronounced, with additional weaker spectral peaks at 40, 20 and 10 ka, and an asymmetric saw-tooth structure (a slow build-up of land ice and relatively abrupt melting), as can be seen for example in marine records of $\delta^{18}$O (Imbrie et al., 1989) or in ice core records (Petit et al., 1999; Bender, 2002).

In recent years, the correlation between glacial periods and the flux of mineral aerosols to the atmosphere has attracted much interest (Harrison et al., 2001a). Ice core records from Vostok station (located at 78°28′S 106°52′E, 3500 m above sea level) and from Concordia station at Dome C (located at 78°06′S 123°21′E, 3233 m above sea level) show 10–12 times larger fluxes of dust during the maximum glaciations relative to the mean flux, and up to 27–30 times larger fluxes of dust during last glacial maximum (LGM) relative to present day (Petit et al., 1999; Delmonte et al., 2004). As is well known from recent studies on the effects of large volcanic eruptions, sudden large emissions of atmospheric aerosol particles that persist in the atmosphere for a period of months to years can certainly influence global climate, causing a negative climate forcing (cooling) during that time period (Ramachandran et al., 2000; Oman et al., 2005; Douglass et al., 2006).

The interaction between dust and climate is far from fully understood (Harrison et al., 2001a; Ramaswamy et al., 2001, pp. 372–384), with changes in climate affecting the amount of dust in the atmosphere and, conversely, high concentrations of dust having potential climatic implications. For example, glaciation has been proposed to increase dust flux into the atmosphere through increased surface winds, low surface humidity and soil moisture, and increased desertification (Elenga et al., 2000; Tarasov et al., 2000; Yu et al., 2000; Harrison et al., 2001a, b; Harrison and Prentice, 2003) as a result of decreasing sea level and decreasing vegetation (Mahowald et al., 1999; Reader et al., 1999, 2000). Furthermore, radiative and microphysical effects of dust can lead to both positive and negative feedbacks on glaciation. Possible radiative and microphysical effects of atmospheric dust include (1) the aerosol direct radiative effect (an increase in aerosol optical depth decreases the flux of solar radiation to the surface of the Earth (Yoon et al., 2005)), (2) the effect of contaminants on...
Understanding the radiative and microphysical effects of dust and their positive and negative feedbacks on glaciation is also relevant in the context of future anthropogenic climate change. At present, there are still major uncertainties regarding the impact of dust’s different forcings, including uncertainties in the radiative parameters, size distributions, spatial distributions, and vertical profiles of dust, and uncertainties in implementing assumed radiative parameters in order to calculate a radiative forcing (Ramaswamy et al., 2001).

A number of previous studies have investigated the role of dust on the temperature changes during the ice ages using complex 2.5- or three-dimensional models. For example, Mahowald et al. (2006b) found a global mean surface temperature decrease of approximately 2°C during the LGM, and Schneider von Deimling et al. (2006a, b) found a northern hemisphere decrease of up to 2.3°C during the LGM.

Other studies have concentrated on the effect of dust on snow albedo and show a clear positive radiative forcing caused by the decreased albedo of snow due to dust sedimentation. Warren and Wiscombe (1980) demonstrated the importance of increased albedo to fast deglaciation. Peltier and Marshall (1995) described the dust effect on the snow albedo during the glacial periods as a multiplicative constant used for accelerating the ablation rate of ice sheets. They found a clear effect on global ice sheets, noting that the Euroasian ice sheet is more sensitive to the dust effect on snow albedo, probably because of the low precipitation rate in that area which leads to older and “dirtier” snow. Calov et al. (2005) found that the dust effect on snow albedo may have an important role in the rapid transition in snow cover due to bifurcation in the system. According to their research, there are some time periods where the astronomical forcings lead to a state with multiple equilibrium points, and decreased snow albedo may be a trigger for switching between equilibrium states and for altering the trend in ice sheets.

Owing to intensive computing requirements, most of these past studies investigated the role of dust in equilibrium or in relatively short transient experiments. In contrast, in the present study, we are interested in the role of dust during full glacial–interglacial cycles. To this end, we conduct million-year simulations using a relatively simple two-dimensional model that has been used in the past to elucidate the role of many processes in the climate system on glacial–interglacial time scales. We demonstrate that dust likely took part in shaping the structure of glacial cycles and in determining glacial–interglacial temperature differences.

This paper is organized as follows. In Section 2, we describe the model used. In Section 3.1 we investigate the model sensitivity to aerosol radiative properties. In Sections 3.2, 3.3 and 3.4, we investigate the forcing of climate by variations in dust optical depth, the effect of dust on surface albedo, and both effects combined, respectively. We conclude in Section 4.

2. Model and methods

We used the LLN 2D NH (Louvain la Neuve 2D Northern Hemisphere) model, a two-dimensional, latitude–altitude–time-dependent coupled zonally averaged climate–ice-sheet model, which was built to simulate the northern hemisphere climate and ice-sheet evolution during long time series (Galleé et al., 1991, 1992; Loutre and Berger, 2000). This model was used successfully in the past in numerous studies investigating a number of aspects of the glacial cycles, simulating ice volume (IV) for the last 500 ka to 3 million years (Berger and Loutre, 1997; Berger et al., 1998, 1999). Being simpler than a general circulation model, it includes the necessary components of the climate system needed to study glacial cycles, such as a description of ice-sheet evolution over long time series, yet it is efficient enough to perform both sensitivity studies and forcing experiments over a large parameter space. We next give a brief description of the model, emphasizing the relevant features for our study. For further details, see Gallée et al. (1991,1992) and Pépin et al. (2001).

2.1. The climate model and ice-sheet sub-model

In the climate model component of LLN 2D, in each latitudinal belt, the surface is represented as a time-dependent ratio of seven different surface types (sectors): sea ice, ice-free ocean, ice-free continent, snow field, North American ice cap, Euroasian ice cap, and Greenland's ice cap. Atmospheric dynamics are computed during each iteration using a dual layer quasi-geostrophic scheme. Precipitation, and vertical and turbulent heat fluxes are taken into account as well. The ice-sheet (sub)-model is initialized with values provided by the climate model (surface temperature, precipitation, etc.) after a spin up of 15 years calculated with 1800 iterations of 3 days each. It calculates the advance of the ice cap sectors using internal equations of motion, the equations of heat transfer, and the same parameters provided by the climate model for initialization, in an on-line fashion updated for each iteration time step (1 ka).

2.1.1. Aerosol optical properties

The climate model specifies three types of aerosols: (1) marine, (2) continental, and (3) background, above two surface types: continent and ocean. Each aerosol type over each surface type is assigned a representative set of single scattering parameters (optical depth, single scattering albedo, and asymmetry factor) for solar wavelengths, chosen to provide a reasonable past and present climate (Loutre, personal communication); see Table 1. As the
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lower for $\tau = 0.5$. This surface mean annual temperature change is relatively large. The higher values of dust optical depth also cause an increase in the average northern hemisphere IV, by $13.3 \times 10^6$ km$^3$ for $\tau = 0.3$ and by $19.7 \times 10^6$ km$^3$ for $\tau = 0.5$, and an increase in the difference between glacial and interglacial IV, by an average of 15% between $\tau = 0.3$ and $\tau = 0.5$. The ice-volume change is smaller than the mean temperature change, but still significant. Clearly, the climate in our model is sensitive to dust optical depth.

In the second set of sensitivity runs, we modify the dust single scattering albedo ($\omega$), setting it to values in the range 0.69–0.96. This range encompasses the model’s default value and is essentially the range of values reported for different compositions of atmospheric dust (Kalashnikova and Sokolik, 2003; Lafon et al., 2006). The results are shown in Fig. 2.

High values of single scattering albedo correspond to more scattering of solar radiation back to space and hence to lower surface temperatures. For $\omega = -0.96$, the annual mean surface temperature is lower than the default by 1.9°C, and the mean IV is higher than the default by $2.0 \times 10^6$ km$^3$. Lower values of single scattering albedo correspond to more atmospheric absorption of solar radiation, which can either translate into more diffusion of heat to the surface (surface warming) or to less solar radiation reaching the surface (surface cooling). Which of the two occurs depends on the aerosol optical depth and the vertical distribution of the aerosols (see, e.g., Ramaswamy and Kiehl, 1985). Given our dust aerosol optical and vertical distribution (from the WMO database, 1987), the former occurs. For $\omega = 0.69$, the mean annual temperature is higher than the default by 2.5°C, and the mean IV is lower than the default by $1.4 \times 10^6$ km$^3$.

3.2. Forcing of LLN 2D climate with a time-dependent dust optical depth

As mentioned above, records of dust load show an order of magnitude variation during glacial–interglacial cycles. We therefore force the model with time-dependent optical depth based on reconstructed dust records. These results are shown in Fig. 3, upper panel.

The forcing of dust optical depth decreases the mean annual temperature during the LGM by $-3.9$ °C (Fig. 3, upper panel, dotted line). Other studies have found a maximal decrease of $-2$ °C at latitudes 40–90° N due to the direct effect of dust (Mahowald et al., 2006a, b) and up to $-2.3$ °C for the northern hemisphere with a global mean (i.e., including the southern hemisphere) of $-1.1 \pm 0.7$ °C (Schneider von Deimling et al., 2006a, b). The wide spread of values demonstrates the large uncertainty involved in estimating the role of dust in the climate system. Although our model seems to be over-sensitive to the effect of dust in comparison to the other studies, when we also consider the effect of dust on the surface albedo (Section 3.4), we obtain a lower average cooling of 3.3 °C. In addition, we note that we applied an altitude-independent forcing because
the ice-core records contain only the surface level dust flux. However, one would expect an exponential decay in dust concentration with altitude.

Using time-dependent dust load has two additional important consequences. First, the timing of the LGM varies by a few ka. The reference simulation gives the IV maximum at 15 ka BP, while the forced simulations give the maximum at 19 ka BP. Second, it significantly increases the mean continental IV (Fig. 3, middle panel, dotted line). The LGM IV reaches $58.82 \times 10^6$ km$^3$ compared to the reference simulation LGM IV of $47.82 \times 10^6$ km$^3$.

3.3. Forcing of LLN 2D climate with a time-dependent dust effect on snow albedo

As discussed in Section 1, in addition to modulating the optical properties of the atmosphere, dust is expected to change the surface albedo, and hence the surface energy balance. This should have strong effect on the mass balance of the ice sheets, as was demonstrated before (e.g., Warren and Wiscombe, 1980; Hinkler, 2003; Motoyoshi et al., 2005). In the present experiment, we take this effect into account by changing the surface albedo based on expression (2). The forcing of snow albedo increases the mean annual temperature of the LGM in comparison to the reference run by 1.4 $^\circ$C (Fig. 3, upper panel, dashed line), while it decreases the global mean continental IV, which reaches an extreme low value of $26.16 \times 10^6$ km$^3$ (Fig. 3, middle panel, dashed line). The forcing of snow albedo has a much larger impact on the IV than on the mean surface temperature, likely due to the fact that it operates only on icy and snowy regions, unlike the dust optical depth forcing which affects all regions equally.

3.4. Forcing of LLN 2D climate with a combined time-dependent dust optical depth and effect on surface albedo

In the final experiment, we consider the combined effect of dust on both the atmospheric optical depth and on the surface albedo (Fig. 3, thin solid line). In this case, the combined forcing decreases the mean annual LGM temperature in comparison to the reference run by $3.3 \pm 1.3$ $^\circ$C and increases the global mean continental IV to a value of $48 \times 10^6$ km$^3$ at 15 ka BP and a value of $48.2 \times 10^6$ km$^3$ at 18 ka BP. The combined forcing shows that the direct radiative (optical depth) forcing is the major
influence on the mean annual temperature. The snow albedo forcing plays a more minor role in controlling the mean surface temperature, but has a much more significant impact on ice-sheet retreat.

3.5. Asymmetry of the glacial cycles

An important and robust outcome of the inclusion of the dust is the more emphasized asymmetry in the glacial cycles. Although the pattern of the dust flux forcing contains mostly symmetric peaks, the glacial cycles become more asymmetric with dust optical depth forcing. The asymmetry in both the surface temperature minima and IV peaks is congruent with similar asymmetries in the $\delta^{18}O$ and dust record (Fig. 3, lower panel), whereby ice-sheet retreat is much faster than growth and begins simultaneously with the decrease in dust flux. This may provide some explanation to the questions about the rate at which glaciers began to retreat at the end of the ice ages, mentioned in Section 1. However, because in our model dust is specified, it is not clear whether in reality dust could have forced such asymmetry or whether the decreases in the measured dust flux were triggered by the beginning of the retreat of the glaciers caused by some other mechanism. Nevertheless, our results raise the possibility that there is a two-way feedback between the dust load and the IV.

4. Conclusions

In this work, we investigate the possible climate effects of variations in dust flux during the last six glacial cycles (575–0 ka BP) using the LLN 2D model. Our results show that accounting for increases in atmospheric dust as expected strongly affects the mean annual surface temperature, and more importantly affects the evolution of the ice sheets. We found the same cooling trend as previous studies due to the direct radiative forcing, with a perhaps a small overestimate that can be explained by the assumed vertical profile of the dust aerosols. We have also found that the effect of dust on snow albedo has a significant impact on the speed of ice-sheet retreat (Gallée et al., 1992). Furthermore, we found that dust radiative forcing emphasizes the asymmetry of the glacial cycles, especially in the cycles that were symmetric in the reference simulation.

Our findings show a clear effect of increased dust concentration in the atmosphere on climate, but it should be noted that the dust concentration in the model is specified while in nature it is affected by climate properties (e.g., winds, surface humidity, and desertification). Therefore, we suppose that there is a dust-glaciation bidirectional feedback mechanism yet to be revealed. We also plan to study the radiative/microphysical effects of atmospheric dust mentioned in Section 1, namely aerosol indirect and semi-direct effects on clouds.
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