Climate response and radiative forcing from mineral aerosols during the last glacial maximum, pre-industrial, current and doubled-carbon dioxide climates

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[1] Mineral aerosol impacts on climate through radiative forcing by natural dust sources are examined in the current, last glacial maximum, pre-industrial and doubled-carbon dioxide climate. Modeled globally averaged dust loadings change by +88%, +31% and -60% in the last glacial maximum, pre-industrial and future climates, respectively, relative to the current climate. Model results show globally averaged dust radiative forcing at the top of atmosphere is -1.0, -0.4 and +0.14 W/m² for the last glacial maximum, pre-industrial and doubled-carbon dioxide climates, respectively, relative to the current climate. Globally averaged surface temperature changed by -0.85, -0.22, and +0.06 °C relative to the current climate in the last glacial maximum, pre-industrial and doubled carbon dioxide climates, respectively, due solely to the dust radiative forcing changes simulated here. These simulations only include natural dust source response to climate change, and neglect possible impacts by human land and water use. Citation: Mahowald, N. M., M. Yoshioka, W. D. Collins, A. J. Conley, D. W. Fillmore, and D. B. Coleman (2006), Climate response and radiative forcing from mineral aerosols during the last glacial maximum, pre-industrial, current and doubled-carbon dioxide climates, Geophys. Res. Lett., 33, L20705, doi:10.1029/2006GL026126.

1. Introduction

[2] Mineral aerosols both absorb and scatter shortwave and longwave radiation, and thus are thought to modify climate [e.g., Miller and Tegen, 1998]. Additionally, mineral aerosol deposition to high latitude ice cores are 2–20 times higher during cold periods, such as the last glacial maximum, than warm periods like today [e.g., Petit et al., 1999]; and marine sediment records suggest that globally dust deposition is 3–4 times higher during cold periods than warm periods [Rea, 1994]. Thus, the large expected changes in dust deposition in response to climate can play an important role in modulating climate.

[3] Although climate models can include the impact of mineral aerosols on climate [e.g., Miller and Tegen, 1998], there have not been published simulations of the climate response of mineral aerosols under different climate regimes using realistic dust distributions. Additionally, there have been limited estimates of radiative forcing under different climates [Clauquin et al., 2002; Woodward et al., 2005]. Here, we include both estimates of radiative forcing for four different time periods, as well as the climate response to dust radiative forcings in the National Center for Atmospheric Research’s (NCAR) Community Climate System Model (CCSM3) [Collins et al., 2006a]. We include only the climate response to ‘natural’ sources of desert dust, because current estimates of the land use or water use impacts are not well constrained (see Mahowald et al. [2005] for review).

2. Modeling Methodology

[4] Climate models simulations are conducted in the Community Atmospheric Model (CAM3) of the CCSM [Collins et al., 2006b]. The dust source, transport, and deposition parameterizations used for these simulations are described briefly in Text S1 in the auxiliary material and in detail by Mahowald et al. [2006] and are based on the Dust Entrainment and Deposition module [Zender et al., 2003]. Radiative forcings and climate response are calculated as described by Yoshioka et al. [2006]; a brief description is given Text S1. We use the slab ocean model version of the model to allow dust feedbacks onto the sea surface temperature, but this does not allow for changes in the ocean circulation from the dust. The simulations in this paper have exactly the same boundary conditions and radiative forcing (except for dust) as the slab ocean model simulations they are an extension of, which are described in more detail by Kiehl et al. [2006] and Otto-Bliesner et al. [2006]. Please note that for the last glacial maximum, the slab ocean model heat fluxes are based on a fully coupled simulation of these climates [Otto-Bliesner et al., 2006]. Simulations for the current and doubled-carbon dioxide climate are based on the ocean heat fluxes of the fully coupled system in the current climate [Kiehl et al., 2006].

[5] The radiative forcing of dust is calculated online using just one year of simulations (interannual variability in loading is less than 10% in this simulation), as described in more detail by Yoshioka et al. [2006]. The default version of the CAM3 includes a prescribed dust climatology for shortwave radiative forcing [Collins et al., 2006b]. For this paper, climate response is calculated relative to the case where this forcing is turned off, described by Yoshioka et al. [2006]. Longwave and shortwave forcings from dust are included in these results. The radiative forcings reported in

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1Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006GL026126. Other auxiliary material files are in the HTML.
this paper are estimated as instantaneous net forcings from both long wave and short wave without stratospheric adjustment.

[6] The sources of dust are allowed to change with climate based on changes in vegetation calculated in the BIOME3 equilibrium vegetation model [Haxeltine and Prentice, 1996], following the methodology of Mahowald et al. [1999]. We include the impact of carbon dioxide on vegetation in modifying the sources for the simulations included here (see Mahowald et al. [2006] for more cases). These cases are called SOMB, SOMBLGMC, SOMBPIC and SOMBDC for the BIOME3 vegetation based simulations for the current climate (SOMB, B meaning using the BIOME3 output), last glacial maximum (LGM), pre-industrial (PI) and doubled-carbon dioxide climates (D), respectively (the C at the end of the acronym means that the carbon dioxide fertilization effect is included in the vegetation change). We also include a case where the radiative forcing was examined in more detail, compared to other models and observations [Yoshioka et al., 2006], using the default vegetation in the model (SOM). For the last glacial maximum, we include a case where glaciogenic sources are included and tuned to match observations (SOMBLGMC). We deduced the size of these sources using an optimization algorithm and available observations (terrestrial sediment, ice and marine sediment cores), and use those source areas for this study. These simulations, including comparisons to observations (concentration, deposition and aerosol optical depth) are described in more detail by Mahowald et al. [2006].

3. Results

[7] A comparison of the results of this study to available observations is given by Mahowald et al. [2006]. The climate response of dust to these different climates includes the impact of changes in vegetation (from carbon dioxide fertilization, precipitation, temperature and insolation changes), surface winds, precipitation and soil moisture. The dust response to source area is much stronger than to surface winds or precipitation in this model, as described by Mahowald et al. [2006]. The globally averaged dust source changes by +105%, +164%, +51% and −64% relative to the current climate (SOMB) for the SOMBLGMC, SOMBLGMT, SOMBPIC, and SOMBDC cases, respectively, when dust direct radiative feedback is included in the models (Table 1). The latitudinal distribution of the sources expands to northern high latitudes under last glacial maximum conditions, similar to previous studies [e.g., Mahowald et al., 1999]. Notice that adding the impact of the glaciogenic sources on dust (and tuning the model to best match the observations) increases our dust source and loading in the extra-tropics in the last glacial maximum in our simulations (SOMBLGMC vs. SOMBLGMT). Atmospheric desert dust aerosol optical depth (500 nm) changes dramatically during the different climates due to the changes in source strength (Figure 1a). Globally averaged dust aerosol optical depth (AOD) change by +61%, +88%, +31% and −60% in the SOMBLGMC, SOMBLGMT, SOMBPIC and SOMBDC cases relative to the SOMB case, respectively (Table 1). The response of dust sources and deposition to climate change is discussed in more detail and compared to available observations from Mahowald et al. [2006]. Note that the dust source strength and loadings in this study will differ slightly from that by Mahowald et al. [2006] because we are reporting the results from simulations including the radiative feedbacks of prognostic dust, while those results were without radiative feedback of predicted dust.

[8] Dust radiative forcing changes with climate and the amount of dust, and the radiative forcings are highest at the latitudes with the most dust, although the relationship is not strictly linear (Figures 1a, 1b, and 1c). The globally averaged largest radiative forcings are seen in climates with the largest change in aerosol optical depth (Table 1). Our top of atmosphere radiative forcing tend to have larger longwave and smaller short wave components than previous modeling studies, although these results are consistent with available observations, as discussed in detail by Yoshioka et al. [2006], and briefly in Text S1. The case where we consider the impact of glaciogenic sources in the LGM has higher dust loading than without these sources (case SOMBLGMC vs. SOMBLGMT in Figure 1a) and a larger magnitude of radiative forcing (Figures 1c and 1d). If we look in more detail at the radiative forcings, we see that this increase is a balance between large negative radiative forcings over ocean, small negative forcings over land and positive radiative forcings over the ice sheets (see Figures S1–S4). Even though adding glaciogenic sources increases our dust over ice sheets, it increases the dust loading more over oceans, and thus is more negative (SOMLGMT vs. SOMBLGMT—see Figures S1–S4). More discussion on the comparison of our radiative forcing results to published results is in Text S1.
The climate response to dust can occur at different latitudes than the radiative forcing. Here we show the difference in surface temperature (radiative) between the case where dust radiative forcing is included in the climate simulation minus the case where there is no radiative forcing, for each climate. The response of surface temperature to dust radiative forcing tends to be between 0.1 and 2.1 °C cooling, and these values are statistically significant across a broad range of latitudes (Figure 1d). The strongest cooling occurs in northern midlatitudes (Figure 1d), even when the dust optical depth and radiative forcing has a larger magnitude in the tropics (Figures 1a, 1b, and 1c). The strongest response in temperature occurs at 40–90° N in the last glacial maximum cases, and is approximately 2 °C. It is unclear why the response should be largest at northern midlatitudes, but it could be due to the lower heat capacity of land versus ocean, and the large portion of land at this latitude.

The climate response of precipitation to the dust radiative forcing tends to be a shift in the precipitation to the hemisphere with less dust (Figure 1e) and a decrease in the globally averaged precipitation (Table 1). Our results suggest that further study of the importance of climate feedbacks of desert dust aerosols is warranted, and suggests some patterns that are robust across different climates in our simulations.

4. Discussion

Radiative forcings and climate feedbacks from atmospheric desert dust for last glacial maximum, pre-industrial, current and doubled-carbon dioxide climates are calculated for the first time in one single modeling framework. Included in these dust scenarios are changes in dust sources due to changes in vegetation using the BIOME3 equilibrium vegetation model [Haxeltine and Prentice, 1996] and glaciogenic sources in the last glacial maximum. We include in the model only the response due to vegetation changes, soil moisture and surface winds in this simulation, and ignore possible changes due to human land or water use [e.g., Mahowald and Luo, 2003; Mahowald et al., 2005]; estimates of anthropogenic radiative forcing and climate feedbacks including land use are given in Text S1, based on previous studies. Comparisons of the dust distribution in this study to available observations is conducted in a separate paper [Mahowald et al., 2006]; and shows a good performance of the model. The net instantaneous top-of-atmosphere radiative forcing differences due to dust between the last glacial maximum, pre-industrial and doubled-carbon dioxide climates and the current climate are 0.53, 0.43, and +0.14 W/m², respectively. If we include the impact of glaciogenic sources, the net top-of-atmosphere radiative forcing difference between the last glacial maximum and the current climate increases in magnitude to 1.04 W/m². In the future we simulate a 0.14 W/m² increase in radiative forcing because of a reduction in dust from carbon dioxide fertilization of the vegetation. It is uncertain that the carbon dioxide fertilization effect will continue in the future, when other nutrients may become limiting [Smith et al., 2000; Schlesinger and Lichter, 2001]. Indeed other studies include the impact of climate induced desertification and obtain a significant increase in desert dust in the future [Tegen et al., 2004], while others simulate little change [Tegen et al., 2004], suggesting that more studies of vegetation and climate interactions are vital to predicting future dust.

There is roughly a linear relationship between annually averaged aerosol optical depth and radiative forcing under different climates in the model simulations (see Table 1 and Figures S1–S4); the correlation coefficients are −0.96 and −0.92 and the slopes are −14.7 and −13.0 W/m²/AOD, for top-of-atmosphere and surface radiative forcing, respectively. Globally averaged surface temperature changed by −0.85, −0.22, and +0.06 °C relative to the current climate in the last glacial maximum, pre-industrial and doubled carbon dioxide climates, respectively, due solely to the dust radia-
Radiative forcing changes simulated here. The response in surface temperature or precipitation to dust forcing is approximately linear in this model in these different climates, with correlation coefficients of −0.94 and −0.98, respectively (see Table 1 and Figures S1–S4). The slope in the global response is −12.7 °C/AOD and −1.0 mm/day/AOD for surface temperature and precipitation, respectively. These values should be considered tentative, due to both the shortness of these simulations, and the dependence of these values on specific model characteristics. However, that the response remains linear while the surface albedo changes so strongly, suggests a robust response of surface temperature and precipitation to aerosol optical depth with this set of optical properties. More analysis of the differences between dust impacts on climate in this model and other models are discussed by Yoshioka et al. [2006]. The sensitivity of dust feedback results to optical properties is explored by Miller et al. [2004]. These results will ignore the impact of dust radiation on changes in ocean circulation, since we use a slab ocean model. We explore the efficacy of dust forcing within our model in Text S1.

In the last glacial maximum, our results suggest a radiative forcing relative to the current climate of −1.04 W/m² at the top of atmosphere, for the case including glaciogenic sources and best matches available deposition observations. Compared to the forcings from carbon dioxide (−1.7 W/m²) and insulation and albedo (−5.2 W/m²) [e.g., Hewitt and Mitchell, 1997], the dust forcings are about 15% of the total of other forcings. The surface temperature response from dust is −0.85 °C relative to the current climate, while the changes in carbon dioxide, insulation and albedo in the same simulations cause a change in surface temperature of 5.6 °C.

Despite the possible sensitivity of the results to our model specifications, our results suggest some interesting relationships across the different climate studies. Radiative forcing at the top-of-atmosphere and surface is linear with aerosol optical depth, even in different climates. Climate response in surface temperature and precipitation are roughly linear with aerosol optical depth in our model, with a decrease in both surface temperature and precipitation associated with increasing optical depth. Finally, our model predicts statistically significant decreases in temperature at many latitudes (not just close to the dust sources) when dust is added in the different climates, and a shift in precipitation from the northern part of the ITCZ to the southern part of the ITCZ.

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