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A less dusty future?

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[1] Atmospheric desert dust is potentially highly sensitive to changes in climate, carbon dioxide and human land use. In this study we use 6 different scenarios of the processes responsible for changes in source areas and explore changes in desert dust loading in pre-industrial and future climates, although all the scenario results are likely to be sensitive to the climate model simulations used for this study. Simulations suggest that future dust may be 20 to 60% lower than current dust loadings. The anthropogenic portion of the current dust loading may be as large as 60%, or humans may have caused a 24% decrease in desert dust, depending on the relative importance of land use, carbon dioxide and human induced climate change. These results suggest there may be a high sensitivity of 'natural aerosols' to human intervention, which has enormous implications for climate and biogeochemistry in the future. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1610 Global Change: Atmosphere (0315, 0325); 1615 Global Change: Biogeochemical processes (4805); 1809 Hydrology: Desertification. **Citation:** Mahowald, N. M., and C. Luo, A less dusty future?, *Geophys. Res. Lett.*, *30*(17), 1903, doi:10.1029/2003GL017880, 2003.

1. Introduction

[2] Mineral aerosols interact with incoming solar and outgoing planetary radiation directly [*Miller and Tegen*, 1998] or through their interactions with liquid and ice clouds [e.g., *Rosenfeld et al.*, 2001], modulate ocean and terrestrial biogeochemistry [e.g., *Martin*, 1990; *Swap et al.*, 1996], and impact atmospheric photochemistry [e.g., *Dentener et al.*, 1996], thus future predictions of climate must include the impacts of mineral aerosols. Atmospheric mineral aerosols are observed to vary 2–4-fold with glacial cycles [e.g., *Mahowald et al.*, 1999] as well as within the past 40 years [*Prospero and Nees*, 1986], suggesting that mineral aerosols are sensitive to climate change. Causes of past fluctuations in mineral aerosols and the role of humans in modulating mineral aerosols are not well understood. Explanations for the large changes observed between glacial and interglacial time periods include changes in transport, surface winds, precipitation, and carbon dioxide [e.g., *Mahowald et al.*, 1999]. Because higher carbon dioxide levels may reduce stomatal conductance leading to increased water use efficiency and increased photosynthesis by C3 plants in general, arid regions may be more productive at higher carbon dioxide levels and thus, unvegetated regions may be reduced under higher carbon dioxide conditions (carbon dioxide fertilization). Human disturbance of vegetation and soils has been shown to increase easily erodible soils substantially in in situ studies [*Gillette*, 1988], but the potential magnitude of this impact is not well established globally [e.g., contrast *Prospero et al.*, 2002 vs. *Tegen and Fung*, 1995]. Recent studies argue that satellite retrievals of the absorbing aerosol index from the TOMS suggest that natural low-lying regions are the current optimal sources of mineral aerosols [*Prospero et al.*, 2002; *Ginoux et al.*, 2001; *Goudie and Middleton*, 2001]. These regions are thought to contain soil particles in the optimal size distribution due to water based erosion currently or during previous wetter time periods. However, model studies have suggested that atmospheric aerosol distributions are likely to be similar between 'natural' source of mineral aerosols and a combination of 50% natural and 'disturbed' sources [*Tegen and Fung*, 1995; *Mahowald et al.*, 2002; *Luo et al.*, 2003]. This is because low-lying regions can have not only easily erodible soils but sometimes more fertile soils than surrounding highland regions (e.g., Niger River basin in Africa). Thus, the relative role of humans in disturbing soils and causing desert dust sources is not currently well constrained.

[3] In this paper we estimate the future atmospheric dust loading using six different scenarios and general circulation model output for 1880–9, 1990–9, and 2090–9. We use the results from the pre-industrial climate simulations to attempt to constrain the most likely scenarios by comparison to ice core data.

2. Model Description

[4] In this study, we use six different scenarios during three different time periods (total of 18 simulations) for the processes causing changes to mineral aerosol source areas, along with results from the National Center of Atmospheric Research's coupled Climate System Model (CSM) 1.0 [*Boville and Gent*, 1998] for 1880–1889 (preindustrial), 1990–1999 (current) and 2090–2099 (future), to make a range of predictions about future mineral aerosol sources, distributions and deposition. For future predictions, the model simulations follow the A1 scenario [*Houghton et al.*, 2001] including sulfate aerosols and green house gases. Meterological fields are archived from CSM1.0 simulations and the offline dust model MATCH/DEAD is used to simulate dust under different climate regimes following the methodology similar to previous studies [*Mahowald et al.*, 2002; *Zender et al.*, 2003a; *Mahowald et al.*, 2003; *Luo et al.*, 2003]. Wet and dry deposition are simulated as the

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loss mechanisms for four different size bins of aerosols transported in the model. Simulations are conducted for the first scenario for 10 years, but comparisons between the 10 year mean and first 3 years suggest that a 3-year simulation is sufficient for this study, and only 3 years are simulated for the other scenarios. Note that predictions of changes in temperature, precipitation, soil moisture, cloudiness, surface winds, as well as transport characteristics are likely to be very sensitive to the climate model simulation used, adding uncertainty to our dust results.

[5] The first scenario assumes that currently active sources defined as topographic lows [*Ginoux et al.*, 2001] continue to be active sources (TIMIND or time independent). The second scenario (BASE) allows the vegetation to shift following temperature, precipitation and cloudiness using the BIOME3 equilibrium vegetation model [*Haxeltine and Prentice*, 1996] and output from the CSM1.0 similar to *Mahowald et al.* [1999], assuming an easily erodible source based on geomorphological processes [*Zender et al.*, 2003b]. The third scenario is similar to the BASE scenario, but also allows carbon dioxide fertilization to modulate desert regions (BASE-CO2). In addition, we have three additional scenarios, using the first three scenarios with land use source that accounts for 50% of the entrained dust globally for desert dust (CULT + TIMIND, CULT + BASE, CULT + BASE-CO2). Estimates of future cultivation are highly uncertain. We assume that land use in arid regions in 2090 will be in approximately the same places as today (and assume that land use in arid regions is zero in the 1880s) which is similar to one prediction http://www.ciesin.org/datasets/rivm/image2.0-home.html, *Alcamo et al.*, 1994, and for both the current and future cultivation in desert use a land use estimate [*Matthews*, 1983] that appears to match available desert dust data for the current climate [*Luo et al.*, 2003]. The similarity in the spatial distribution of the sources from the TIMIND and CULT sources have been previously published [*Luo et al.*, 2003]. Note that because we tune the source magnitude in the current climate, in the pre-industrial simulations, the CULT sources will have 50% of the source magnitude of the non-CULT scenario (e.g., the magnitude of the TIMIND source in the pre-industrial simulation is twice that of the preindustrial simulation of the TIMIND-CULT scenario).

3. Results

[6] Table 1 shows the changes in desert dust source area for the pre-industrial and future climate under the different scenarios, where the change is calculated relative to the current climate (e.g., (future-current)/current). Notice that depending on the scenario, the source area in the future may stay constant or decrease. The model results for the BASE case indicate decreased aridity in both the 1880–9 and 2090–99 relative to the current climate (by 10–20%), a result that is likely to be model dependent [e.g., *Houghton et al.*, 2001]. Once the impacts of carbon dioxide fertilization are included in the vegetation model, the deserts in 1880s expand 14% due to lower carbon dioxide, while in the 2090s decrease in size by 40% (Table 1).

[7] The model predicts the entrainment of soil particles into the atmosphere based on surface winds, soil moisture and atmospheric stability. The model results suggest the changes in source magnitude shown in Table 2 (note that deposition equals source). In the current climate, we adjust all the simulations to have the same magnitude source as estimated from studies with forecast center winds (1650 Tg/year) [*Luo et al.*, 2003]. In the case of no change in source areas (TIMIND), the model suggests an 11% increase in desert dust in the past and a 20% decrease in desert dust in the future due to changes in soil moisture and surface winds. Including the changes in source areas (from Table 1) decreases of 20–60% are predicted in the dust sources in the future (Table 2). In the pre-industrial climate, dust entrainment into the atmosphere may increase by 26% or be smaller by 58%, depending on the scenario. Notice that changes in the scenario (such as between vegetation changes, carbon dioxide fertilization or cultivation in deserts) appear to produce larger changes than merely a change in meteorology as predicted by the climate model (seen in the TIMIND scenario).

Table 1. Changes in Global Desert Dust Source Areas Relative to Current Climate (Percentage Changes in Area)

	1880–9	2090–9
Case	Total	Total
TIMIND	0	0
BASE	−9	−24
BASECO2	14	−39
CULT + TIMIND	−57	0
CULT + BASE	−59	−10
CULT + BASECO2	−48	−17

[8] Because the lifetime of the aerosols can change, the model predictions of atmospheric loading are not necessarily linear with the source strength. When cultivation is not included, the lifetime generally stays within 15% of 4.2 days, but in the cases with 50% cultivation source, the lifetime is longer by 20–30%. Figure 1 shows atmospheric mineral aerosol loading under the three different climate regimes and six scenarios. While not shown here, there are changes in the relative geographical distribution of dust between different climate regimes and scenarios. Due to space constraints we do not show comparisons of modeled concentration, deposition and optical depth with observations for the current climate scenarios, however the comparisons suggest the model does a good job in simulating the location and strength of dust plumes in an annual average.

[9] Simulations in the current climate have been unable to determine the relative roles of the different processes responsible for the forming and modifying the sources (i.e., sedimentation from water erosion, land use or carbon dioxide fertilization) [*Mahowald et al.*, 2002; *Luo et al.*, 2003]. However, the large changes in preindustrial desert dust predicted using different scenarios may allow us to distinguish between these scenarios using available data from preindustrial times. The best source of data for the 1880s relative to today are several high resolution ice cores. Unfortunately, ice cores tend to be located in regions far from desert regions and thus may not reflect changes in desert dust sources or distributions in larger regions. Here we present the ratio of pre-industrial to current climate mineral aerosol mass or number concentration in the ice cores (mass concentrations are more consistent with the

Table 2. Changes in Global Desert Dust Entrainment Relative to Current Climate (Percentage Changes in Tg/year)

	1880–9	2090–9
Case	Total	Total
TIMIND	11	−20
BASE	−16	−51
BASECO2	26	−63
CULT + TIMIND	−45	−26
CULT + BASE	−58	−41
CULT + BASECO2	−37	−47

model and we prefer those when available). For the observations we use average of 1950–1990 (or the extent of the data) for the current climate, and 1850–1899 for the preindustrial climate.

[10] Unfortunately, comparison of the ice core data to model predictions does not constrain which scenario is most likely. In the high northern latitudes, GISP suggest a 14% increase in pre-industrial relative to current climate records [*Donarummo et al.*, 2002; *Zielinski and Mershon*, 1997], while Penny Ice Cap data suggest a 15% decrease [*Zdanowicz et al.*, 1998]. In Asia, Dasuopu data suggest a 35% decrease [*Thompson et al.*, 2000]. In the Andes, Huascaran records suggest a 45% decrease [*Thompson et al.*, 1995], while Quelccaya data suggests a 15% increase [*Thompson et al.*, 1984]. In the African tropics, Kilimanjaro records suggest a decrease by 25% [*Thompson et al.*, 2002]. In the southern high latitudes, records at Newall Glacier suggest a 20% increase [*Mayewski et al.*, 1995], while Siple Station data suggest a 50% decrease [*Mosley-Thompson et al.*, 1990]. Thus, ice cores close to each other often suggest different trends, making interpretation of the ice cores more difficult. If we ignore the spatial distribution of the ice cores, the ice cores suggest a mean decrease in deposition of 17% in preindustrial times relative to the current climate (but with a standard deviation of ~25%), similar to the global model estimates for the BASE case (Table 2). Comparisons between observed and modeled ratios are shown in Figure 2 for each ice core. As seen in Figure 2, no one model scenario can capture the fluctuations at all the ice cores well, perhaps due to local and mesoscale effects or errors in the model. Figure 3 shows a box-plot of each model scenario and the errors at the 8 ice core sites. The BASE scenario has a median (or mean value) closest to the ice core data, however the spread in errors is quite large. The next best scenario in terms of smallest bias is the CULT + BASECO2 scenario, however, again, the variance is quite large. If we instead evaluated the scenarios based on root mean squared difference between observations and model, we would obtain the result that the TIMIND and CULT + BASECO2 were the closest to the observations. None of the scenarios is clearly much better or much worse, and we are unable to use the limited ice core data to determine which scenario is most likely.

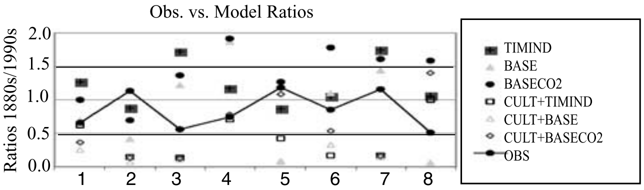

Figure 2. Preindustrial/Current climate ratio: Ice core data vs. model results. Ice core data represents mass or number concentrations (indicated by an *) ratios between pre-industrial and current climate, while model values are mass concentration ratios between pre-industrial and current climate. Locations of the ice cores are as follows: 1) Dasuopu (28°N, 85°E), 2) GISP (72°N, 38°W), 3) Kilimanjaro (3°S, 37°E), 4) Huascaran (9°S, 77°W), 5) Newall Glacier (77°S, 162°E), 6) Penny Ice Cap (67°N, 66°W), 7) Quelccaya (13°S, 70°W), 8) Siple Station (76°S, 84°W).

4. Summary and Conclusions

[11] This study presents estimates of future mineral aerosol loadings under six different scenarios. In the scenarios included here, our modeling suggests reductions of between 20 to 60% in the 2090–9 mineral aerosol loadings compared with present ((future-current)/current). In addition, simulations suggest increases of 24% or decreases of 63% in atmospheric loading between the pre-industrial climate relative to today ((past-current)/current). This implies that the anthropogenic portion of current desert dust can be between 14 to 60%, or that humans and climate change have caused a 9 to 24% decrease in mineral aerosols since pre-industrial times ((current-past)/current), depending on which scenario is most realistic. Because of uncertainties in observations in the current climate [*Mahowald et al.*, 2002; *Luo et al.*, 2003], as well as in ice core data presented here, it is not possible to determine conclusively which of these scenarios is most probable. Our model does not allow interactive vegetation or dust interactions with radiation or clouds and the subsequent impact on vegetation, which would improve the realism of our simulations. Some of the results of these simulations will be sensitive to the particular model and realization used for the dust simulation [e.g., *Houghton et al.*, 2001], although the variability between the scenarios is likely to be similar in different models.

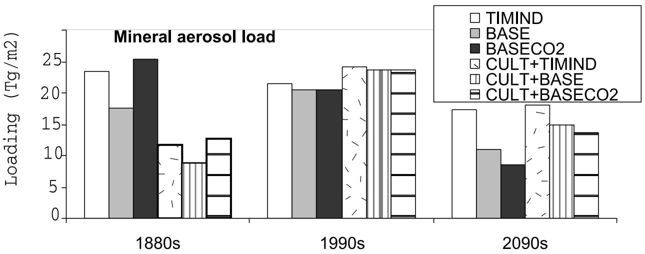

Figure 1. Mineral aerosol loading under different climate regimes using the six scenarios described in the text.

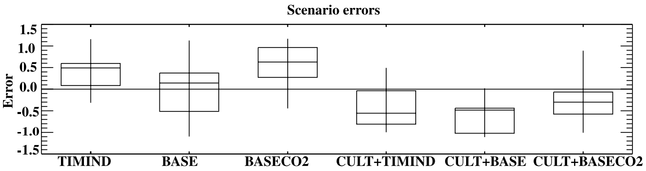

Figure 3. Model minus the observations for the ice core data for each scenario. The maximum and minimum errors are shown as the extent of the vertical line, while the box represents the 1st through 3rd quartiles in errors. The median value is a line through the middle of the box.

[12] The future reductions in mineral aerosols suggested in this study may have a profound impact on future climate predictions. The substantial reductions in iron inputs to the ocean in atmospheric mineral aerosols predicted here imply a potential reduction in the ability of the ocean to take up anthropogenic carbon dioxide in the future, due to the fertilizing effect of iron [*Martin*, 1990], causing a positive feedback in carbon dioxide. Additionally, reductions in mineral aerosols may increase surface temperatures [*Miller and Tegen*, 1998] and modify clouds [e.g., *Rosenfeld et al.*, 2001], terrestrial biogeochemistry [e.g., *Swap et al.*, 1996] and atmospheric photochemistry [*Dentener et al.*, 1996] near arid regions. These results suggest that the magnitude and uncertainties in aerosol direct and indirect forcing in the current climate may be underestimated in the latest IPCC [*Houghton et al.*, 2001] and highlights the importance of understanding how human activity can impact 'natural' aerosols. Our goal in presenting these results is to inspire more detailed studies of both source processes in the current climate as well as feedbacks of mineral aerosols on climate and biogeochemistry in the future.

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