Sea-salt aerosol response to climate change: Last Glacial Maximum, preindustrial, and doubled carbon dioxide climates

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Received 1 July 2005; revised 31 October 2005; accepted 17 November 2005; published 2 March 2006.

[1] Sea-salt aerosols represent a significant fraction of the aerosol optical depth over the oceans, and thus their response to changes in climate represents an important potential feedback on climate. Model results for sea-salt aerosols in the Community Atmospheric Model (CAM3) show good agreement with observations for the current climate. Additionally, the current climate model simulations presented here are not sensitive to the sea surface temperature boundary conditions or model resolution. We show model results for the response of sea-salt aerosols to climate change for the Last Glacial Maximum, preindustrial, current, and doubled carbon dioxide climate model simulations. Our model results suggest that globally averaged sea-salt sources, deposition, and loading are not very sensitive to climate change and change <5% for these disparate climates. Regional differences are much larger, with differences in zonally averaged concentrations as large as 40% seen between the current climate and a doubled carbon dioxide climate. While ice core studies show twofold to fivefold changes in sea-salt fluxes between Last Glacial Maximum and the current climate, our simulations cannot reproduce these changes, even after including a proposed sea ice source of sea salts.


1. Introduction

[2] Sea-salt aerosols are the leading contributors to the global-mean clear-sky radiative balance over oceans [Haywood et al., 1999] and can modulate cloud radiative properties [O’Dowd et al., 1999]. Thus there is the potential for substantial feedbacks of sea-salt aerosols onto climate. Ice core records indicate twofold to fivefold changes in fluxes of deposited sea salts between glacial and interglacial periods, indicating a strong sensitivity of sea-salt aerosols to climate, at least at high latitudes [DeAngelis et al., 1997; Petit et al., 1999; Roethlisberger et al., 2002]. Sea-salt entrainment into the atmosphere is proportional to surface winds cubed [Monahan et al., 1986], suggesting that small changes in surface winds can impact the source of this aerosol. Additionally, downwind transport, removal and distributions can be modified by changes in atmospheric transport pathways and precipitation patterns, modifying the climate impacts of this important aerosol.

[3] Wagenbach et al. [1998] hypothesized from aerosol ion concentration measurements that much of the sea-salt aerosols being observed and deposited into the ice cores in Antarctica may not be from open ocean wind effects, but rather from new sea ice formation. During the process of new sea ice formation, brine is rejected and very salty surfaces, including frost flowers are formed, and these frost flowers display similar chemical signatures to the observed aerosols [Rankin et al., 2002; Kaleschke et al., 2004]. Thus the increase in “sea salts” observed in the ice cores could be interpreted as increases in sea ice in the LGM versus the current climate [Wolff et al., 2003].

[4] Previous studies have attempted to simulate the Last Glacial Maximum changes in sea-salt aerosols and the deposition to ice cores [Genthon, 1992; Reader and McFarlane, 2003] and were unable to capture the increase observed in the ice cores. The study by Reader and McFarlane [2003] also included the new sea ice source of sea-salt aerosols but needed a sevenfold to tenfold source enhancement to match the ice core measurements.

[5] In this study, we estimate changes in the natural aerosol sea salt due to climate change for the Last Glacial Maximum, preindustrial and doubled carbon dioxide climates compared to the current climate. We also compare deposition from the modeled simulations against ice core measurements for the LGM compared to the current climate. Additionally, we test the hypothesis that new sea ice formation of sea-salt aerosols may explain the observed increase in sea-salt aerosols at the ice cores. In section 2, we described the model. In section 3, we compare the current climate results to observations, show model results of the sea salt aerosol sensitivity to climate, and compare these results to ice core results for the Last Glacial Maximum.
Glacial Maximum. In section 4, we summarize our results and discuss conclusions.

2. Model Description

Sea-salt aerosols are incorporated into the National Center for Atmospheric Research’s (NCAR) Community Atmosphere Model (CAM3), which is part of the Community Climate System Model (CCSM3) [Collins et al., 2006]. There are several parameterizations for the source term for sea-salt aerosols [e.g., Andreas, 1998], and we use the one developed by Gong et al. [1997a], similar to several other global modeling studies [e.g., Chin et al., 2003; Tie et al., 2005]. We correct the source for humidity biases following Andreas [1998]. We include 4 size bins (0.2–1.0, 1.0–3.0, 3.0–10.0, 10.0–20.0 μm diameter). For our source scheme, the source of sea-salt aerosols to the atmosphere is the open ocean under high wind speed conditions, so the source is proportional to the wind speed at 10 m to the 3.41 power [Gong et al., 1997a]. The mass going into each size bin is wind speed and relative humidity independent, and is 2%, 21%, 49% and 28% of the total source, for size bins 1–4, respectively.

The loss mechanisms for sea-salt aerosols include gravitational settling, turbulent dry deposition and wet deposition and are parameterized within the model, including the effects of hygroscopic growth on gravitational settling rates [Seinfeld and Pandis, 1998; Rasch et al., 2001]. Optical depths are calculated using a humidity dependence in the optical parameters [Hess et al., 1998; Collins et al., 2002]. Aerosol optical depths are calculated outside of the model and are based on monthly averaged concentrations and humidities, which may lead to an underestimate of aerosol optical depth (as discussed in section 3.1).

For the current climate, we simulate the following three cases: T42 (2.8° × 2.8°) slab ocean model (the control for our climate change experiments) (SOM), T42 historical sea surface temperature simulation (AMIP), and a T85 (1.4° × 1.4°) constant sea surface temperature. For the climate change studies, slab ocean model simulations of the Community Climate System Model (CCSM3) are conducted for the Last Glacial Maximum (LGM), preindustrial, current climate and doubled carbon dioxide climate [Collins et al., 2006; Kiehl et al., 2006; Otto-Bliesner et al., 2006]. Once the climate is in equilibrium, 10-year simulations of sea salts are conducted, with the last 9 years included in the averages presented here.

For sensitivity studies, we also include a source of sea-salt aerosols from new sea ice formation, as postulated by Wagenbach et al. [1998], Wolff et al. [2003], and Kaleschke et al. [2004]. In this case, the only change is where the sea-salt aerosols are formed; the source, transport and deposition are all assumed identical to open ocean sea-salt aerosols in the model, but with a proportionality factor with the amount of new sea ice formed or amount of sea ice existing. Only the last 3 years of 4 year integrations are used from these sensitivity studies. We conducted this simulation using both new sea ice formation in a slab ocean model and using all sea ice as the source. Because the slab ocean model does not allow for the movement of ice due to winds or currents, the sources of new sea ice are all on the low-latitude edges of the sea ice. This is in contrast to the sources of new ice in the fully coupled version of the model, where the new sea ice formation occurs throughout the sea ice covered regions of the model (not shown). Therefore, for the slab ocean model simulations conducted here, a more realistic distribution of new sea ice formation is obtained from using the total sea ice as the source of sea salts, and the ratios at the ice cores are higher (and thus more similar to the observations: see section 3.3).

3. Results

3.1. Current Climate Model Results

Table 1 shows the sea-salt budget in the current climate simulations. Wind speeds are too high in the CCSM3 (not shown), similar to Gong et al. [1997a], but we did not apply a correction to the wind speeds as done by Gong et al. [1997a]. The atmospheric source used here is smaller than that of Gong et al. [1997a] because of the humidity correction from Andreas [1998], but matches the observations as well as previous studies (see comparisons below). In this study, dry deposition is more important than wet deposition, similar to Gong et al. [1997a].

First we compare the results of the current climate cases against in situ observations of sea-salt sodium from the University of Miami observational network and additional observations close to Antarctica from Harder et al. [2000] and Wagenbach et al. [1998]. Observations from 26 locations, as well as model simulation results, are shown in Figure 1. The SOM, AMIP and T85 simulations tend to be very similar, consistent with their similar climatology and surface wind speeds over ocean (not shown). At many of the stations, the model gets approximately the right annual mean, but misses some part of the seasonal cycle (Barbados, Bermuda, Cape Point, Fanning Island, King George, Mace Head, and Miami), but at Cape Grim, Iceland, Maldives and Samoa, the model tends to underestimate the sea salts year round. At Chatham Island, Dumont, Halley Bay, Izana, Marion Island, Neumayer, Norfolk Island, Oahu, Palmer Station, Reunion, Sal Island and the South Pole the model overpredicts concentrations. However, at most of these stations, the annually averaged sea-salt concentrations are within a factor of 2 of the observations, similar to previous studies [Gong et al., 2002, 1997b]. In midlatitudes, annually averaged concentrations at Izana and Marion Island are a factor of 3 too high relative to the observations. Most of the exceptions are close to Antarctica, where annually averaged modeled concentrations can be between a factor of 2 (South Pole) and a factor of 28 (Halley Bay) too high. These large biases are likely to be due to problems with model resolution.
of land/sea contrasts and to the overprediction of surface winds in the Southern Ocean in the CCSM (not shown), although there may be transport errors as well.

[12] The annual average aerosol optical depths calculated in the model are shown in Figure 2, and they show maximum aerosol optical depths over high-wind ocean regions, consistent with our understanding of sea-salt aerosols [e.g., Tegen et al., 1997; Smirnov et al., 2002]. Optical depths are calculated using a humidity dependence in the optical parameters [Collins et al., 2002; Hess et al., 1998]. Note, however, that observed aerosol optical depths will include other types of aerosols, and thus optical depths from satellites and Sun photometers will provide only an upper bound on model values. The comparison between the model optical depths is consistent with the in situ comparison, in that SOM, AMIP, and T85 cases are very similar. In a review of maritime aerosols observations, Smirnov et al. [2002] argue that the optical thickness is less than 0.1 over most of the clean ocean, with a mean of 0.07. The mean optical depth over oceans from the model simulation is 0.047, 0.048 and 0.049 for the SOM, AMIP and T85 simulations, respectively, less than that estimated from the observations [Smirnov et al., 2002] for total aerosol optical depth. Figure 3 shows a comparison between five island AERONET Sun photometer sites [Holben et al., 2001; Smirnov et al., 2002] and the model predicted aerosol optical depths, again showing that the modeled values are less than the observed values. The observed optical depths should be higher because of the inclusion of other aerosols. Additionally, we use monthly averaged relative humidity to calculate our optical depths, based on Collins et al. [2002] and Hess et al. [1998], which may result in an underestimate in our optical depth, because of the strong nonlinearities in optical depth with humidity due to the hydroscopic growth. However, it may be that the optical depths from sea salts are underestimated in the model simulations. Modeled values do not show the spring peak at Lanai or Midway, which should be due to the springtime advection of pollution and dust from Asia. Indeed, Figure 3 suggests that the observed optical depth seasonality is quite different than the modeled optical depth at Rottnest Island and Tahiti, which may be due to problems in the winds in the CCSM, or due to other aerosols (e.g., natural sulfates) having large seasonalities different than the sea salts. Notice that the in situ concentration comparisons suggest that the model overpredicts sea salts at many stations, but the optical depth comparisons suggest that the model underpredicts total column sea salts, or the optical parameters used here are incorrect, although they are commonly used [Collins et al., 2002; Hess et al., 1998].

[13] Figure 4 shows zonal average vertical profiles of the sea-salt concentrations in the cases considered here and

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**Figure 1.** Monthly averaged sodium (Na) concentration (ng/m$^3$) comparisons against University of Miami observations (solid black line) (for Dumont, Halley Bay, and Neumayer, comparisons are against Wagenbach et al. [1998], and for South Pole, comparisons are against Harder et al. [2000]) for the three different model simulations for the current climate (diamonds for the SOM case, triangles for the AMIP case, and squares for the T85 case). The stations are listed in alphabetical order, first for stations outside the Southern Ocean and Antarctic region and then for the latitudes less than 60°S.
shows that the SOM, AMIP and T85 simulations are quite similar. Zonal average optical depths are similar for these cases, as seen in Figure 4d.

3.2. Results From Climate Change Scenarios

The response of the CCSM3 to climate change is documented in more detail in other papers [Kiehl et al., 2006; Otto-Bliesner et al., 2006]. Here we briefly discuss the changes in climate that are relevant to the sea-salt aerosols. The global mean surface temperature, precipitation, and surface winds are shown in Table 2 for the 9 years of simulation used in this paper. Global mean surface temperatures are shown in Table 2, and the surface temperature is 5 degrees cooler in the LGM, 1.7 degrees cooler in the preindustrial and 2.6 degrees warmer in the doubled carbon dioxide climate, when averaged over the 9 years used in these simulations. Global mean precipitation is about 10% smaller in the LGM relative to the current

![Figure 3](http://aeronet.gsfc.nasa.gov).

![Figure 4](http://aeronet.gsfc.nasa.gov).

Figure 3. Aerosol optical depth measurements from AERONET Sun photometry sites (500 nm) and model simulations (500 nm) [Holben et al., 2001] (http://aeronet.gsfc.nasa.gov).

Figure 4. (a–c) Zonally averaged concentration distributions from the model simulations as a function of pressure (hPa) and (d) zonally averaged aerosol optical depth from the model simulations.
climate and about 6% larger in the doubled carbon dioxide climate, with only a 2% change between the preindustrial compared with the current climate. Globally averaged mean surface winds increase by 6% in the LGM relative to the current climate, but are within 1% of the values seen in the current model simulation in both the preindustrial and doubled carbon dioxide simulations. Figure 5 shows the latitudinal distribution of surface winds and precipitation in each of the climate simulations. The LGM simulation has a different zonal structure of precipitation and surface winds from the rest of the simulations.

[16] Also shown in Figure 5 is the zonally averaged distribution of the sea-salt source and loading. These show that the LGM simulation has a different zonal structure than the other climate simulations, and that the source changes roughly follow the changes in surface winds. However, there is a larger sea ice extent in the LGM, which dampens the sea-salt source during that time period close to the poles (see discussion of Figure 7 below in section 3.3).

[17] The zonally averaged vertical distribution of sea salts in the model is shown in Figure 6, along with the differences from the current climate. Only results that are statistically significant at the 95% level using a Student t test are shown, with differences larger than 40% in some regions. The zonally averaged optical depths are similar for these climate scenarios, as seen in Figure 6. Climate forcing by sea salts will be dependent on the optical depths, but may be different because of the different vertical distribution of the sea salts (seen in Figure 6).

[18] The source of sea salts to the atmosphere is a function of winds to the 3.41 power, and this is calculated every time step in our CCSM3 simulations. We would like to test the sensitivity of our results to the model used for the simulation, but only daily mean winds are available in the PCMDI archive of IPCC models at the time we obtained the data https://esg.llnl.gov:8443/index.jsp). We generally did not archive winds in the CCSM3 at a daily averaged timescale, but did for the T85 simulation, which was examined for one year in more detail. We found in our CCSM3 simulation that the annual averaged source of sea salts is highly correlated spatially (0.99) with the appropriate sum of the daily means (annual mean of (daily mean zonal wind squared plus daily mean meridional wind squared) to the 3.41 power) (with a slope of 1.0), suggesting

*Relative to current climate.

<table>
<thead>
<tr>
<th>LGM</th>
<th>Preindustrial</th>
<th>Current</th>
<th>2 × CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, K</td>
<td>281.4</td>
<td>285.3</td>
<td>287.0</td>
</tr>
<tr>
<td>Precipitation, mm/d</td>
<td>2.51</td>
<td>2.74</td>
<td>2.79</td>
</tr>
<tr>
<td>Surface winds, m/s</td>
<td>5.42</td>
<td>5.13</td>
<td>5.10</td>
</tr>
<tr>
<td>Sea salt aerosols</td>
<td>Source, Tg/yr</td>
<td>5679</td>
<td>5947</td>
</tr>
<tr>
<td>Loading, Tg</td>
<td>12.1</td>
<td>12.4</td>
<td>12.2</td>
</tr>
<tr>
<td>Percent Change*</td>
<td>Source</td>
<td>−4.8</td>
<td>−0.3</td>
</tr>
<tr>
<td>Loading</td>
<td>−1.2</td>
<td>1.0</td>
<td>−0.5</td>
</tr>
</tbody>
</table>

Figure 5. Zonally averaged surface winds (m/s), precipitation (mm/d), sea-salt aerosol source (Tg/m²/s), and sea-salt aerosol loading (Gg/m²) for the current (SOM, solid line), Last Glacial Maximum (LGM, dotted line), preindustrial (PI, dashed line), and doubled carbon dioxide (DCO₂, dash-dotted line) climates.
that using daily mean winds can give us a rough estimate of the response to climate of sea-salt aerosol in other models. For the future scenarios (using 2080–2100 from the SRES A1B scenario) relative to current climate (1960–2000 for the 20th century (20C3M) simulations), we obtain a change of 48, 18, 5, 18, 17, 13, 16 and 24% in the wind speed to the power of 3.41 for the GFDL_CM2, GISS_AOM, GISS_E_R and MIROC, CRM_CM3, IAP_FGOALS1_g, IPSL_CM4 and MPI_ECHAM5 model simulations, respectively. These changes are much larger than those seen in our CCSM simulations. For the future scenarios, all models have an increase between 5 and 48% of sea-salt source, in contrast to the 3.7% decrease shown above in the detailed CCSM3 modeling study. This suggests two things: our results may be quite sensitive to the model used, and that sea salts may be quite responsive to climate in other modeling frameworks. Of course, this sensitivity study using other model results is very coarse, and simulations should be conducted with other models.

3.3. Last Glacial Maximum Sea-Salt Aerosols

In order to understand whether our model is able to simulate the changes in sea-salt aerosol which are observed in past climates, we show ice core data for changes in sea salts for the LGM compared to the current climate in Table 3 [DeAngelis et al., 1997; Petit et al., 1999; Roethlisberger et al., 2002; Parrenin et al., 2001; Schwander et al., 2001; http://www.ngdc.noaa.gov/paleo/icecore.html]. Many papers looking at sea-salt and other aerosol fluctuations use concentration in the ice cores [e.g., DeAngelis et al., 1997] in part because of problems in the derivation of flux measurements [e.g., Meeker et al., 1997]. However, at least for central Antarctic sites, where dry deposition is assumed to dominate, the atmospheric deposition of sea salts is proportional to atmospheric loading of sea salts, while the concentration in the core is the atmospheric deposition divided by the ice accumulation rate, which varies strongly during different climates. As shown in Table 3, estimated deposition ratios (LGM/current climate) are between 2 and 5 while concentration ratios are between 4 and 12 because of the large decrease in ice accumulation observed in the ice cores in the LGM relative to the current climate. Model results for precipitation can also be compared to observations: The model shows a ratio (LGM/current climate) of precipitation of \(0.2–0.3\), a larger decrease than seen in observational estimates (0.4–0.6).

The model tends to not be able to show increases in sea-salt deposition as observed at the ice cores between the LGM and current climate, similar to previous studies [Genthon, 1992; Reader and McFarlane, 2003]. As shown in Figures 7a, 7c, and 7e, this is not because of a decrease in aerosol deposition in the Southern Ocean in general, but because of the covering of open ocean close to the Greenland and Antarctic coast by sea ice (Figures 7i and 7j show the maximum (blue) and minimum (red) extent of sea ice), and a decrease in transport to the high-altitude ice core regions. Figures 7e and 7g show the LGM/current climate ratios for deposition fluxes and concentrations in the ice cores, which are the most different in the high-latitude regions where the ice cores are measured.
Figure 7
Comparisons to observed concentrations in the Southern Ocean and the South Pole (Figure 1) suggest that the model is overpredicting by a factor of 2–28 current sea-salt aerosol concentrations close to Antarctica. Precipitation comparisons show the model does a good job of capturing both large-scale precipitation in the region, and at the Dome C ice core (not shown). The modeled sodium deposition to the Dome C ice core is 0.021 g/m$^2$/yr, while observations suggest 0.0007 g/m$^2$/yr [Roethlisberger et al., 2002], showing that the model is a factor of ~30 too high. Problems with transport to Antarctica have been explored in some detail by Genthon [1994], although it appears that in our simulations the errors are in both the source (too strong of winds in the Southern Ocean), and the transport/deposition in the current climate.

The obvious reason for the discrepancy between the ratio of deposition flux in the model and observations could be that the changes in surface winds (or specifically the wind speed at 10 m) in our model may not be simulated well. Another possibility is that the parameterization based on winds at 10 m may not be the best for this problem; it may be that the sea-salt source calculation would be better done using friction velocity or another variable tied more closely to the surface momentum budget.

Additionally, there is some uncertainty in the size distribution of sea-salt sources. The ratio of sea salts in the LGM to the current climate is sensitive to the size of the aerosol in this model, with the ratio being 0.6, 0.6, 0.5, 0.2 for the size bins 1–4 (4 is the largest size) at Dome C. Most of the deposition to the ice cores is in the smaller size bins; if the size distribution were much smaller than simulated here, it may be possible to increase the modeled sea-salt ratio. If there were processes that would increase the relative production of small particles in the LGM versus the current climate, this would also impact the modeled ratios.

Closer analysis of the mean wind speeds and sea ice fraction suggests that the surface winds cubed over ocean regions are slightly larger in the LGM versus the current climate (+8%), but that the open ocean fraction is slightly smaller (~8%), and that these terms roughly cancel and make the LGM sea-salt aerosol source approximately the same as today. Additionally, the spatial distribution is roughly similar (Figure 5).

Since the source processes for the sea-salt aerosols formed from new sea ice formation is not known, we assume that the process is identical to that from open ocean sea salts in terms of size distribution and wind speed dependence. We then simulate the new sea ice sea salts for the current climate and LGM climate (using existing sea ice distributions as a proxy for new sea ice, see section 2). Results from these simulations are included in Table 3 and Figures 7b, 7d, and 7f. Note that while there are more sea salts being deposited in the LGM versus the current climate over the sea ice region, they are not being transported efficiently inland, and the modeled deposition ratios from the new sea ice formation are higher than from open ocean sea salts but lower than observed in the ice cores, even if all the sea salts come from new sea ice formation (Table 3). While there is a stronger sea ice source in the LGM versus current climate, the atmospheric loadings are also lower over Antarctica in the LGM relative to the current climate, again arguing that the model simulation has a reduced transport efficiency in the LGM relative to the current climate (Figure 8). It may be that the new sea ice formation of sea salts is dependent on processes not included in our model, such as temperature, open ocean fraction or other processes [Kaleschke et al., 2004]. These processes may favor an enhanced source during the LGM versus the current climate beyond what we model here, to overcome the reduced transport efficiency in the LGM. Or the reduced transport efficiency in the LGM in the model may be incorrect. Note that we have not made an assumption about the fraction of the sea salts come from new sea ice formation, since this is poorly known, and is not necessary for our modeling study.

**Figure 7.** (a) Current climate deposition of sea salts (annual average) in g/m$^2$/yr, (b) Current climate deposition of sea salts from the new sea ice source only, (c) LGM deposition, (d) LGM deposition from new sea ice source only, (e) LGM/current ratio for deposition fluxes (Figure 7c/Figure 7a), (f) LGM/current ratio for deposition fluxes from new sea ice source only (Figure 7d/Figure 7b), (g) LGM/current ratio for concentration in integrated precipitation, equivalent to ice core concentration ratio (Figure 7c/Figure 7a/Figure 7k), (h) similar to Figure 7g, but for new sea ice source (Figure 7d/Figure 7b/Figure 7k), (i) current climate model sea ice distributions, with maximum extent shown in blue and minimum extent shown in red (above 0.2 fraction sea ice), (j) LGM sea ice distributions (similar to Figure 7i), and (k) LGM/current precipitation.

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**Table 3.** LGM/Current Ratios in Ice Cores Versus Model Results

<table>
<thead>
<tr>
<th>Ice Core</th>
<th>Flux Ratio</th>
<th>Concentration Ratio</th>
<th>Precipitation Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Model (New Sea Ice)</td>
<td>Observed</td>
</tr>
<tr>
<td>Vostok$^{a}$</td>
<td>2.3</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Dome C$^{b}$</td>
<td>1.9</td>
<td>0.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Taylor Dome$^{c}$</td>
<td>4.8</td>
<td>0.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

$^{a}$Parrenin et al. [2001], Petit et al. [1999], and F. Parrenin (personal communication, 2005).
$^{b}$Roethlisberger et al. [2002] and Schwander et al. [2001].
$^{c}$Mayewski et al. [1996] and Stager and Mayewski [1997]. Note that changes in the accumulation rate or precipitation are not well known at Taylor Dome, so that we cannot look at deposition fluxes in the observations.
$^{d}$DeAngelis et al. [1997]. GRIP, Greenland Ice Core Project.
Also note that while the concentration ratios in ice cores may be more robust than deposition ratios in ice cores [e.g., Meeker et al., 1997], the ice core concentration ratios in the model over the high-latitude land regions are quite different than those in the model over the neighboring ocean region (if there were ice cores there), suggesting that interpreting the concentration ratios in ice cores as regional signals is not straightforward.

4. Summary and Conclusions

We show results of the inclusion of prognostic sea-salt aerosols into the NCAR CAM3, which is part of the CCSM3. Current climate model results show good agreement with available observations, with the largest biases in the Southern Ocean. Results for the current climate suggest that sea-salt aerosol distributions are not sensitive to the sea surface temperature boundary condition changes tested here (slab ocean model versus AMIP sea surface temperature) or changes in resolution between T42 (2.8° × 2.8°) and T85 (1.4° × 1.4°).

We show model results of sea-salt aerosol sensitivity to climate for the Last Glacial Maximum, preindustrial, and doubled carbon dioxide climate using the slab ocean model version of the CCSM3. The source of these natural aerosols is proportional to surface wind cubed, but surprisingly show <5% globally integrated change between different climates. This is due to small changes in globally integrated surface winds, and changes in sea ice extent. Sensitivity studies using daily averaged winds from different IPCC models suggest that the modeled daily mean ocean winds to the 3.41 power will change between 5 and 48% in the future, suggesting that this study should be done with other modeling frameworks in the future. A 48% change in sea salts in the future due to climate change is a substantial change in aerosol optical depth from anthropogenic forcing.

The fourfold to twelvefold increases in the LGM relative to the current climate observed in sea-salt concentrations in the ice cores, or estimates of changes in deposition cannot be matched in this model. Some improvement in the model/data comparison is achieved if the generation of sea-salt aerosols from new sea ice formation is included, but the LGM/current climate ratios are still considerably underestimated by the model. The model/data discrepancies may be due to (1) deficiencies in the sea-salt source, assumed size distribution and deposition in the model, (2) deficiencies in the surface wind changes in the CCSM3 at high latitudes, (3) deficiencies in the model transport from the coastal ocean to the high-altitude locations of the ice cores or (4) problems in the interpretation of the ice core data. In order to better understand the response of natural aerosols to climate change, more simulations should be conducted using different modeling frameworks.

Acknowledgments. We thank Dennis Savoie and the AERONET network PIs for making available the in situ sea-salt aerosol concentrations and Sun photometer measurements used in this study. We thank Sam Levis, David Fillmore, Masaru Yoshikawa, Paul Ginoux, Chao Luo, Bette Otto-Bliesner, Jim McCaa, and Alexandra Smirnov for contributions to this paper. We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the ISCCP/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy. The manuscript benefited from the comments of four anonymous reviewers and Peter Hess.

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