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[1] A thermomechanical ice sheet model (ISM) is used to investigate the sensitivity of the Laurentide and Fennoscandian ice sheets to tropical sea surface temperature (SST) perturbations during deglaciation. The ISM is driven by surface temperature and precipitation fields from three different atmospheric general circulation models (AGCMs). For each AGCM, the responses in temperature and precipitation over the ice sheets nearly compensate, such that ice sheet mass balance is not strongly sensitive to tropical SST boundary conditions. It was also found that there is significant variation in the response of the ISM to the different AGCM output fields. *INDEX TERMS:* 1655 Global Change: Water cycles (1836); 4267 Oceanography: General: Paleoceanography; 4255 Oceanography: General: Numerical modeling. **Citation:** Rodgers, K. B., S. Charbit, M. Kageyama, G. Philippon, G. Ramstein, C. Ritz, J. H. Yin, G. Lohmann, S. J. Lorenz, and M. Khodri (2004), Sensitivity of Northern Hemispheric continental ice sheets to tropical SST during deglaciation, *Geophys. Res. Lett.*, *31*, L02206, doi:10.1029/2003GL018375.

1. Introduction

[2] Although the CLIMAP reconstruction [*CLIMAP Project Members*, 1981] implied that LGM tropical SSTs were only moderately cooler than present-day SSTs, there is now an emerging consensus that tropical SSTs were 3°C–6°C cooler than they are at present [*Lea et al.*, 2000]. *Yin and Battisti* [2001] and *Rodgers et al.* [2003] demonstrated that for atmospheric general circulation models (AGCMs) configured for LGM boundary conditions [*Joussaume and Taylor*, 2000], there is sizeable sensitivity of atmospheric circulation and surface temperatures over the Laurentide ice sheet (LIS) in response to tropical SST perturbations. Here we use the output from three AGCMs to force a thermomechanical ice sheet model (ISM) to test the sensitivity of continental ice sheet mass balance to tropical SST boundary conditions during deglaciation.

2. Model Description

[3] The thermomechanical ISM is GREMLINS (GREnoble Model for Land Ice of the Northern hemisphere), identical to that described in *Ritz et al.* [1997]. The three AGCMs used are LMDZ [*Donnadieu et al.*, 2002], ECHAM3 [*Roeckner et al.*, 1992; *Lohmann and Lorenz*, 2000], and the Community Climate Model version 3.6 (CCM) [*Kiehl et al.*, 1996]. The effective horizontal grid-point resolution is 72 × 46 for LMDZ, 128 × 64 for ECHAM3, and 48 × 48 for CCM3. For each AGCM, three "snapshot" calculations have been performed:

[4] (1) CTL: control run with modern AMIP boundary conditions;

[5] (2) LGM_WTP (LGM with warm tropical perturbation): PMIP boundary conditions with CLIMAP SSTs;

[6] (3) LGM: same as (2), but with tropical SSTs cooled uniformly by 3°C; this cooling was applied between 15°N and 15°S for CCM3, and between 30°N and 30°S for ECHAM3 and LMDZ.

[7] The 3°C tropical temperature difference between experiments (2) and (3) follows the experimental design

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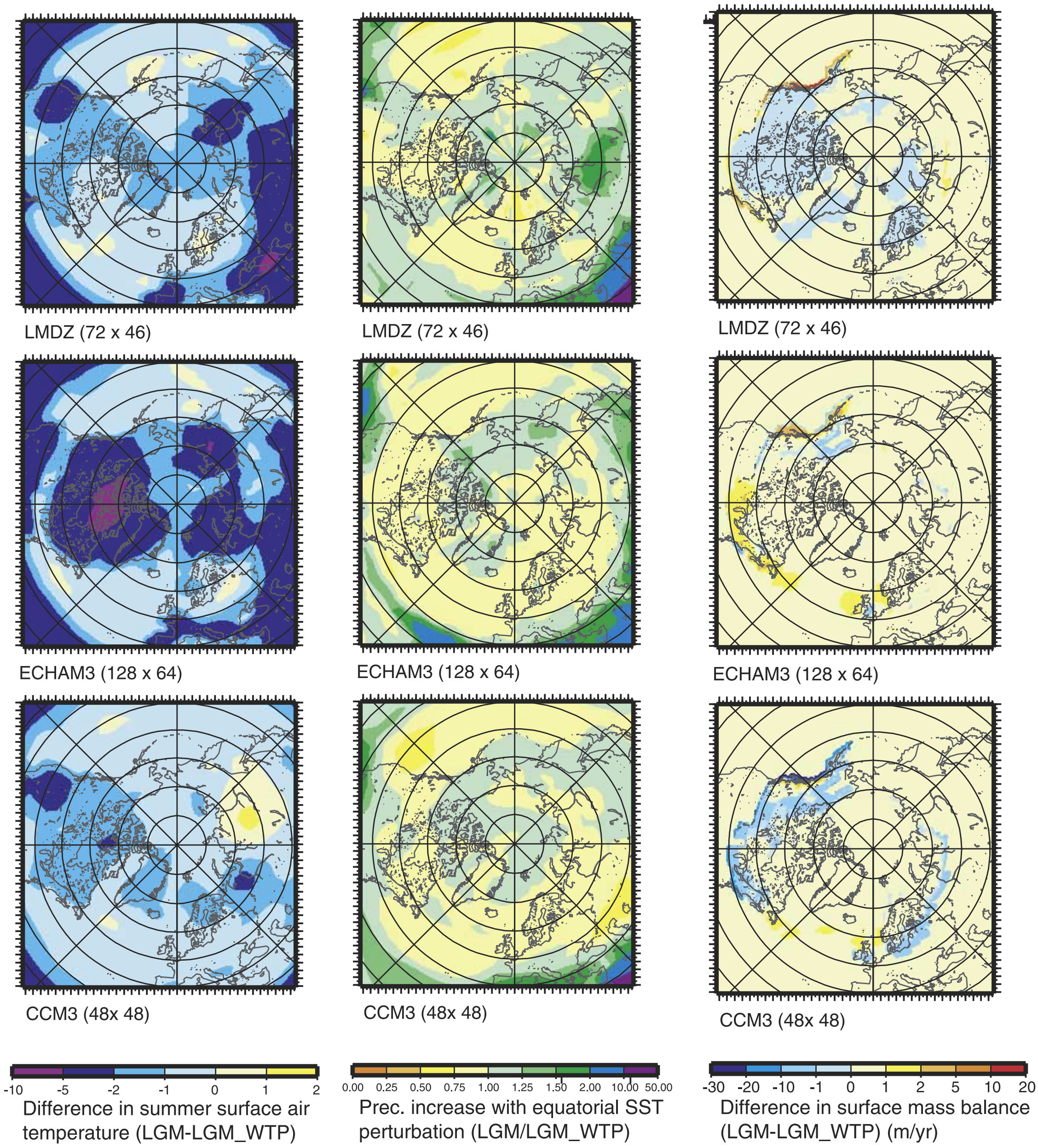

Figure 1. Perturbations: first column [LGM minus LGM_WTP]: (a) LMDZ ΔT_{jja}; (b) ECHAM3 ΔT_{jja}; (c) CCM3 ΔT_{jja}; second column [LGM/LGM_WTP]: (d) LMDZ ΔP_{ann}; (e) ECHAM3 ΔP_{ann}; (f) CCM3 ΔP_{ann}; third column; [LGM minus LGM_WTP]: (g) LMDZ Δmass_balance, (h) ECHAM3 Δmass_balance; (i) CCM3 Δmass_balance.

of *Rodgers et al.* [2003]. For the ECHAM3 and LMDZ cases, the AGCM is run for 15 years, and a climatology was constructed from the last 10 years. For CCM3, the last 17 years of a 20-year run were used.

[8] The ISM was forced with climatological AGCM fields (annual mean surface temperature, summer surface temperature, and annual mean precipitation, i.e., T_{ann}, T_{jja}, and P_{ann}, respectively), as described in *Charbit et al.* [2002]. Two separate deglaciation scenario calculations were performed for each of the three AGCMs. The first is DEGL_WTP (deglaciation using CLIMAP boundary conditions for the glacial maximum), and the second is DEGL (deglaciation using cooled tropics for glacial maximum boundary conditions). For each case, the temporal interpolation for the atmospheric fields used the GRIP-δ^{18}O record.

3. Results

[9] We begin by considering the difference in T_{jja} associated with the tropical SST perturbation (LGM-LGM_WTP) for LMDZ (Figure 1a), ECHAM3 (Figure 1b), and CCM3 (Figure 1c). For each model, there is a cooling over the majority of the Northern Hemisphere in response to cooler SSTs, with the largest perturbations (in excess of -5°C) for ECHAM3. The response over the Fennoscandian ice sheet (FIS) is weaker than the response over the LIS for each of the three models.

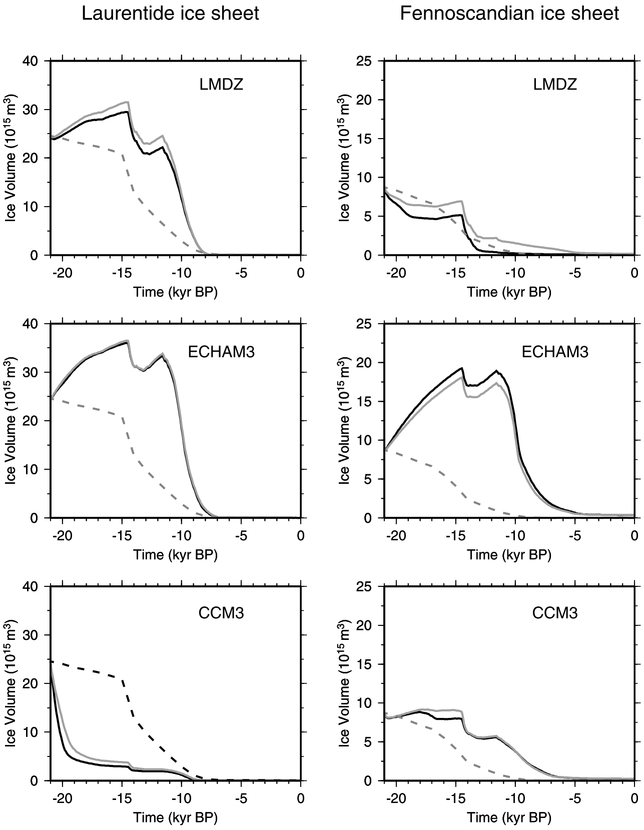

Figure 2. Deglaciation scenarios (DEGL = grey line, DEGL_WTP = black line, *Peltier* [1994] data = dashed line): (a) LIS for LMDZ; (b) LIS for ECHAM3; (c) LIS for CCM3; (d) FIS for LMDZ; (e) FIS for ECHAM3; (f) FIS for CCM3.

[10] Next we consider the ratio of glacial maximum P_{ann} (LGM/LGM_WTP) for each AGCM. With cooler tropics, the LMDZ model (Figure 1d) reveals a decrease in P_{ann} over the Great Lakes and Hudson Bay, but a slight increase over the east and west coasts of North America. For ECHAM3 (Figure 1e) P_{ann} decreases across North America north of 45°N, except for the northernmost reaches of North America. For CCM3 (Figure 1f), P_{ann} decreases between between 45°N and 65°N across North America. P_{ann} increases over the FIS to cold tropical temperatures under glacial maximum conditions for the LMDZ model (Figure 1d). This is in contrast to the ECHAM3 (Figure 1e) and CCM3 (Figure 1f) models, which both show a decrease.

[11] We next consider the surface mass balance anomalies (accumulation minus ablation, in m/y, with values equal to zero in ice free regions) for the three experiments (shown as LGM-LGM_WTP). For LMDZ (Figure 1g), the values are negative over nearly all of Canada (including the Great Lakes) and Scandinavia. For the continental ice sheets, this means that the loss of mass is greater for colder tropical conditions. With ECHAM3 (Figure 1h), the anomalies over Canada are of opposite sign of those found with LMDZ. For CCM3 (Figure 1i), the sign of the anomalies is similar to that found with LMDZ.

[12] The results of the deglaciation scenarios as calculated by the ISM are shown in Figure 2, with the reconstruction of *Peltier* [1994] shown as a dashed curve. For the LMDZ model (Figure 2a), the DEGL scenario (grey line) for the LIS shows a temporal structure which is very similar to the DEGL_WTP scenario (black line). Both curves show an increase of 20%–30% over the first 6kyrs, followed by a non-monotonic decrease. For ECHAM3 (Figure 2b), both the DEGL and DEGL_WTP scenarios exhibit a sharp increase of 35%–45% over the first 6kyrs, followed by a non-monotonic decrease. For CCM3 (Figure 2c), both scenarios yield an 80% melting of the Laurentide ice sheet between 21 kyr and 15 kyr. For the FIS, the DEGL (grey line) and DEGL_WTP (black line) scenarios for LMDZ (Figure 2d) exhibit a similar sharp drop in ice volume at 14 kyr. For ECHAM3, the temporal structure of the DEGL and DEGL_WTP curves is nearly identical for the FIS, and the same holds for CCM3.

[13] It is clear from Figure 2 that inter-AGCM differences are larger than differences found with the sensitivity tests for any particular model. In order to understand this, we consider differences between glacial maximum and modern surface temperature for the AGCMs in Figure 3. This is done by comparing the runs which use CLIMAP

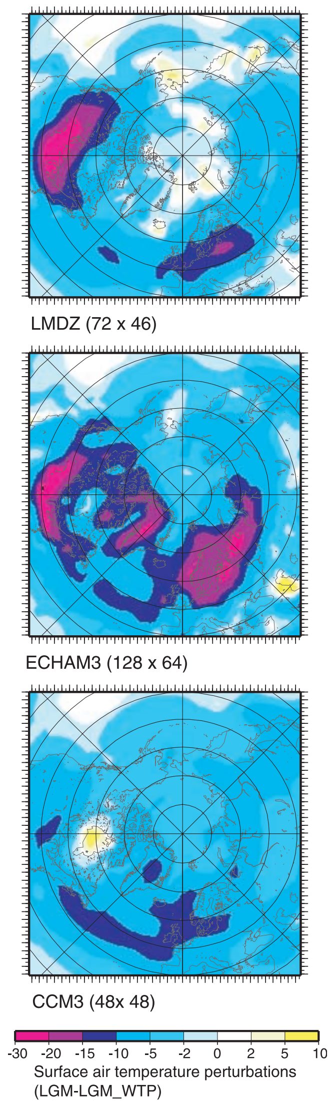

Figure 3. Surface air temperature perturbation ΔT_{jja} (LGM_WTP minus CTL): (a) LMDZ; (b) ECHAM3; and (c) CCM3.

(LGM_WTP) and AMIP (CTL) boundary conditions. Summer (JJA) temperatures over the Northern Hemisphere, corrected to sea level [following the method of *Charbit et al.*, 2002], are shown for LMDZ (Figure 3a), ECHAM3 (Figure 3b), and CCM3 (Figure 3c). Although all three reveal a general cooling for the LGM relative to the modern, with maxima over the subpolar North Atlantic, there are important differences. For LMDZ, the perturbation amplitude over the region between the Great Lakes and northern Hudson Bay ranges from 25°C to approximately 5°C. A similar temperature perturbation structure in this region is found for ECHAM3, although the amplitude is slightly weaker than it was for LMDZ. For CCM3, the response is quite different, and surface temperatures are in fact warmer over Hudson Bay for glacial boundary conditions than for the modern. This is due to the fact that the altitude correction made by applying a constant lapse rate to compute the temperatures at sea level is greater than the difference of temperatures between the glacial maximum and the present.

[14] Over the FIS, all three models show a strong cooling for the LGM boundary conditions relative to the modern. For each case, Scandinavia is of order 5–10°C cooler than Hudson Bay, with this signal being largest for ECHAM3. This response for the three models is related to the proximity to the ocean temperature perturbations between Greenland and Norway, which are the regions of maximum cooling for each of the models.

4. Discussion

[15] As was previously shown by *Rodgers et al.* [2003] for the ECHAM3 model, a spatially uniform tropical SST perturbation changes atmospheric moisture supply, and thus the radiation balance over the ice sheet, impacting T_{jja}. However, changes in moisture supply also induce changes in P_{ann}. In terms of net ice accumulation, the ΔT_{jja} and ΔP_{ann} perturbations have a compensating effect, so that the ice sheet mass balance changes very little under a tropical SST perturbation.

[16] We have seen in Figure 2 that inter-model differences are larger than the separate perturbation experiments for each individual AGCM. In an earlier study of deglaciation, *Charbit et al.* [2002] analyzed the results of *Pollard et al.* [2000], who found negative mass balance for the majority of the AGCMs involved in PMIP. *Charbit et al.* [2002] argued that the problems are likely linked to the choice of the initial topography [ICE-4G, *Peltier*, 1994]. This topography dataset includes several regions which are below the equilibrium line, and in these regions the ablation rate can be substantial.

[17] We have ignored the issue of the relative phasing of tropical and extratropical warming during deglaciation. As the GRIP $\delta^{18}O$ data is used to interpolate between snapshot AGCM fields, the tropical SST changes are required to occur in phase with high latitude changes during deglaciation. This implicit phase-locking is inconsistent with paleoproxy data which suggests that the tropical SST warming could be leading Northern Hemispheric ice sheet melting during deglaciation [*Lea et al.*, 2000; *Visser et al.*, 2003]. We have not directly tested whether imposing a tropical SST perturbation, while maintaining LGM extratropical boundary conditions, can trigger changes in ice sheet mass balance, i.e., the deglaciation scenario of *Rodgers et al.* [2003]. Testing this scenario is further complicated by the fact that our model configuration precludes potentially important processes such as ice-albedo feedback. ISM sensitivity to changes in the spatial pattern of tropical SST perturbations under glacial maximum boundary conditions is left as a subject for further investigation.

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