Title

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Authors

Pritchard, M. S.
Bush, A. B.
Marshall, S. J.

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Neglecting ice-atmosphere interactions underestimates ice sheet melt in millennial-scale deglaciation simulations

Michael S. Pritchard,[1] Andrew B. G. Bush,[2] and Shawn J. Marshall[3]

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[1] Dynamic and thermodynamic interactions between the atmosphere and underlying ice sheets are generally not represented in the traditional one-way boundary condition forcing used to drive ice sheet models. This shortcoming is investigated through a series of idealized millennial-scale deglaciation simulations designed to isolate the mechanisms regulating the deglaciation timescale of the Laurentide ice sheet. Sensitivity experiments indicate that the conventional use of one-way (non-interactive) atmospheric forcing fields leads to an unrealistically insensitive melt response in the ice sheet model even when atmospheric carbon dioxide is set to modern preindustrial levels and Earth's angle of obliquity is set to its early Holocene value. A more realistic deglaciation timescale is obtained only through the application of a new two-way (interactive) asynchronous ice-atmosphere coupling scheme and a seasonal ice albedo parameterization that accounts for the observed darkening of ice in the moist summertime ablation zone. **Citation:** Pritchard, M. S., A. B. G. Bush, and S. J. Marshall (2008), Neglecting ice-atmosphere interactions underestimates ice sheet melt in millennial-scale deglaciation simulations, *Geophys. Res. Lett.*, *35*, L01503, doi:10.1029/2007GL031738.

1. Introduction

[2] Interactions between our atmosphere and continental ice sheets have the potential to generate climate variability on centennial to millennial timescales [e.g., *Crowley*, 1984; *Crowley and North*, 1990; *Roe and Lindzen*, 2001]. However, no tool currently exists that can address the full dynamic and thermodynamic coupling of these two climate components on millennial timescales. Since ice sheet flows are orders of magnitude slower than atmospheric motions, continental ice is usually represented in climate simulations as a static boundary condition within atmospheric general circulation models (AGCMs) [e.g., *Bromwich et al.*, 2004; *Shinn and Barron*, 1989]. Likewise, ice sheet models (ISMs) are typically driven by temperature and precipitation fields derived offline from GCM experiments or proxy data [e.g., *Parizek and Alley*, 2004; *Forsstrom et al.*, 2003; *Forsstrom and Greve*, 2004; *Huybrechts et al.*, 2004; *Gregory et al.*, 2004]. The only atmospheric interaction built into this "one-way" climate forcing scheme is through implementation of the lapse rate effect, whereby climatological air temperatures are vertically interpolated along a constant atmospheric lapse rate to account for changes in the height of the ice sheet surface. Other dynamic and radiative ice-atmosphere interaction processes are not represented in this conventional one-way climate forcing scheme.

[3] Interactive "two-way" coupling is the only way to fully simulate radiative and dynamic interactions between ice sheets and the atmosphere. However, the development of interactively coupled ISM-AGCMs is nontrivial because of the disparity in timescales of the two media. Only one attempt had been made in the context of a future climate simulation of the Greenland ice sheet [*Ridley et al.*, 2005]; in this study atmosphere-ice interactions acted as a stabilizing influence to future deglaciation due to changes in atmospheric dynamics.

[4] We present results based on several simulations of the deglaciation of the Laurentide ice sheet. The framework of *Ridley et al.* [2005] is expanded upon by incorporating variable ice albedos to capture the atmospheric temperature response to albedo depression in the moist ablation zones [*Knap and Oerlemans*, 1996; *Stroeve et al.*, 1997; *Greuell and Knap*, 2000; *Stroeve*, 2001; *Stroeve et al.*, 2001]. Idealistically warm atmospheric conditions drive sensitivity tests to compare the ice sheet response to conventional one-way climate forcing and to an AGCM-ISM coupling scheme that uses constant ice albedos. None of these cases is able to produce realistic deglaciation in light of the timescale of the last deglaciation, on the order of 10 kyr [*Dyke et al.*, 2002]. Only when interactive coupling and seasonally varying ice albedos are included does simulated meltback proceed on a realistic timescale.

2. Model Description

[5] The AGCM that we employ is the Community Atmosphere Model v3.0 (CAM3) [*Collins et al.*, 2006] at T31 resolution (3.7° lat × 3.75° lon) on 25 vertical hybrid sigma levels. Orbital parameters and greenhouse gas mixing ratios for CO_2, CH_4 and N_2O are imposed; present-day values are from *Collins and Rasch* [2004] and LGM values are from *Petit et al.* [1999].

[6] The ISM is the 3-D thermo-mechanic model of *Marshall and Clarke* [1997]. Ice flows according to viscous creep rheology governed by Glen's flow law with an exponent of $n = 3$ [*Glen*, 1958] and is subject to a sliding condition for the basal velocity when the pressure melting point at the base of the ice sheet is attained [*Marshall et al.*, 2002]. Basal topography responds to the evolving ice load on a mantle deformation timescale of 3000 yr through interactive coupling to an isostatic mantle-lithosphere model based on *Wu and Peltier* [1982] and *Peltier* [1985]. A

[1]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA.
[2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada.
[3]Department of Geography, University of Calgary, Calgary, Alberta, Canada.

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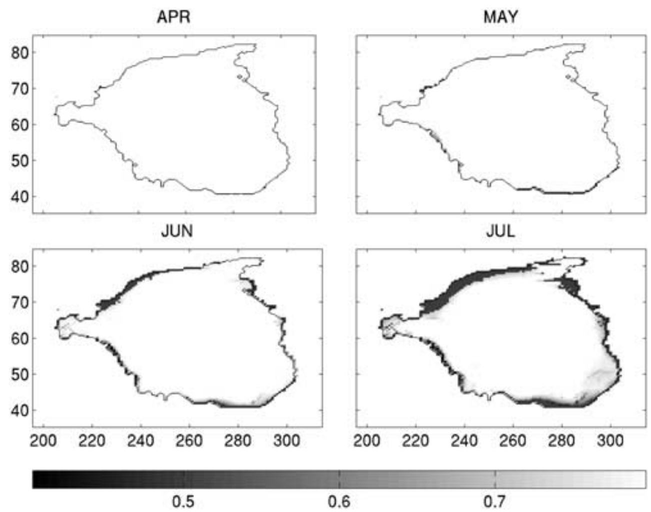

Figure 1. Monthly ice albedo maps (latitude versus longitude) computed during a representative ISM simulation of the Laurentide ice sheet that incorporates the new melt-based ice albedo parameterization. The darkening of ice in the marginal ablation zone is clearly evident as the snowpack melts in this region during the transition to summer.

reconstructed Laurentide Ice Sheet is used as an initial ice state on a North American domain with a longitudinal resolution of 1°, a latitudinal resolution of 0.5°, and 20 vertical ice levels. Near-surface temperature fields from the atmospheric model are linearly interpolated to the evolving ice surface height assuming a constant lapse rate of 6°C/km, driving snow and ice melt through monthly positive-degree-day (PDD) melt parameterization [e.g., *Huybrechts et al.*, 2004].

[7] A coupling infrastructure was developed to communicate the topographic and radiative characteristics of the simulated ice sheet to the CAM3. Ice sheet topography was implemented in the CAM3 by imposing a spectrally decomposed version of the high-resolution ice topography on the surface geopotential boundary condition. Land-surface characteristics in the CAM3 were modified by adjusting the T31 fractional glacier coverage and soil textures of the higher resolution ISM domain. An asynchronous coupling scheme linked separate AGCM and ISM states to produce an interactive coupled integration: Atmospheric dynamics were equilibrated to an initial ice sheet state on a 20 yr timescale, whereafter the climatological annual cycle from this AGCM segment was used to drive 1 kyr of ice sheet evolution and the process repeated. The 1 kyr coupling interval allows sufficient time for the ice sheet to react to the climate update, while being appreciably smaller than the timescale of glacial inception or demise. We note that a more frequent coupling interval would be warranted in atmosphere-ice sheet studies that incorporate mechanisms for rapid climate change (e.g., via volcanic or anthropogenic radiative forcing, or interactive ocean dynamics).

[8] The default albedo for glacier land types in the land component of CAM3 is 0.85, which is on the upper end of observed ice sheet albedos and fails to capture the observed low albedos in the moist marginal ice sheet ablation zones during the summer melt season. An alternative melt-based ice albedo parameterization is used in the final experiment of our AGCM-ISM coupled simulations. Monthly snow accumulation and melt are tracked through the annual cycle to distinguish between fresh dry snow, wet snow, and bare ice in order to parameterize the albedo as

$$\alpha(N) = \max\begin{cases}\alpha_o \\ \alpha_f - \beta\sum_{n=1}^{N} m_s(n)\end{cases}, \qquad (1)$$

where the sum is over months (n = 1 corresponds to September of the preceding year), m_s is the monthly snow melt, and β = 0.5. Dry snow has an albedo of α_f = 0.85 and wet snow darkens in proportion to cumulative melt, following equation (1). A minimum snow albedo of α_o = 0.4 and a constant albedo of α_i = 0.5 for exposed glacial ice are chosen. The latter value is typical for glacial ice [*Paterson*, 1994], but values as low as 0.1 and 0.2 are common if there are meltwater ponds or large concentrations of impurities [e.g., *Brock et al.*, 2000; *Oerlemans and Klok*, 2002]. The value of 0.5 is close to what is expected for relatively clean ice on polar ice sheets.

[9] In low melt regimes (e.g. winter, over the ice sheet interior) the ice albedo remains close to the default value of 0.85. However, a low-albedo fringe of moist, radiatively absorptive snowpack develops near the marginal ablation zone during the transition from winter to summer (Figure 1). This seasonal change better represents observations [*Knap and Oerlemans*, 1996; *Greuell and Knap*, 2000] and constitutes an improvement in the AGCM-ISM coupling scheme developed here.

3. Description of Simulations

[10] Two persistently warm atmospheric scenarios were used to drive conventional non-interactive 15 kyr deglaciation simulations. Since the two primary sources of radiative energy that contributed to the actual deglaciation of the Laurentide ice sheet were atmospheric greenhouse gases and orbital variations, these ice sheet simulations were designed to isolate the sensitivity of the ISM melt response to extrema in both of these sources. In the first scenario (1WAY-GHG), modern orbital parameters are imposed and concentrations of CO_2 and CH_4 are fixed at their present-day values, bracketing the upper limit of natural greenhouse gas variability through the Late Quaternary glacial cycles [*Petit et al.*, 1999]. In the second scenario (1WAY-INS), greenhouse gas concentrations are reduced to their (minimum) LGM values, while insolation over the ice sheet during the summer melt season is at its maximum value since the LGM by imposing orbital parameters from 10,000 BP. In both simulations, the excess radiative forcing over the ice sheet should in theory lead to substantial ice melt, thereby providing a test of the overall ISM melt response under conventional offline climate forcing, as well as its relative sensitivity to orbital versus greenhouse gas forcing extrema during the Last Deglaciation.

[11] The influence of radiative and dynamic ice-atmosphere interactions is further explored for the high GHG scenario by comparing the 1WAY-GHG simulation with an analogous interactively coupled ice-atmosphere integration (2WAY-GHG). In this simulation, near-surface temperature

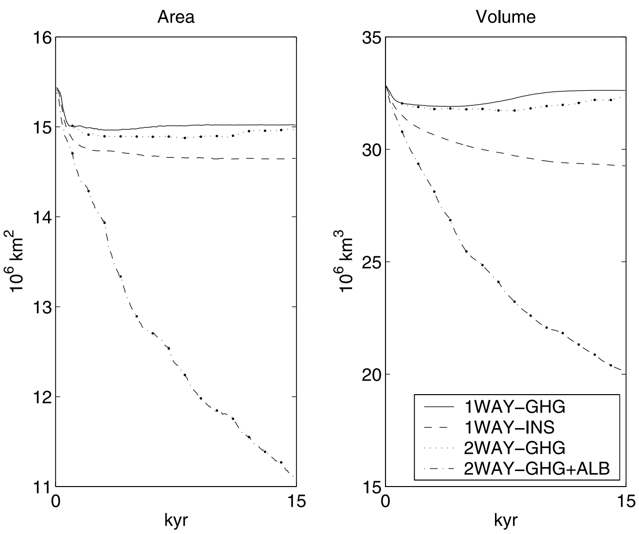

Figure 2. (left) Area and (right) volume time series comparing the two uncoupled ice sheet simulations, 1WAY-GHG (high greenhouse gas, modern orbital forcing) and 1WAY-INS (10 kyr BP maximum summer insolation, low greenhouse gas), to the two interactively coupled ice-atmosphere simulations, 2WAY-GHG (asynchronous coupling enabled) and 2WAY-GHG+ALB (same as 2WAY-GHG but incorporates a seasonal melt-based ice albedo parameterization into the coupling scheme). The asynchronous coupling frequency is indicated by solid points. Only the 2WAY-GHG+ALB simulation results in the expected large ISM melt response to idealistically warm atmospheric conditions.

fields from the atmospheric model drive ice melt and, in turn, ice albedo influences the near-surface temperature. This is at the heart of the two-way coupling scheme.

[12] In a fourth and final experiment, this coupled ice-atmosphere simulation is repeated with the addition of seasonally varying ice albedos (2WAY-GHG+ALB).

4. Results

[13] Figure 2 contrasts the Laurentide ice sheet volume and area evolution during each of the four 15 kyr simulations described above. In each, the initial response to the warm atmospheric forcing is a rapid retreat and steepening of the ice margin; after this initial shock, volume and area trajectories for the four scenarios diverge.

[14] For the non-interactive simulations driven by offline idealized warm atmospheric forcing (1WAY-GHG and 1WAY-INS), neither the greenhouse gas-rich atmosphere nor high summer insolation resulted in substantial deglaciation. However, 1WAY-INS did result in a much larger melt response ($\Delta V = -10.1\%$) than 1WAY-GHG ($\Delta V = -0.9\%$), which may suggest that continental ice sheets are more sensitive to changes in the Earth's orbit than to changes in greenhouse gas concentrations during a glacial cycle.

[15] The ice sheet melt response to greenhouse and orbital radiative forcing of the climate is mediated by radiative and dynamic controls on the air temperature in the evolving ice sheet ablation zones. Due to the seasonality of ice melt and growth, the seasonality of the forcing fundamentally impacts the response. For instance, radiative forcing in the orbitally forced warm atmospheric scenario is concentrated during the summer ablation season and therefore results in a larger ice melt signal than the annually invariant greenhouse gas forcing. The unrealistically low melt response in both the 1WAY-GHG and 1WAY-INS experiments suggests a negative bias in the air temperature due to some misrepresentation of the energy balance at the ice sheet surface in these model configurations.

[16] We hypothesize that ice-atmosphere interactions, which were neglected under conventional one-way climate forcing in the 1WAY simulations, are likely important pathways for energy transfer that impact the air temperature above the ice sheet surface. This notion is confirmed by comparing the 2WAY-GHG and 1WAY-GHG time series in Figure 2. In comparison with 1WAY-GHG there is more than a tripling of the ISM melt response in the 2WAY-GHG simulation ($\Delta V = -2.8\%$ as opposed to $\Delta V = -0.9\%$ in 1WAY-GHG).

[17] Although deglaciation is modestly enhanced due to interactive dynamics in the 2WAY-GHG experiment, the overall melt is still implausibly low given the extreme nature of the atmospheric forcing. This failure to produce substantial deglaciation on a realistic timescale is attributed to the use of temporally invariant ice albedos. Although this procedure is common practice in atmospheric modeling, it effectively underestimates the near-surface air temperature above the ice sheet by neglecting summertime albedo reduction in the ablation zones. By including this atmosphere-ice interaction via the seasonal ice albedo parameterization described in section 2, a significantly improved melt response is achieved (Figure 2; 2WAY-GHG+ALB vs. 2WAY-GHG) with widespread deglaciation occurring within a realistic timeframe. Reduced marginal summertime ice albedos raise the overlying atmospheric temperature in a manner that is precluded if the atmosphere is not allowed to change as the ice sheet albedo field evolves.

[18] In contrast to the recent findings of *Ridley et al.* [2005], we find that two-way, ice-atmosphere interactions result in a destabilizing influence during deglaciation. *Ridley et al.* [2005] noted that the stabilizing effect of interactive ice dynamics (on the retreat of the Greenland ice sheet) was linked to the action of convective cells driven by the summertime convergence of oceanic winds onto the exposed ice sheet interior. Whereas this effect may have been important for the late stages of the retreat of the Greenland ice sheet, in our simulations it is not a significant factor. This is likely due to geographic differences; the development of summertime convective cells straddling the ice boundary at the sensitive southern Laurentide margin is hindered by a strong along-margin mean wind field and a lack of convergent surface winds. The net effect of interactive atmospheric coupling for Laurentide ice sheet deglaciation is instead a destabilizing influence on ice retreat. Whereas under a fixed ice albedo treatment this destabilizing effect is modest, it is greatly amplified when seasonal variations of marginal ice albedos are incorporated into the coupling infrastructure. This seasonal albedo parameterization is an improvement upon the standard approach and in our coupled simulations is key to simulating the retreat of

the Laurentide ice sheet within the constraints of its known timescale of deglaciation.

5. Conclusions

[19] Understanding the coupling between climate and cryosphere is a high scientific priority. We have addressed one aspect of this problem by investigating the role of ice-atmosphere interactions during the simulated demise of a massive North American ice sheet subjected to idealistically warm atmospheric conditions. We find that it is not possible to induce realistic deglaciation without the use of a two-way interactive ice-atmosphere coupling scheme that adequately represents the radiative forcing by seasonal modulations in ice albedo near the ice sheet margin. This finding represents an important step forward in the ongoing development of Earth system models that incorporate interactive cryospheric components.

[20] Ice sheet models are in their infancy due to uncertainties surrounding the treatment of glacier dynamics, ice streams and iceberg calving. These processes are intimately connected to melt and it is prudent to note that their sensitivity to atmospheric coupling was unresolved in this study, and remains uncertain. Further study is also needed to test the sensitivity of the coupled ice-atmosphere model to free parameters in the albedo scheme and to its coupling frequency. More physically based albedo models that depend explicitly on snow age and impurity content also need to be pursued and tested.

[21] Our results suggest that prior ice sheet modeling studies that employ either one-way climate forcing or seasonally invariant ice albedos may have underestimated melt rates. For instance, high resolution AGCM output used to drive offline simulations of the Greenland ice sheet [e.g., *Gregory and Huybrechts*, 2006] exhibit a cooling trend in the ice sheet ablation zone; the results presented here suggest the opposite should occur. The impact of seasonal ice albedo variability on predictions of the fate of the Greenland ice sheet is an important open question- both through its direct impact on melt as described here, and through potential associated impacts on glacier dynamics and iceberg calving.

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A. B. G. Bush, Department of Earth and Atmospheric Sciences, University of Alberta, 126 Earth Sciences Building, Edmonton, AB, Canada T6G 2E3.
S. J. Marshall, Department of Geography, University of Calgary, 2500 University Drive NW, Calgary, AB, Canada T2N 1N4.
M. S. Pritchard, Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA. (mikepritchard@ucsd.edu)