Sea glacier flow and dust transport on Snowball Earth

Dawei Li[1] and Raymond T. Pierrehumbert[1]

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[1] Accumulation of dust on the surface of ice in the tropics has been proposed as a possible mechanism for the termination of Neoproterozoic Snowball Earth episodes. This Mudball hypothesis relies on the assumption that sea glacier flow transports dust to the tropical ablation zone, leading to the accumulation of a dust moraine there and consequent lowering of tropical albedo. Here, we use a 1-D sea-glacier flow model to simulate the ice thickness and flow on a globally glaciated Earth, and study the dust transport associated with the ice flow. Dust is entirely confined to a meteoric ice layer which does not exchange water with the ocean. Dust falling onto the surface of this layer is carried downward with the ice flow in extratropical regions, carried equatorward by the global ice flow, and re-emerges on the top of the ice in the tropical ablation zone. The ice flow acts as a dust conveyor belt which converges dust to tropics, resulting in an amplification of effective tropical dust flux by a factor of 2 to 20 over the global average. This lends support to the Mudball hypothesis. **Citation:** Li, D., and R. T. Pierrehumbert (2011), Sea glacier flow and dust transport on Snowball Earth, *Geophys. Res. Lett.*, *38*, L17501, doi:10.1029/2011GL048991.

1. Introduction

[2] Geological data suggests that twice during the Neoproterozoic Era (around ~720 Ma and ~635 Ma), the Earth may have succumbed to global glaciation severe enough to freeze over tropical oceans [*Hoffman and Schrag*, 2002]. It is far from clear that the amount of CO_2 that could plausibly accumulate during a Neoproterozoic Snowball event would be sufficient to cause deglaciation [*Pierrehumbert*, 2004, 2005; *Pierrehumbert et al.*, 2011]. Geological and geochemical constraints on CO_2 accumulation together with factors governing the deglaciation threshold, are reviewed by *Pierrehumbert et al.* [2011]. As an alternative to requiring extremely elevated CO_2 concentrations, *Abbot and Pierrehumbert* [2010] proposed the Mudball hypothesis for deglaciation, in which the tropical ablation zone which appears in Snowball Earth general circulation models (GCM), leads to the formation of a dust layer on the top of ice and significantly lowers the albedo. They found that a tropical dust layer of this sort could lower the CO_2 deglaciation threshold to $pCO_2 = 0.01–0.1$ bar in the two GCMs studied.

[3] *Abbot and Pierrehumbert* [2010] imposed the hypothesized dust moraine by fiat rather than computing it from a dust and ice model. The purpose of this Letter is to study the effect of the transport of dust by viscous sea-glacier flow, and to obtain a quantitative estimate of the associated dust accumulation rate. The calculation is carried out by adding a dust transport module to a reimplementation of the sea glacier flow model formulated by *Goodman and Pierrehumbert* [2003]. The ice/dust model is described in section 2. We present results from the model in section 3, and discuss the implications of these results in section 4.

2. Methods

[4] The ice flow model follows the one-dimensional zonally symmetric formulation of *Goodman and Pierrehumbert* [2003]. (In the course of re-implementing the model, we discovered and corrected a coding error in the treatment of the back-pressure term in the implementation used for *Goodman and Pierrehumbert* [2003]. For meridionally isothermal ice, the coding error has no effect, but when ice is colder (and stiffer) towards the poles, the erroneous back pressure is too large at the pole, and too small at the equator, resulting in excessive variations in ice thickness. A detailed comparison between the original and corrected simulation is given in the auxiliary material.[1] When run with identical surface forcing, the correction makes the ice thickness significantly more uniform in the globally glaciated case, but does not much change the ice velocity. The correction does not affect the results of *Goodman* [2006], which were based on an independently coded ice model. Additional issues concerning the proper formulation of sea glacier dynamics are also noted in the auxiliary material, and a typographical error in the statement of the equations by *Goodman and Pierrehumbert* [2003] is corrected.) It consists of a prognostic equation for the ice thickness h driven by depth independent meridional ice velocity v and net mass balance m_t at the top and m_b at the bottom, expressed as thickness per unit time. The full set of model equations and rheological constants are reproduced in the auxiliary material for the convenience of the reader.

[5] The annual mean precipitation-minus-evaporation (P-E) and surface air temperature are defined from the output of a Snowball Earth simulation carried out with the FOAM (Fast Ocean Atmosphere Model) GCM [*Jacob*, 1997], as shown in Figures 1a and 1b. The run is done with 100 mb CO_2 in the atmosphere, and with the FOAM standard albedo as described by *Pierrehumbert et al.* [2011]. All of these fields are symmetrized about the equator, and the $P - E$ is recentered so that its area-weighted global mean comes out zero, which keeps the surface water budget in balance. Based on these forcing fields, we calculate m_t and m_b as by *Goodman and Pierrehumbert* [2003]. m_b represents basal freezing or melting, and is controlled by the rate of heat diffusion through the ice.

[1]Department of Geophysical Sciences, University of Chicago, Chicago, Illinois, USA.

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL048991.

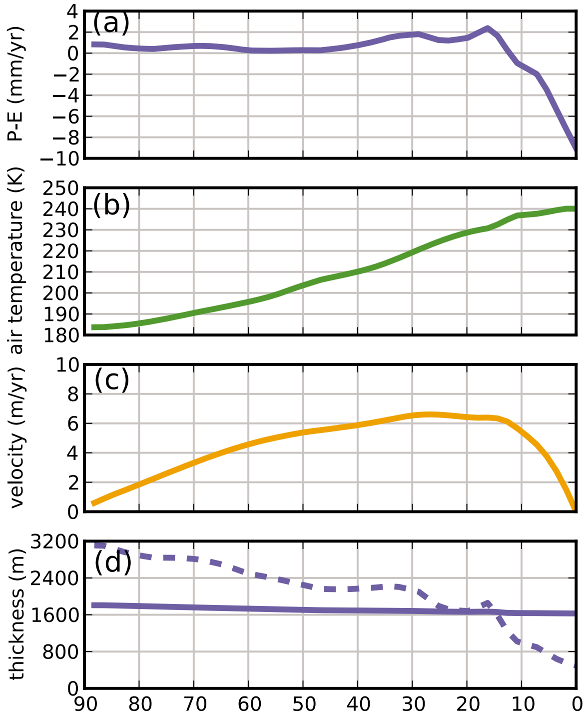

Figure 1. (a) Annual mean precipitation minus evaporation used to drive the ice model. (b) Annual mean surface air temperature. (c) Horizontal velocity of the glacier flow after the model reaches equilibrium. (d) Equilibrium ice thickness (solid line). The dashed line shows what the ice thickness would be in the absence of flow.

[6] The model was integrated with 50 grid points from the pole to the equator, with v sitting at each grid point and h sitting at the center of each grid. Time stepping was done with an adaptive fourth-order Runge-Kutta method.

[7] Dust concentration within the ice is a conserved tracer, with transport driven by the two dimensional steady (v, w) ice velocity field yielded by the model. Adopting the convention that positive w is upward, we have $w = -m_t$ at the top of the ice; ice sinks where $P - E$ is positive, carrying dust with it. At the bottom, $w = m_b$. Since the mass-divergence is independent of depth, the vertical velocity inside the glacier varies linearly between the boundary values given at the top and the bottom of the ice.

[8] Dust transport was computed by tracking an array of Lagrangian trajectories launched at the surface of the accumulation zone, where w points into the surface. Computing dust concentration and flux requires a boundary condition on surface concentration in this region, which is obtained by diluting the assumed dust sedimentation rate S_d with the net precipitation. The resulting dust mixing ratio at latitude ϕ is

$$C_d(\phi) = S_d(\phi)/m_t(\phi) \tag{1}$$

Concentration is conserved along each trajectory, and where a trajectory broaches the surface in the ablation zone, the dust it carries with it is added to the surface dust flux. This surplus accumulation of dust at latitude ϕ is:

$$S_d^{flow}(\phi) = C_d(\phi_o) \times m_t(\phi) \tag{2}$$

where ϕ_o is the latitude from which the trajectory originated. The total dust accumulation rate is $S_d^{tot} = S_d + S_d^{flow}$. The dust amplification factor is then $1 + S_d^{flow}/S_d$.

3. Results

[9] We ran the model for 50,000 years starting with 1500 m thick ice, to reach a near equilibrium with ice thickness tendency below 0.1 m/kyr everywhere. Figure 1c shows the resulting horizontal velocity of the sea glacier. The flow velocity reaches its maximum value of ~7 m/yr at the subtropics, diminishing to zero at both the pole and the equator. The ice flow carries water equatorward, with mass balance maintained by return flows in the atmosphere and ocean. As shown in Figure 1d, the equilibrium ice thickness is around 1,700 meters, with an equator-pole difference of ~190 m, well below the gradient seen in the absence of flow. Without flow the net surface ablation in the Tropics would be balanced by basal freezing, leading to a sea ice elevator bringing marine ice to the surface. Instead, the ice flow thickens tropical ice, leading to basal melting there.

[10] Figure 2b shows the velocity field inside the sea glacier. As noted by *Goodman* [2006], when ice flow thickens tropical ice sufficiently to cause basal melting, then

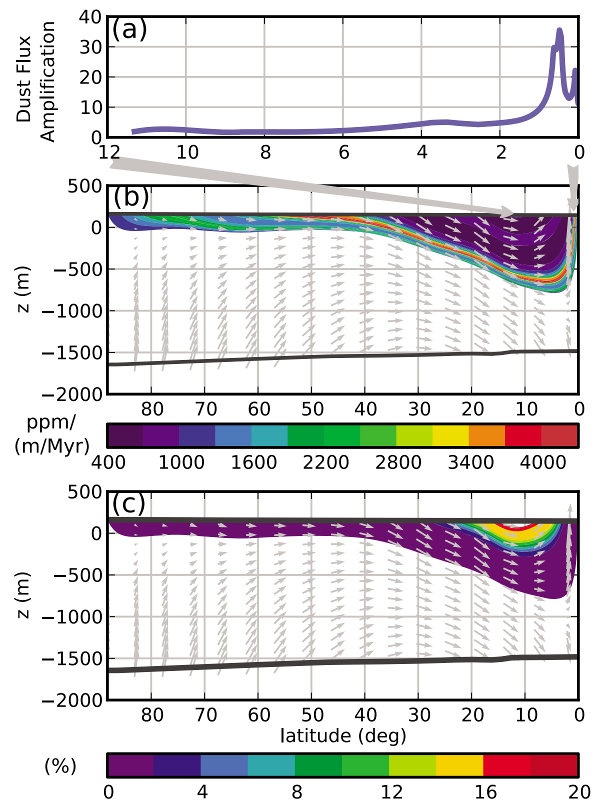

Figure 2. (a) Surface dust flux amplification factor in the ablation zone. (b) Flow and dust concentration inside the glacier. Black lines mark the top and the bottom surfaces of the glacier, arrows indicate the direction and speed of ice flow and colors show dust concentration (ppmv). Dust concentration is normalized to a uniform input dust flux of 1 m/Myr. (c) Dust concentration after 10 million years in a model assuming strong aeolian transport which sweeps the ablation zone clear and redeposits dust in midlatitudes. Concentrations normalized as for Figure 2b.

(provided the globally integrated $P - E$ vanishes) the flow from the top and that from the base are separated. The meteoric ice (formed by precipitation) cannot reach the bottom, and the marine ice (formed by basal freezing) cannot come to the surface. Dust falling onto the surface will be trapped in the meteoric layer. The meteoric ice gets thicker towards the equator, increasing from ~200 m to ~1000 m; the marine ice layer decreases from ~1,500 m at the pole to ~500 m at the equator.

[11] Our object is to illustrate the degree to which ice flow concentrates dust flux in the tropics, and so we present results for a globally uniform input dust flux S_d, set without loss of generality to S_d = 1 m/Myr. The dust concentrations and surplus accumulation S_d^{flow} are linear in S_d, so the flux amplification factor is independent of S_d, and the concentrations can be scaled to an arbitrary estimate of dust input rate.

[12] The structure in the dust concentration in Figure 2b arises from the meridional variation of net extratropical accumulation, since regions of small (but positive) net accumulation lead to high surface dust concentrations, which are carried into the interior by the ice flow. The weak $P - E$ (leading to isolation of meteoric ice) and the pattern of moisture transport from a tropical ablation zone to a subtropical/extratropical accumulation zone are robust consequences of Clausius-Clapeyron and the nature of the Snowball seasonal cycle [*Goodman*, 2006; *Abbot and Pierrehumbert*, 2010; *Pierrehumbert et al.*, 2011]. The overall pattern of dust transport to the tropics is thus expected to be a generic feature of Snowball climates, though the details of where concentrated dust streaks occur are likely to be model-dependent. It is conceivable that some Snowball climates might lead to a secondary midlatitude ablation zone which could trap dust before it got to the Tropics. We have carried out a simulation (not shown) with a small, weak ablation zone artificially imposed at the location of the accumulation minimum in the standard simulation. This leads to a small, shallow midlatitude dust bubble, while dust from higher latitudes continues to be transported to the tropics at greater depths. Dust brought to the surface in the dust bubble is not trapped in midlatitudes, but is transported to the tropics by the equatorward flow of the ice.

[13] The color streaks in Figure 2b illustrate the path of the ice flow. Dusty meteoric ice which was born at higher latitudes and slept underneath for thousands of years is carried equatorward and upwells to the surface where it sublimates leaving dust behind. The flow is similar to that which creates the Allan Hills blue ice region near the Transantarctic Mountains [*Cassidy et al.*, 1992], but played out on a global scale. The dust streaks also help to delineate the catchment area of the dust transported to the tropics, and provide some insight as to the effect of meridionally inhomogeneous dust deposition. For example, most of the ice poleward of 40° feeds into a strip within a few degrees of the Equator. Thus, it matters little how dust deposition is distributed over this part of the extratropics, since it is all going to wind up in the same place anyway.

[14] The dust transported to the tropical ablation zone significantly amplifies the dust accumulation there. Figure 2a shows that the dust accumulation rate at the surface is enhanced by a factor of 2 or more in the tropical region, with largest values near the equator where horizontal velocity stagnates.

[15] Aeolian transport sweeps the Allan Hills blue ice zone clear apart from a thin dust band and meteorites that are too heavy to be transported by wind. Such a situation could not be maintained over the tropical ablation zone of Snowball Earth, because the open ocean is not available as a sink of dust. Dust swept out of the tropics would be deposited in the extratropics, where it enriches the dust concentration of the meteoric ice which ultimately flows back into the tropics. We calculated the consequences of this process in the limit of strong aeolian transport which sweeps the ablation zone bare and deposits the transported dust in the extratropics with a Gaussian deposition profile proportional to $\exp[-\phi^2/(2 \cdot (20°)^2)]$. The resulting dust concentration after 10 million years, scaled to input flux 1 m/Myr, is shown in Figure 2c. Dust concentrations exceed 2% over most of the ablation zone, which will very significantly darken the ice.

4. Discussion and Conclusions

[16] *Abbot and Pierrehumbert* [2010] found that resetting surface albedo to 0.2 within 10° of the Equator was sufficient to allow deglaciation at 100 mb CO_2 even in the FOAM GCM, which is otherwise far from deglaciation at that concentration. How does ice flow affect the accumulation of a moraine that could bring about such an albedo alteration? Dust arriving at the surface of the ablation zone does not stay put, but is advected equatorward by the ice flow. The moraine thickness D is governed by the equation

$$\partial_t D + \frac{1}{r_o \cos\phi} \partial_\phi (vD\cos\phi) = S_d^{tot}(\phi, t) \tag{3}$$

where r_o is Earth's radius and v is the meridional ice velocity. As $t \to \infty$, S_d becomes steady and moreover D converges to a steady profile $D(\phi)$, which has a singularity at the equator where v = 0. In equilibrium, the thickness at any latitude ϕ does not grow indefinitely, but saturates at a value corresponding to the net dust accumulation experienced along the ice surface back-trajectory. The closer one gets to the equator, the longer one has to wait before equilibrium is approached since it takes an infinite time for ice to reach the equator. The result is a steady profile away from the equator, with a peak value near the equator that grows with time. We have integrated equation (3) subject to the asymptotic steady S_d yielded by our model. Scaled to an input dust flux of 1 m/Myr, after 1 My the moraine height at 10° is in equilibrium at about 1m and shows no amplification by flow, but there is substantial accumulation amplification further equatorward. The height is 2.5 m at 6°, 5 m at 2° and almost 30 m near the equator. Though the ice flow helps to build the moraine near the equator, it simultaneously confines the moraine and limits its spread poleward. This result may change substantially in a model where the moraine accumulation feeds back on climate and alters the $P - E$ pattern and hence ice flow stagnation point. Weak aeolian erosion would also help to spread the sharp equatorial peak over a broader region of the tropics.

[17] If aeolian dust transport is very strong, the Mudball mechanism works by increasing the dust concentration of tropical ice to the point where the ice itself becomes dark, rather than by accumulating a dust moraine.

[18] We presented results only for 100 mb CO_2, which might be typical of the late stages of a Snowball, but for the cold conditions of high albedo ice, the climate sensitivity to CO_2 is quite low [*Pierrehumbert et al.*, 2011]. Thus, early stages of the Snowball are only moderately colder, and have moderately reduced $P - E$. This leads to a somewhat more sluggish ice flow in the early stages, but the effect is partly offset by the higher extratropical dust concentration arising from weaker snow accumulation. Snowball climates can also be warmer than the climate in Figure 1, by virtue of higher CO_2, stronger cloud feedbacks or lower ice and snow albedo; warmer states also have higher $P - E$. An example of such a case is given in the auxiliary material, and leads to thinner ice, which flows faster. Dust transport results for that case (Figure 3 in Text S1) show lower dust concentrations, but this is made up for by faster ice flow, leading to tropical dust flux amplification similar to that found in the colder simulations.

[19] The correction of the back-pressure coding error by *Goodman and Pierrehumbert* [2003] leads to more uniform ice thickness in the globally glaciated case, and strengthens the conclusions of that paper regarding the importance of sea glacier flow. The thick tropical ice resulting from ice flow leads to basal melting there and implies that sea glaciers will almost invariably be in the weak $P - E$ regime described by *Pierrehumbert et al.* [2011], in which the surface consists entirely of meteoric ice.

[20] A number of important processes have been neglected in our study, and need to be revisited in future work. Chief among these is the feedback of the evolving near-surface dust concentration on surface temperature and the $P - E$ pattern, which must be addressed by coupling the ice/dust model to a climate model. The effects of dust on thermal conductivity and suppression of sublimation are most naturally treated in the context of a coupled model. Similarly, accurate representation of solar penetration into the ice, incorporating effects of dust, needs to be introduced. This could have important implications for the possibility of tropical thin ice solutions [*Pollard and Kasting*, 2005; *Warren and Brandt*, 2006], especially if aeolian transport is effective enough to sweep the tropical ice bare, leaving the main expression of dust effects to be manifest through dust within the ice itself. Three dimensional ice flow around continents may permit dust transport pathways significantly more complex than the highly constrained ones permitted by the two dimensional geometry of our model. Finally, once the climate has warmed to the point where diurnal or seasonal surface melt occurs, the fate of the resulting meltwater exerts a strong influence over the deglaciation threshold [*Pierrehumbert et al.*, 2011]. In the presence of dust, the transport of dust by surface meltwater adds additional challenge to the already complex problem of surface meltwater hydrology, which needs to be met in any full account of the deglaciation process.

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D. Li and R. T. Pierrehumbert, Department of Geophysical Sciences, University of Chicago, 5734 South Ellis Ave., Chicago, IL 60637, USA. (ldw@uchicago.edu; rtp1@geosci.uchicago.edu)