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Comment on "Snowball Earth: A thin-ice solution with flowing sea glaciers" by David Pollard and James F. Kasting

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1. Introduction

[1] *Pollard and Kasting* [2005] (hereinafter referred to as PK) have coupled an energy-balance climate model to an ice-shelf flow model, to investigate the Snowball Earth episodes of the Neoproterozoic, ∼600–800 million years ago, when the ocean apparently froze all the way to the equator [*Hoffman and Schrag*, 2002]. PK's particular concern was to investigate the possibility that over a wide equatorial band where sublimation exceeded snowfall, the bare ice may have been thin enough to permit transmission of sunlight to the water below, providing an extensive refugium for the photosynthetic eukaryotes that survived the Snowball events. This possibility was first proposed by *McKay* [2000], whose model of radiative transfer and heat conduction predicted tropical ice only a few meters thick for ice albedo up to 0.7, under assumed conditions of sunlight and temperature at the Snowball equator. However, when spectral resolution was incorporated into the radiative transfer model [*Warren et al.*, 2002], the ice albedo had to be reduced below 0.4 to obtain the thin-ice solution under otherwise identical conditions. It seemed unlikely that such dark sea ice could avoid melting under the equatorial Sun. But even if it could avoid melting, the thin ice would risk being crushed by the inflow of kilometer-thick "sea glaciers" from higher latitudes [*Goodman and Pierrehumbert*, 2003]. To further investigate the feasibility of tropical thin ice, it was therefore necessary to couple a climate model to models of sea-ice thermodynamics and sea-glacier flow. This is what PK have done. Surprisingly, they conclude that thin ice (<3 m thick) "may have prevailed" in a 20-degree latitude band centered on the equator. We argue here that this conclusion is too optimistic, because PK's thin-ice solution apparently required that several controlling variables be set outside their measured ranges: the albedo of cold glacier ice, the depth of transition from snow to ice, and the thermal conductivity of ice. We then raise the more general question of how wide is the thin-ice domain in the parameter-space of model variables.

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2. Choices of Model Variables That Favor Thin Ice

2.1. Albedo of Cold Glacier Ice

[2] As sea glaciers flowed equatorward into the tropical region of net sublimation, their surface snow and subsurface firn would sublimate away, exposing bare glacier ice to the atmosphere and solar radiation. This ice would be freshwater (meteoric) ice, which originated from compression of snow, so it would contain numerous bubbles, giving a high albedo. The albedo of cold (nonmelting) glacier ice exposed by sublimation (Antarctic "blue ice") has been measured as 0.55–0.65 in four experiments in the Atlantic sector of Antarctica [*Bintanja and van den Broeke*, 1995; *Bintanja et al.*, 1997; *Liston et al.*, 1999; *Reijmer et al.*, 2001], 0.63 in the Transantarctic Mountains [*Warren et al.*, 2002], and 0.66 near the coast of East Antarctica [*Weller*, 1968]. (Weller's blue-ice albedo is often quoted as 0.69 [e.g., *Weller*, 1980; *King and Turner*, 1997], but that is an average value, which included a few times with patchy snow cover on the ice.) Not all glacier ice is bubbly: under several hundred meters of ice thickness, the pressure becomes so great that each air bubble dissolves in the ice to form a clathrate crystal, and the ice becomes relatively clear [*Price*, 1995]. However, when this ice becomes depressurized as its cover sublimates away (as in the Antarctic blue-ice areas where the albedos were measured), the bubbles reform [*Lipenkov*, 2000], so that the albedo of 0.55–0.66 is observed at the surface.

[3] In contrast to glacier ice, which forms by compression of snow, sea ice forms by freezing of liquid water. In their model, PK tried two values of scattering coefficient, each of which they applied uniformly to both sea ice and glacier ice. With albedo 0.47 (a reasonable value for meter-thick snow-free sea ice [*Brandt et al.*, 2005, Figure 1]), the sea glaciers terminated at 9 degrees latitude, leaving an equatorial strip of thin ice. But with albedo 0.64 (i.e., within the measured range for glacier ice), the sea glaciers advanced to the equator, with a thickness of 1 km. To add realism to the model, it would be good to assign different values of scattering coefficient to these two very different types of ice.

2.2. Depth of Transition From Snow to Ice

[4] In cold ice sheets the grain size of snow increases with depth as it metamorphoses into firn, and the transition from firn to glacier ice (where the bubbles close off) occurs at a depth of about 70 m [*Herron and Langway*, 1980]. The

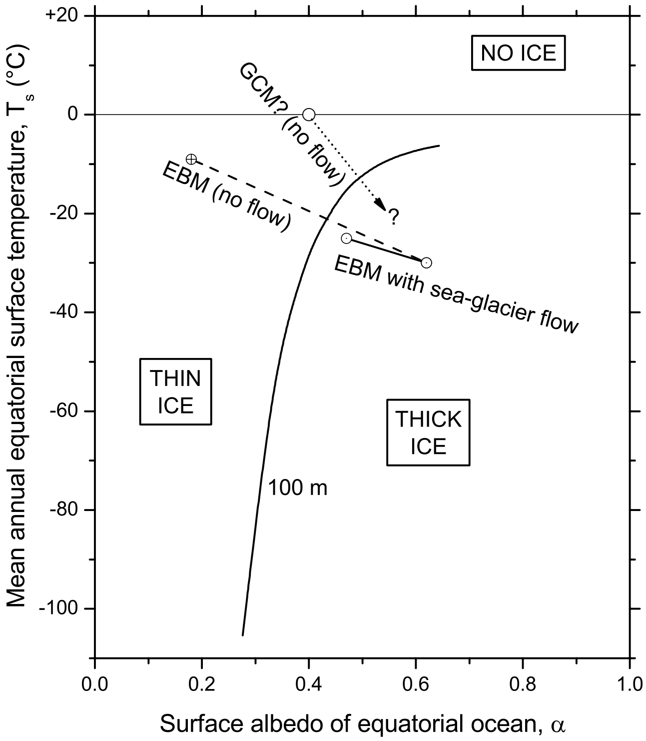

Figure 1. Domains of stability of thick ice, thin ice, and no ice for the equatorial ocean, in the two-dimensional space of surface albedo α and surface temperature T_s, for Neoproterozoic solar constant and expected atmospheric transmittance. The curve labeled "100 m" indicates the combination of specified values of T_s and bubble-density (represented by the corresponding surface albedo) required to maintain ice of equilibrium thickness 100 m at the equator in the absence of flow, from Figures 9 and 11 of *Warren et al.* [2002]. Those calculations assumed a solar flux of 320 W m^{-2} (average over day and night), geothermal heat flux F_g = 0.08 W m^{-2}, and negligible latent heat release at the base of the ice. The points labeled "EBM" are four solutions of PK's energy-balance climate model (two different albedo specifications, with and without sea-glacier flow). The point and dotted line labeled "GCM?" is a speculation of the possible behavior of the GENESIS general circulation model without sea-glacier flow (see text).

scattering properties of the firn change continuously with depth. Therefore, as a sea glacier flows into the tropical region of net sublimation, the albedo of the exposed surface would gradually decrease from the albedo of snow (0.8) to the albedo of glacier ice (0.6). This process can be simplified in a model by making a step-change in albedo from snow to ice after a specified thickness of snow and firn has sublimated. In their standard model, PK set this depth of transition at 10 m (but in effect 6–7 m, because PK assumed a snow density of 250 kg m^{-3}, whereas the observed average value in the top 10 meters is 400 kg m^{-3} [*Herron and Langway*, 1980]). With that assumption (and with glacier-ice albedo at the low value of 0.47 as discussed above), PK were able to get thin ice in the tropics. But using a more realistic transition depth of 30 m, the sea glaciers advanced to the equator in spite of their unrealistically low albedo.

2.3. Thermal Conductivity of Ice

[5] PK's standard model set the thermal conductivity of ice (k_i) to 2.1 W m^{-1} K^{-1}, and the model was able to obtain thin ice at the equator (if the other variables were set to favor thin ice). In reality k_i varies with temperature, from 2.7 at −40°C to 2.2 at 0°C. When PK put this temperature dependence into their model (PK, Appendix, Note 6), the sea glaciers advanced to the equator.

3. How Wide Is the Thin-Ice Domain?

[6] The sensitivity of the tropical ice thickness to precise values of ice albedo, snow-ice transition depth, and thermal conductivity, suggests that the width of the thin-ice domain, in the parameter-space of the model variables, is narrow. In Figure 1 we offer a simplified examination of this question, considering ice thickness as a function of just two variables: surface temperature T_s and ice albedo α. (Albedo is not actually specified; it is computed using a radiative transfer model. *Warren et al.* [2002] computed albedo from specified bubble densities; PK computed albedo using specified single-scattering albedos.)

[7] The curve labeled "100 m" indicates the combination of specified values of T_s and bubble-density (representing the bubble densities by their resulting albedos) required to maintain ice of equilibrium thickness 100 m at the equator in the absence of flow, from Figures 9 and 11 of *Warren et al.* [2002]. Those calculations assumed a solar flux of 320 W m^{-2} (average over day and night), geothermal heat flux F_g = 0.08 W m^{-2}, and negligible latent-heat release at the base of the ice. This curve designates the boundary between the thick-ice domain on the right and the thin-ice domain on the left. (If 10 m is used instead of 100 m as the criterion for the boundary, the curve moves only slightly, because of the bimodal nature of the solution for ice thickness, as discussed by *Warren et al.* [2002].) The third domain, "no ice," occupies the region $T_s > 0$°C.

[8] In a climate model, T_s and α are interactive. In Figure 1, the equatorial values of T_s are plotted against their corresponding albedos, for four versions of the PK model (PK, Figures 3 and 4). The points are joined by lines labeled "EBM" (energy-balance model), indicating the equatorial T_s as a function of equatorial surface albedo: two points with sea-glacier flow (joined by a solid line), and two points for the no-flow model (joined by a dashed line). The point at α = 0.47, T_s = −24°C is near the thin/thick boundary curve; in the PK model it is actually in the thin-ice domain. [This offset is not our major concern here, but it does illustrate that the "100 m" curve will move somewhat depending on the model's values of k_i, F_g, and atmospheric transmittance, and on the details of the radiative transfer computation.]

[9] It was surprising to us that PK obtained an equatorial surface temperature of −9°C for a surface albedo of 0.18 (the upper-left "no flow" point in Figure 1). Such a dark surface at the equator absorbs a large amount of solar radiation; in the EBM this heat is efficiently transported to higher latitudes by the atmosphere. Other models may behave differently. Pollard and Kasting have also been using

a general circulation model (the GENESIS GCM) to investigate Snowball climates [*Pollard and Kasting*, 2004]. When the albedo of snow-free sea ice was set to 0.4 in the GCM (without sea-glacier flow), the tropical surface temperature rose to the melting point and the ice melted (personal communication from Pollard, quoted by *Warren et al.* [2002, ¶30]). This point is plotted in Figure 1 at (α = 0.4, T_s = 0°C), and a purely speculative dotted line labeled "GCM?" is drawn from this point, suggesting that the GENESIS GCM (without sea-glacier flow) may have a narrower thin-ice domain than does the EBM. The difference may be due to the presence of a diurnal cycle in the GCM and its absence in the EBM, and to their different parameterizations of meridional heat transport by the atmosphere. *Pierrehumbert* [2005] argues for the importance of using a GCM to compute this atmospheric transport for the Snowball Earth.

[10] We remind the reader that the "no-flow" models in Figure 1 are unrealistic. The thin-ice domain will be narrower (or nonexistent) in models that permit sea-glacier flow. If the width of the thin-ice domain is very narrow, then a thin-ice solution is a delicate equilibrium that would be vulnerable to interannual anomalies of temperature or snowfall. These perturbations could switch the tropical climate rapidly into a thick-ice state or an ice-free state, where it would tend to remain because of the positive albedo-temperature feedback. To assess the feasibility of the thin-ice solution, it will therefore be important to examine its response to climatic perturbations.

4. Summary

[11] The thin-ice domain may occupy only a narrow region of parameter-space. The thin-ice domain may be narrower if atmospheric heat transports are computed using a general circulation model rather than an energy-balance model.

[12] Consideration of the snow/ice transition process in glaciers, and the measured albedos of bare cold glacier ice, suggests that the thin-ice solution will disappear from the PK model when sea glaciers are modeled more realistically.

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