The Effect of Dust on Snowball Earth Climate |

Dawei Li &
Ray Pierrehumbert

The Snowball Earth Climate

- Two Neoproterozoic Snowball Earth events have been identified from geological data (Marinoan ~635Ma, Sturtian ~720Ma).[3]
- High albedo of ice causes extremely low surface temperature.
- Low thermal capacity of ice surface lead to further excursion of ITCZ into summer hemisphere, and net sublimation near the Equator.
- Dust may deposit in the equatorial ablation zone ("Mudball" hypothesis).[1]

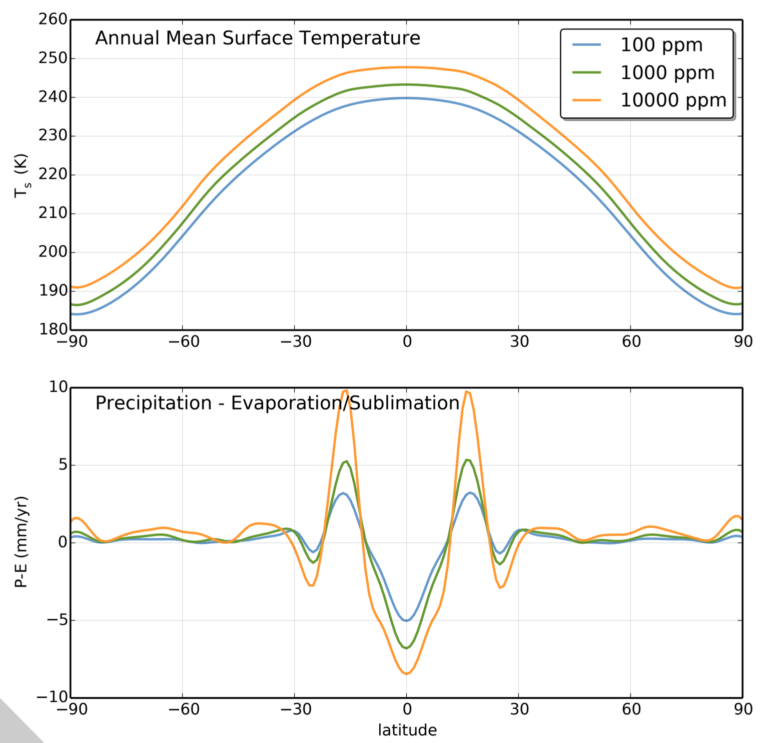


Figure 1. Snowball Earth climate (FOAM GCM).

Why Dust Should be Important for Snowball Climate?

- **The Snowball deglaciation problem**: Implausibly high level of CO_2 would be required to compensate the radiative forcing from the highly reflective ice surface.
- Sluggish hydrological cycle of Snowball Earth leads to high concentration of dust in snow ice.[4]
- Dust can lower surface albedo, warm the climate and help deglaciation.
- A layer of dust over ice surface can suppress sublimation, and a planetary scale dust strip could potentially change the atmospheric general circulation, via its effects on surface albedo and precipitation/sublimation.
- Nature of the "Mudball" state: **self-sustaining** or **self-destructive**? Would dust attract more precipitation and lead to its own demise?

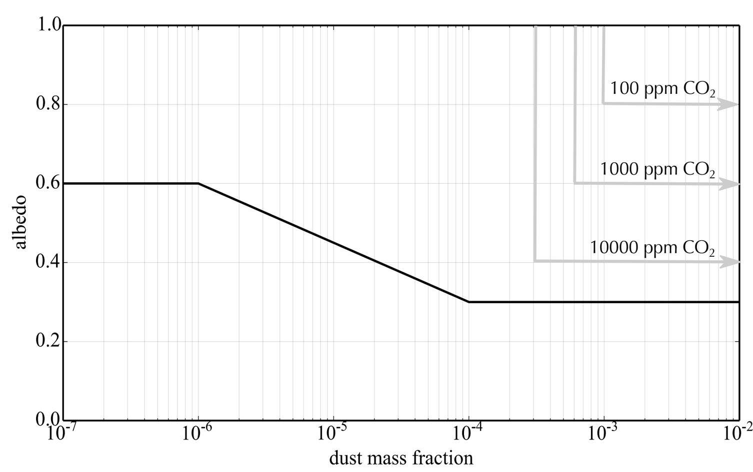


Figure 2. Albedo of dusty ice (adapted fro)m [2]).

The Flowing Ice Cover over Ocean

- Equator-pole surface temperature gradient gives rise to heterogeneity in ice thickness.
- Ice deforms under gravity and tends to homogenize the thickness --> ice flows down gradient (from pole to Equator).
- High latitude: thinning of ice causes insufficient insulation --> basal freezing
  Low latitude: thickening of ice brings in excess insulation --> basal melting
- The planetary ice flow is sustained by the surface temperature gradient (a thermally-driven flow)

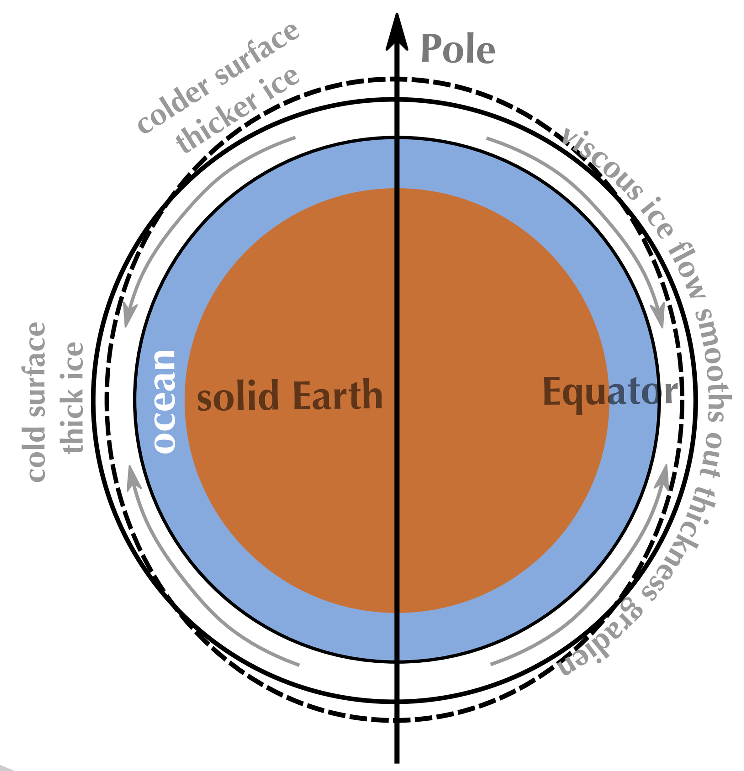
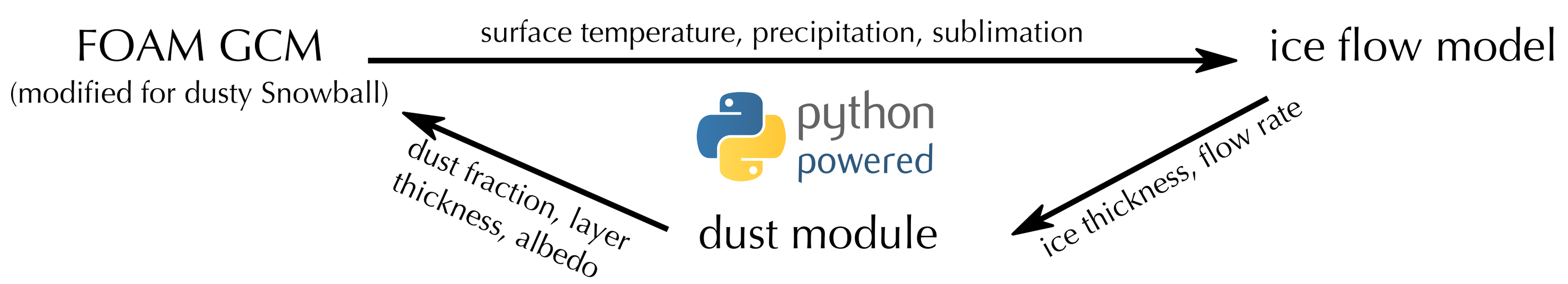


Figure 3. Viscous flow of thick oceanic ice cover.

Coupling the Dust/Ice Flow Model with a GCM



- **A Simplified Ice Cover Flow Model** (all-ocean, zonally-symmetric)
  Assuming an uniform ice shell, the ice thickness is only determined by the strength of geothermal heat flux and surface temperature, $H = \kappa \frac{T_f - \int T_s(\theta)\sin\theta d\theta}{\int F_g(\theta)\sin\theta d\theta}$
  Basal melting rate, $m_b(\theta) = \kappa \frac{(T_f - T_s(\theta))\kappa/H - F_g(\theta)}{\rho_i l}$
  combined with surface accumulation (from GCM), the flow rate of ice
  $$v(\theta) = \frac{a}{H\sin\theta}\int_0^\theta (m_b + m_t)\sin\theta d\theta$$
- The simplified uniform ice shell model agrees well with more sophisticated models under typical Snowball Earth conditions (relatively warm ice, Figure 4).

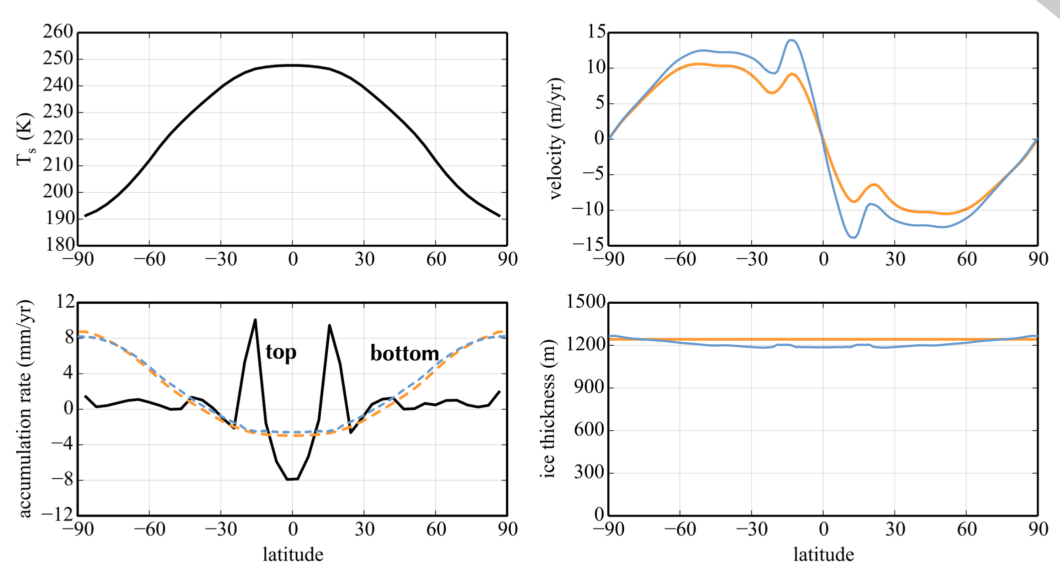


Figure 4. Comparison of the simplified model with Tziperman's model [5]

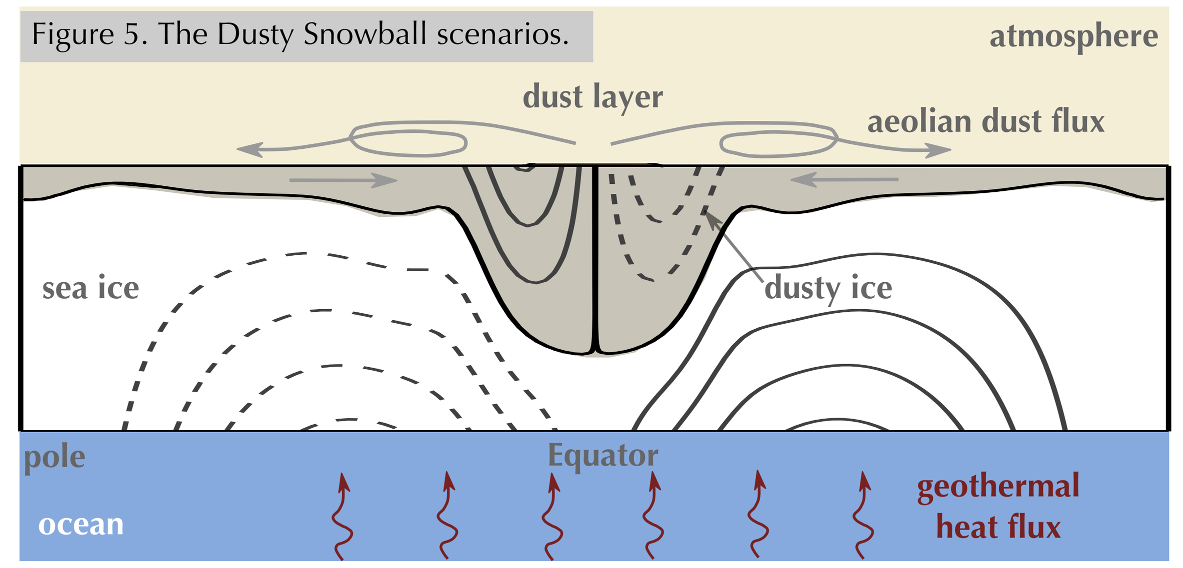


Figure 5. The Dusty Snowball scenarios.

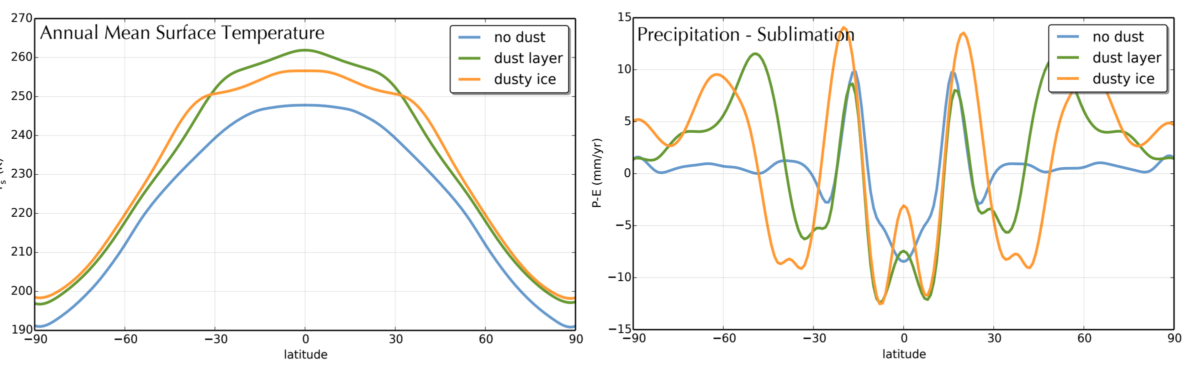


Figure 6. Comparison of the Dusty Snowball climate with no-dust one.

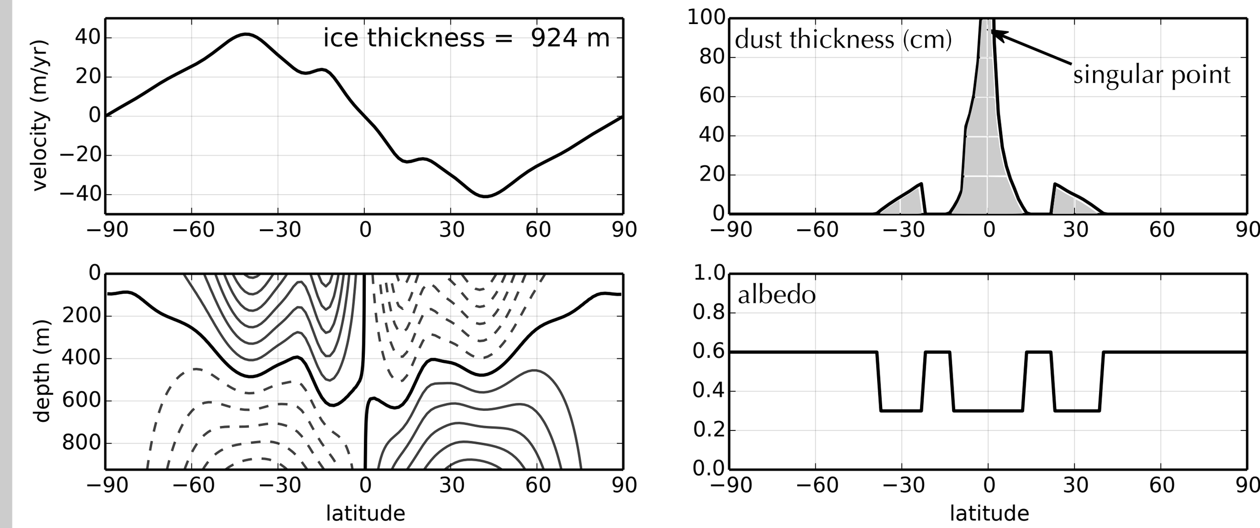


Figure 7. Dust transport for the "Dust Layer" scenario.

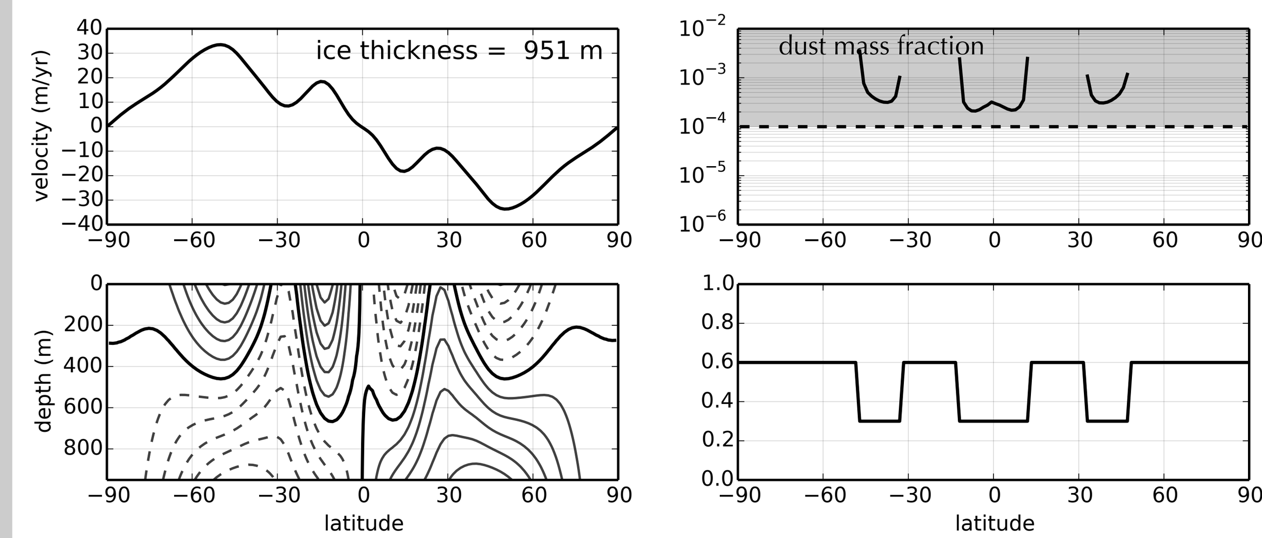


Figure 8. Dust transport for the "Dusty Ice" scenario.

References

1. Abbot, D. S. & Pierrehumbert, R. T. Mudball: Surface dust and Snowball Earth deglaciation. Journal of Geophysical Research: Atmospheres 115, (2010).
2. Dadic, R. et al. Effects of bubbles, cracks, and volcanic tephra on the spectral albedo of bare ice near the Transantarctic Mountains: Implications for sea glaciers on Snowball Earth. Journal of Geophysical Research: Earth Surface (2013). doi:10.1002/jgrf.20098
3. Hoffman, P. F. & Schrag, D. P. The snowball Earth hypothesis: testing the limits of global change. Terra Nova 14, 129–155 (2002).
4. Li, D. & Pierrehumbert, R. T. Sea glacier flow and dust transport on Snowball Earth. Geophysical Research Letters 38, (2011).
5. Tziperman, E. et al. Continental constriction and oceanic ice-cover thickness in a Snowball-Earth scenario. Journal of Geophysical Research 117, (2012).

Dusty Snowball Earth -- Two Tales

- **Dust Layer:** Dust deposited in the ablation zones remains on ice surface, forming a dust layer, which affects albedo and sublimation. Water vapor diffuses through the dust layer (like present-day Mars): $J = D\frac{\rho_{sat} - \rho_s}{h_d}$
- **Dusty Ice:** Surface dust would be instantly blown away, no dust layer formed. Blue ice contaminated by dust would be exposed, which again lowers albedo, but has negligible effect on sublimation.

Coupled Ice-Dust-GCM Simulations

CO2=10000 ppm, initialized from no-dust FOAM simulation, to equilibrium

Surface Temperature:

- Coupled simulations show an additional warming of 8~14K in the tropics, which is equivalent to raising CO2 level by ~100 times.

Surface Mass Balance:

- The ablation zones become wider in coupled simulations, a "Mudball" state is self-sustaining rather than self-destructive.
- Due to limited exposure time in ablation zones, dust layers are not thick enough to drastically suppress sublimation.

Dust Transport by Ice Flow

- Warmed by dust, ice cover is thinner and flows faster in both scenarios.
- Dusty ice is isolated from the underlying ocean.
- Dust stays in snow ice or on ice surface.
- The great **dust conveyor belt** -- Carried by ice flow, dust converges to tropics.

Dust Layer:

- Advection of dust by ice flow leads to a singular point at the Equator (where ice flow from two hemispheres converges), but dust layer still cannot become very thick through the limited life time of a Snowball Earth event (~Myr).

Dusty Ice:

- Bare blue ice has sufficient dust to become as dark as dust. (**black ice**?)
  The fate of dust blown away is not important to the Snowball climate.

Vistas

- Like dust, cloud could provide additional warming effect, too. How cloud and dust would interplay in Snowball climate?
- At near-melting temperature, ice contains less dust due to stronger hydrological cycle, then has higher albedo. (**Dust thermostat**?)

Contact: **Dawei Li** (ldw@uchicago.edu)
Department of Geophysical Sciences, University of Chicago

AGU Fall Meeting 2013, C43B-0680