New Developments (This talk)

Glacial dynamics
- How much CO2 sequestered at poles?
- Recycling of CO2 by glacial flow
- Ice-albedo-greenhouse feedback

Atmospheric dynamics
- Boundary layer mass flux (keeps surface pressure uniform)
- Width and strength of Hadley cell. Seasonal cycle? Global or tropical?
- Baroclinic instability (in progress; come to Edmonton to find out.)

“White Mars” a viable solution?
- Cold Early Mars, no liquid water. Cryoclastic flows.
- Is cold (Amazonian) Mars compatible with existence of large condensed CO2 inventory?
Importance of Glacial Flow

Stress-Strain relation for CO2 ice implies:

\[ \frac{dh}{dt} = 2.25 \times 10^{-6} \left( \frac{h^2}{L} \right)^{4.9} \]

(T-dependent)

- A 500m high glacier 1000km long subsides at about 1/10 meter per Martian year.
- Very steep dependence on h.
- Basal melting decreases effective L

*Return branch of Hadley circulation is partly in solid form!*
Precipitation Balance

- Dominant balance is between infrared cooling and latent heat release in condensation.

- In optically thick limit (>1bar CO2), IR cooling is approximately = OLR (= net loss out top of atmosphere).

- In a non-convective region, condensation is fed by imported CO2 from distant convecting regions.

\[ P = \frac{\text{OLR}}{\rho L_c} \]

- Global mean OLR = abs. solar
- Early Mars, mean P = 3.6 m/yr
- Polar precip less, owing to colder temperatures, polar clouds, and subsidence
Early Mars Hadley Cell

- Present Mars has “global” Hadley cell, but mostly under Solstice conditions. Large width primarily due to very hemispherically asymmetric heating.
- Early Mars atm. has weak thermal damping, and weak seasonal cycle. Therefore Hadley cell is like Equinox solution all year.
- Equinox solution is somewhat wider than Earth’s Hadley cell (in latitude) but not truly “global”
- Weak radiative damping leads to weak Hadley cell.
For constant angular momentum aloft,

\[ \text{C}_p \Delta T^* = -\frac{\Omega^2 a^2}{2} \left( \frac{1}{\cos^2 \phi} + \frac{1}{2} \cos(2\phi) \right) \]

where

- \( \Omega \) = rotation rate,
- \( \phi \) = latitude
- \( a \) = radius of planet
- \( \text{C}_p \) = specific heat of atmosphere
- \( \Delta T^* \) = mean tropospheric temperature,
  (relative to global average)

- Small \( \Delta T^* \) allows Hadley cell to extend further
Ideal Hadley cell meridional temperature profile

Temperature relative to Equator (Kelvin) vs Latitude

- Tbar Earth
- Tbar Mars
Boundary layer mass fluxes inhibit formation of large surface pressure gradients

Relaxation time $= \frac{f^2 L^2}{g \delta} \tau \sim 60$ days
White Mars Solution


- Posited for Amazonian (1 billion years ago)
- Cold, Sub-freezing (water)
- Valley/channels due to cryoclastic flow from breakdown of buried CO2 and clathrate ice.
- What are implications of existence of a large CO2 reservoir, though?
Dry ice decomposition feedback

\[ p_{\text{sat}} = \exp(23.02 - 3148./T) \]

Present Mars 6mb atm. in eq. with \( T = 148K \)

Higher \( T \) \( \rightarrow \) more \( p_s \) \( \rightarrow \) more greenhouse effect.

(like water vapor feedback on Earth)

But which \( T \)?

![Surface pressure in equilibrium with T-dT graph](image)

Cold solution could work,

*if* you don’t believe in warming effect of CO2 ice clouds.