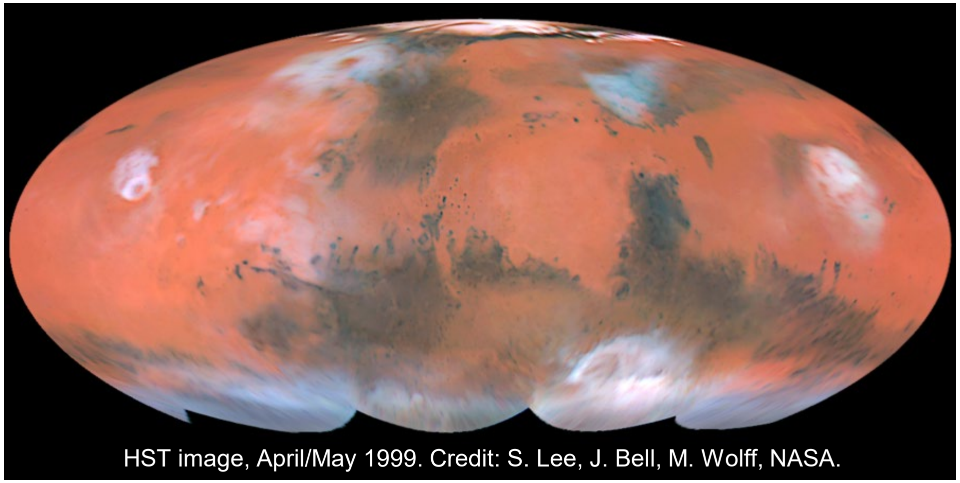
Presentation No. PPS03-06, JpGU Meeting 2012, Makuhari Messe, Chiba, Japan, 24 May 2012

Glaciation of Mars from 10 million years ago until 10 million years into the future simulated with the model MAIC-2



HST image, April/May 1999. Credit: S. Lee, J. Bell, M. Wolff, NASA.

Ralf Greve[1], Björn Grieger[2], Oliver J. Stenzel[3]

1 Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan
2 European Space Astronomy Centre, Madrid, Spain
3 Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany

Background

Mars experiences large periodic changes of the orbital elements (obliquity, eccentricity, equinox precession)

↓

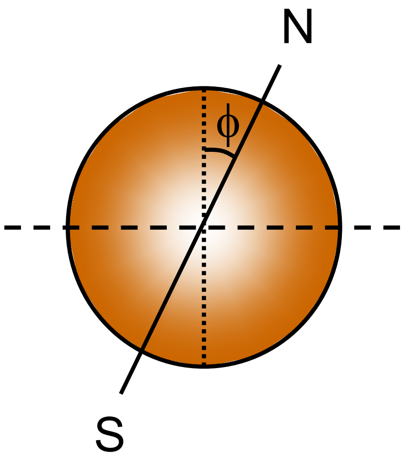
Climate change (like on Earth, Milankovitch cycles)

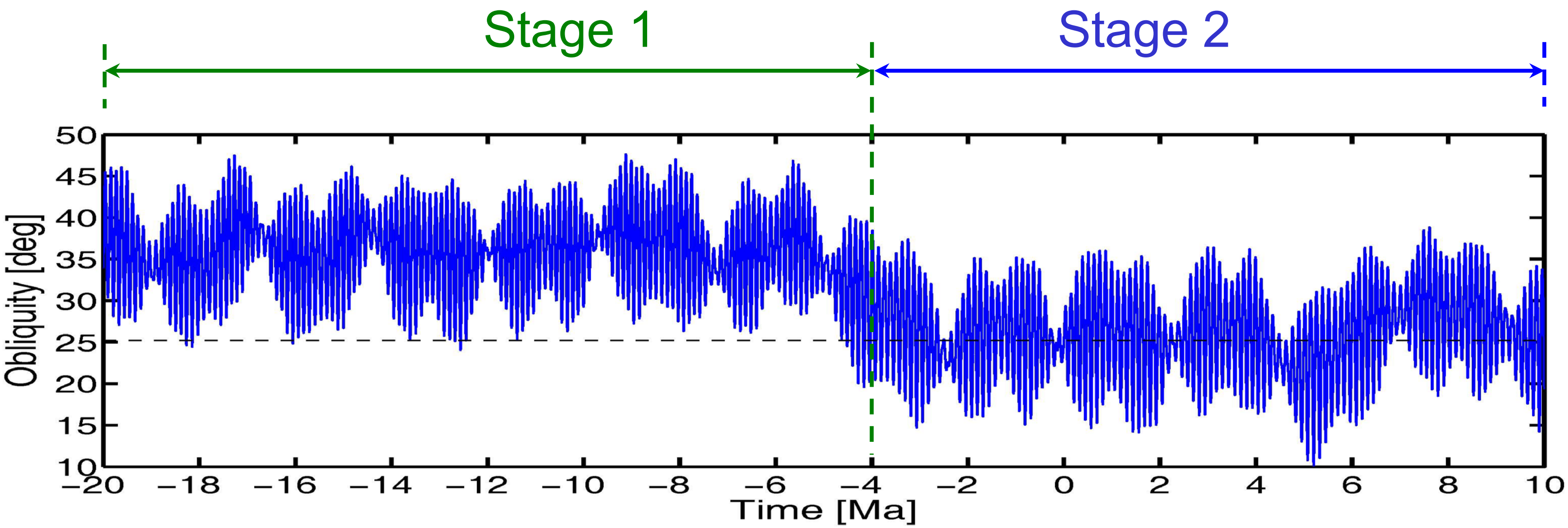
↓

Redistribution of water ice (surface/subsurface, high/mid/low latitudes)

Background

- Orbital parameters by Laskar et al. (2004) from *t* = –20 Ma until *t* = +10 Ma.
- Main driving force for changes: Obliquity ϕ (= axial tilt).





Scientific questions re water ice deposits

- What is the history of the Martian water ice deposits?

  In particular, how did they evolve during the high-obliquity stage 1?

- Can we understand the present-day situation?

  (Polar layered deposits = PLDs, absence of notable surface ice deposits elsewhere.)

- How will the present-day PLDs evolve into the future?

  Are they expected to grow or to shrink, and what are the consequences for water ice deposits elsewhere on the planet? Does glacial flow play a role in their evolution?

Model MAIC-2

M	Mars
A	Atmosphere
I	Ice
C	Coupler (Version 2)

(Greve, Grieger and Stenzel, 2010)

Purpose: Modelling the Martian glaciation (H_2O ice) over climatic time scales

Forcing: Directly driven by orbital parameters: obliquity, eccentricity and L_s of perihelion (Laskar et al., 2004)

Surface temperature: LIT scheme

(LIT = Local Insolation Temperature)

- Orbital parameters → daily mean insolation flux *F*.

- Radiation balance:

$$\sigma T^4 = (1-A)\,F, \qquad \begin{array}{rl} \sigma: & \text{Stefan-Boltzmann constant,} \\ T: & \text{daily mean surface temperature,} \\ A: & \text{surface albedo (globally } A = 0.3 \text{ assumed).} \end{array}$$

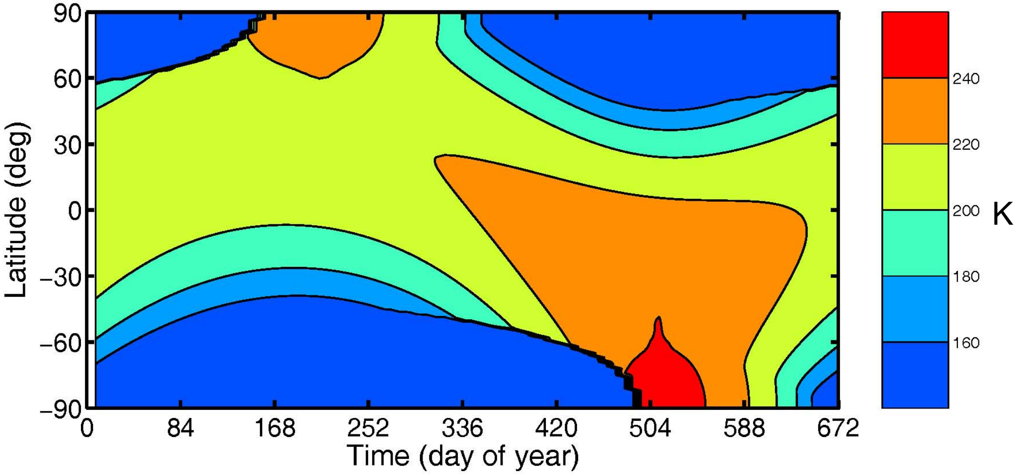
- However, this does not account for the secondary condition

$$T \geq T_{\mathrm{cond}} \approx 148\,\mathrm{K}$$

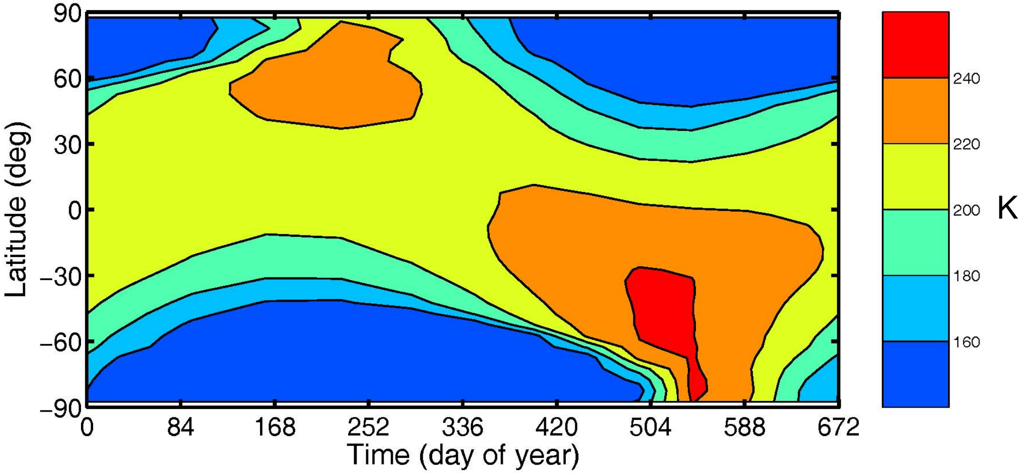
due to CO_2 condensation → latent heat flux into and from the seasonal CO_2 caps taken into account.

Surface temperature: LIT scheme

Daily mean surface temperature for present-day conditions:

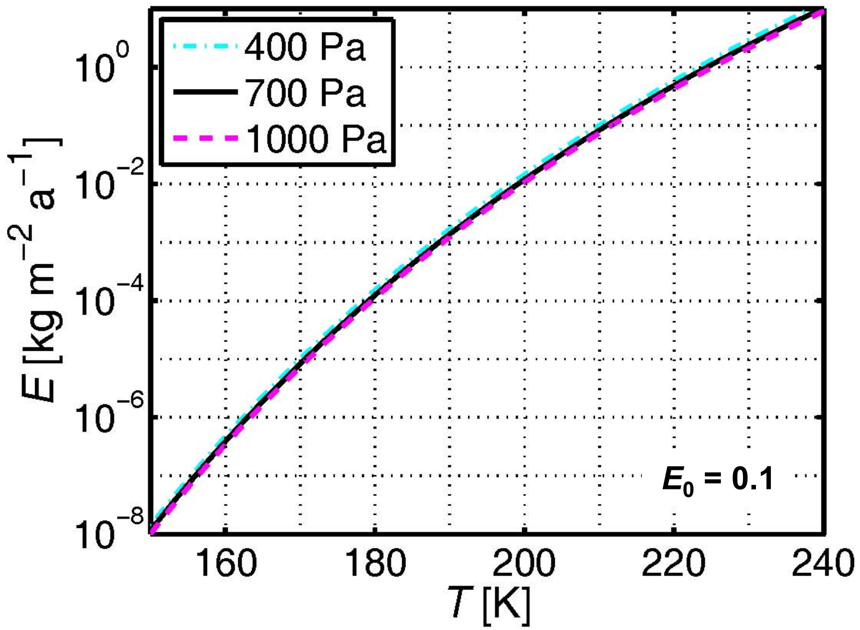


Mars Climate Database (Lewis et al. 1999):



Evaporation (sublimation)

- Parameterisation by Ingersoll (1970);
  additional dust insulation factor $E_0 < 1$.
- Result:
  Strong temperature dependence, slight pressure dependence.



Condensation (deposition)

- Any water vapour that exceeds the local saturation pressure condenses instantly and is deposited as H_2O ice.

Water transport in the atmosphere

- Instantaneous mixing on a time-scale of several days
  → uniform distribution of atmospheric water all over the planet.

Ice evolution

- Net surface mass balance (in m ice equiv. a^{-1}):

$$a_{\mathrm{net}} = \frac{C - E}{\rho_{\mathrm{ice}}}$$

- Glacial flow of ice deposits neglected

→ ice thickness evolution:

$$\frac{\partial H}{\partial t} = a_{\mathrm{net}}$$

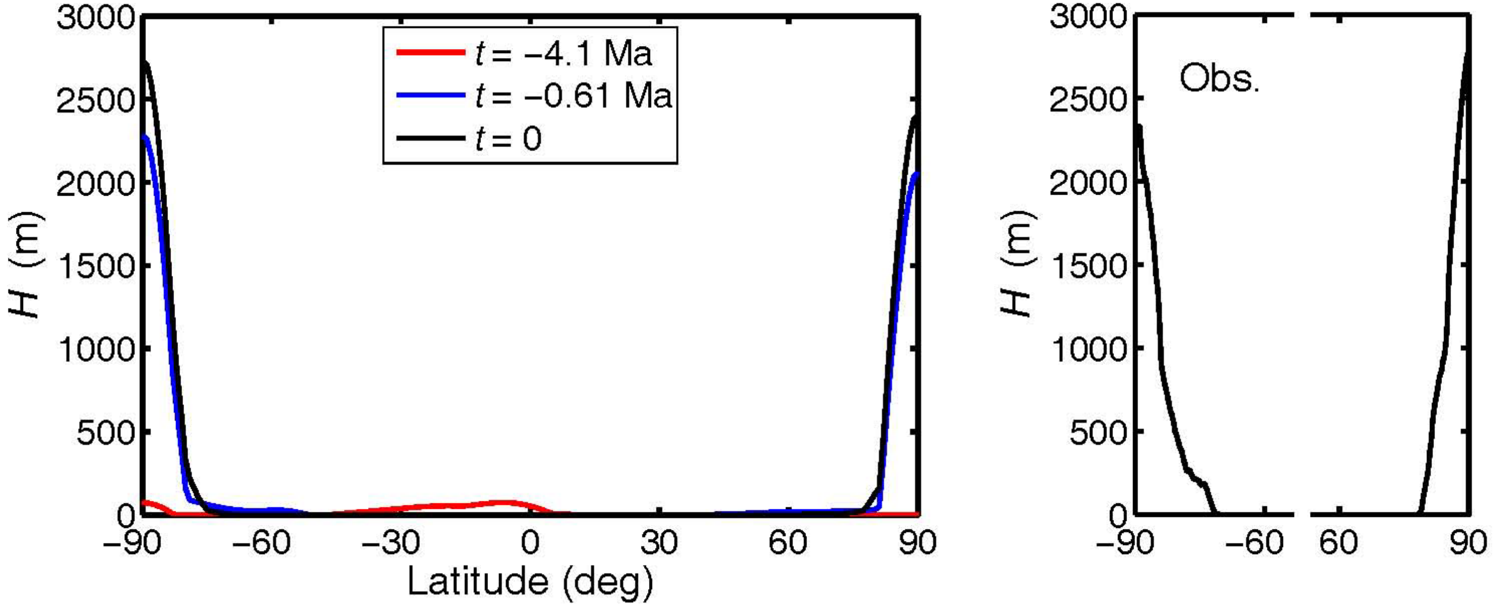
Best-fit simulation by Greve et al. (2010)

(MAIC-2 simulation run_t06)

- Orbital parameters by Laskar et al. (2004).
- Simulation time from $t = -10$ Ma until $t = 0$ (today).
- Time-step 0.02 years (≈ 7 sols).
- Initial ice layer of 19 metres thickness on the entire surface.
- Dust insulation factor $E_0 = 0.1$.

Best-fit simulation by Greve et al. (2010)

Selected ice thickness distributions:



Present-day PLDs very well reproduced!

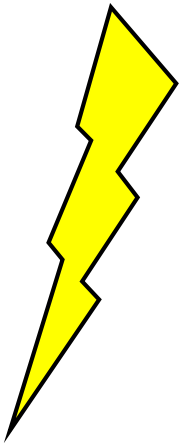
But…

Crater statistics (e.g., Herkenhoff and Plaut, 2000)

→ Basal unit of NPLD

and almost entire SPLD

much older than a few millions of years!

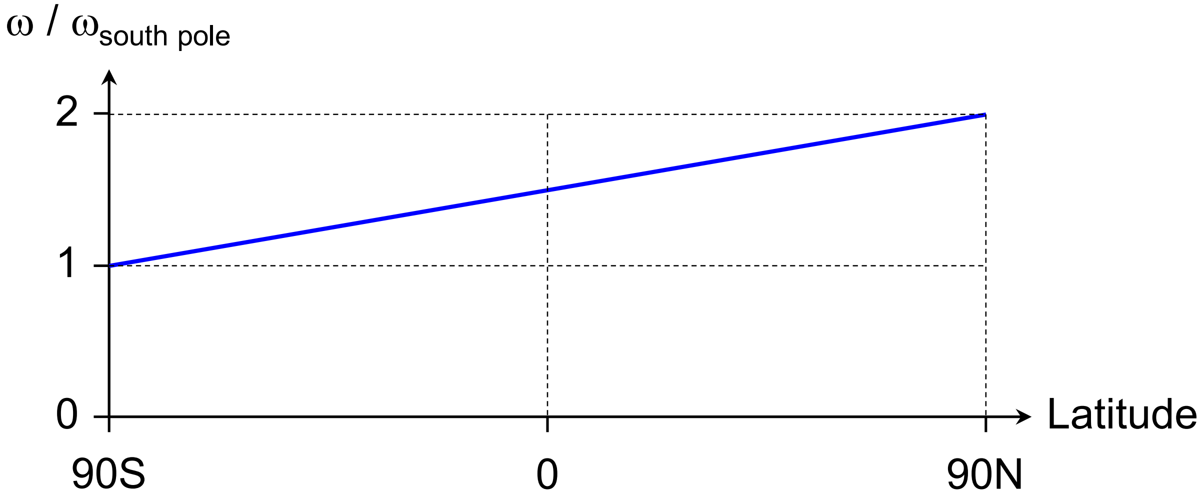


Change in MAIC-2

Water transport in the atmosphere:

Instantaneous mixing on a time-scale of several days with prescribed north-south gradient $(\, \omega_{\mathrm{north\,pole}} / \omega_{\mathrm{south\,pole}} = 2 \,)$

(motivated by Richardson and Wilson, 2002)



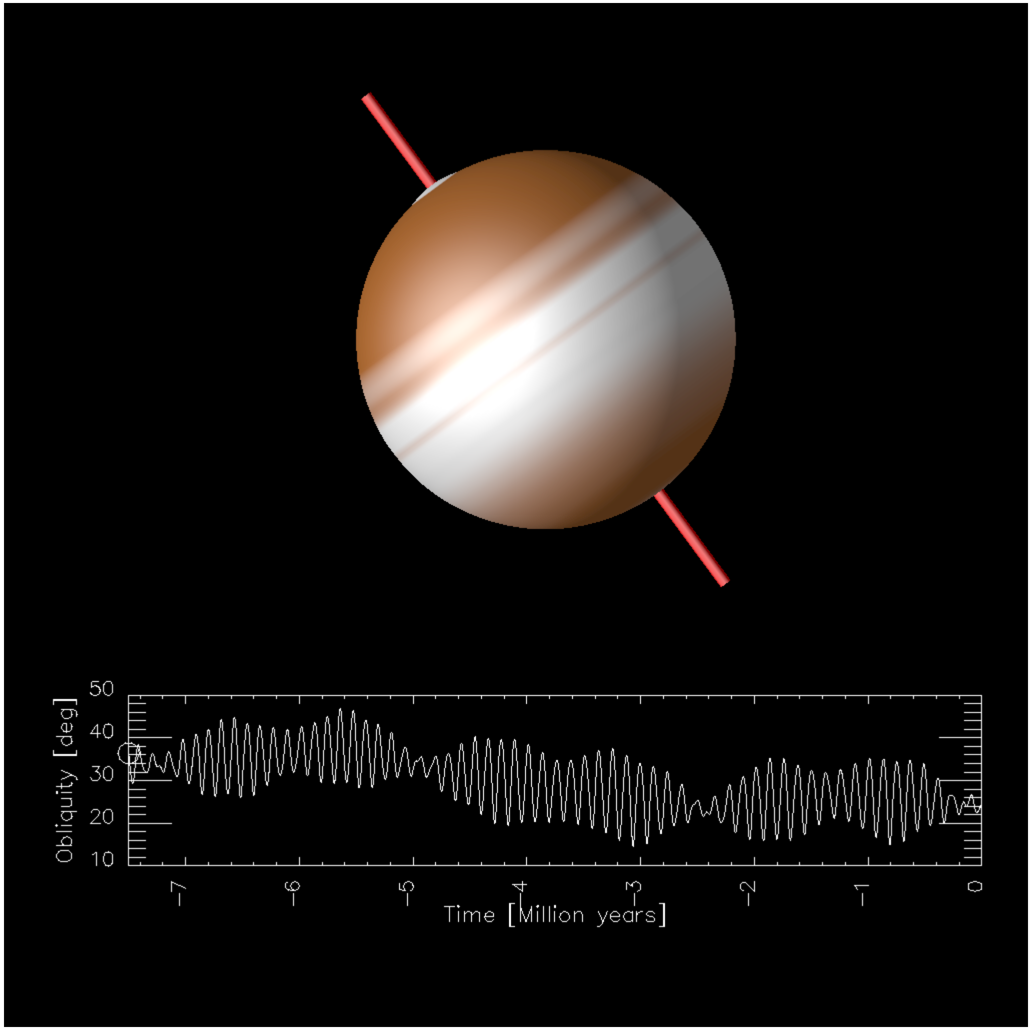
New simulation

- Orbital parameters by Laskar et al. (2004).
- Simulation time from t = –10 Ma until t = 0 (run_t39),
  continued into the future until t = +10 Ma (run_t40).
- Time-step 8 sols.
- Initial ice layer of 5.25 metres thickness on the entire surface.
- Dust insulation factor E_0 = 0.05.

Ice deposits from *t* = –7.5 Ma until *t* = 0

t = –7.5 Ma

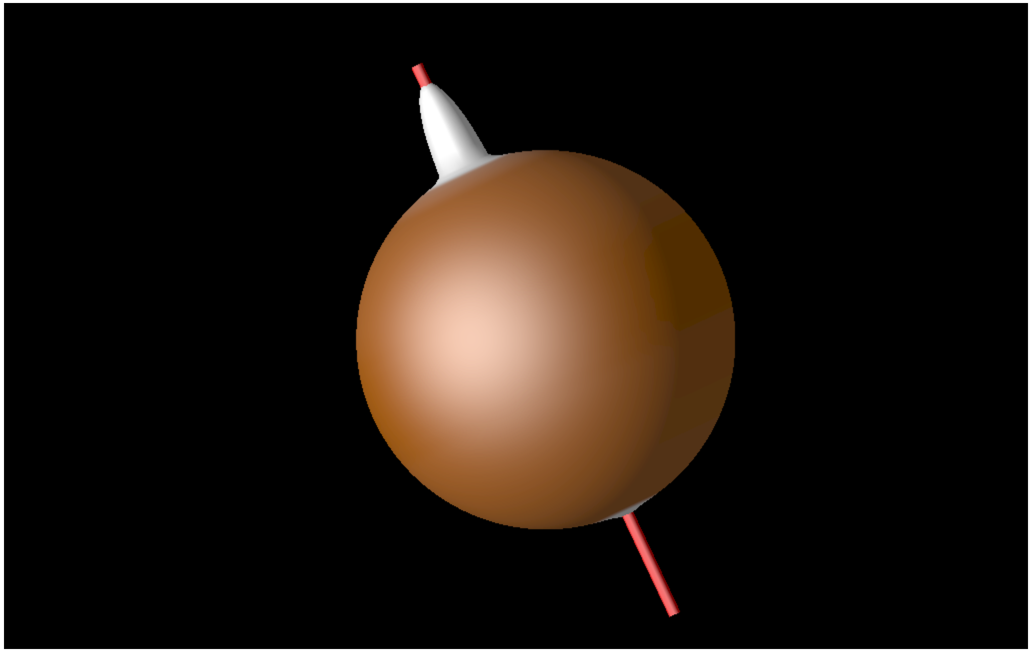
Vertical exaggeration factor 750



Ice deposits from $t = -7.5$ Ma until $t = 0$

$t = 0$ (today)

Vertical exaggeration factor 750

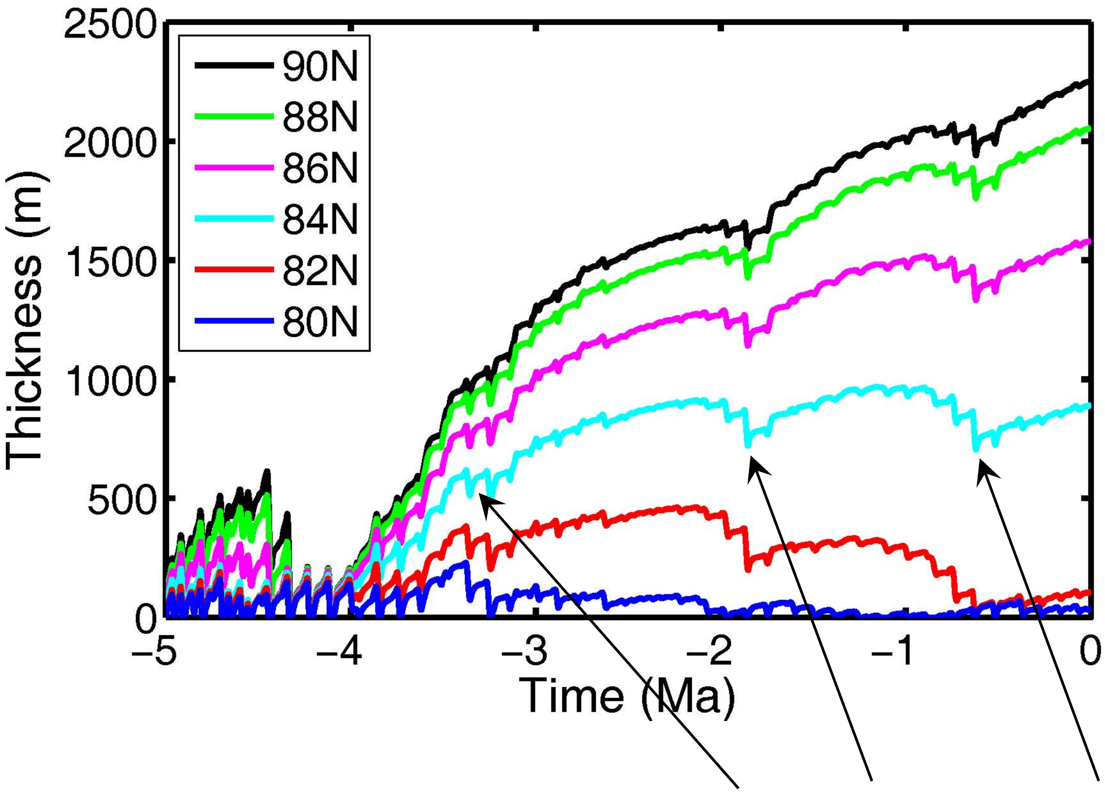


$H_{NP} = 2.256$ km (obs. 2.367 km)

$V_{NPLD} = 8.0394 \times 10^5$ km^3 (obs. 8.0355×10^5 km^3)

(without the basal unit;
T. C. Brothers and J. W. Holt, pers. comm. 2012)

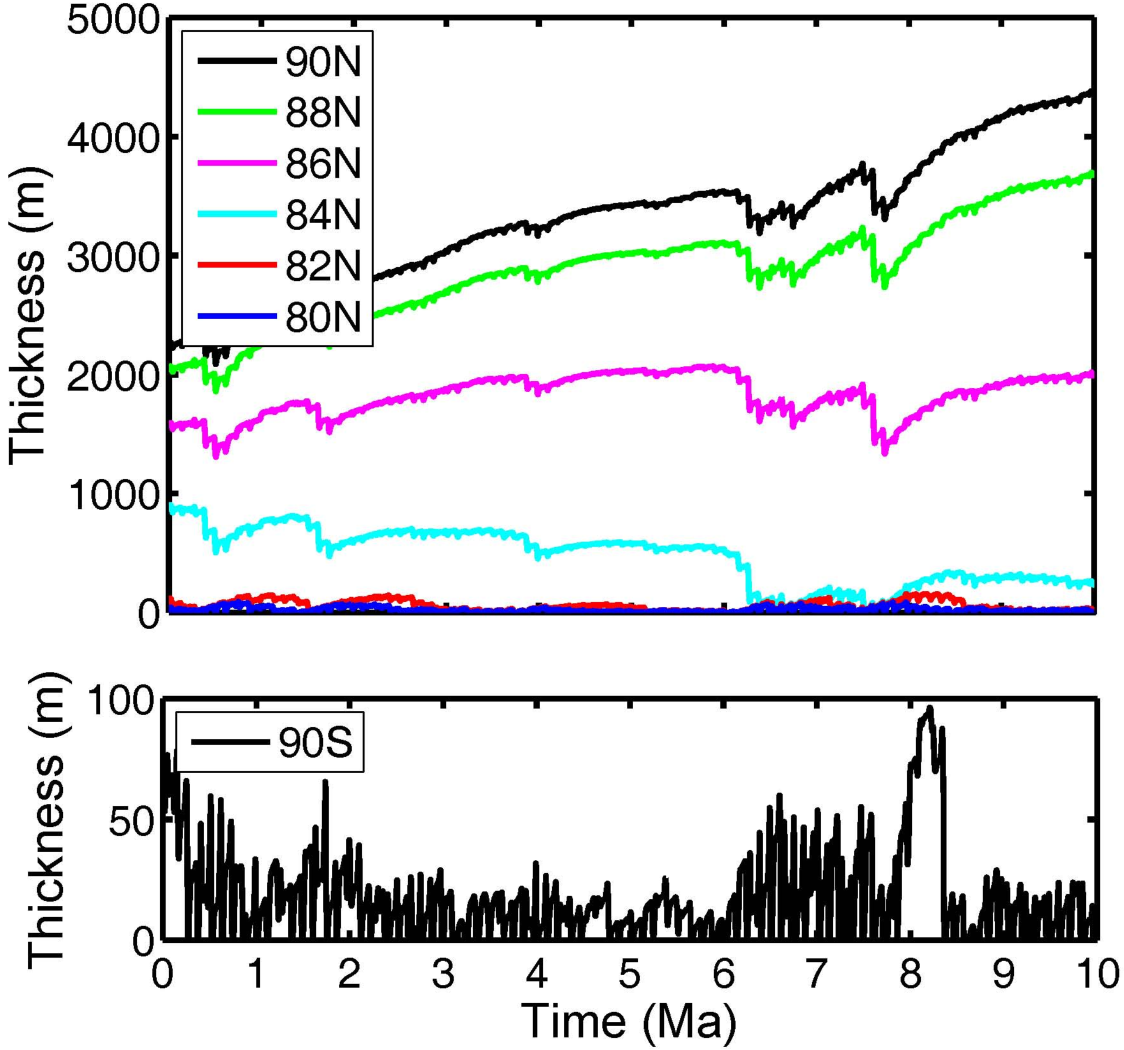
NPLD from *t* = –5 Ma until *t* = 0



Erosional events at about –3.2, –1.9 and –0.7 Ma, essentially consistent with radar stratigraphy

(Holt el al., LPSC Abstract 2012)

NPLD/SPLD from *t* = 0 until *t* = +10 Ma



Summary

- Prior to 4 Ma ago (“stage 1”):
  very mobile glaciation all over the planet.
- Since 4 Ma ago and into the future (“stage 2”):
  essentially monotonically growing NPLD,
  no significant new ice deposition in the south.
- Past erosional events to first order consistent with radar stratigraphy, similar events predicted for the future.

Acknowledgements

- DFG (German Science Foundation) Priority Programme "Mars and the Terrestrial Planets".
- ILTS Research Fund.

MAIC-2 code available as free software (GNU GPL)
at http://maic2.greveweb.net/.

Thank you!

ご清聴ありがとうございます。

Appendix

Surface temperature: LIT scheme

- Seasonal cap at latitude φ assumed to exist between the onset of the polar night (t_{dusk}) and an unknown time *t* after the end of the polar night (t_{dawn}).
- Condensation during polar night:

$$W_{\mathrm{cond}} = \int_{t_{\mathrm{dusk}}}^{t_{\mathrm{dawn}}} \sigma T_{\mathrm{cond}}^4 \, \mathrm{d}t.$$

- Evaporation after dawn:

$$W_{\mathrm{evap}} = \int_{t_{\mathrm{dawn}}}^{t} \left((1-A)\,F - \sigma T_{\mathrm{cond}}^4 \right) \, \mathrm{d}t.$$

- The time *t* at which CO_2 is completely evaporated follows from

$$W_{\mathrm{evap}} = W_{\mathrm{cond}}.$$

Evaporation

- Daily cycle of the surface temperature taken into account for computing the evaporation rate:

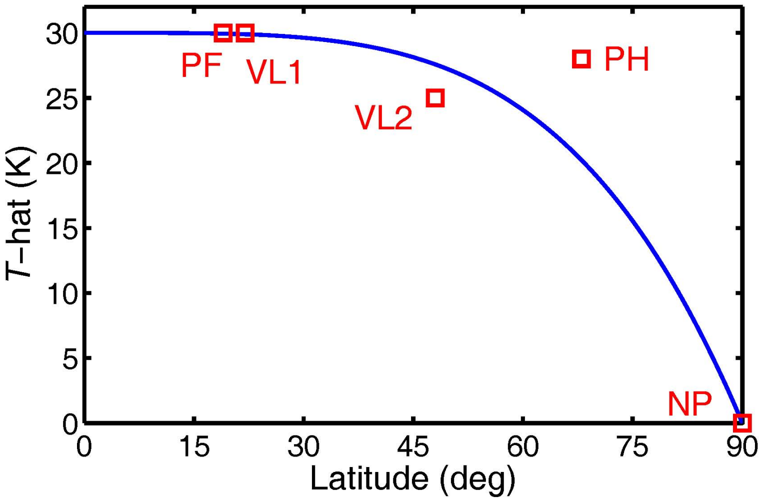
$$\hat{T}(\varphi) = \hat{T}_{\mathrm{EQ}} \left[1 - \left(\frac{|\varphi|}{90^\circ} \right)^4 \right] ,$$

φ : latitude,

$\hat{T}$: amplitude of daily cycle,

$\hat{T}_{\mathrm{EQ}}$: $\hat{T}$ at the equator $(= 30\,\mathrm{K})$.

Approximates measured data from Pathfinder, Viking Landers 1, 2 and Phoenix.



Condensation

- Condensation rate *C* computed under the assumption that any water vapour which exceeds the local saturation pressure P_sat condenses instantly:

$$C = \frac{1}{\Delta t}\left(\omega - \frac{P_\mathrm{sat}(T)}{g}\right), \quad \text{if } g\omega > P_\mathrm{sat}(T),$$

ω : water content,
expressed as area mass density in $\mathrm{kg\,m^{-2}}$,

g : acceleration due to gravity,

Δt : numerical time-step.

Water transport in the atmosphere

- Transport equation:

$$\frac{\partial \omega}{\partial t} = -\nabla \cdot \mathbf{F} + E - C$$

- Purely diffusive flux:

$$\mathbf{F} = -K\nabla\omega$$

- Special case of instantaneous mixing:

$$K \to \infty \quad \text{(infinite diffusivity)}$$

References

Greve, R., B. Grieger and O. J. Stenzel. 2010. MAIC-2, a latitudinal model for the Martian surface temperature, atmospheric water transport and surface glaciation. *Planetary and Space Science* **58** (6), 931-940, doi: 10.1016/j.pss.2010.03.002.

Herkenhoff, K. E. and J. J. Plaut. (2000). Surface ages and resurfacing rates of the polar layered deposits on Mars. *Icarus* **144** (2), 243-253, doi: 10.1006/icar.1999.6287.

Holt, J. W., R. Greve, I. B. Smith, L. E. Steel and T. C. Cowan. 2012. Stratigraphic and modeling evidence in support of a young age for the North Polar Layered Deposits, Mars. In: 43rd Lunar and Planetary Science Conference, #2879. LPI Contribution No. 1659, Lunar and Planetary Institute, Houston, Texas, USA.

Ingersoll, A. P. 1970. Mars: occurrence of liquid water. *Science* **168** (3934), 972-973, doi: 10.1126/science.168.3934.972.

Laskar, J., A. C. M. Correia, M. Gastineau, F. Joutel, B. Levrard and P. Robutel. 2004. Long term evolution and chaotic diffusion of the insolation quantities of Mars. *Icarus* **170** (2), 343-364, doi: 10.1016/j.icarus.2004.04.005.

Lewis, S. R., M. Collins, P. L. Read, F. Forget, F. Hourdin, R. Fournier, C. Hourdin, O. Talagrand and J.-P. Huot. 1999. A climate database for Mars. *Journal of Geophysical Research: Planets* **104** (E10), 24177-24194, doi: 10.1029/1999JE001024.

Richardson, M. I. and R. J. Wilson. 2002. A topographically forced asymmetry in the Martian circulation and climate. *Nature* **416** (6878), 298-301, doi: 10.1038/416298a.