

Nuages et poussières de l'atmosphère martienne: télédétection, modélisation des rétroactions climatiques et application aux paléoclimats

Thèse de doctorat de l'Université Pierre et Marie Curie
présentée par :

Jean-Baptiste MADELEINE

Directeur : François FORGET



4 Février 2011



Dust and clouds on Mars: Remote sensing, modeling of climate feedbacks and paleoclimate applications

a thesis by

Jean-Baptiste MADELEINE

Advisor: François FORGET

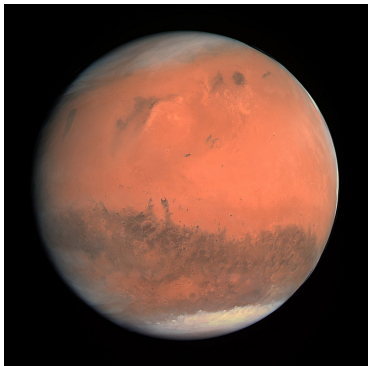
presented in fulfillment of the requirements for the degree of
Doctor of Physics at the Paris 6 university



February 4th, 2011



Mars: Main characteristics



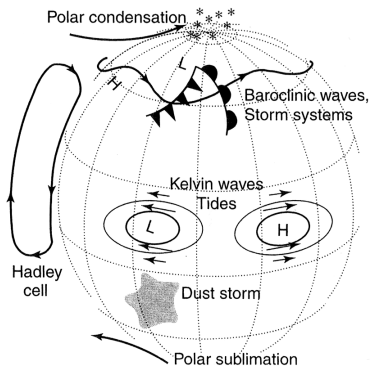
[OSIRIS/Rosetta]

True-colour image of Mars.

Equatorial radius	3396 km
Mean distance from Sun	$227.9 \cdot 10^6$ km
Solar constant	594 W m^{-2}
Eq. temperature T_e	210 K
Atm. composition	95% CO ₂
Mean surface pressure	6.1 hPa
Obliquity ϵ	25.19°
Length of day	24h40
Scale height H_p	~ 10 km
Deformation radius L	~ 1000 km
Rad. time constant τ_r	$\sim 1\text{-}2$ days

[Read and Lewis, 2004; Leovy, 1969]

Mars: Main characteristics



[Haberle, 2000]

General circulation during
northern winter.

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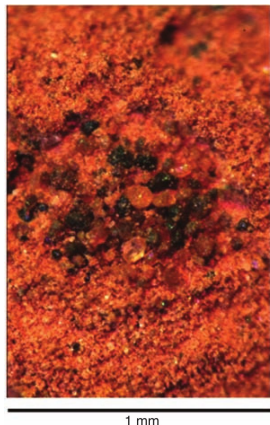
Mars: General circulation (MY25, $L_s = 270^\circ$)

Purple: 140 K – Red: 245 K

[UK Reanalysis]

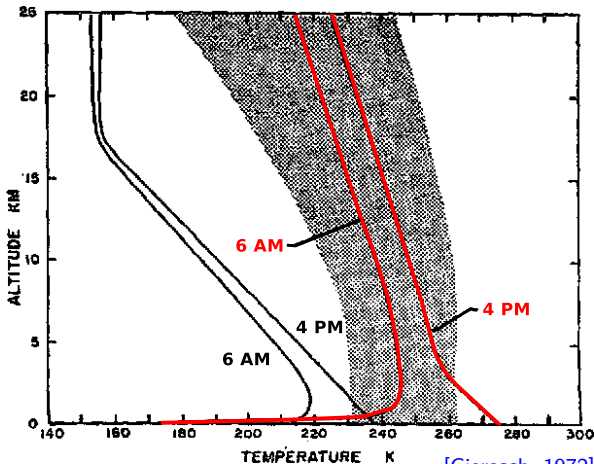
Mars: a strong control of atmospheric dust

Microscope image of the surface by Phoenix.



[Smith, 2009]

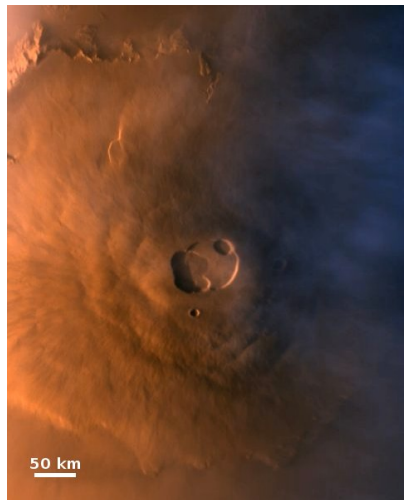
Black: pure CO₂ – **Red:** CO₂ + solar abs.
Grey area: Mariner 6 & 7 temperatures.



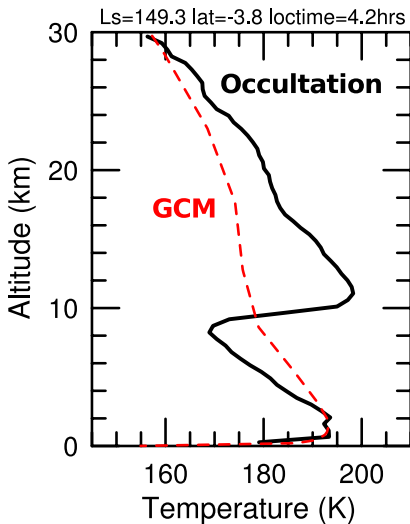
[Gierasch, 1972]

Mars: an added effect of water-ice clouds

Olympus Mons in the late afternoon.



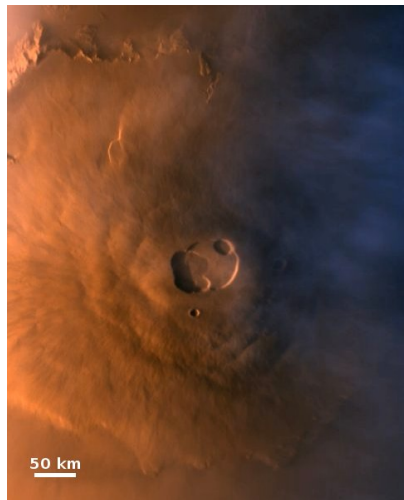
[MOC/MGS – MY23, $L_s = 201^\circ$, $LT = 17.5$]



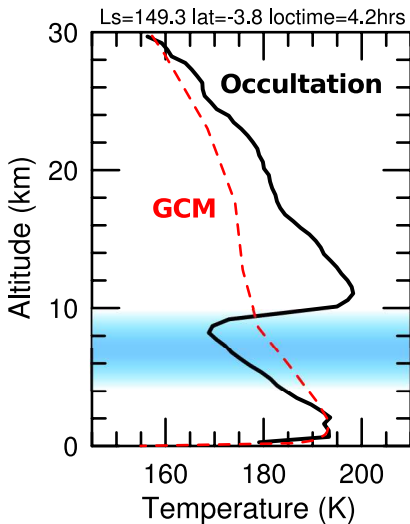
[RS/MGS – Forget, 2001]

Mars: an added effect of water-ice clouds

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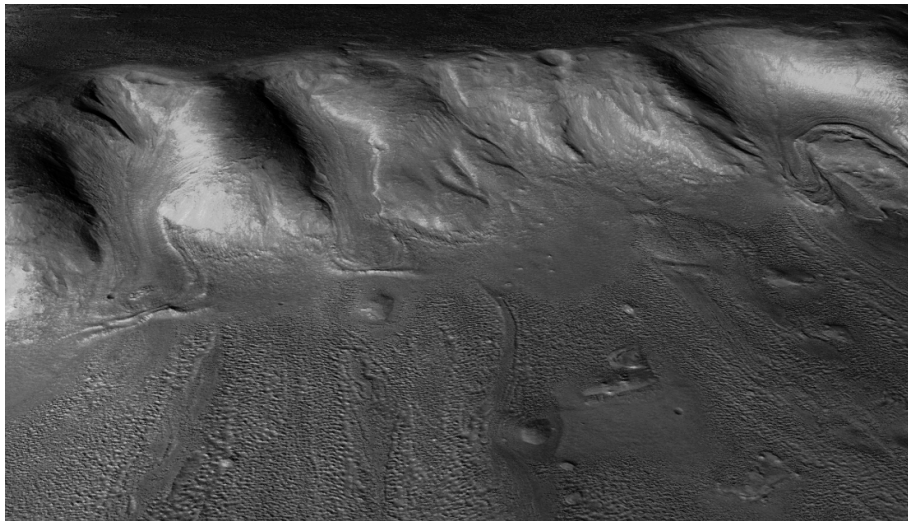
[MOC/MGS – MY23, $L_s = 201^\circ$, $LT = 17.5$]



[RS/MGS – Forget, 2001]

Mars: evidence for past changes

Glaciers of Deuteronilus Mensae (cliff is about 1 km high).



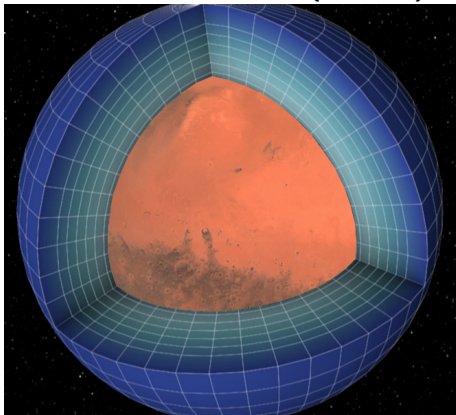
[CTX/MRO & MOLA/MGS – Courtesy of James Dickson]

Outstanding questions

1. What is the detailed impact of atmospheric dust on the martian climate?
2. What are the properties of water-ice clouds and how do they affect the climate?
3. Under which atmospheric conditions did the observed glaciations occur?

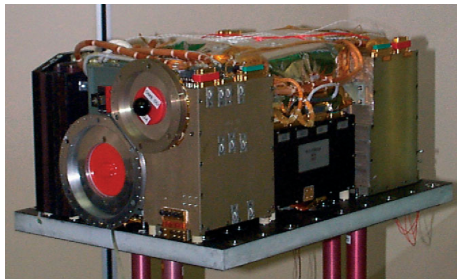
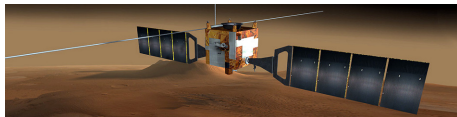
Research methodology

Three-dimensional **Global Climate Model (GCM)**



Modeling of aerosol feedbacks under past and present conditions

Satellite observations



Retrieval of cloud properties using the OMEGA near-IR spectrometer

Plan

1 Revisiting the role of atmospheric dust

- Aerosol characterisation
- Dust in the previous version of the GCM
- Updating the radiative properties of dust
- Implementation of a semi-interactive dust scheme

2 Observing and modeling Mars water-ice clouds

- The Martian water cycle
- Retrieval of the cloud physical properties
- Radiatively active water-ice clouds

3 The aerosol cycles during Amazonian glaciations

- Amazonian climate cycles
- The origin of the northern mid-latitude glaciation

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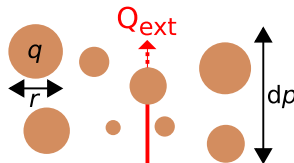
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Aerosol characterisation

Optical depth or Opacity τ_λ

$$d\tau_\lambda = \frac{3}{4} \frac{Q_{\text{ext},\lambda}}{\rho_p} \frac{q}{r_{\text{eff}} g} dp$$



Aerosol characterisation

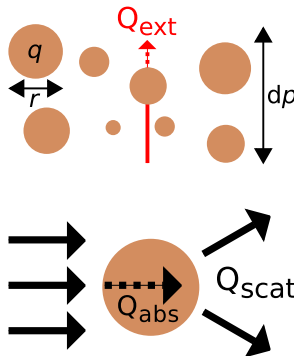
Optical depth or Opacity τ_λ

$$d\tau_\lambda = \frac{3}{4} \frac{Q_{\text{ext},\lambda}}{\rho_p} \frac{q}{r_{\text{eff}} g} dp$$

Single Scattering Albedo ω_0

$$\omega_0 = \frac{Q_{\text{scat}}}{Q_{\text{abs}} + Q_{\text{scat}}} = \frac{Q_{\text{scat}}}{Q_{\text{ext}}}$$

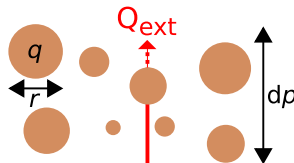
Reflects the optical index of refraction n



Aerosol characterisation

Optical depth or Opacity τ_λ

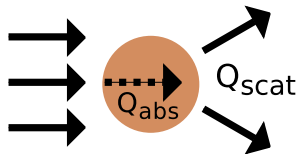
$$d\tau_\lambda = \frac{3}{4} \frac{Q_{\text{ext}\lambda}}{\rho_p} \frac{q}{r_{\text{eff}} g} dp$$



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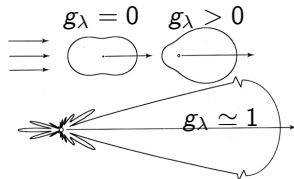
Reflects the optical index of refraction n



Asymmetry factor g_λ

$$g_\lambda = \frac{1}{2} \int_{-1}^1 P_\lambda(\cos \Theta) \cos \Theta d \cos \Theta$$

Reflects the phase function $P_\lambda(\theta)$



[Salby, 1996]

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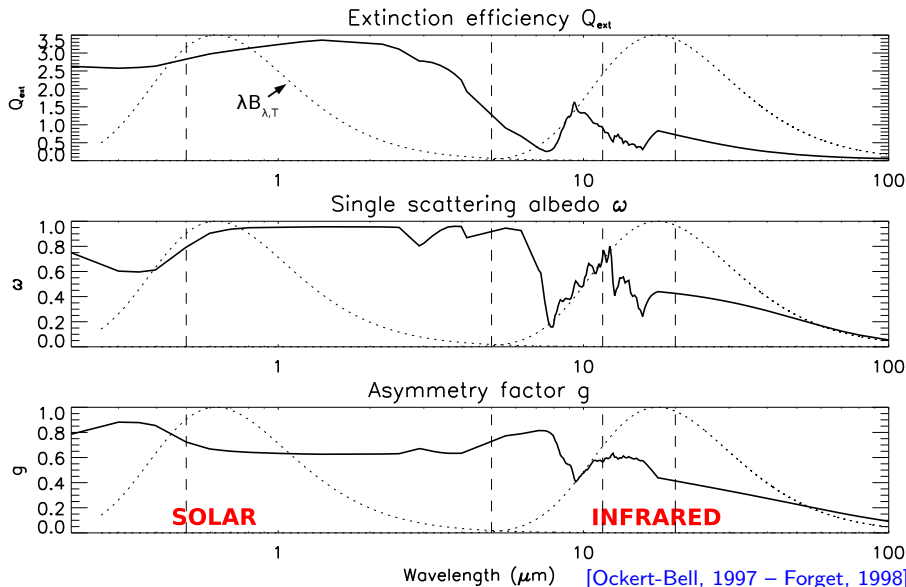
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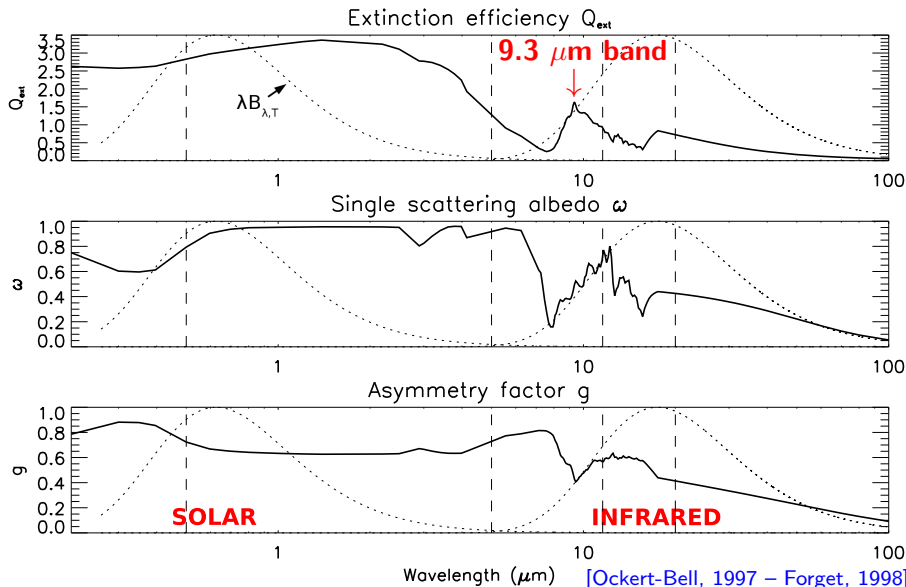
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- The origin of the northern mid-latitude glaciation

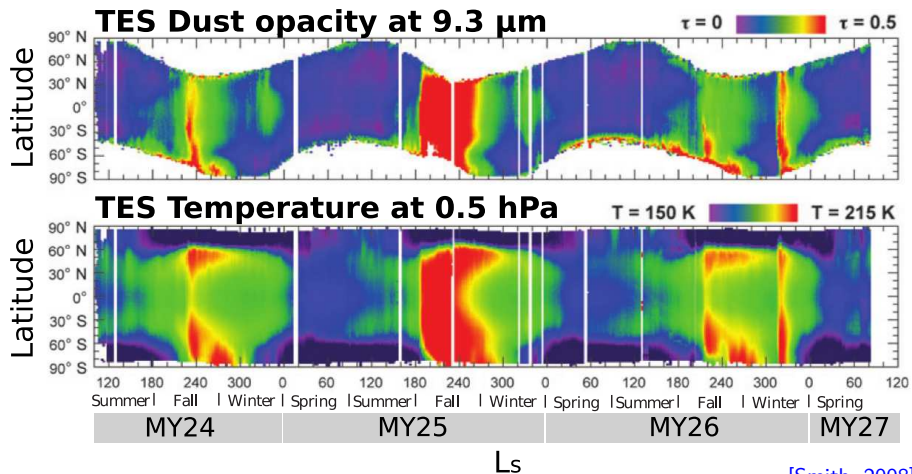
Dust radiative properties: first dataset



Dust radiative properties: first dataset



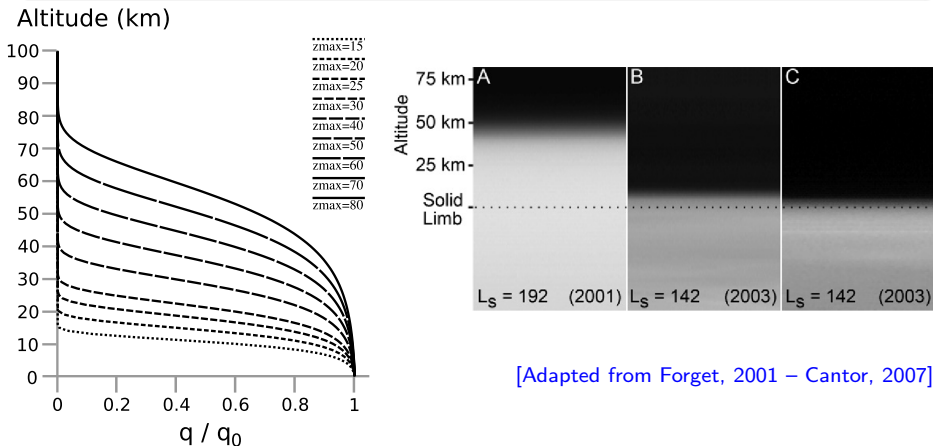
Observed dust opacity



Description of the dust layer in the model

Constant size case: Analytical distribution

$$d\tau_\lambda = \frac{3}{4} \frac{Q_{\text{ext}\lambda}}{\rho_p} \frac{q}{r_{\text{eff}} g} dp \rightarrow d\tau_\lambda = f(p, z_{\text{max}})$$

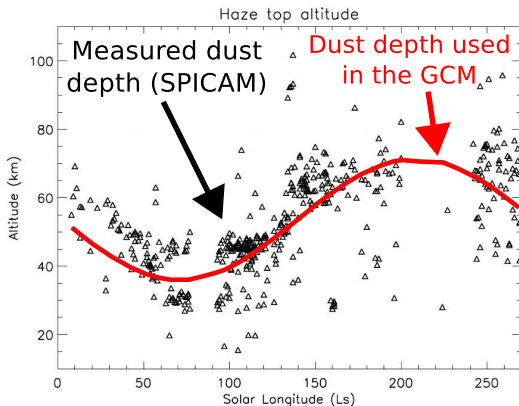
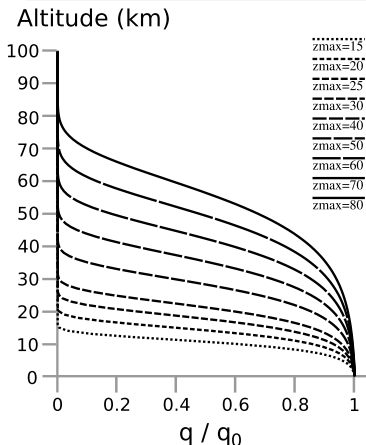


[Adapted from Forget, 2001 – Cantor, 2007]

Description of the dust layer in the model

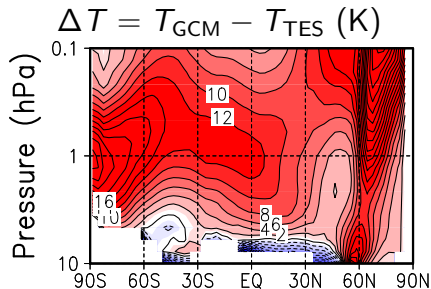
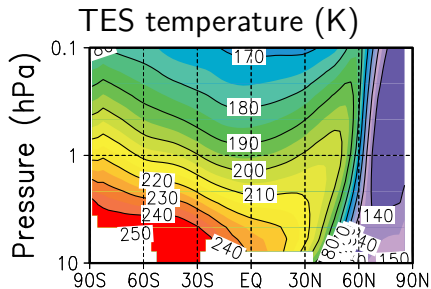
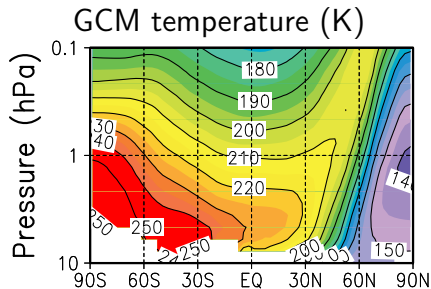
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[Adapted from Forget, 2001 – Montmessin, 2006]

Zonal mean temperature - $L_s = 270^\circ$

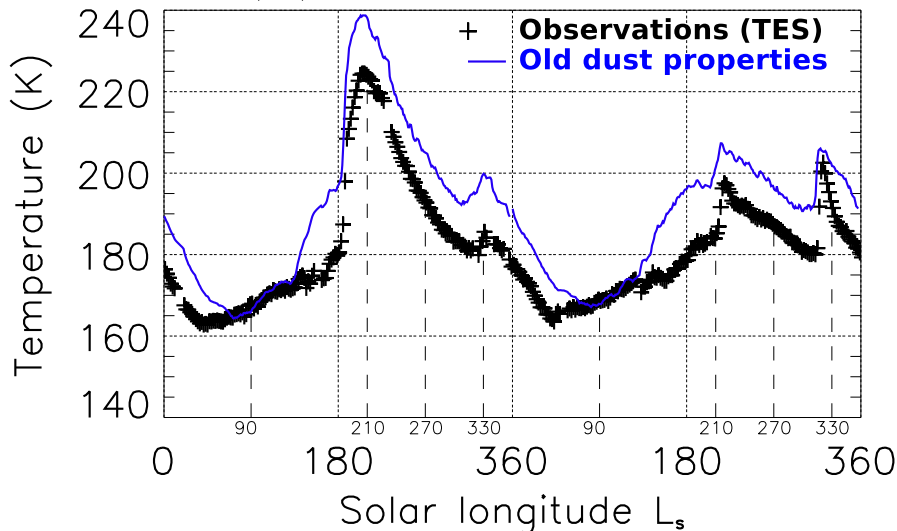


Overall warm bias

Inconsistency between the observed dust opacity and the simulated temperatures.

Constant bias toward higher temperatures

$T(K)$ at 0.5 hPa – 2PM



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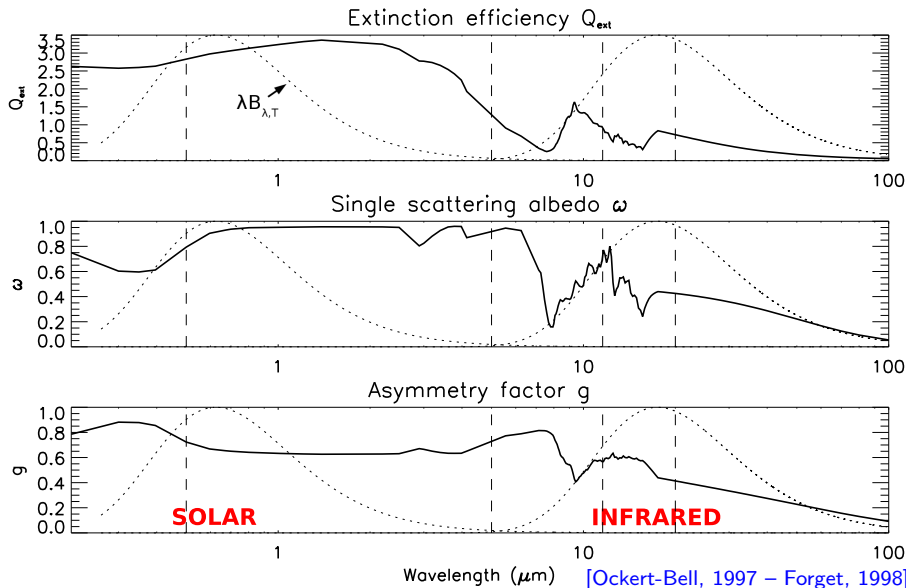
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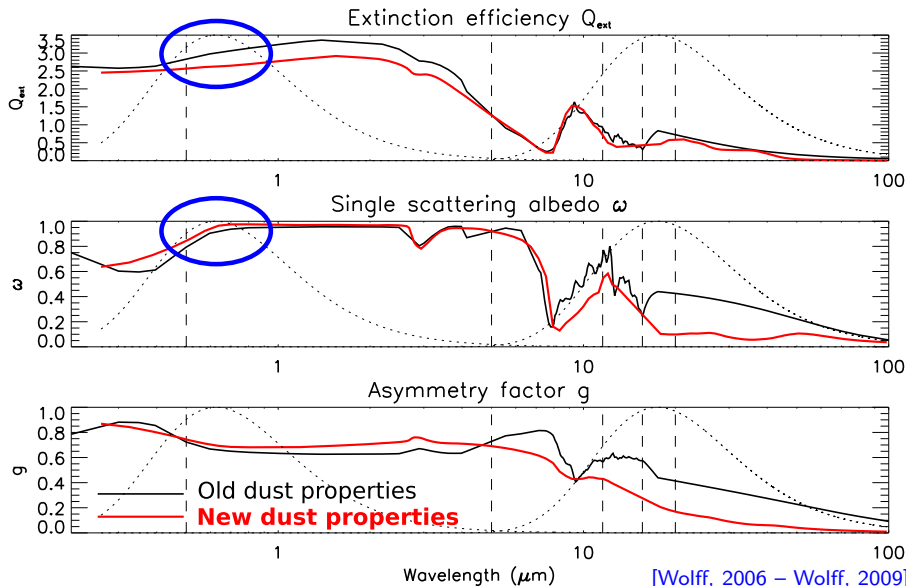
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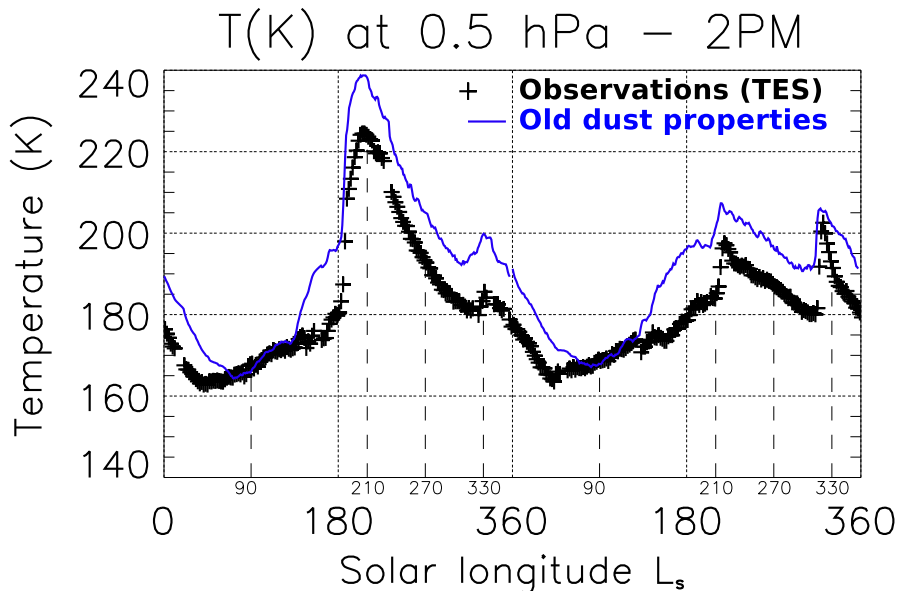
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Dust radiative properties: second dataset



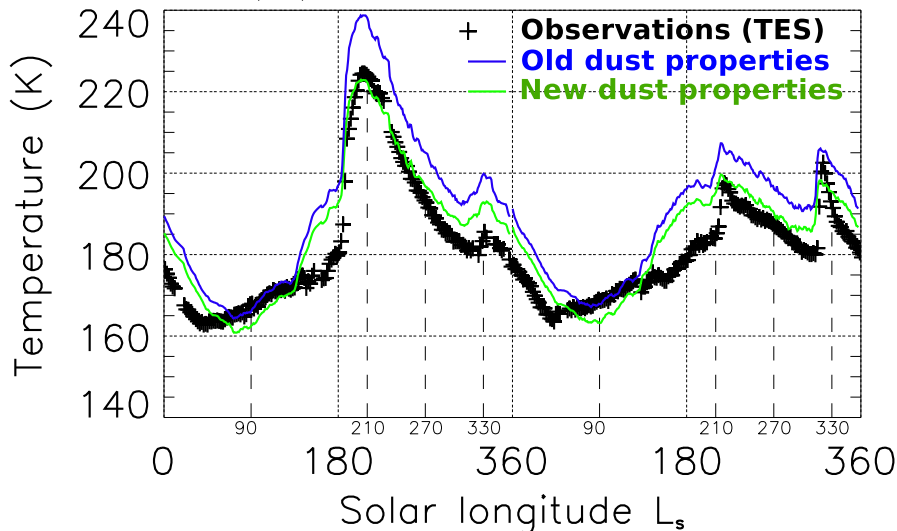
Dust radiative properties: second dataset





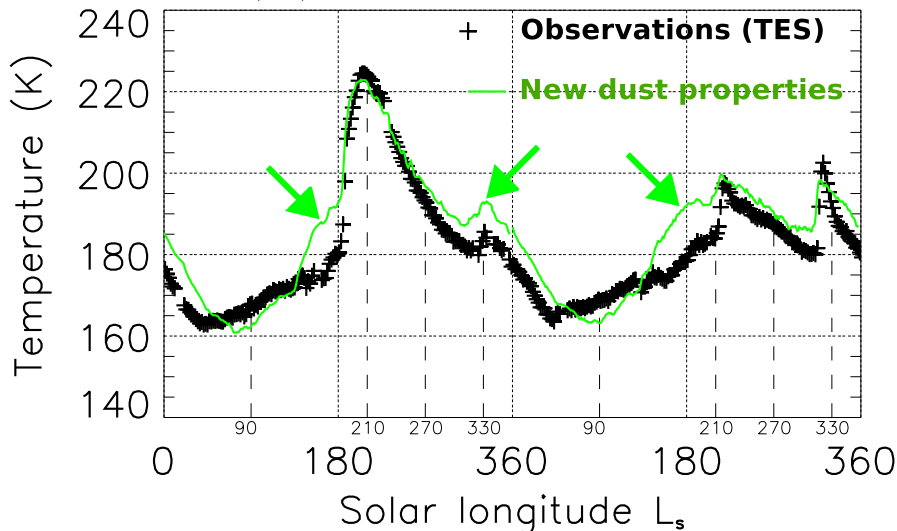
General cooling due to increased ω_0

$T(K)$ at 0.5 hPa – 2PM



General cooling due to increased ω_0

$T(K)$ at 0.5 hPa – 2PM



Possible reasons for the remaining biases

- The vertical distribution of dust does not always follow the prescribed analytical function (Kahre, 2008);
- The thickness of the dust layer is highly variable and only partially represented by the z_{\max} function, whose values are often too high (Basu, 2004 – Wilson, 2008);
- Dust particles vary in size, and radiative properties are not constant at all (Wolff, 2006).

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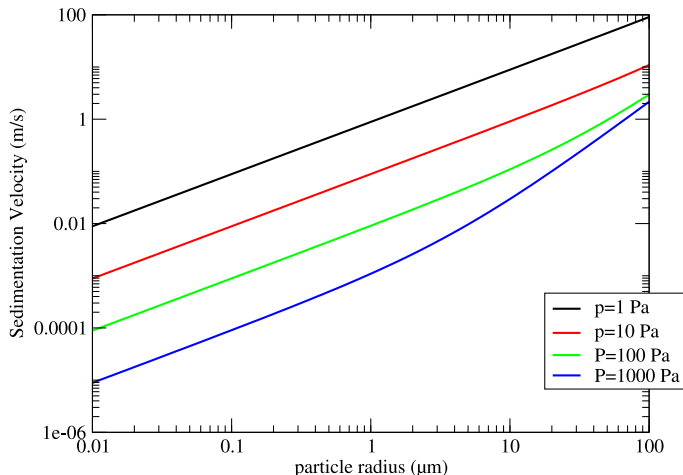
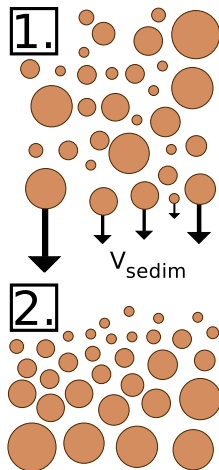
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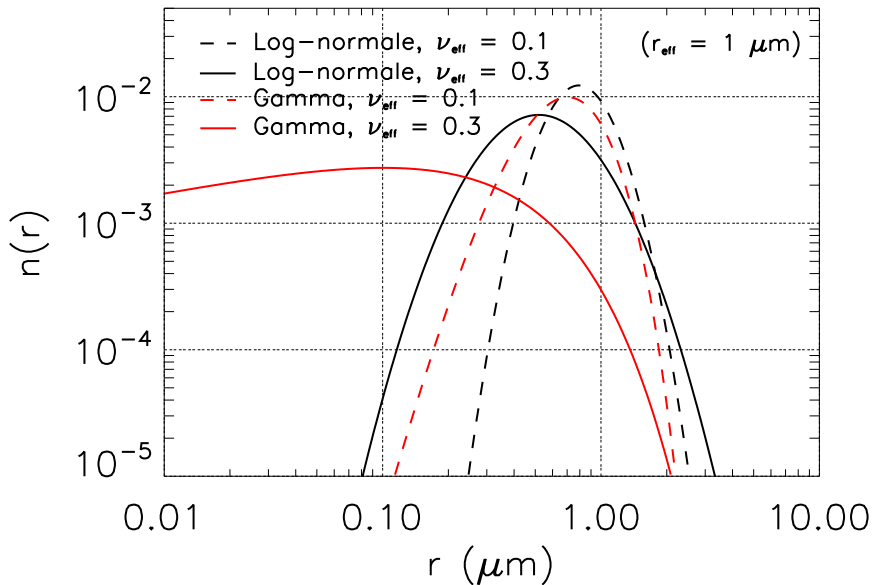
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Vertical segregation of dust particles

Sedimentation velocity depends on atmospheric pressure and particle radius.



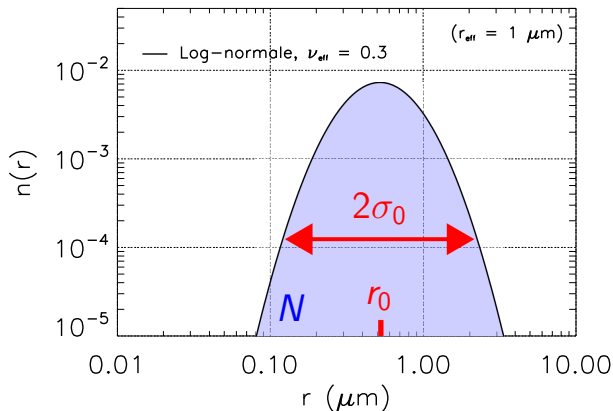
Particle size distributions



Two-moment scheme

Lognormal distribution

$$n(r) = \frac{N}{\sqrt{2\pi} \sigma_0 r} \exp \left[-\frac{1}{2} \left(\frac{\ln(r/r_0)}{\sigma_0} \right)^2 \right]$$



N, r_0, σ_0



$r_0 = f(N, q, \sigma_0)$



N and q are transported in the GCM, and σ_0 is assumed constant.

Semi-interactive dust scheme

Computed N and \mathbf{q} , constant ν_{eff}

$$\mathbf{r}_{\text{eff}} = \left(\frac{3}{4} \frac{\mathbf{q}}{\pi \rho_p N} \right)^{1/3} (1 + \nu_{\text{eff}})$$

\mathbf{q} (kg kg^{-1}) and \mathbf{r}_{eff} (μm)

\mathbf{q}

3D scattering properties

Offline

Index of refraction

$$n = n_r + i n_i$$

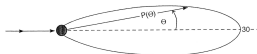
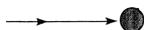
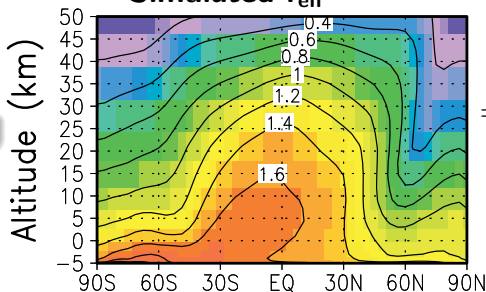


Mie/T-Matrix code

$$Q_{\text{ext}}, \omega_0, g$$



Look-up
table for a
range of
particle
sizes

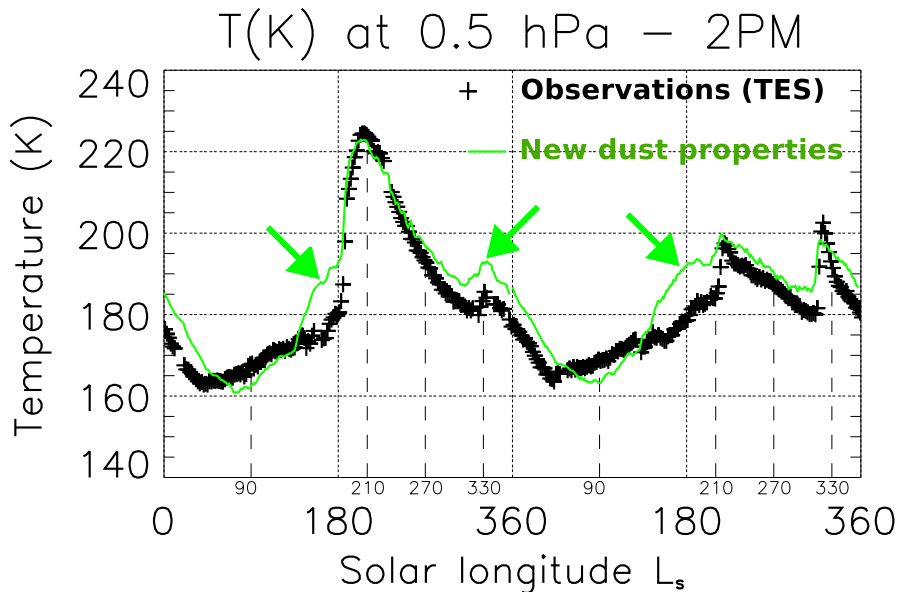
Simulated r_{eff} 

3D calculation of
 $Q_{\text{ext}}, \omega_0, g$ for the
simulated sizes



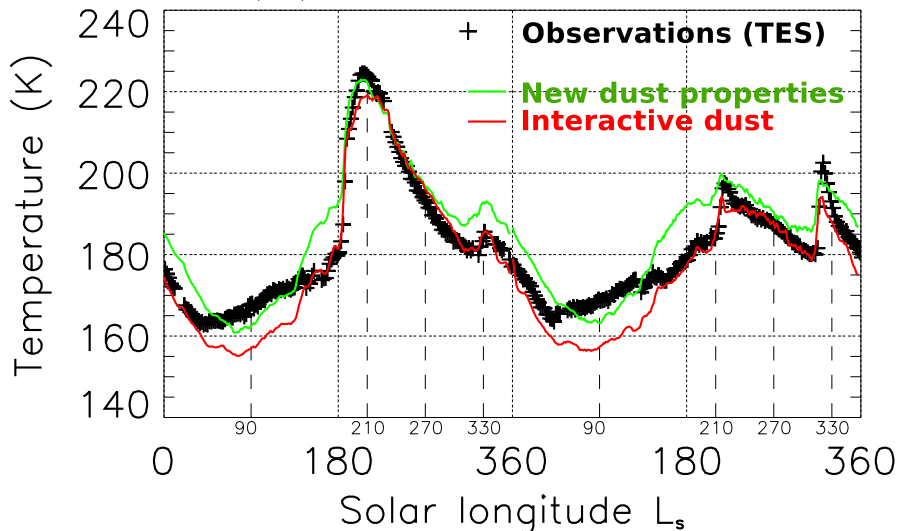
Radiative transfer
calculations

Online

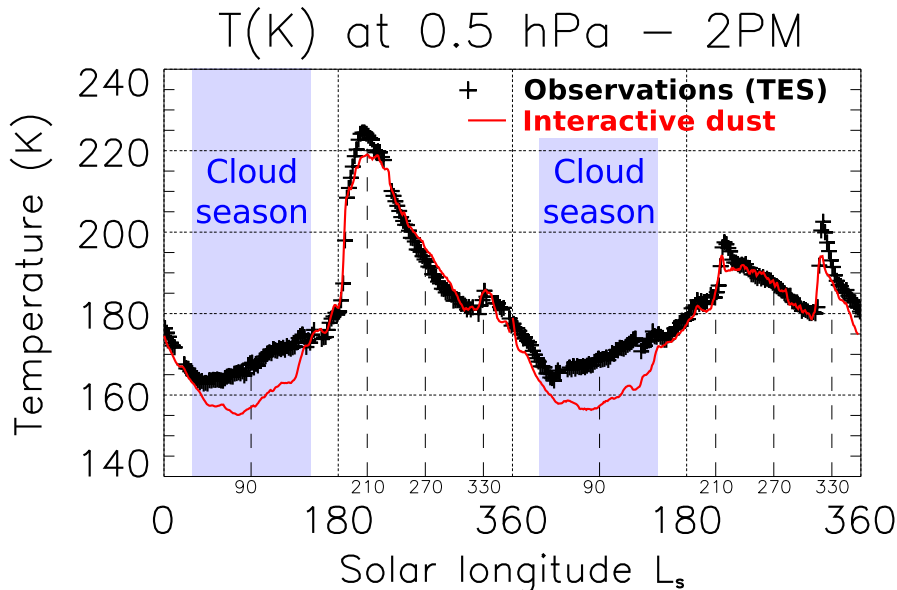


Improvement due to interactive dust cycle

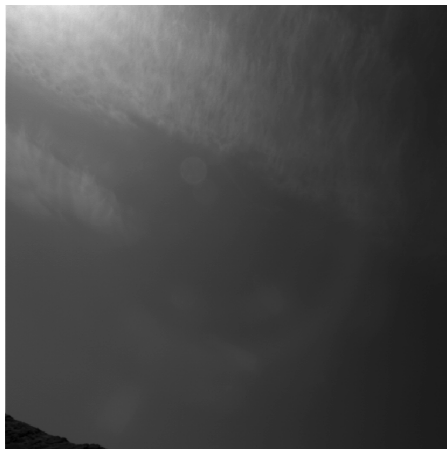
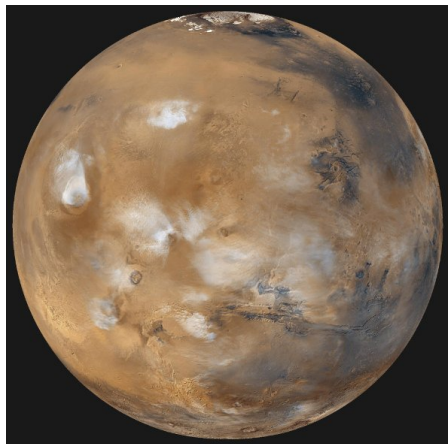
$T(K)$ at 0.5 hPa – 2PM



Remaining biases occur during cloud season



Martian water-ice clouds



The aphelion cloud belt seen by the Mars Orbiter Camera (**left**) and by Opportunity (**right**) around $L_s = 120^\circ$.

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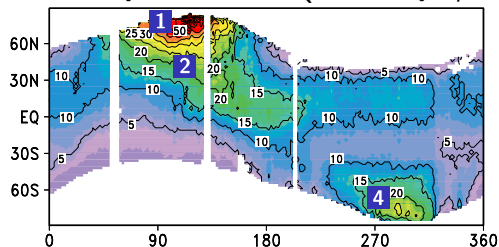
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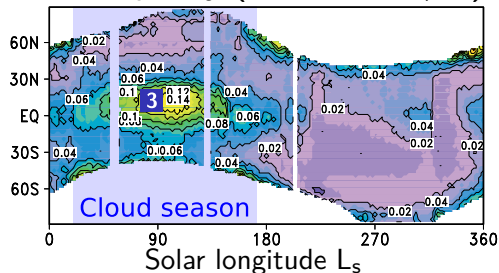
Water cycle as observed by TES (MY26)

- 1** Sublimation of the north polar cap during northern summer;
- 2** Advection into the overturning Hadley cell;
- 3** Formation of the aphelion cloud belt;
- 4** Beginning of southern summer, formation of the north polar hood.

Water vapor column (2 PM, pr. μm)



Cloud opacity (2 PM, 12.1 μm)



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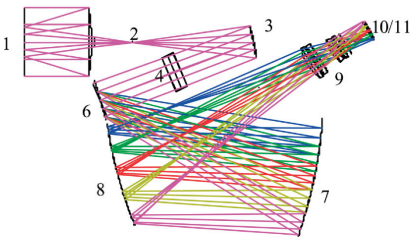
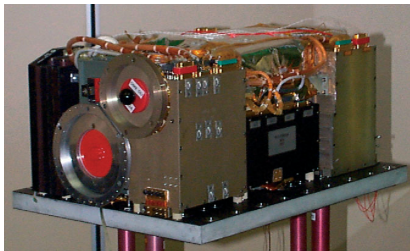
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The OMEGA near-IR imaging spectrometer



[Bibring, 2004]

Imaging

IFOV	1.2 mrad
Resolution	300 m – 4.8 km
Visible channel	CCD detector pushbroom mode
IR channel	InSb linear arrays whiskbroom mode

Spectrometry

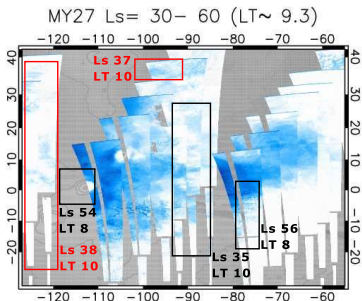
Spectral range	0.35 – 5.1 μm
Number of spectels	352
Spectral resolution	7 – 20 nm

Photometry

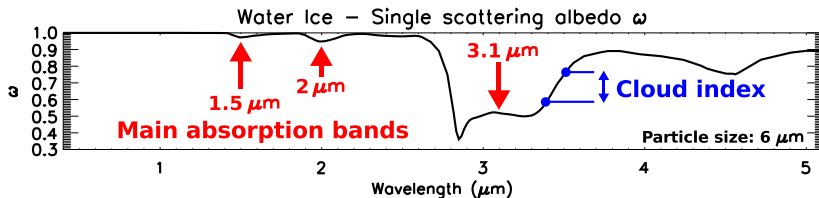
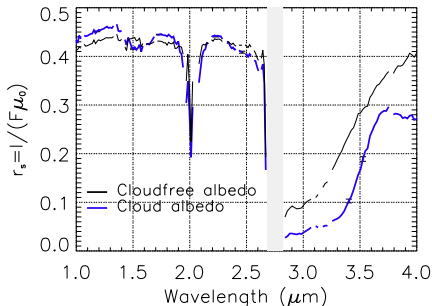
S/N	> 100
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Cloud mapping and property retrieval

Cloud mapping



Retrieval of $r_{\text{eff,ice}}$ and τ_{vis}



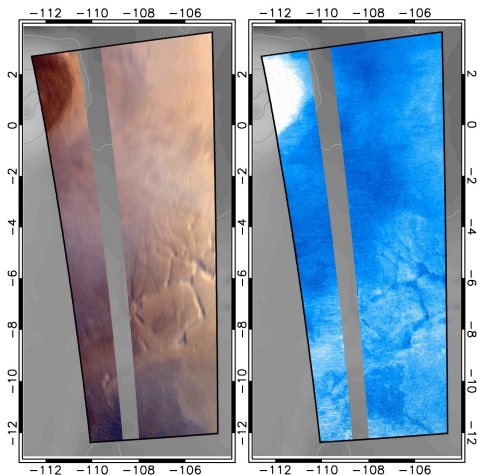
Monitoring of cloud types

Four main morphologies

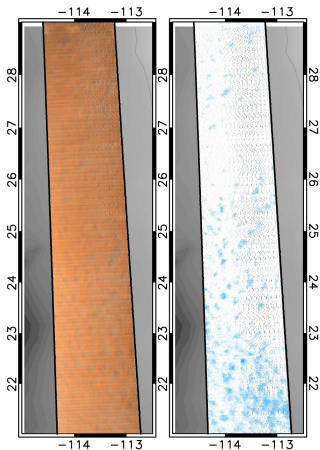
- 1 **Morning hazes** are found at around **8 AM**, form during the night, and dissipate before noon.
- 2 **Topographically controlled hazes** are observed at **various local times**, at the beginning and end of the cloud season.
- 3 **Cumulus clouds** grow in the **early afternoon**.
- 4 **Thick hazes** grow rapidly **through the afternoon**.

Monitoring of cloud types: Cloud examples

Morning hazes near Pavonis Mons
($L_s = 53.6$, $LT = 8.5$, orbit 563_3)



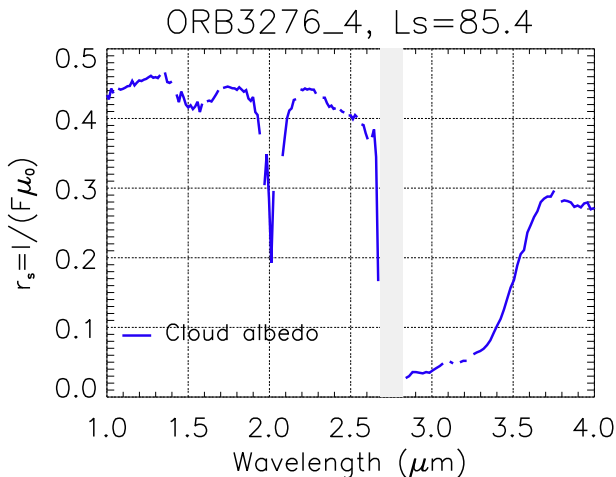
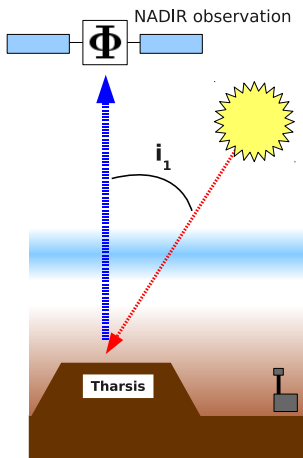
Cumulus clouds ($L_s = 115.3$,
 $LT = 10.6$, orbit 3514_1)



Visible channel image (left) and cloud index (right).

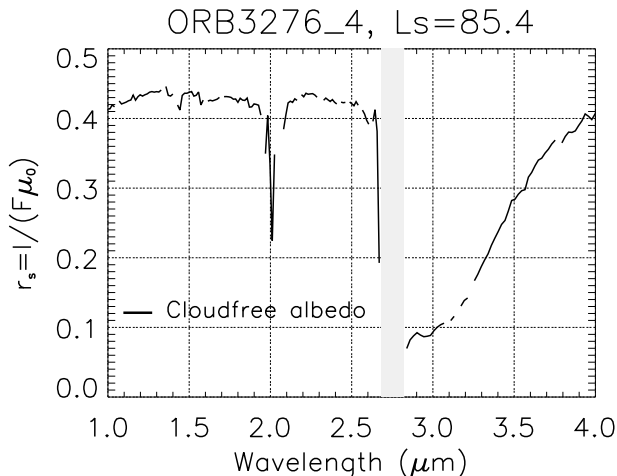
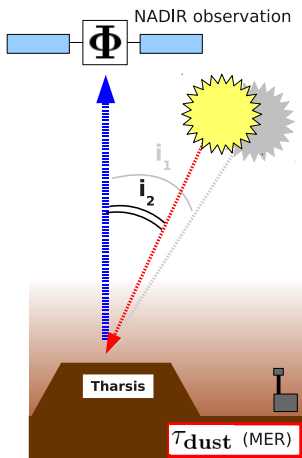
Retrieval of crystal size and cloud opacity

1. Selection of a cloud spectrum



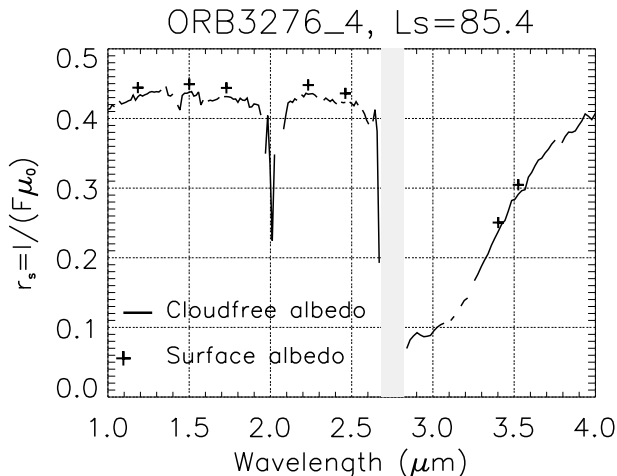
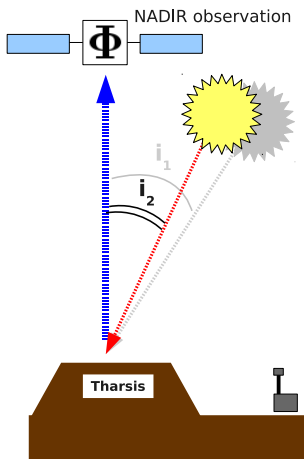
Retrieval of crystal size and cloud opacity

2. Selection of a cloud-free spectrum of the same region



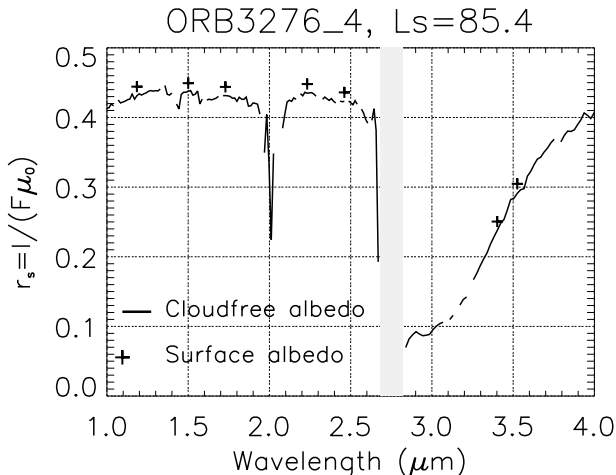
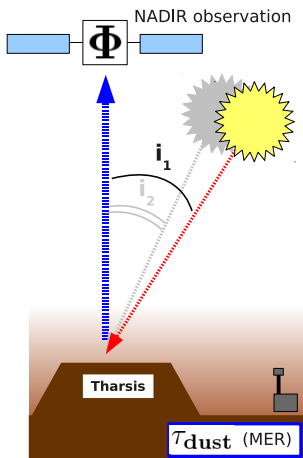
Retrieval of crystal size and cloud opacity

3. Removal of the dust layer contribution



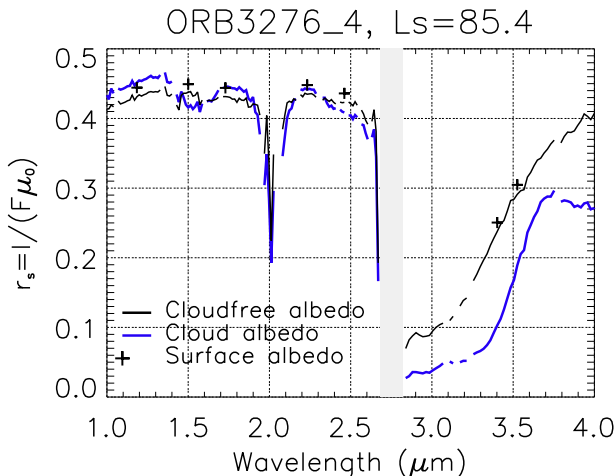
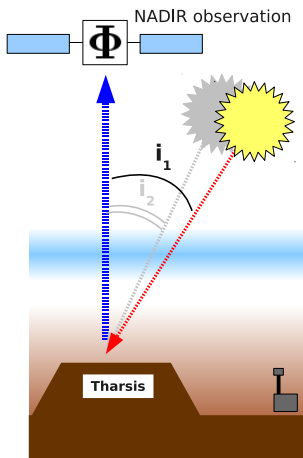
Retrieval of crystal size and cloud opacity

4. Addition of a synthetic layer of dust observed at cloud season



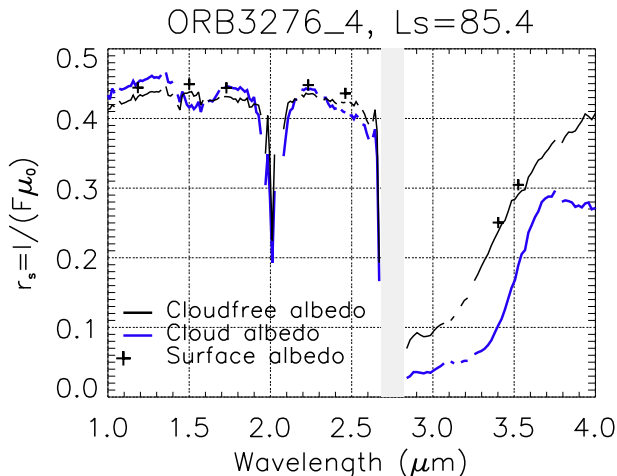
Retrieval of crystal size and cloud opacity

5. Minimization using a synthetic cloud of various r_{eff} and τ_{vis}



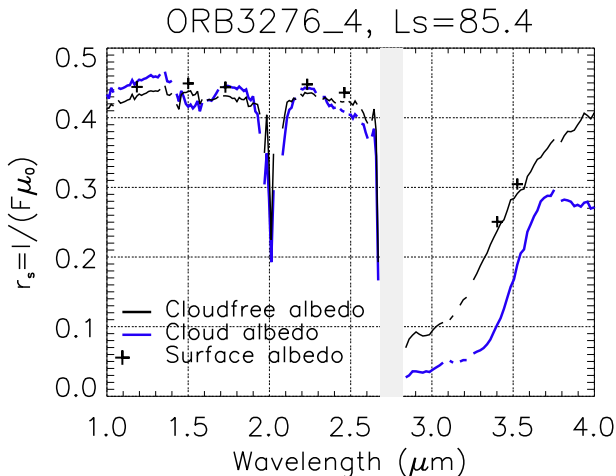
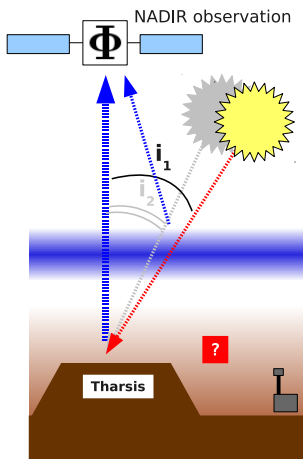
Retrieval of crystal size and cloud opacity

6a. Making sure dust opacity introduces small error



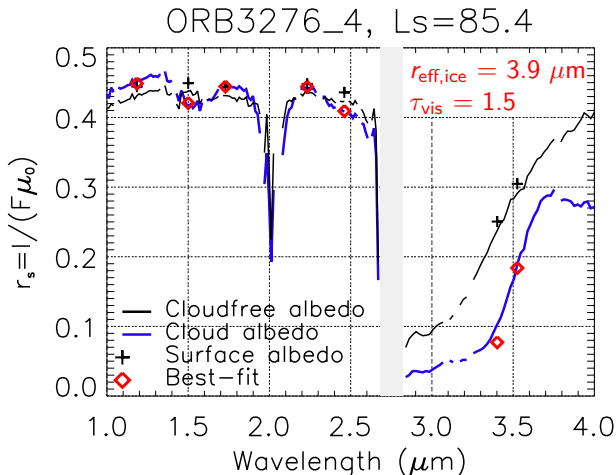
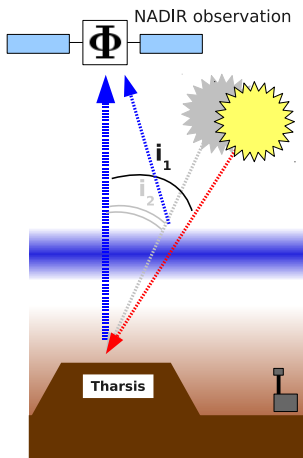
Retrieval of crystal size and cloud opacity

6b. Restriction to thick clouds ($\tau_{\text{vis}} > 1$)



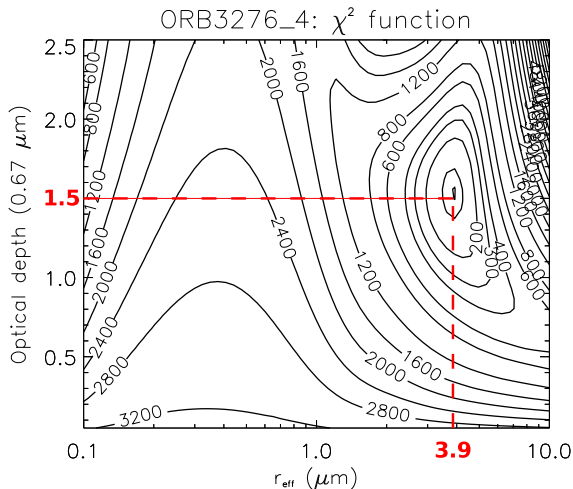
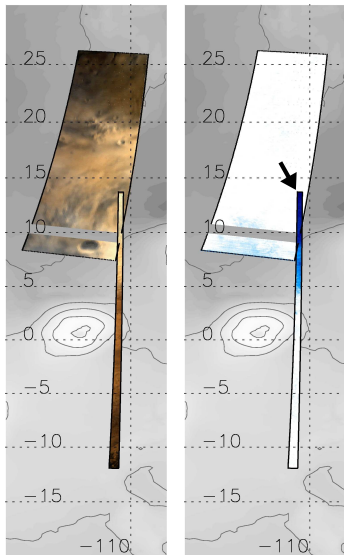
Retrieval of crystal size and cloud opacity

7. End of the minimization and property retrieval

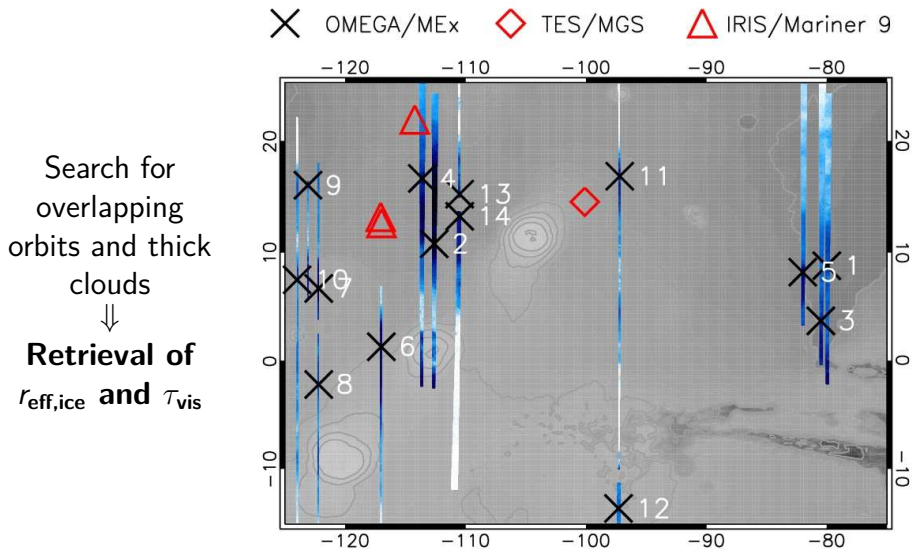


χ^2 function and minimization result

Left: True-color composition and cloud index for the two selected orbits. **Below:** The χ^2 function, which shows the accurate retrieval of $r_{\text{eff,ice}}$ and τ_{vis} .

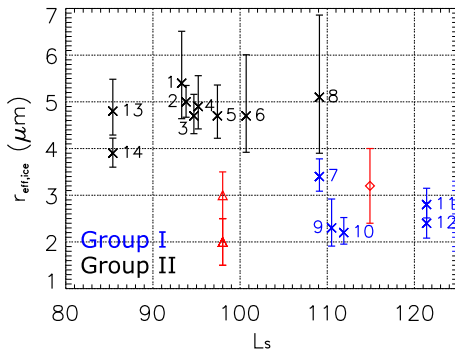


Retrieval of $r_{\text{eff,ice}}$ over the Tharsis plateau

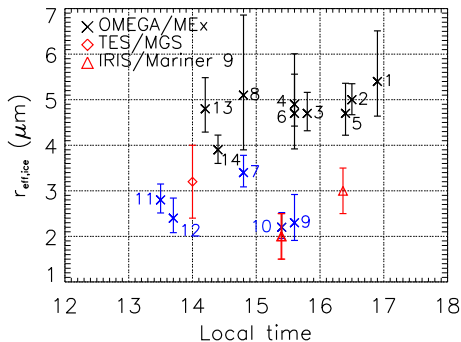


Retrieved $r_{\text{eff,ice}}$ as a function of L_s and LT

Variations in ice particle size as a function of L_s



Variations in ice particle size as a function of local time



Difficult to affirm any correlation with L_s or local time.

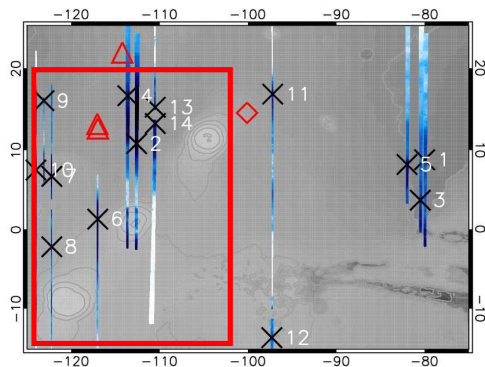
However, there seems to be two distinct groups of particles.

Explanation of the variations in $r_{\text{eff,ice}}$

Map of the OMEGA retrievals.

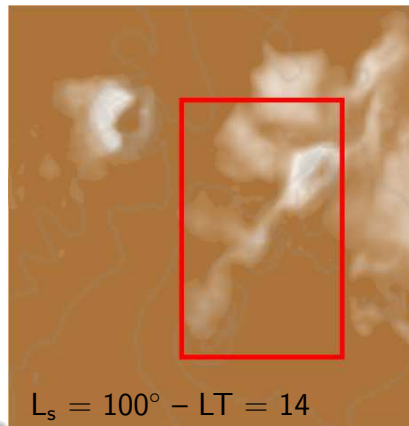
Small particles: # 7,9,10,11,12.

✕ OMEGA/MEx ◇ TES/MGS △ IRIS/Mariner 9



Largest particles are found near the volcanoes, in strong anabatic flows.

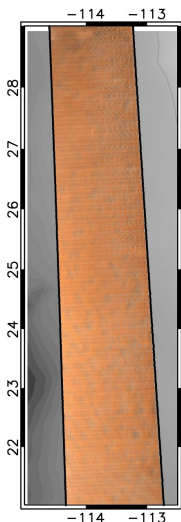
Cloud opacity ($0.4\text{--}0.8\ \mu\text{m}$) predicted by Michaels (2006).



[Michaels, 2006]

Retrieval of cloud properties: Summary

Cumulus clouds
(VIS channel)



- Ice particle sizes of thick clouds ($\tau_{\text{vis}} > 1$) are measured, and range from **2.2 to 5.4 μm** ;
- Ice crystals are larger near the volcanoes, probably due to **enhanced cloud formation** in strong anabatic flows.



Climate model validation

These observations are used to adjust the water cycle predicted by the GCM.

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- Radiatively active water-ice clouds

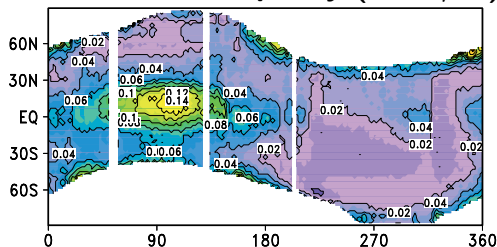
3 The aerosol cycles during Amazonian glaciations

- Amazonian climate cycles
- The origin of the northern mid-latitude glaciation

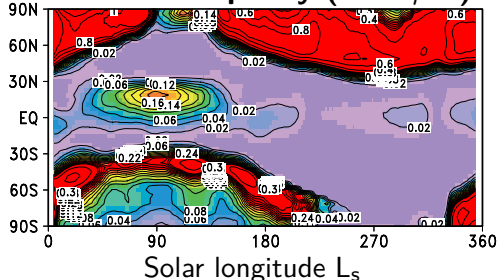
Water-ice clouds simulated by the GCM

- Coupling of the water cycle model described in [Montmessin \(2004\)](#) with the semi-interactive dust scheme;
- Adjustment of the unknown microphysical parameters in order to reach good agreement with the observations (including OMEGA);
- The predicted amount and size of ice particles are used to compute 3D time-dependent scattering parameters, using the model described previously.

Observed cloud opacity ($12.1 \mu\text{m}$)

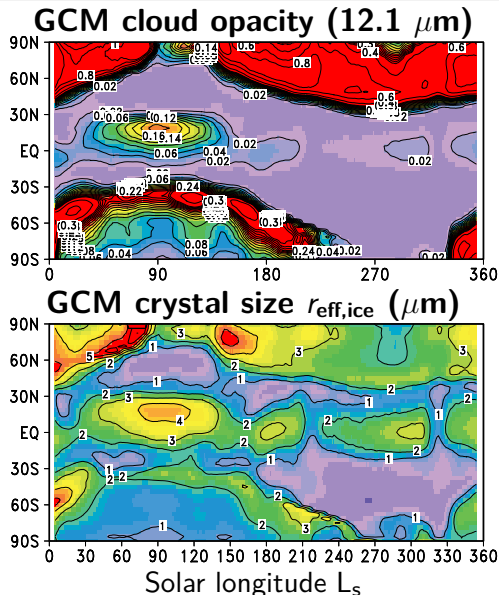


GCM cloud opacity ($12.1 \mu\text{m}$)



Water-ice clouds simulated by the GCM

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Cloud – Radiation – Temperature system

Atmospheric conditions

Humidity, temperature changes, condensation nuclei



Cloud properties

Particle size and opacity predicted by the microphysical scheme



Heating rates

Strongly dependent on cloud altitude and local time

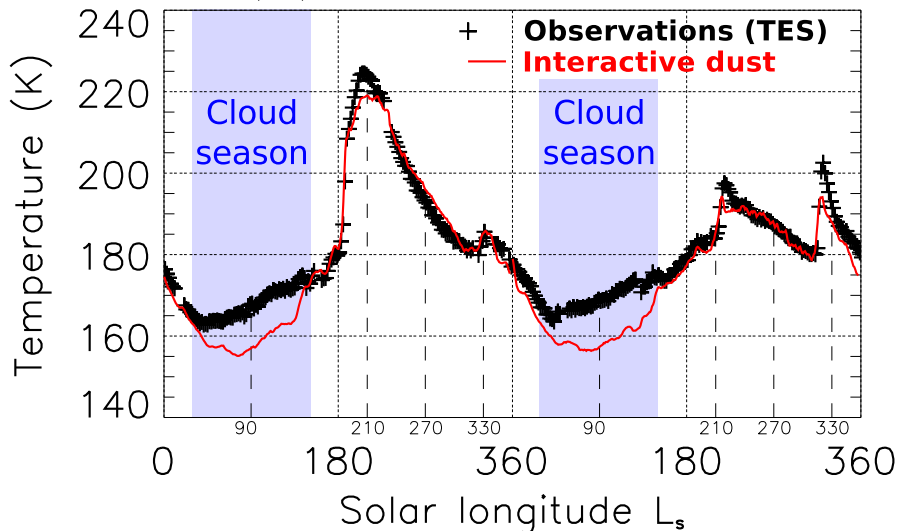


Scattering parameters

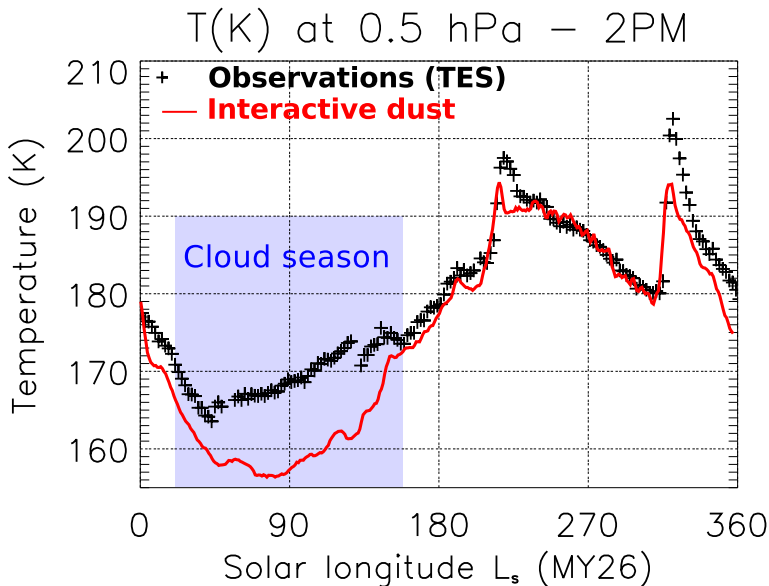
Computed by the GCM based on the size of the crystals predicted by the microphysical scheme

Results without radiatively active clouds

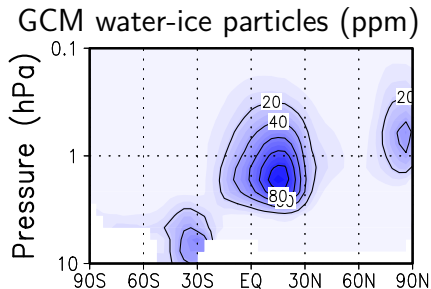
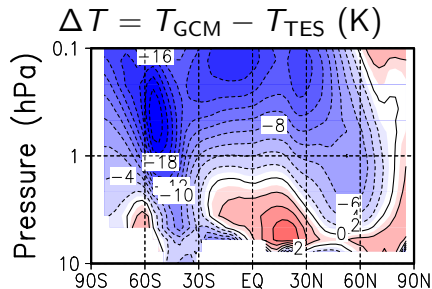
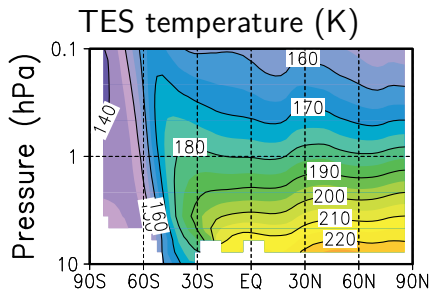
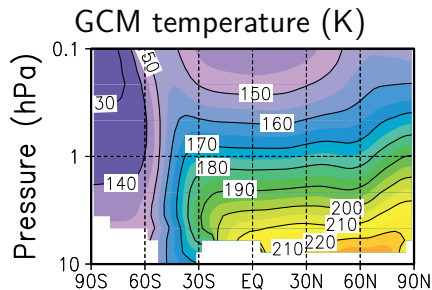
$T(K)$ at 0.5 hPa – 2PM



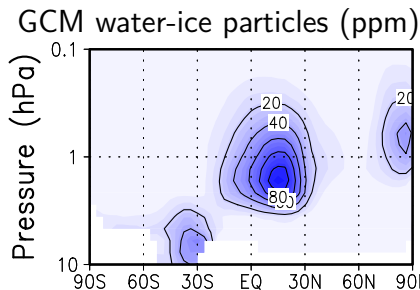
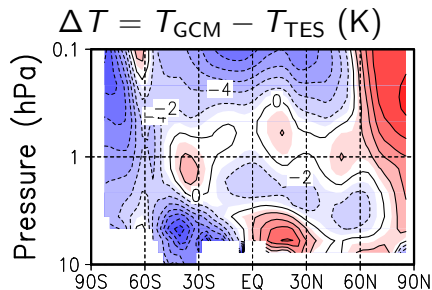
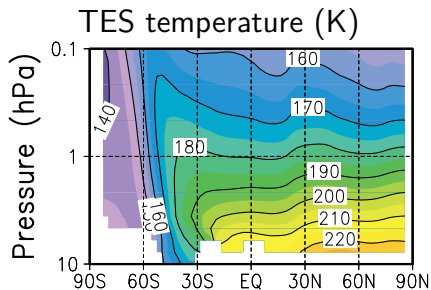
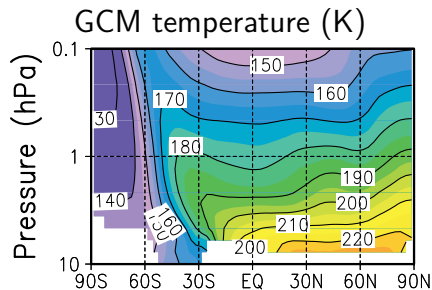
Results without radiatively active clouds



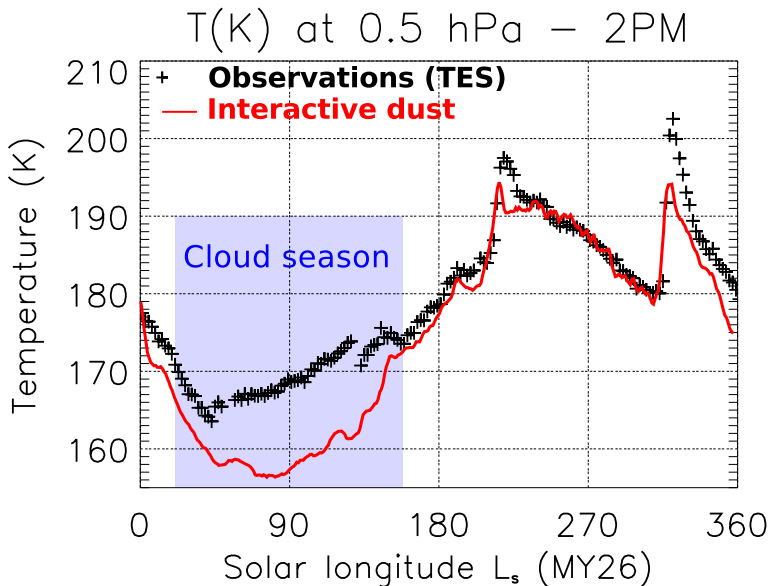
Temperature without active clouds ($L_s = 90^\circ$)



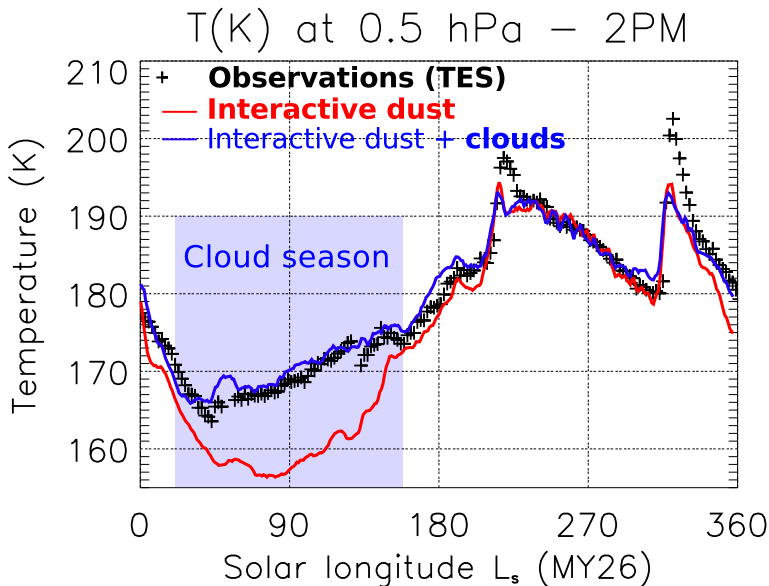
Temperature when clouds are active ($L_s = 90^\circ$)



Results without radiatively active clouds

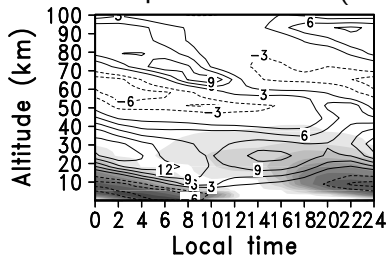


The bias vanishes when clouds are active

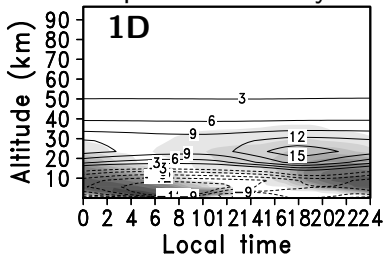


Detailed effect of clouds on temperature

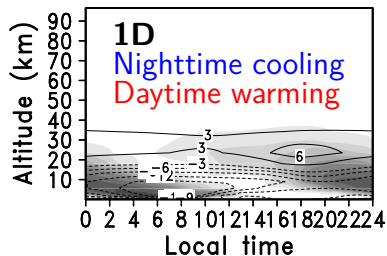
a. Total impact of clouds (3D)



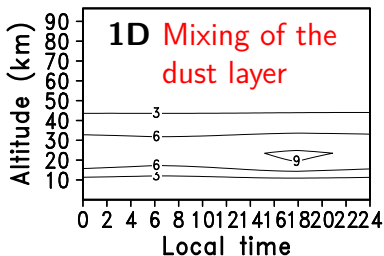
b. Total impact without dynamics



c. Direct radiative effect of clouds



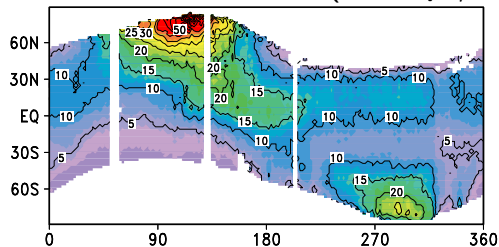
d. Indirect effect of clouds



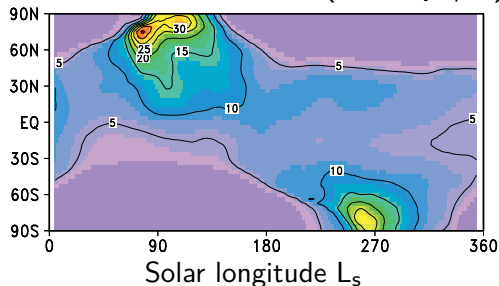
New questions: radiatively active clouds

When clouds are radiatively active, the water cycle is **too dry by $\sim 5 \text{ pr.}\mu\text{m}$**

Observed WV column (2 PM, $\text{pr.}\mu\text{m}$)



Modeled WV column (2 PM, $\text{pr.}\mu\text{m}$)



Climate changes on Mars



Plan

1 Revisiting the role of atmospheric dust

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- Amazonian climate cycles
- The origin of the northern mid-latitude glaciation

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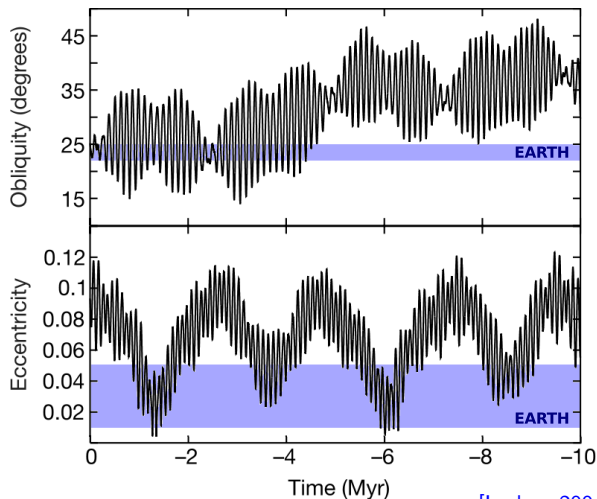
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- The origin of the northern mid-latitude glaciation

Variations in Mars orbital parameters

Large variations in Mars orbital parameters

Insolation variations are **much larger** than in terrestrial Milankovitch cycles

Many geological evidences for **cyclic climate changes**

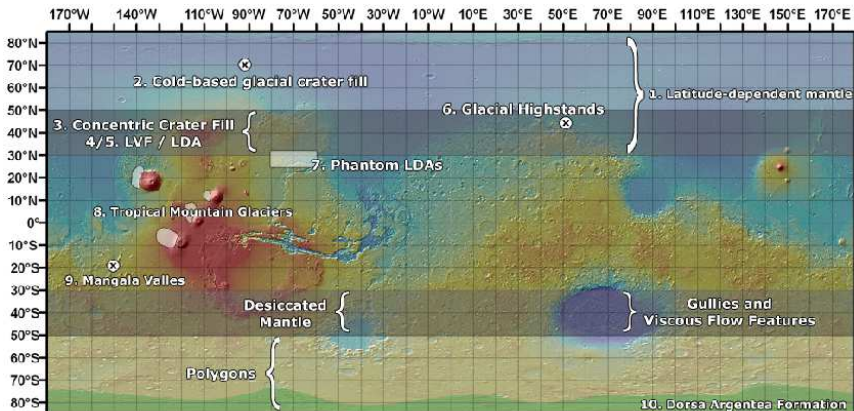


[Laskar, 2004]

Geological evidences for climate changes

Late Amazonian period ($< 250\text{--}700\text{ Myr}$)

- Latitude dependent mantle: meter thick layered deposits, above 50° ;
- Northern mid-latitudes: valley glaciers and plateau glaciation;
- Tropical mountain glaciers: mountain glacial systems.

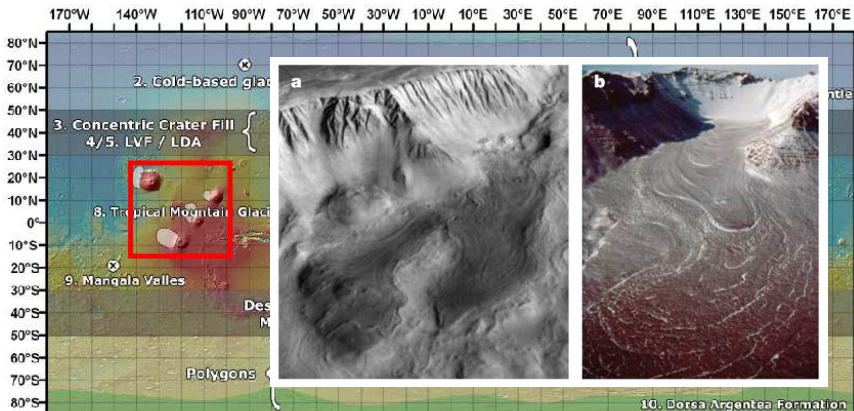


[Head, 2008]

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[Head, 2008]

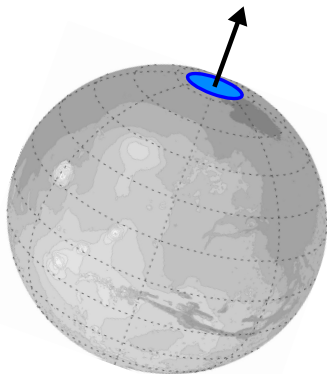
Simulation of past climates using the GCM

Modified orbital parameters (obliquity ϵ , eccentricity e and L_s of perihelion)

Present-day conditions

$$\epsilon = 25.19^\circ - e = 0.093$$

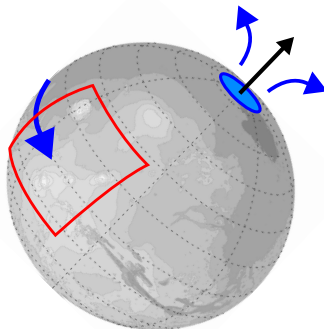
$$L_p = 251^\circ - \text{Observed } \tau_{\text{dust}}$$



High obliquity conditions

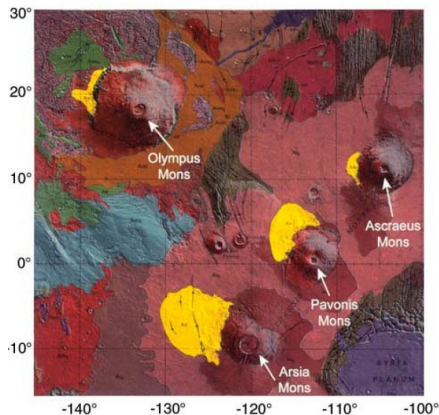
$$\epsilon = 45^\circ$$

$$e = 0 - \tau_{\text{dust}} = 0.2$$

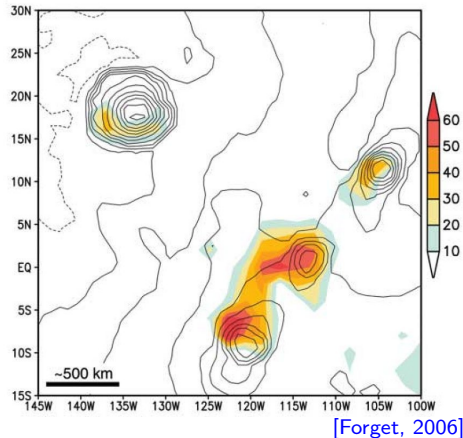


Origin of the Tropical Mountain Glaciers

A. Geological map, showing the glaciers in yellow



B. Net annual accumulation of ice simulated by the GCM (mm yr^{-1})



Ice builds up in the right regions when **obliquity is increased to 45°**

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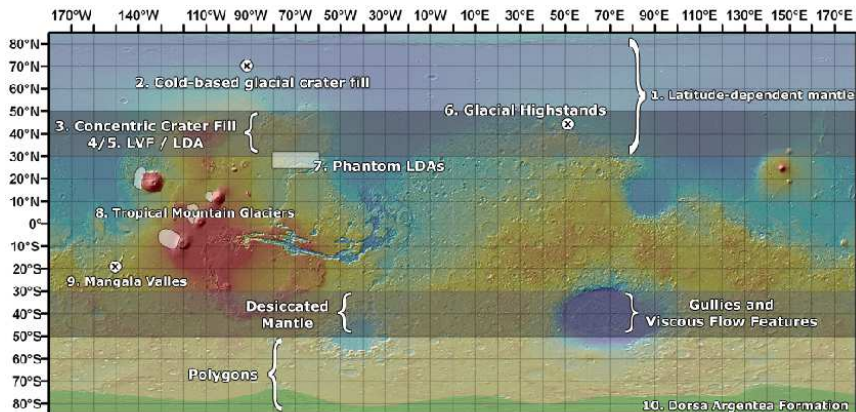
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The northern mid-latitude glaciation

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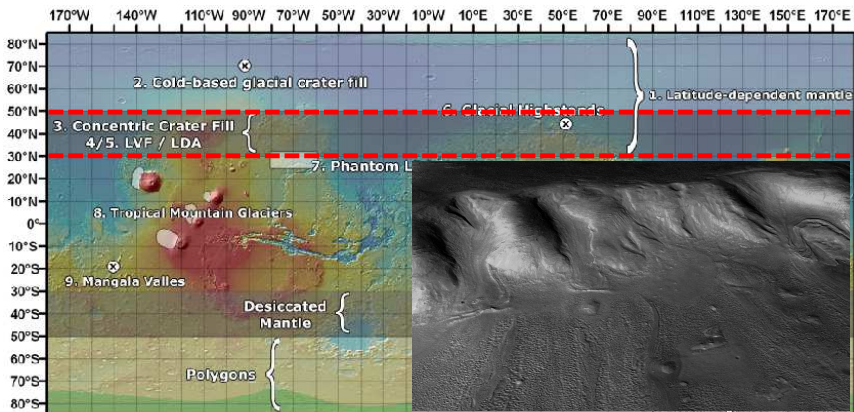


[Head, 2008]

The northern mid-latitude glaciation

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[Head, 2008]

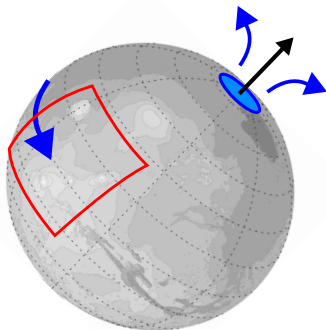
Switching from 45° to 35° obliquity

The tropical mountain glaciers become the new source of the water cycle

High obliquity conditions

$$\epsilon = 45^\circ$$

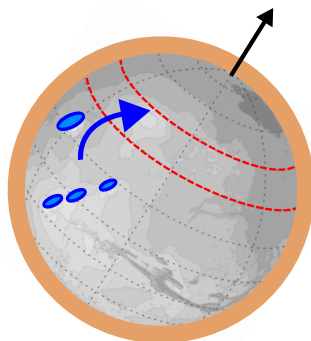
$$e = 0 - \tau_{\text{dust}} = 0.2$$



Intermediate obliquity

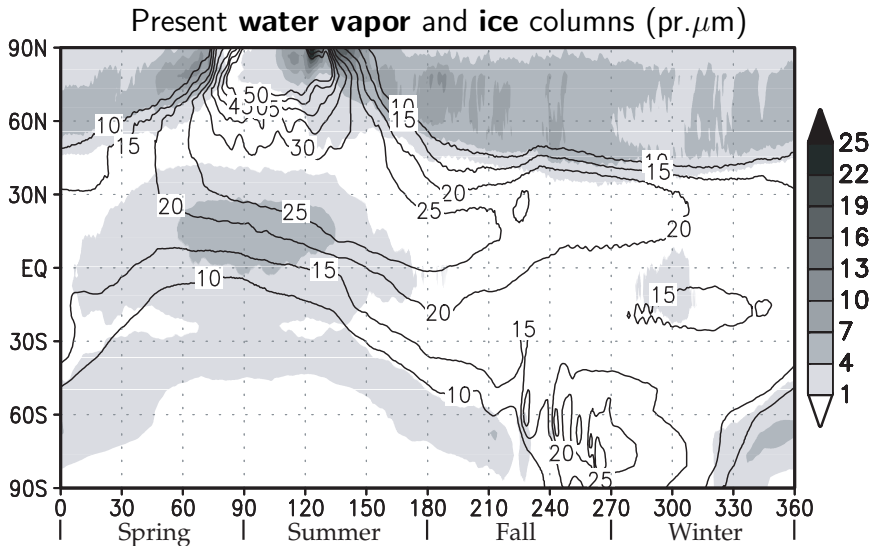
$$\epsilon = 35^\circ - e = 0.1$$

$$L_p = 270^\circ - \tau_{\text{dust}} = 2.5$$



Northern mid-latitude glaciation

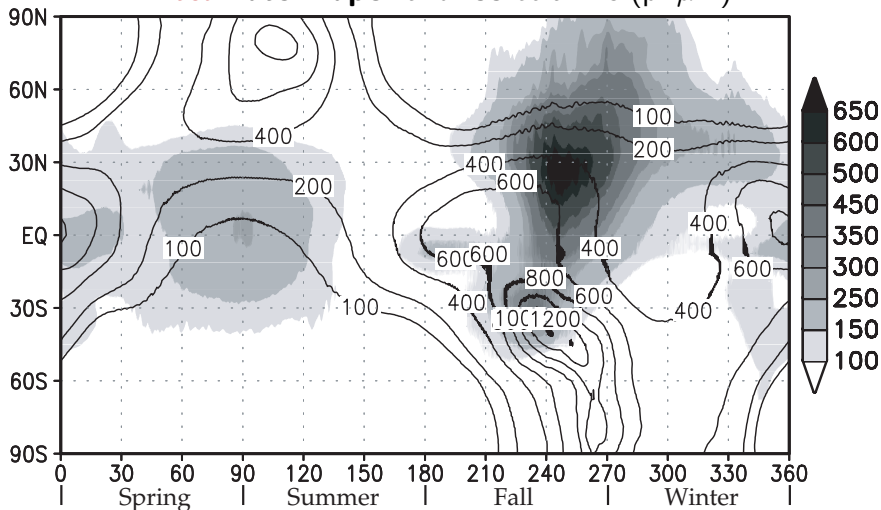
Changes in global water cycle



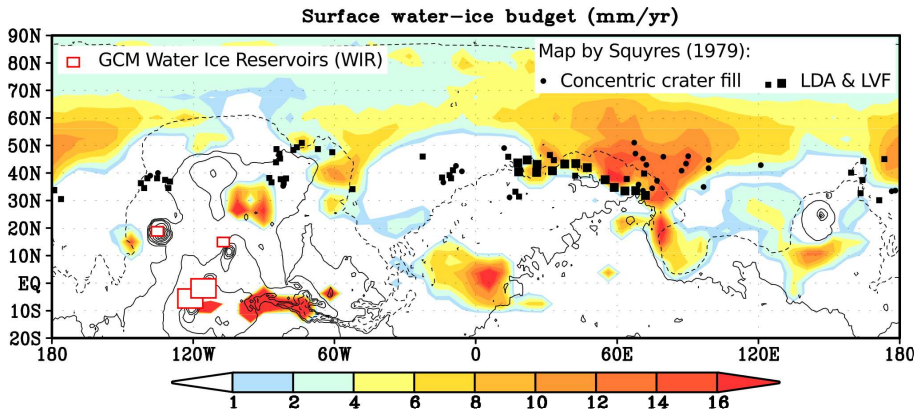
Northern mid-latitude glaciation

Changes in global water cycle

Past **water vapor** and **ice** columns (pr. μm)



Ice accumulation rates in mm yr^{-1}



Main conclusions

- **Both mineral dust and water-ice clouds** play a central role in shaping the thermal structure of the Mars atmosphere.
- The climate simulated by the LMD/GCM is extremely **sensitive to aerosol properties**, which are now measured with sufficient accuracy to reach good agreement with the observations.
- The dust cycle is, along with orbital conditions, the **main driver** of the glaciations.

Questions and perspectives

■ Modeling of the dust cycle

- How to improve the representation of dust lifting and the prediction of dust particle sizes?
- What is the impact of dust scavenging by clouds?

■ Radiatively active water-ice clouds

- Why do radiatively active clouds dry the whole water cycle?

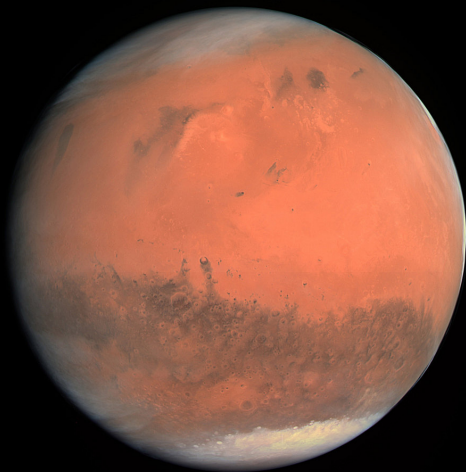
■ Cloud property retrieval

- What are the cloud properties in other regions than Tharsis?
- How can we retrieve the properties of thinner clouds, e.g. cumulus clouds?

■ Late Amazonian glaciations

- What will be the impact of interactive dust and radiatively active clouds on the glaciations?
- What is the origin of the latitude-dependent mantle?

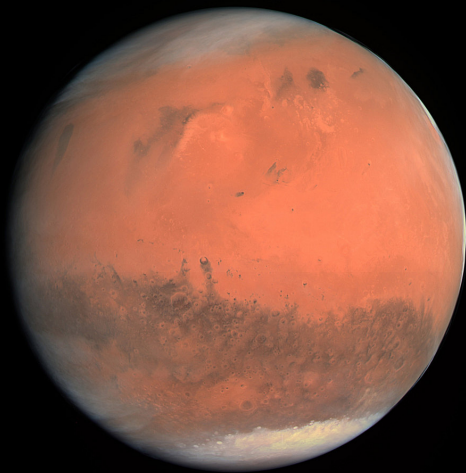
A treasure of the solar system



Mars is a fantastic opportunity to study major components of the terrestrial glacial climate under different conditions.

[OSIRIS/Rosetta]

A treasure of the solar system



Thanks!

[OSIRIS/Rosetta]

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