A Mars Climate tutorial:
part2

- The CO_2 cycle
- The water cycle

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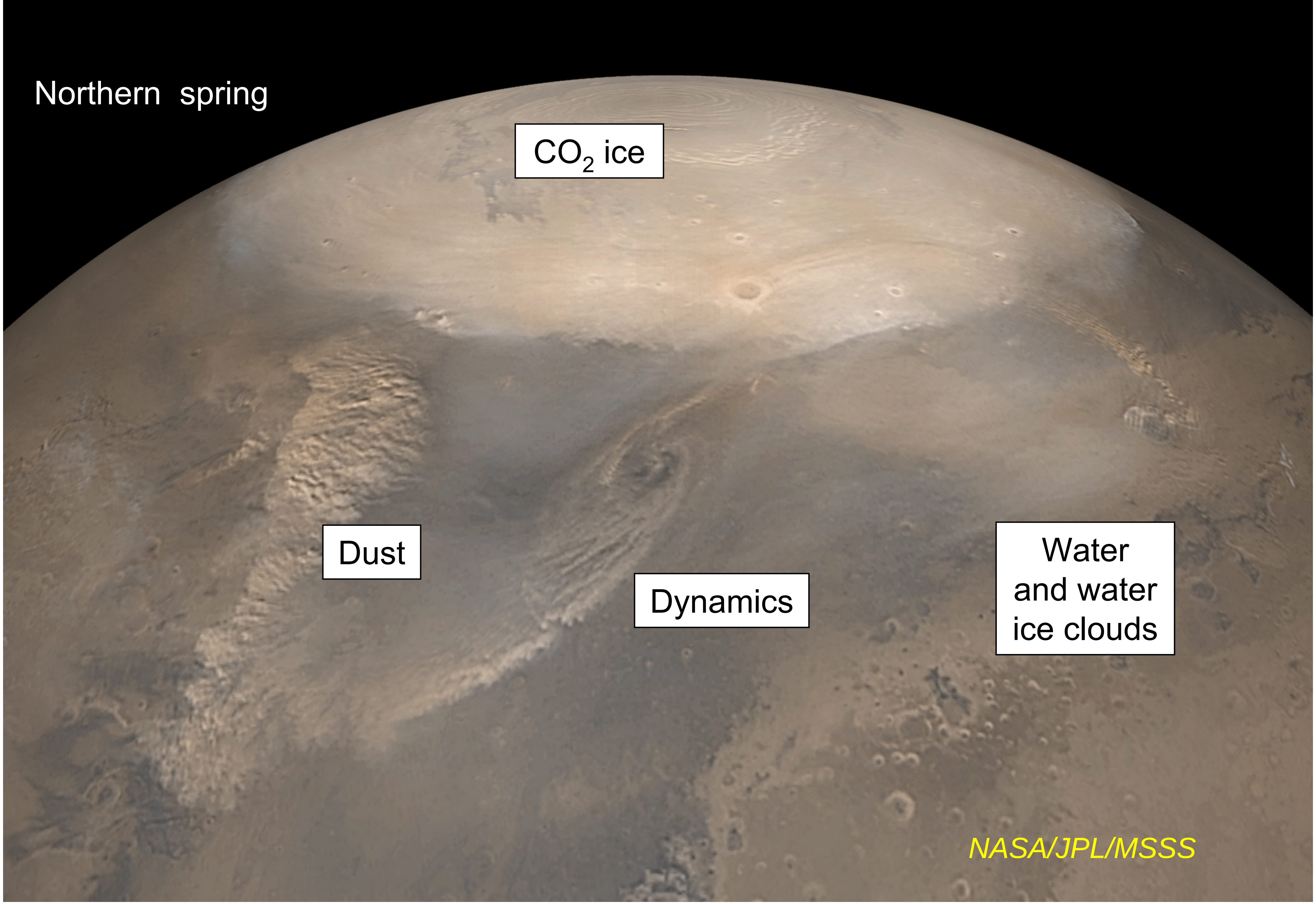
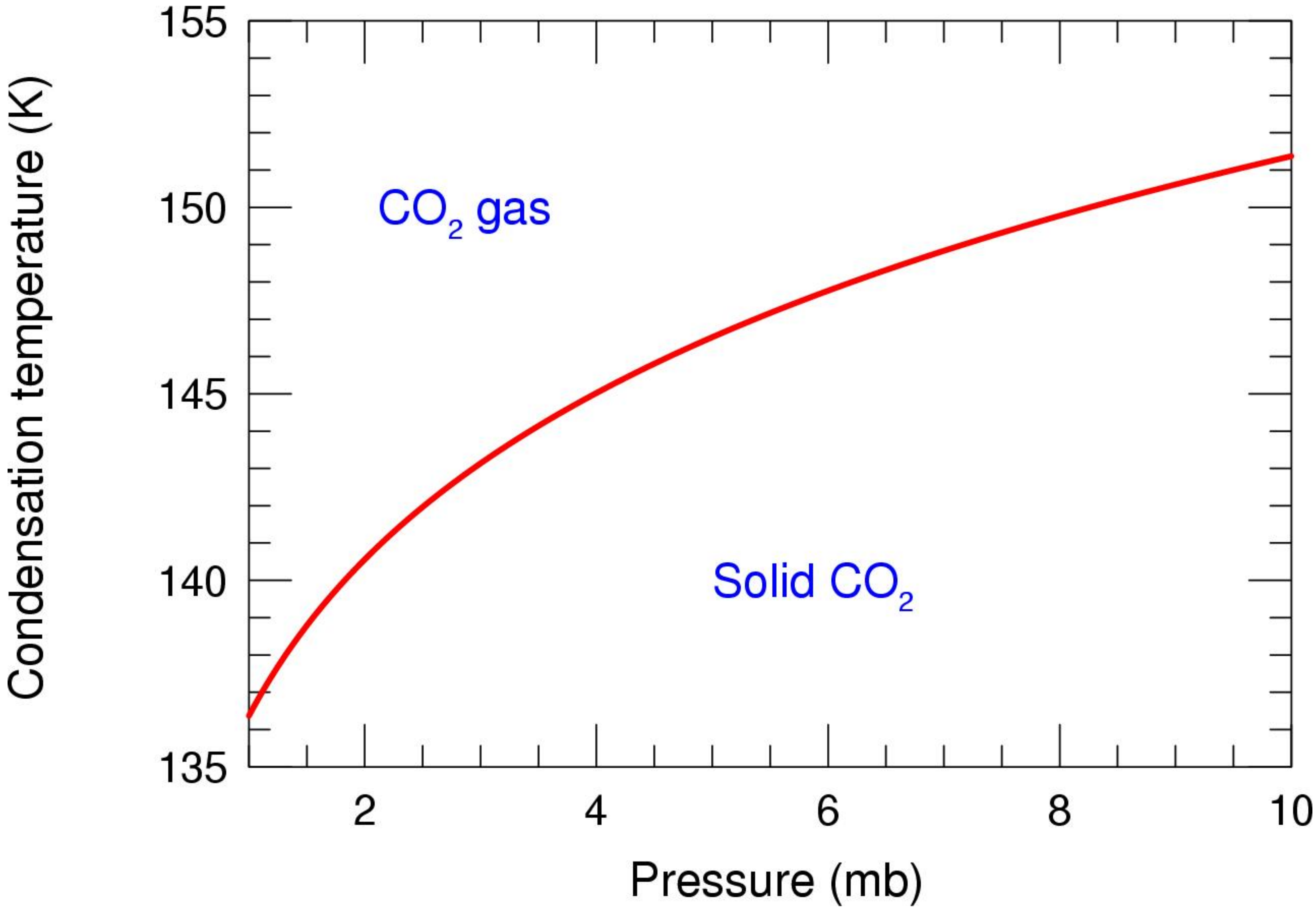
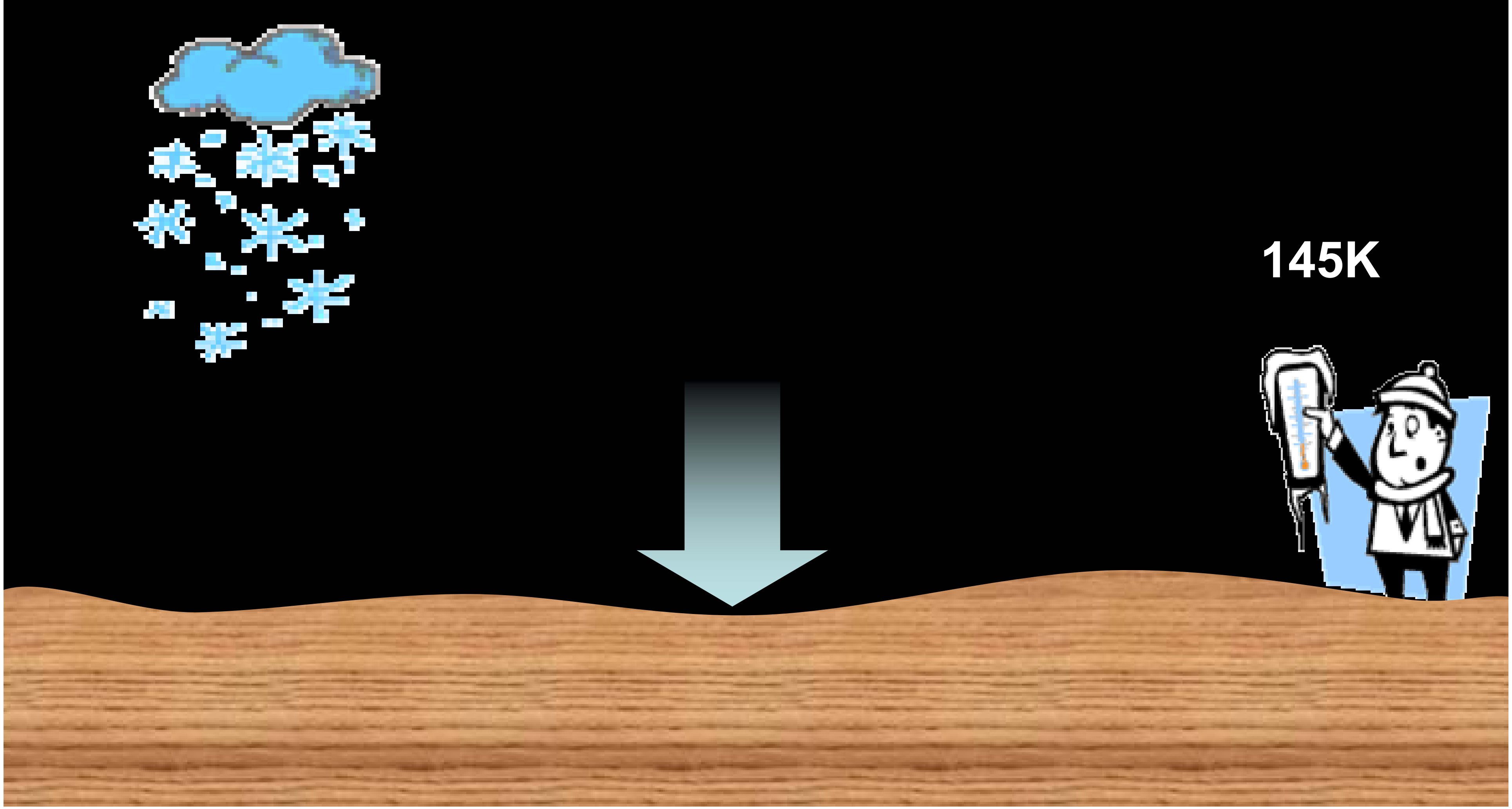
Mars climate now : atmospheric circulation, dust , $CO2$ (and some water)



CO_2 phase change on Mars



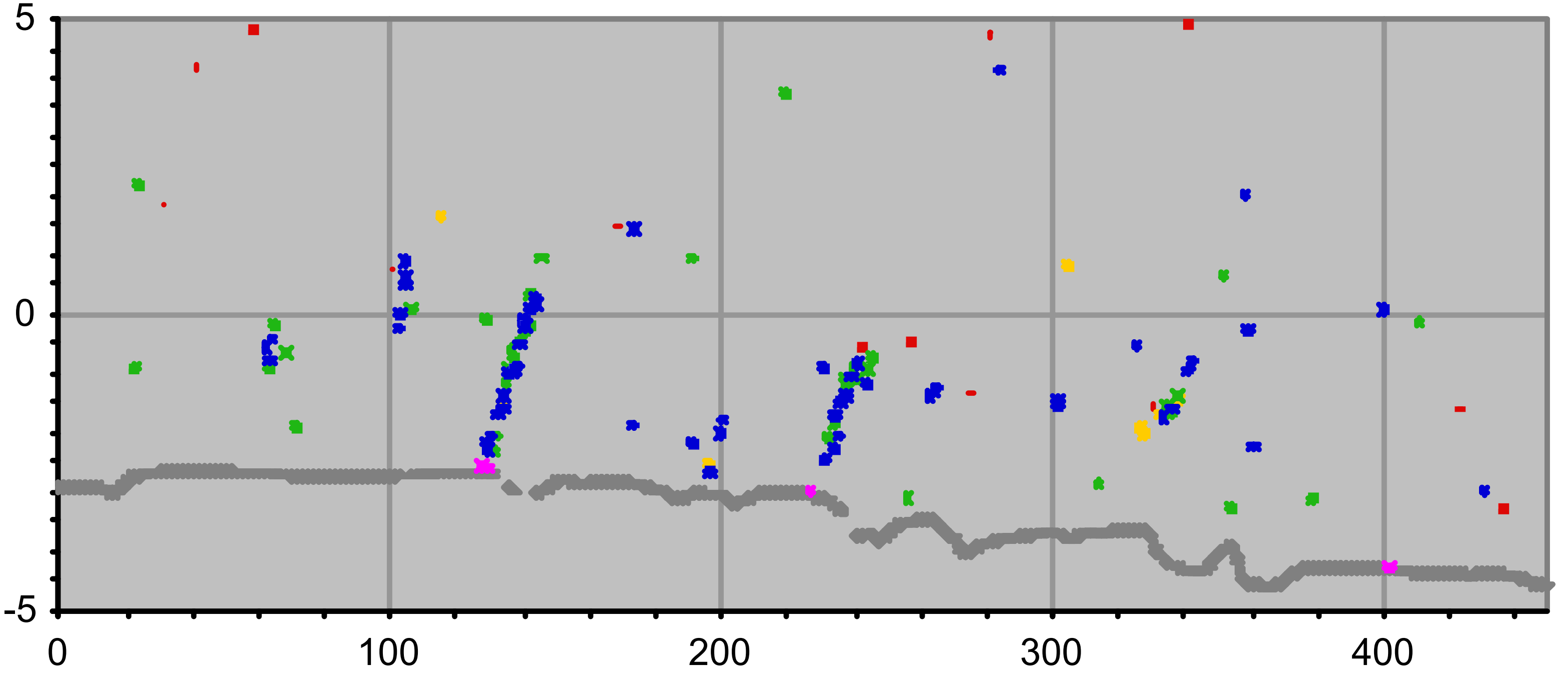
Winter : polar night



Different kinds of CO2 ice clouds observed by the laser altimeter MOLA

(Pettengill and Ford 2000)

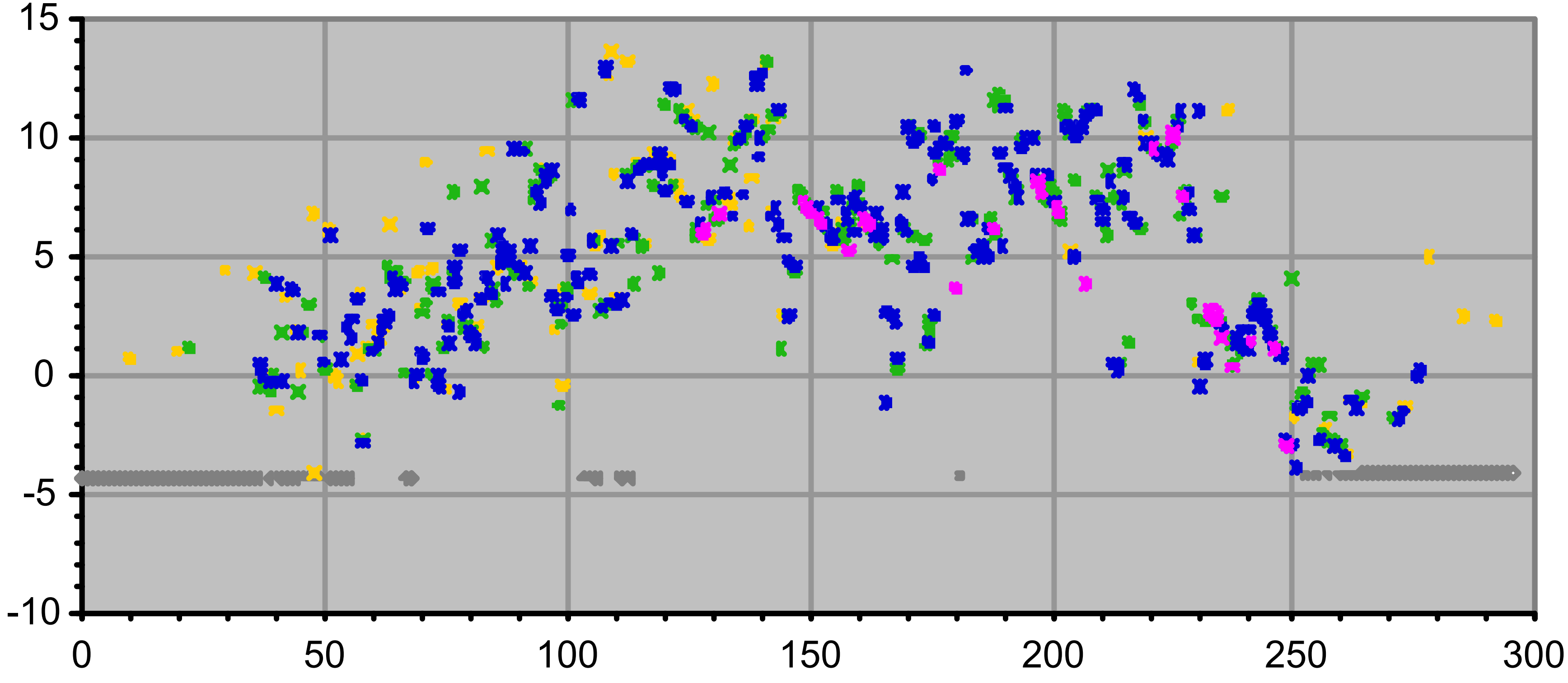
Isolated clouds linked to topography features



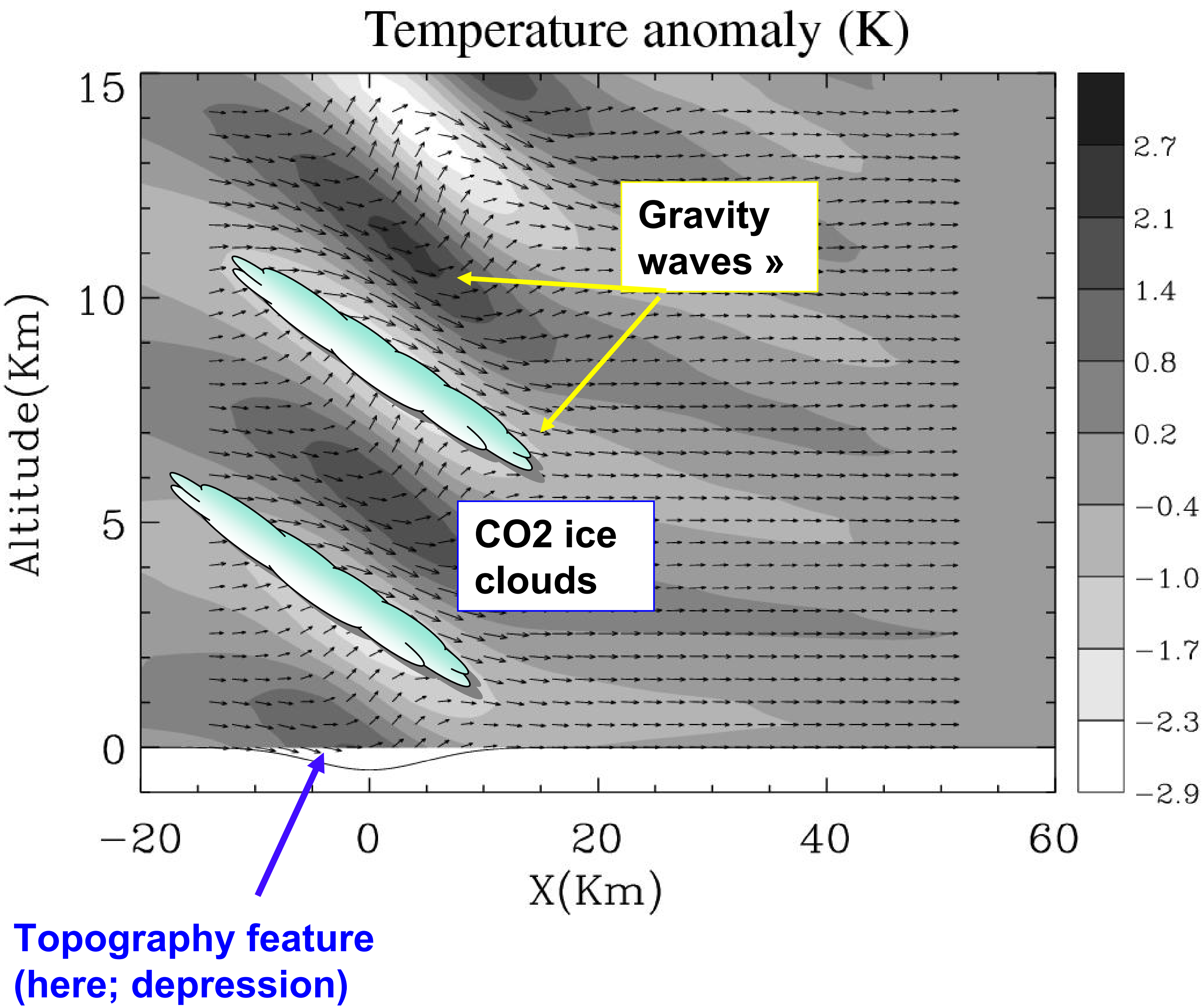
Different kinds of CO_2 ice clouds observed by the laser altimeter MOLA

((Pettengill and Ford 2000)

Train of clouds ?

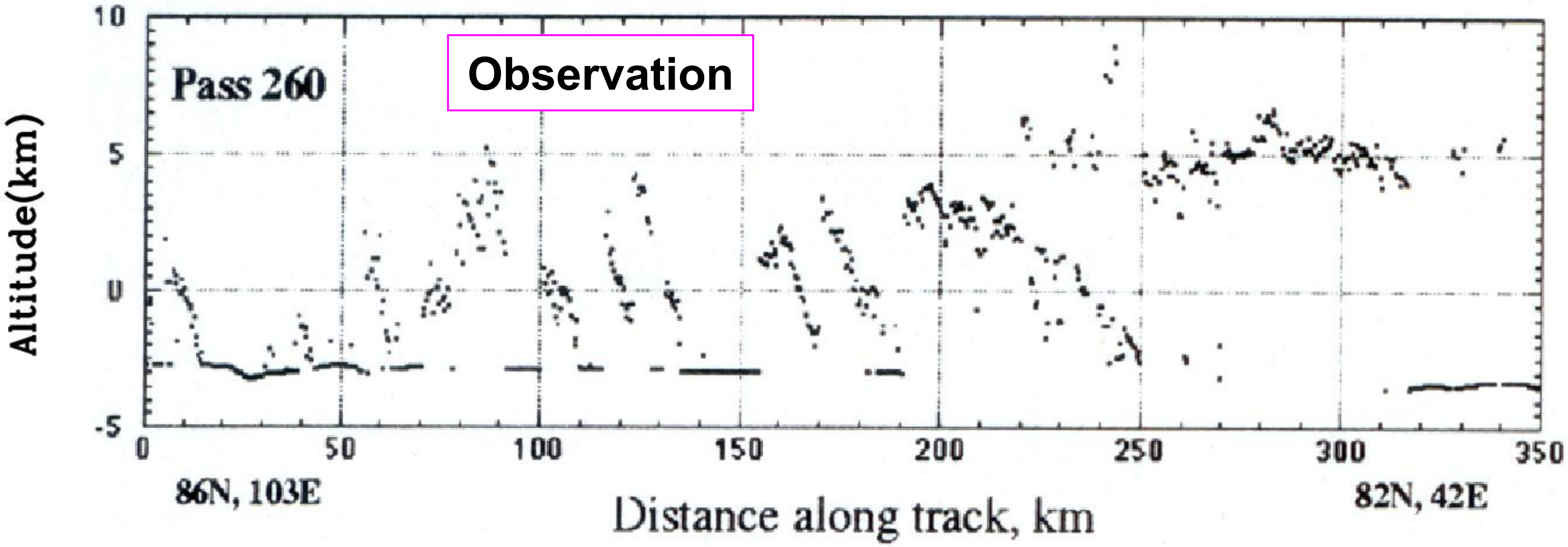


2d Mesoscale modelling in the polar night (Tobie et al. 2003)

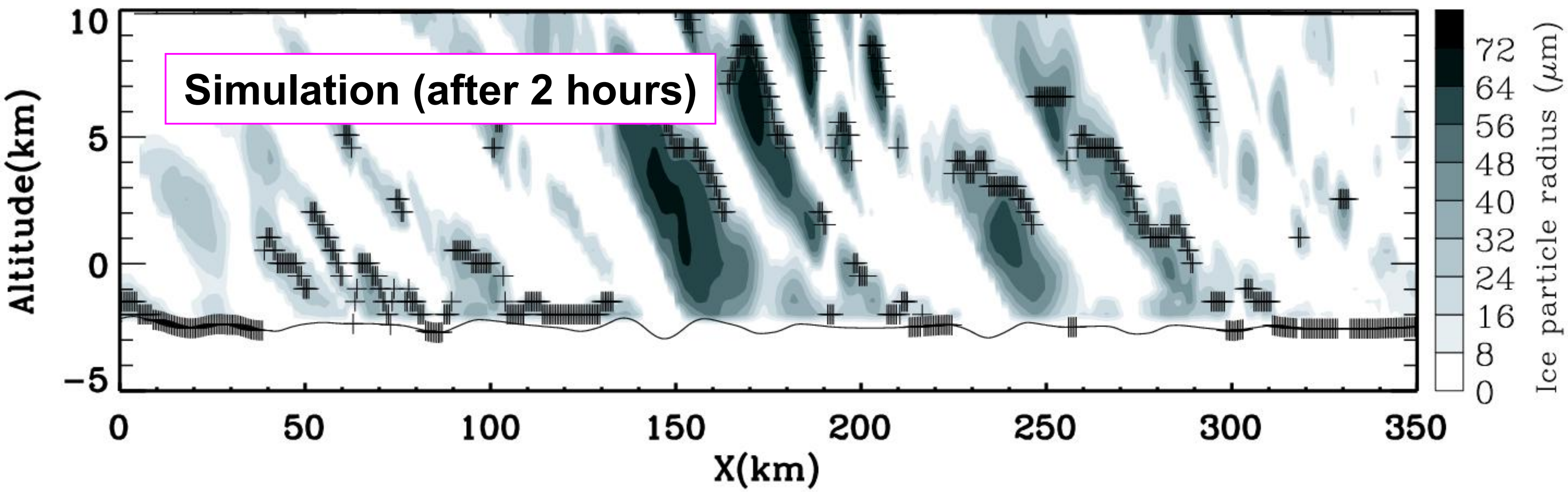


Simulation over realistic topography: Large scale flat topography

Tobie et al. 2003

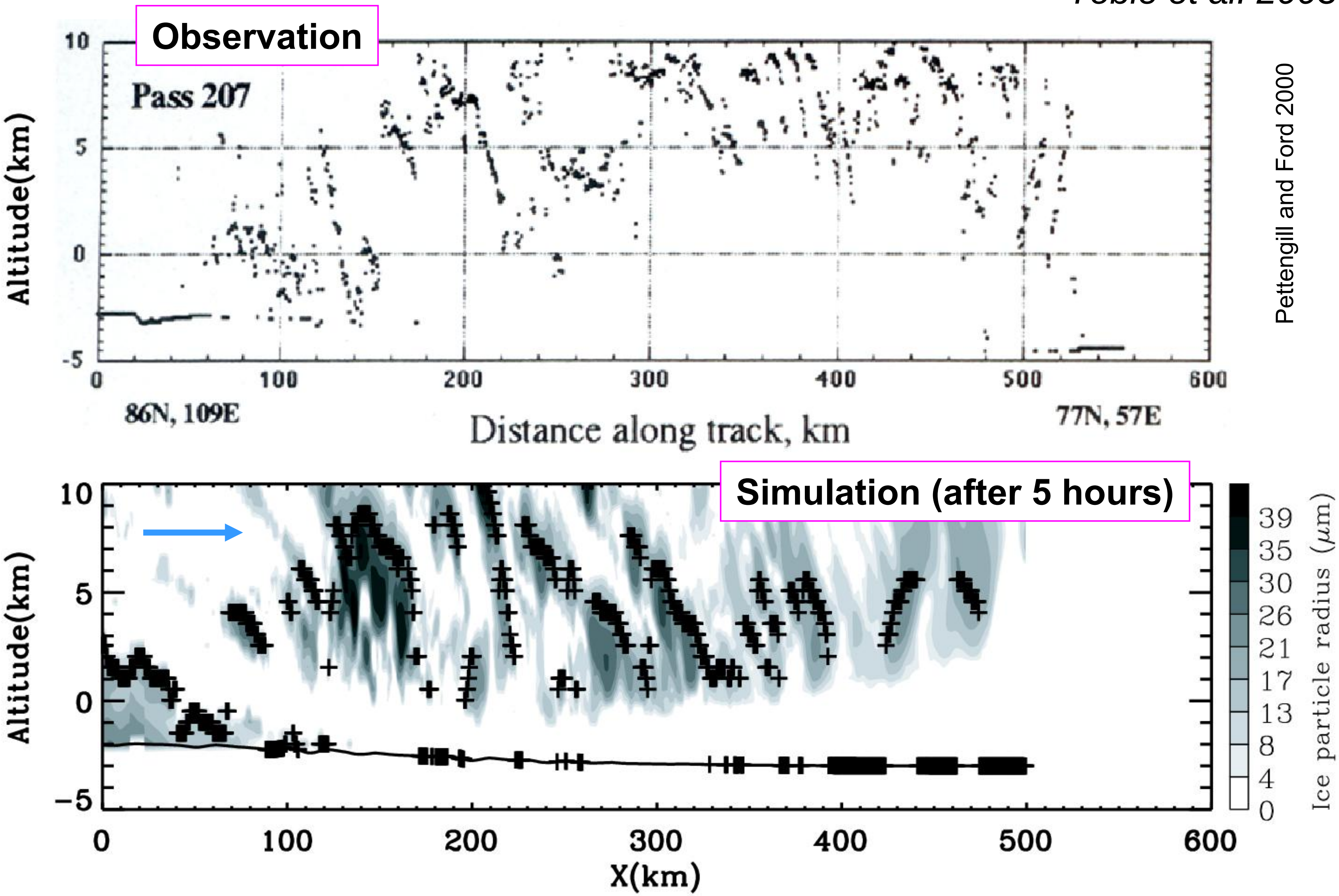


Pettengill and Ford 2000

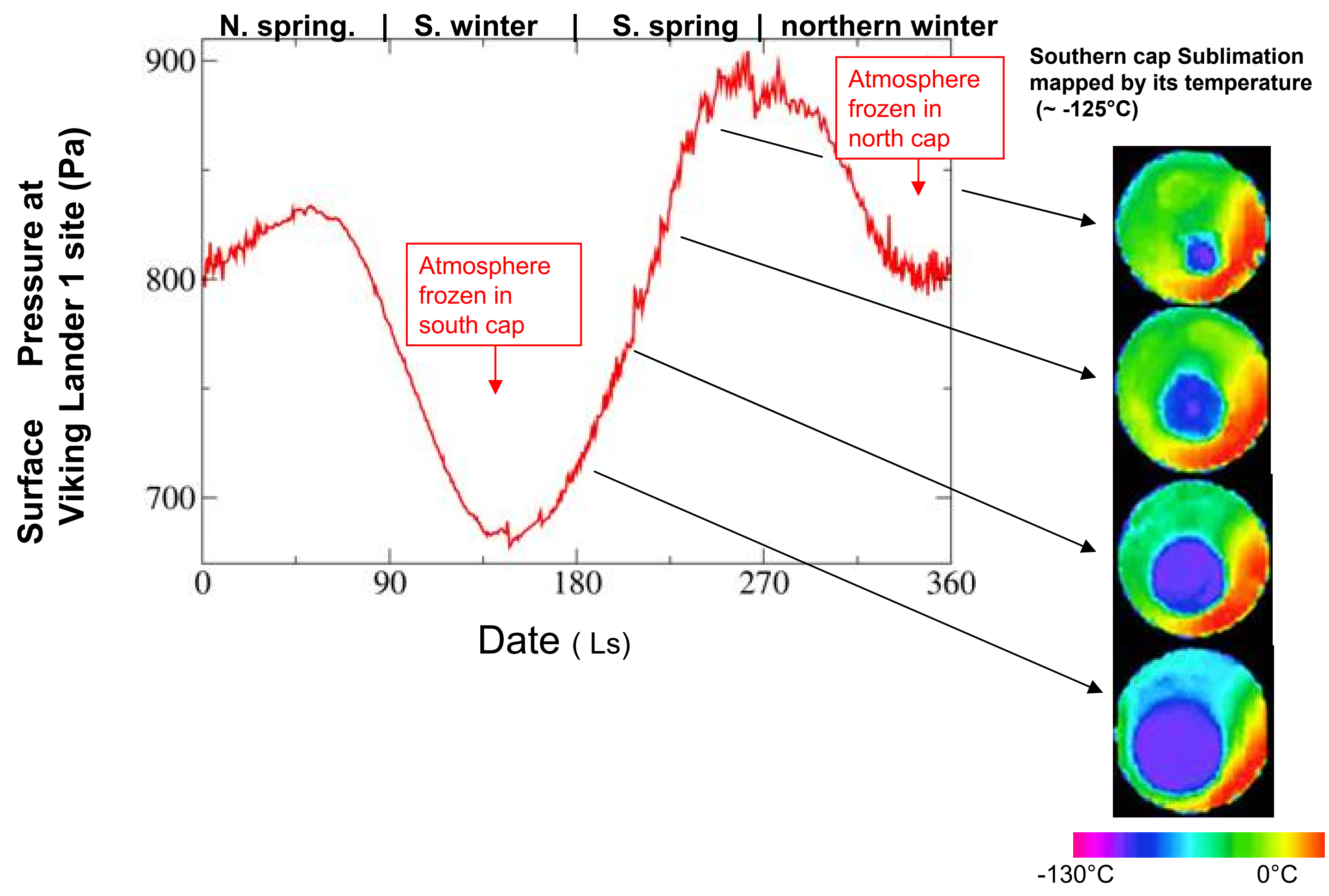


Simulation over realistic topography: Large scale downward air motion

Tobie et al. 2003



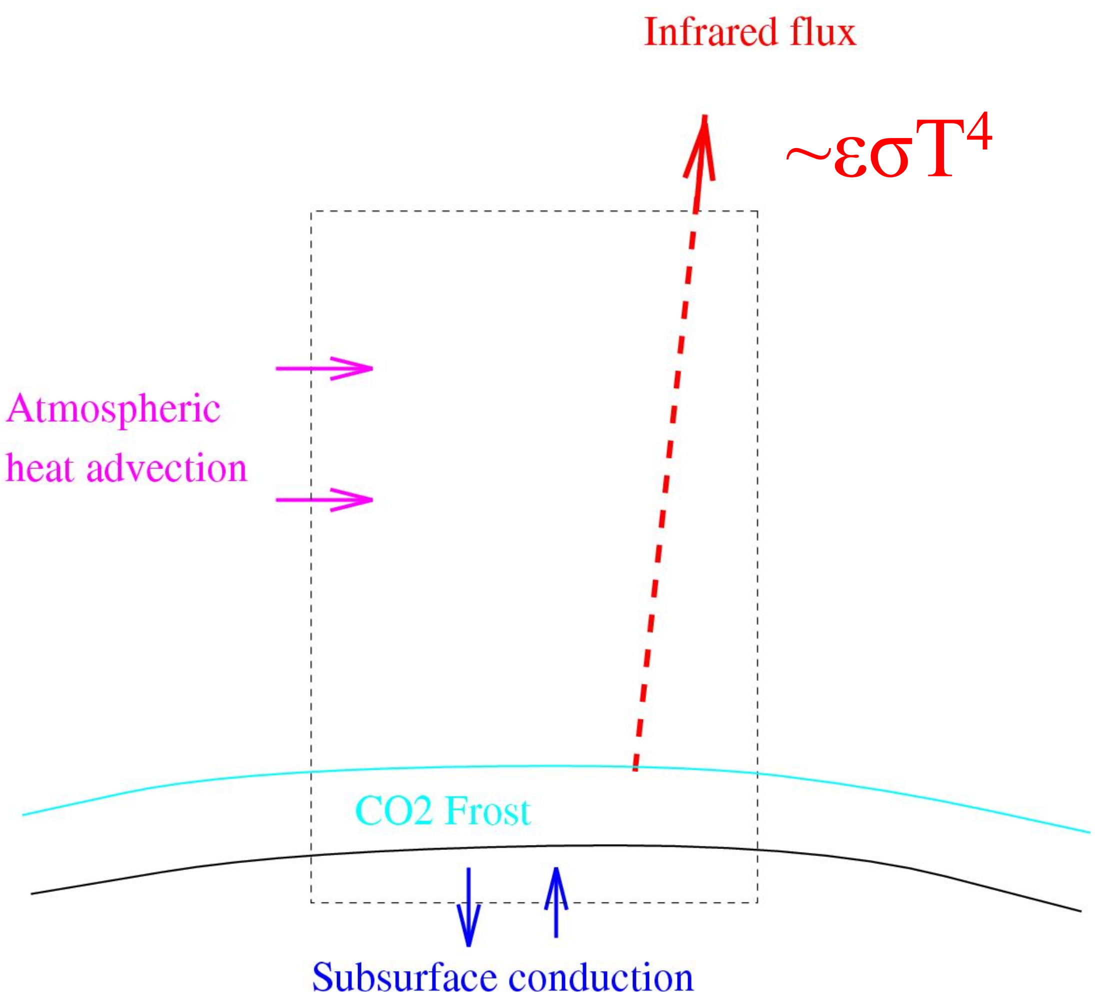
Atmospheric Pressure at Viking 1 Lander site



Energy balance of the condensing polar caps

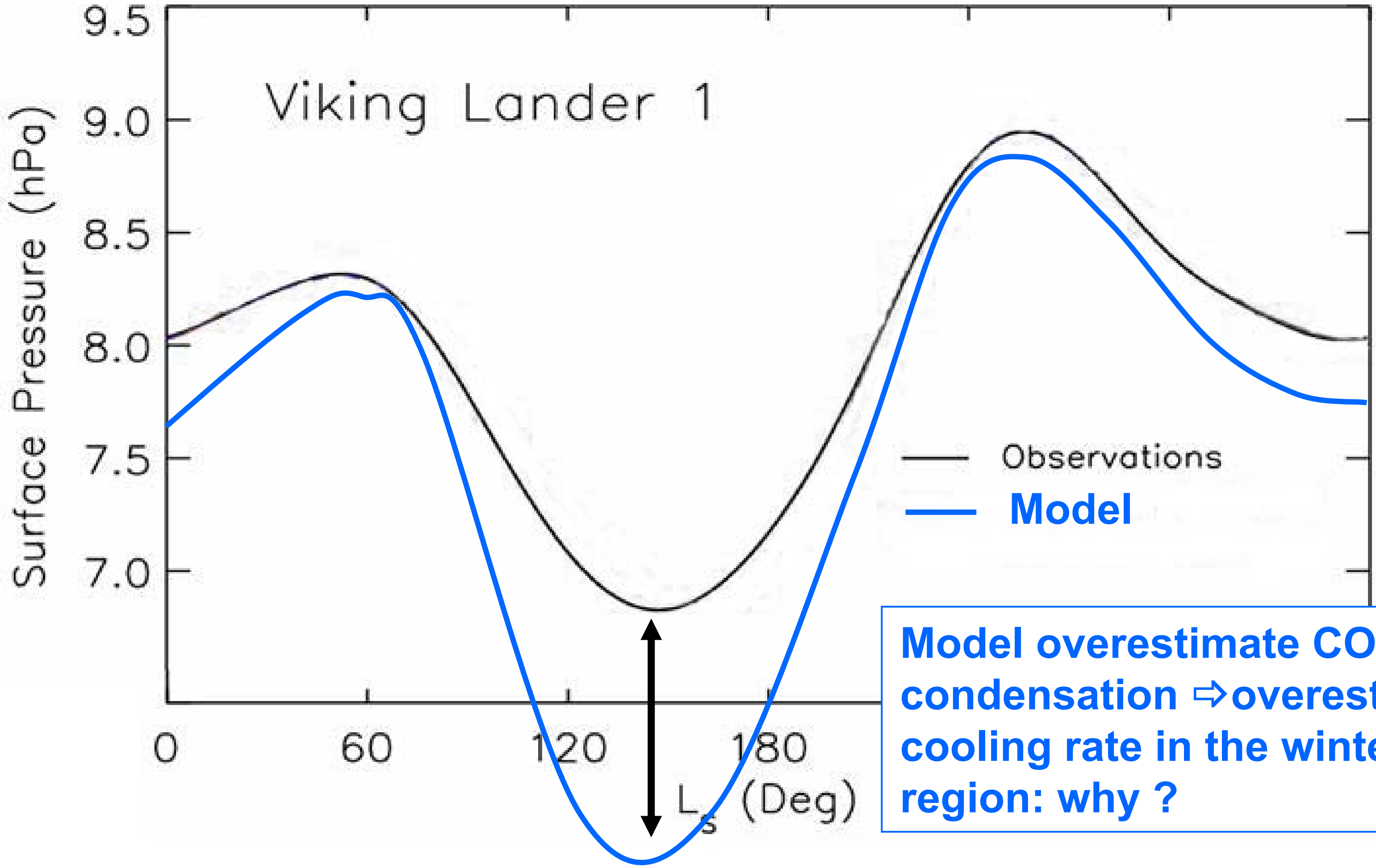
Condensation rate = - Δ (Energy Fluxes) / L (kg. m s)

In the polar night :



Energy balance or global climate simulations of the CO2 ice condensation

James and North, 1982; Hourdin et al. 1993,1995
Wood and Paige, 1992 Pollack et al. 1993,1995
Forget et al. 1998 Guo et al. 2009 Haberle et al. 2007



Model overestimate CO2 condensation ⇨overestimate cooling rate in the winter polar region: why ?

Energy balance of the condensing polar caps

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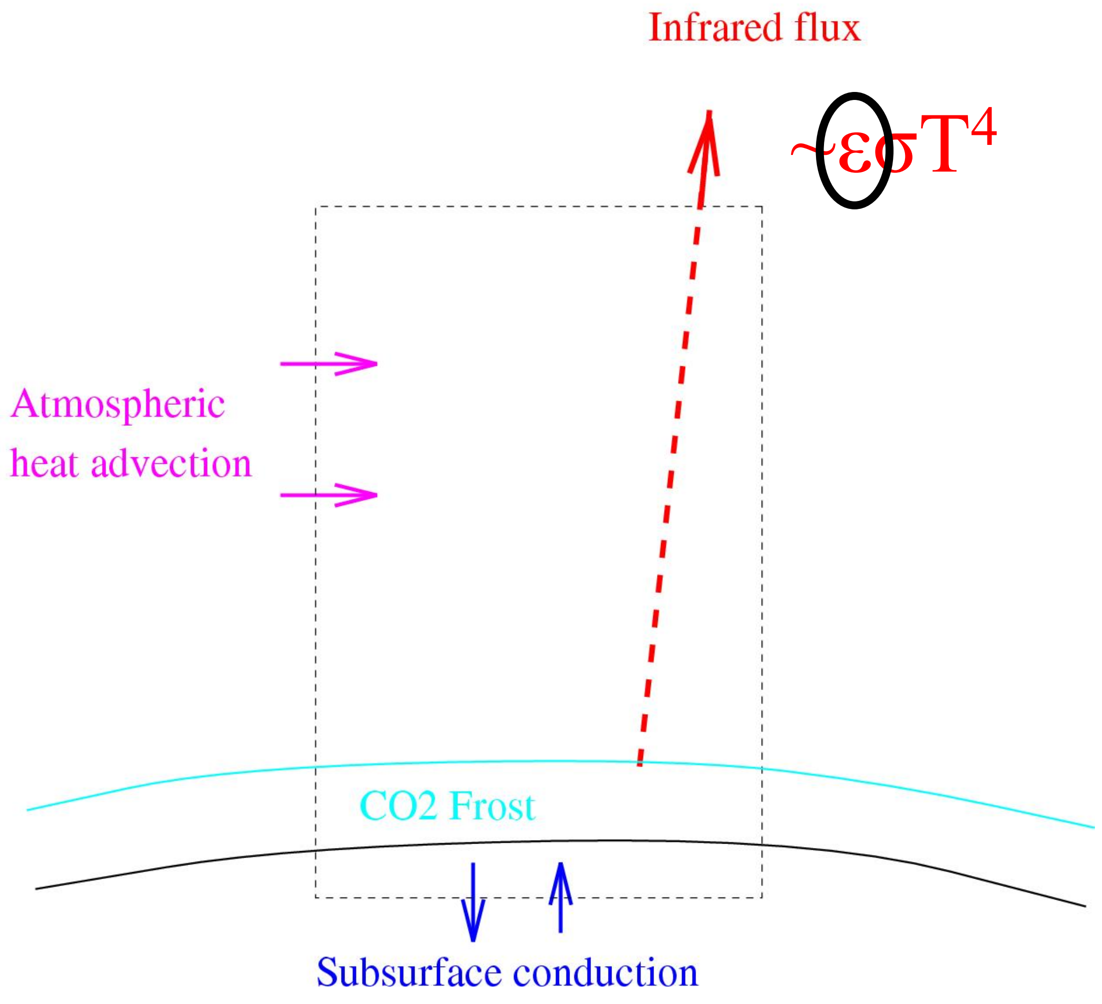
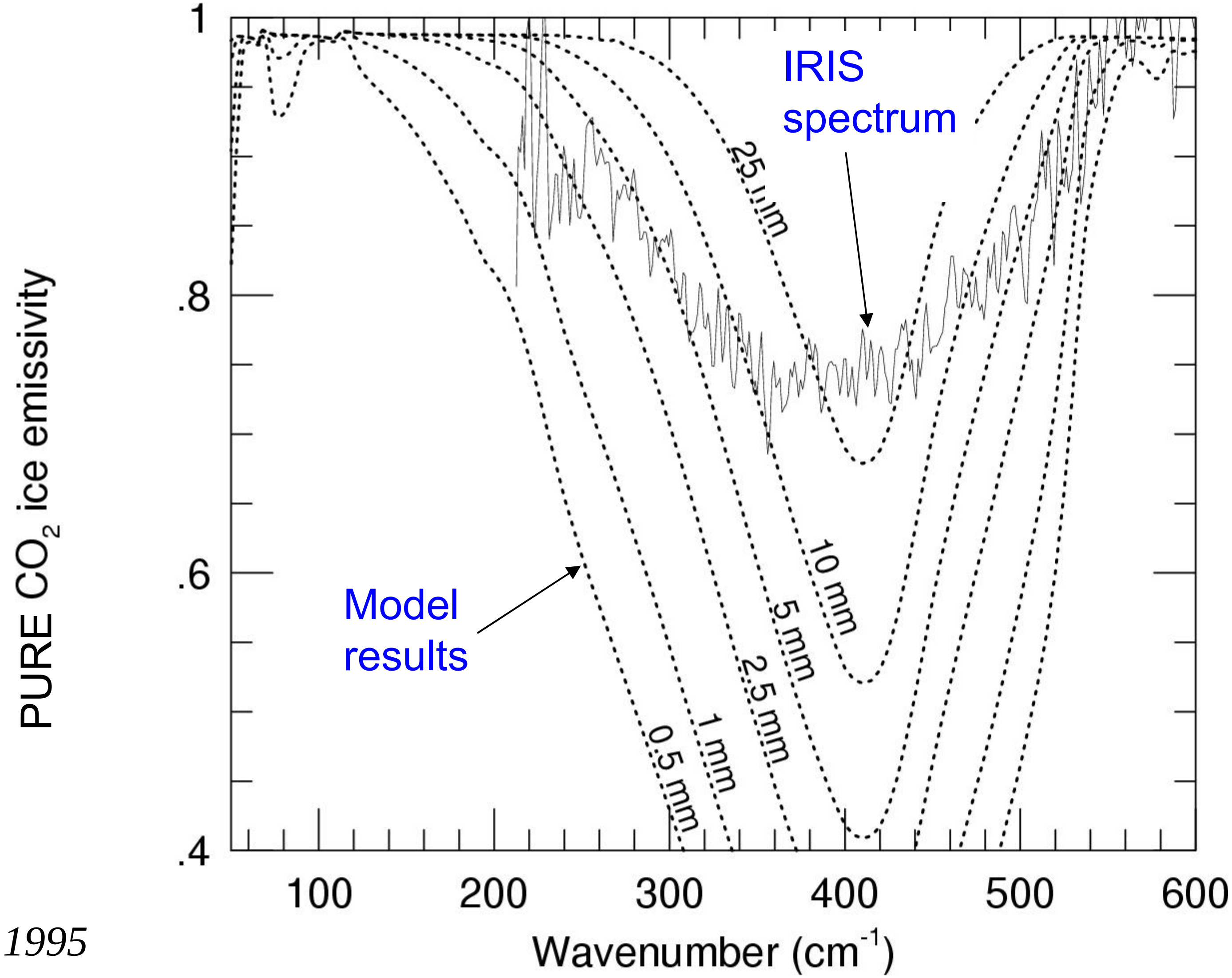
In the polar night :



CO2 ice emissivity as a function of particle size



Forget et al. 1995

Energy balance or global climate simulations of the CO2 ice condensation

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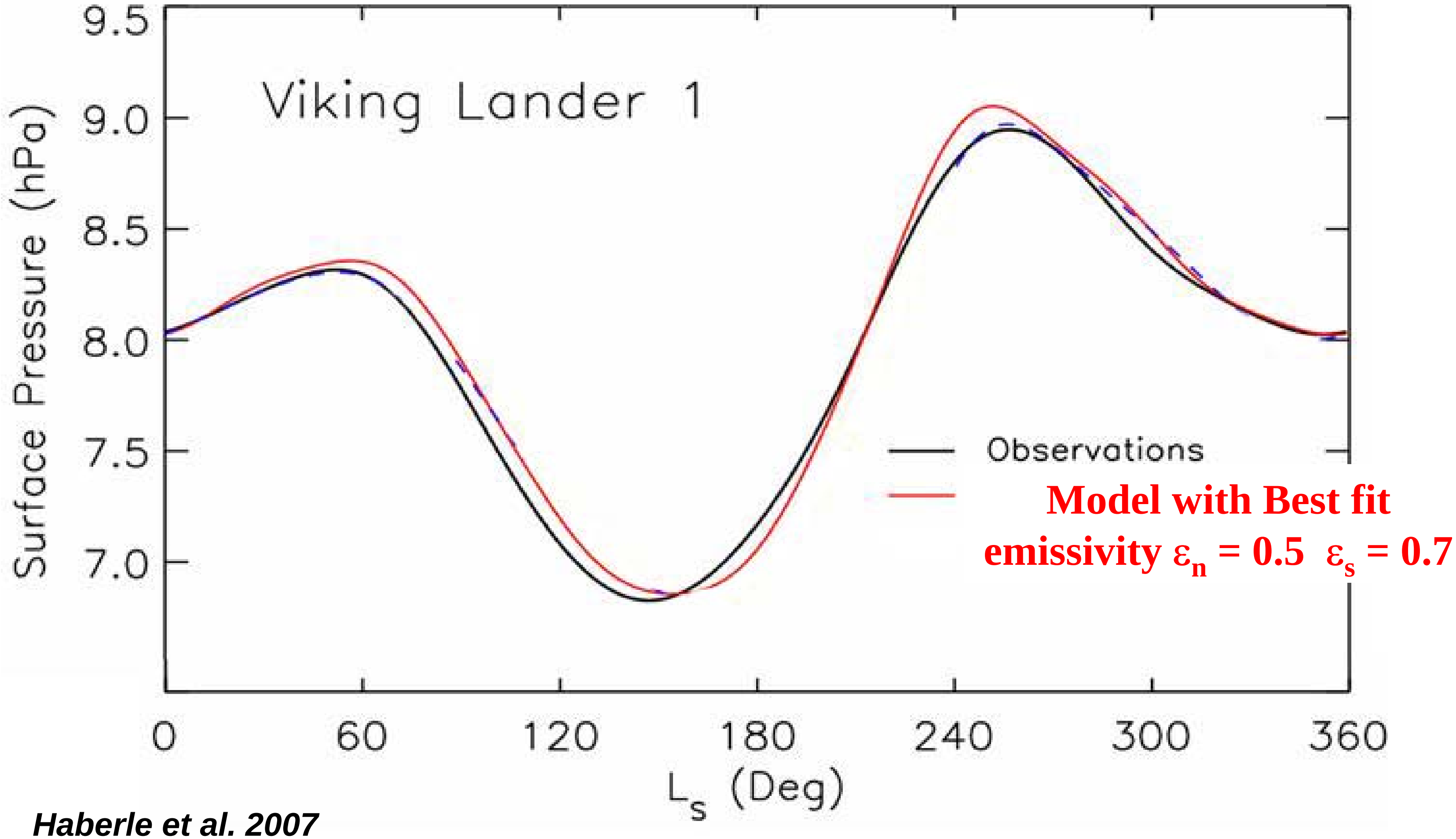


Haberle et al. 2007

“Cold spots” : Emmissivity can locally be low, but not that low on spectral-spatial average.

(low IR emission zone around 25 microns)

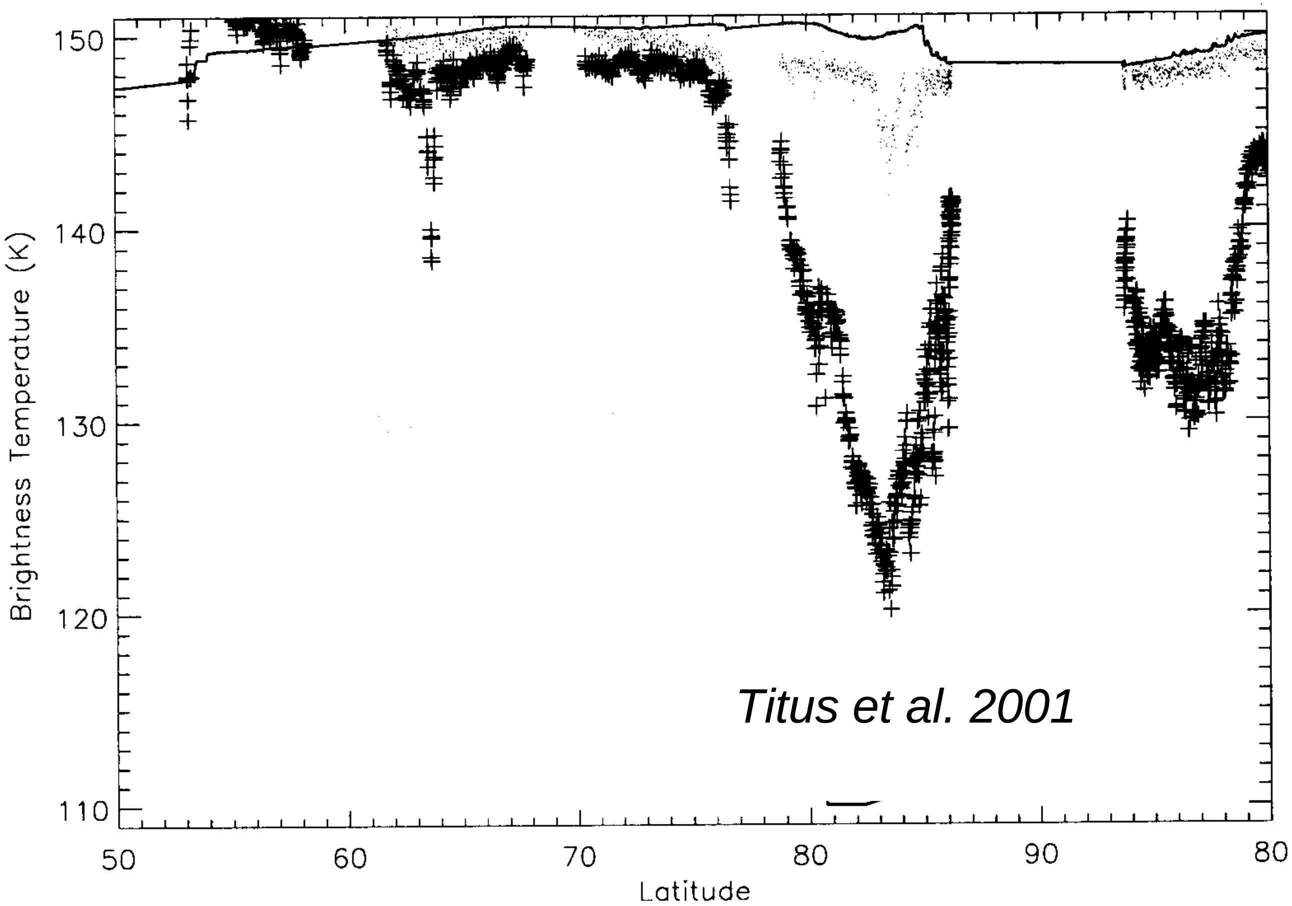
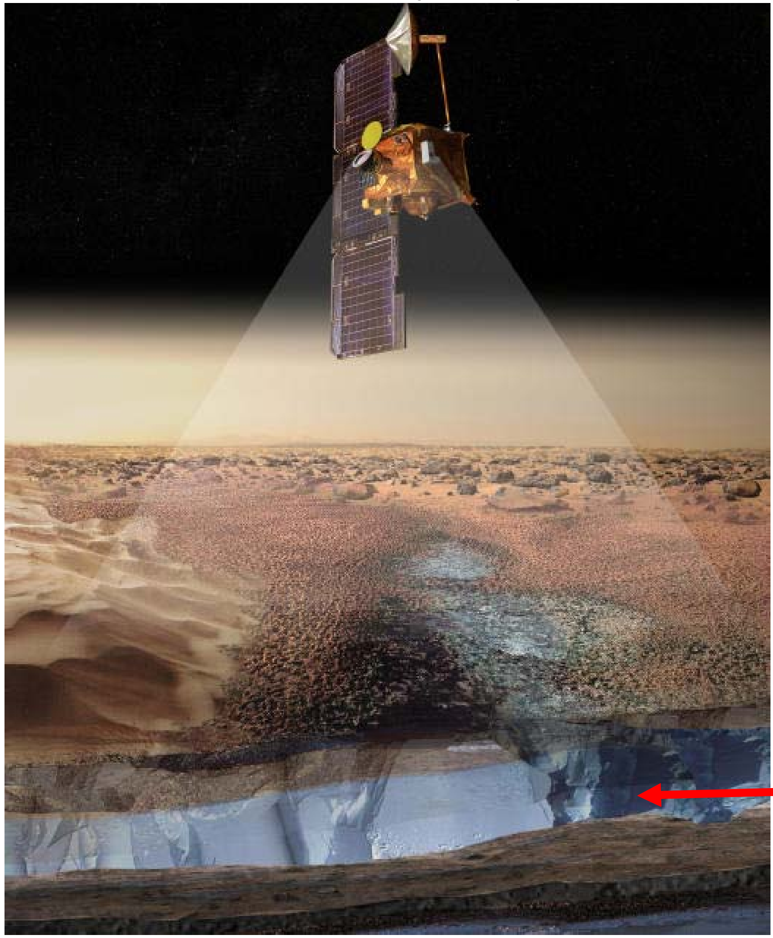
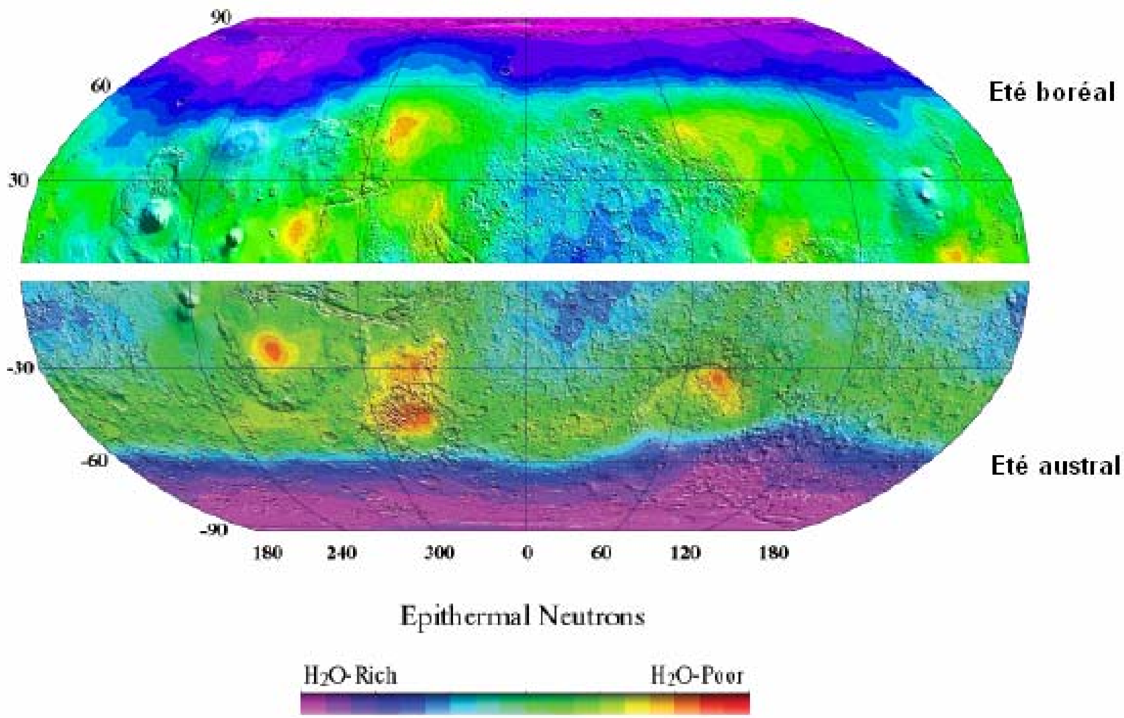


Figure 4. Brightness temperatures versus latitude at $L_s = 309°$. The T_{18} and T_{25} are plotted as grey dots and black plus signs, respectively. The solid line is the expected kinetic surface temperature.

Near surface ice detected by Mars Odyssey GRS

NASA Mars Odyssey

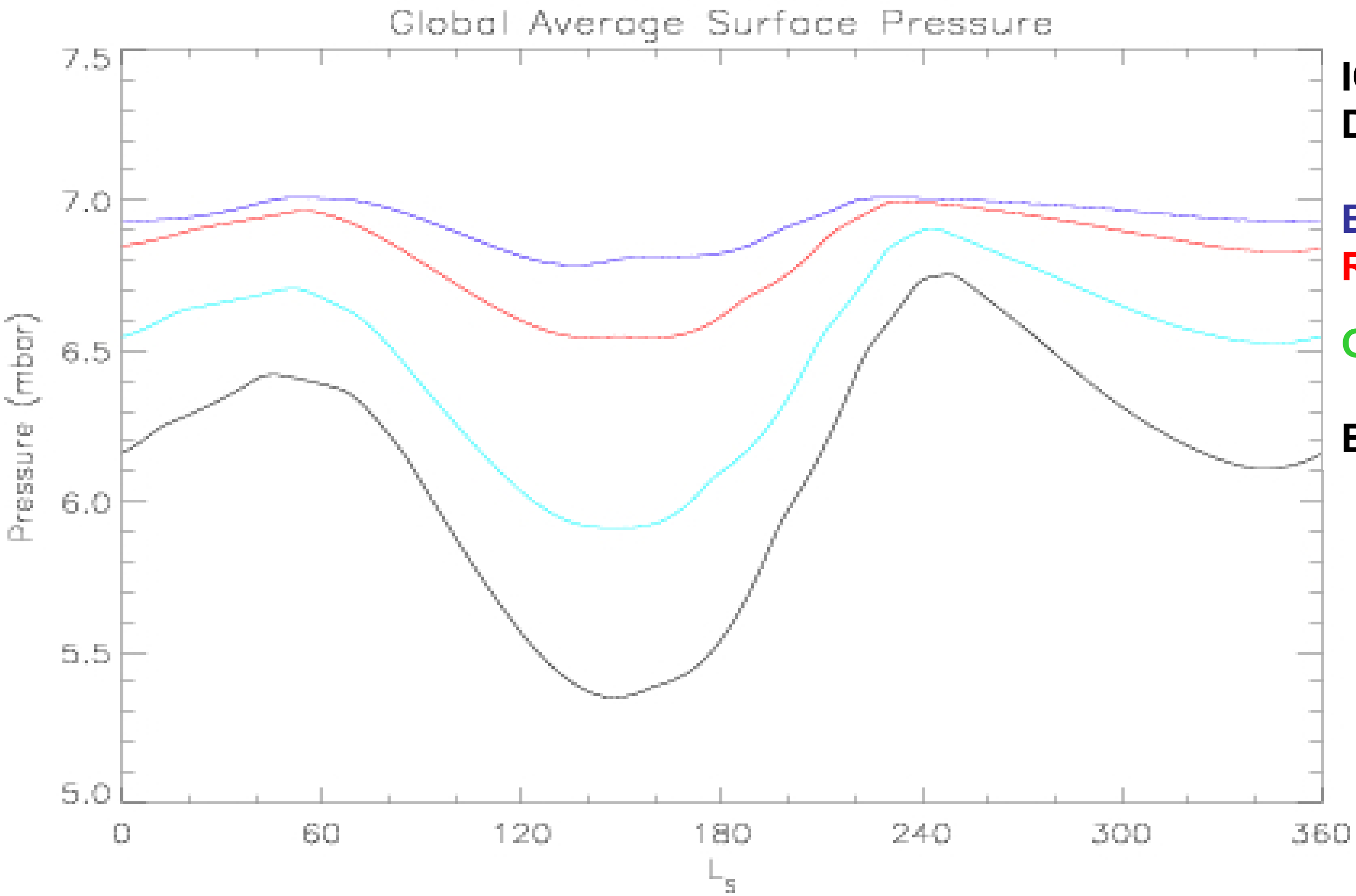




« Hidden ice with high thermal inertia:
- Store heat during summer
- Release heat in winter and reduce CO_2 condensation

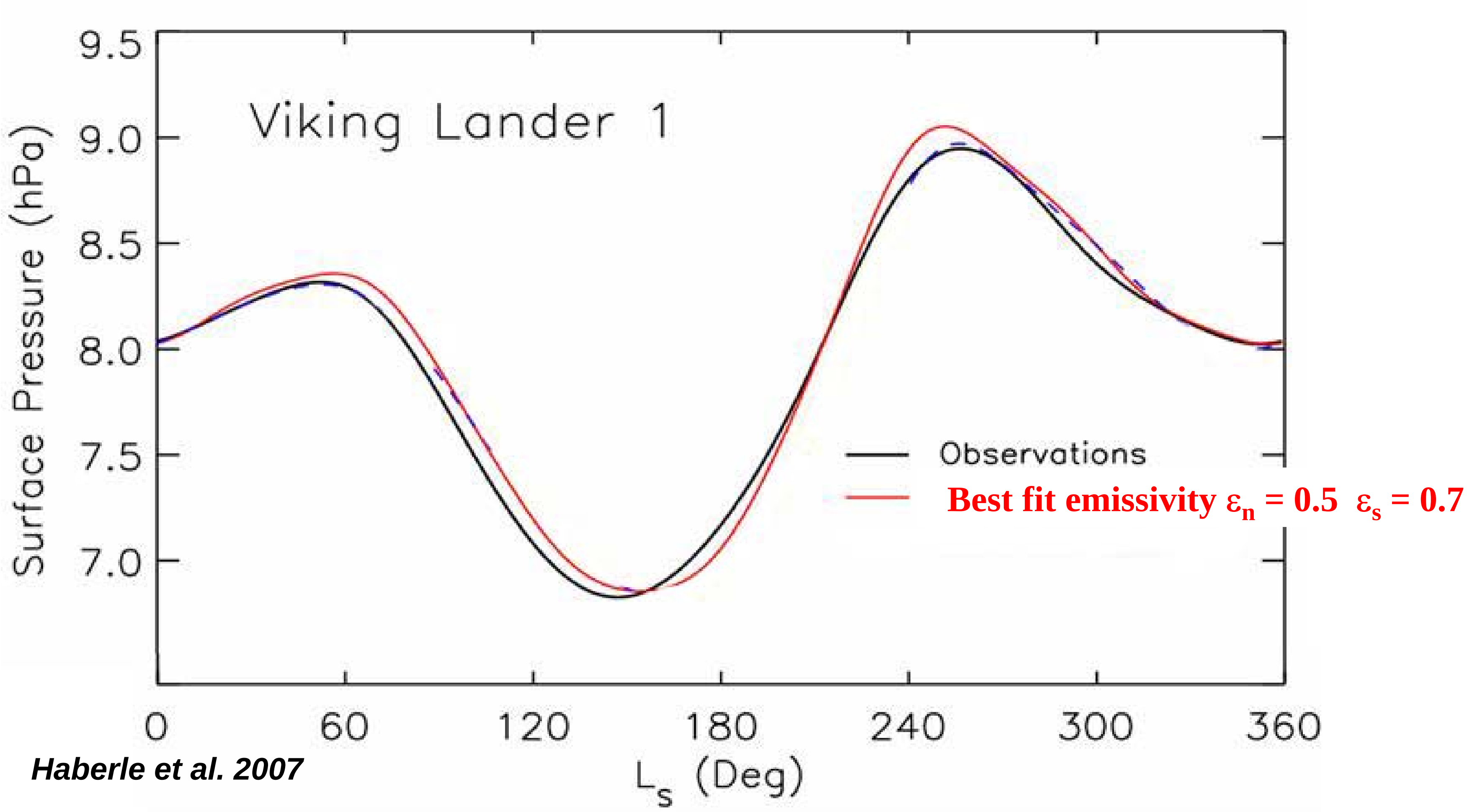
Impact of subsurface ice on Global Mean Surface Pressures

(Haberle et al. 2007 ; NASA Ames GCM)



ICE TABLE DEPTH

Blue: 0
Red: 10 cm
Green: 50 cm
Black: Infinity



Haberle et al. 2007

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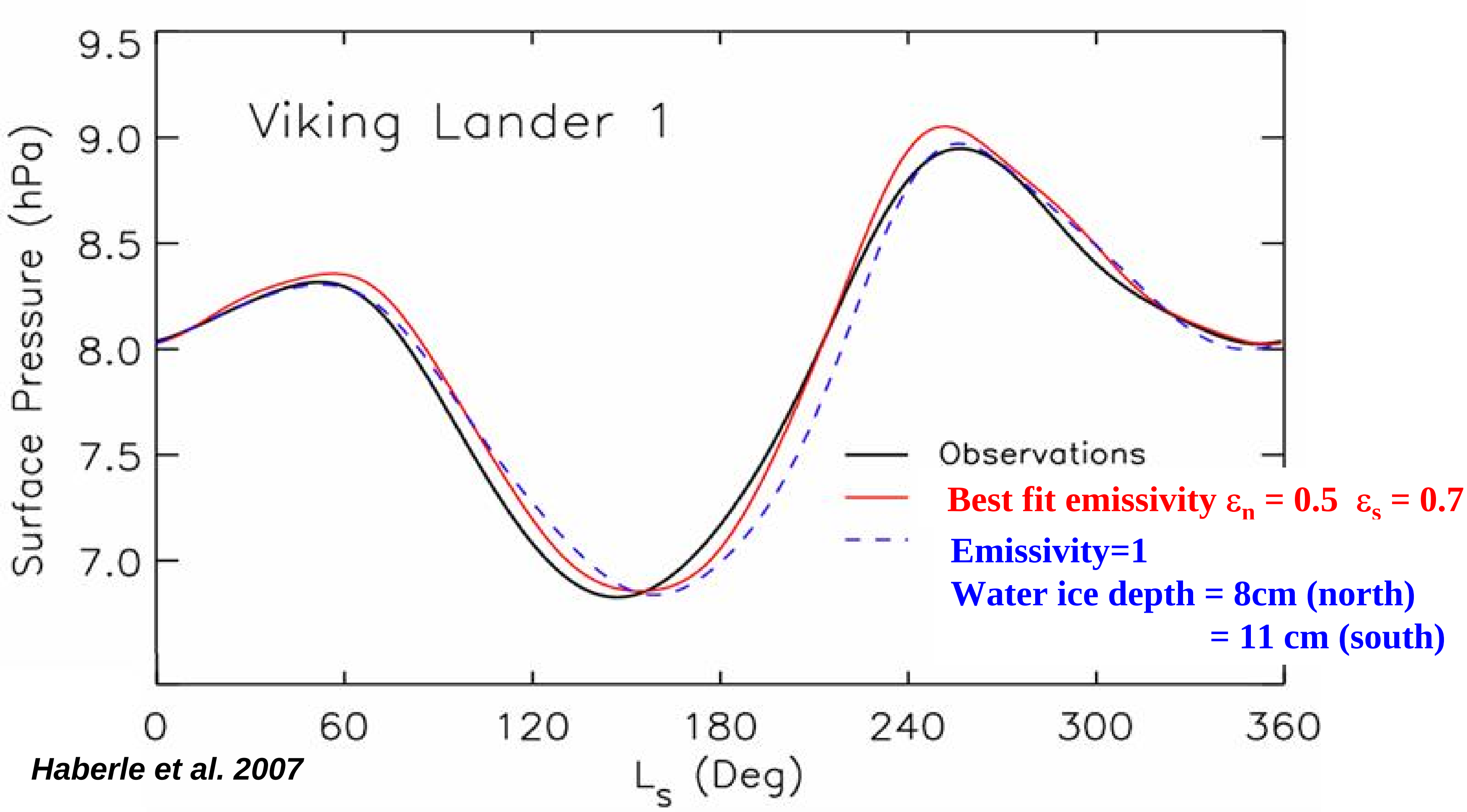
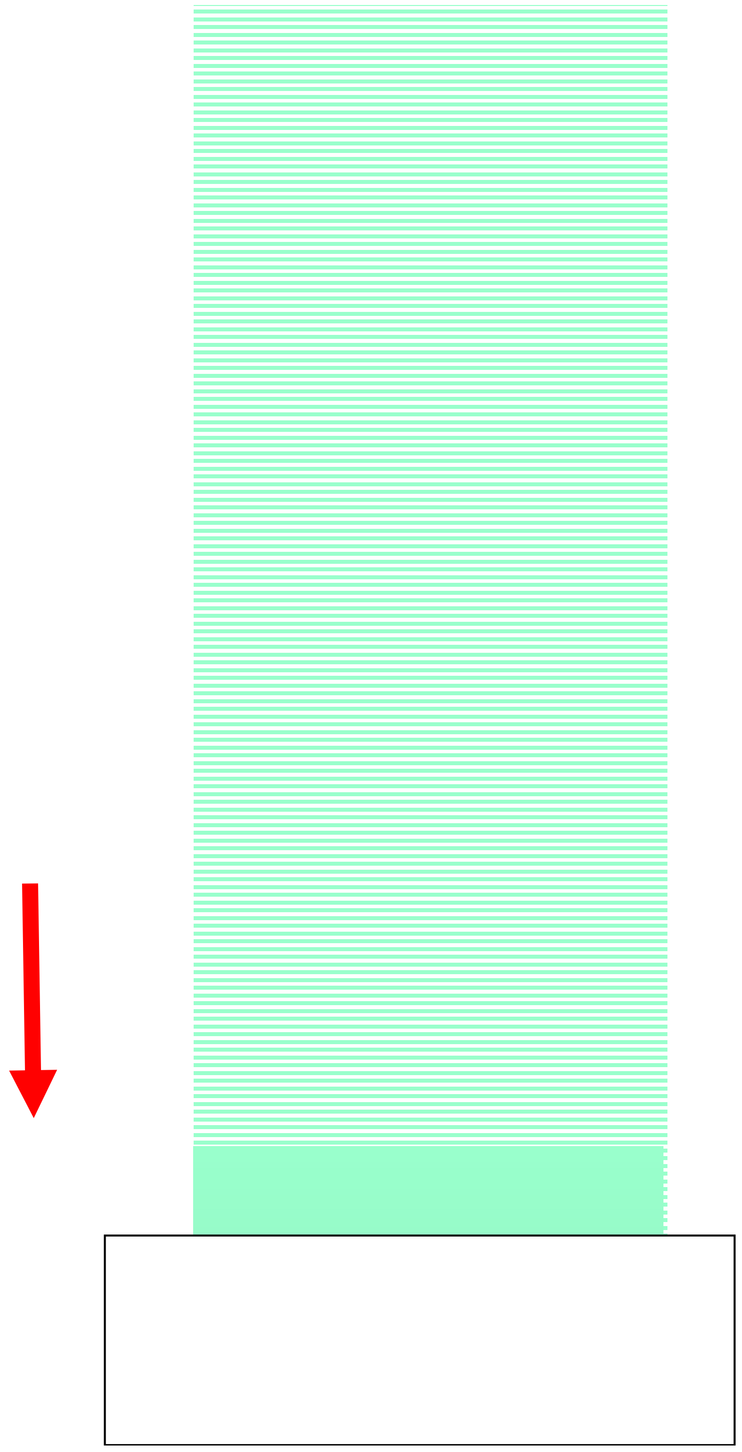


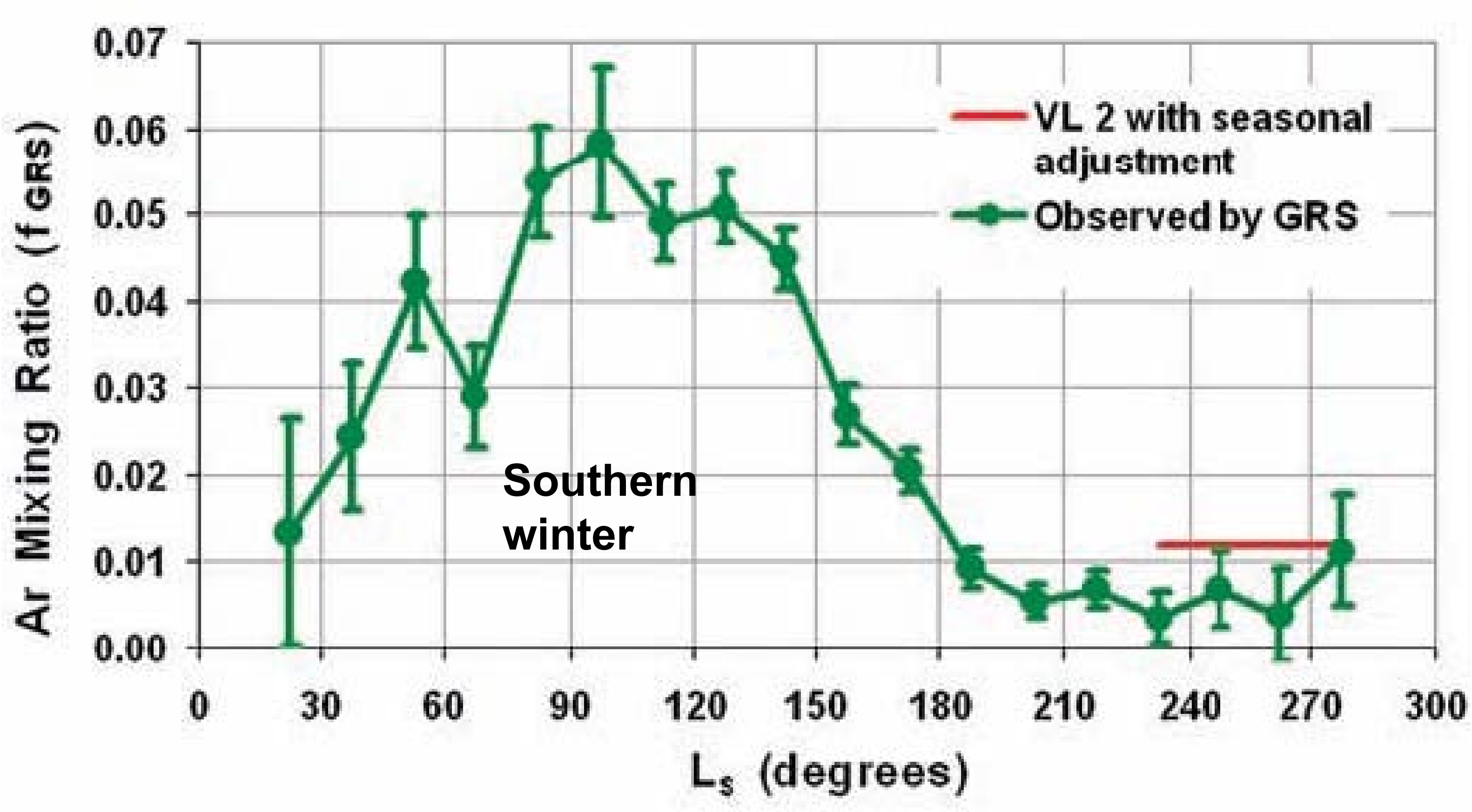
Haberle et al. 2007

Another polar night phenomenon: Condensation of CO2 induce enrichment of other gases



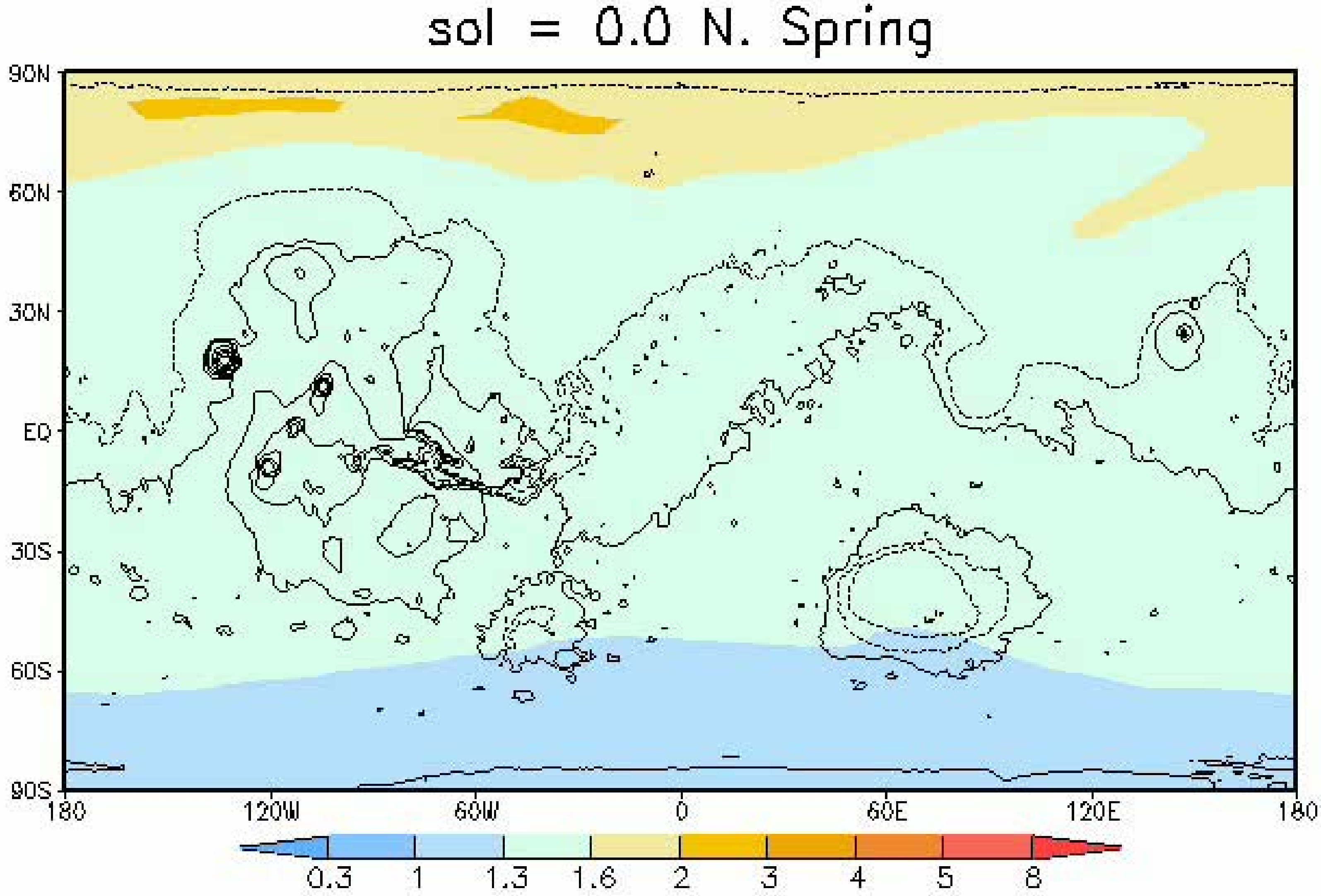
Detection of Argon enrichment due to CO2 condensation by Mars Oddyssey Gamma Ray Spectrometer (GRS)

(mean Ar mixing ratio in 75°S-90°S)



Sprague et al. 2004, 2007

Argon column averaged mixing ratio (%)



Change of atmospheric composition near the surface

- In the polar region originally :
  - 95% CO_2,
  - 5% non-condensible gas (N_2, Ar, etc…)
- Only CO_2 condense. Other gas are left behind
- More atmosphere is transported into the polar regions…
- Polar atmosphere is enriched in non-condensible gas (N_2, Ar)

⇨ In the polar night, the near surface composition is different than CO_2 … and less dense :

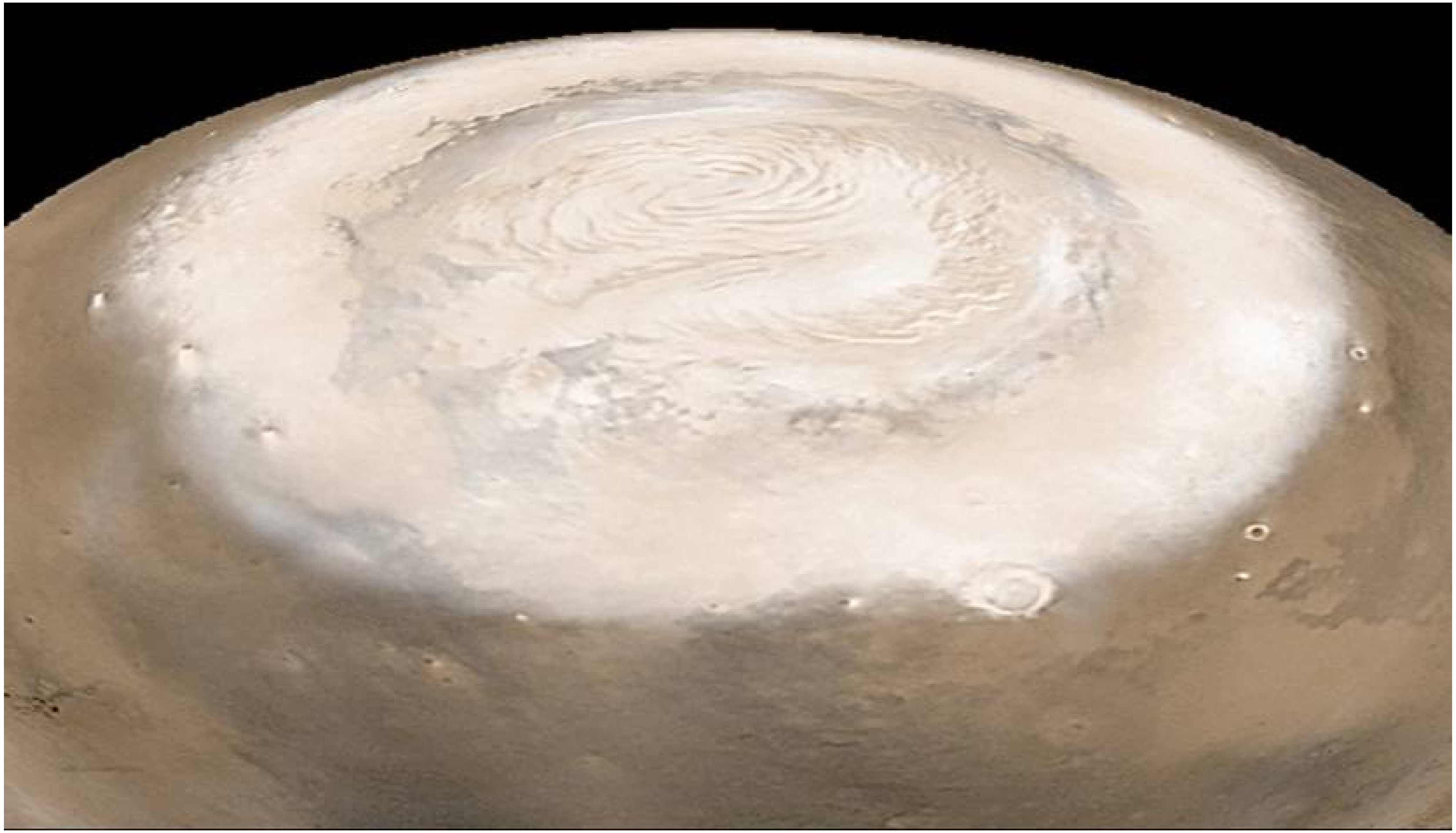
- CO_2 : m = 44.0E-3 kg mol-1
- Non-condensible gas (N_2, Ar) m = 32.37E-3 kg mol-1

⇨ Density Induced convection, affect circulation, etc…

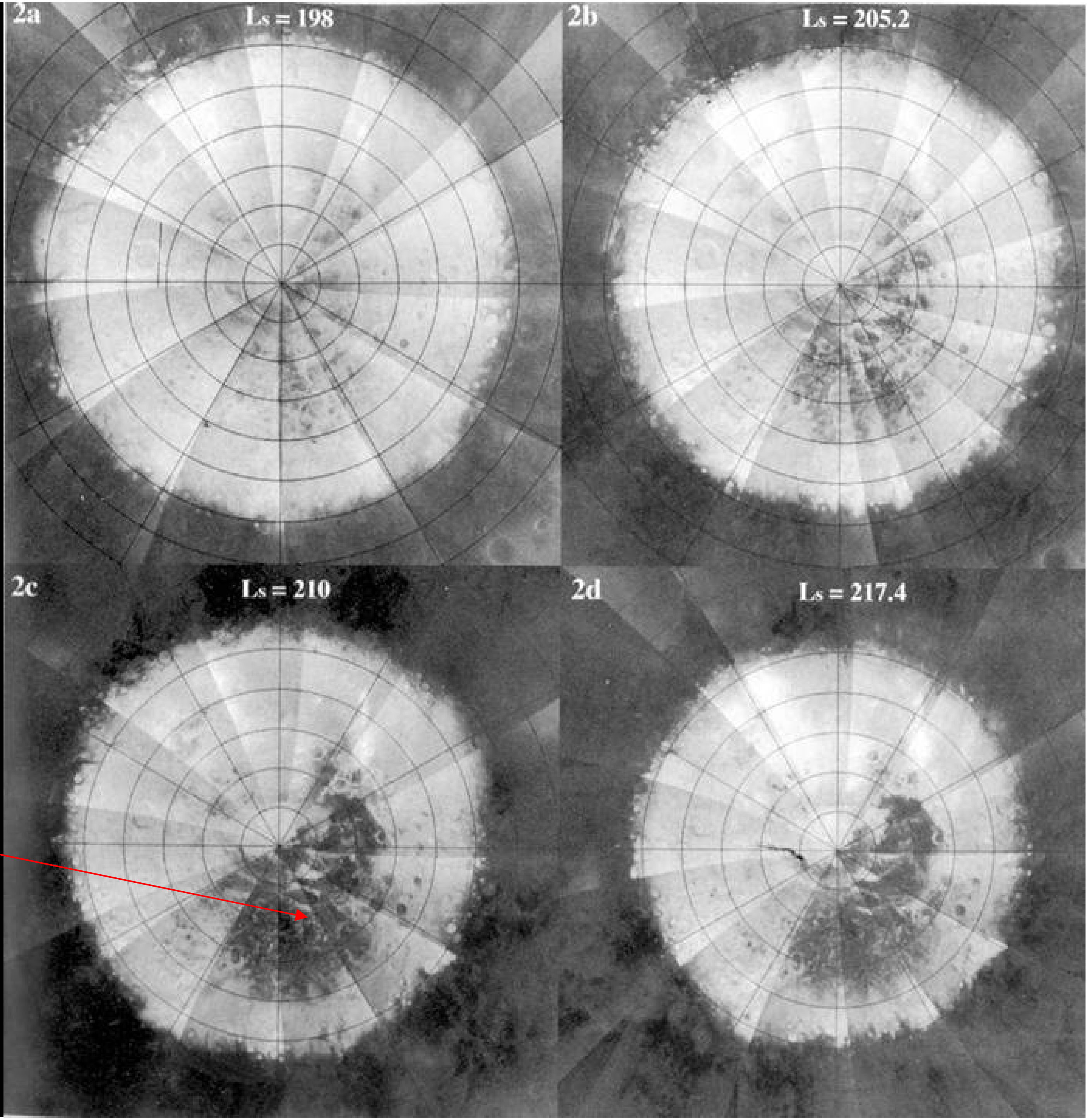
⇨ Very « alien » meteorology

Seasonal CO2 ice cap in spring

(mosaic of the northern polar cap)

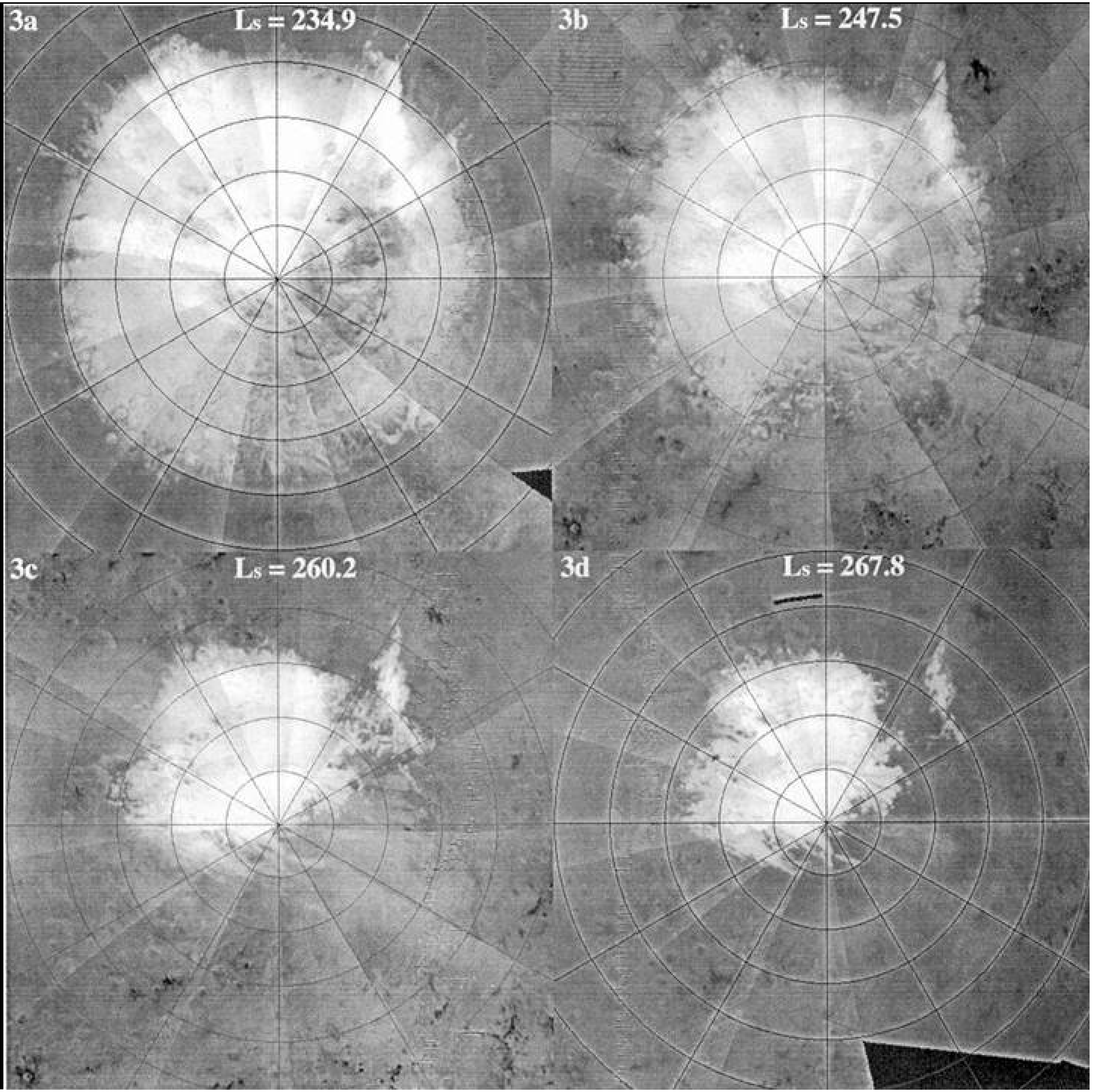


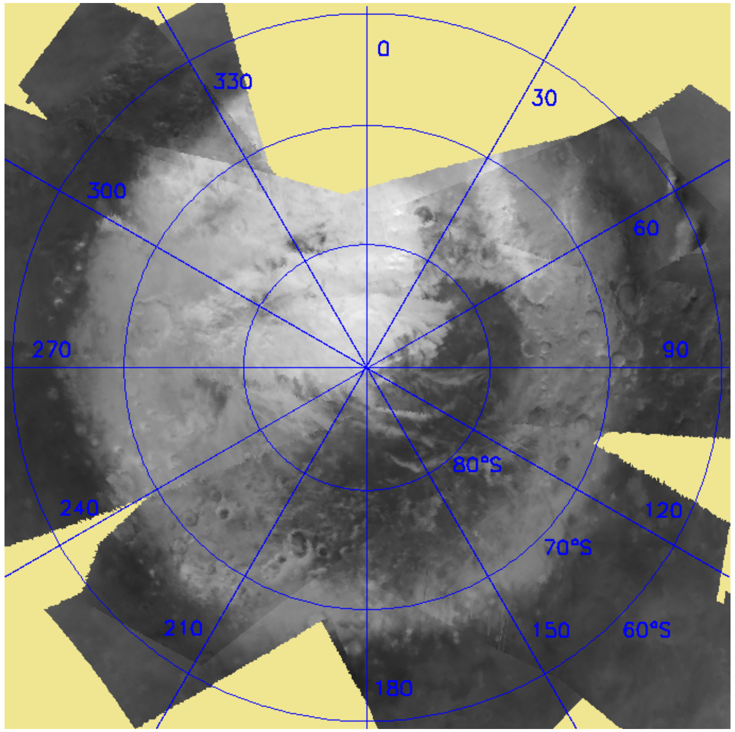
Recession of the south polar cap (*James et al. 2002*)



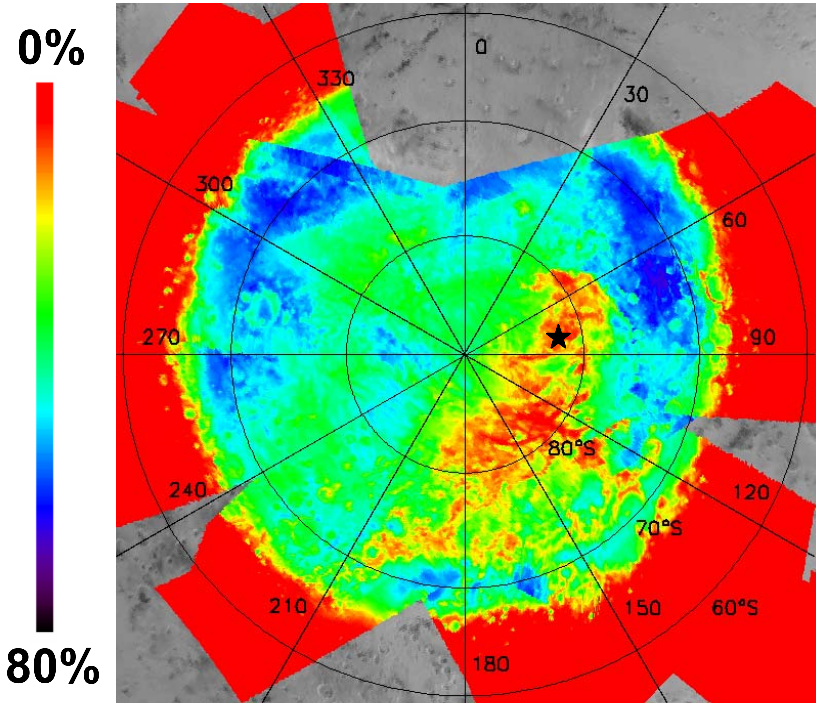
Cryptic region: Dark, but remains at CO2 frost temperature !

Recession of the south polar cap (*James et al. 2002*)

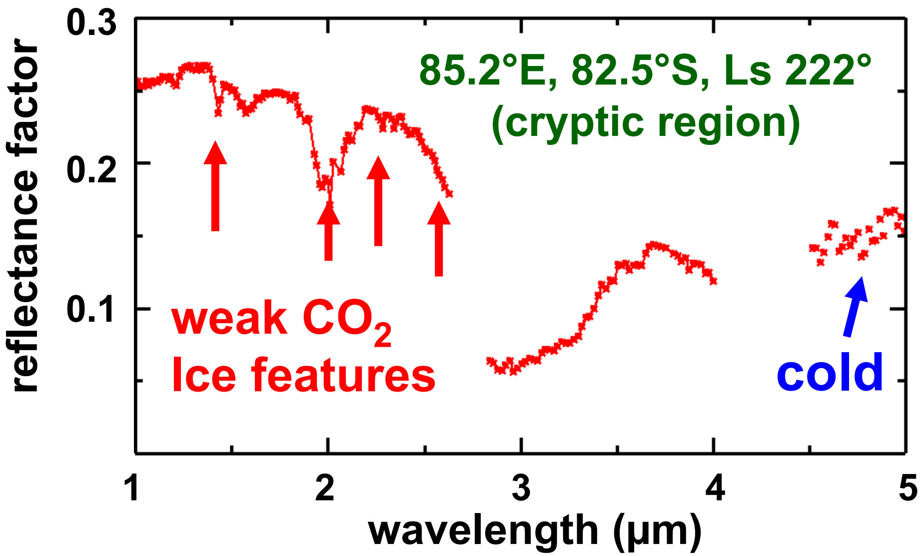




Ls
222°



CO_2 ice band depth (1.435 µm)

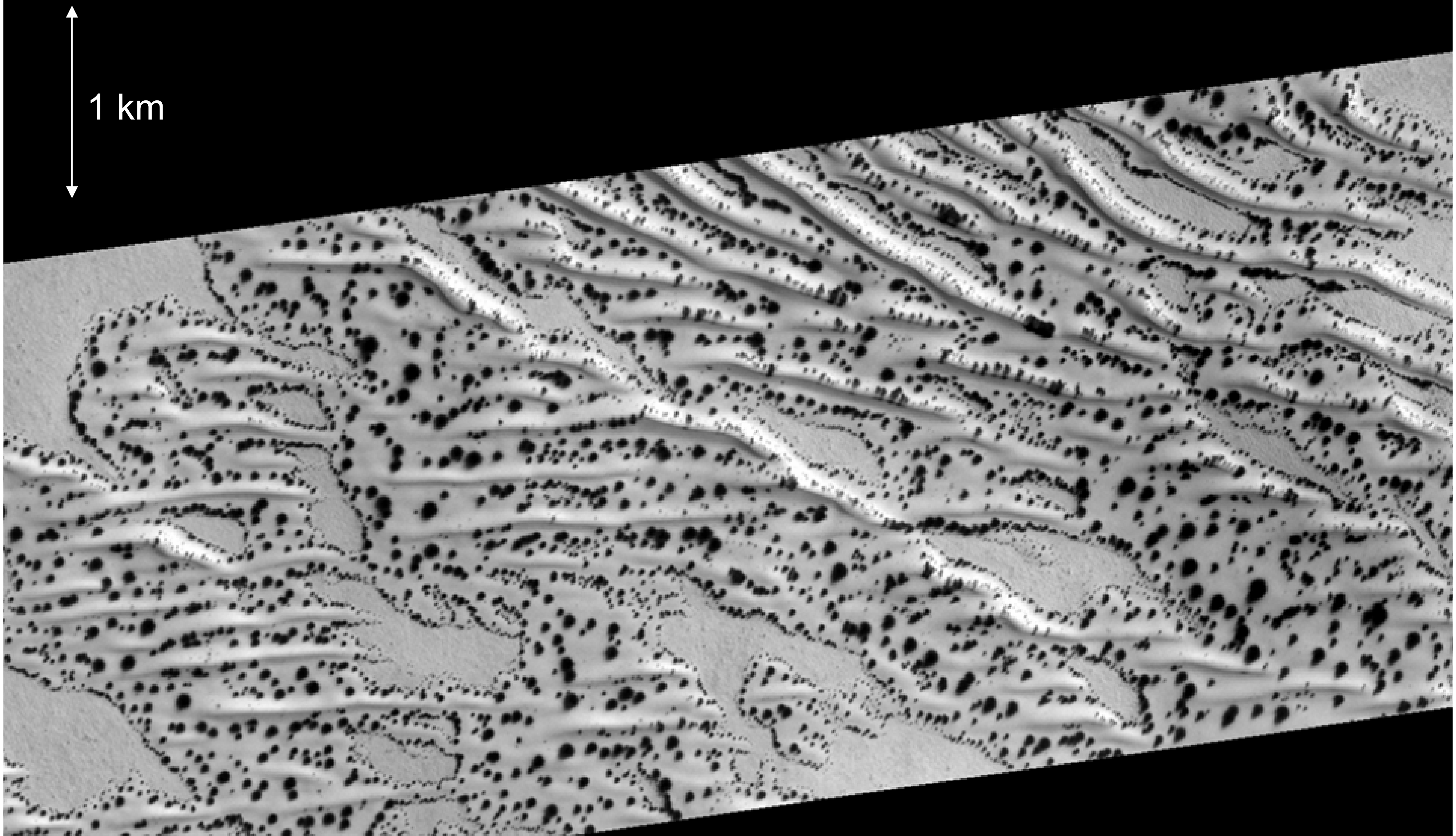


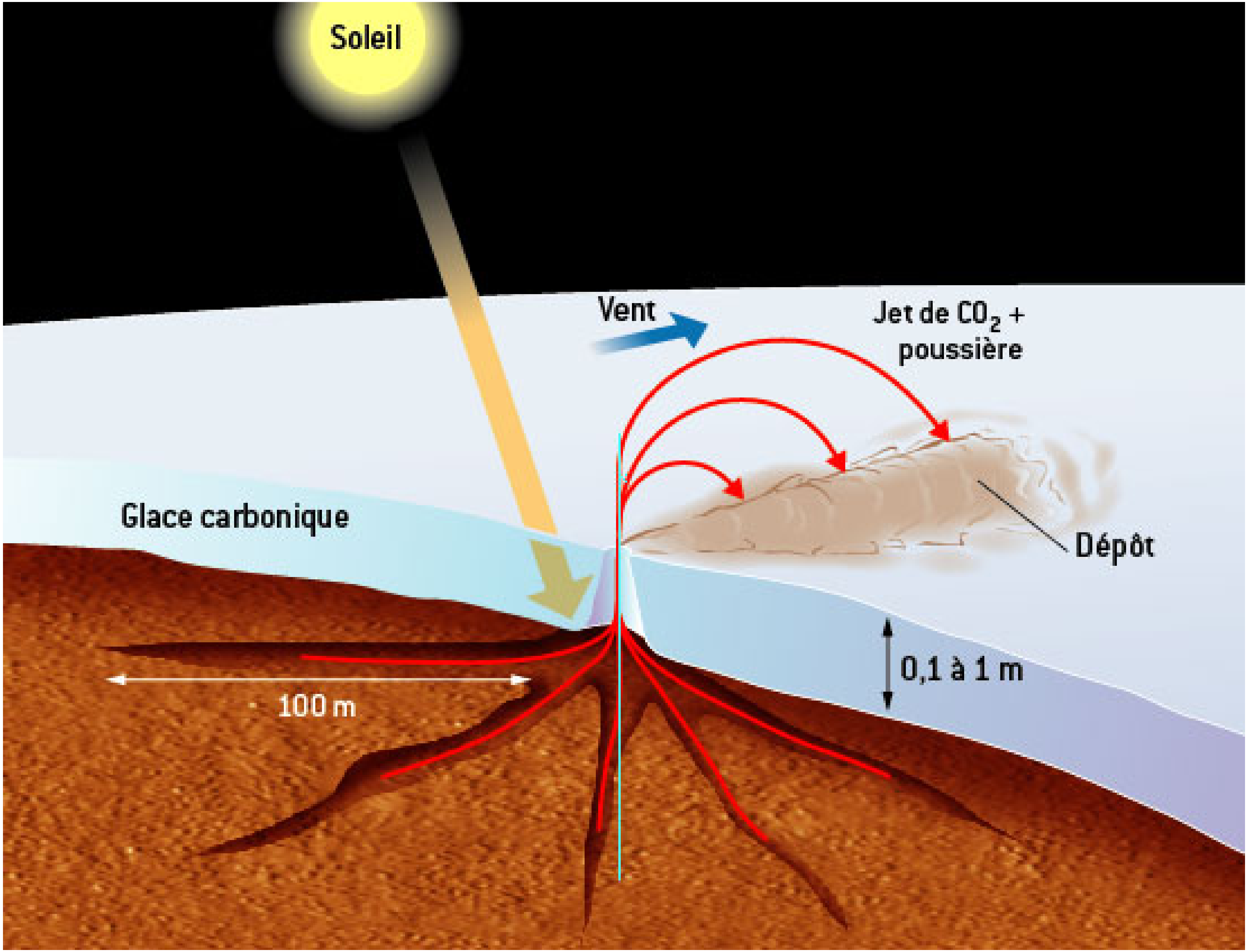
« Cryptic region » (Ls 195° – 235°)
Seen by Mars Express OMEGA
Imaging spectrometer

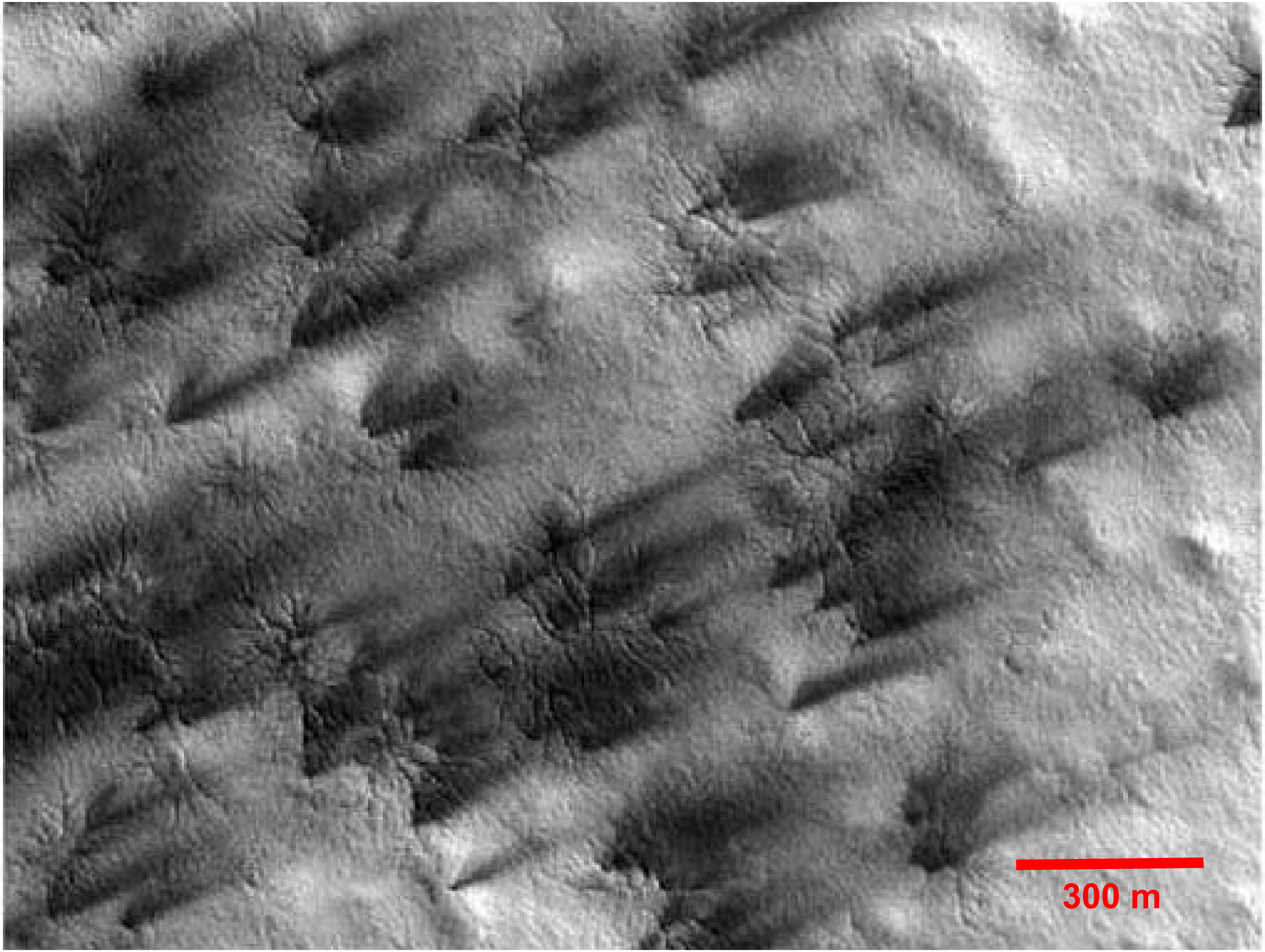
CO_2 ice is covered by dust !!

Langevin et al., Nature, 08 / 2006

Sublimation of CO_2 ice and snow

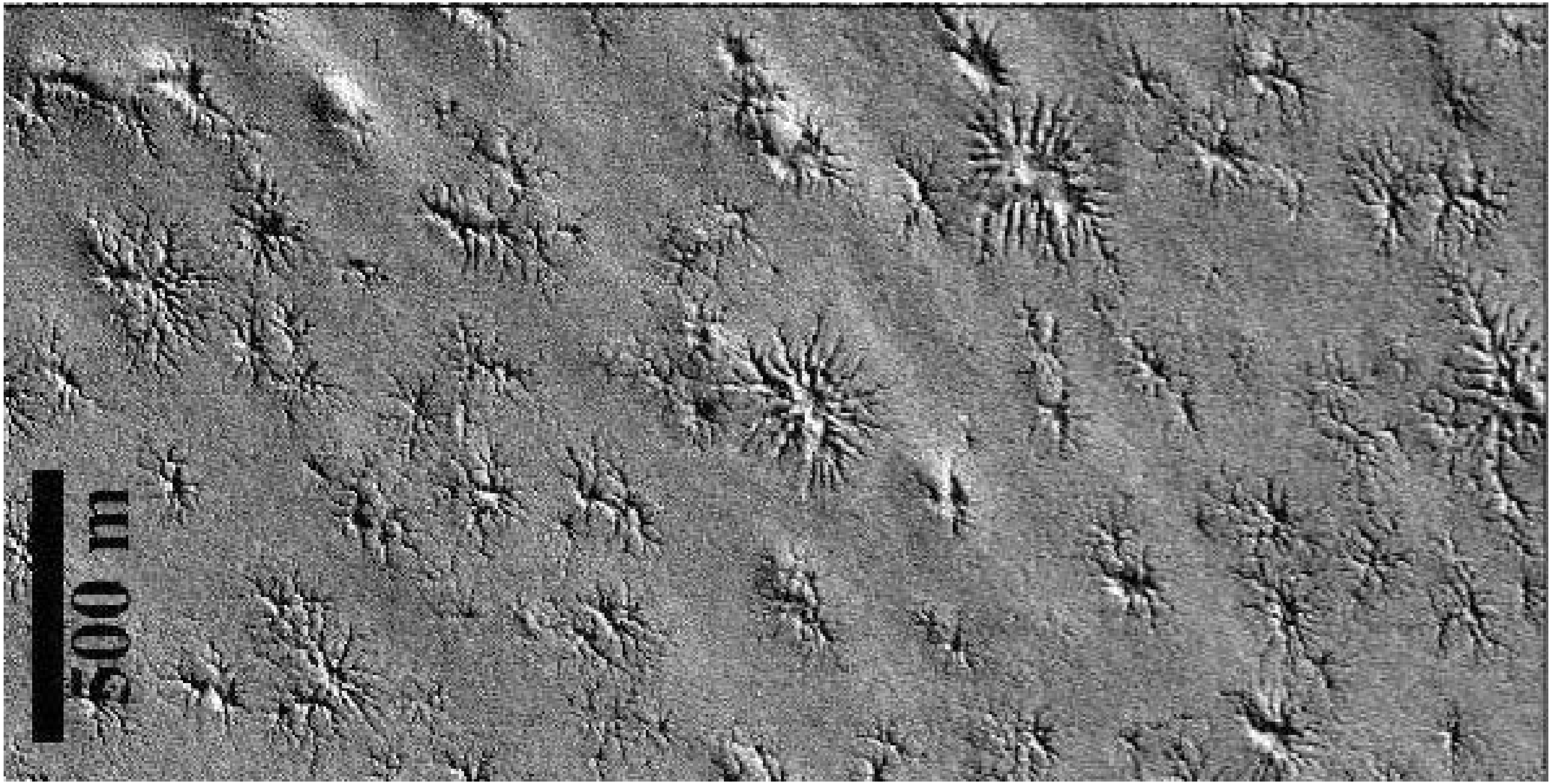



Soleil
Vent
Jet de CO_2 +
poussière
Glace carbonique
Dépôt
0,1 à 1 m
100 m

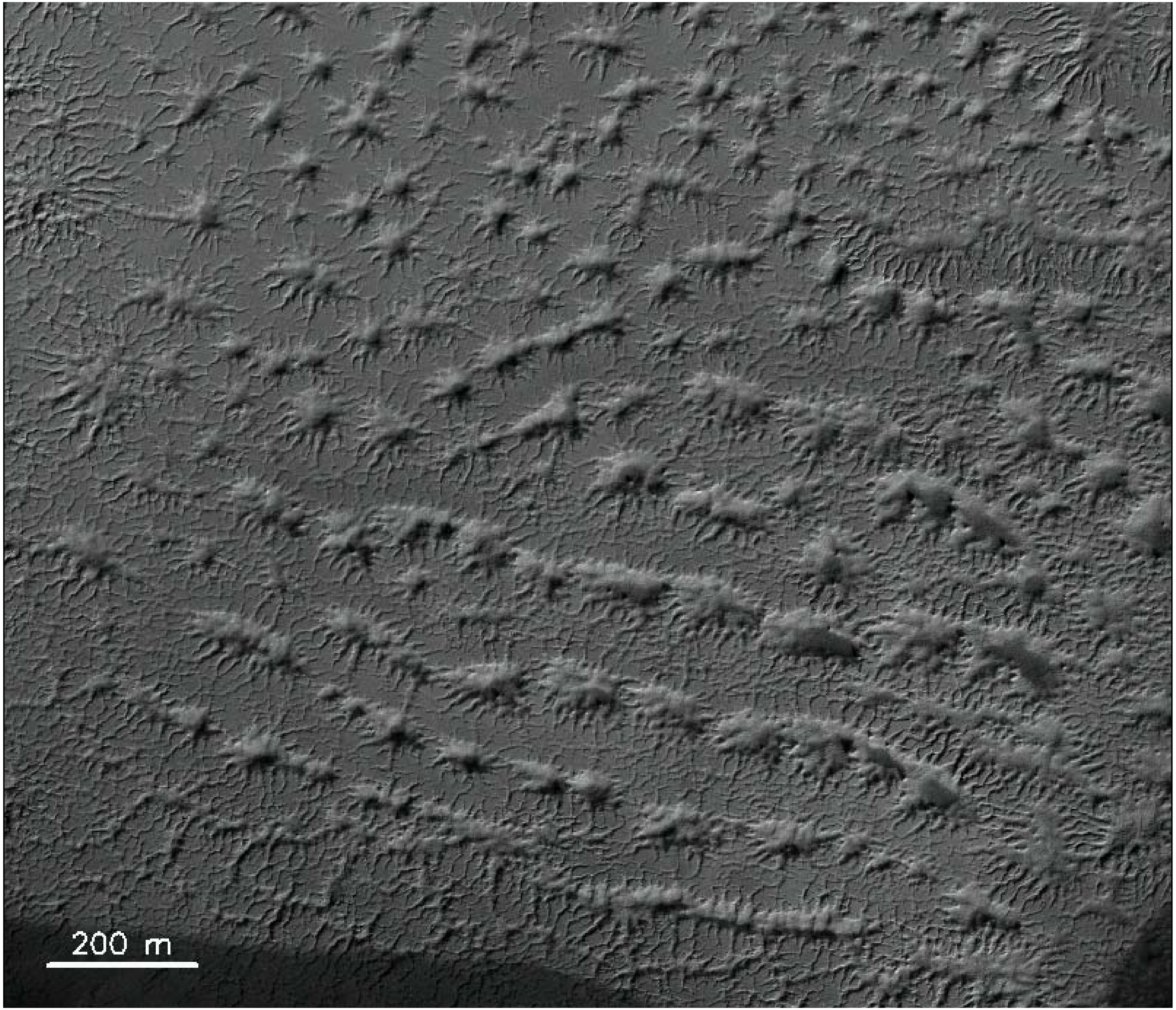

300 m

Formation of “Spider” in the “criptic” region

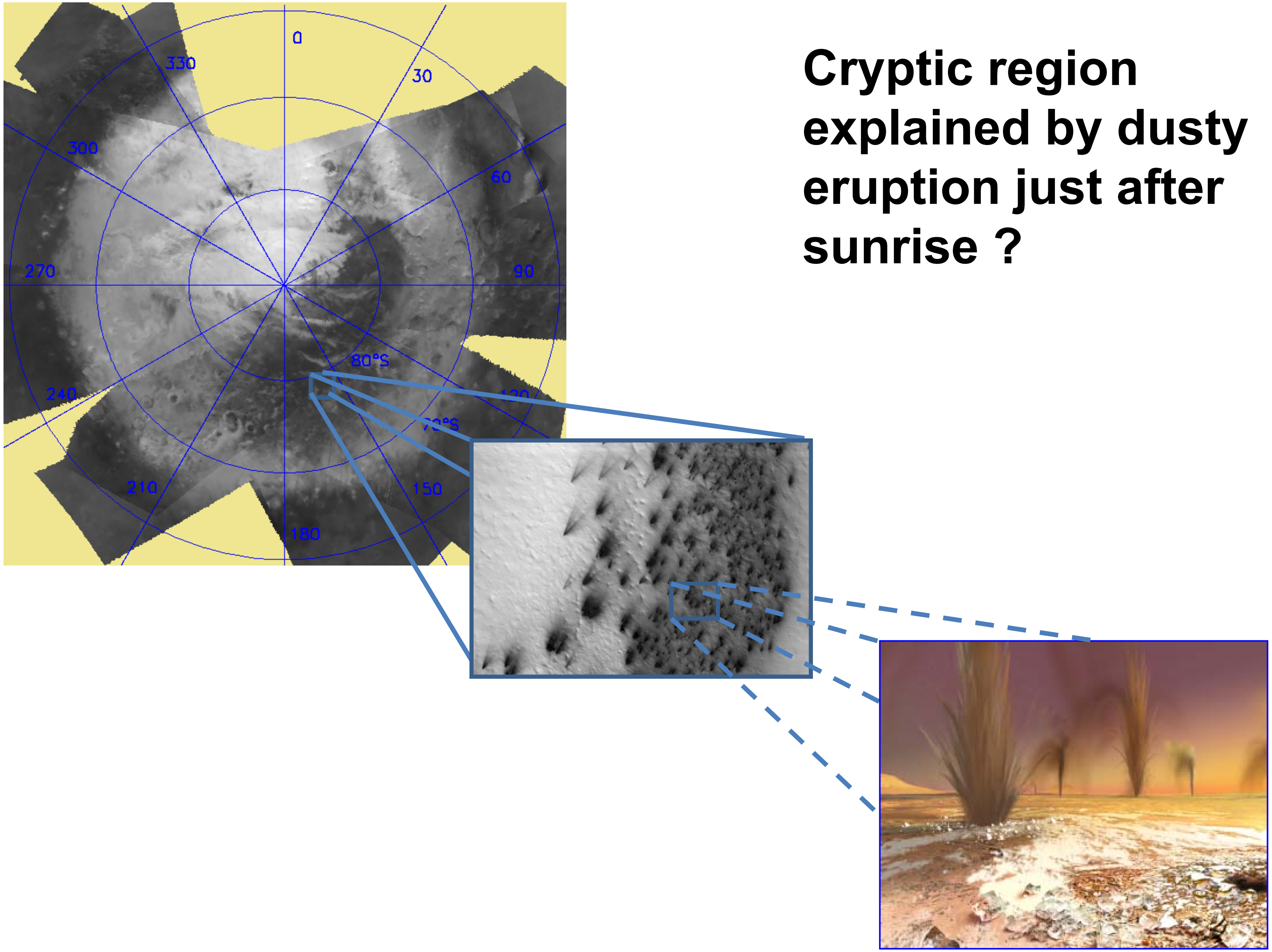
(Piqueux et al. 2003, Kieffer et al. 2006)



)


200 m

Cryptic region explained by dusty eruption just after sunrise ?

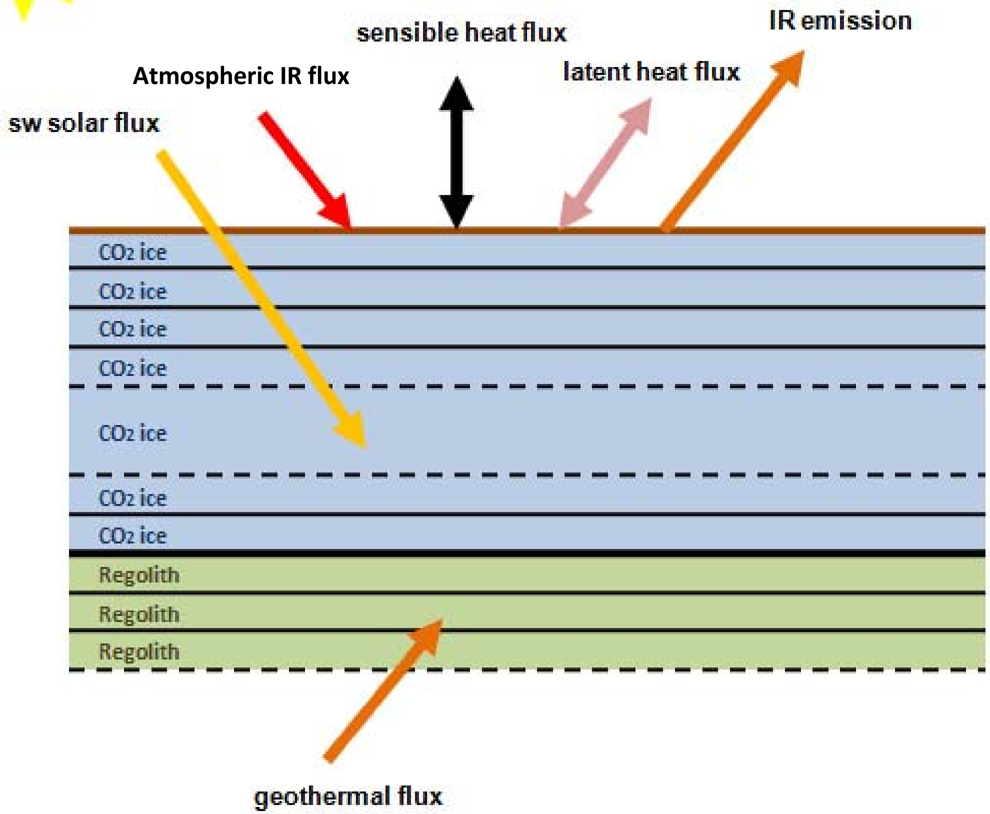


C. Pilorget

Modelling the detailed ice thermodynamics

(Pilorget et al. 2010)

A 1D model that solves conduction, radiation, mass evolution equations



Finite volume approach

Vertical grid: 1cm layers

Radiative transfer code for the atmosphere: Toon et al. [1989]

Conduction: implicit first order Euler scheme

Results

The evolution of the temperature

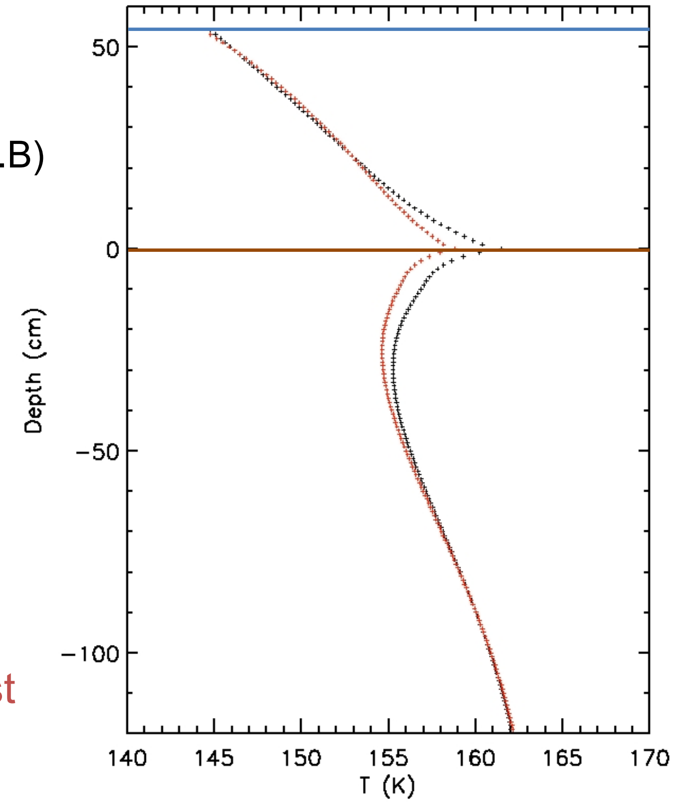
Ls190

Latitude: 85°S
$I_{regolith}$=200
$A_{regolith}$=0.24
T_{dust_atm}=0.1 (O.B)

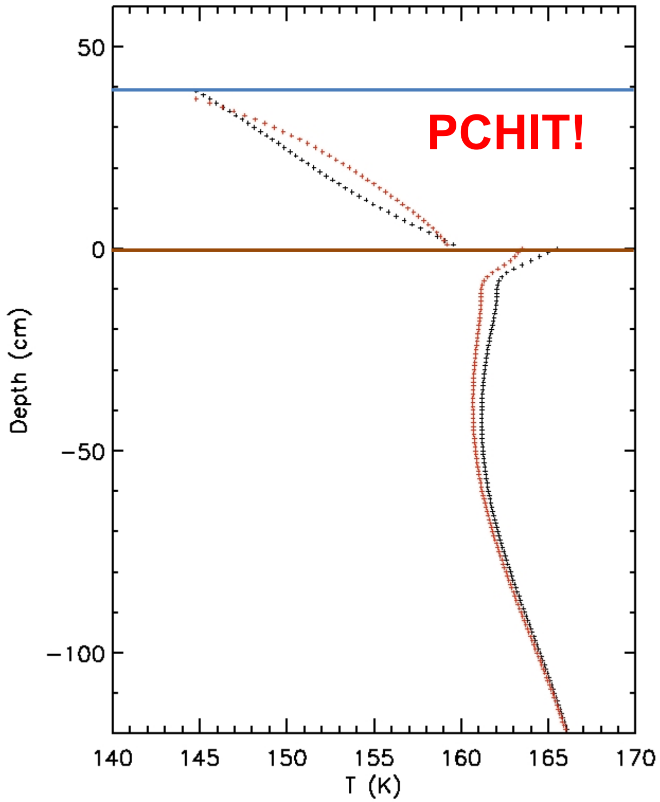
dust free

10 ppm dust

Flat terrain



30° N oriented slope



(Pilorget et al. 2010)

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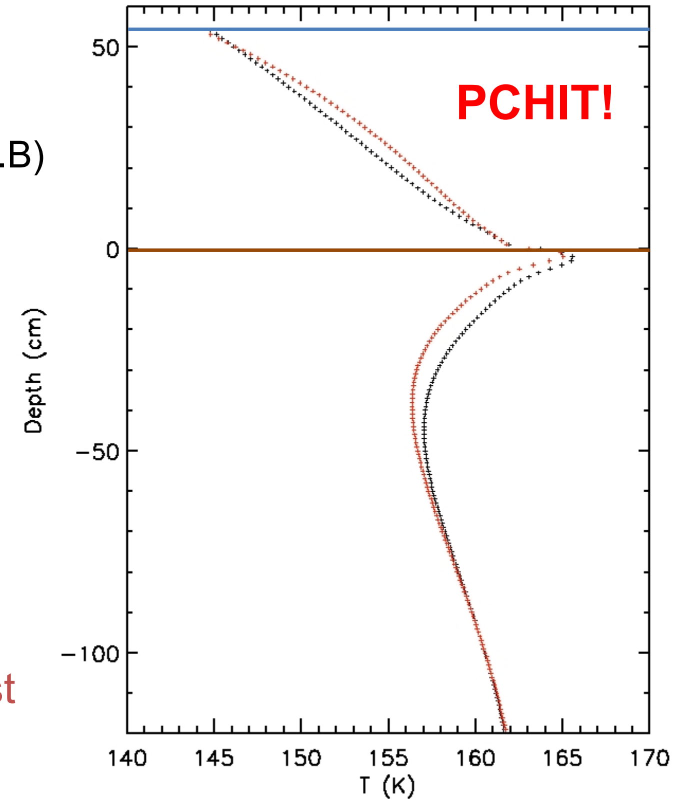
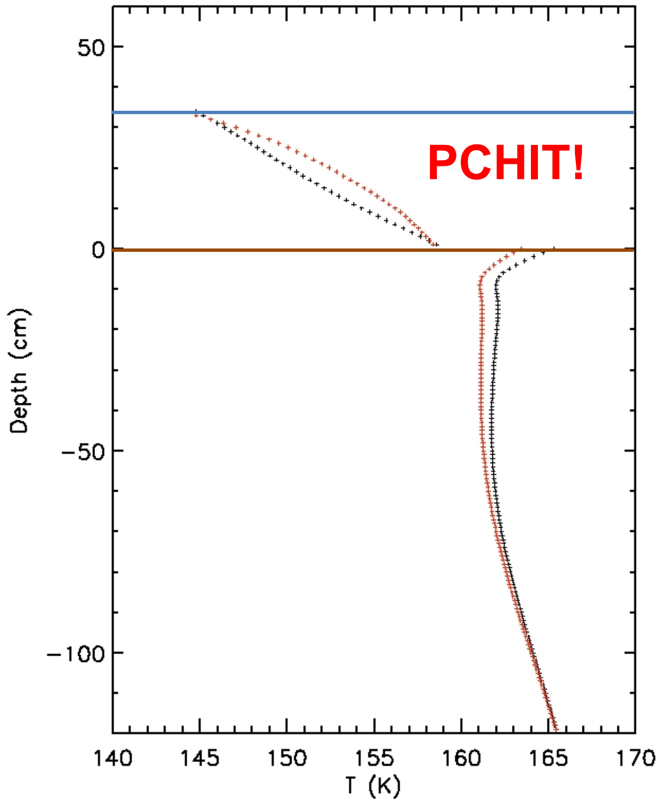
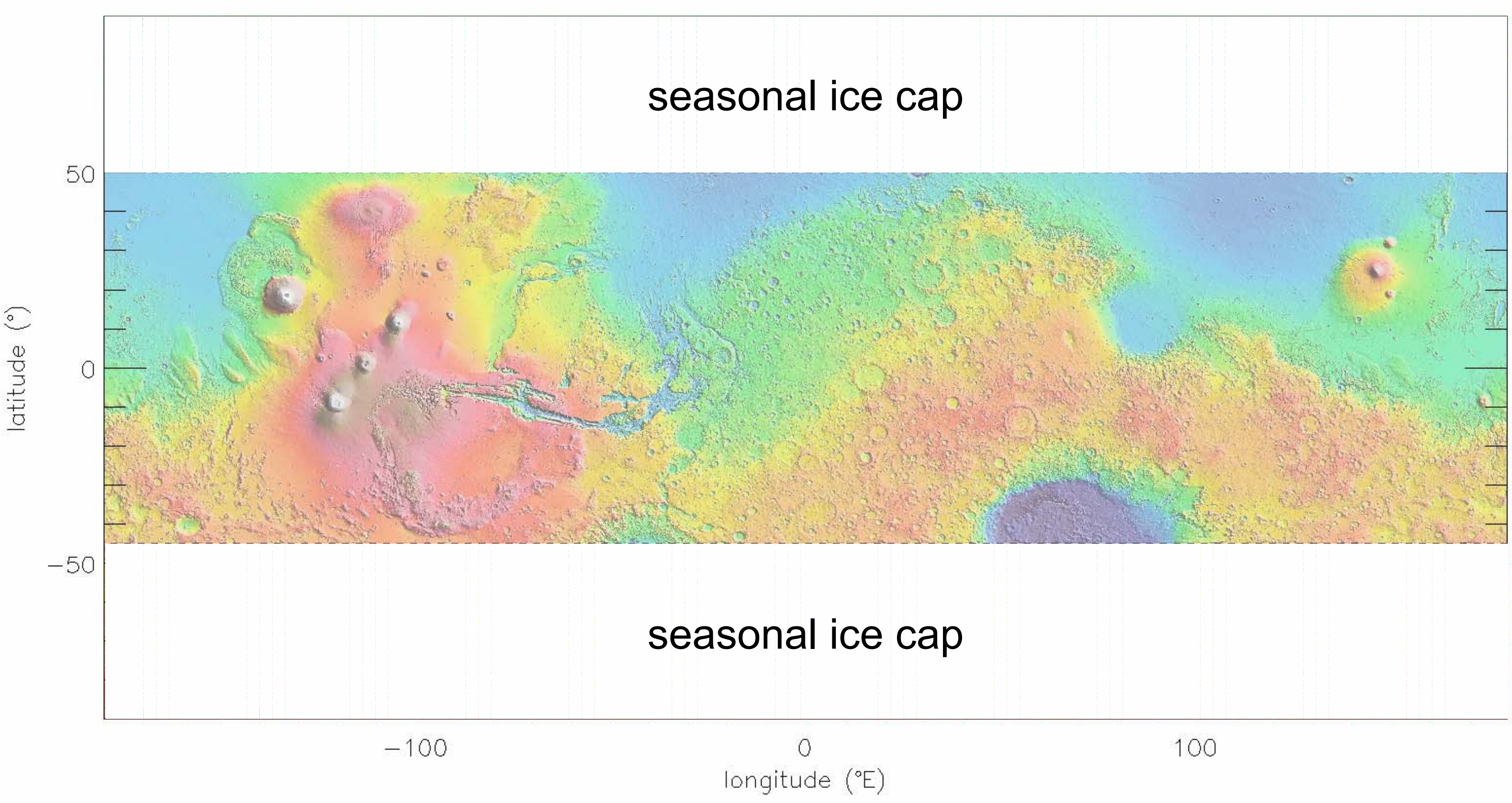


30° N oriented slope



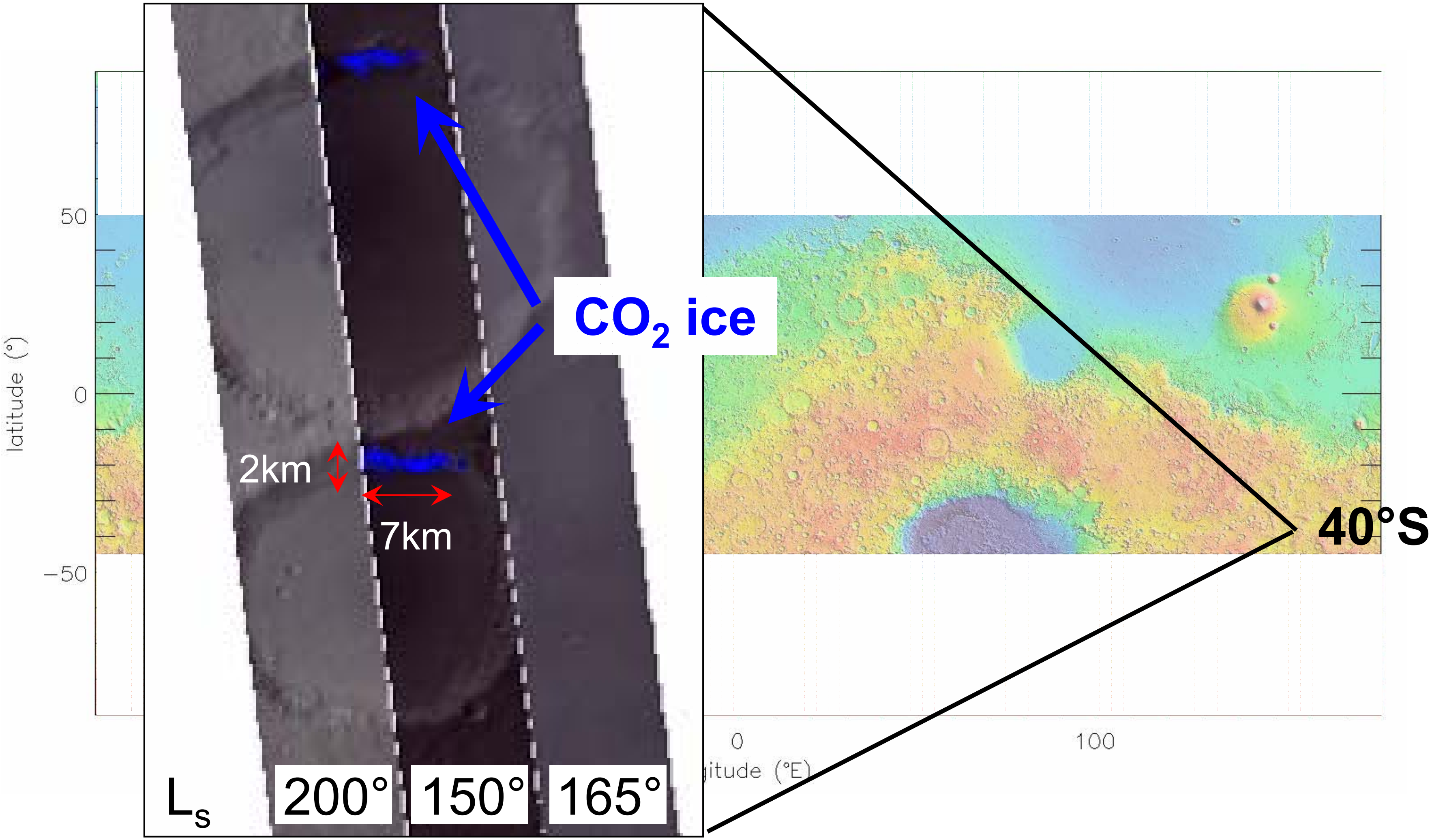
(Pilorget et al. 2010)

CO2 ice outside the polar caps ? Search using Omega and Crism imaging spectrometer **(Mathieu Vincendon)**



Ice on flat surface is observed down to ~ 50°N / 45°S in fall and winter

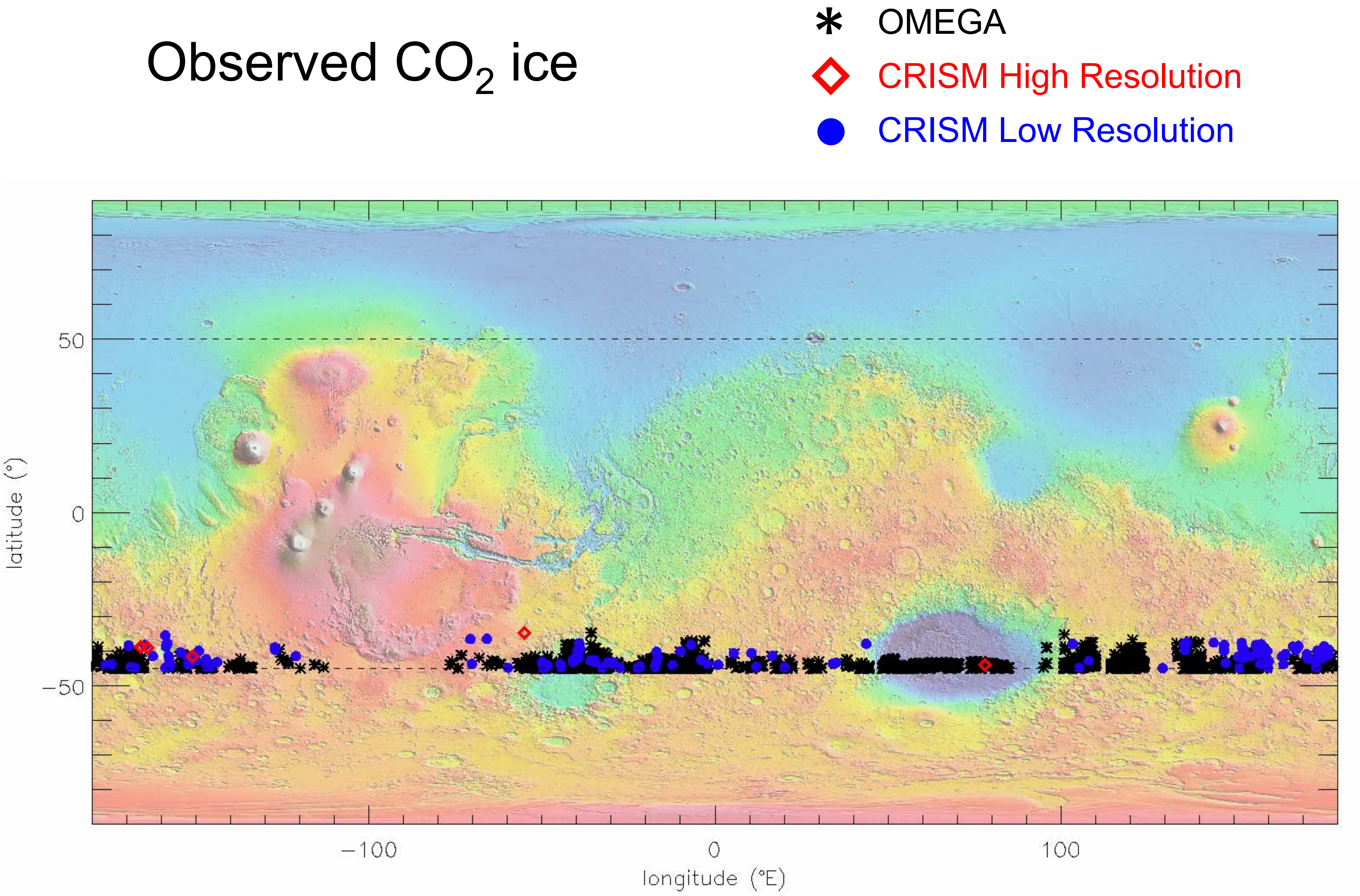
On pole facing slopes, ice is stable closer to the equator



CRISM “MSP” data – 230 m spatial resolution

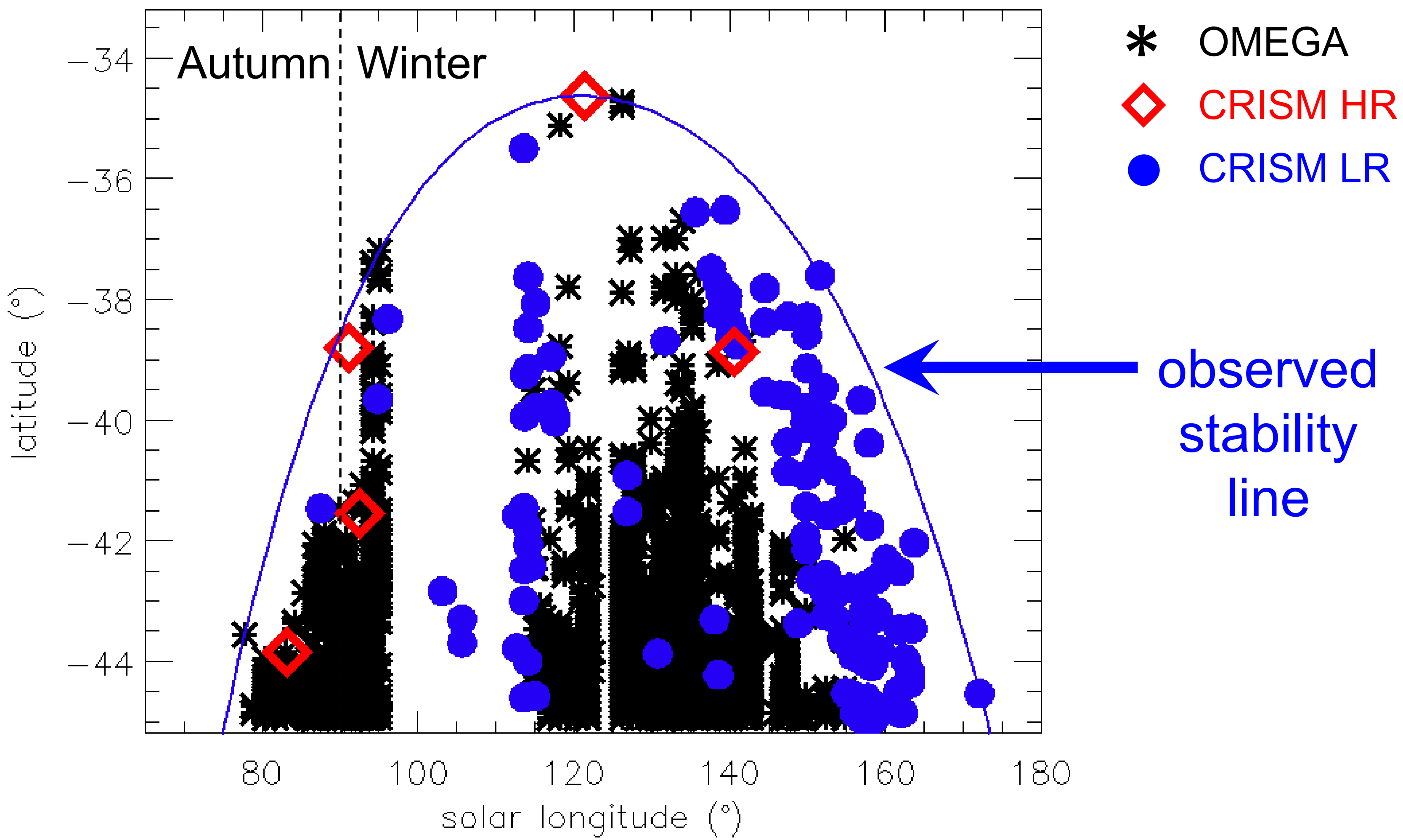
Vincendon et al. 2009

Observed CO_2 ice



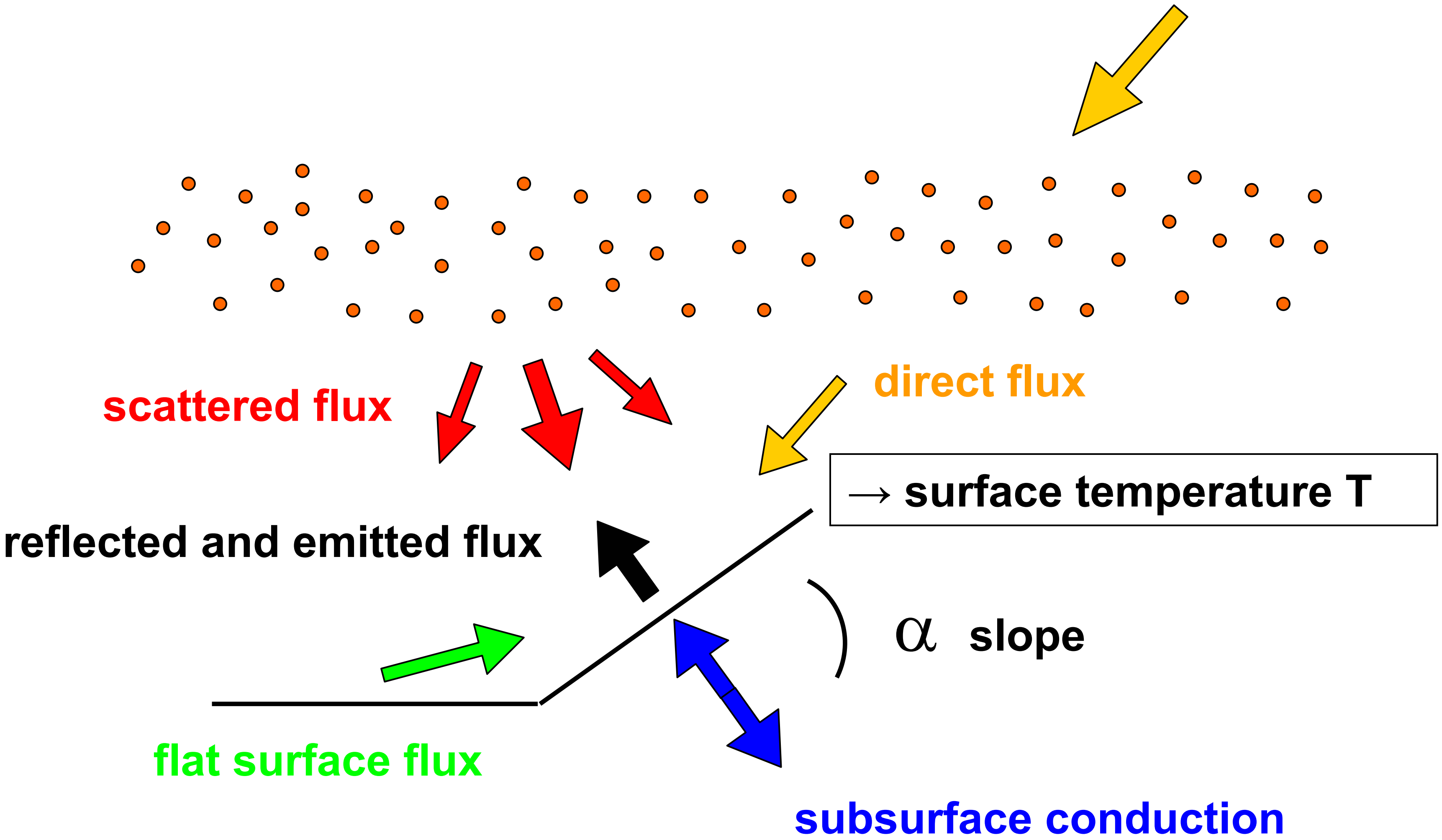
Vincendon et al. 2009

Observed CO_2 ice stability pattern (latitude versus season)



Vincendon et al. 2009

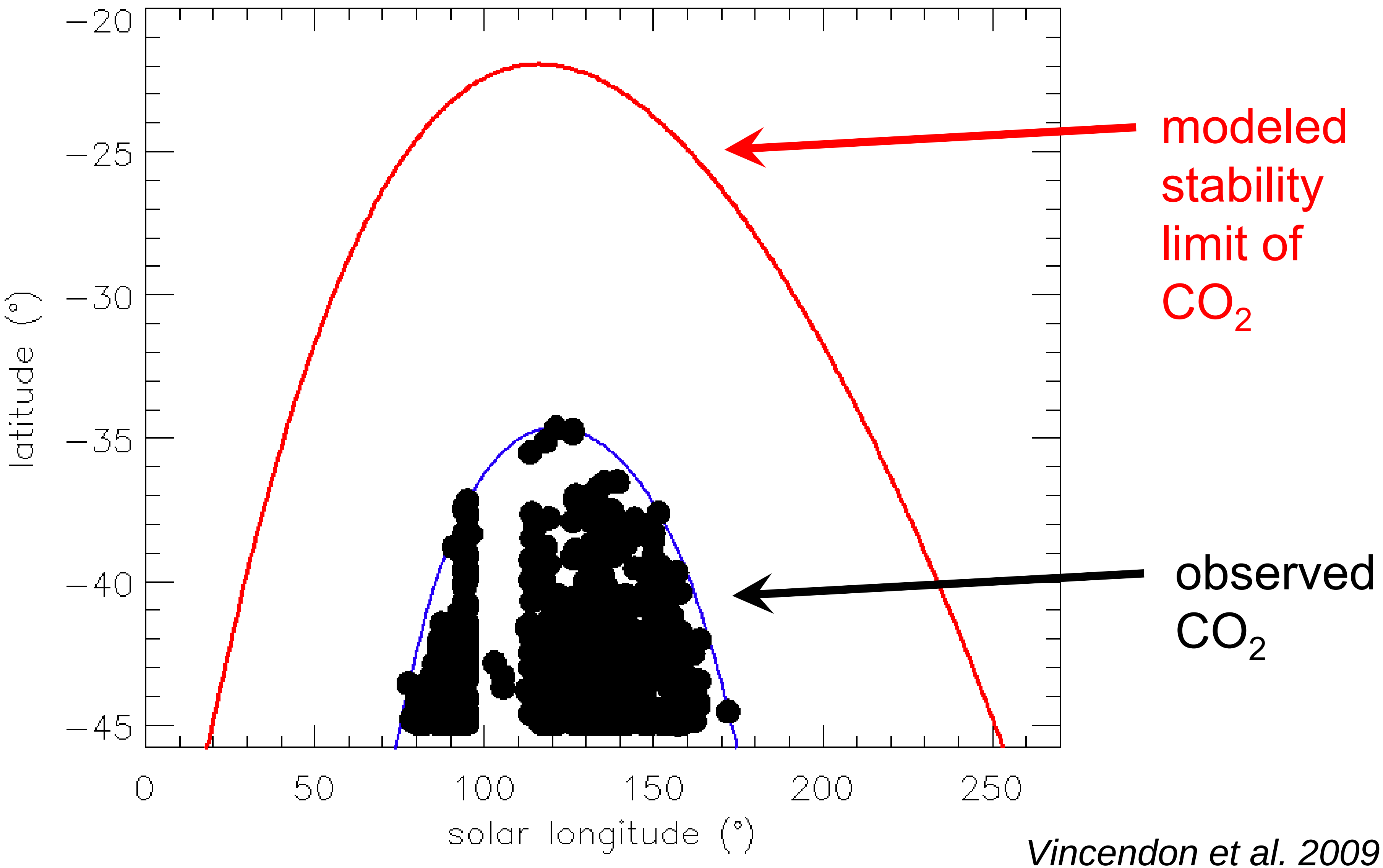
A 1D local energy balance code derived from the LMD GCM is used to predict the stability of ice



Vincendon et al. 2009

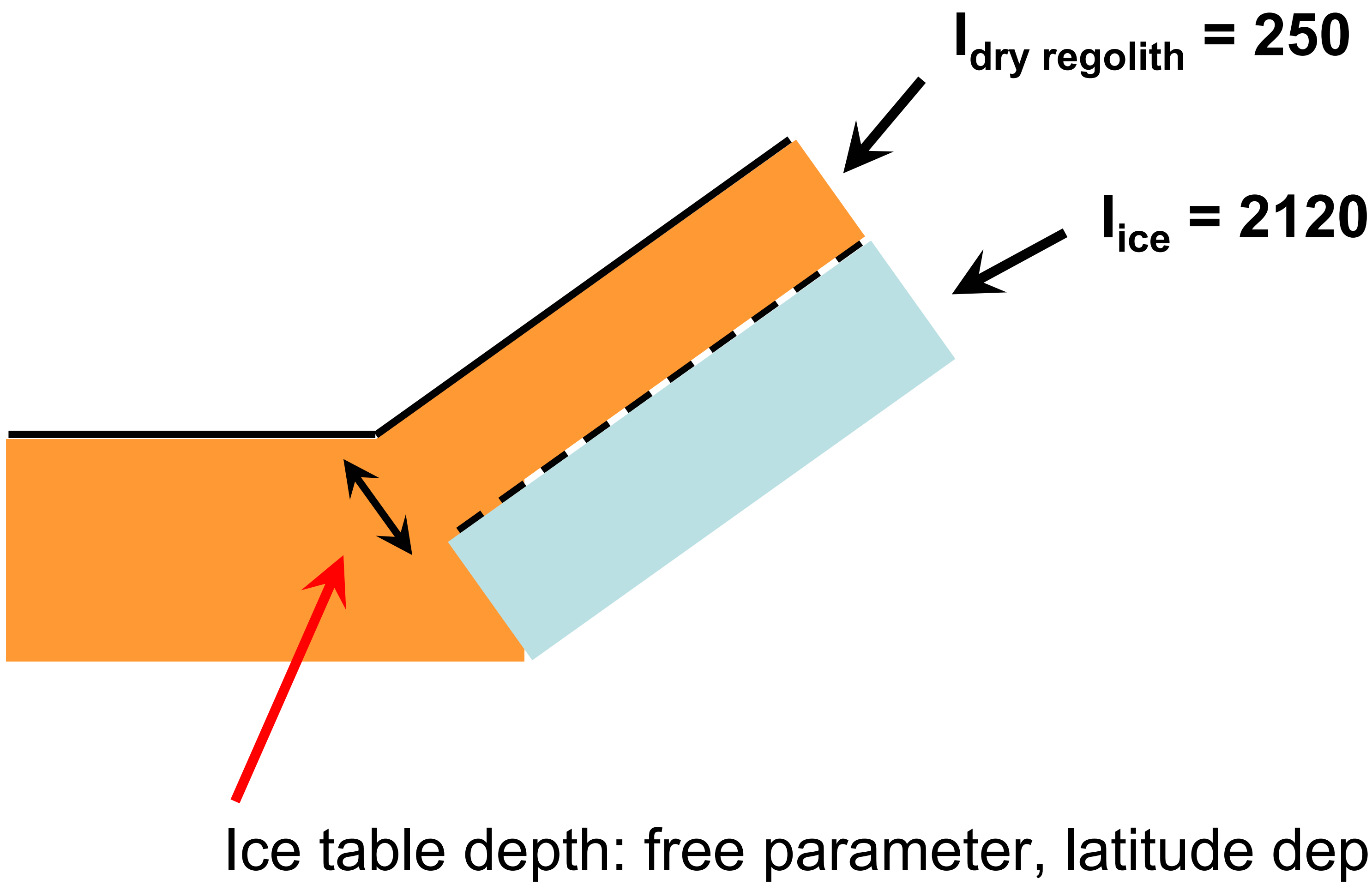
First prediction of the model: ice stability over-predicted

a source of heat localized on slopes is required



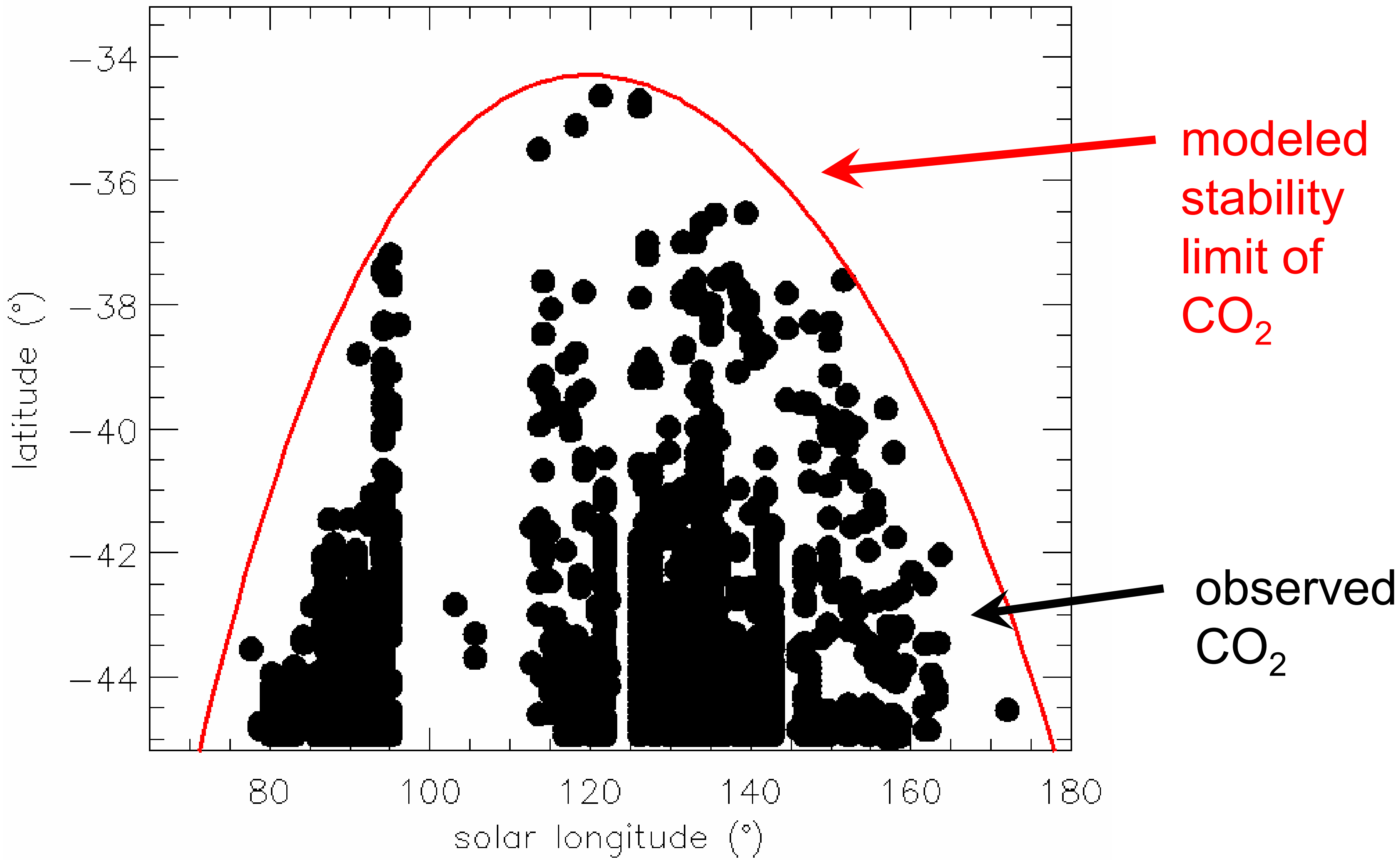
Vincendon et al. 2009

Ground model: dry regolith above H_2O ice rich regolith



Vincendon et al. 2009

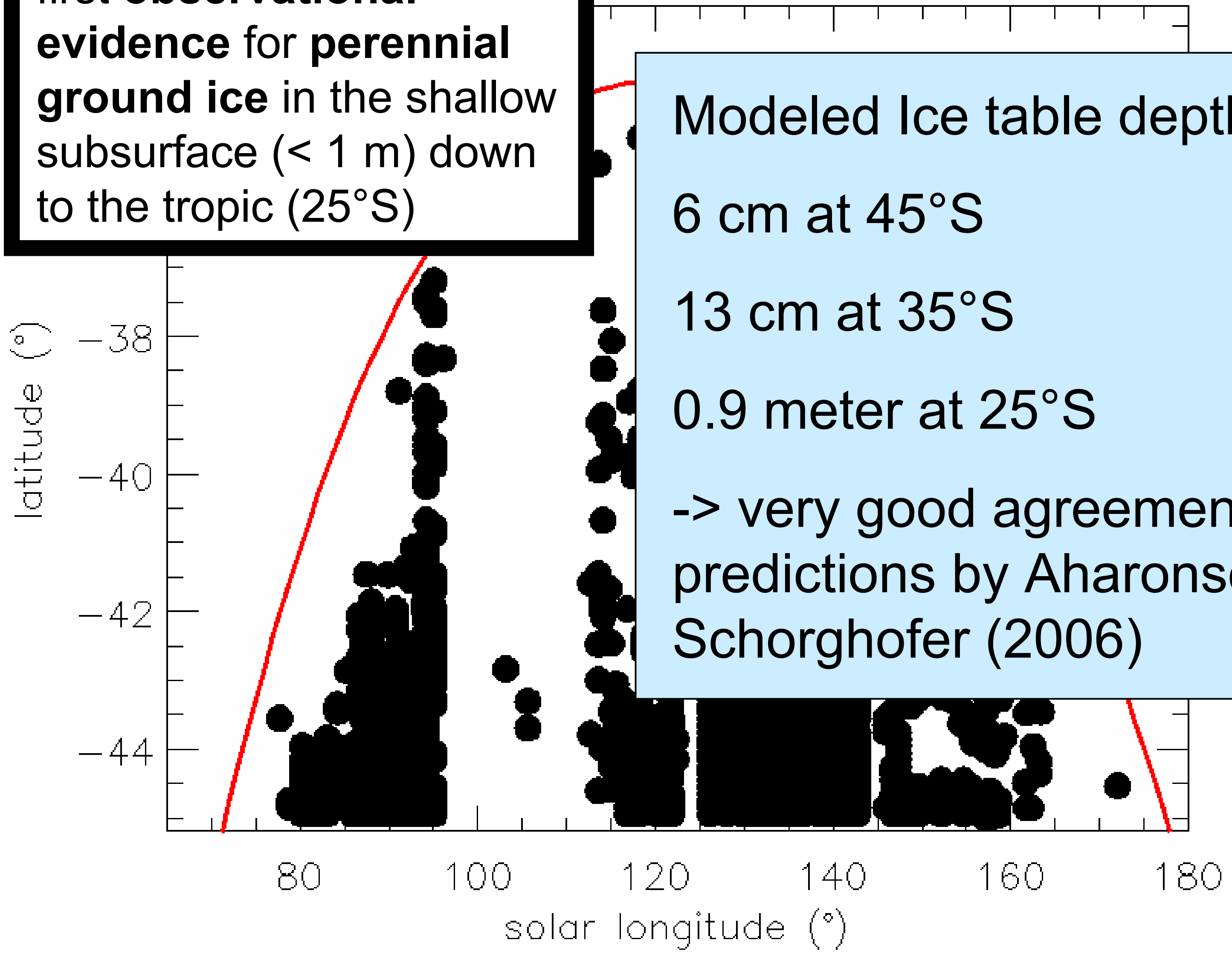
Result with ground H_2O ice



Vincendon et al. 2009

Result with ground H_2O ice

first **observational evidence** for **perennial ground ice** in the shallow subsurface (< 1 m) down to the tropic (25°S)



Modeled Ice table depths:

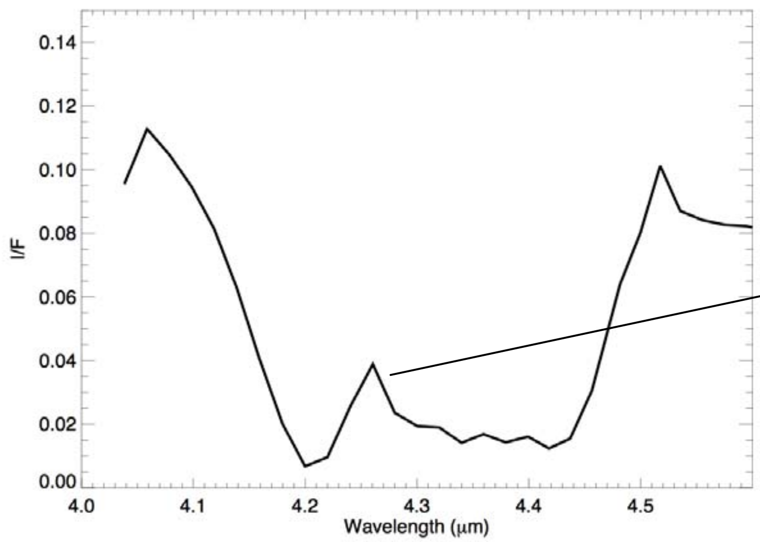
6 cm at 45°S

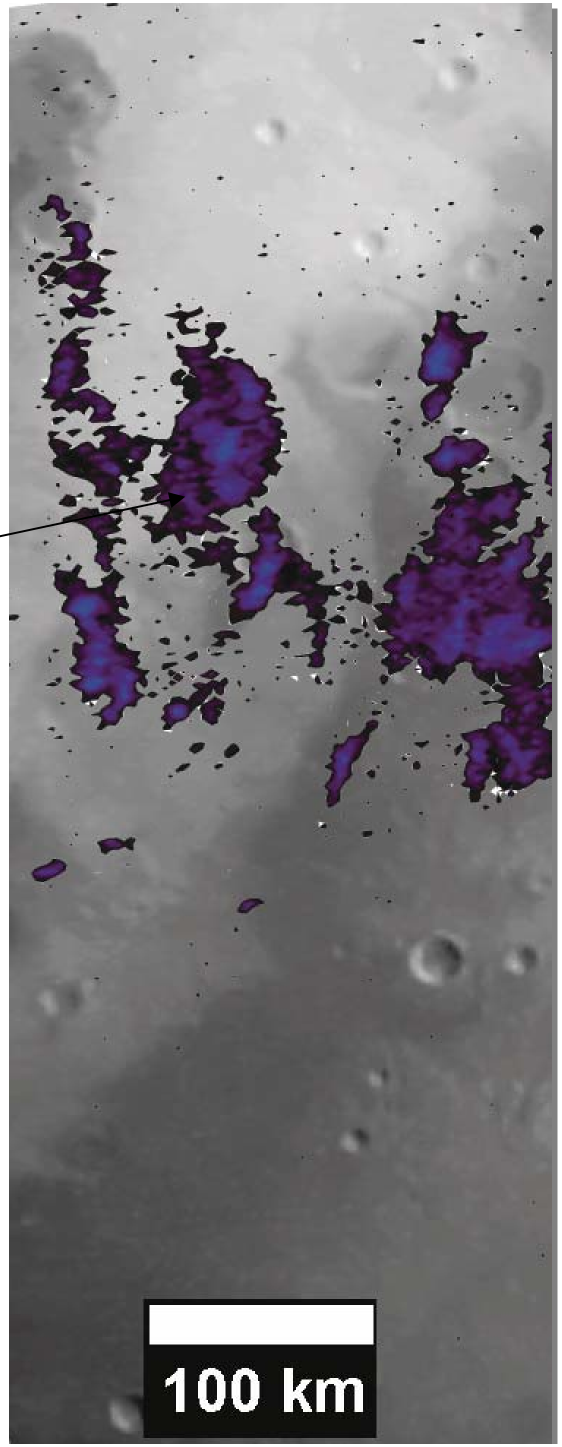
13 cm at 35°S

0.9 meter at 25°S

-> very good agreement with predictions by Aharonson & Schorghofer (2006)

Detection of high altitude CO2 ice clouds with OMEGA (Montmessin et al. 2007)



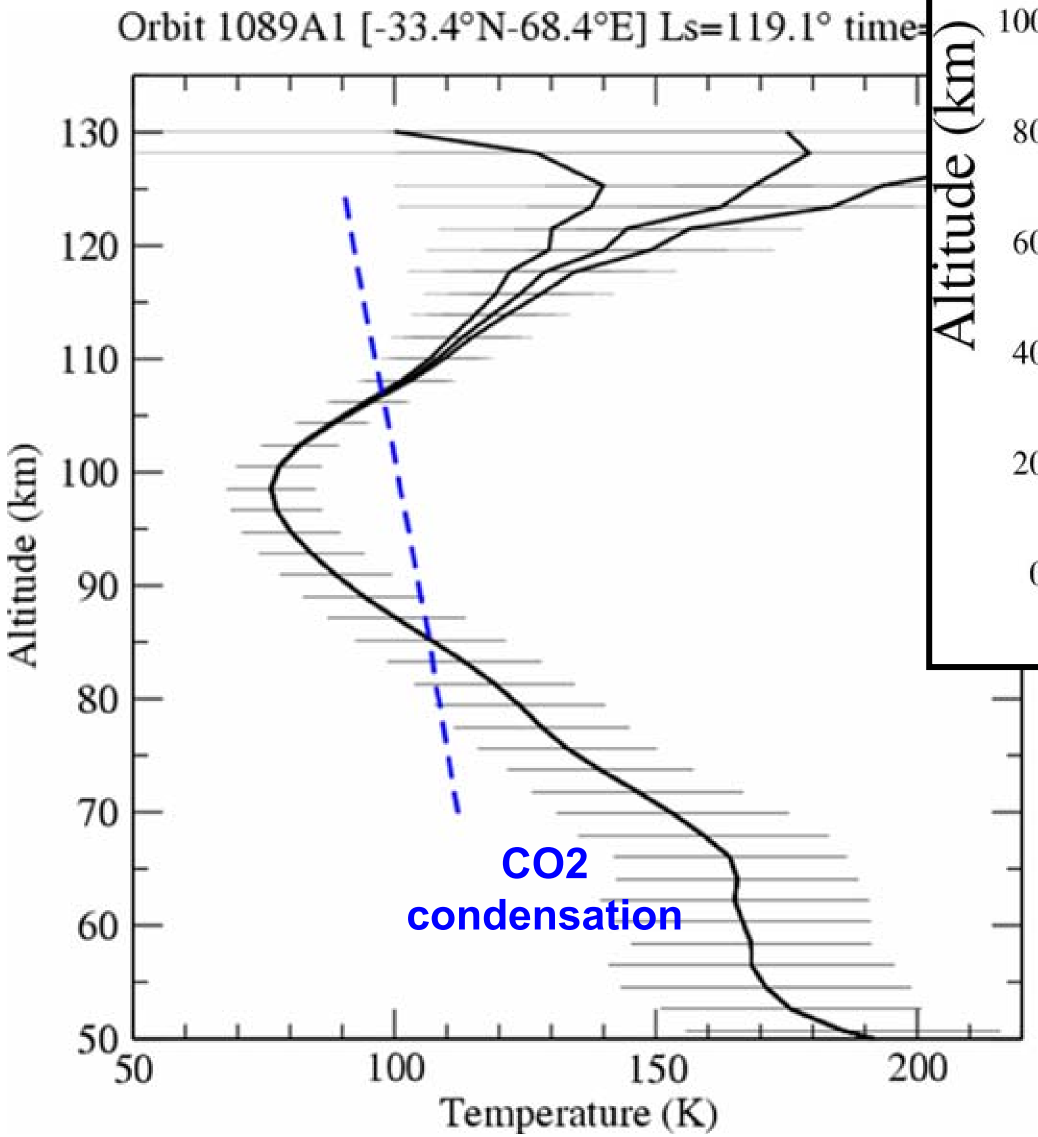


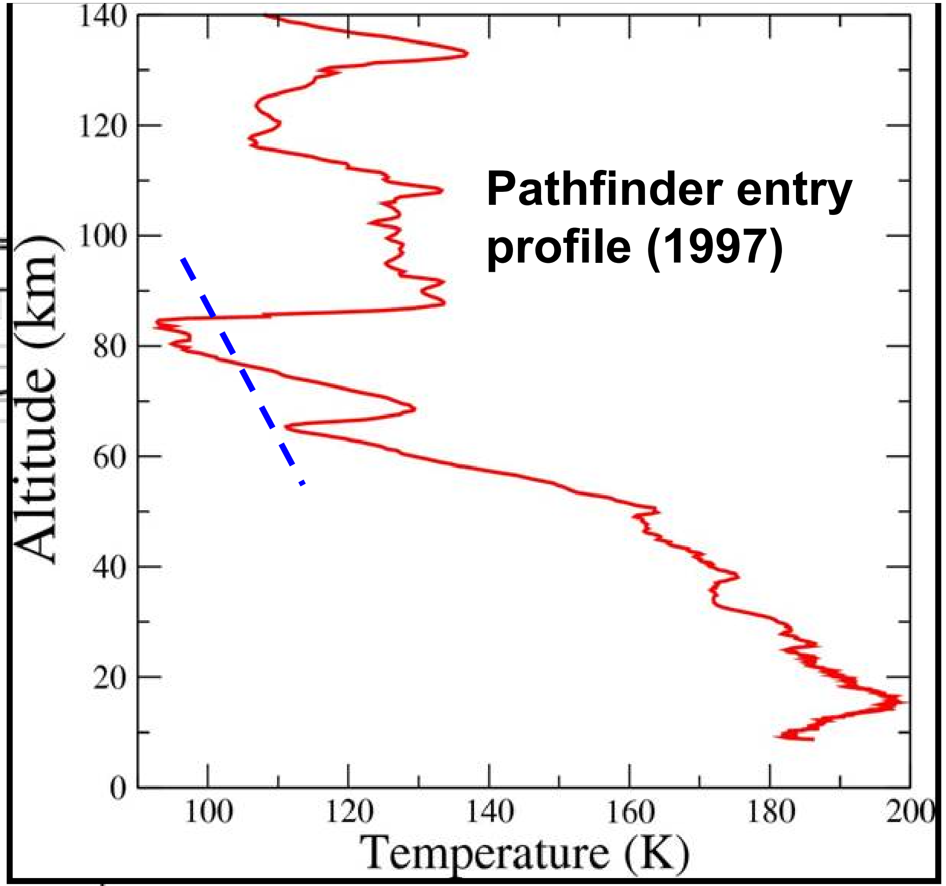
Opacity > 0.2
Altitude ~80 km
Reff up to 1.5 μm

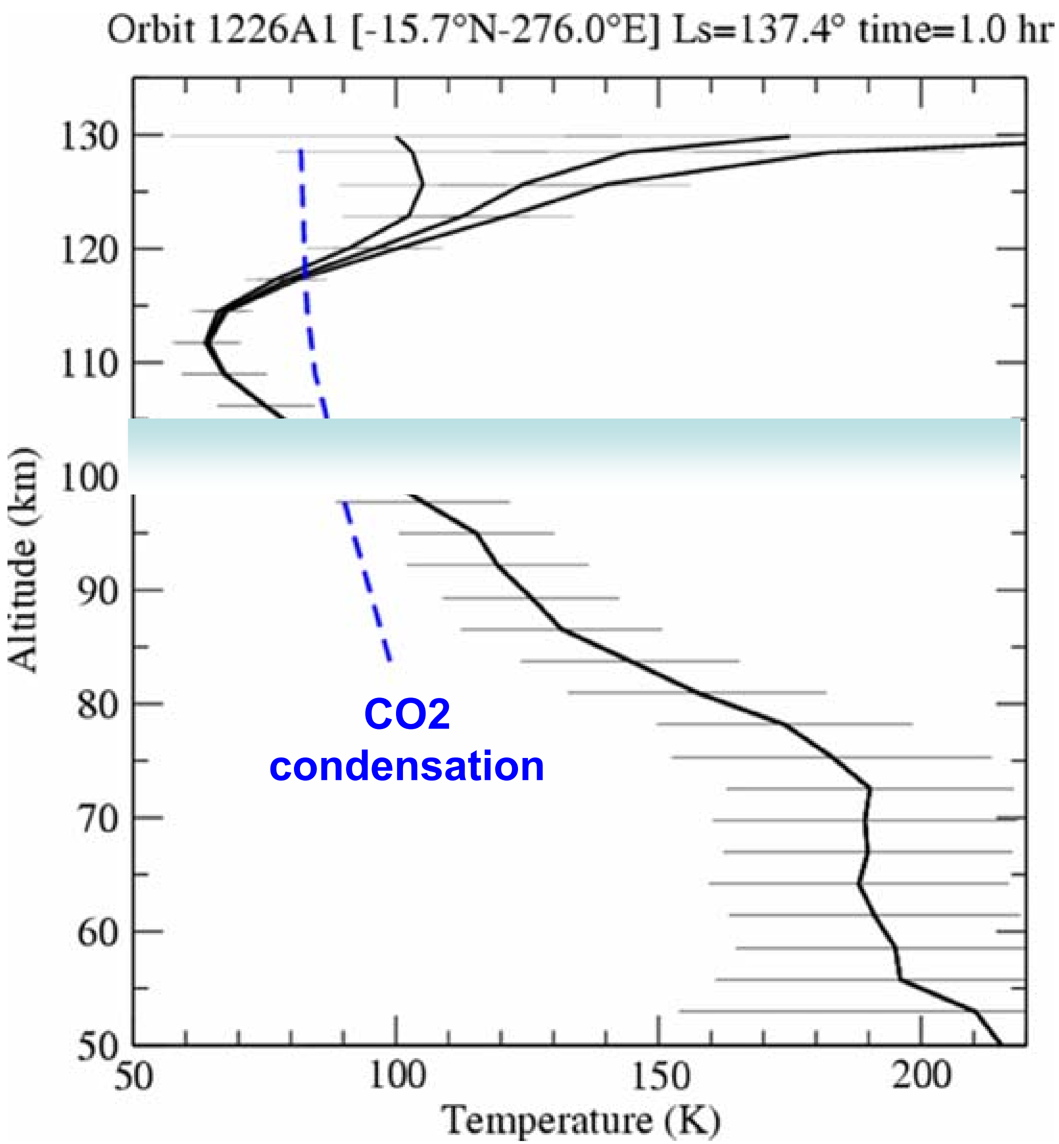
First spectroscopic identification by Mars Express (PFS, OMEGA, Formisano et al. 2006, Montmessin et al. 2007)
Observations by MOC & TES (Clancy et al. 2007), SPICAM (Montmessin et al. 2006), VMC, THEMIS (McConnochie et al.)

SPICAM stellar occultation

Forget et al. 2009



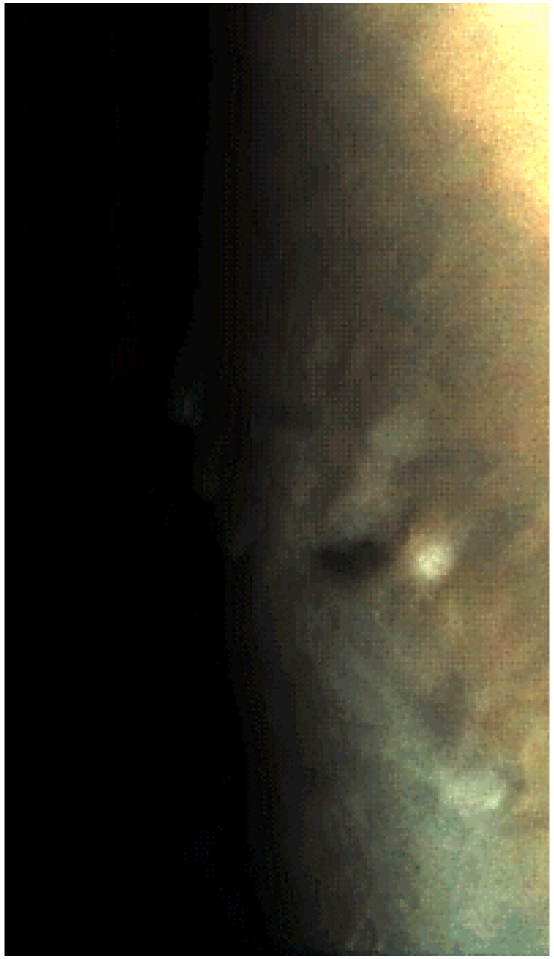


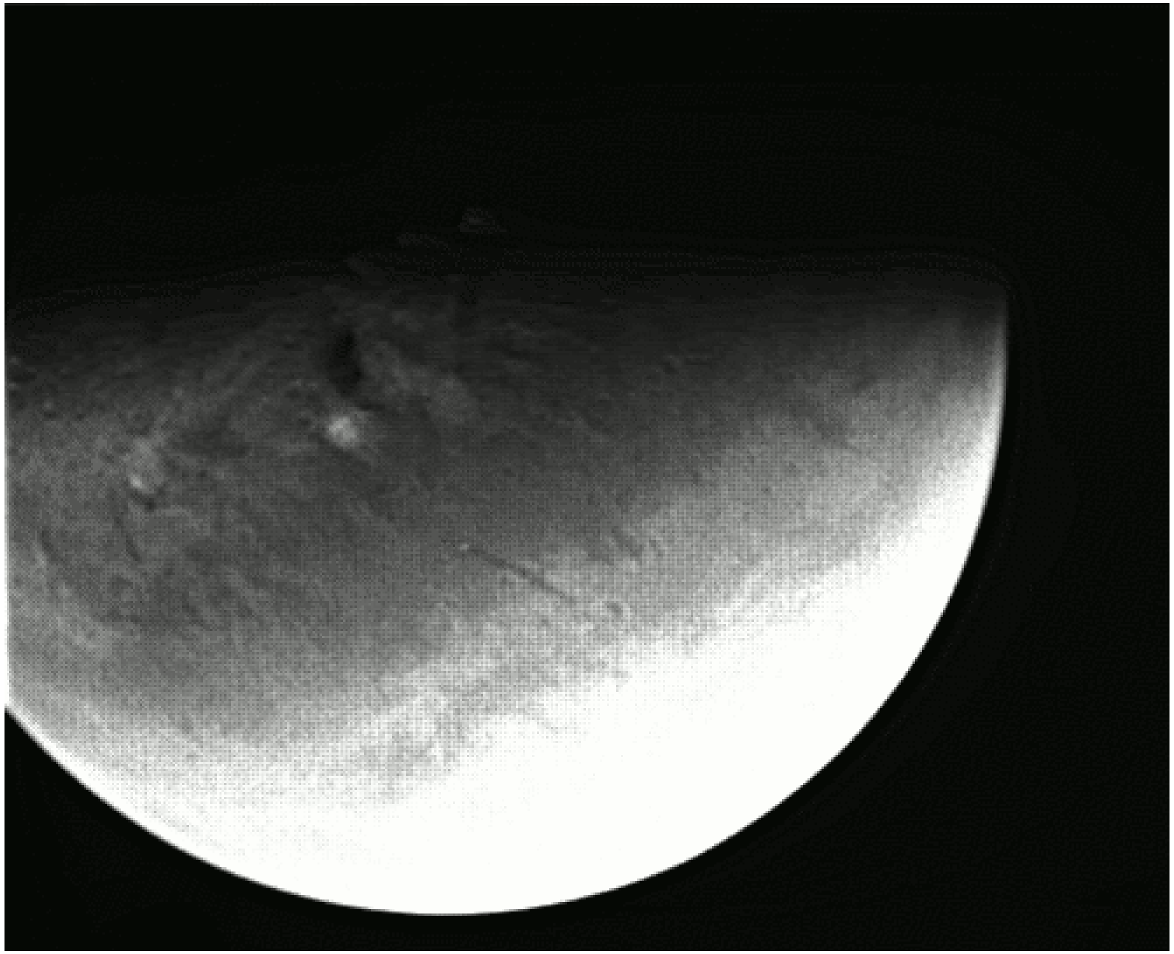


Detached aerosol layer simultaneously in the stellar occultation

Montmessin et al., Icarus 2006

Mars Cloud Videos

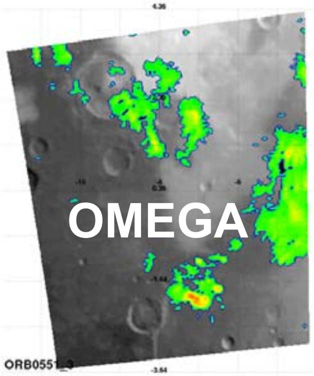


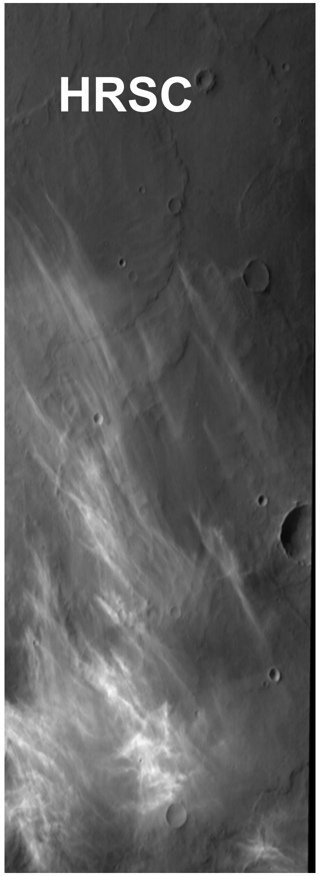


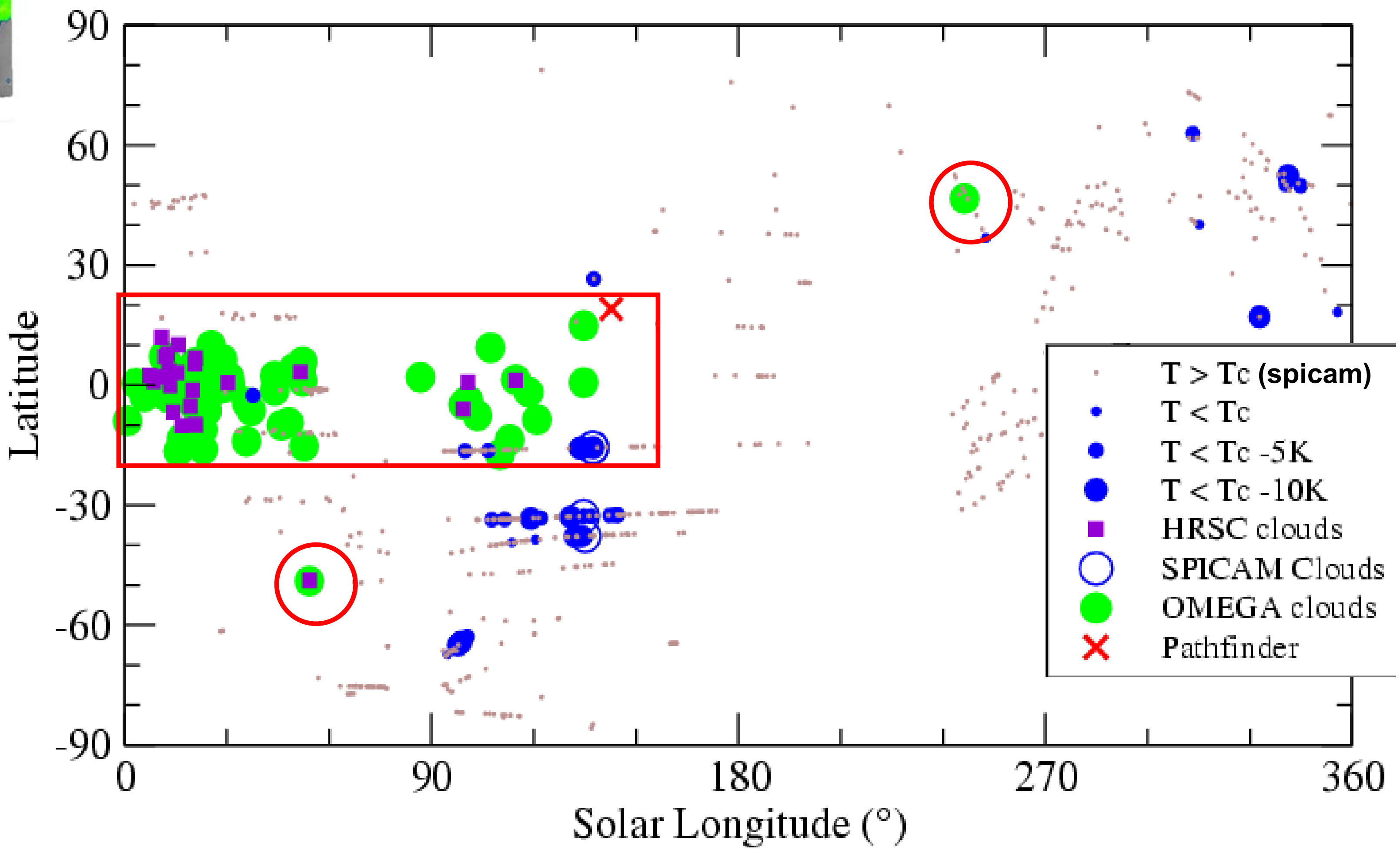
Acknowledgements: OMEGA team, HRSC team, Centre National d’Etudes Spatiales

Maattanen et al. 2010

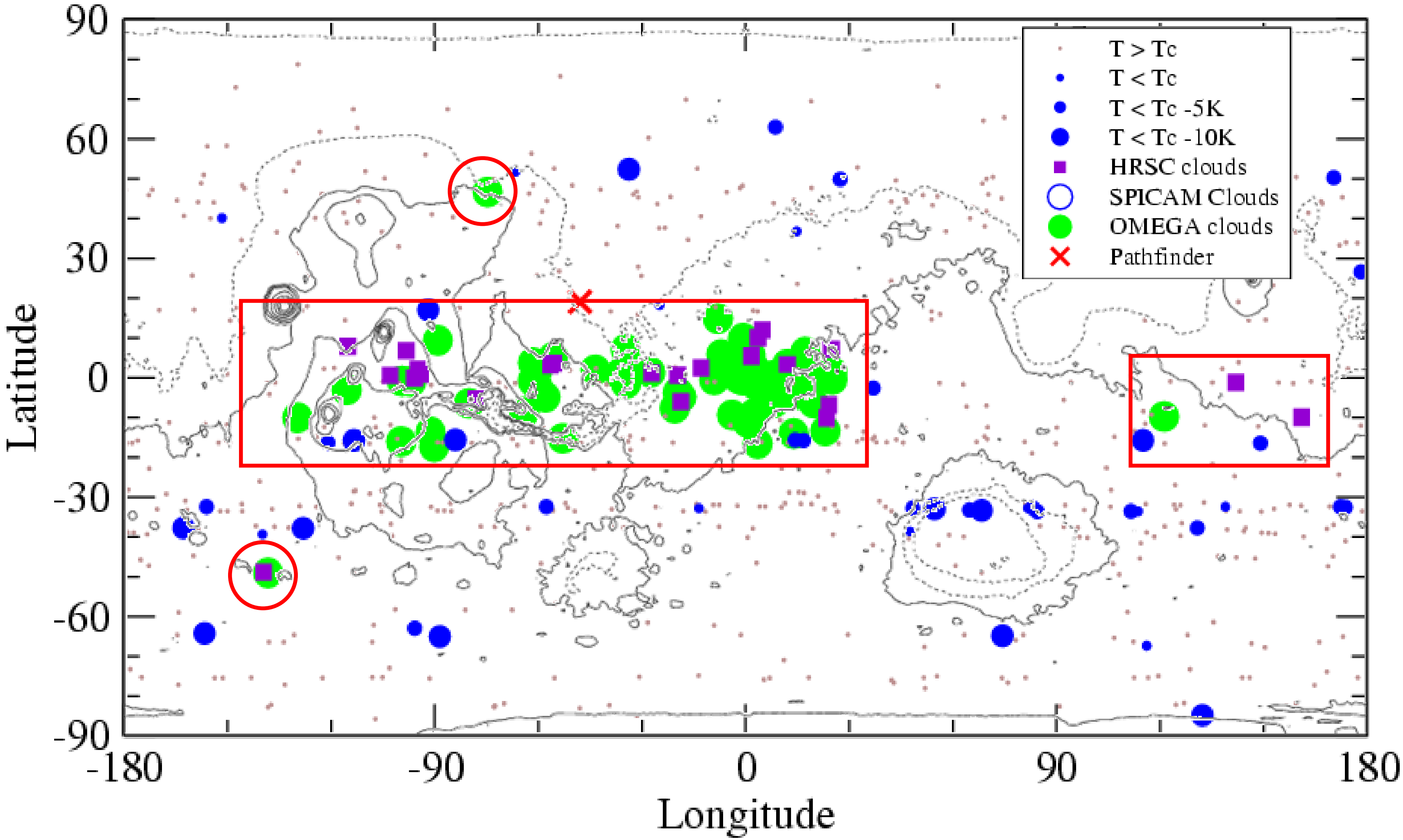
Seasonal evolution map







Global map



T > Tc
T < Tc
T < Tc -5K
T < Tc -10K
HRSC clouds
SPICAM Clouds
OMEGA clouds
Pathfinder
Latitude
Longitude
90
60
30
0
-30
-60
-90
-180
-90
0
90
180

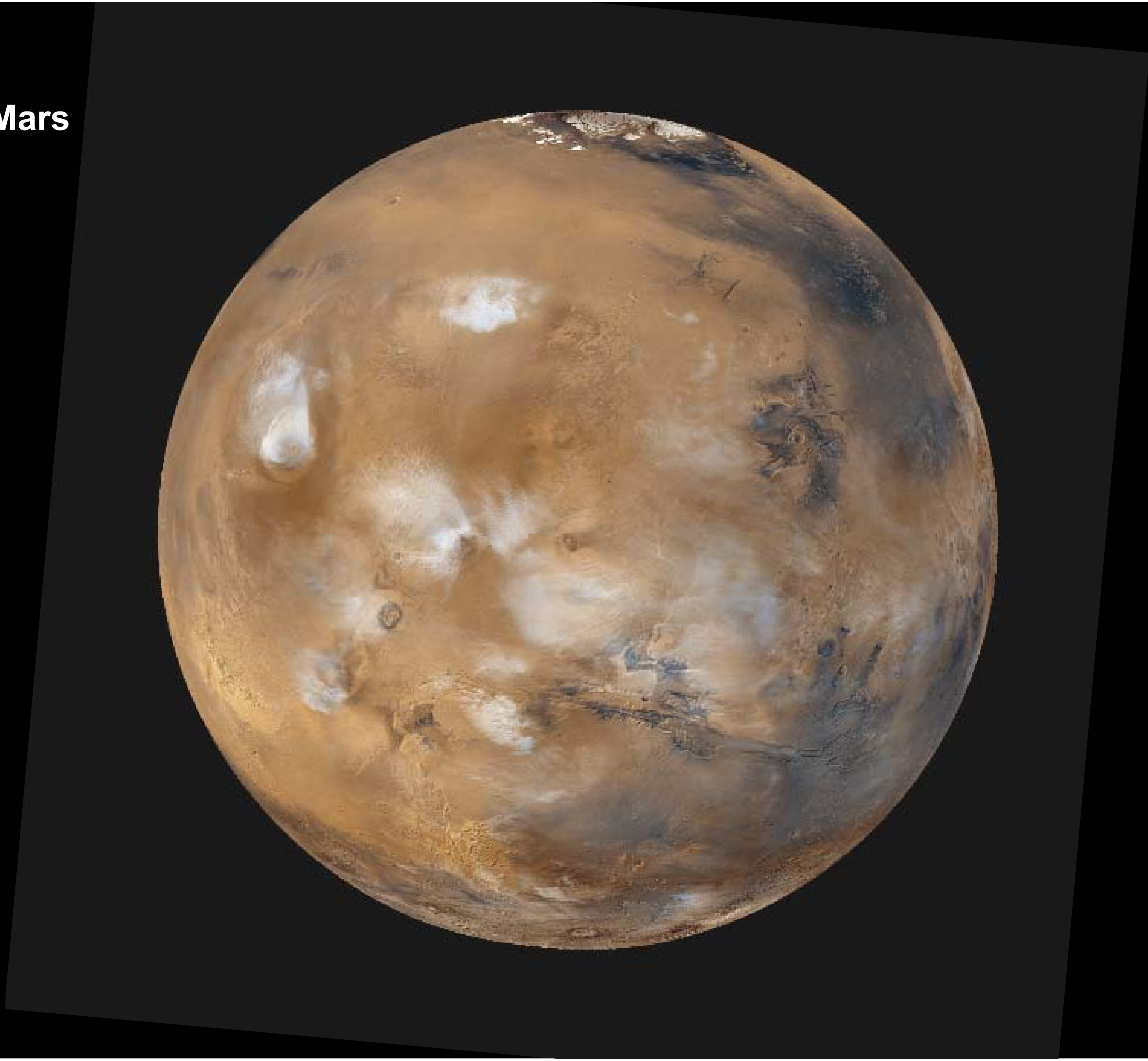
A Mars Climate tutorial:

Part3 : the Mars water cycle and its variations

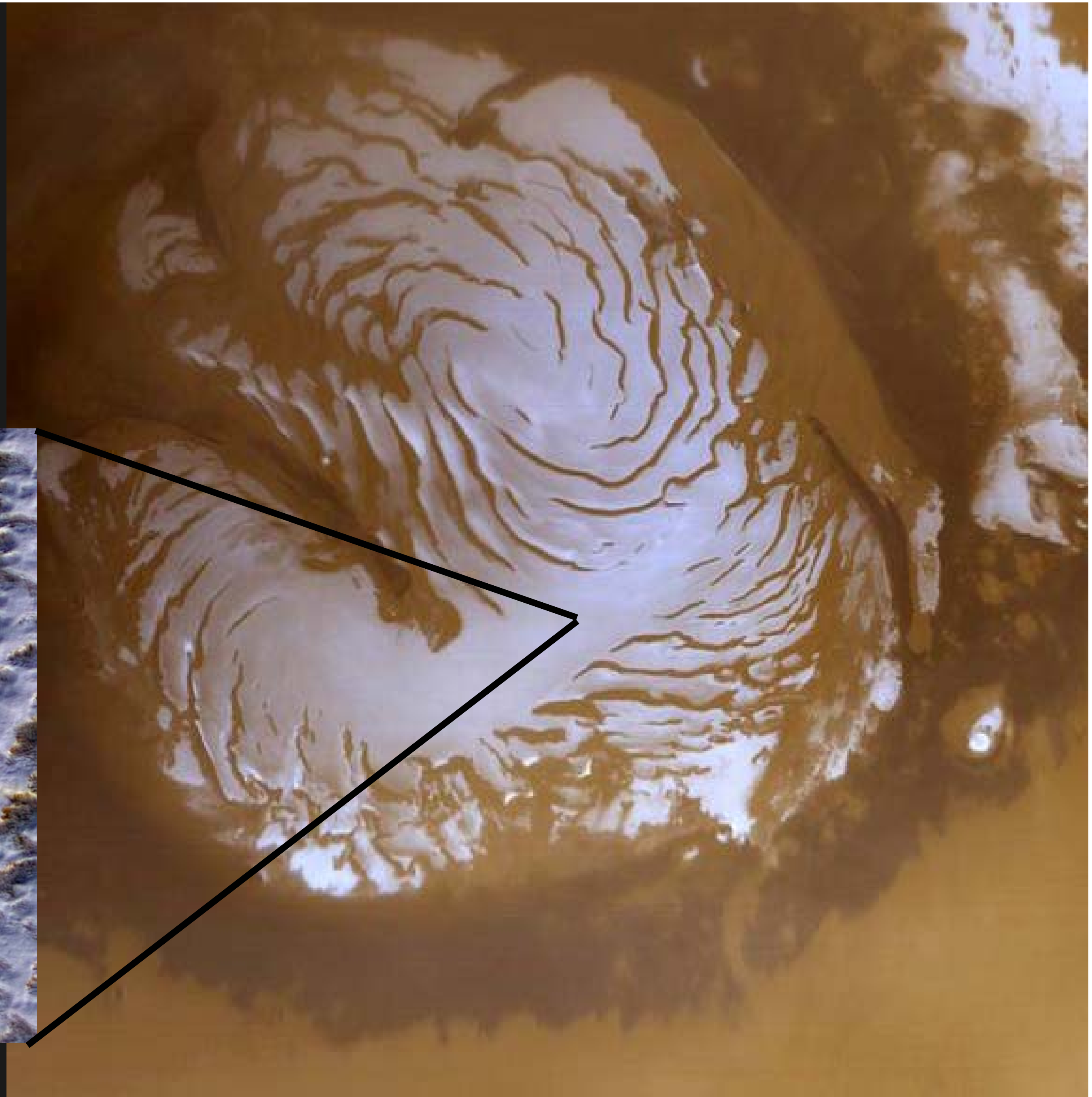
François Forget

Laboratoire de Météorologie Dynamique, IPSL,
Paris, France

Water on Mars



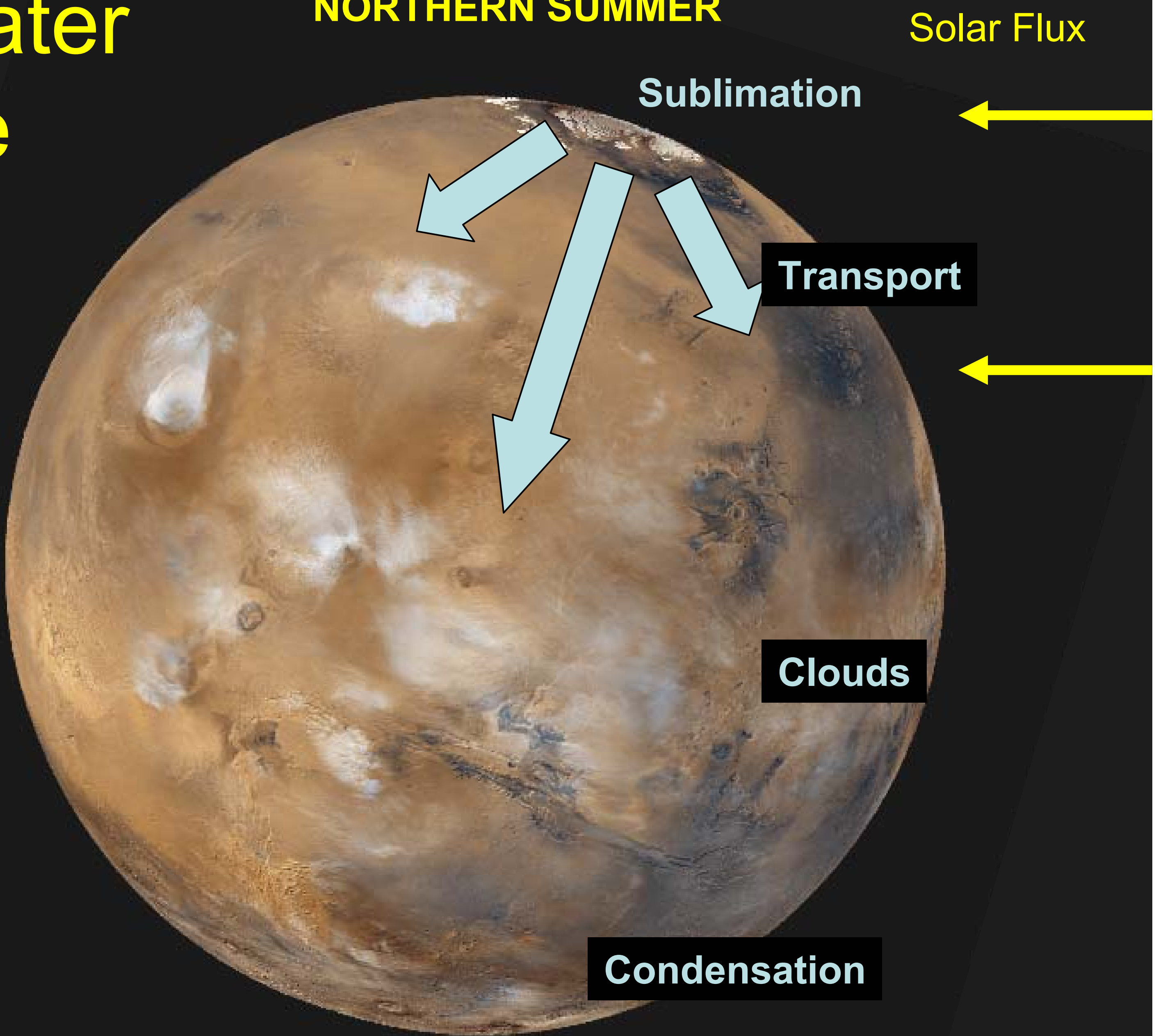
Around North Pole : a relatively fresh and pure water ice layer interacting with the atmosphere (diameter : 1000 km)



MRO Hirise

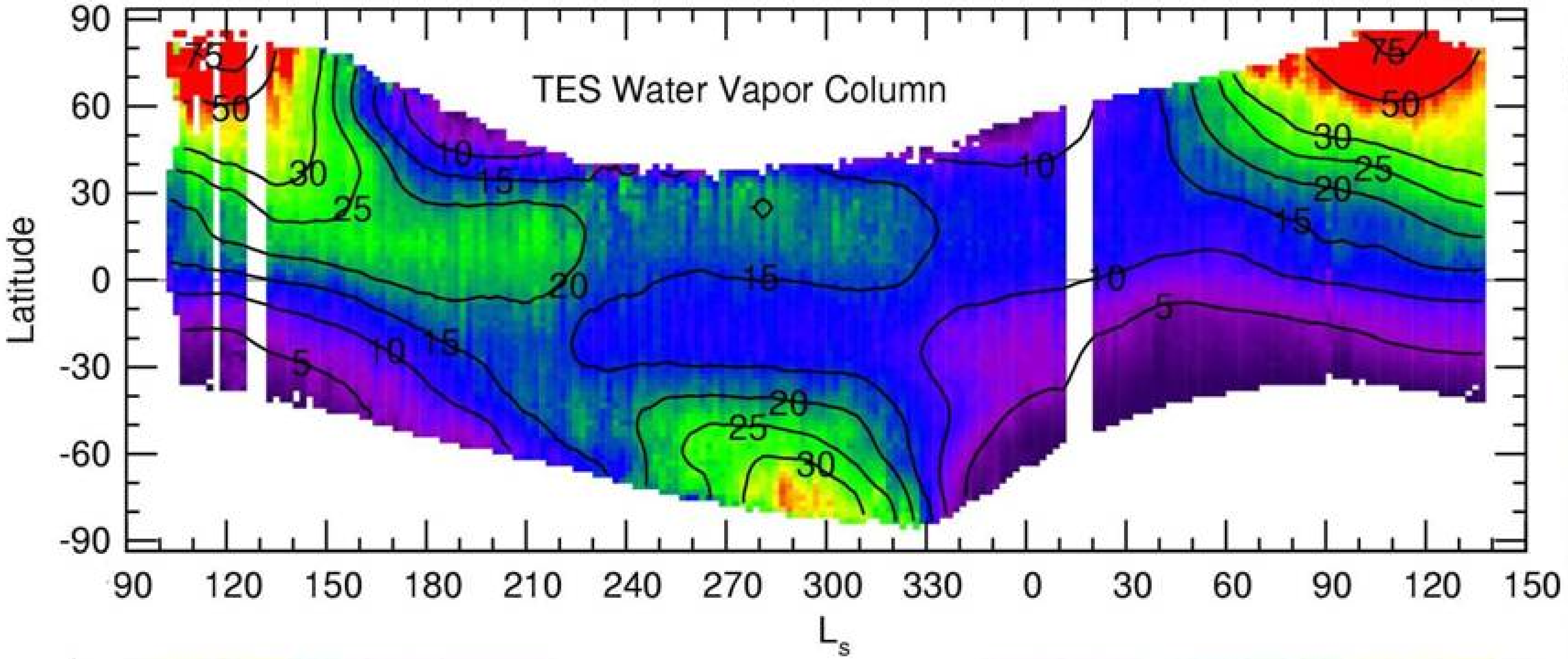
Mars water cycle

NORTHERN SUMMER



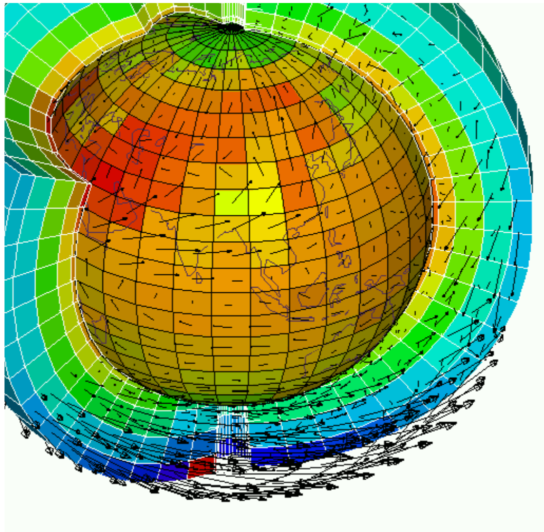
Mars water cycle

Atmospheric column of water vapor (précipitable microns)
(TES NASA Mars Global Surveyor data)

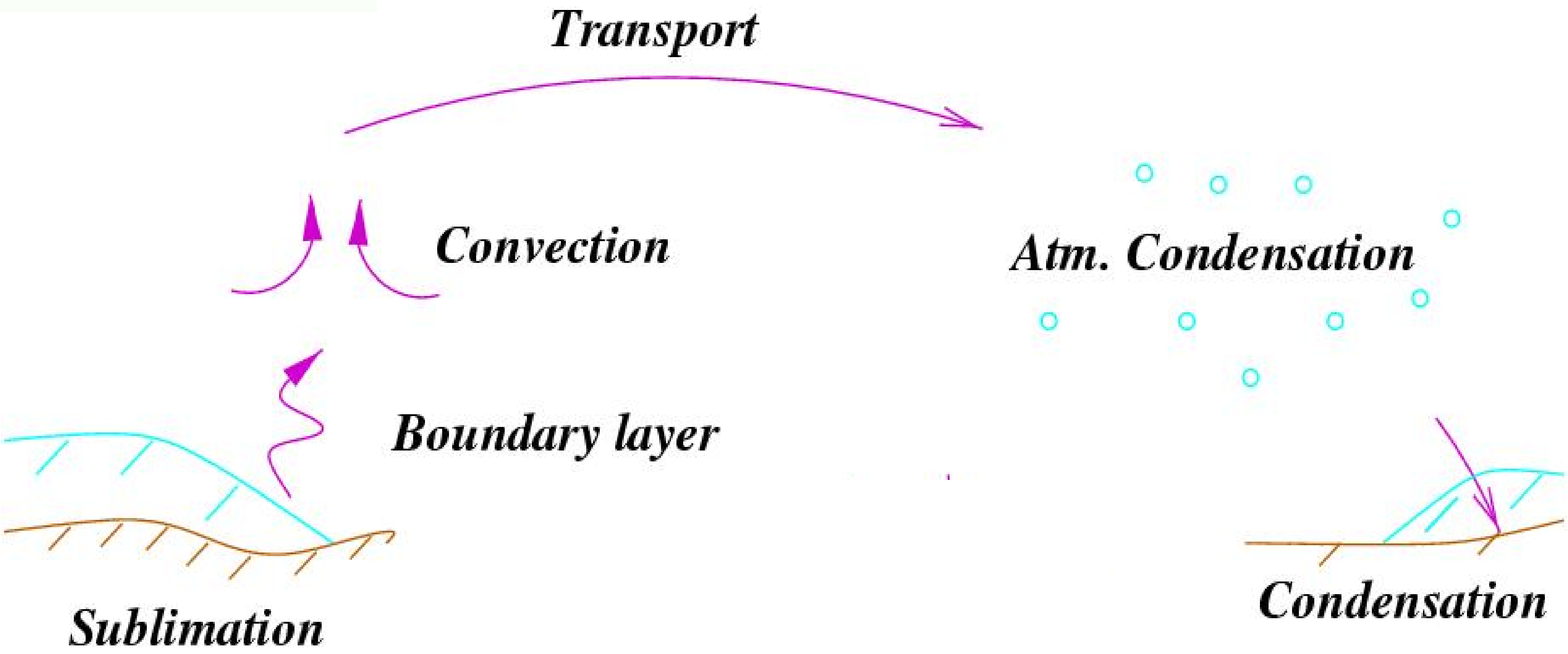


N Summer Fall Winter Spring Summer

Other observations from SPICAM, Omega, PFS, CRISM

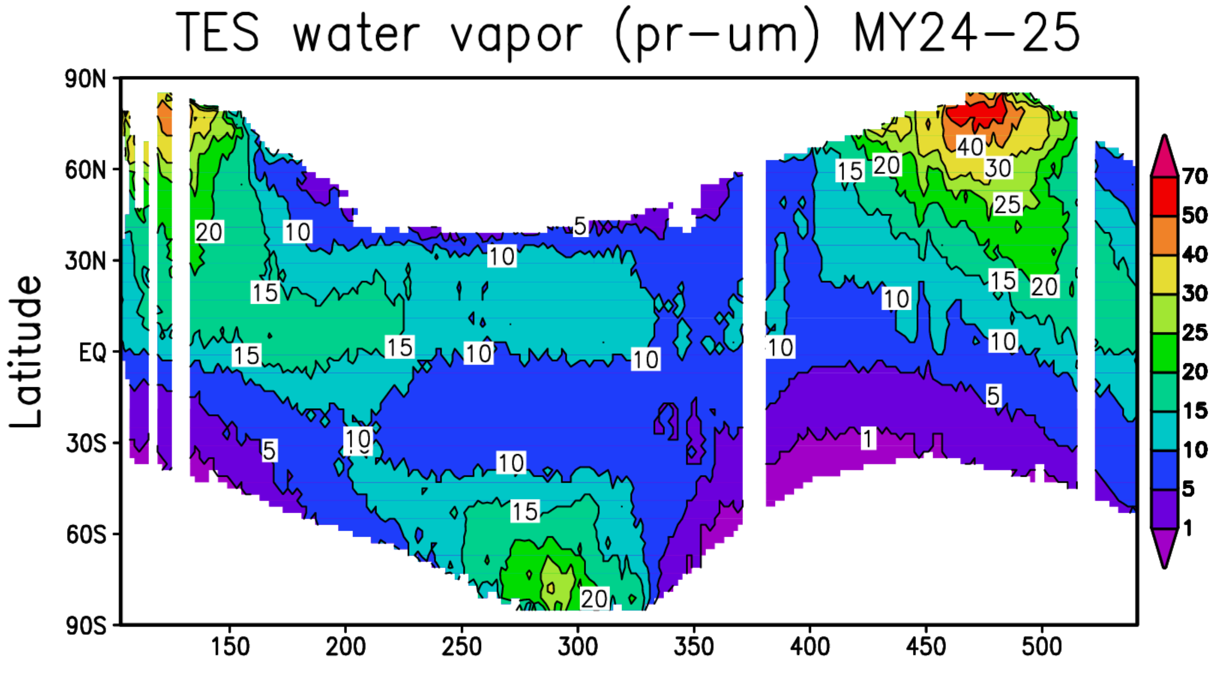


Modelling the water cycle with General Circulation Models

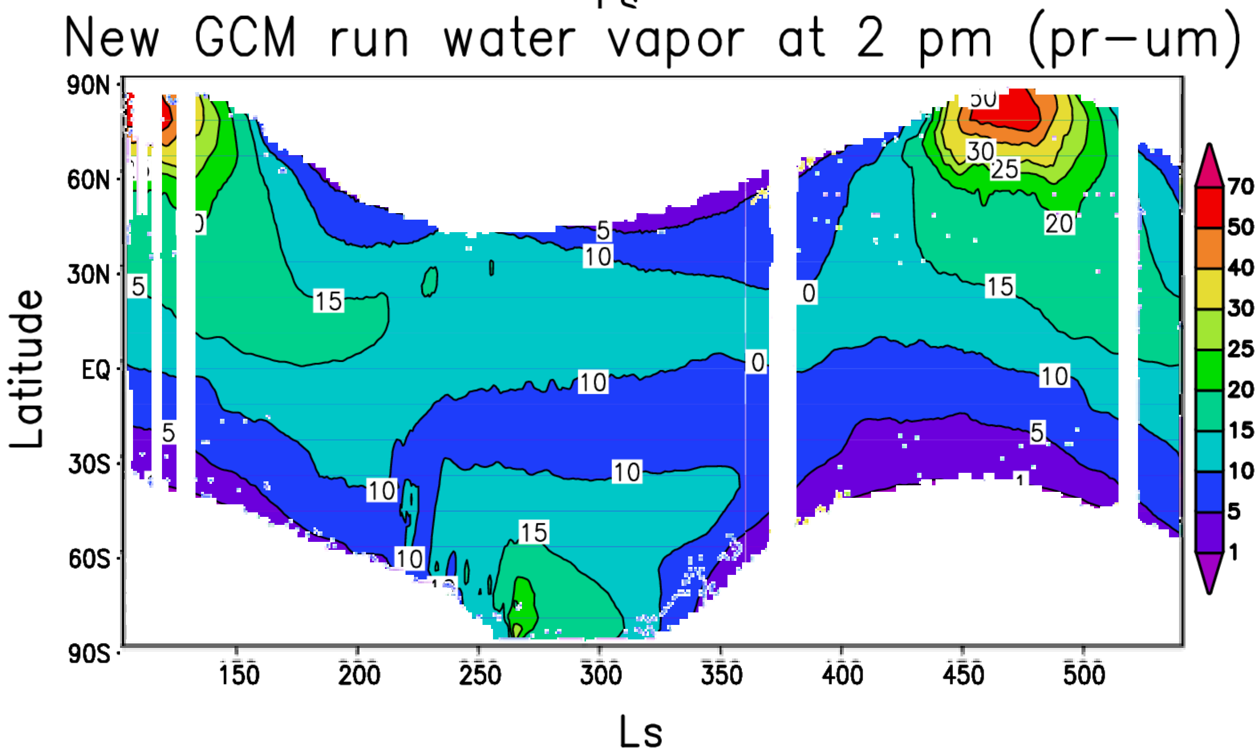


SEASONAL WATER CYCLE

OBSERVATION



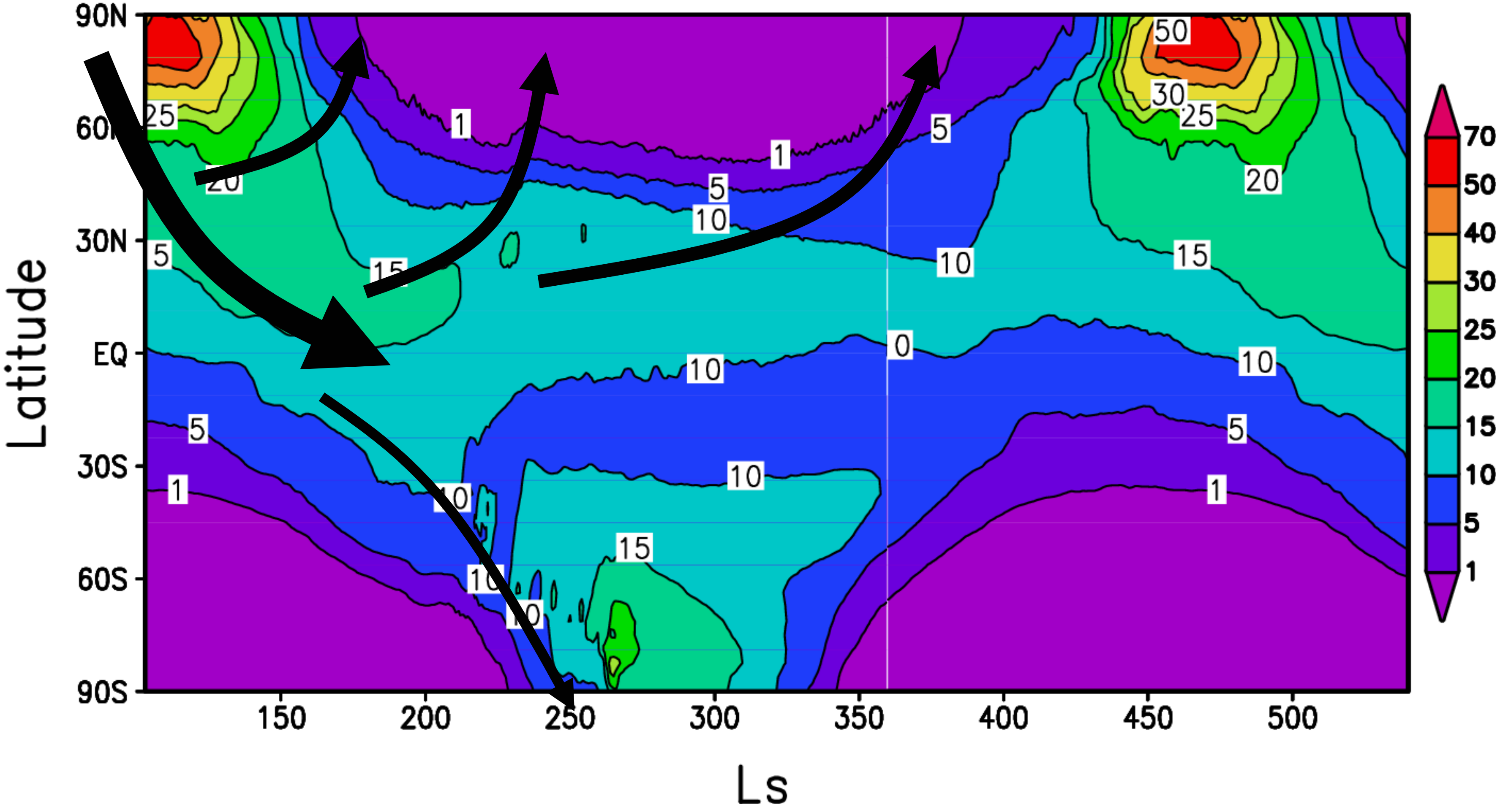
MODEL



A closed seasonal cycle : most water released in summer goes back to North polar cap

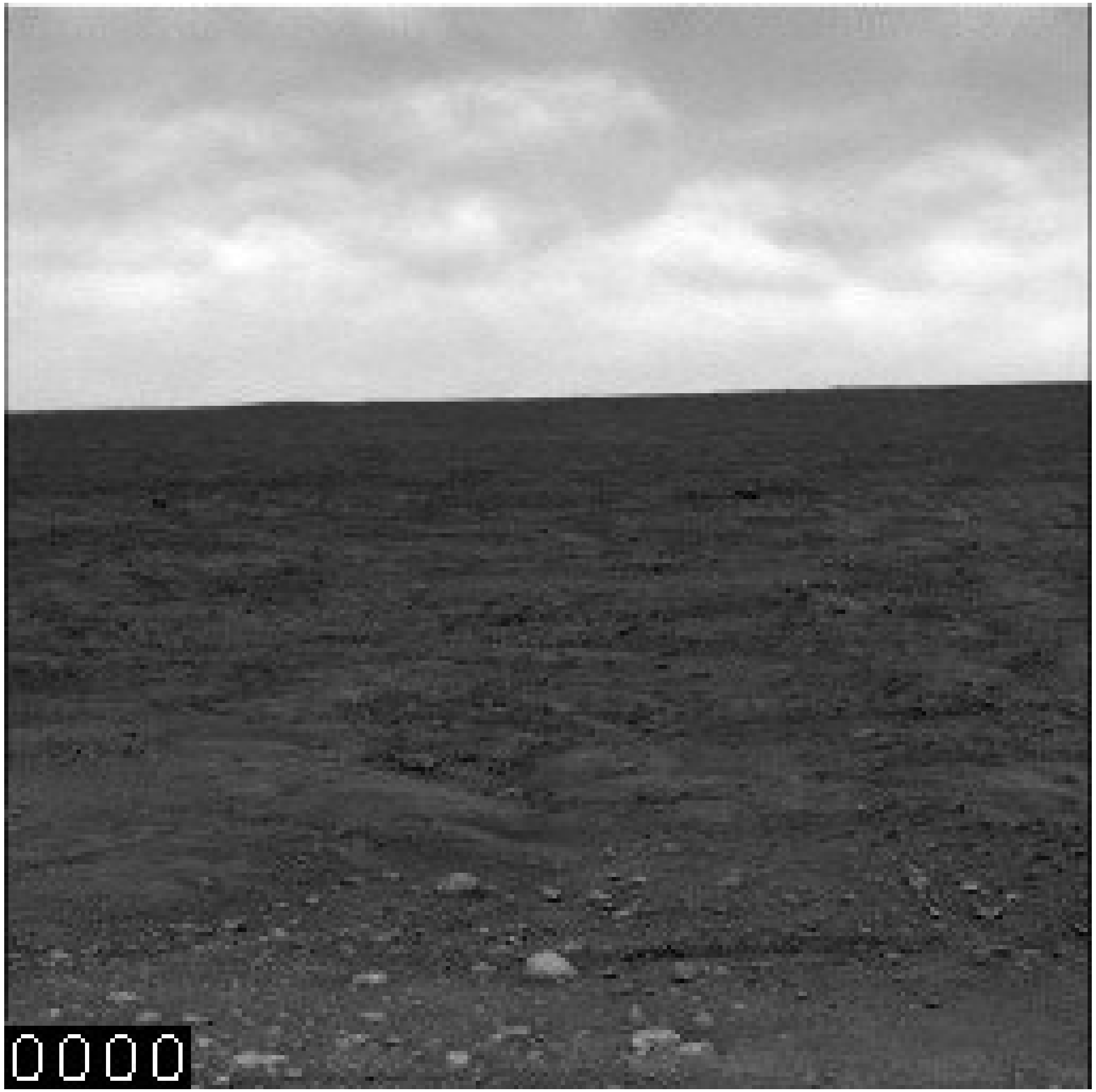
(the remnant get trap in the perrenial CO2 ice southern cap)

(see e.g. *Richardson and WIlson. 2002, Montmessin et al. 2004*)

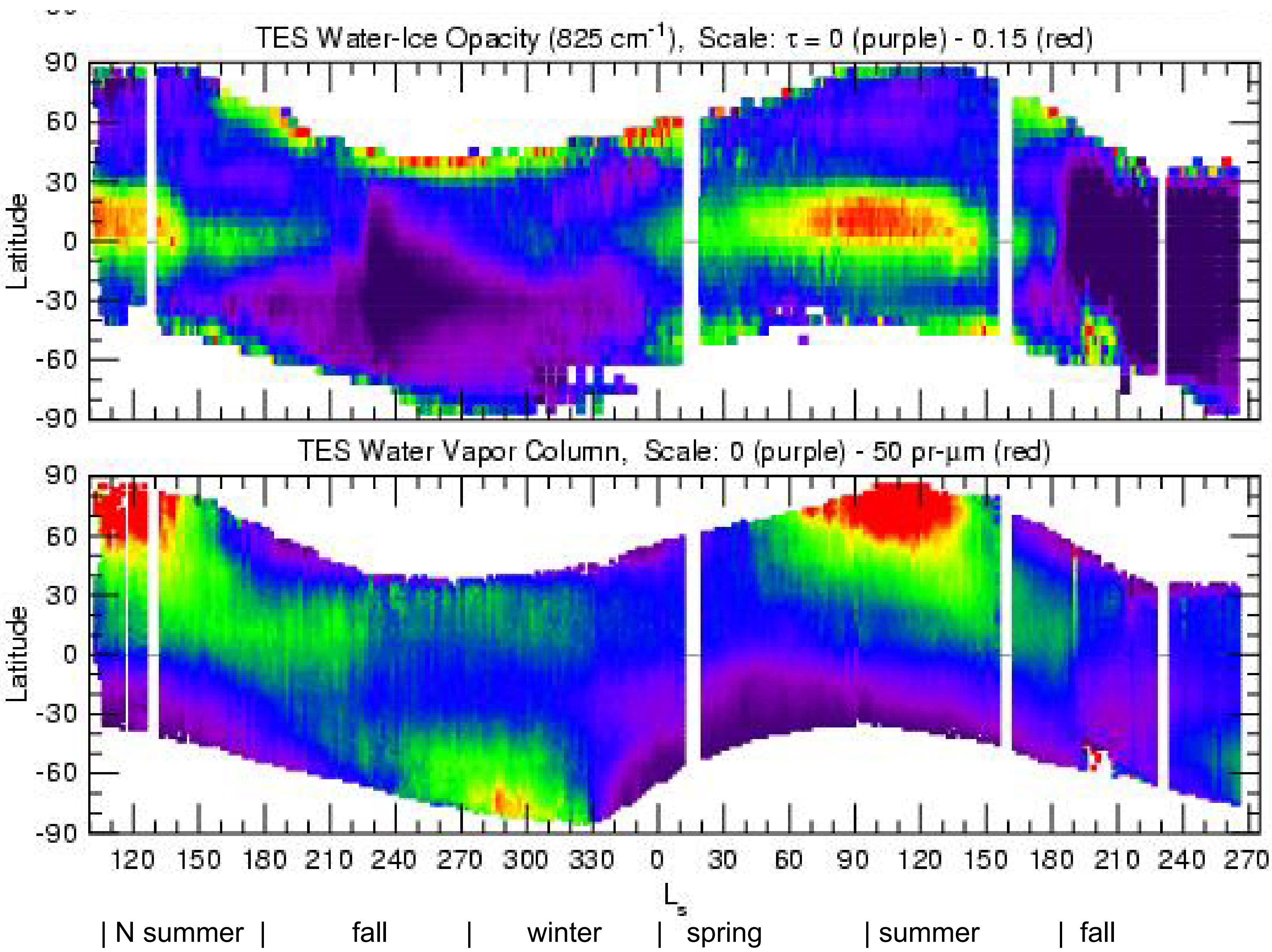


Formation of water ice clouds

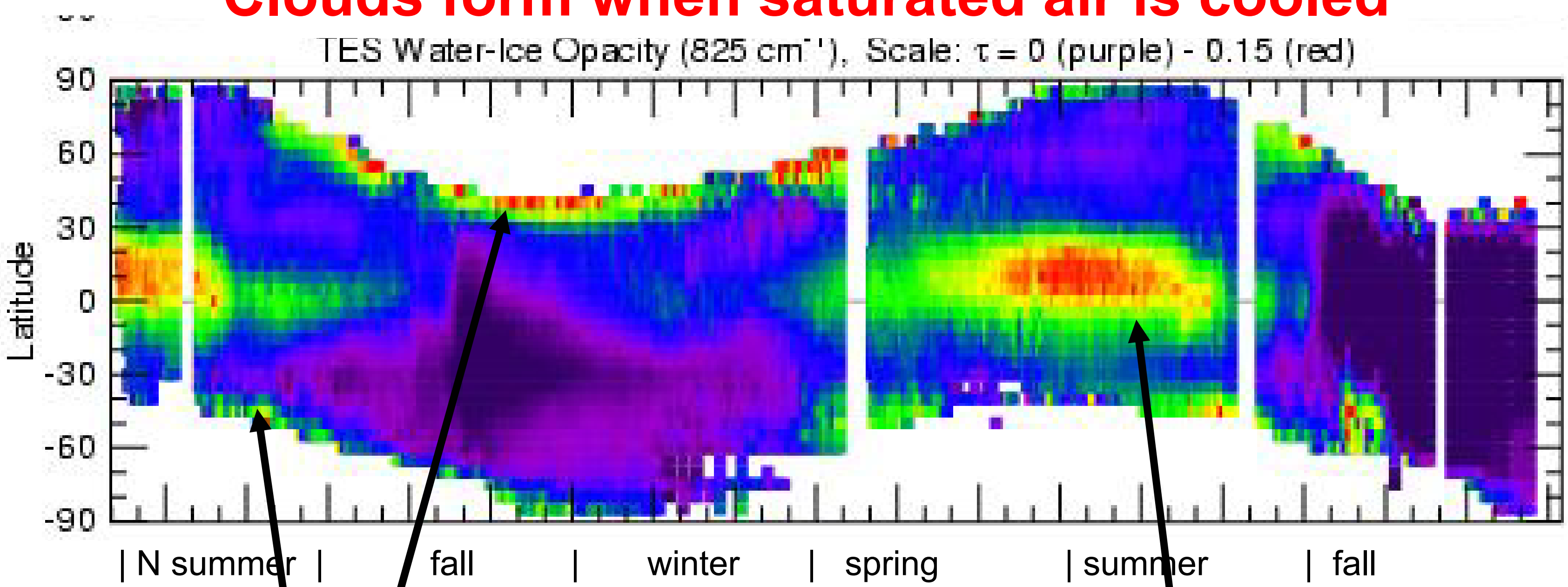
Image from Phoenix SSI camera



Remote sensing by TES (Mike Smith et al. , GSFC)



Clouds form when saturated air is cooled



- The "polar hood"
  - Warm air meet cold polar air
  - *Ice particle radii ~ 2-3 microns*

- The "aphelion cloud belt"
  - Air cooled in the ascending branch of the Hadley cell.
  - Locally air cooled on large volcanoes
  - *Ice particle radius ~ 5-8* microns (*Clancy and Wolff, TES data)*

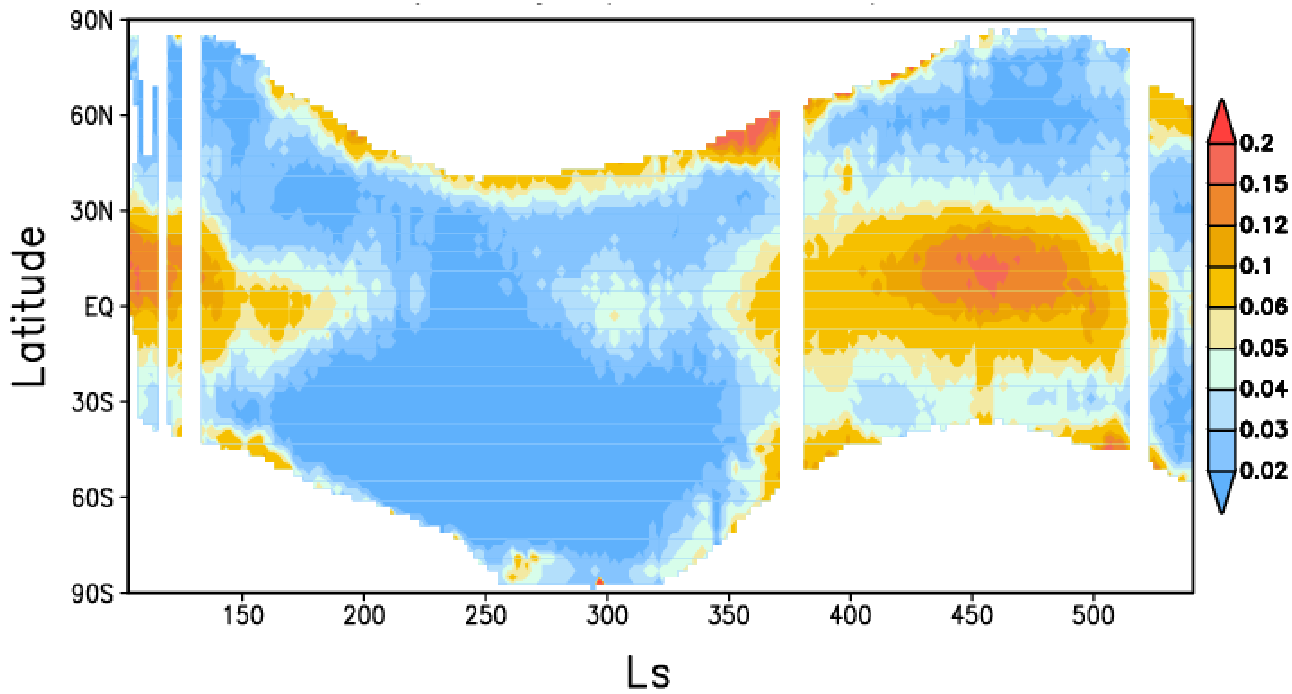
GCM SIMULATION of Mars water cycle: 2) water clouds

TES ice absorption opacity

2pm

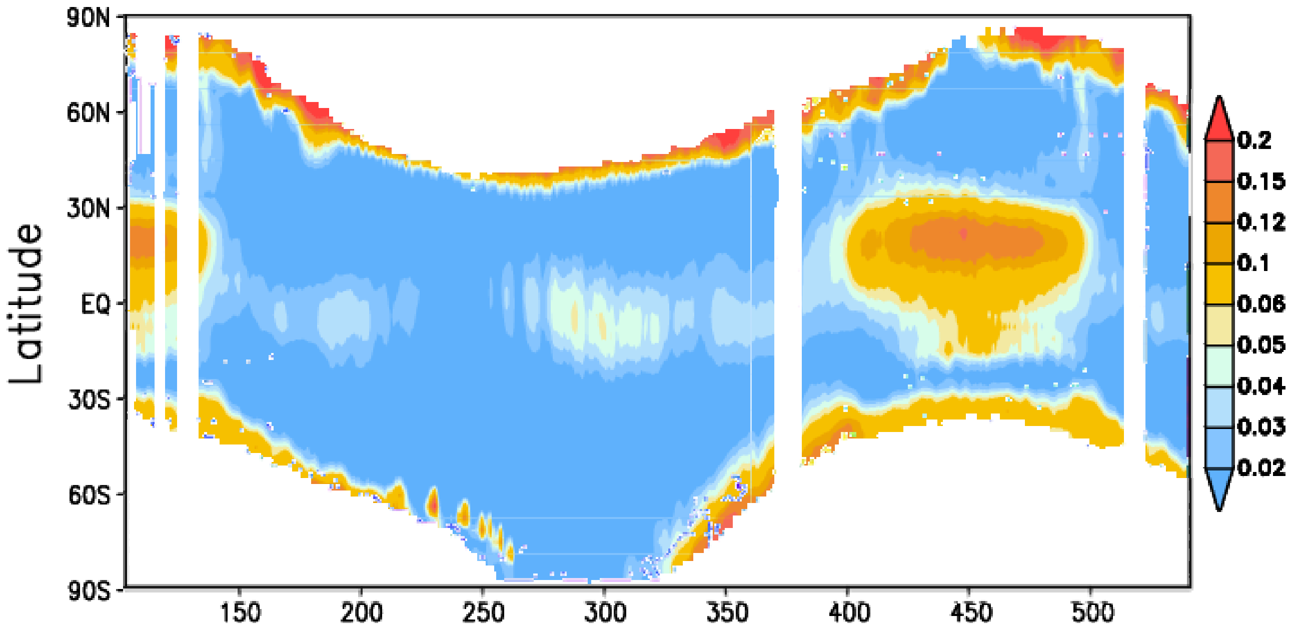
(825 cm-1)

MY24-25

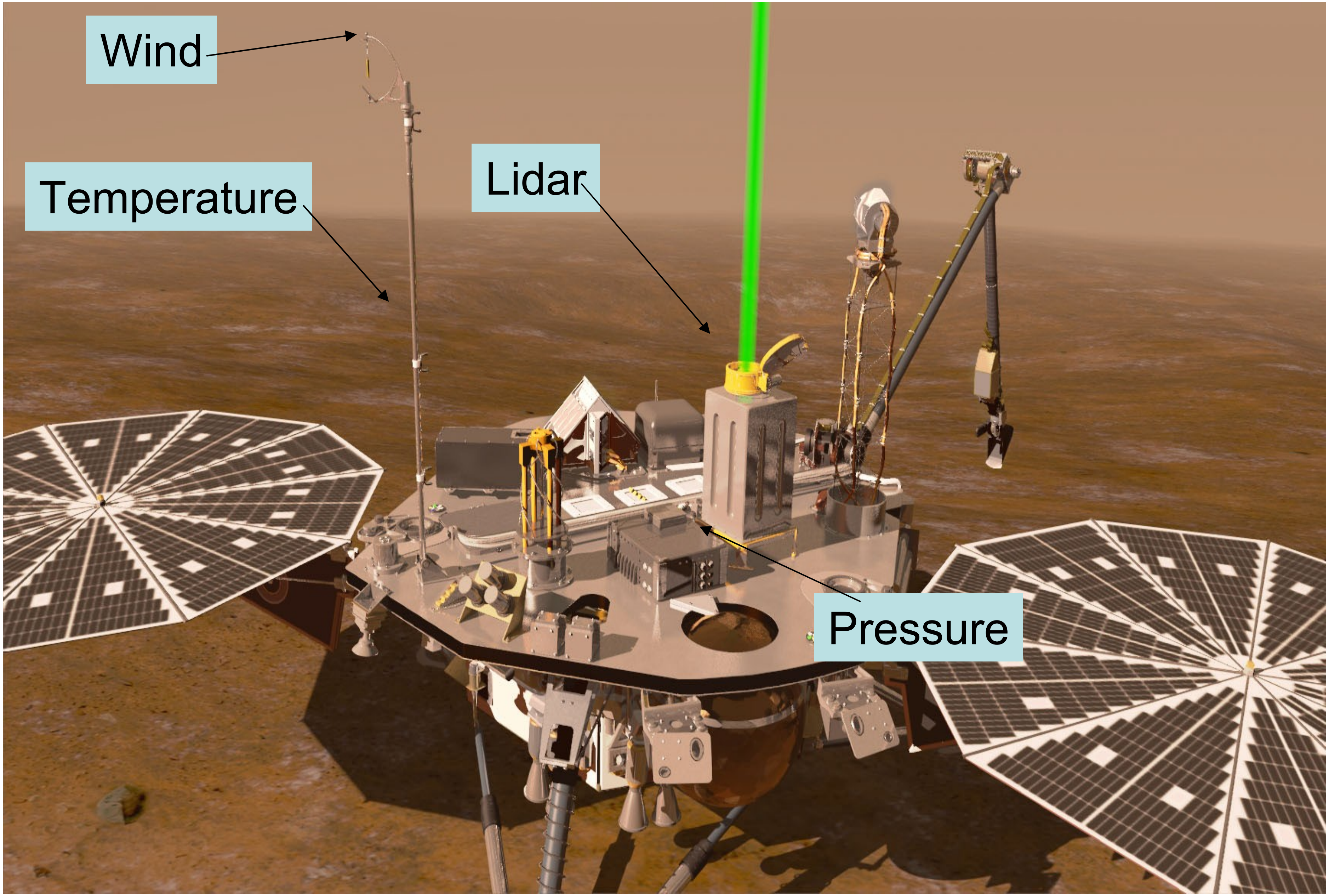


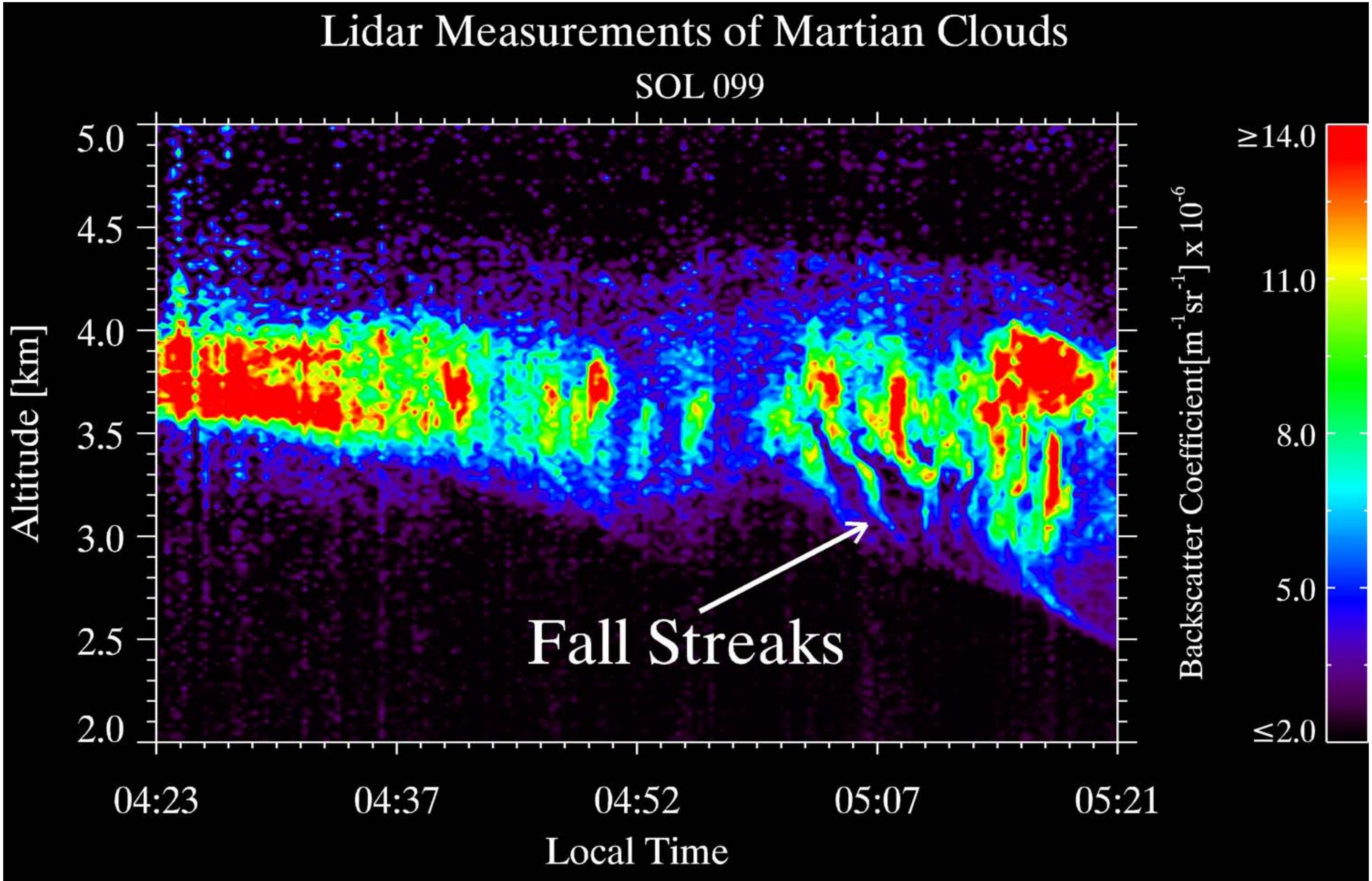
LMD GCM ice absorption opacity

2pm



Phoenix Observations



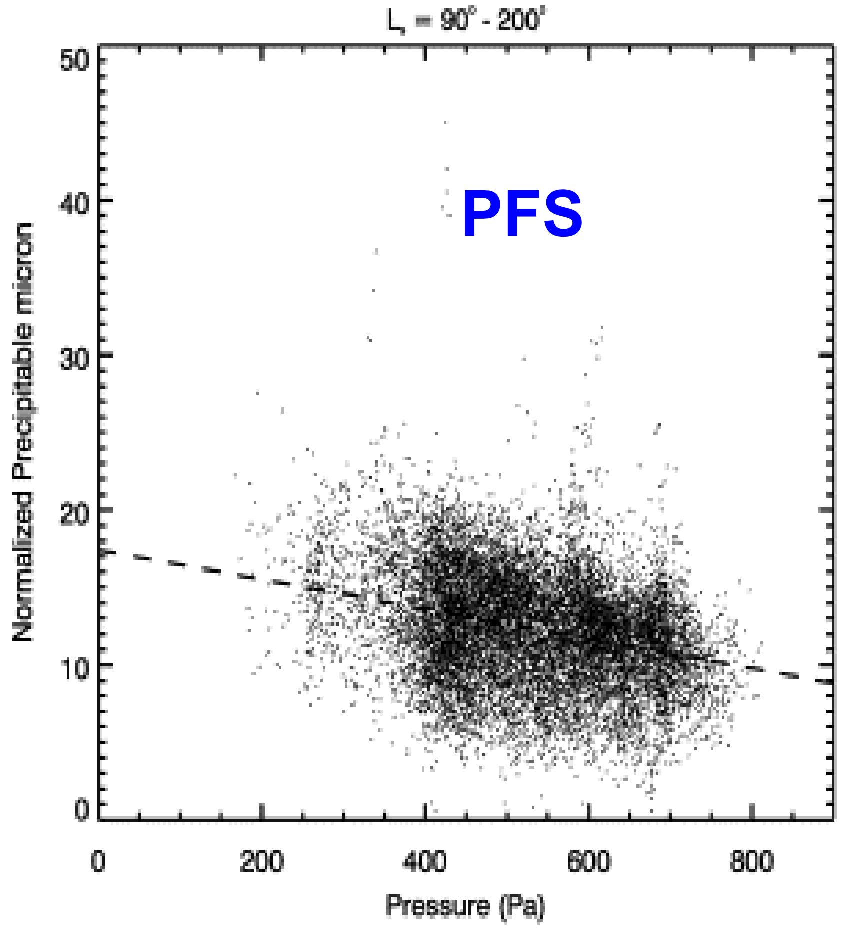


Whiteway et al. 2009

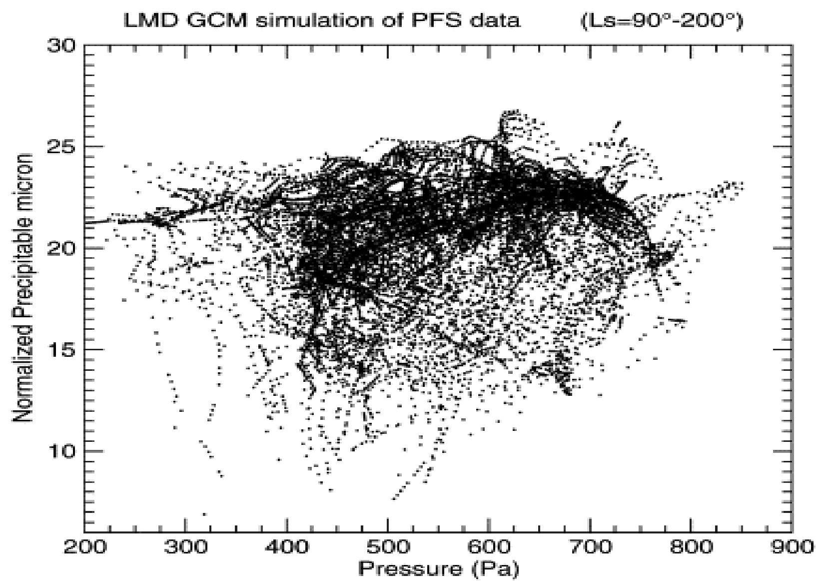
GCM compared to PFS data

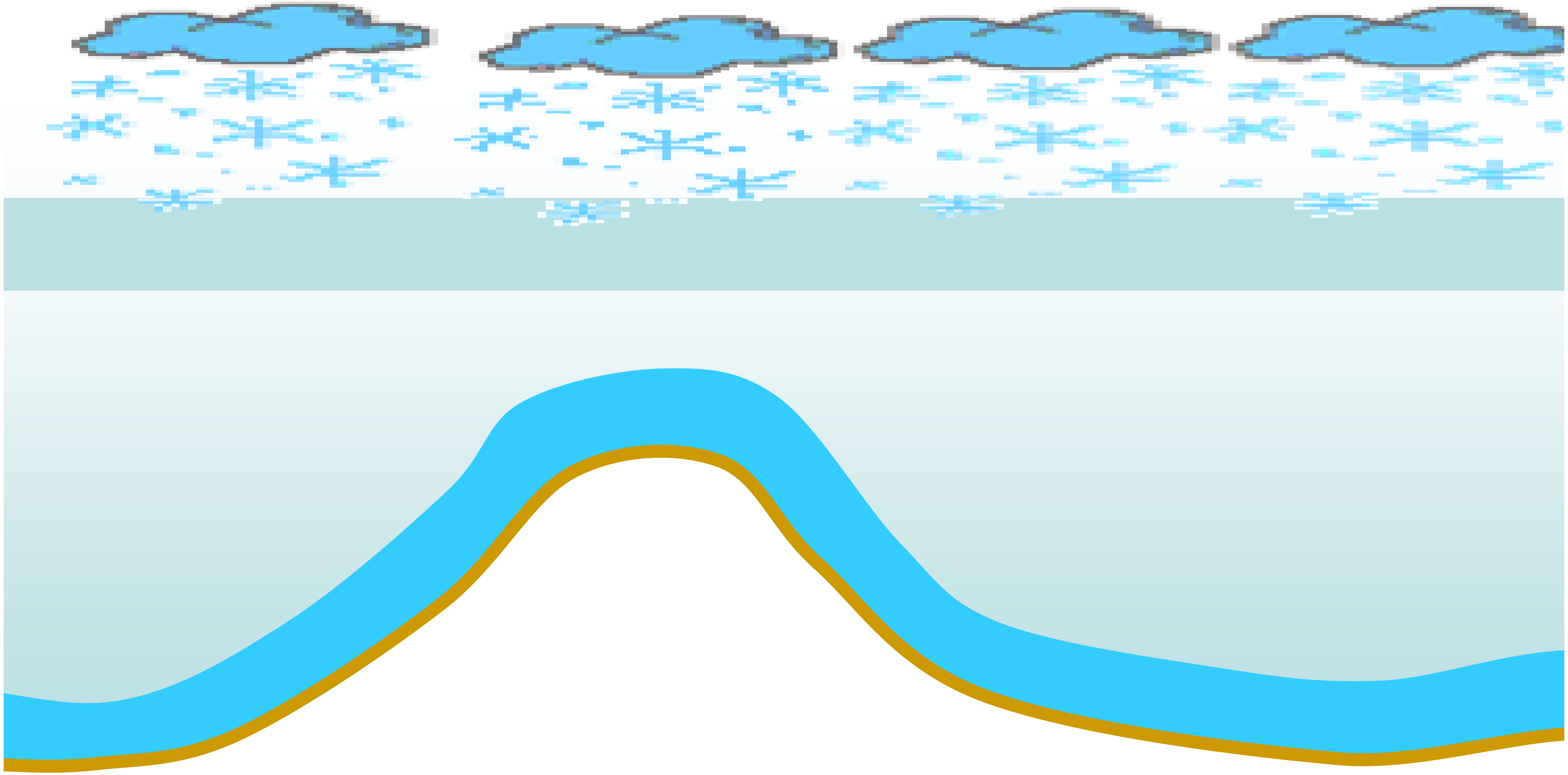
Distribution of water vapor “mean mixing ratio” (normalized column) in N. summer

(*Fouchet et al. 2007*)



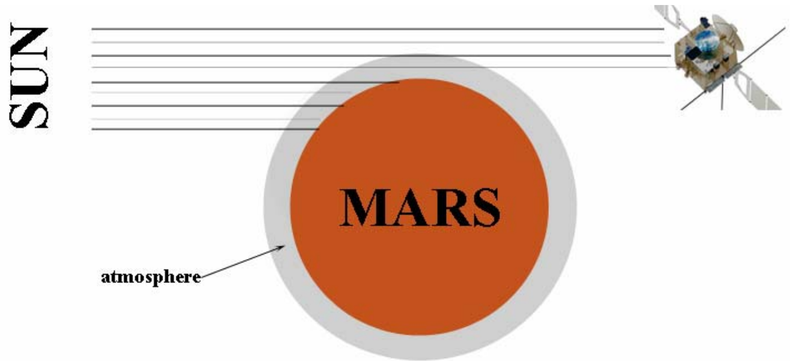
GCM (old H2O)

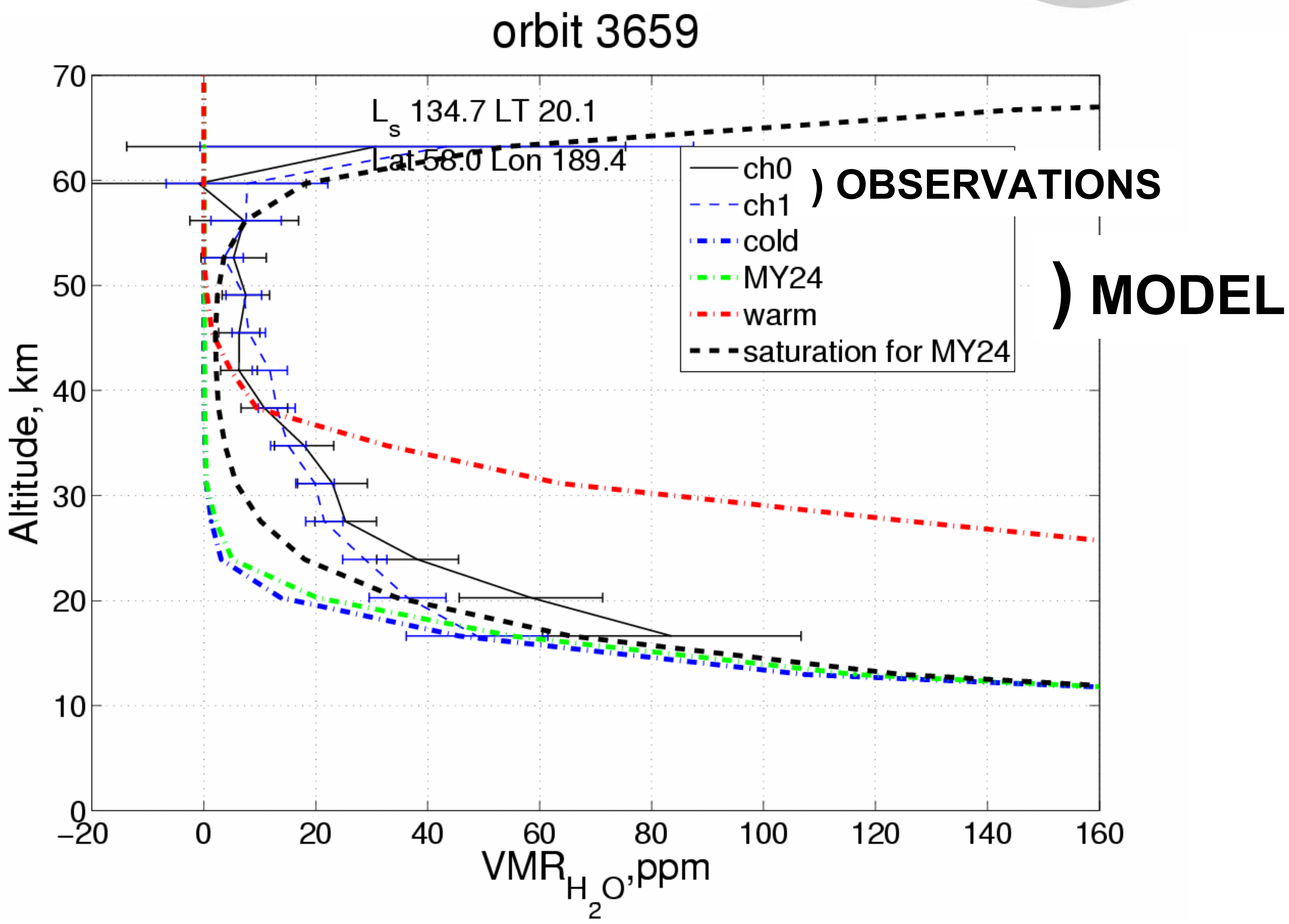




Vertical profile of H_2O measured by stellar occultation with SPICAM

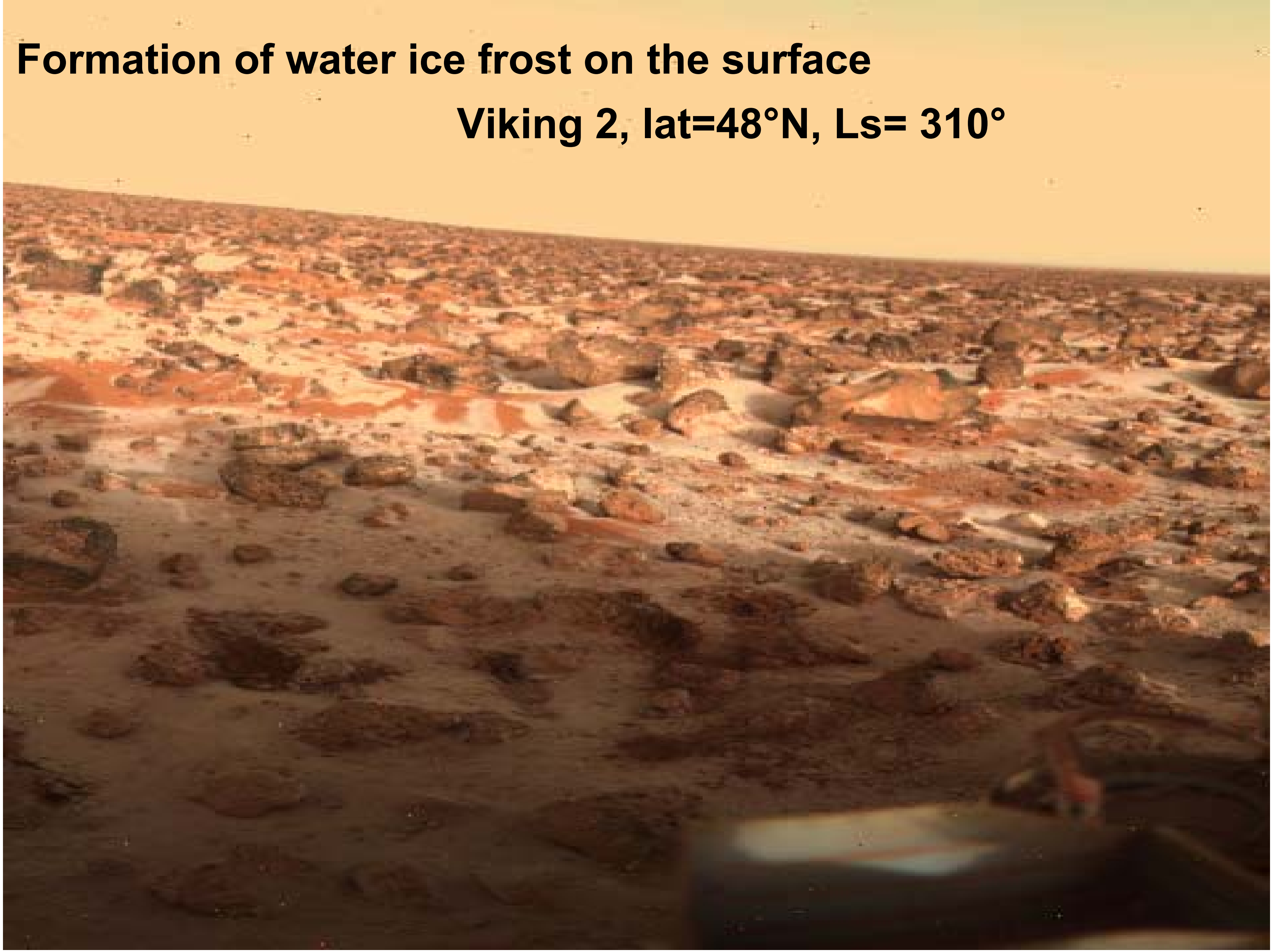
(Fedorova et al. 2008)





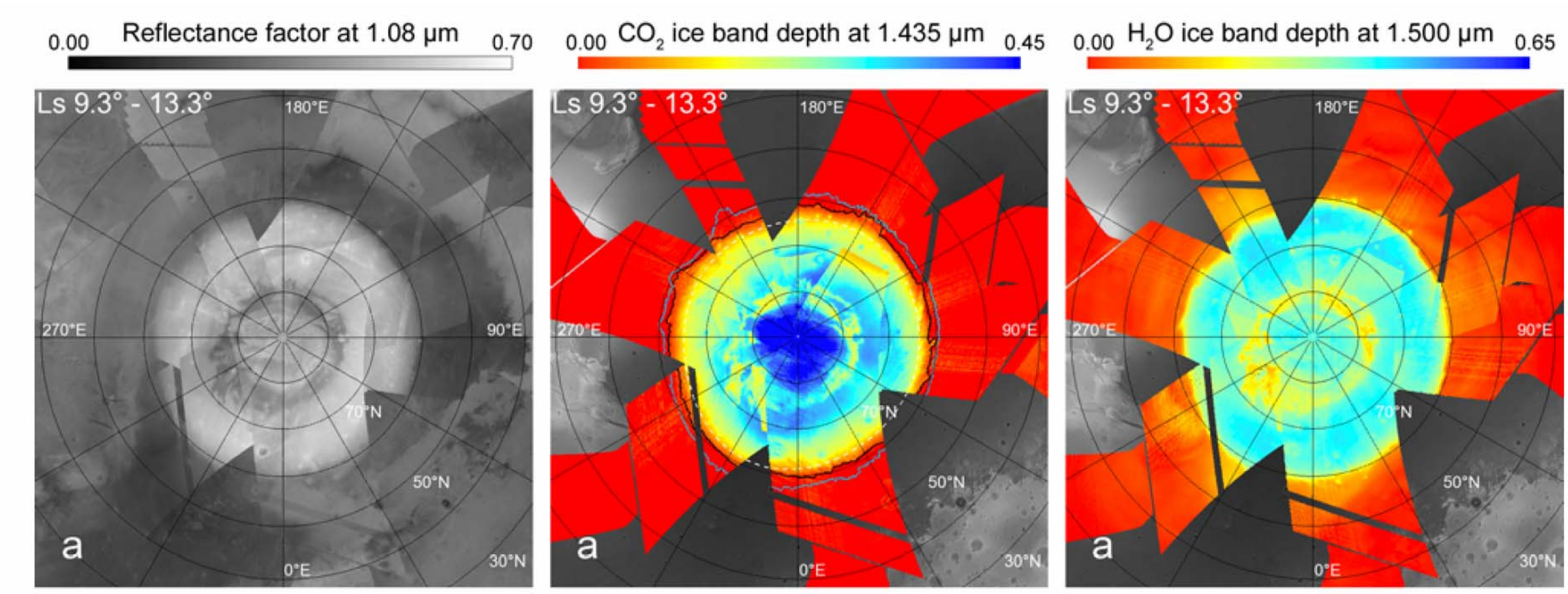
Formation of water ice frost on the surface

Viking 2, lat=48°N, Ls= 310°



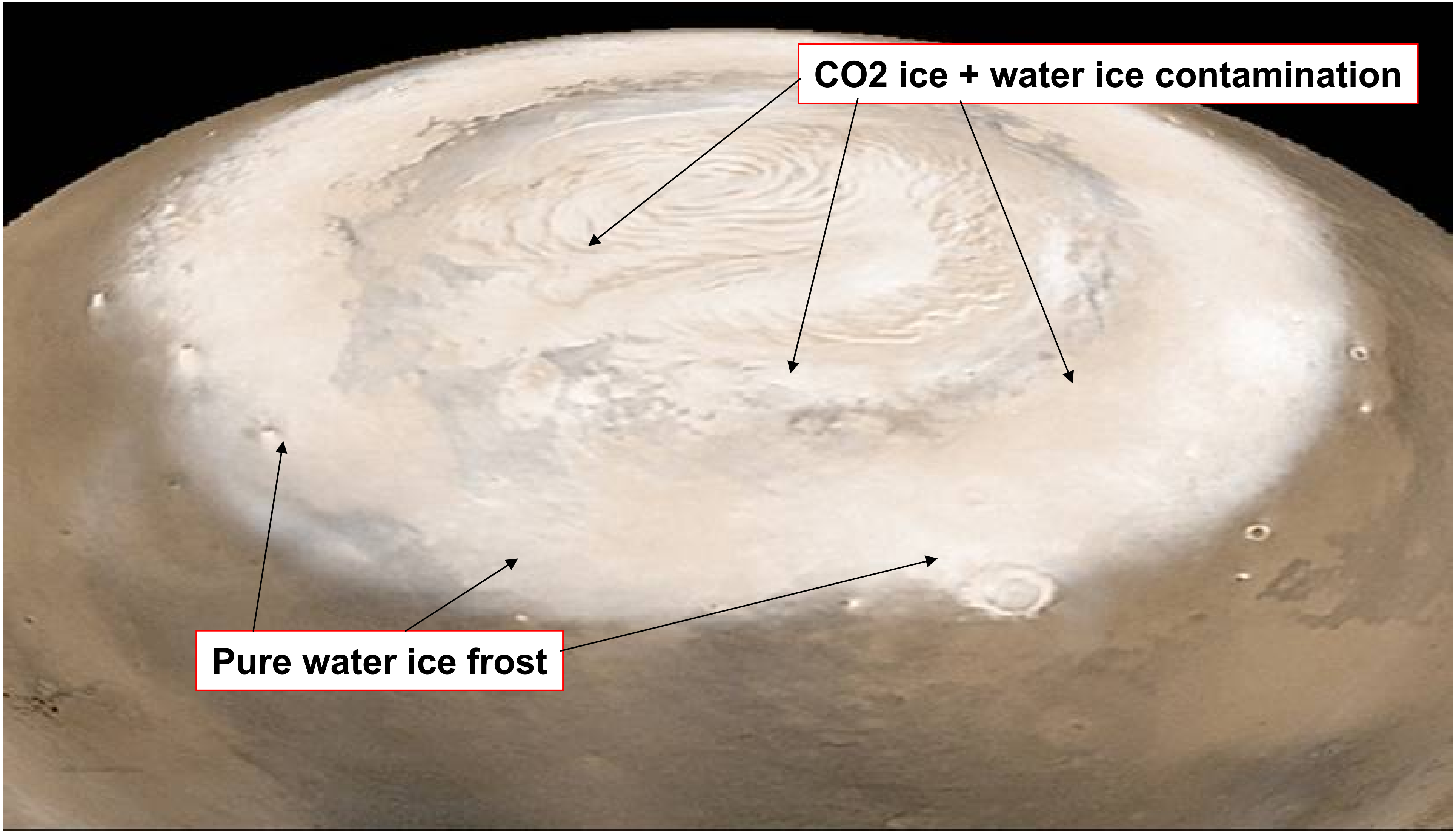
Water Surface frost within and surrounding the CO2 ice seasonal polar caps : monitoring with OMEGA

(Figure from Appere et al. 2010 ; See also Langevin et al. 2007)



Seasonal CO2 ice cap in spring

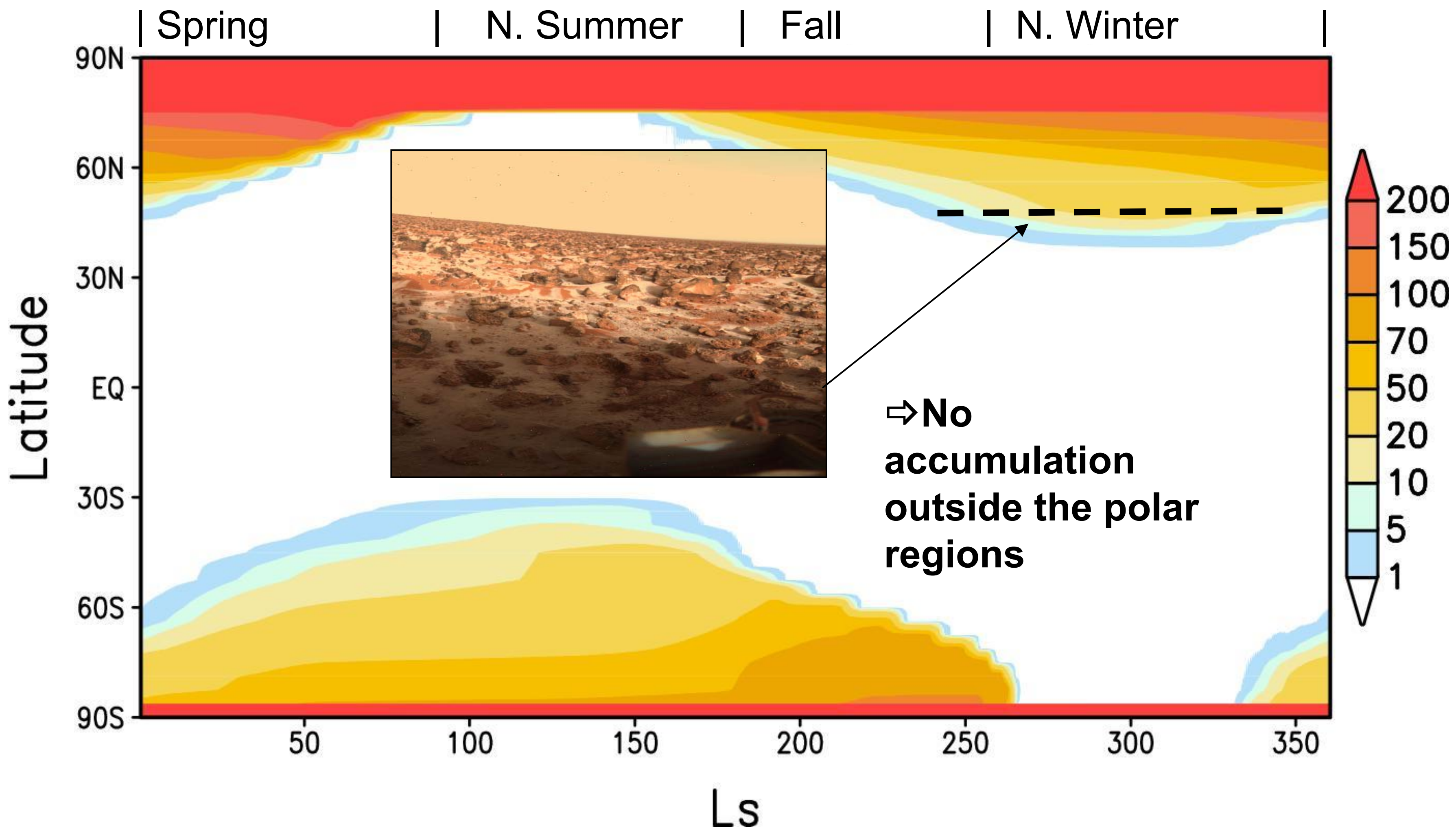
(mosaic of the northern polar cap)



Surface frost (μm)

New CRISM and OMEGA Observations

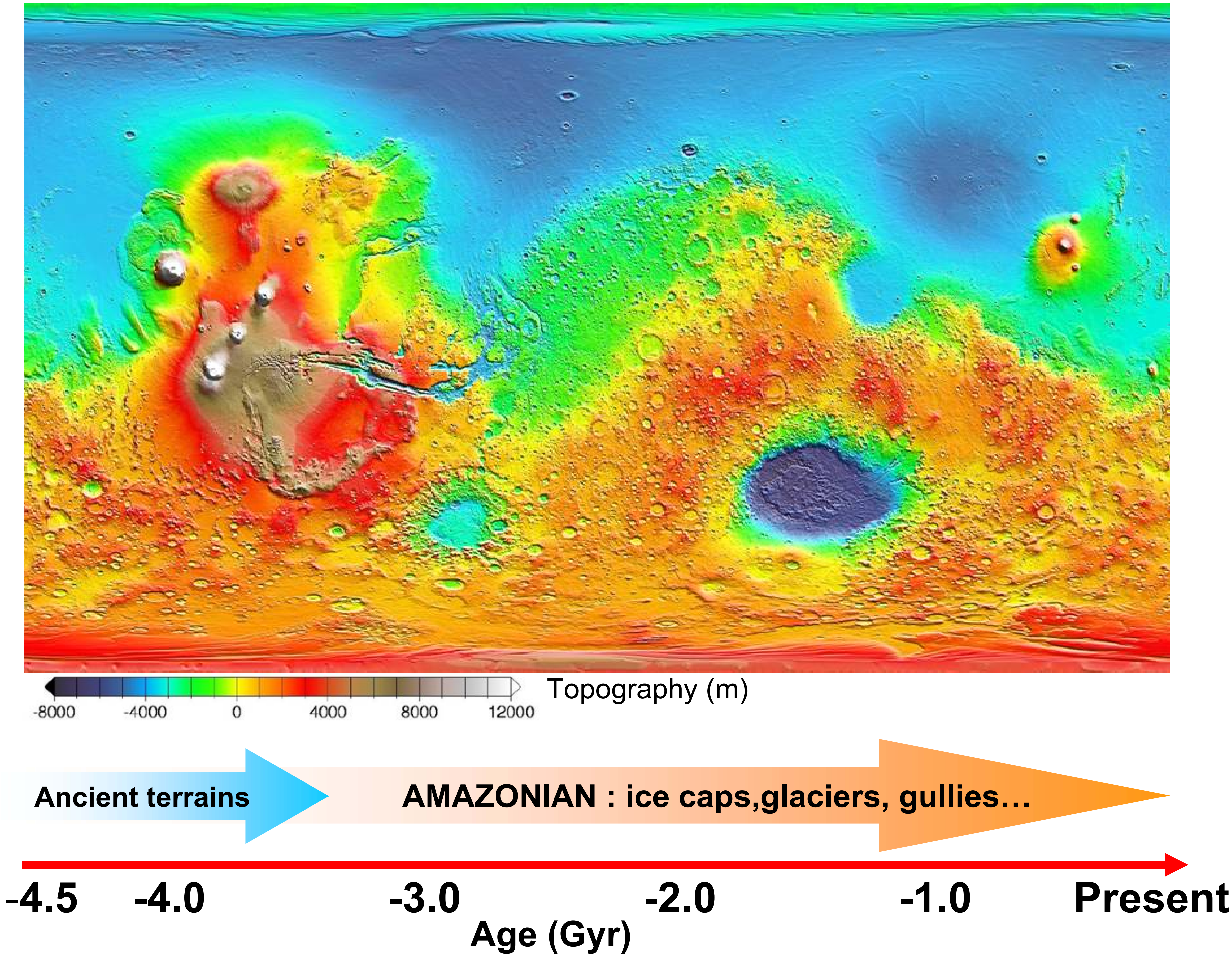
GCM simulations



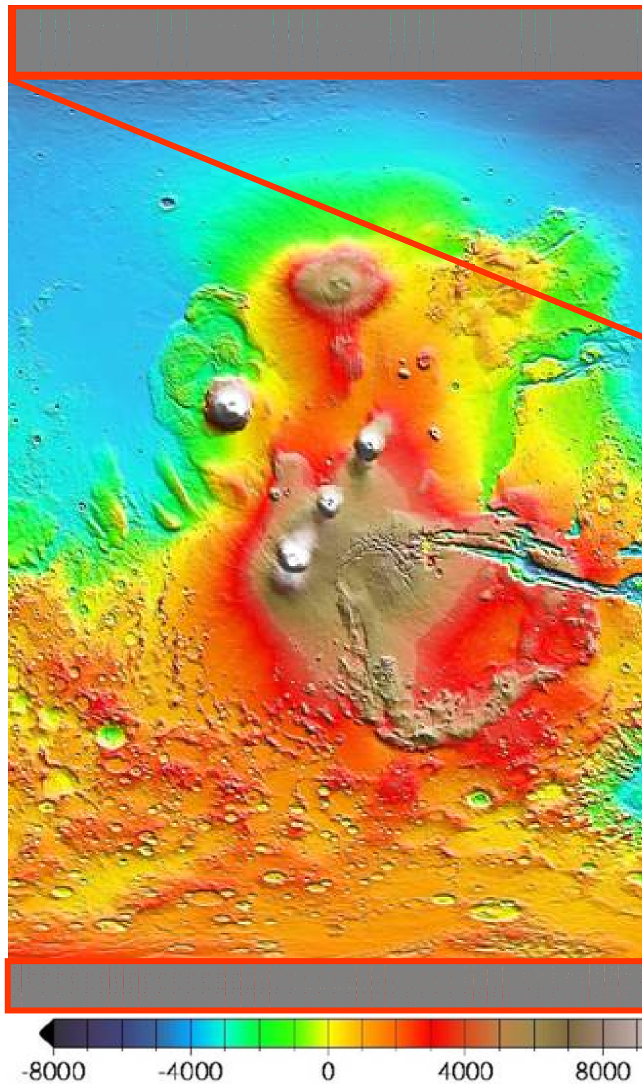
Basic facts learned from present-day water cycle studies :

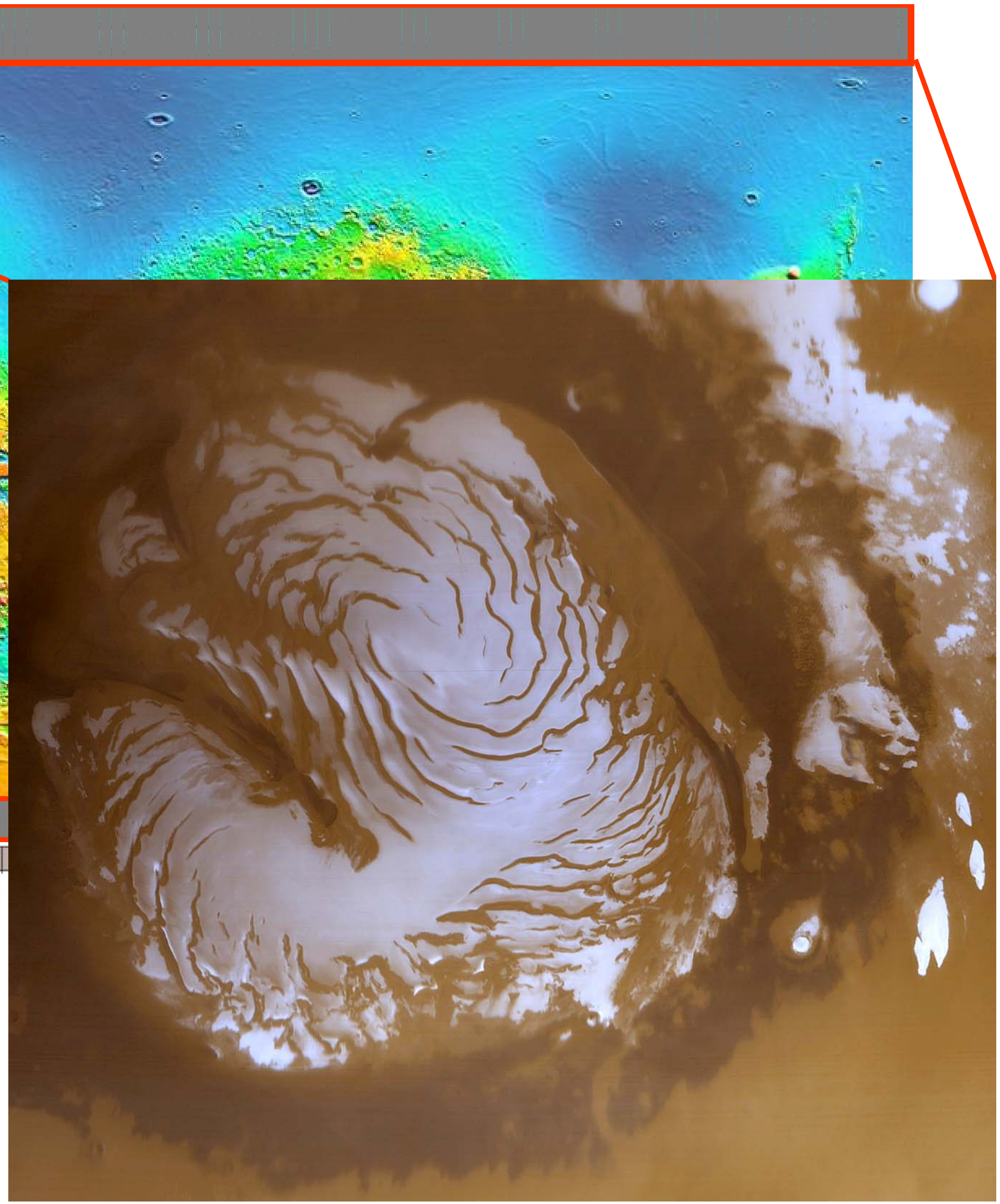
1. An almost « closed » water cycle
2. Surface water ice cannot accumulate outside the polar regions

An in the past ?? How can we explain the glaciers and the icy landforms observed on Mars ?

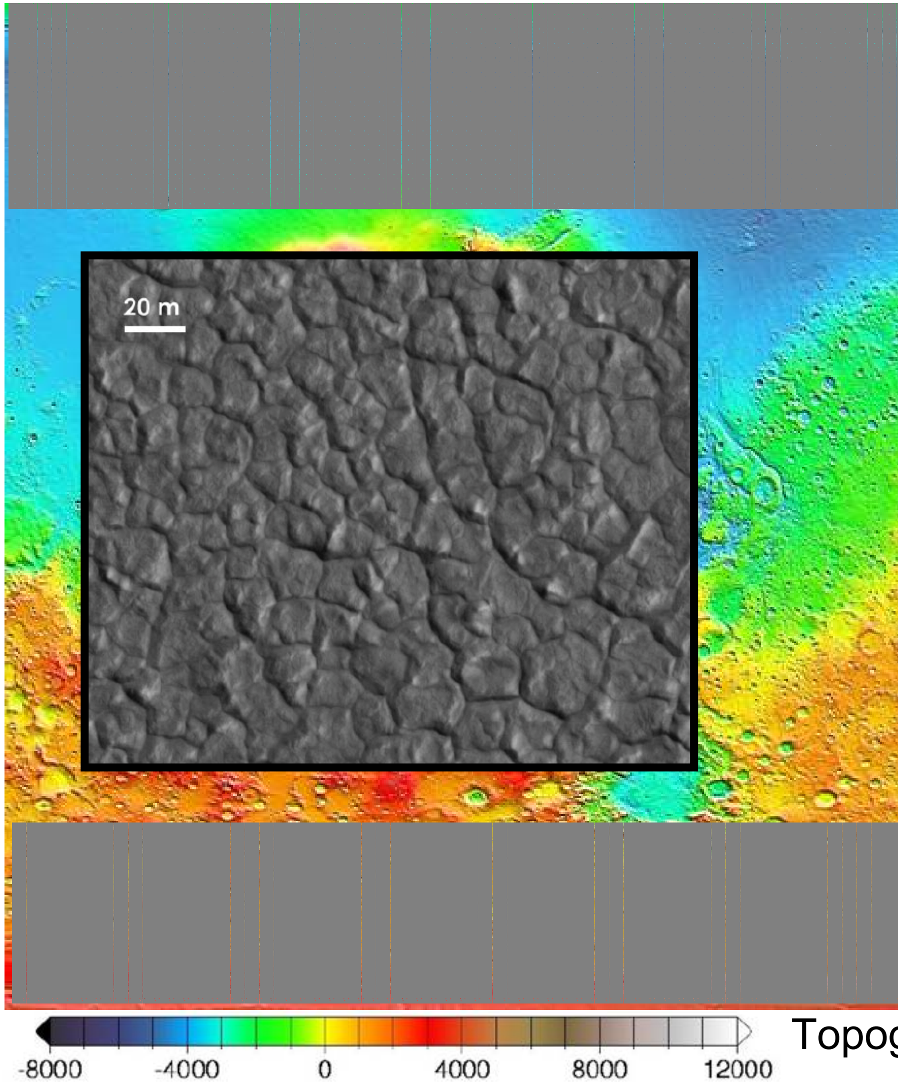


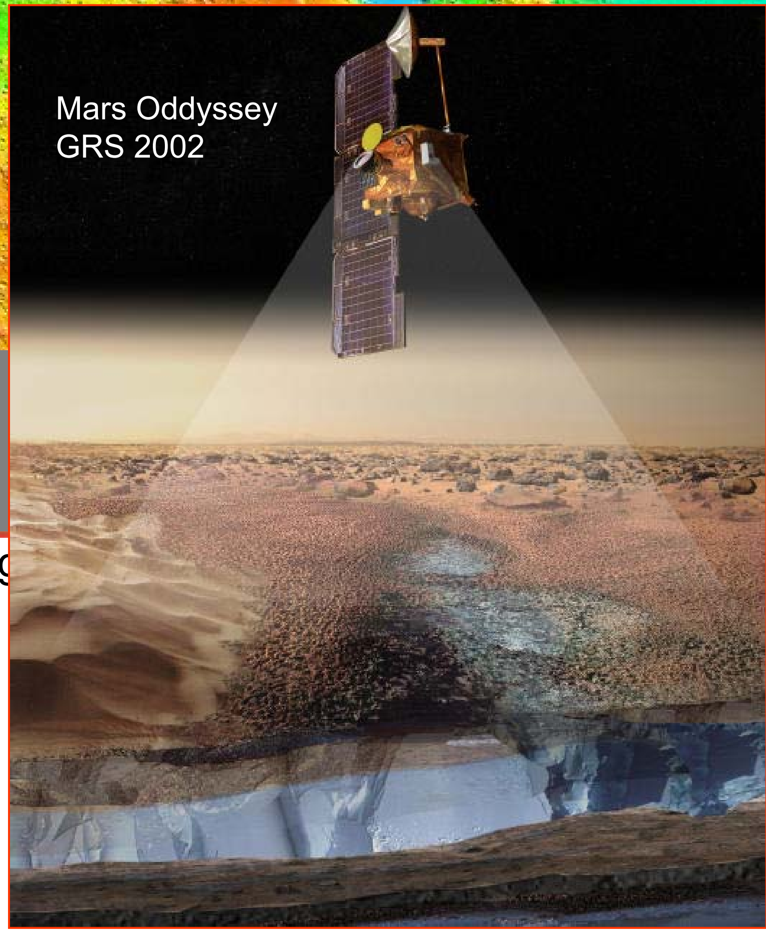
-8000
-4000
0
4000
8000
12000
Topography (m)
Ancient terrains
AMAZONIAN : ice caps,glaciers, gullies…
-4.5
-4.0
-3.0
-2.0
-1.0
Present
Age (Gyr)



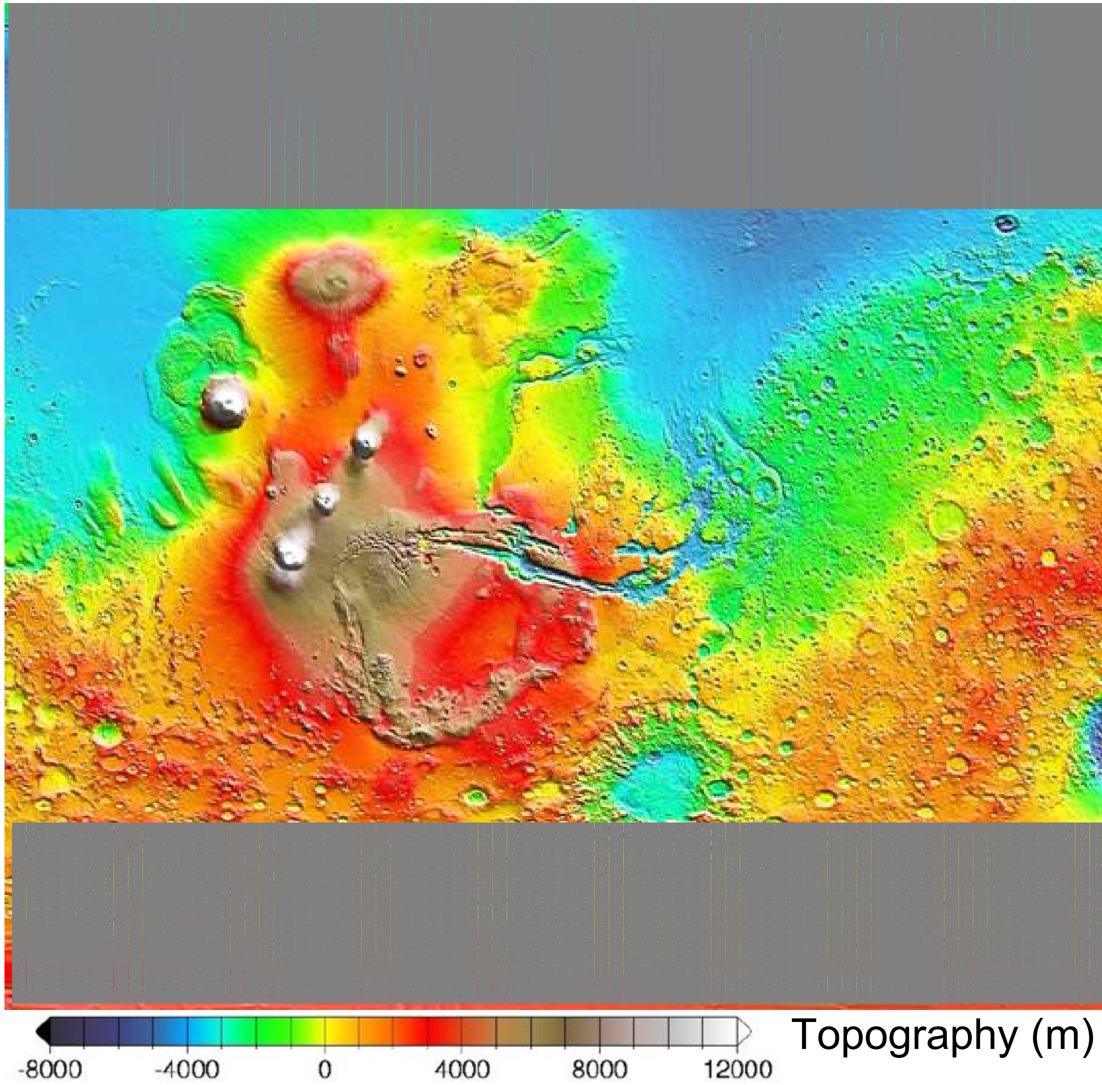


Ice landforms on Mars in polar regions (> ~80° lat)

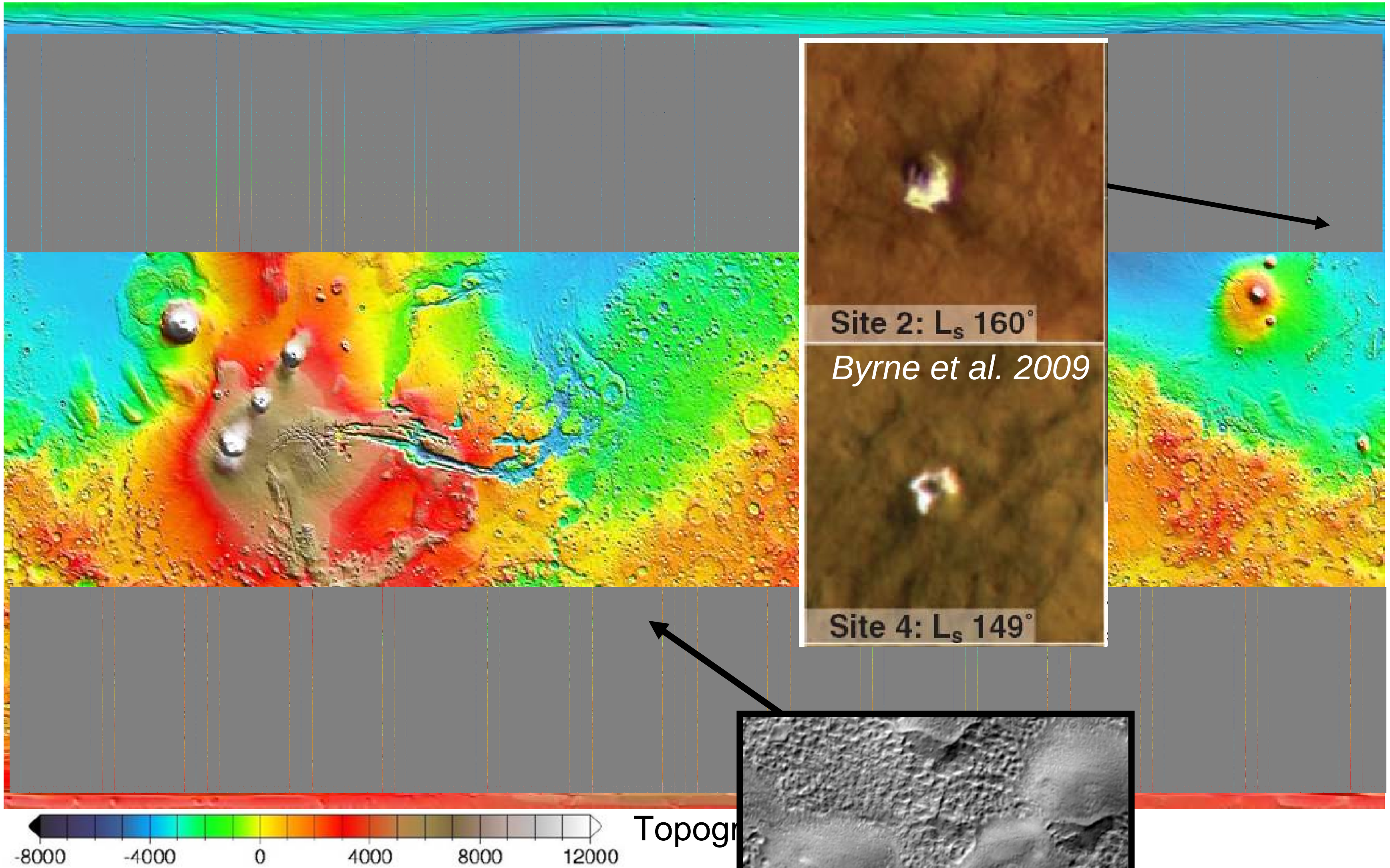


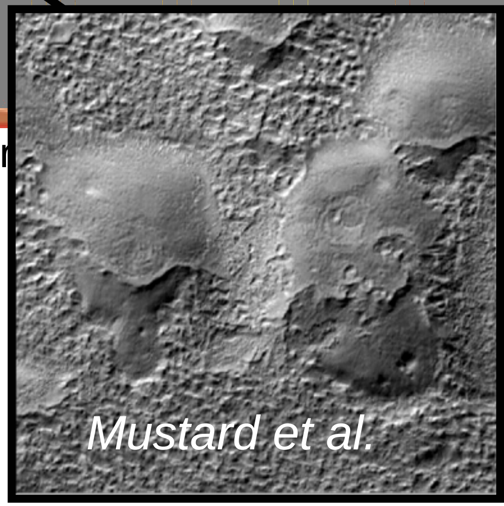


Near surface Ice mantling on Mars at high latitudes > 60°

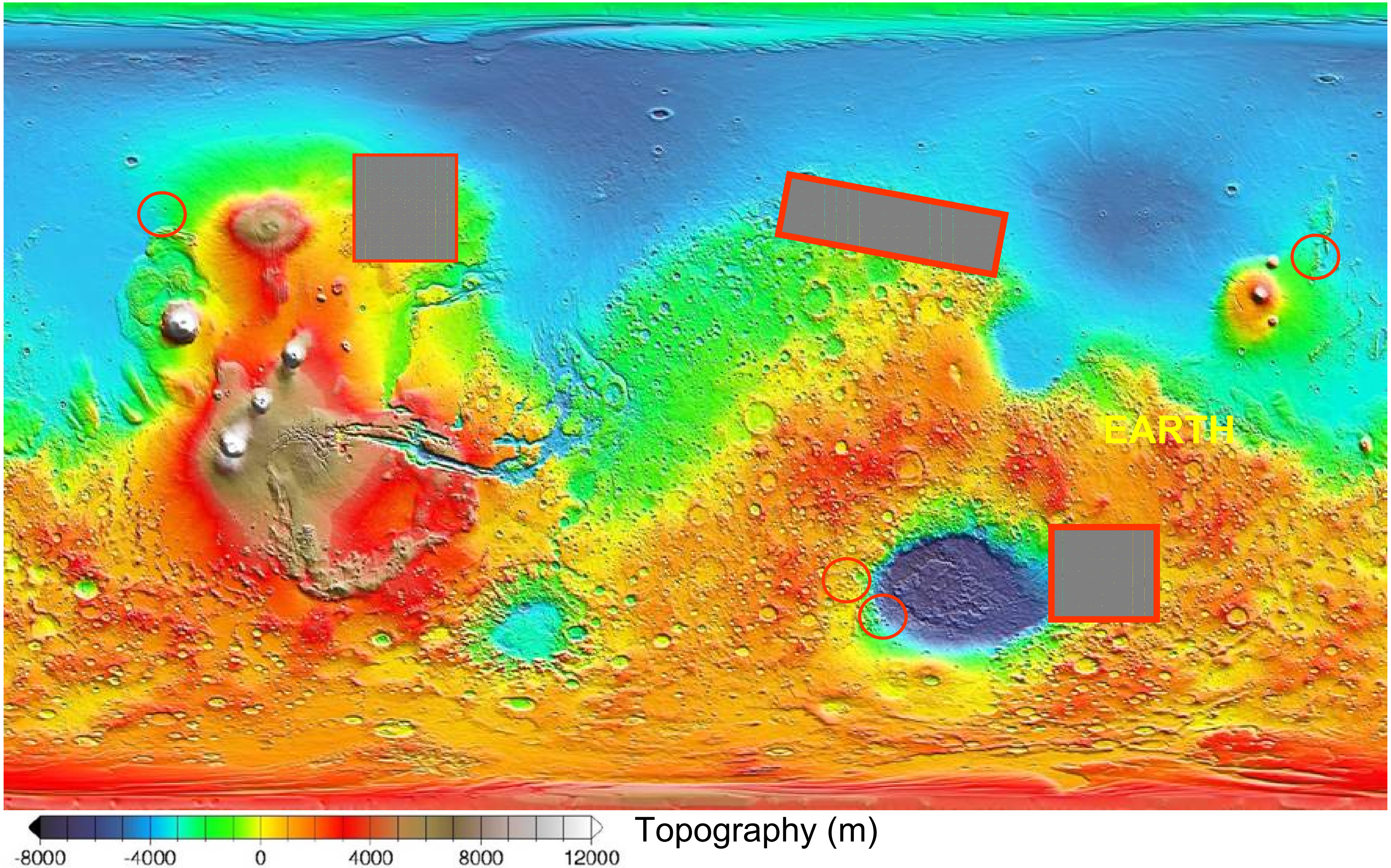


Near surface Ice mantling on Mars at high latitudes > 60°

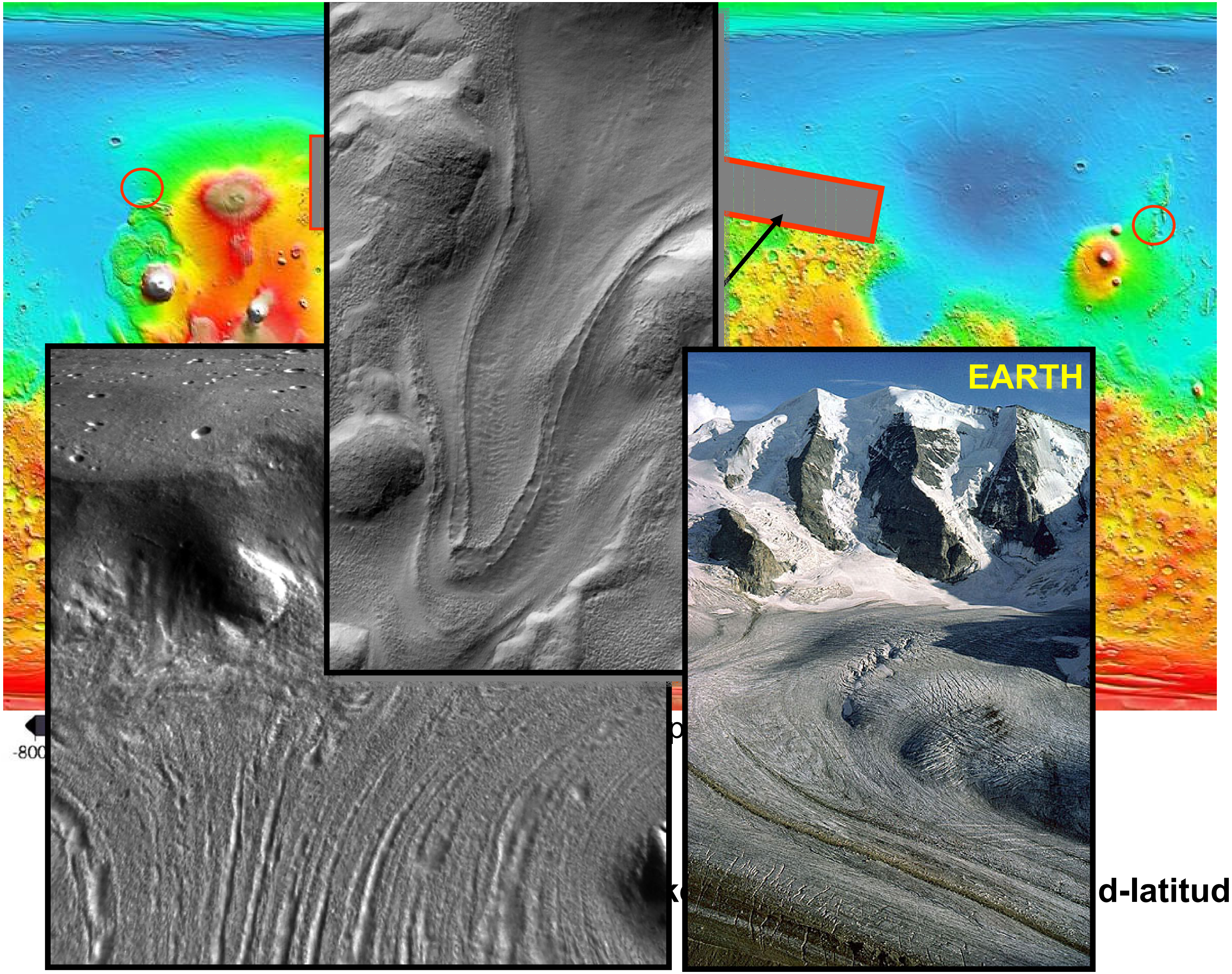




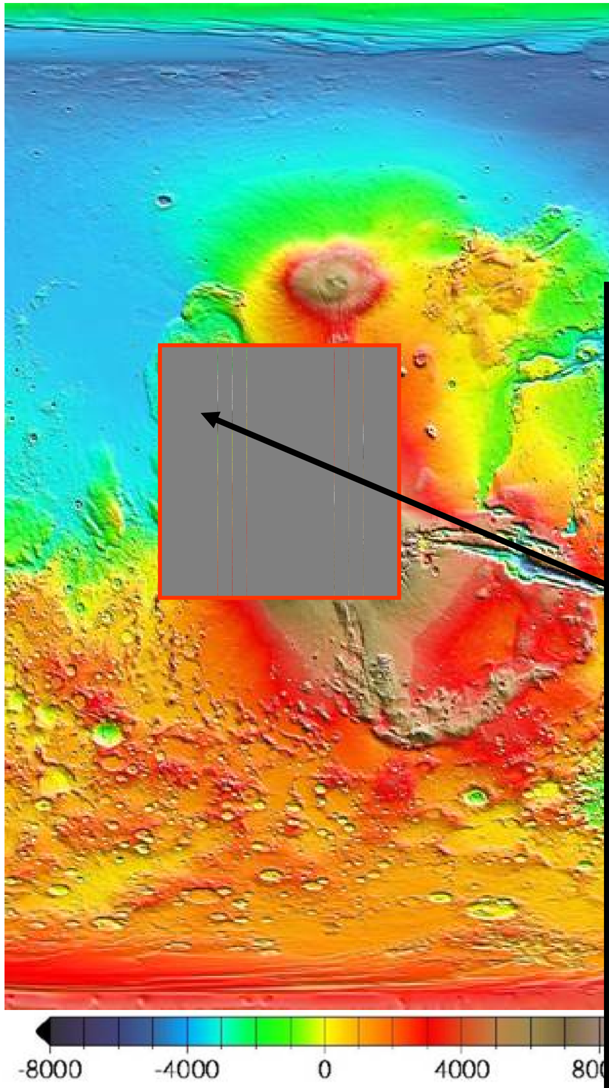
Near surface Ice mantling on Mars at high latitudes > 30°

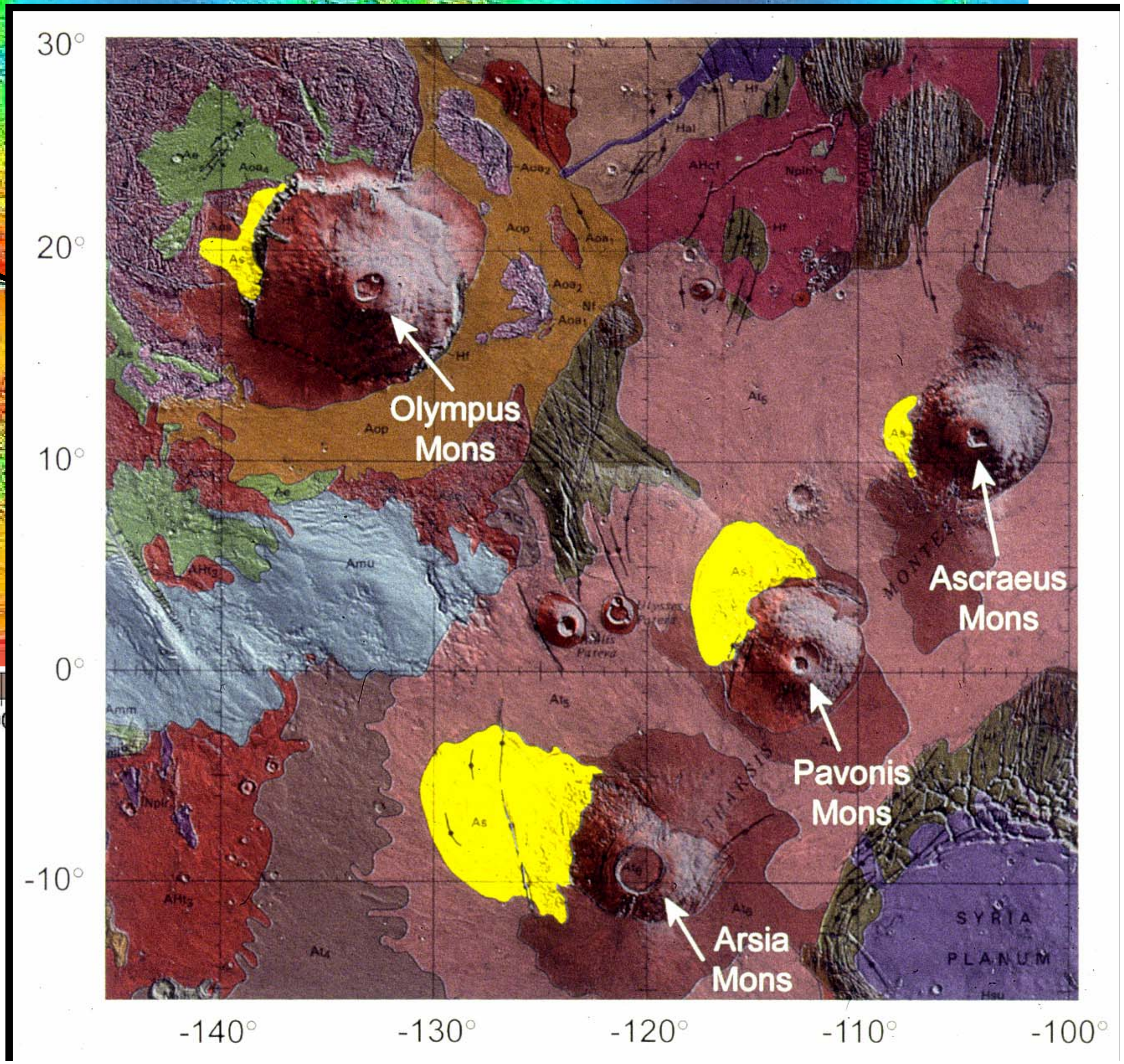


Glacier like landforms on Mars at mid-latitudes
Head et al. 2006



d-latitudes





Glacier-like landforms in the tropics

- Ice mantling and glaciers :

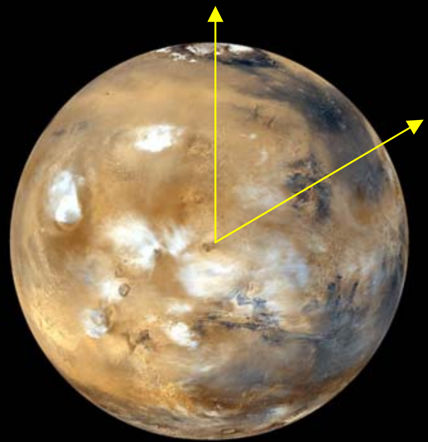
What happened ?

  - Diffusion of water vapor in the subsurface pores ? (e.g. *Mellon et al.)*
  - Role of hydrothermalism ? (e.g. *Neukum et al.)*
  - Atmospheric Ice precipitation ? *(e.g. Mishna et al. Forget et al. ,.)*

Climate changes resulting from obliquity variations

Earth obliquity: variations ± 1.3°

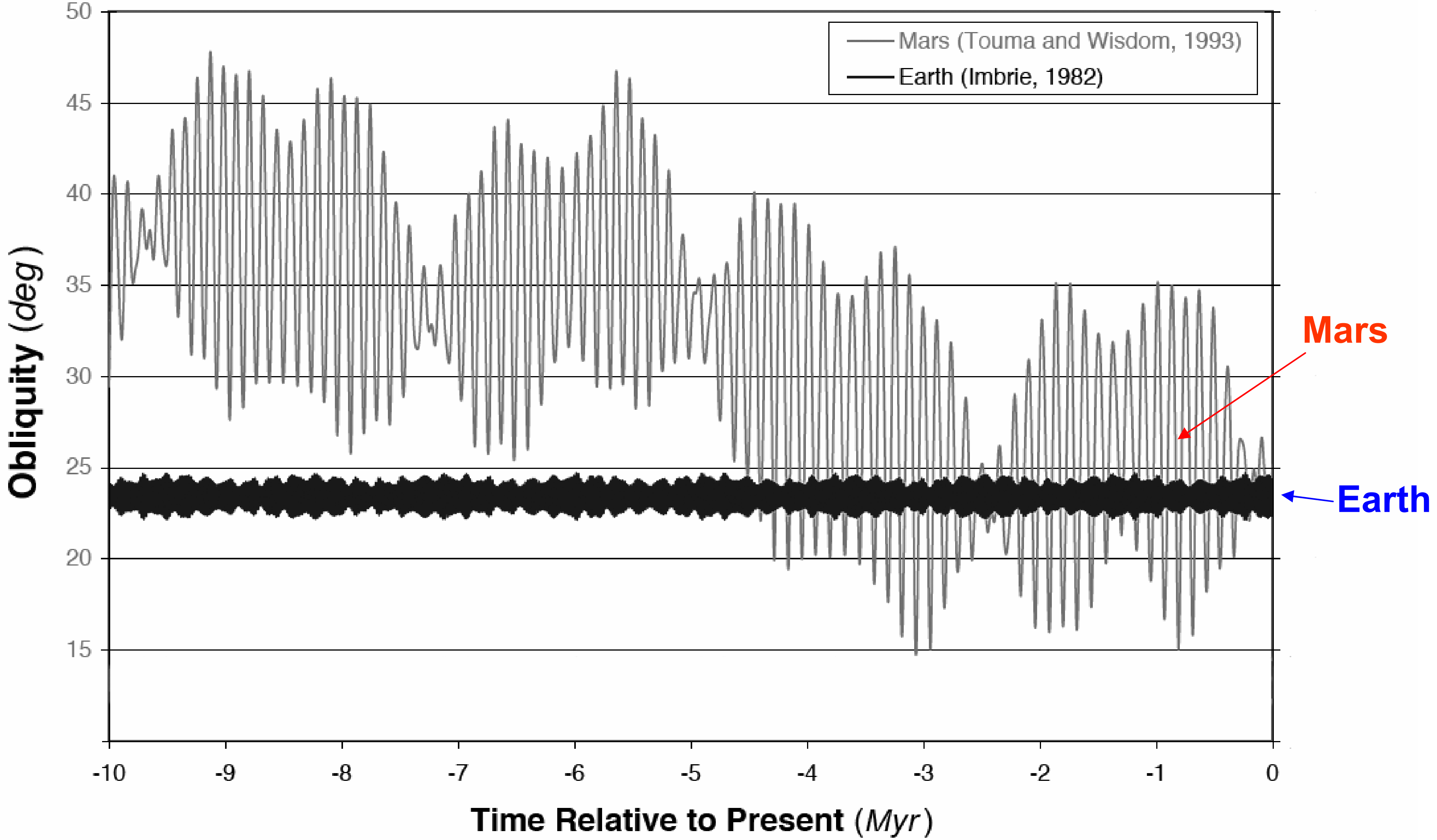
Mars: variations
between 0° et >60° !



Laskar et al. 2004
Laskar and Robutel 1993
Touma and Wisdom 1993

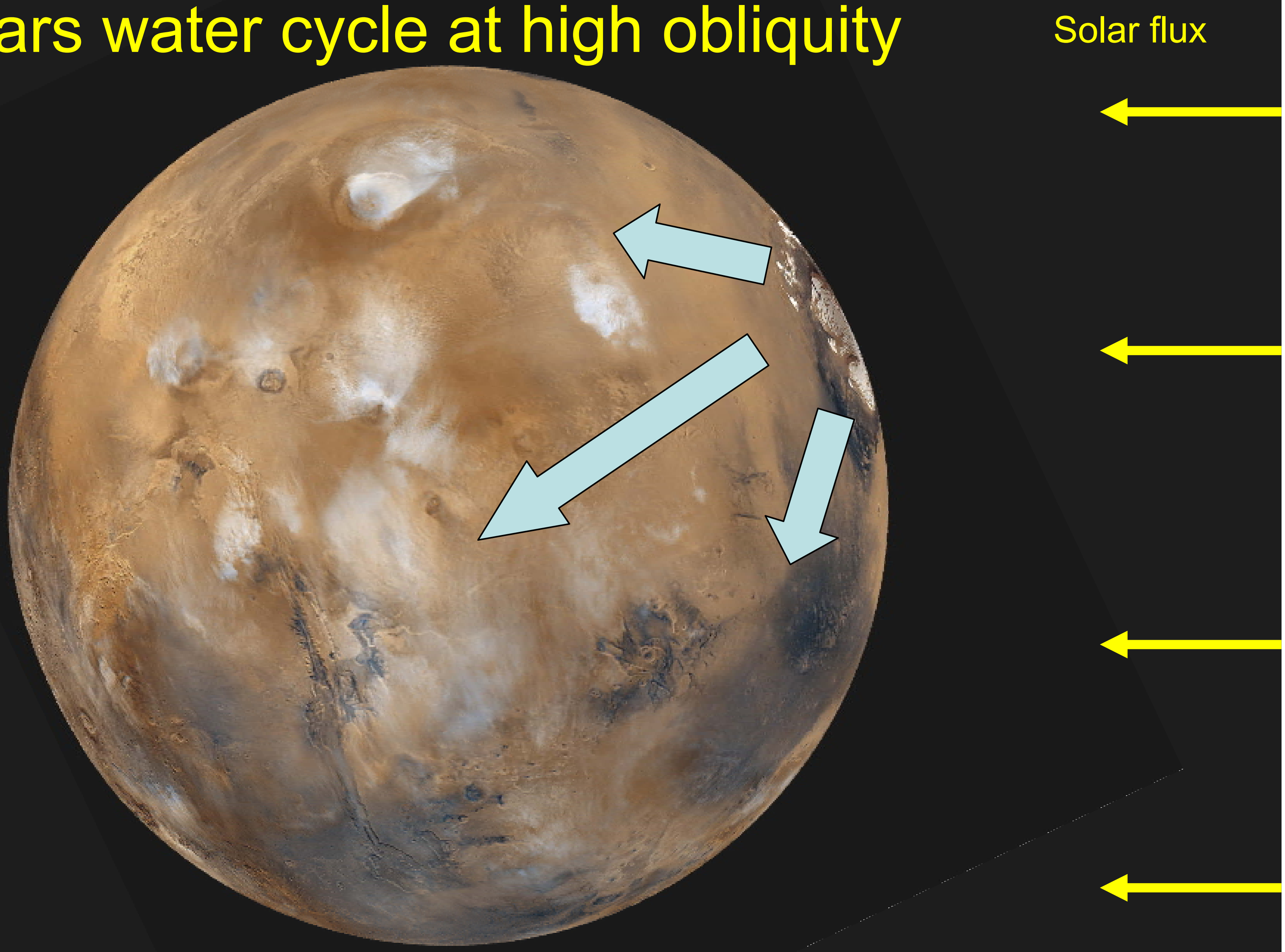
Mars and Earth obliquity in the past 10 Myr

Laskar et al. 2004
Laskar and Robutel 1993
Touma and Wisdom 1993



Before ?? => During Mars History, most likely obliquity: 41.8° (Laskar et al. 2004)

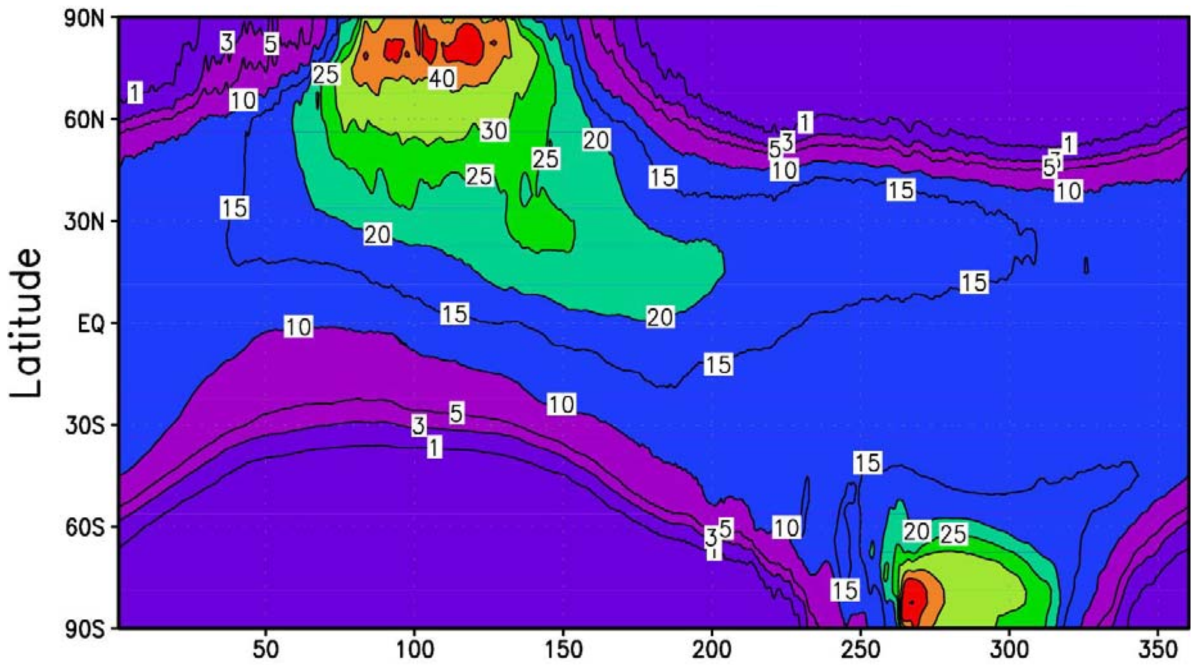
Mars water cycle at high obliquity



LMD GCM Simulations:

Water vapor column

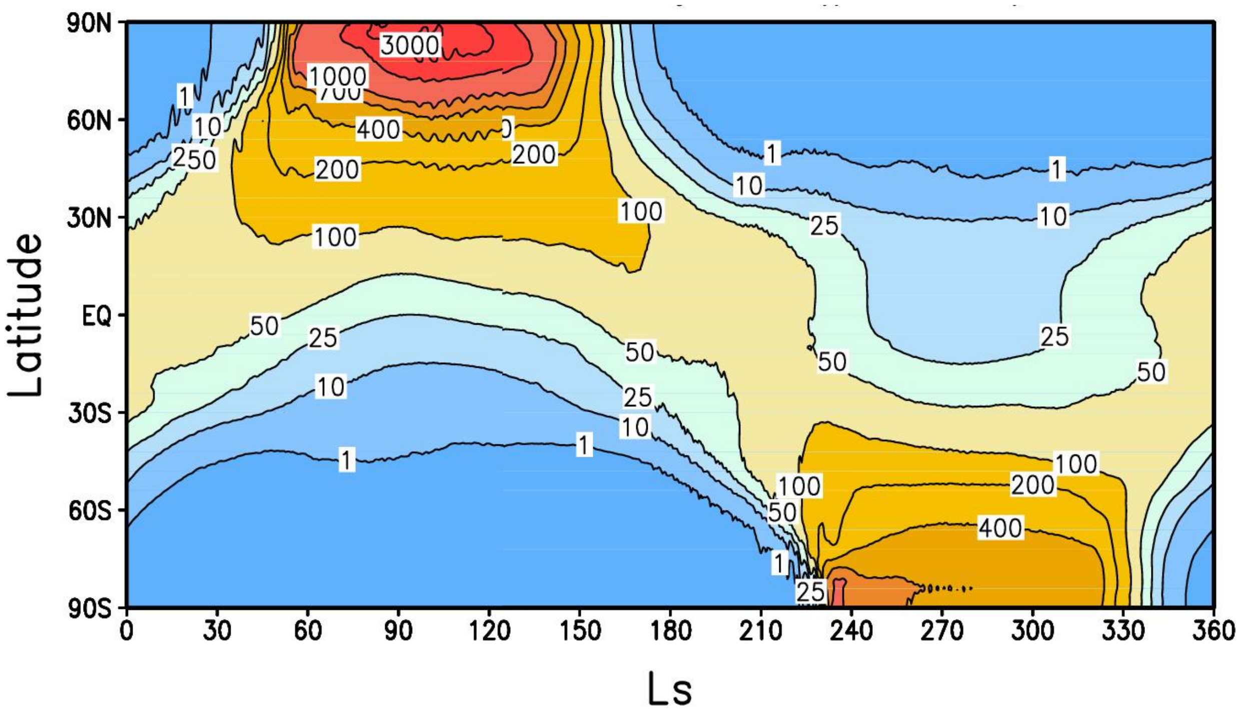
(*precipitable –microns*)



On present-day Mars :

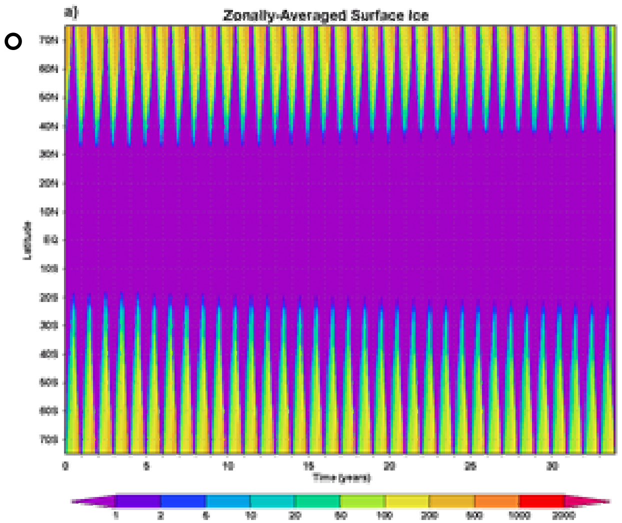
Same, but 45° Obliquity

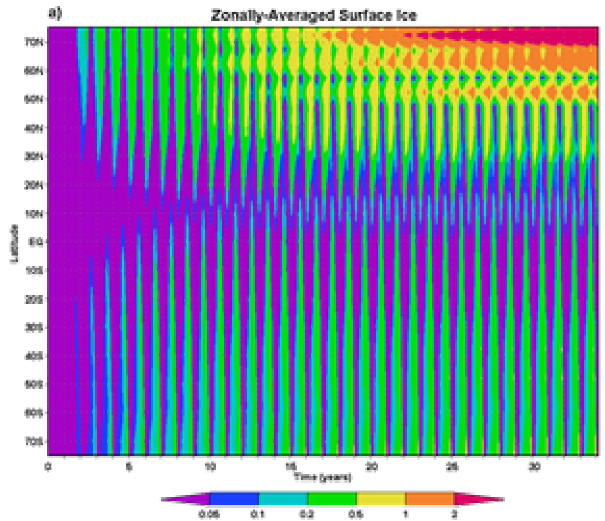
(Circular orbit)



Surface Ice simulated by **Mischna *et al.* (2003)**

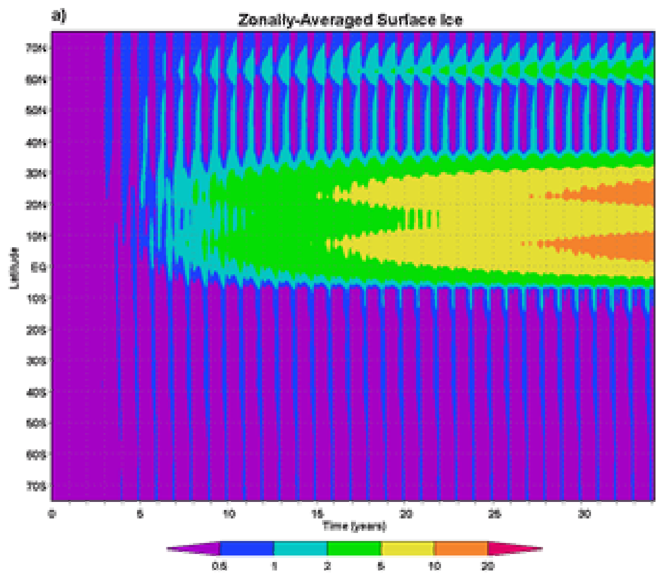
θ=25°



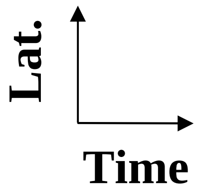


θ=35°

θ=45°



Zonally-Averaged Surface Water Ice

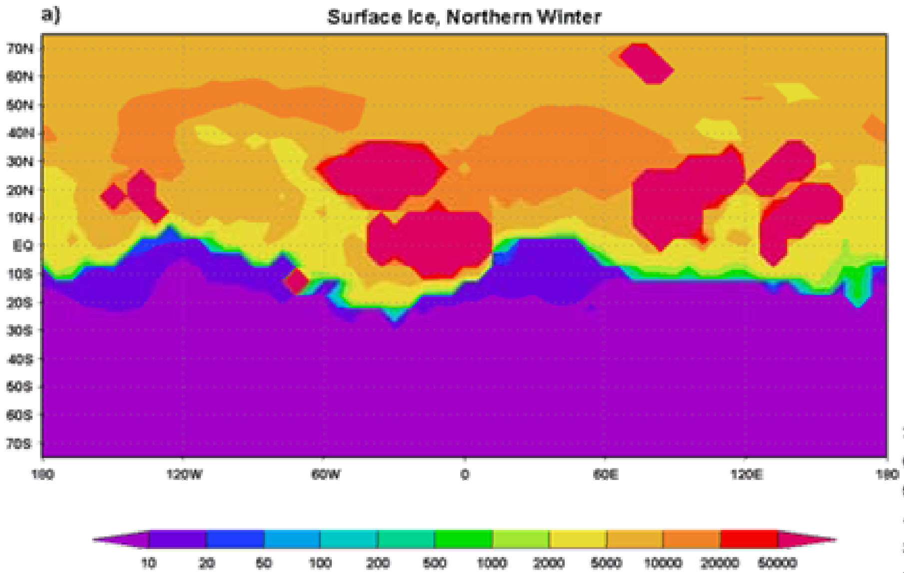


Surface Ice simulated by **Mischna *et al.* (2003)**

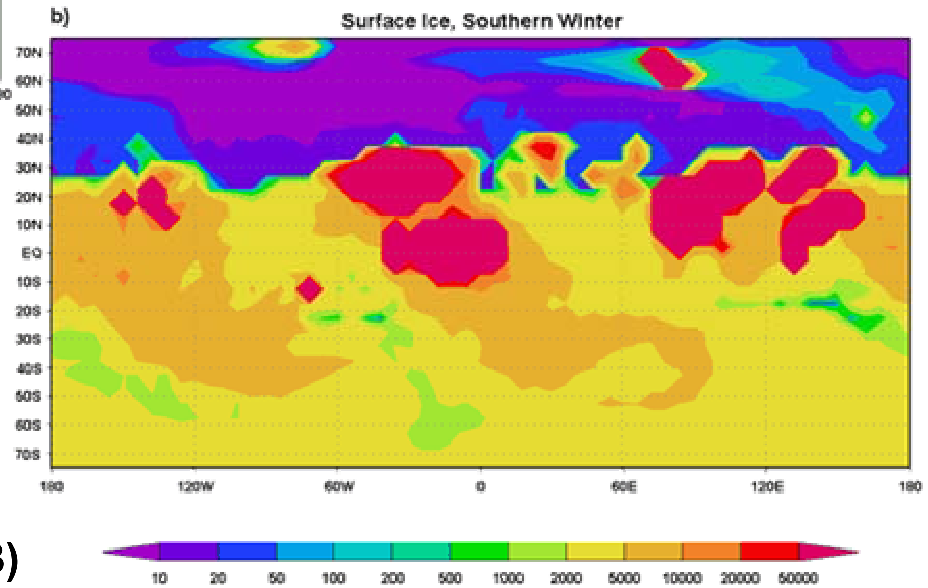
Obliquity 45°

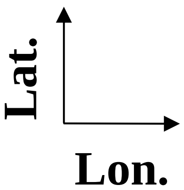
- Ice is not distributed homo-geneously, but influenced by thermal conditions of surface.

- Thick deposits can survive year-round at high obliquity.



Surface water ice (μm)





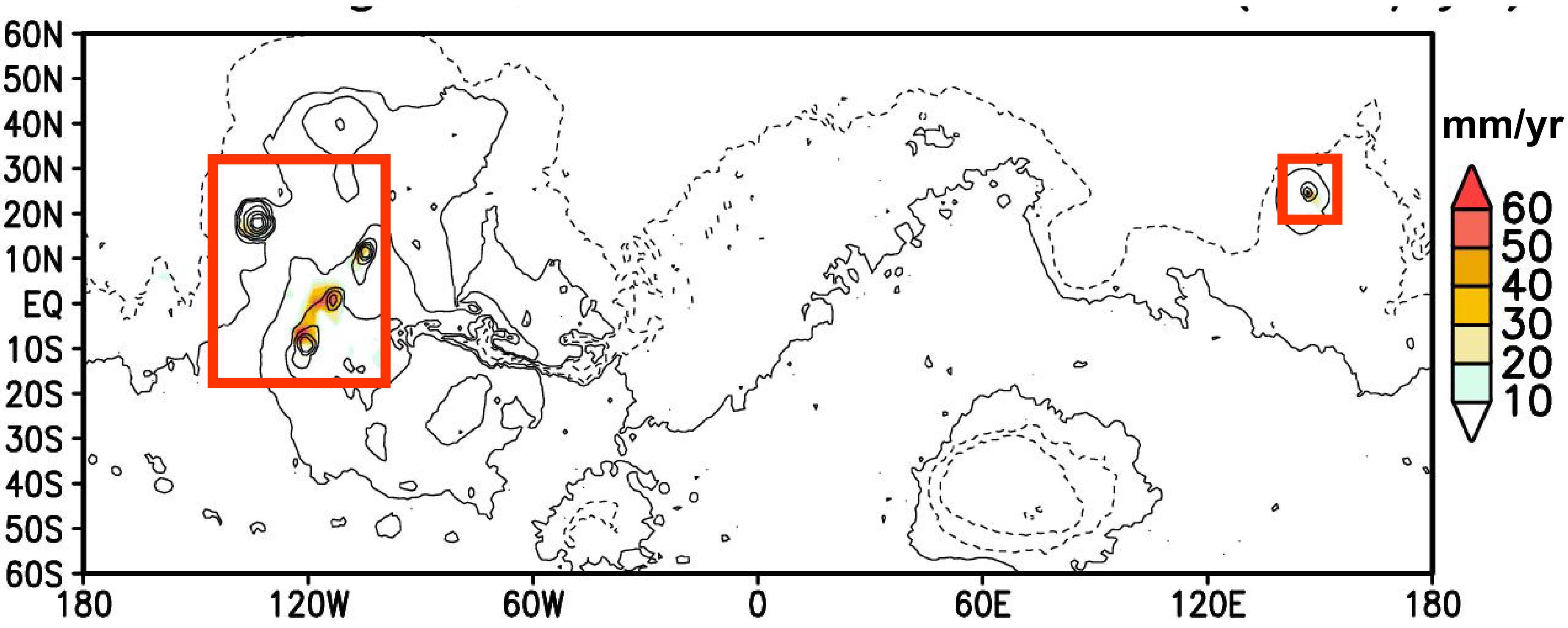
Mischna *et al.* (2003)

Ice accumulation rate (mm/yr)

high resolution simulation (2°x2°)

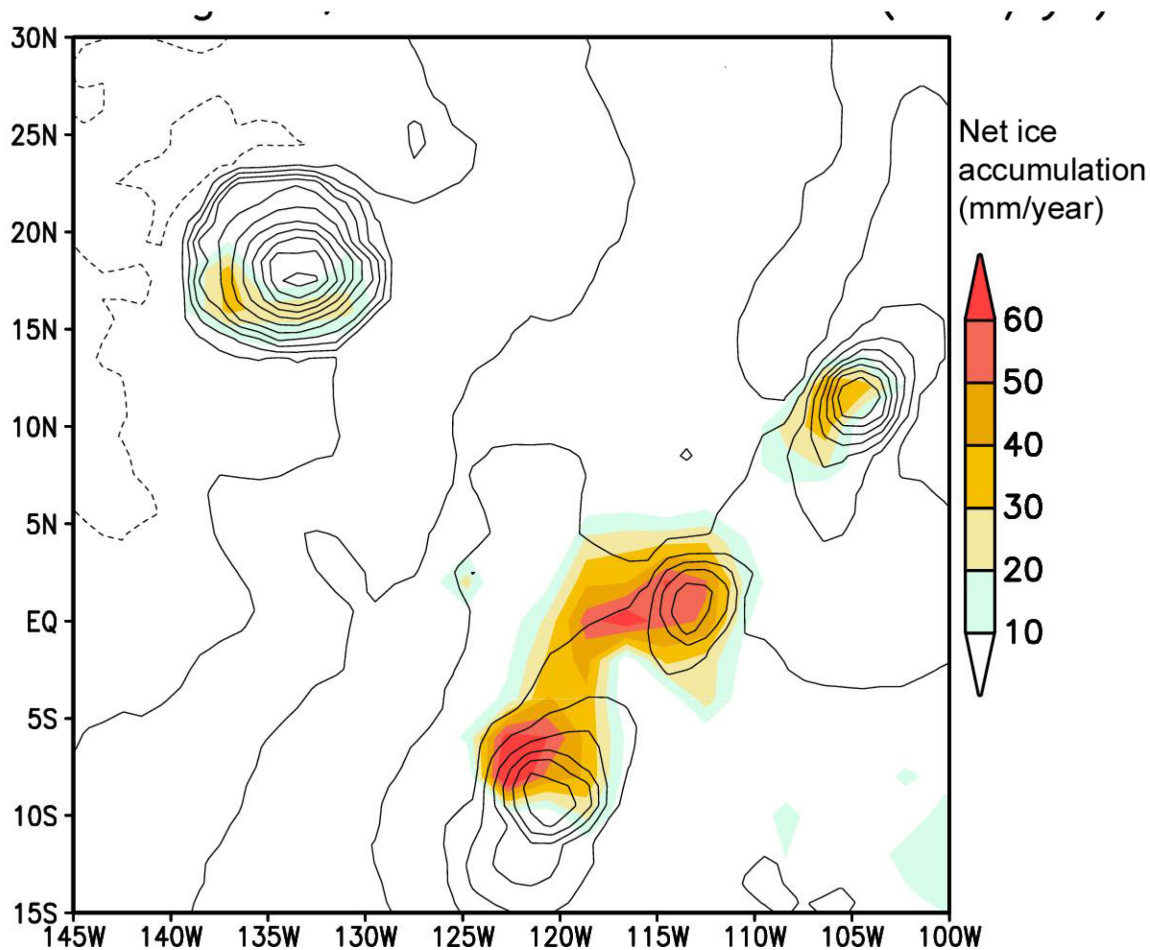
Obliquity = 45° , Excentricity = 0, Dust Opacity =0.2

Forget et al. Science 311, p368, 2006



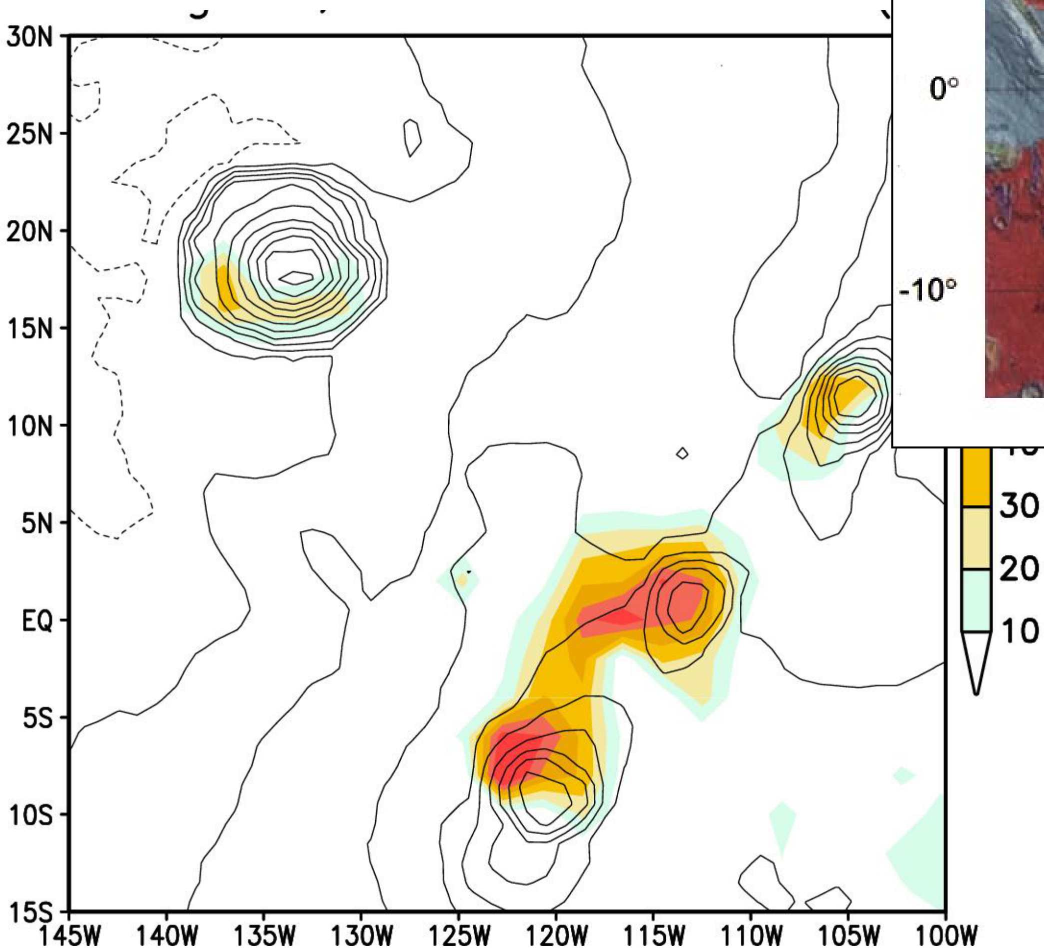
The formation of glacier : Ice accumulation rate (mm/yr) in a new very high resolution simulation

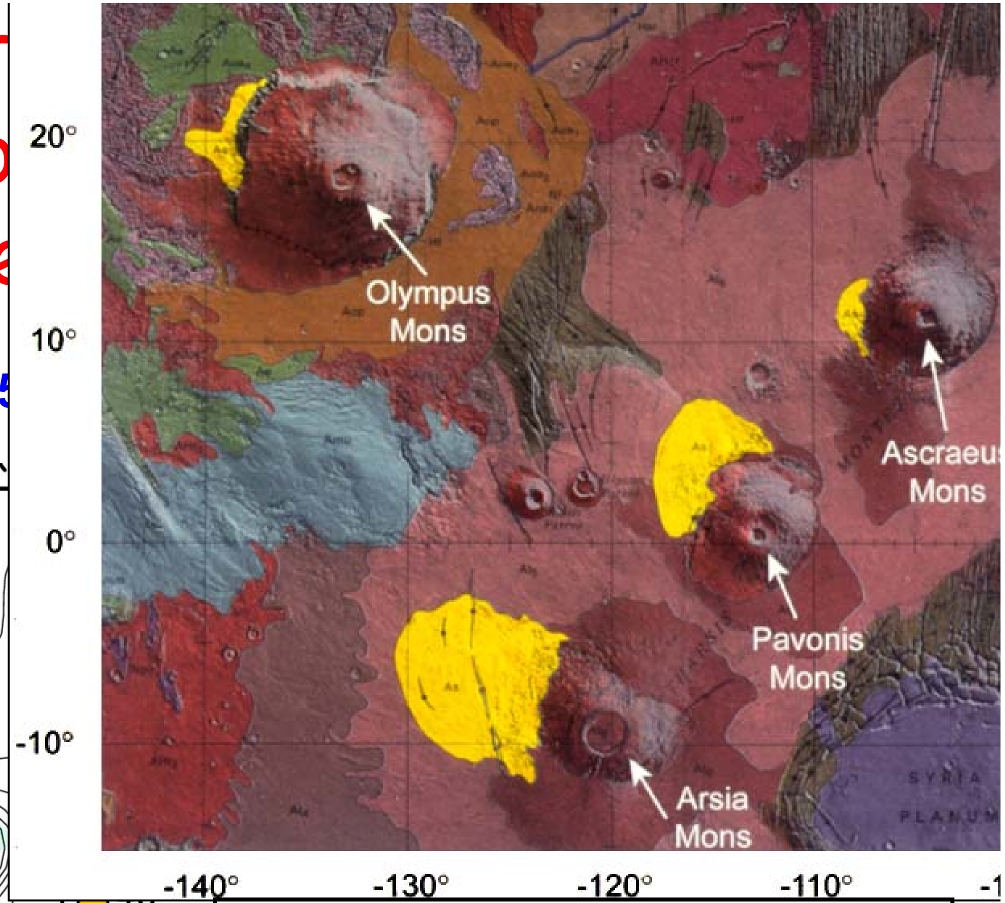
Forget et al. 2006: Obliquity = 45° , Excentricity = 0, Dust Opacity =0.2



The format
accumulatio
very high re

Forget et al. 2006: Obliquity = 45

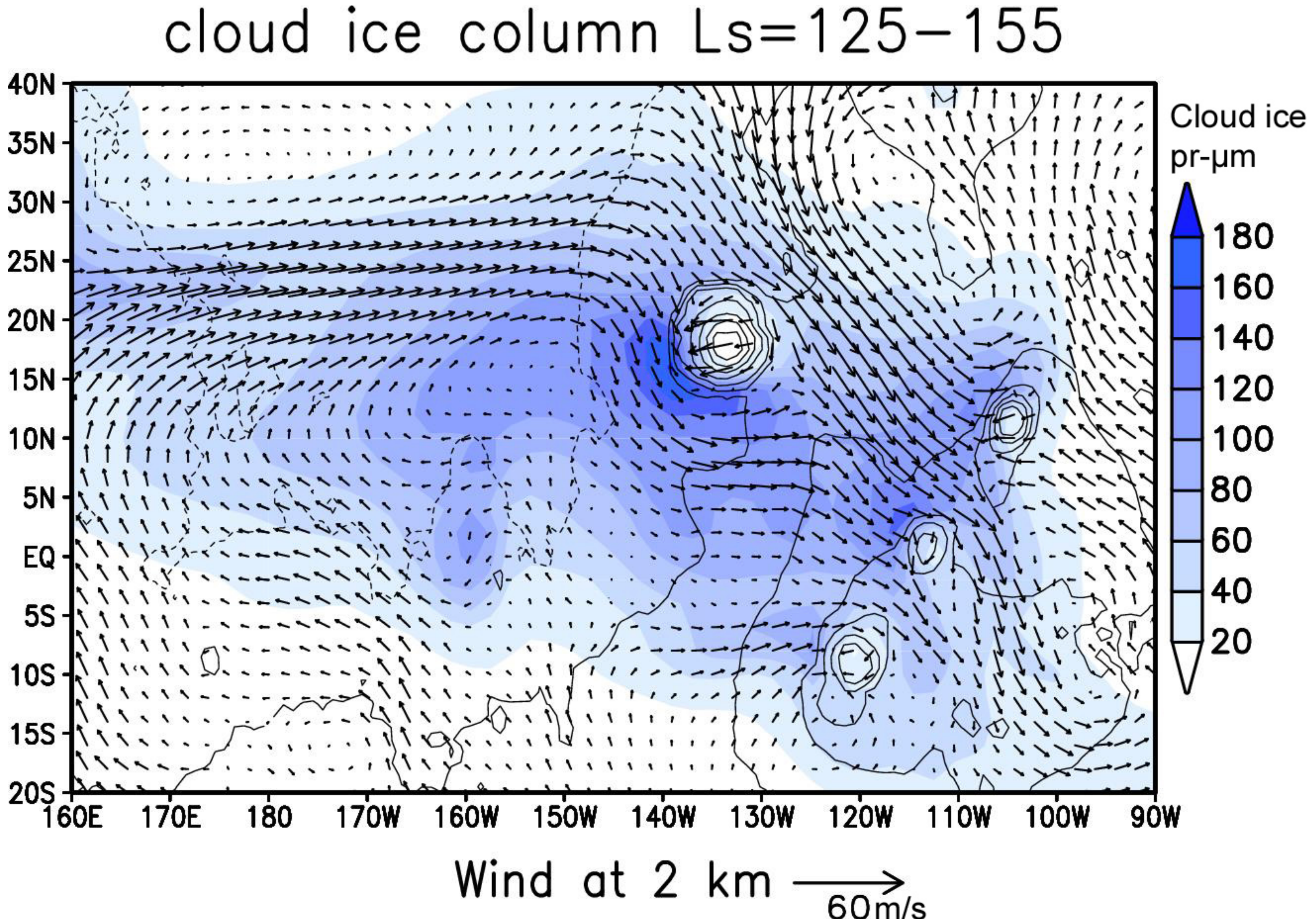




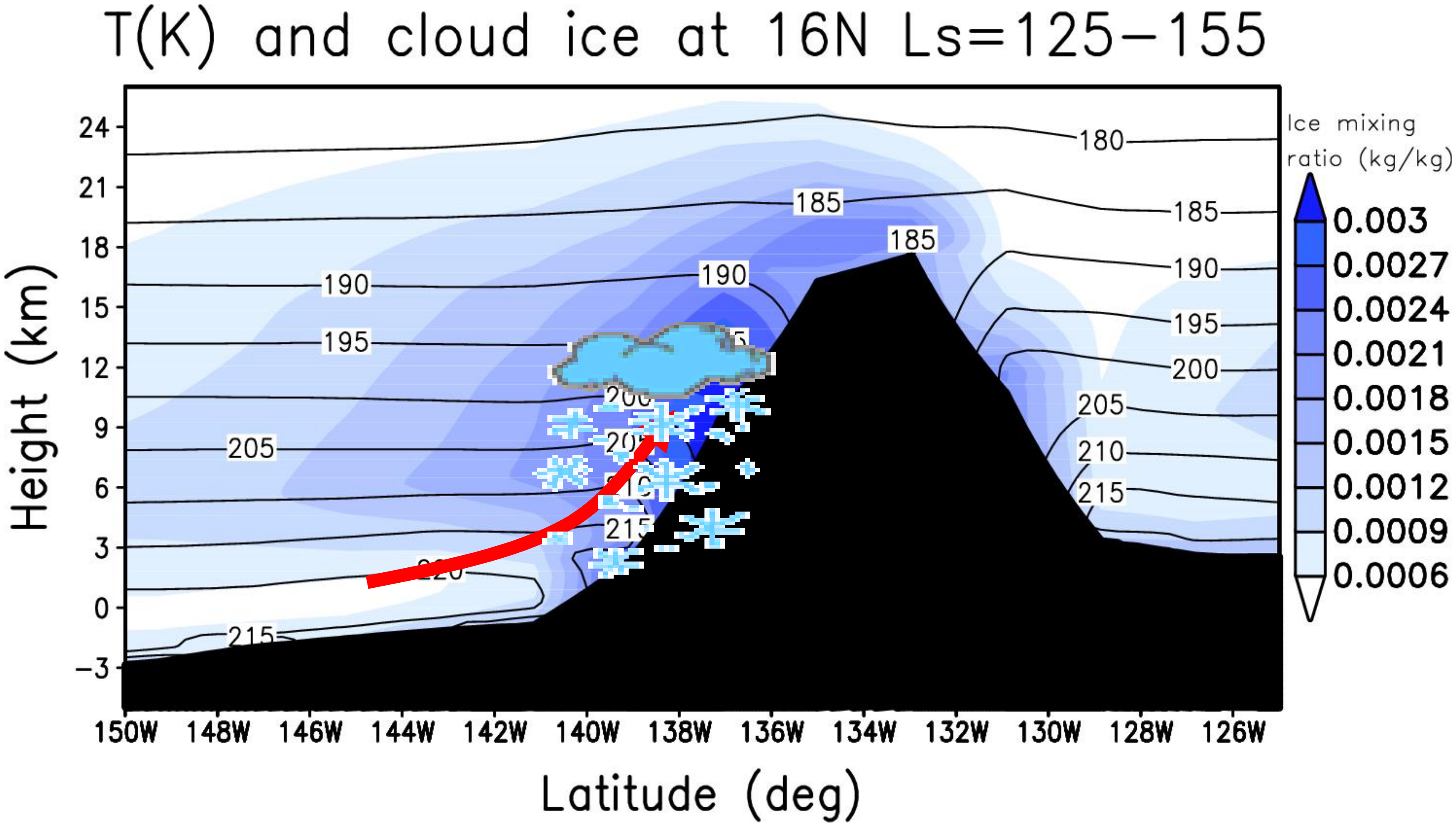
- **Fan shaped deposits, drop moraines characteristic of cold based glaciers.**
- **Rock glaciers**

Head et al. 2003, Shean et al. 2005, Head et al. 2005 Lucchitta 1981

At high obliquity: Ice accumulation by ice precipitation on windward slope

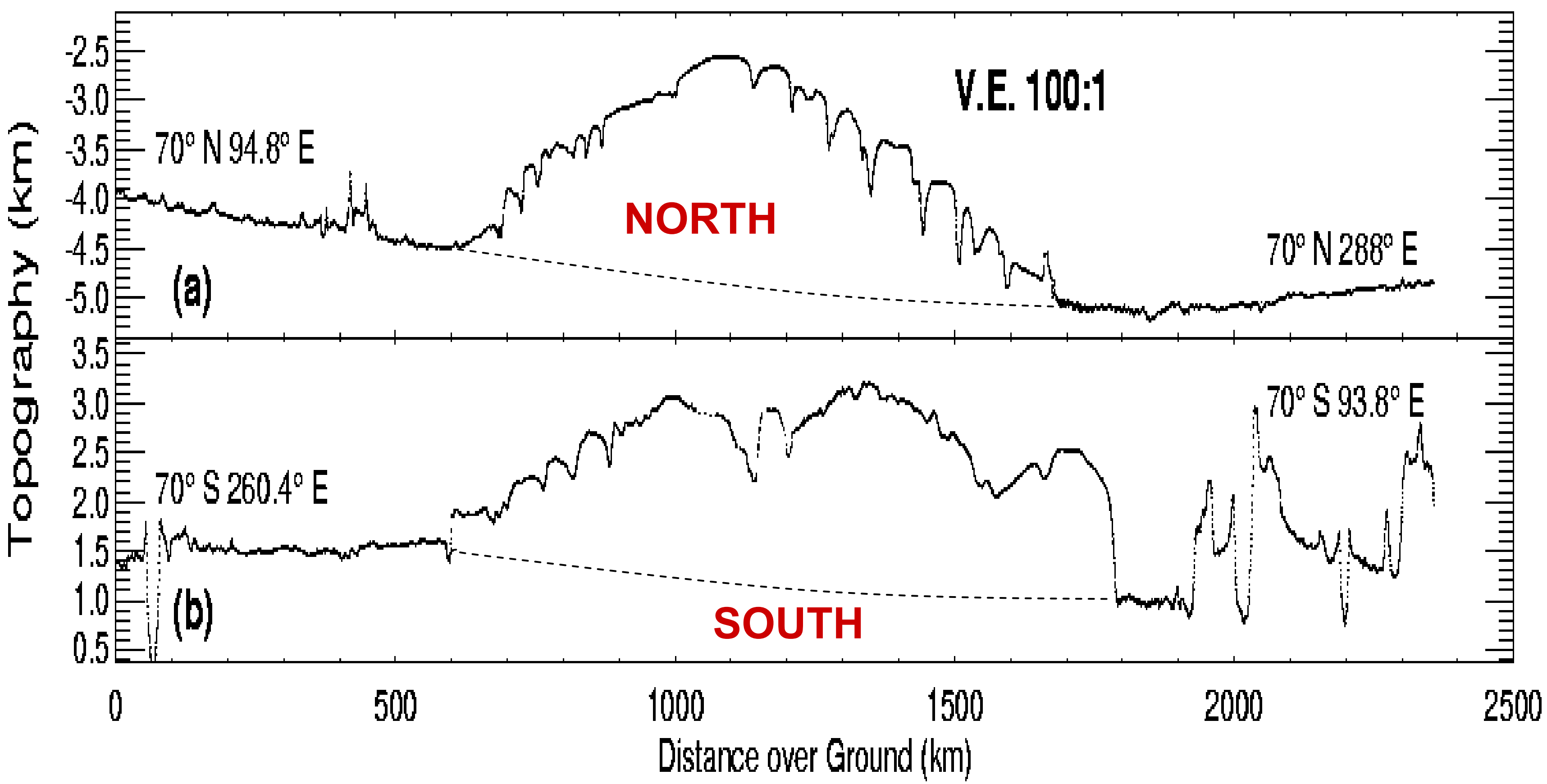


At high obliquity: Ice accumulation by ice precipitation on windward slope

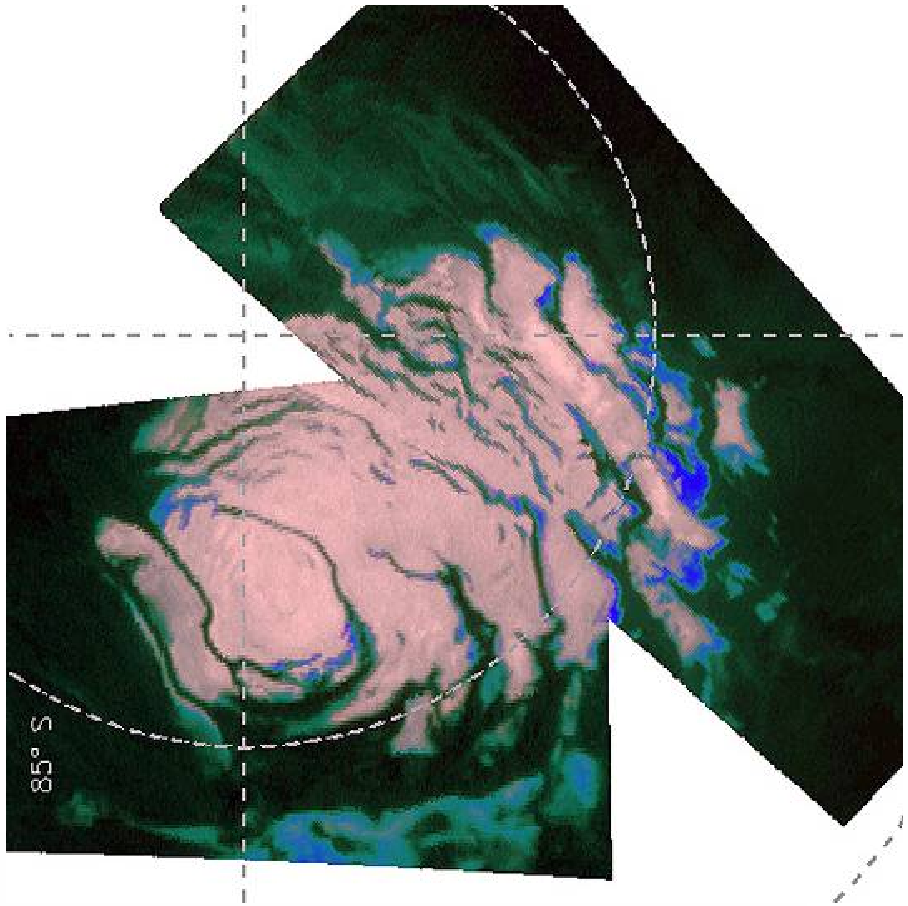


What if water ice is also available **<u>at</u> the south pole ?**

Topography of the polar regions



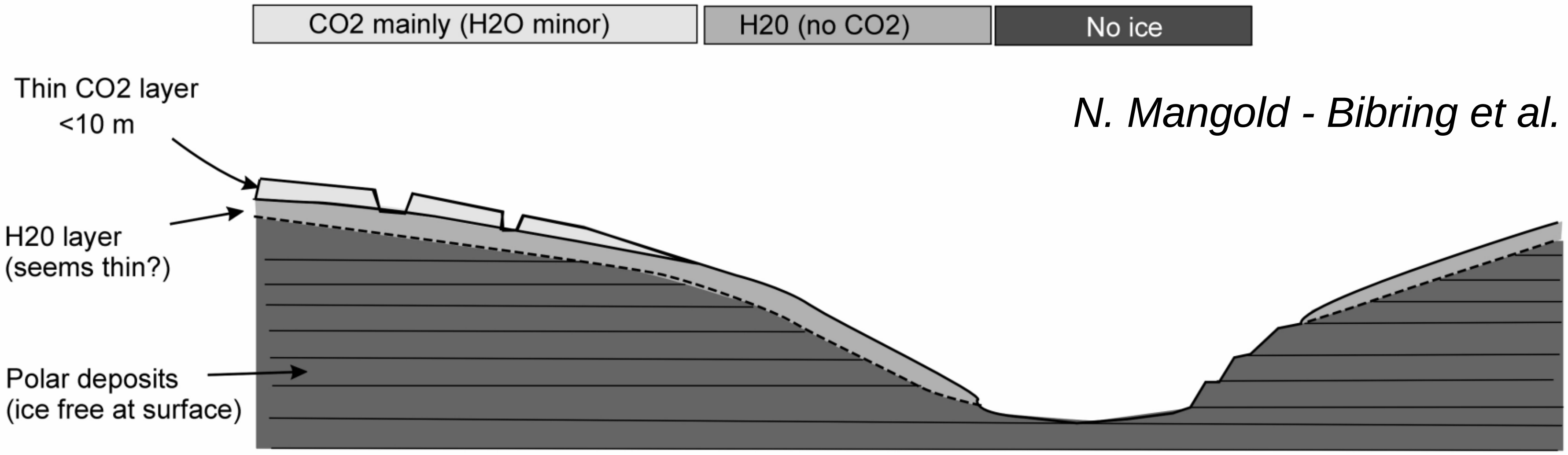
Near the south pole: permanent surface WATER ICE seen by Mars Express OMEGA



Blue: H_2O ice

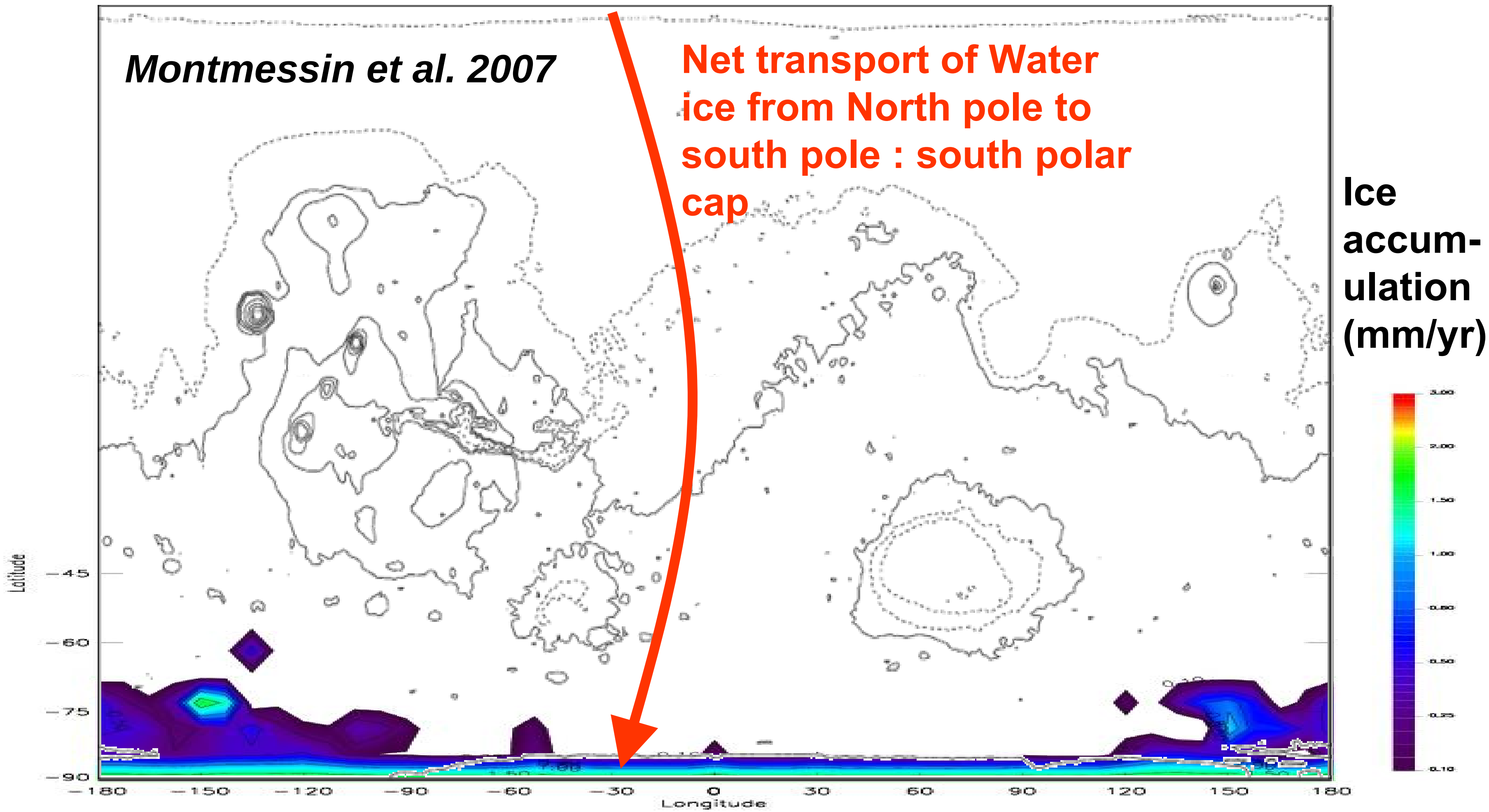
White CO2 ice

Bibring et al. 2004



N. Mangold - Bibring et al. 2004

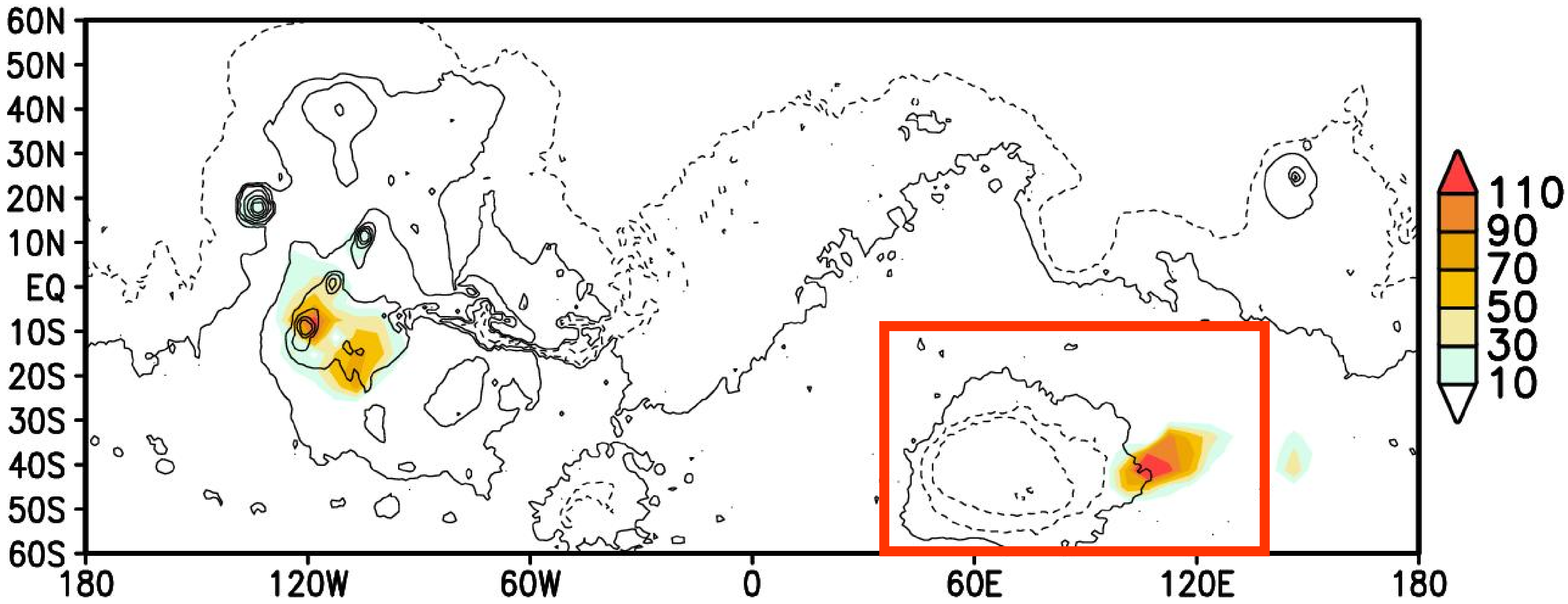
Ice accumulation -75000 years ago
Perihelion = Northern summer (≠today)

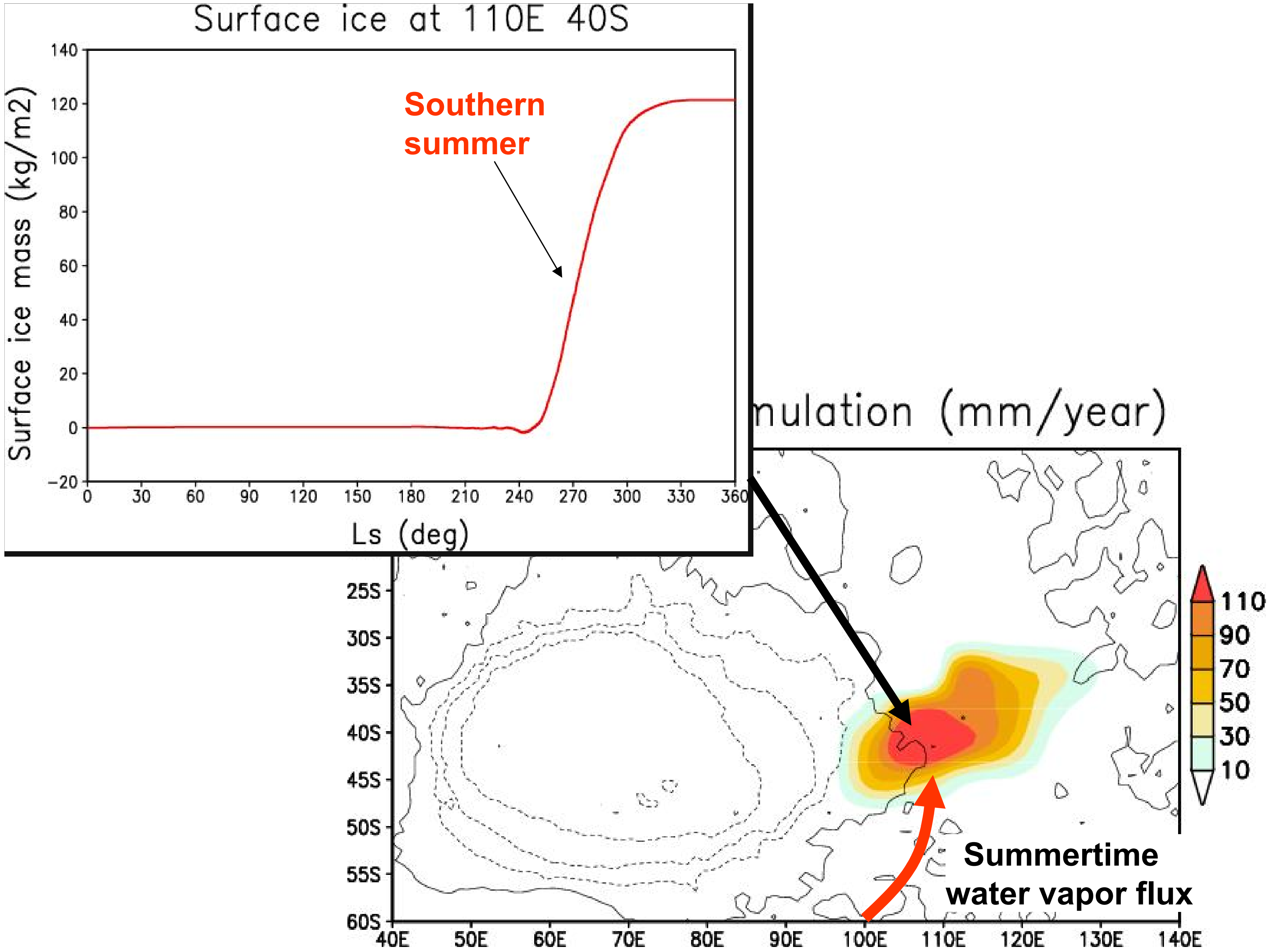


High Obliquity Simulation with a water ice cap **<u>at the south pole</u>**

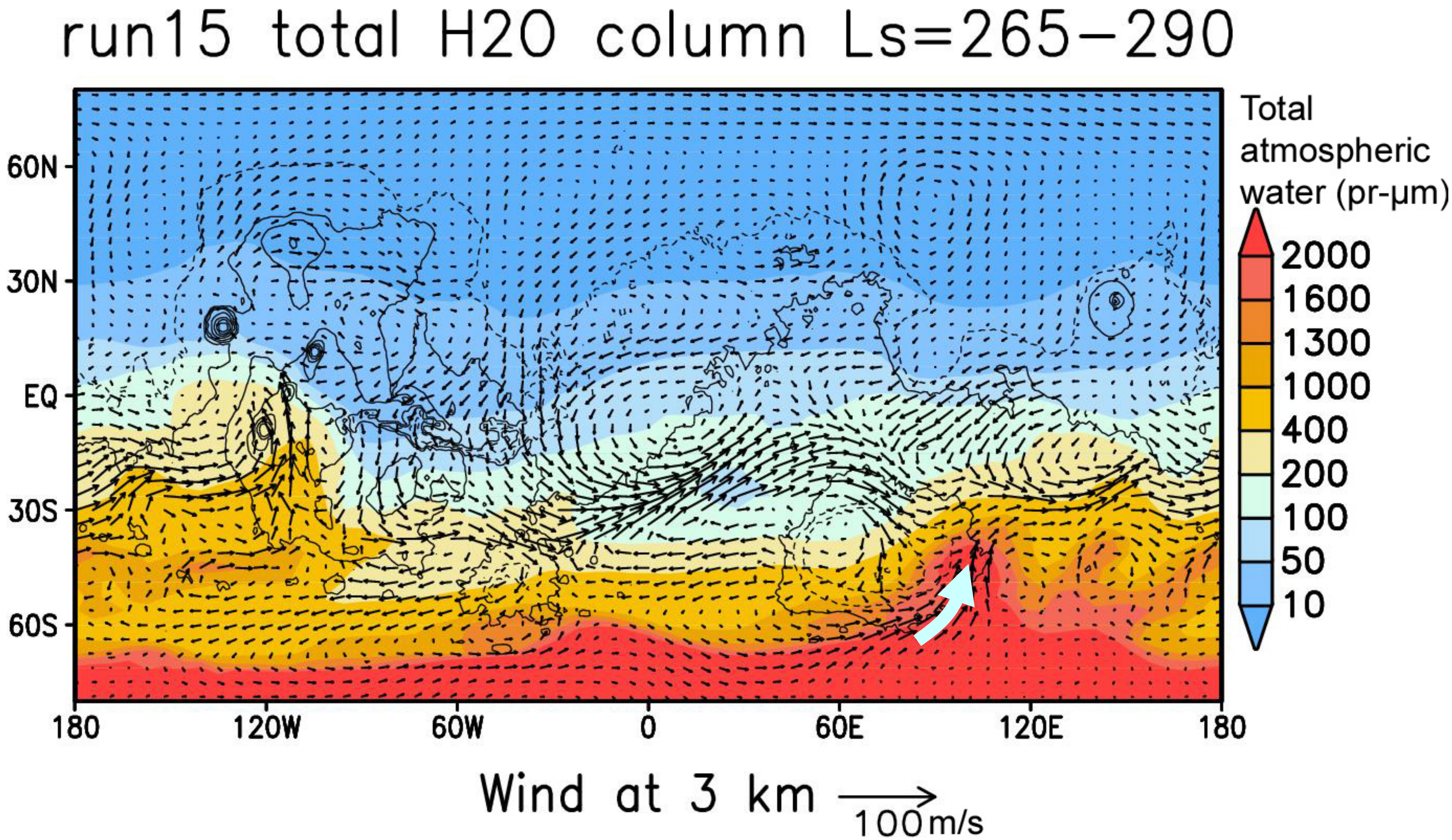
(Forget et al. 2005)

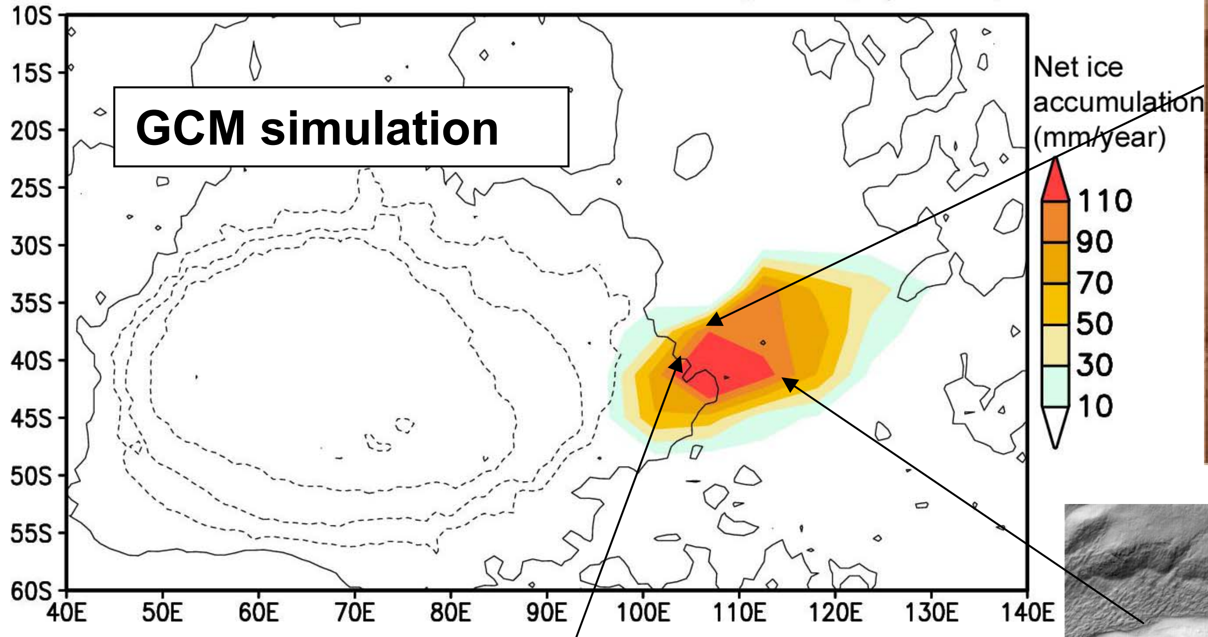
Yearly accumulation rate (mm/year) (1Oth year simulation)

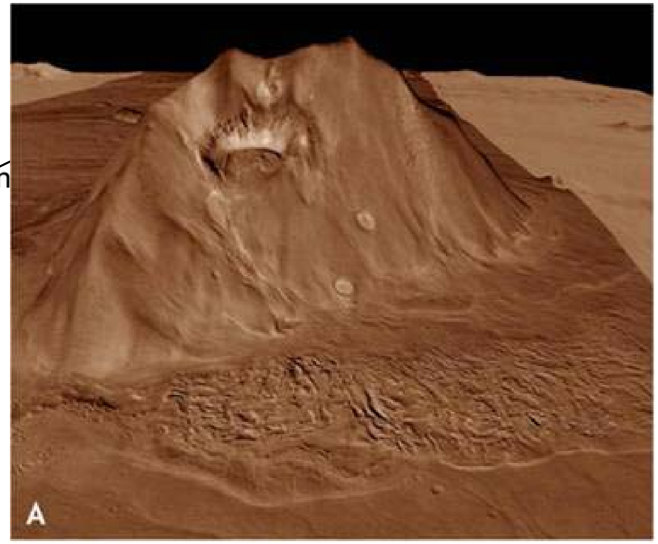


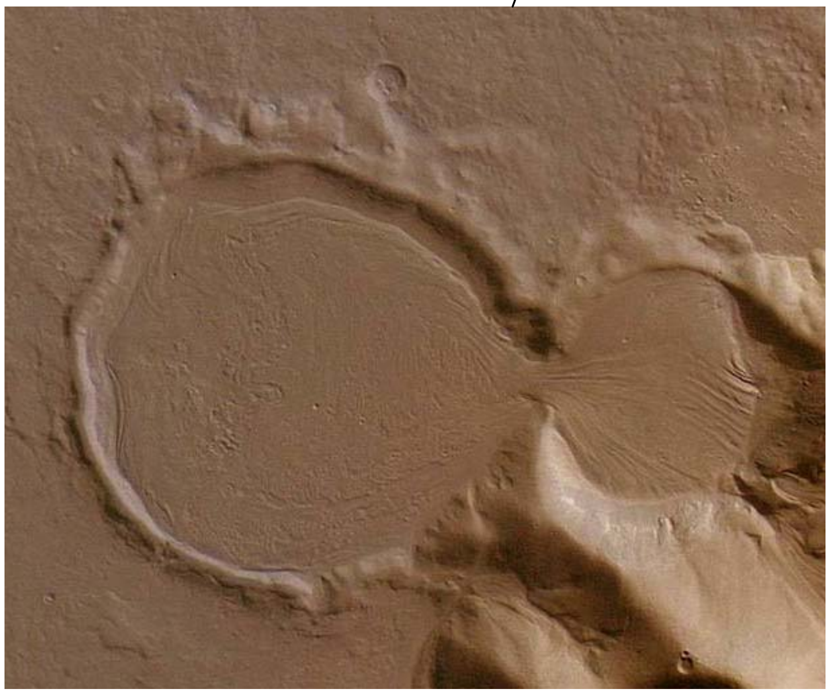


Surface ice at 110E 40S
Surface ice mass (kg/m2)
Ls (deg)
Southern summer
mulation (mm/year)
Summertime water vapor flux


run15 total H2O column Ls=265-290
60N
30N
EQ
30S
60S
180
120W
60W
0
60E
120E
180
Total
atmospheric
water (pr-μm)
2000
1600
1300
1000
400
200
100
50
10
Wind at 3 km
100m/s



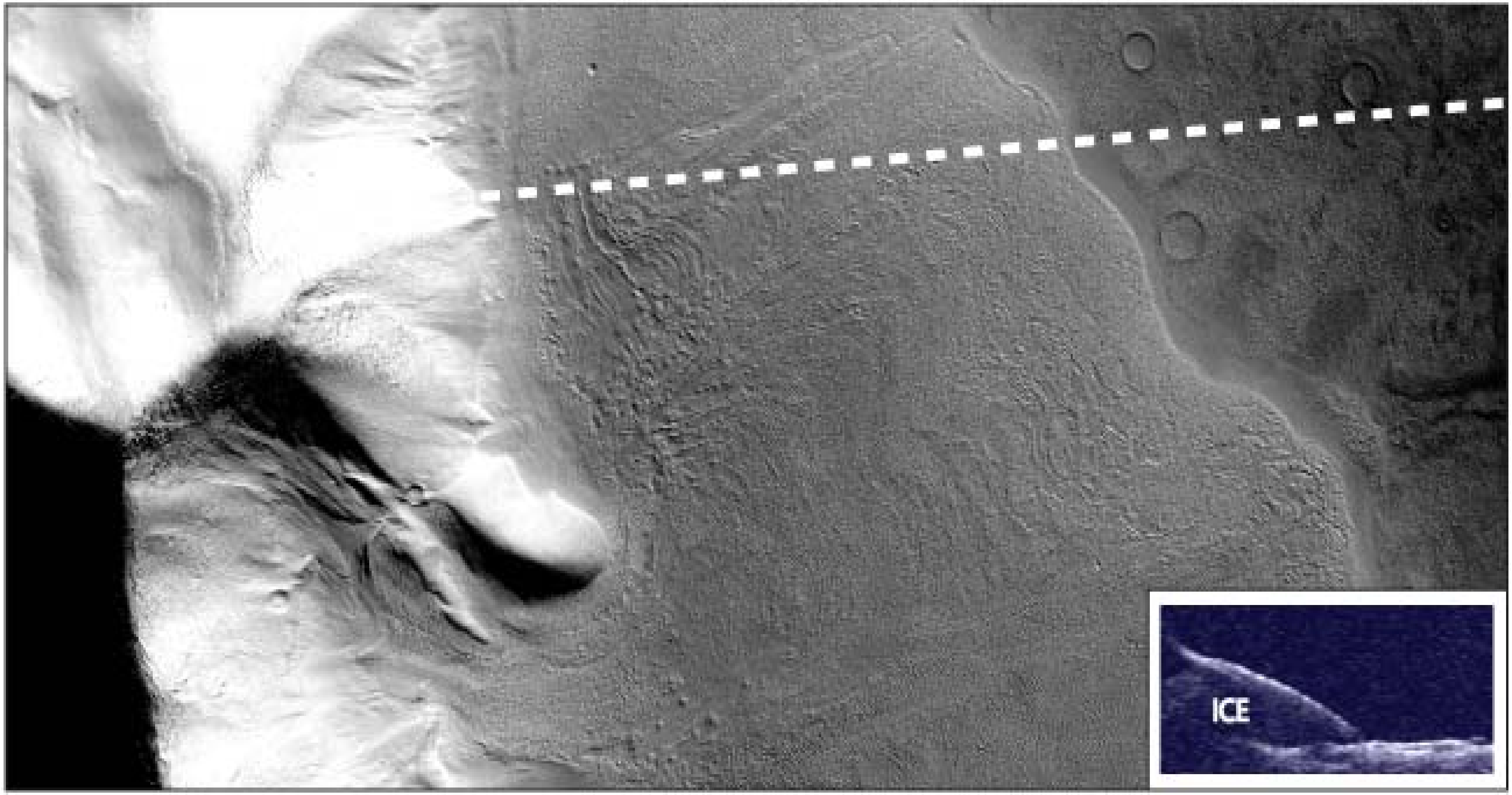


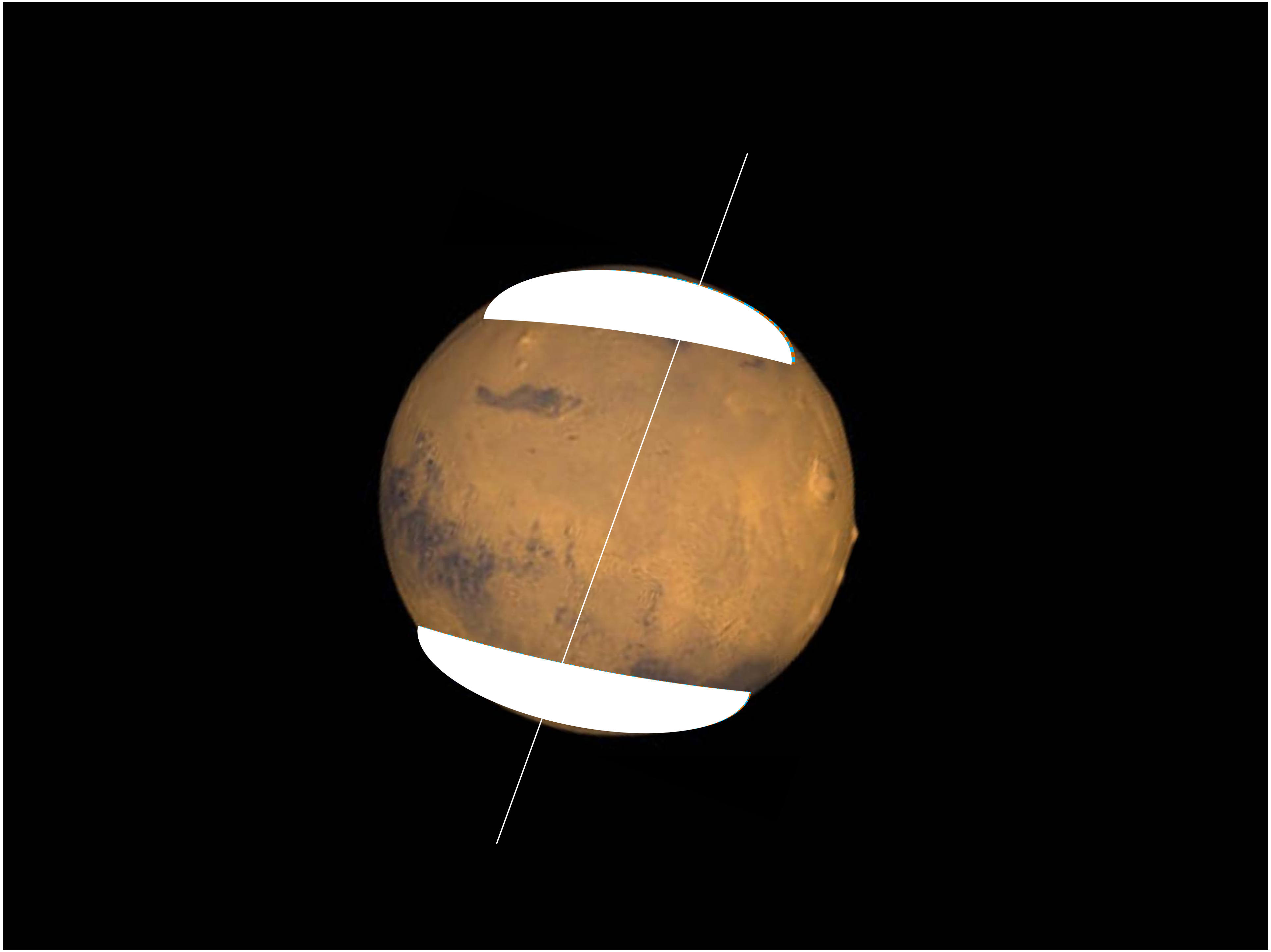


Head et al.
Hartmann et al.
Crown et al.
Etc…

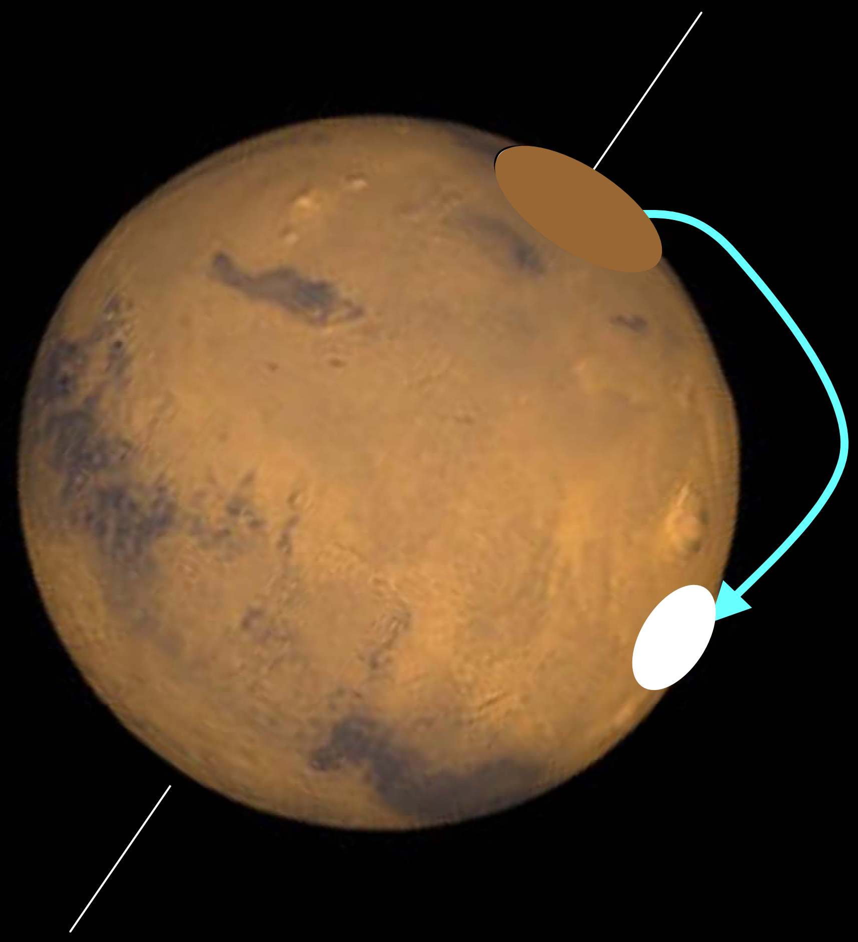
MARSIS Radar sounding of lobate debris aprons in eastern hellas: debris covered glacier

(cf. J. Plaut's talk)



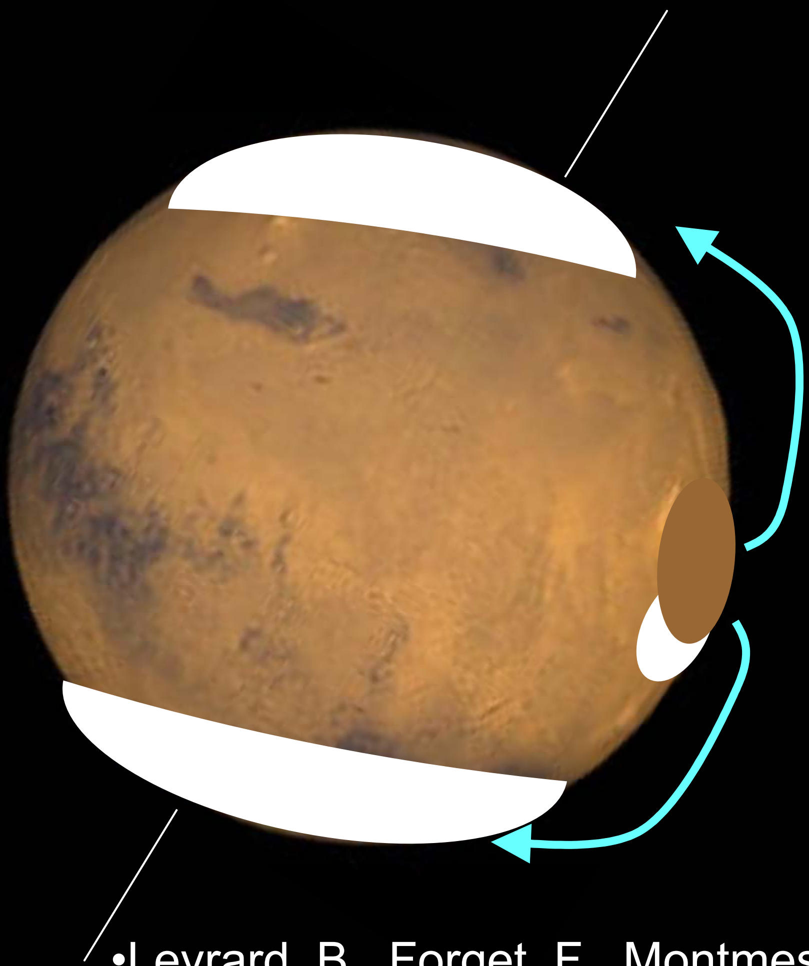


GCM simulation of high obliquity

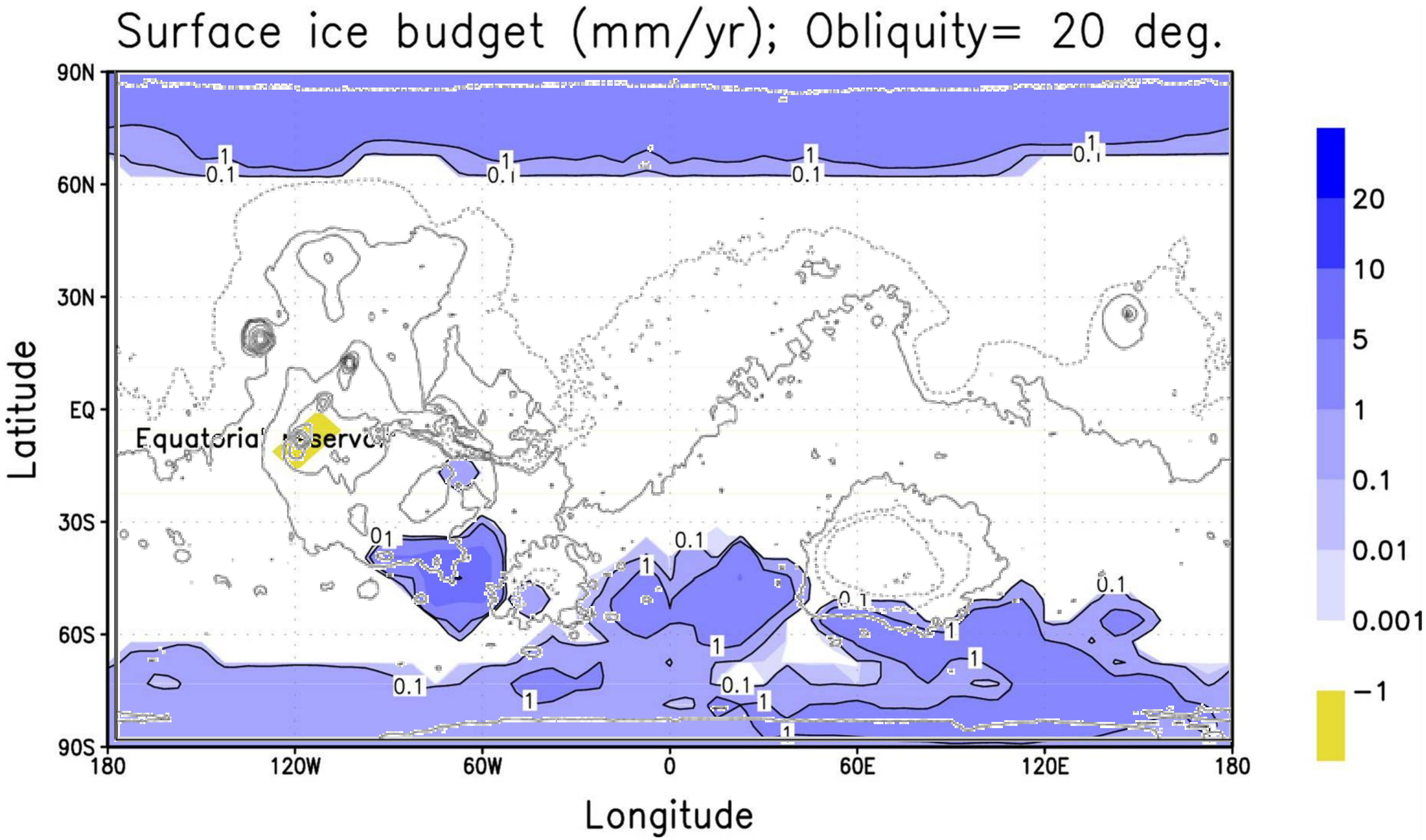


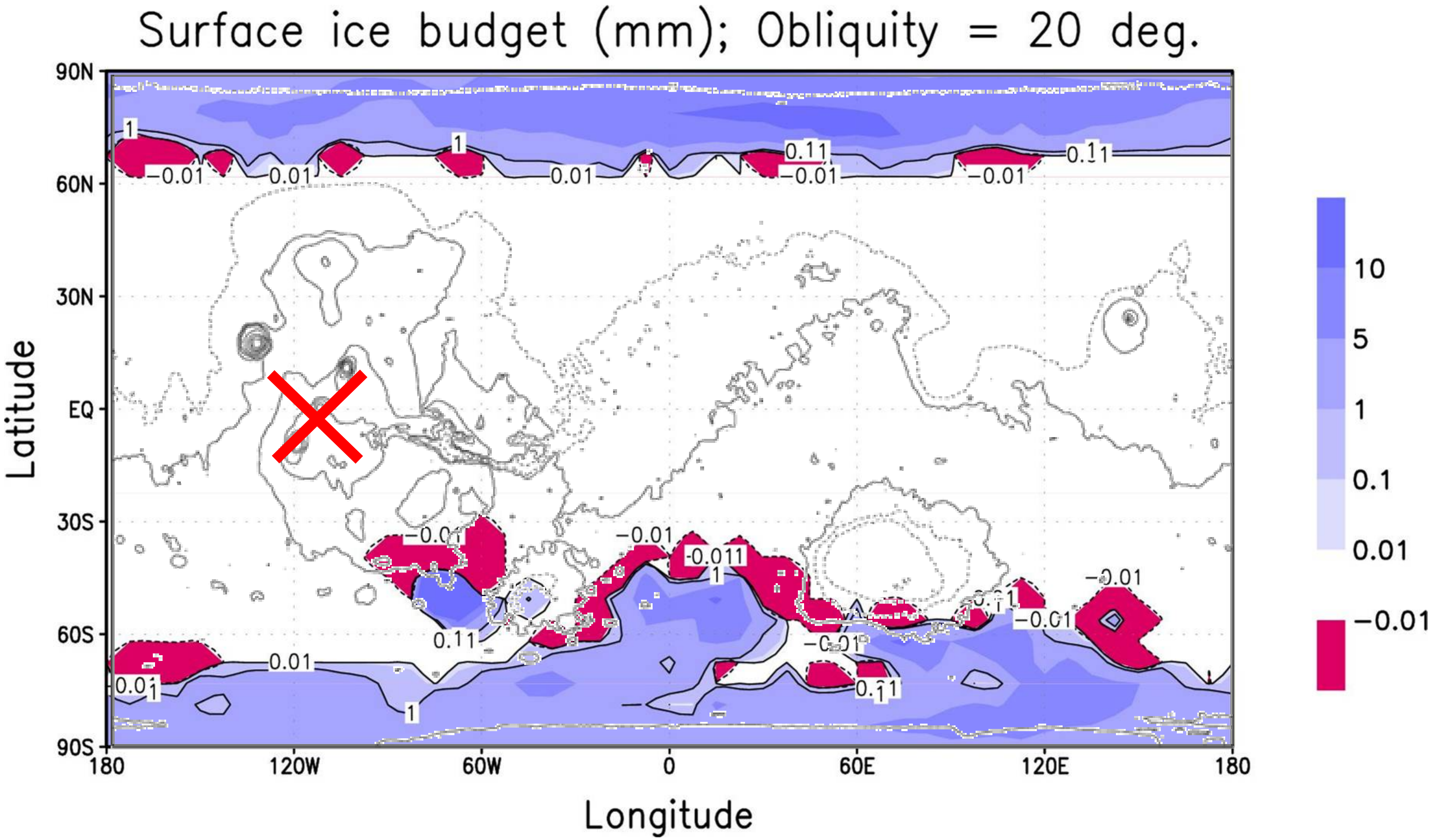
What happened next ?

Back from high obliquity to low obliquity

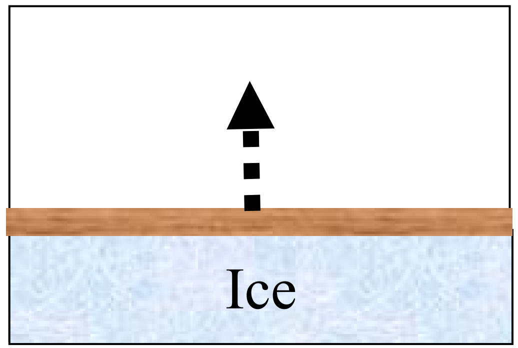


•Levrard, B., Forget, F., Montmessin, F. and Laskar, J. Recent ice-rich deposits formed at high latitudes on Mars by sublimation of unstable equatorial ice during low obliquity *Nature*, 431, 1072-1075 (2004)


Surface ice budget (mm/yr); Obliquity= 20 deg.
Latitude
Longitude
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
20
10
5
1
0.1
0.01
0.001
−1



Surface ice budget (mm); Obliquity = 20 deg.
Latitude
Longitude
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
10
5
1
0.1
0.01
−0.01

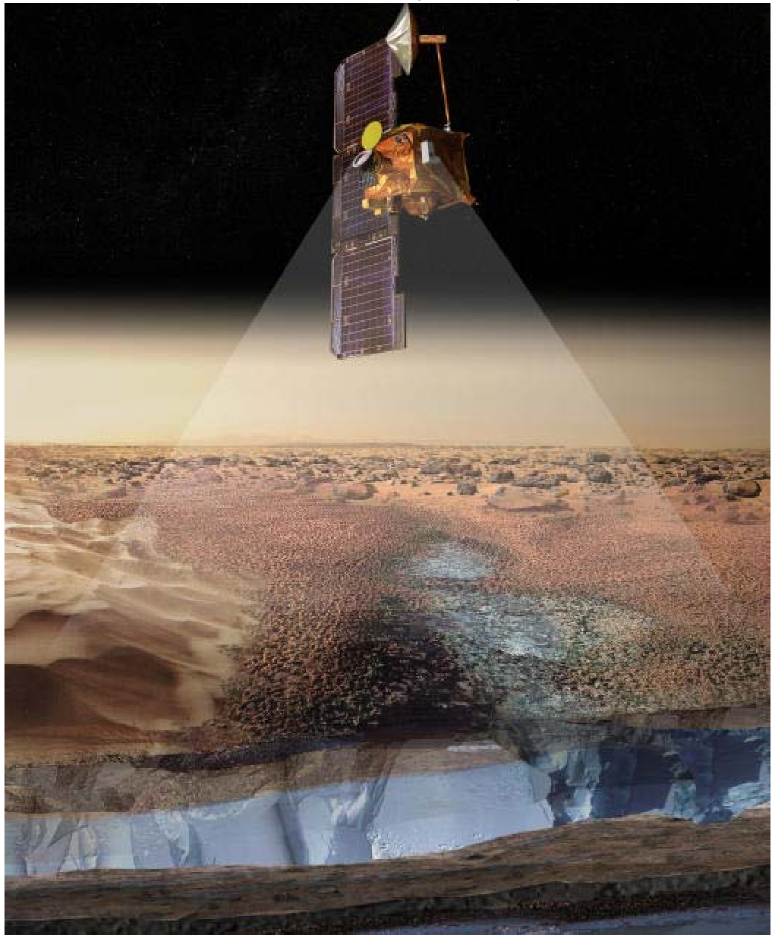


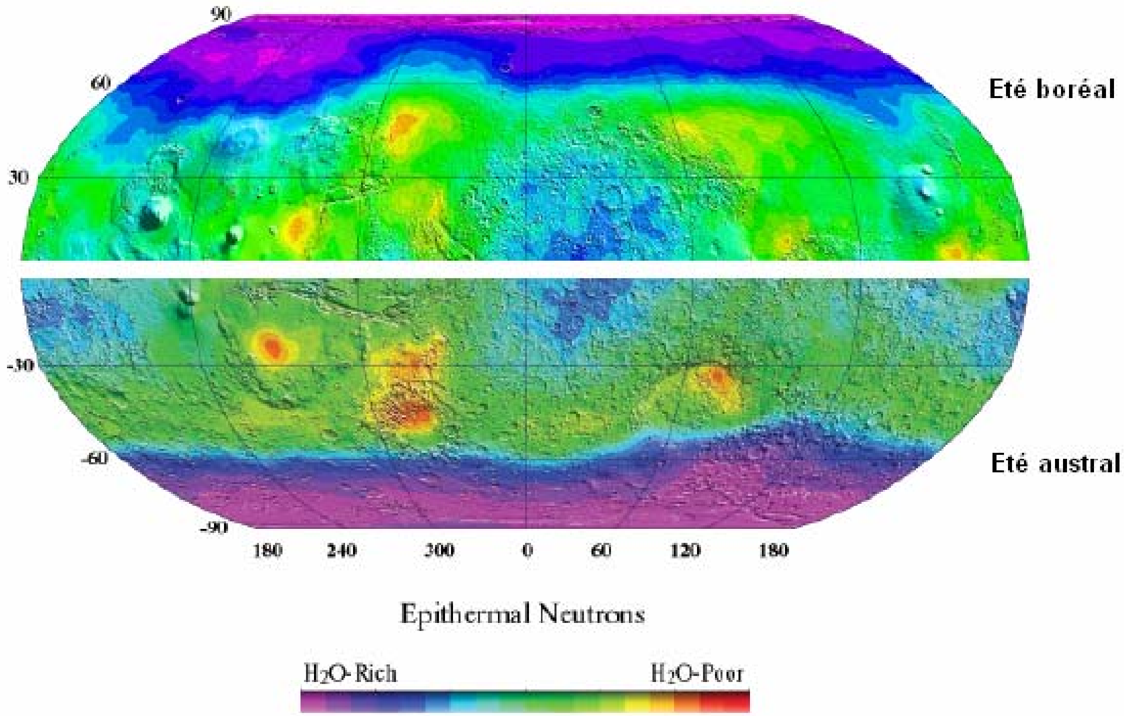
Mischna et al. 2003

Near surface ice detected by Mars Odyssey GRS

(Boynton et al., Feldman et al., Mitrovanov et al…)

NASA Mars Odyssey

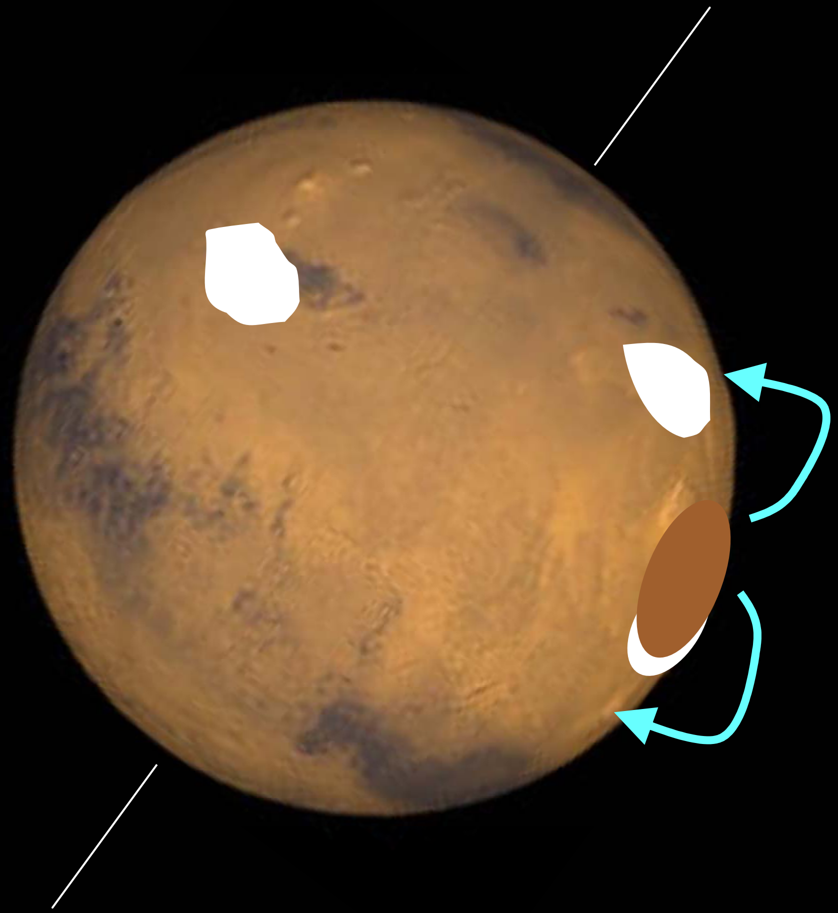


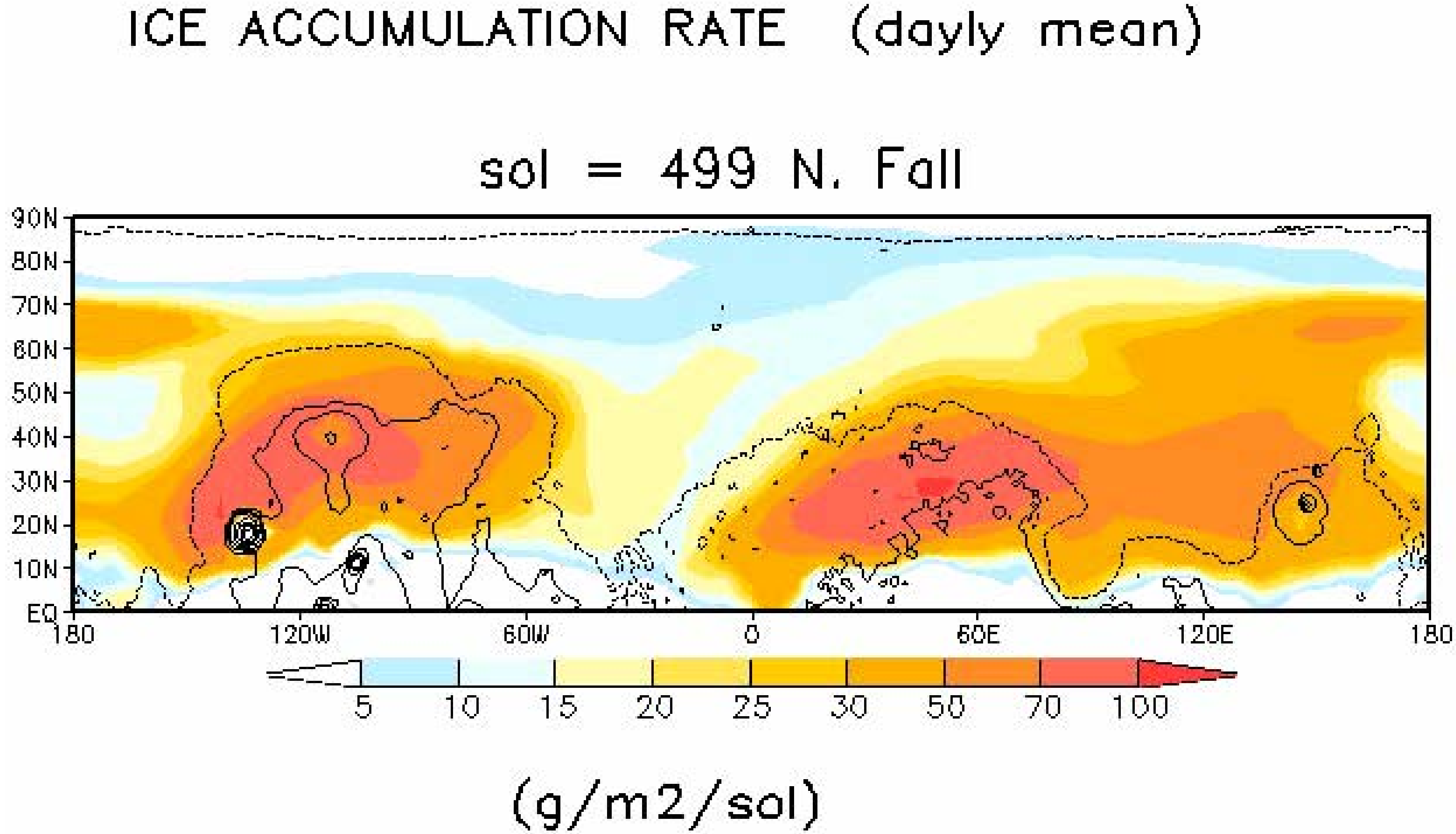


Back from high obliquity to low obliquity

WITH HIGH ATMOSPHERIC DUST OPACITY

(J-B Madeleine et al.)



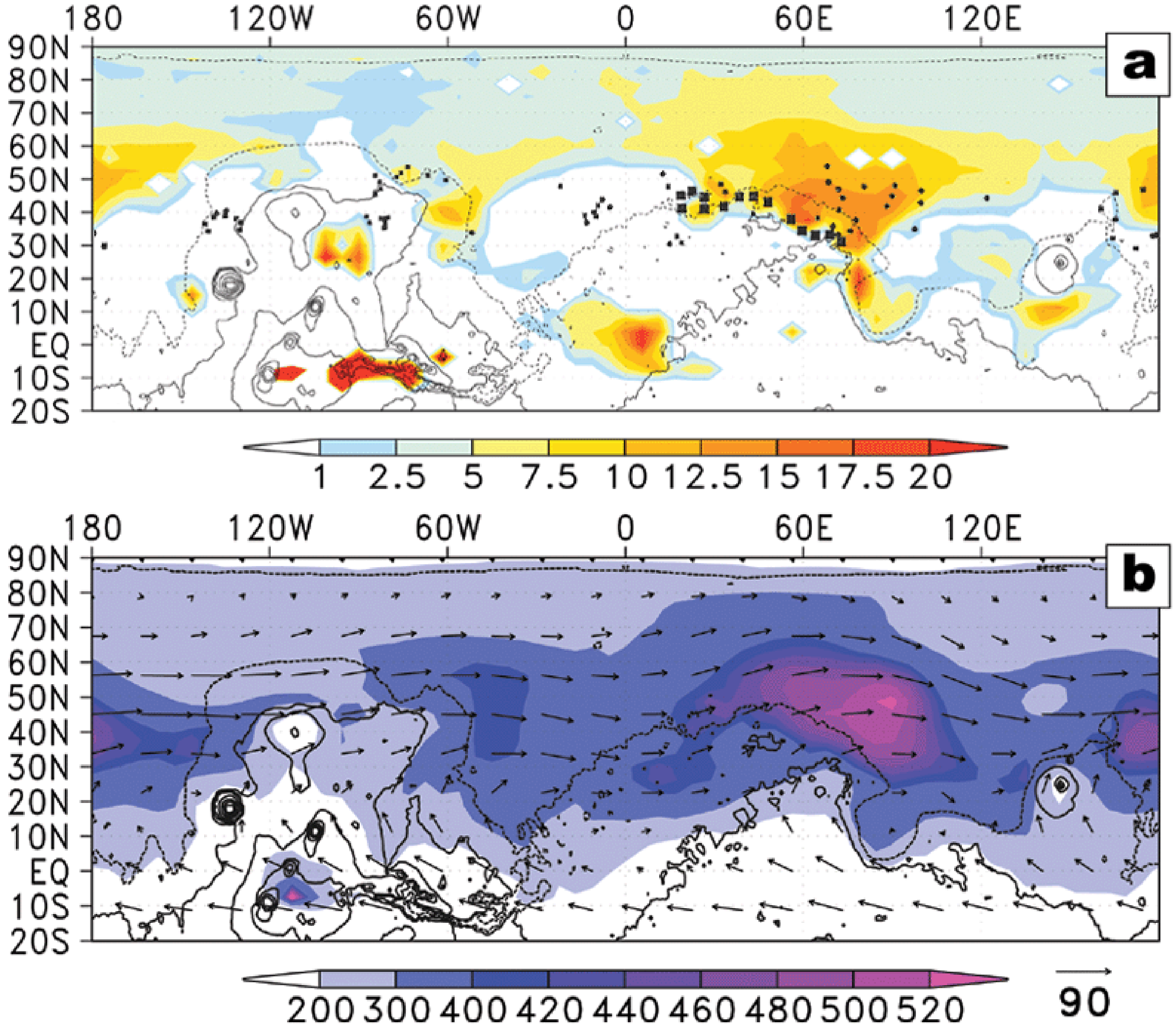

ICE ACCUMULATION RATE (dayly mean)
sol = 499 N. Fall
90N
80N
70N
60N
50N
40N
30N
20N
10N
EQ
180
120W
60W
0
60E
120E
180
5
10
15
20
25
30
50
70
100
(g/m2/sol)

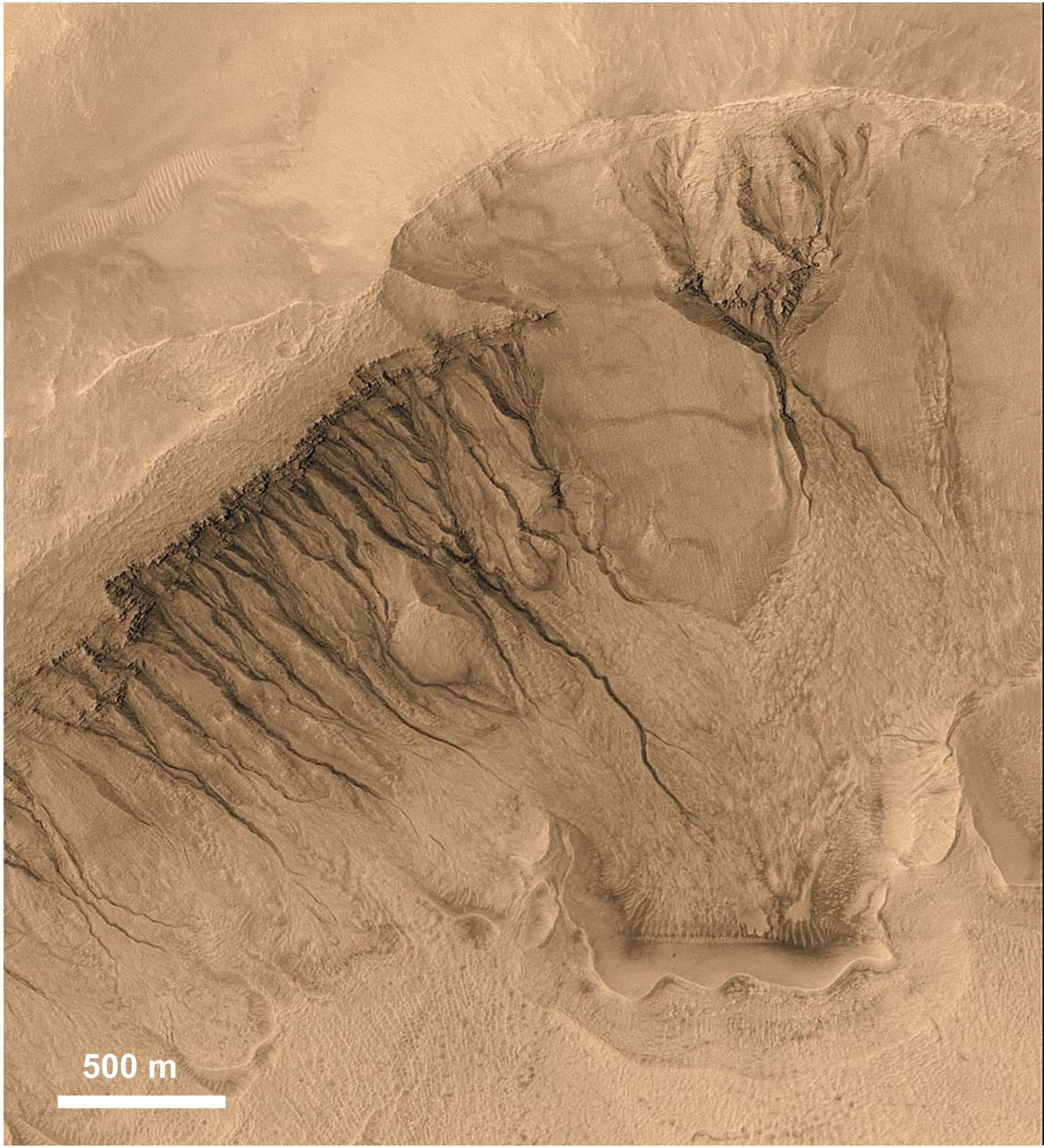
Dust opacity = 2.5 **Obliquity = 35°** **Ls(perihelion)=270°** **Water source = Tharsis Glaciers**

Yearly Ice accumulation (mm/yr)

Cloud (pr-µm) and winds during Northern winter (Ls=270-300°)

Head et al. 2006





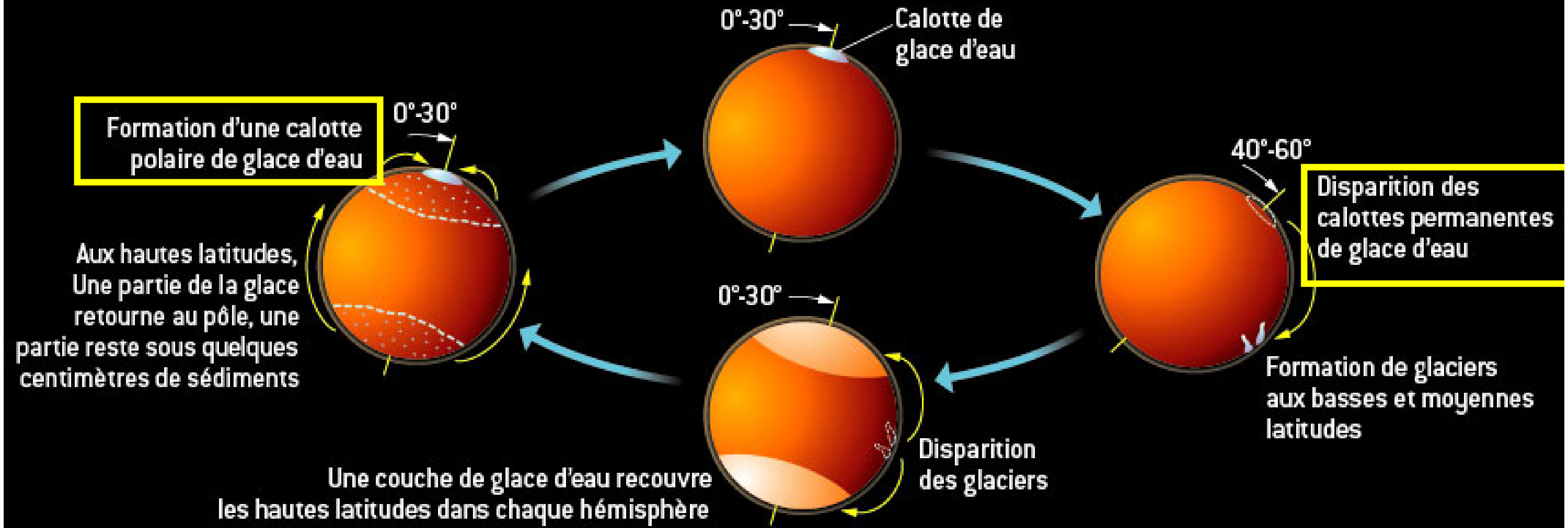
Gullies “recently” formed by liquid water

• subsurface aquifer ?
(Malin and Edgett. , Mellon et al. , Heldman et al.)

• Melted ice at high obliquity
(Costard et al., Forget et al. , Williams et al.)

Malin and Edgett, 2000

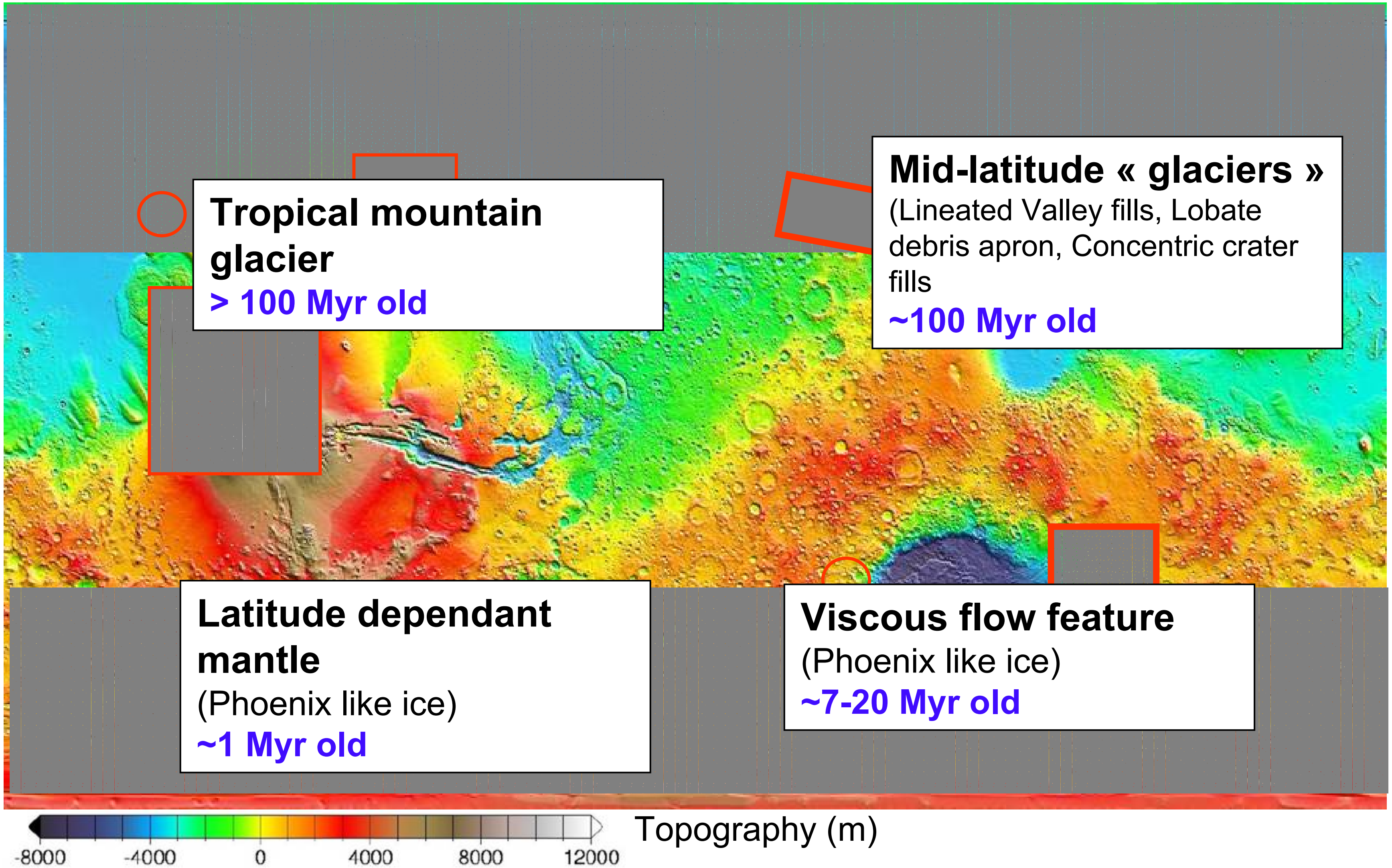
SO, the same present day climate system than today, but forced by obliquity variations, has been able to



- **Can we use the modeled past climates to reconstruct the north polar layered deposits history ?**
- ⇨ *Levrard et al.*, **JGR**, june 2007
-

It's a nice story, but…. Some caveats:

Can we reconcile the age of the icy landforms with the climate models ?



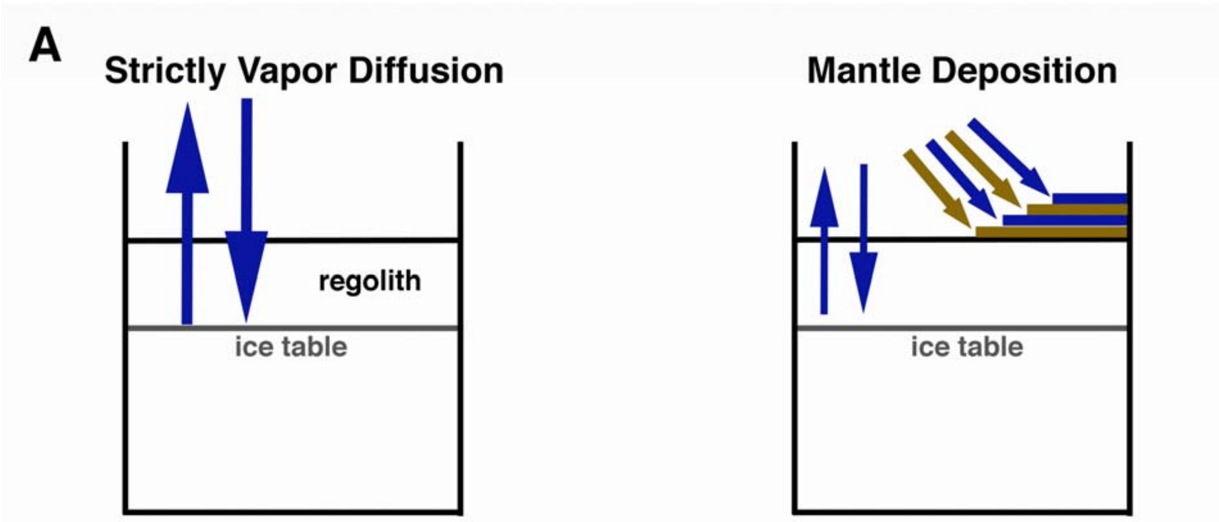
Age from J. Head's team : R. Miliken,

An ongoing hot debate on ice

What is the origin of the latitude dependant ice mantle ?

- **Diffusion of atmospheric water vapor into and out of a porous regolith forms ice-cemented soils ?**
- **Past atmospheric deposition of ice, snow, and dust produces dusty ice-rich layers which have partly sublimed.**

- Both are consistant with the fact that water ice is currently in equilibrium with the atmosphere *(Mellon et al. 2004, shorgoffer 2007)*



Head et al.

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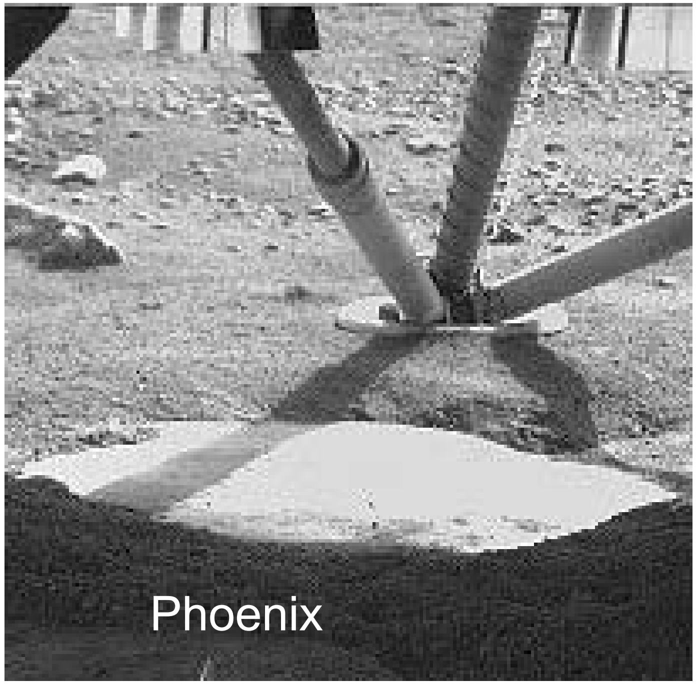
- **Pro snow**: Phoenix and GRS ice appear to be quite pure !
- **Pro diffusion**: Analysis of phoenix observations by *Mellon et al. (2009)* conclude : « The origin of these relatively pure ice deposits appears most consistent with the formation of excess ice by soil ice segregation, such as would occur by thin film migration and the formation of ice lenses, needle ice, or similar ice »



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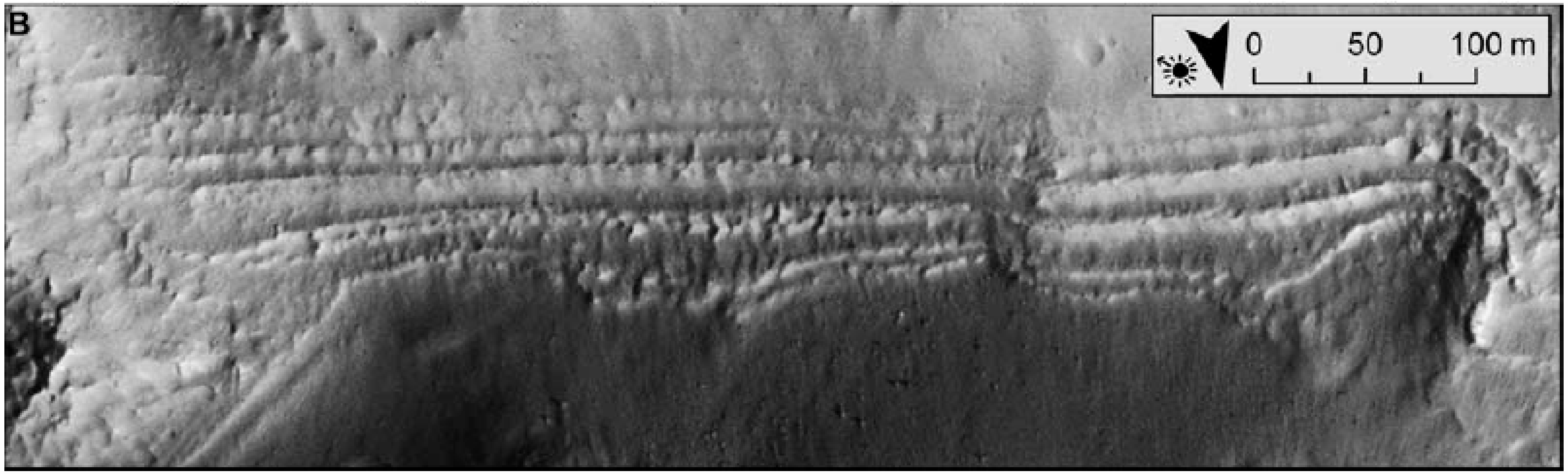

- **Pro snow** : outcrops of dessicated mantle at low latitudes show meters-thick layers *(Shon et al. 2007)*
-

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- **Pro snow** : outcrops of dessicated mantle at low latitudes show meters-thick layers *(Shon et al. 2007)*
- **Pro diffusion :** Ice down to 30°lat better explained with than snow with present GCMs

- **A suggestion** : the dessication of « past snow » may look like ice Ice-cemented soil *(shorgoffer 2007)*

Are current Mars Climate models really able to simulate past climates and water cycles ?

Several physical processes must be better taken into account (1/2):

- Radiative effect of thick clouds
- Radiative effects of water vapor
- Microphysics of precipitation : dust scavenging, coalescence
- Change of thermal inertia due to thick seasonal and permanent ice deposits

Are current Mars Climate models really able to simulate past climates and water cycles ?

Several physical processes must be better taken into account (2/2):

- Latent heat release at « high » ice temperature
- In depth absorption of solar photons in snow/ice deposits (key role in surface ice temperature, sublimation and melting)
  (see Clow 1980, Williams, Toon et al. 2008)
- Effects of lag deposits when subliming long terme reservoir (cap, glaciers, ice mantling).

Conclusions

- Models of Current Mars water cycle shows that the current Mars Climate system has been able to move large amount of water around the planet ⇨ Allowed to suggest various mechanisms to explain ice related geological features.
- « Accurate » quantitative simulation of past climates requires improved water cycle models.