Mars Past Climates

François Forget

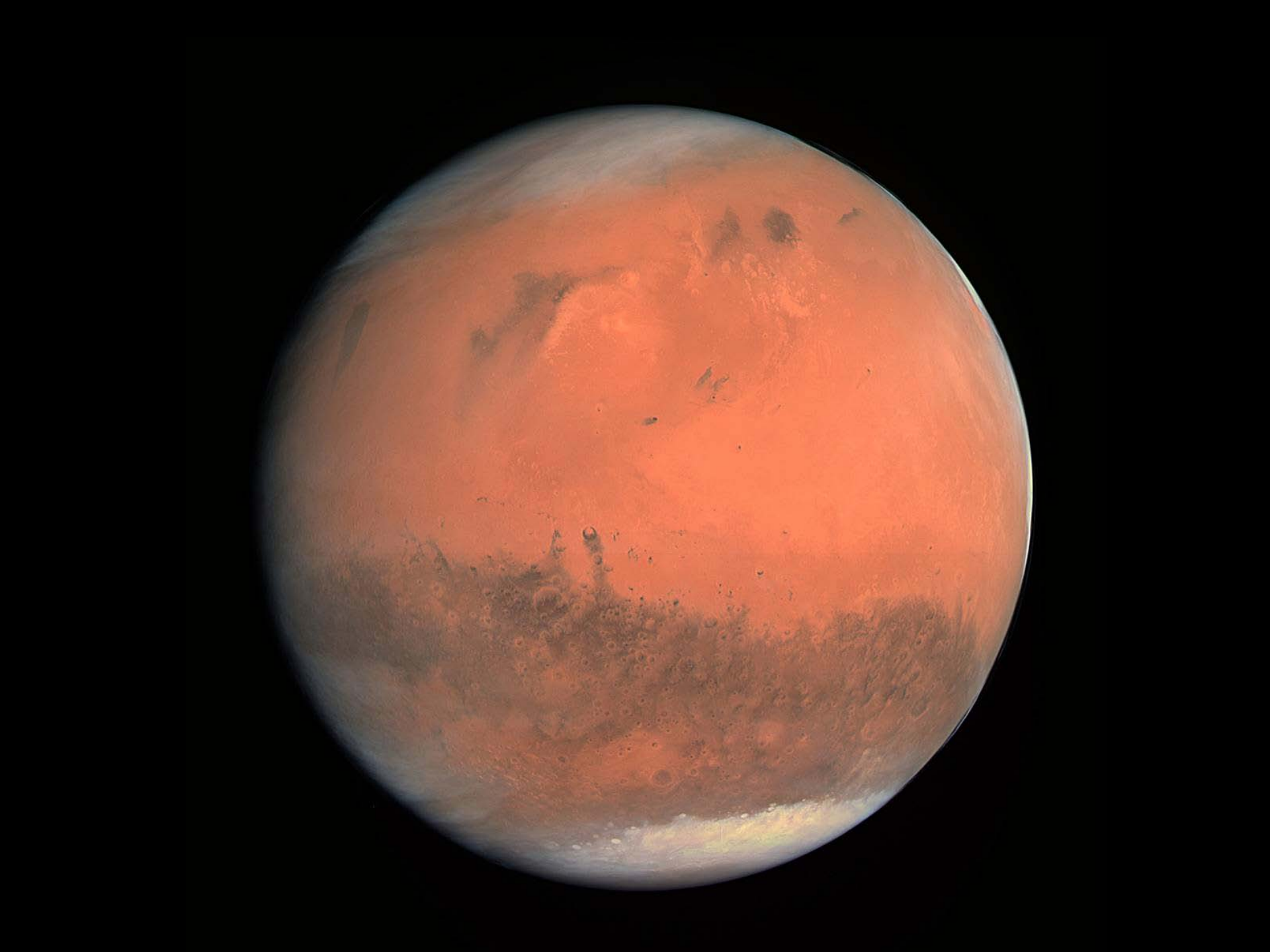
CNRS, Laboratoire de Météorologie Dynamique, IPSL, Paris, France

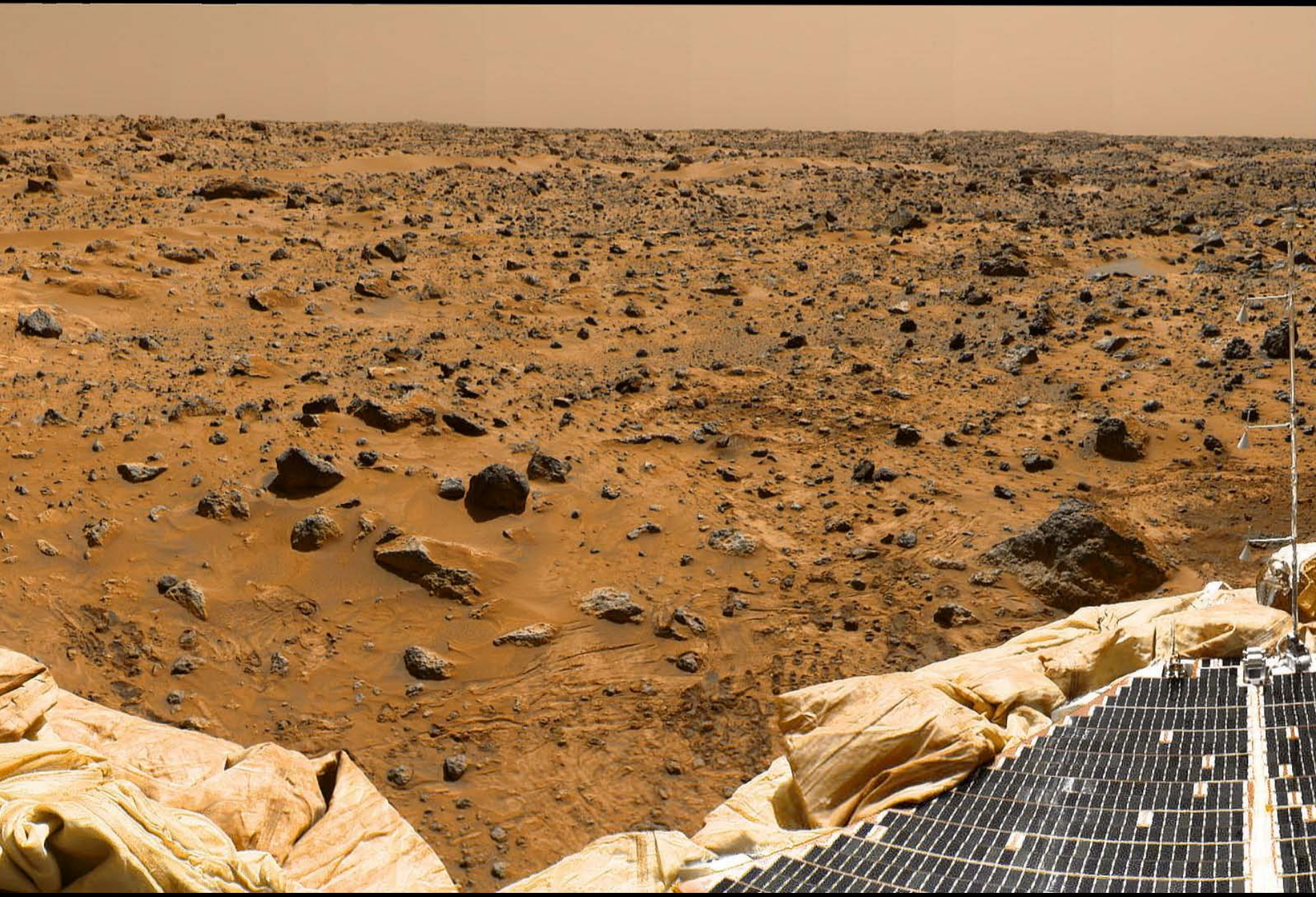
Outline

- Foreword : Mars present-day climate and water cycle (*more on this tomorrow*)

- "Recent" climate variations (10^6 – 10^8 years ago)
  - Past climate variations revealed by icy landforms
  - Simulating and understanding past climate variations

- The early Mars climate (~3.8 billions years ago)
  - Was why early Mars climate different ?

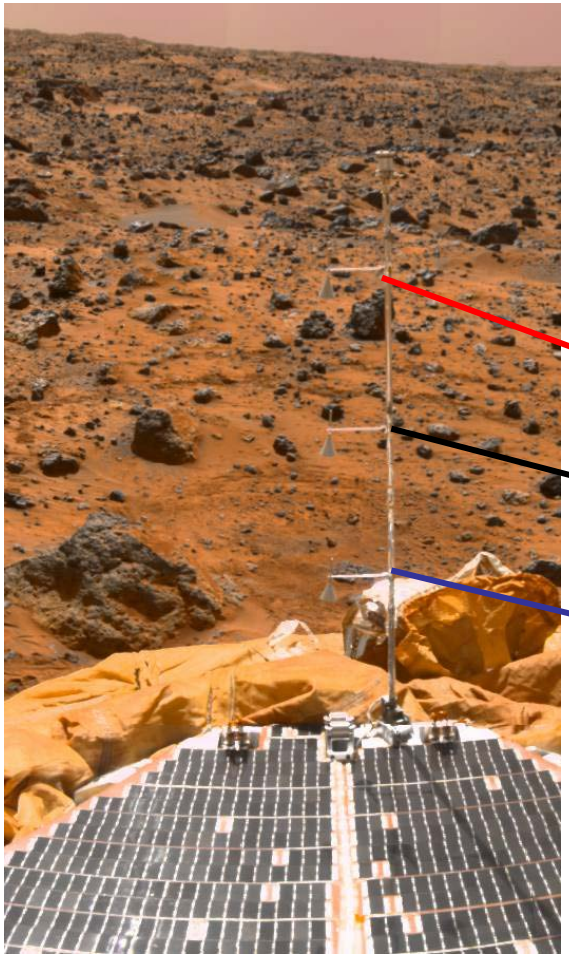


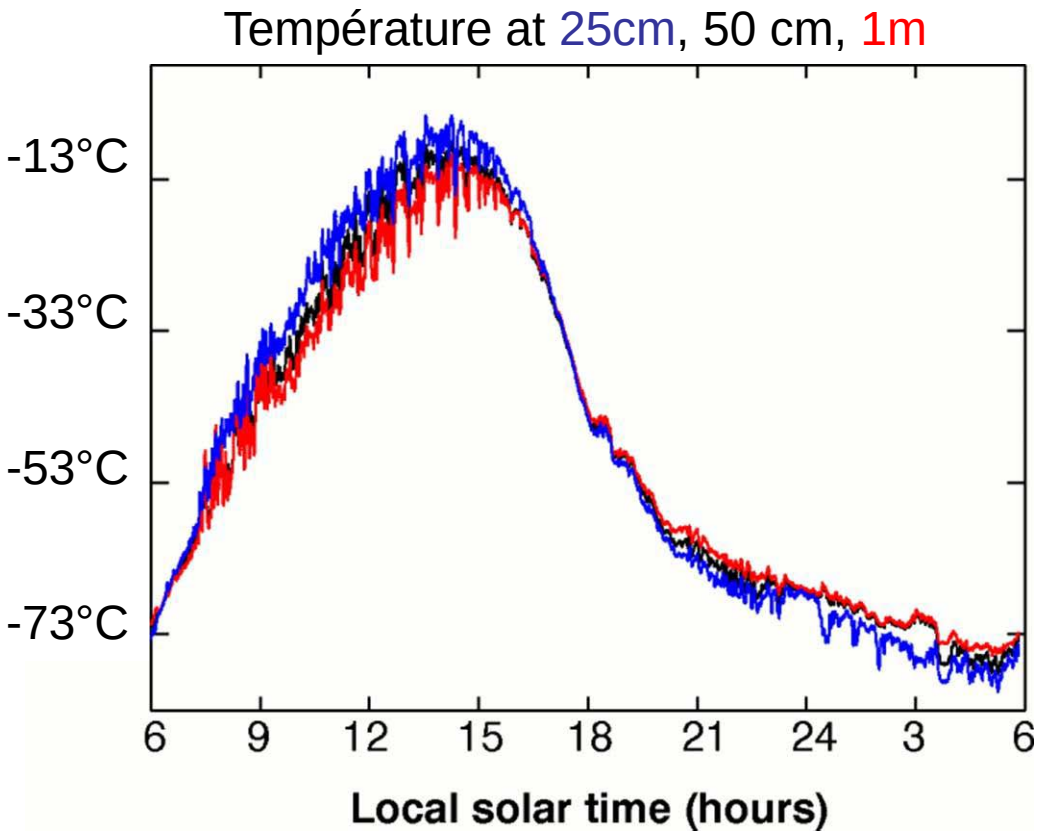


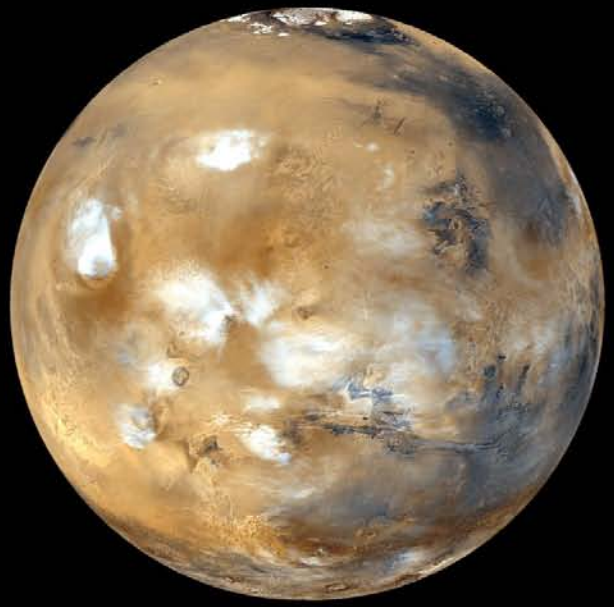
On the surface (Mars Pathfinder 1997) : atmosphere : 5 to 10 hPa , 95%CO_2

Near Surface Temperature on Mars

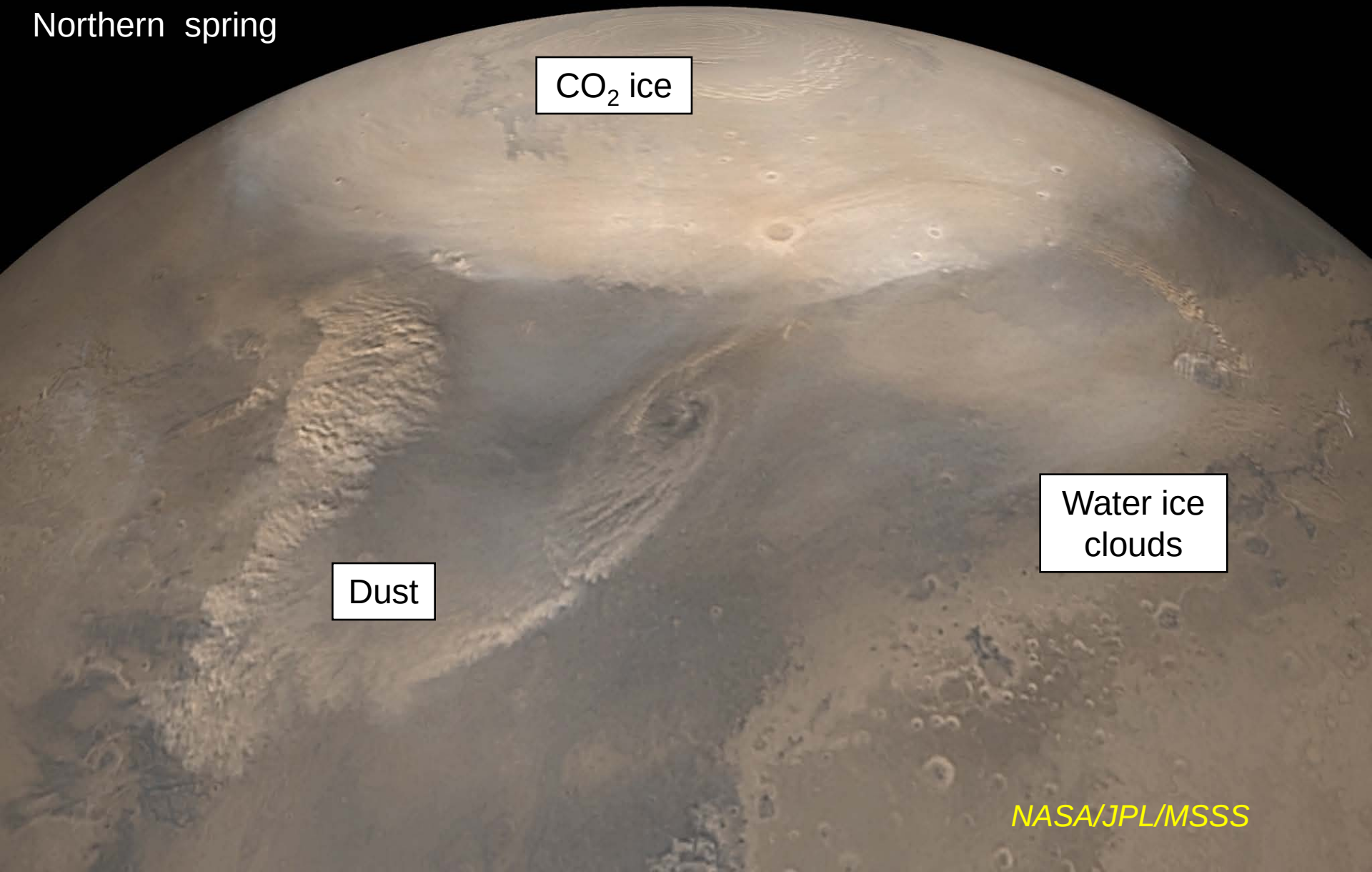
(Pathfinder, july 1997, martian summer 20°N)



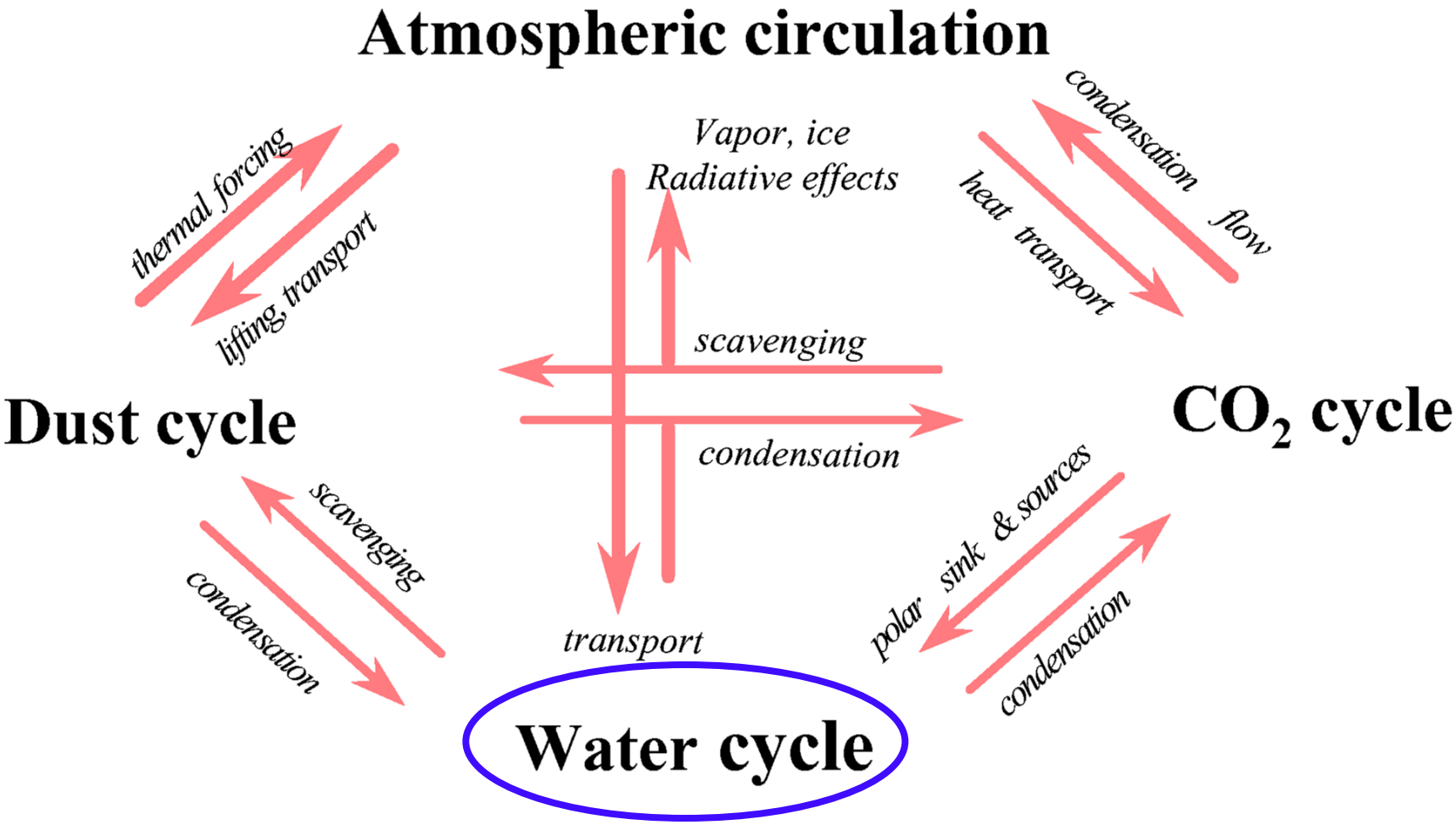




Mars climate now : atmospheric circulation, dust , CO2 (and some water)

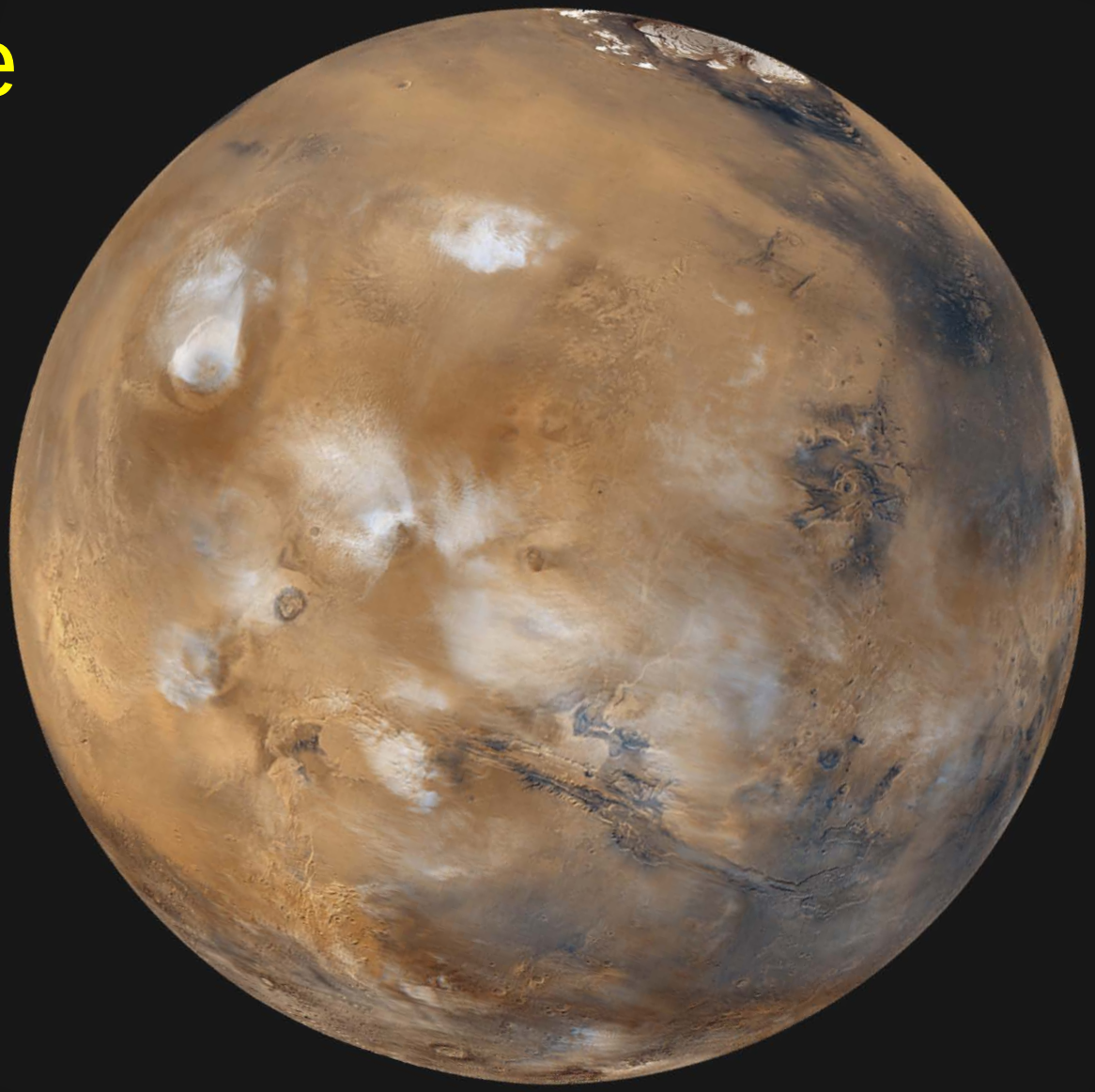


Mars climate : a complex system

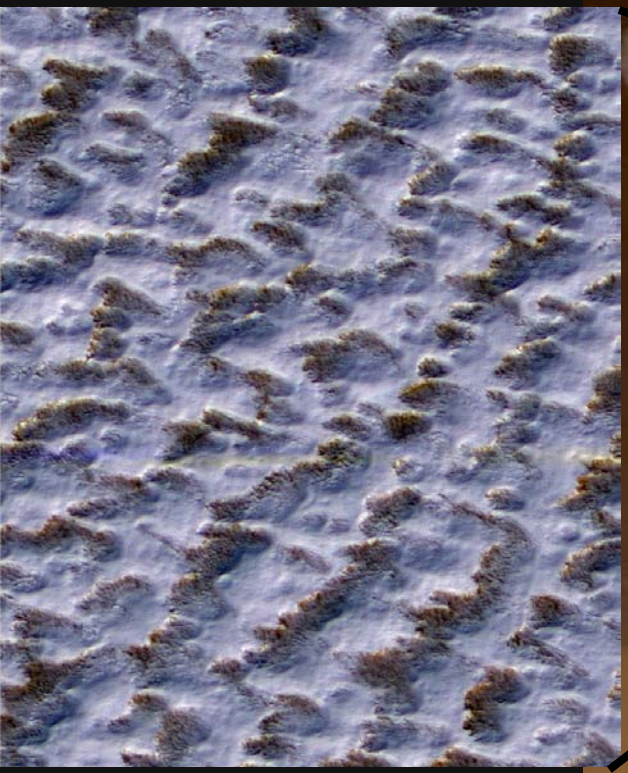


More on this tomorrow 10:00-11:30: "The present-day Mars Climate system"

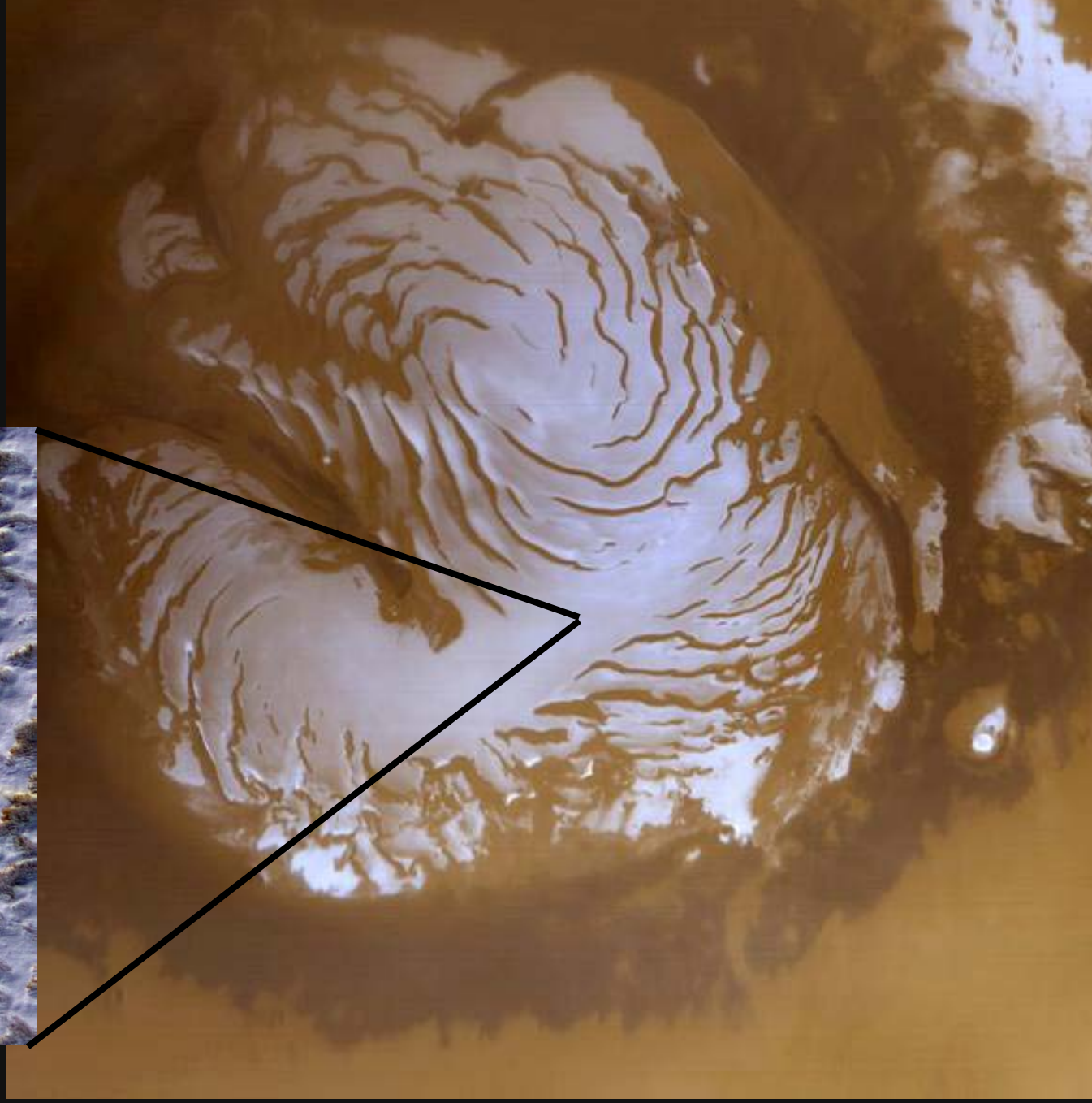
Mars water cycle



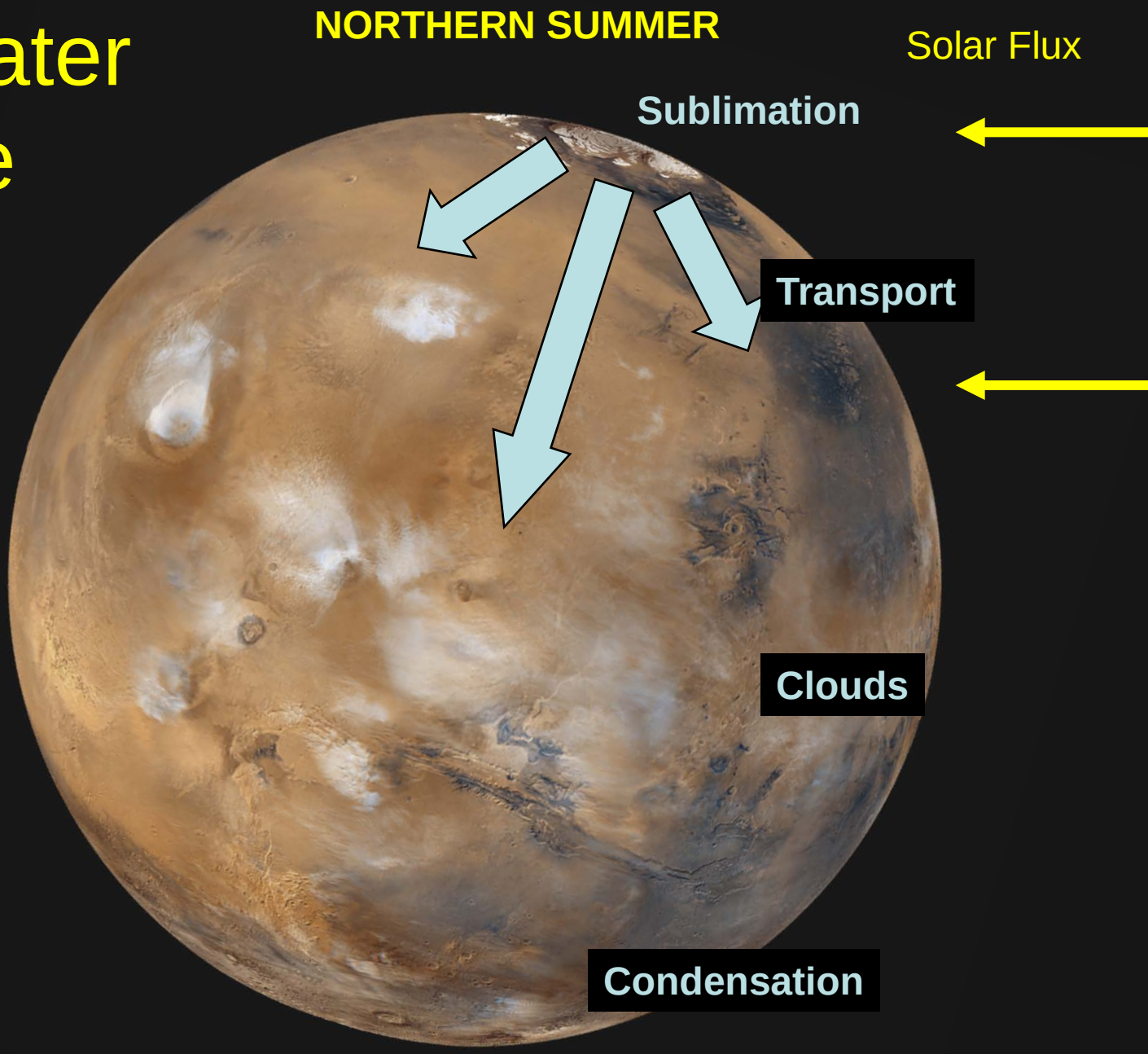
Around North Pole : a relatively fresh and pure water ice layer interacting with the atmosphere (diameter : 1000 km)



MRO Hirise

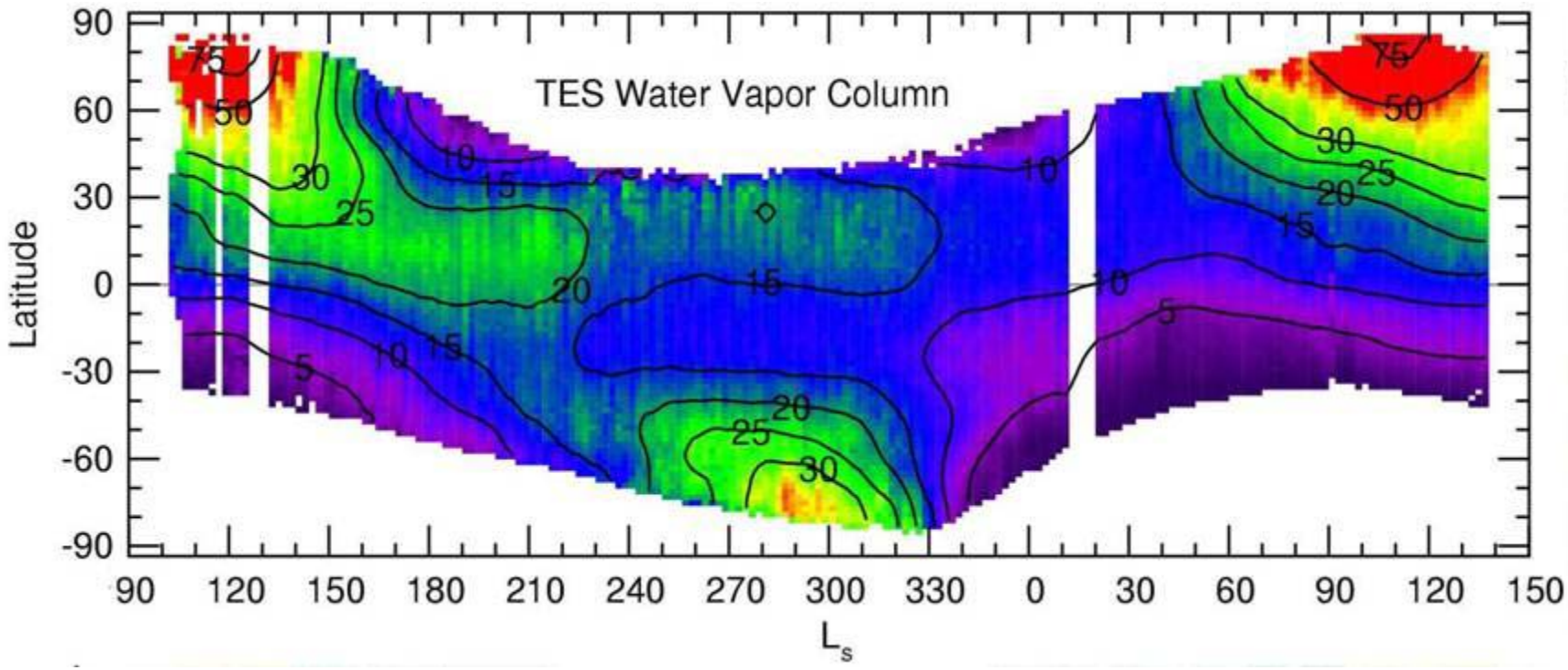


Mars water cycle



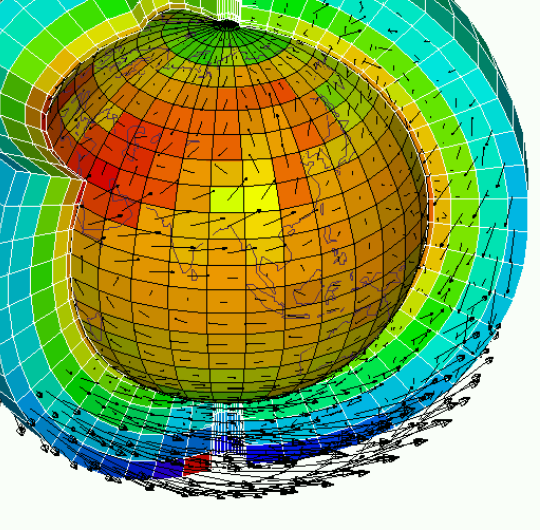
Mars water vapor cycle

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

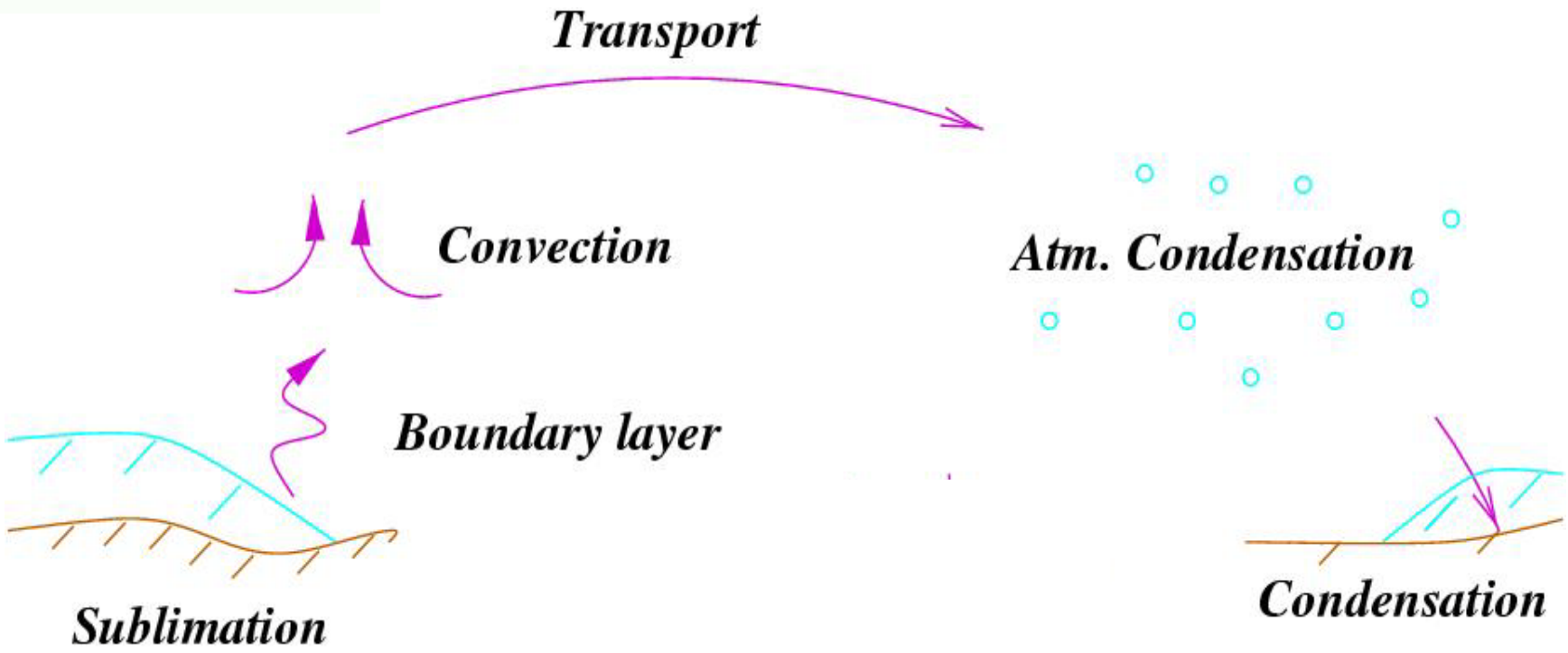


N Summer Fall Winter Spring Summer

Other observations from SPICAM, Omega, PFS, CRISM

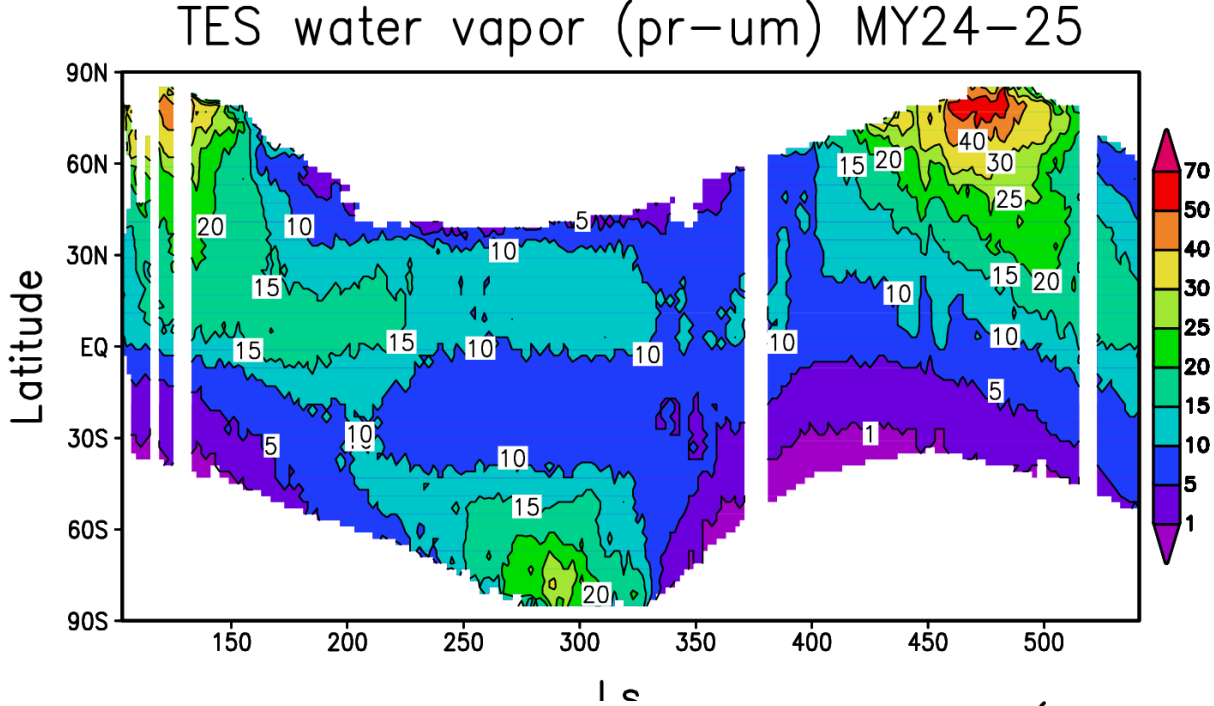


Numerical simulations of the water cycle with Global Climate Models

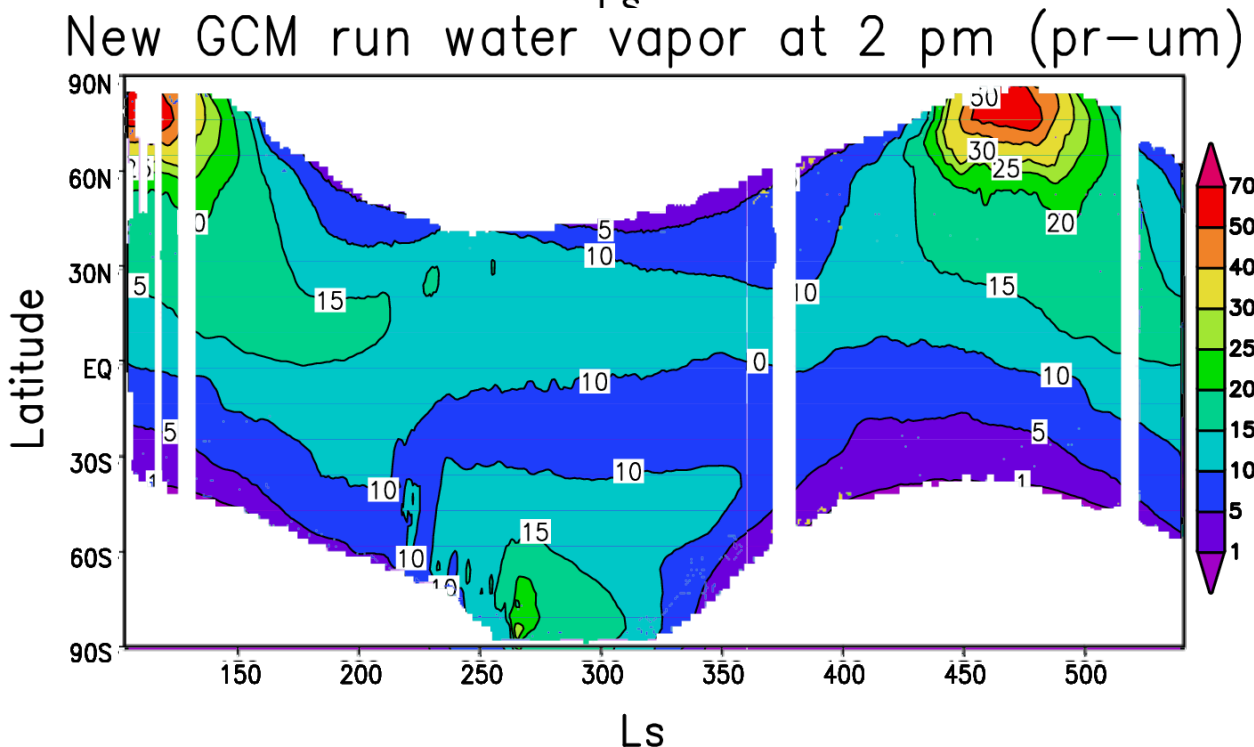


SEASONAL WATER CYCLE

OBSERVATION

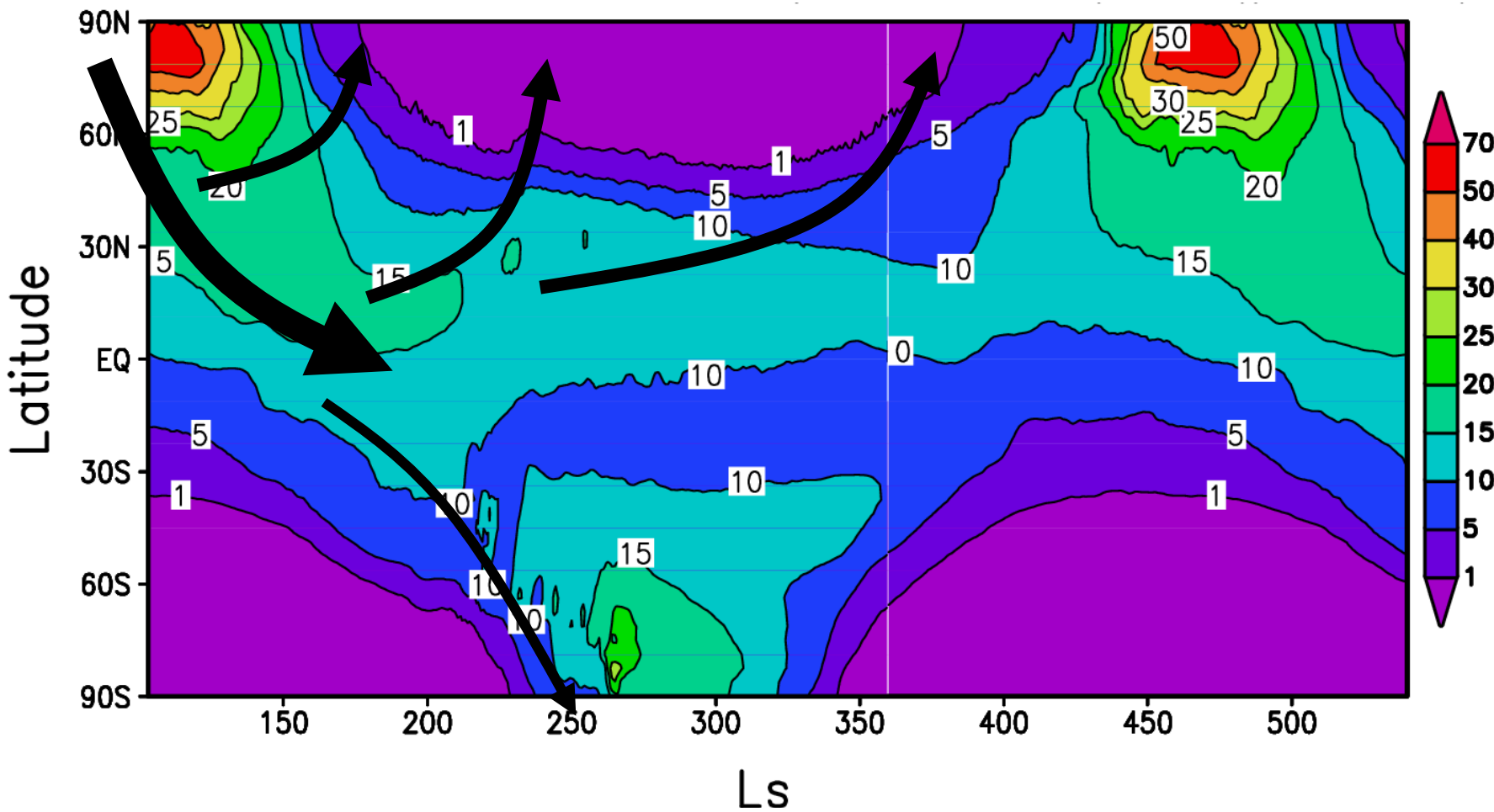


MODEL



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

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



SIMULATION of Mars water cycle: 2) water clouds

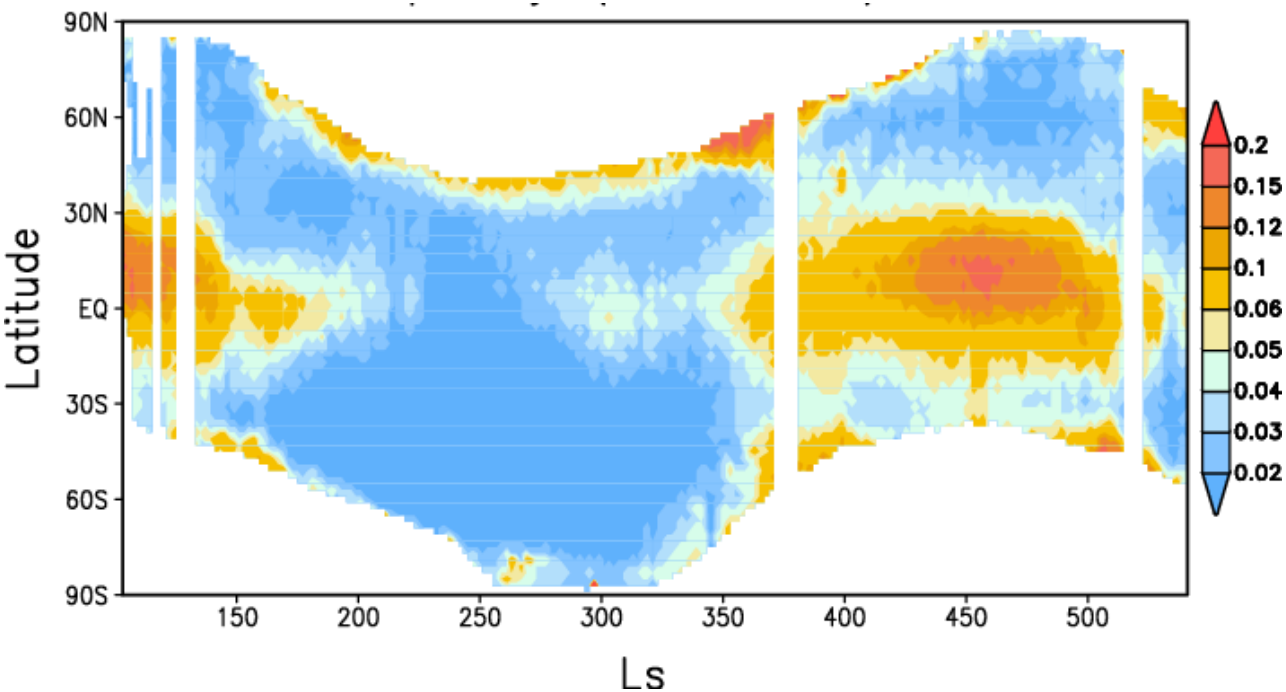
Observations

TES ice absorption opacity

2pm

(825 cm-1)

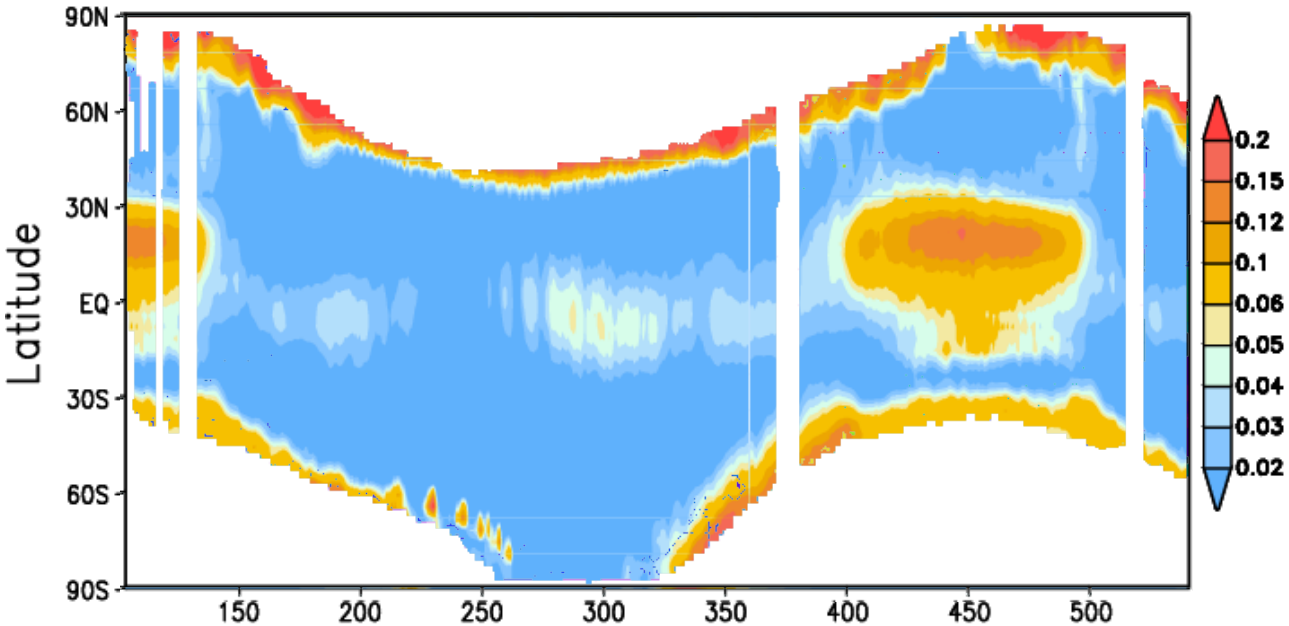
MY24-25



Model

LMD GCM ice absorption opacity

2pm

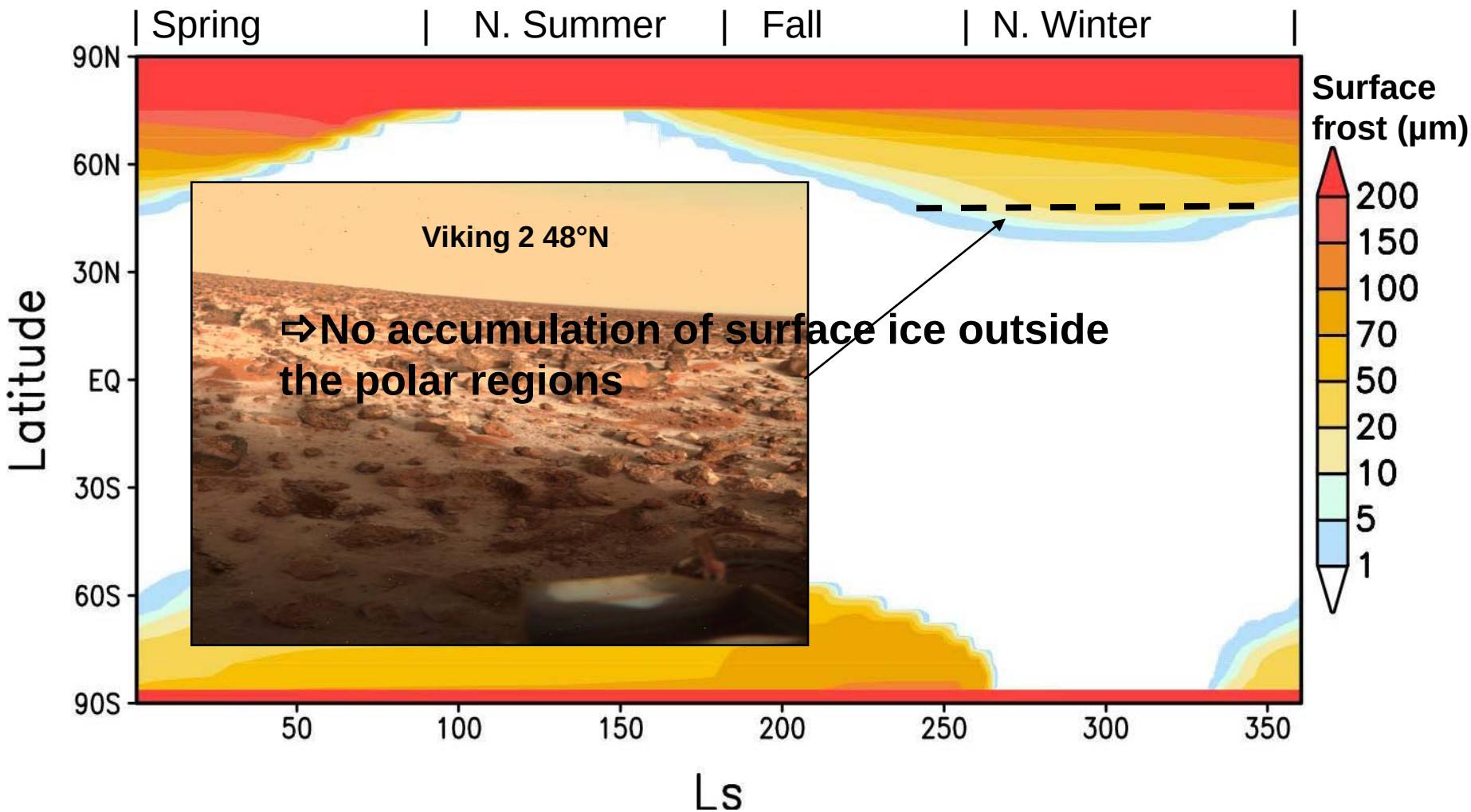


Formation of water ice frost on the surface

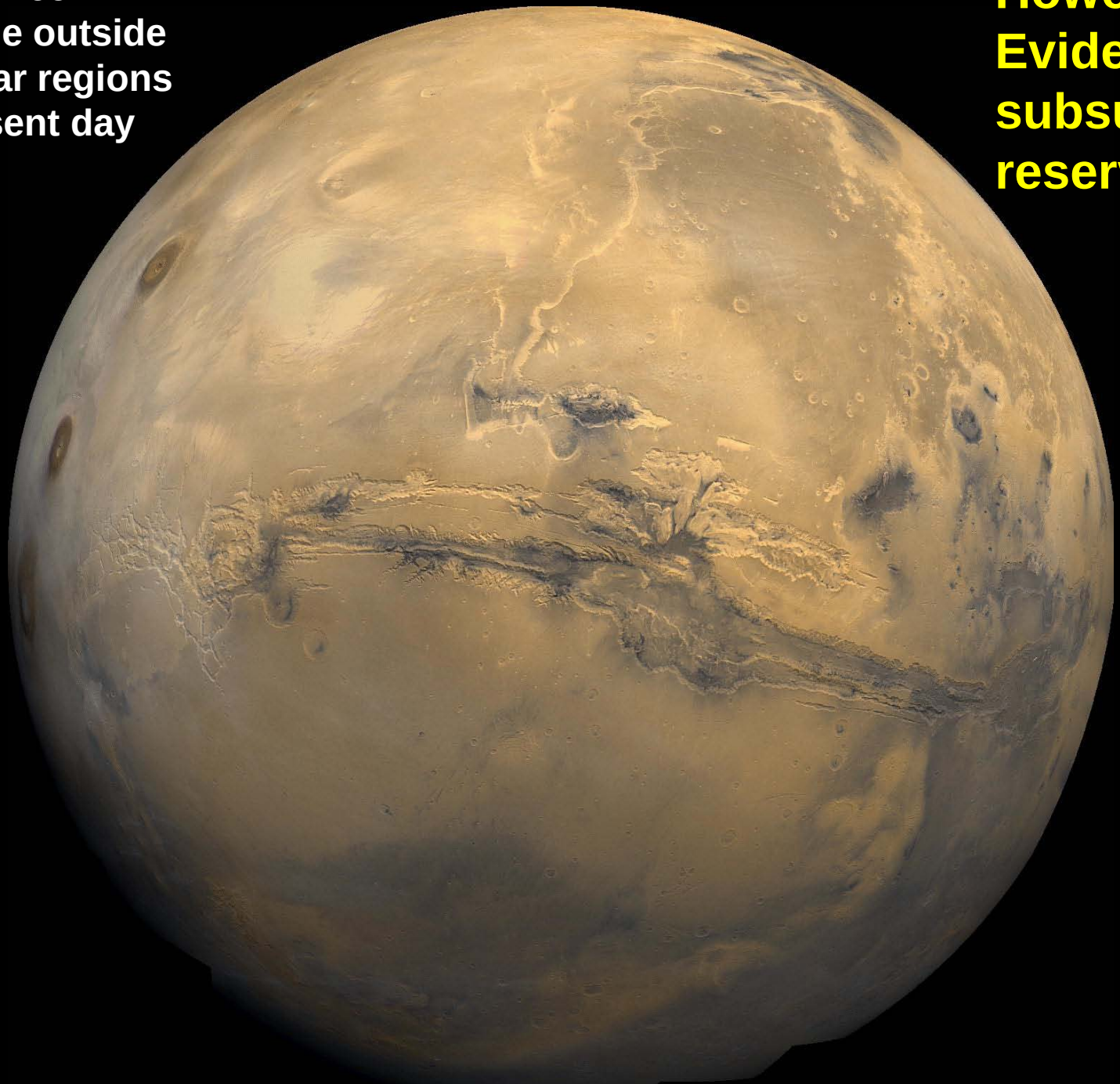
Viking 2, lat=48 N, Ls= 310

Surface frost (µm)

- **Now well mapped by OMEGA and CRISM**
- **Modeled by Global Climate Models :**

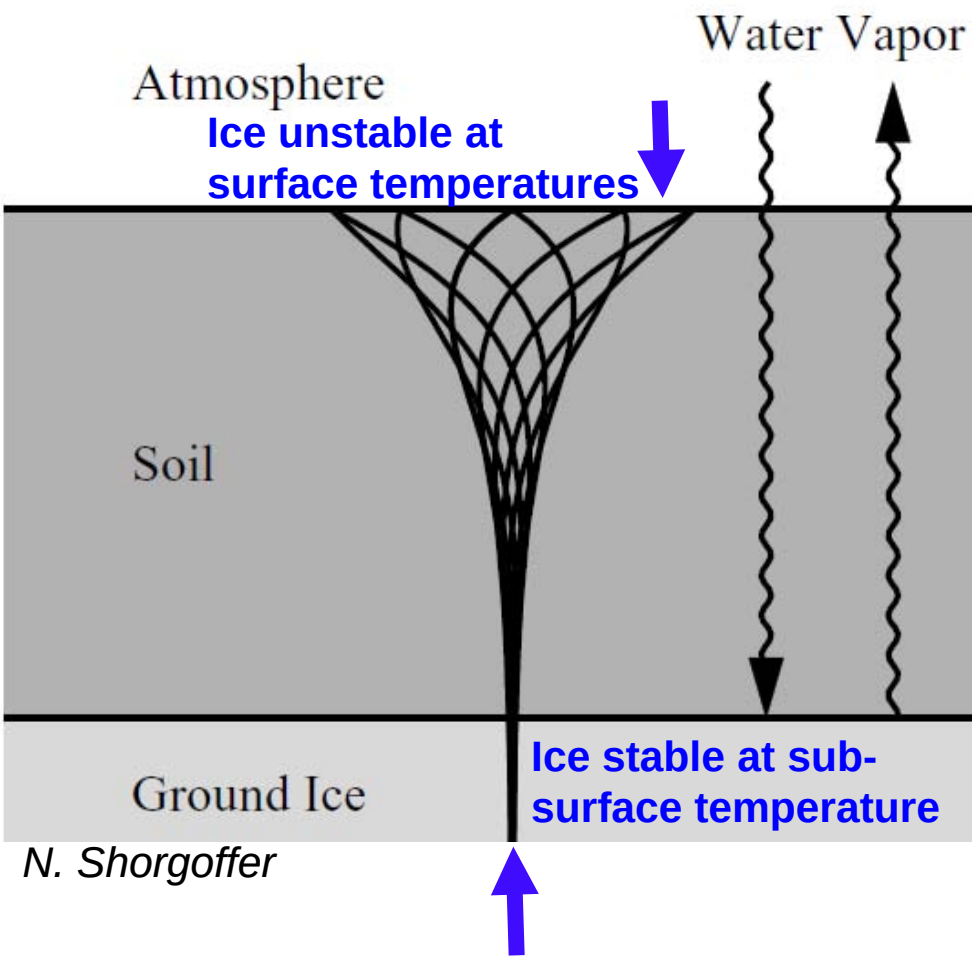


Surface ice unstable outside the polar regions on present day Mars



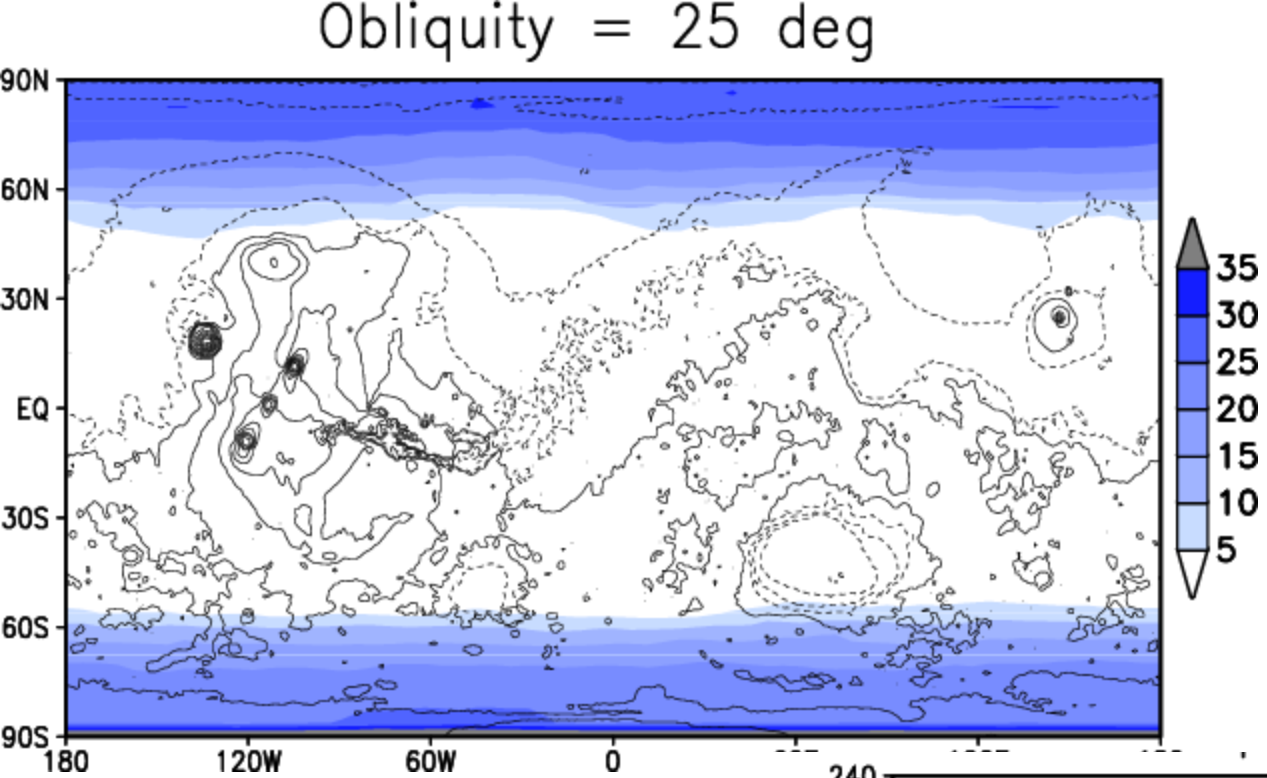
However: Evidences for subsurface ice reservoirs

Near subsurface ice stability on Mars



N. Shorgoffer

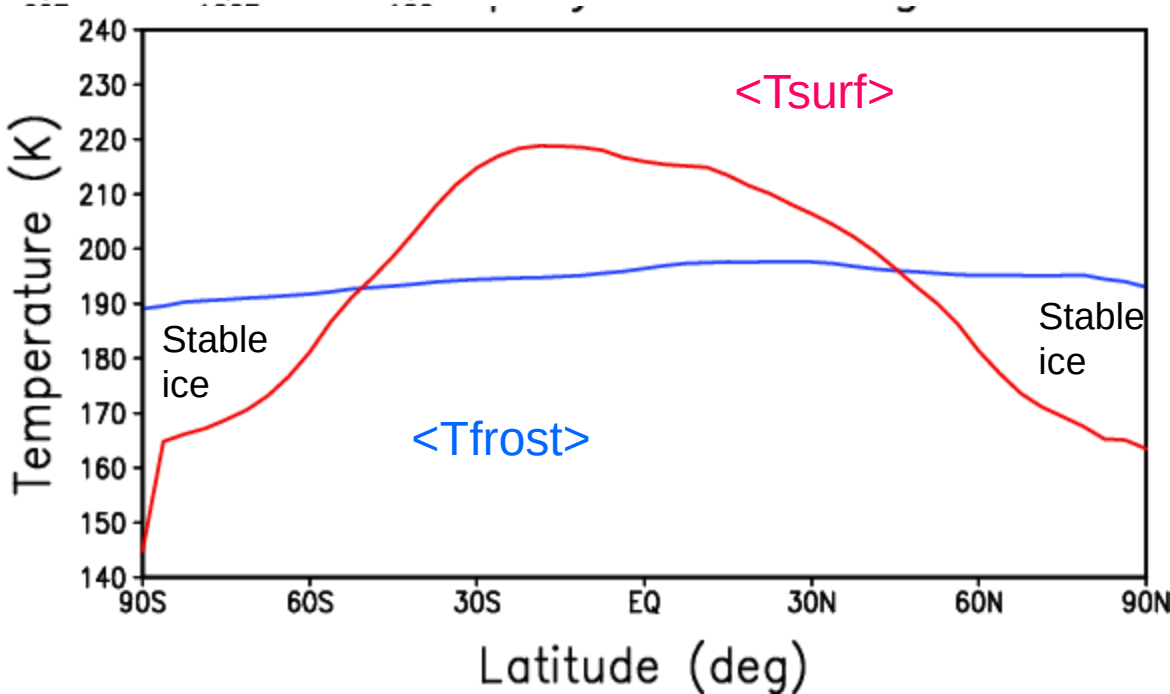
Subsurface Ice in equilibrium with the atmosphere



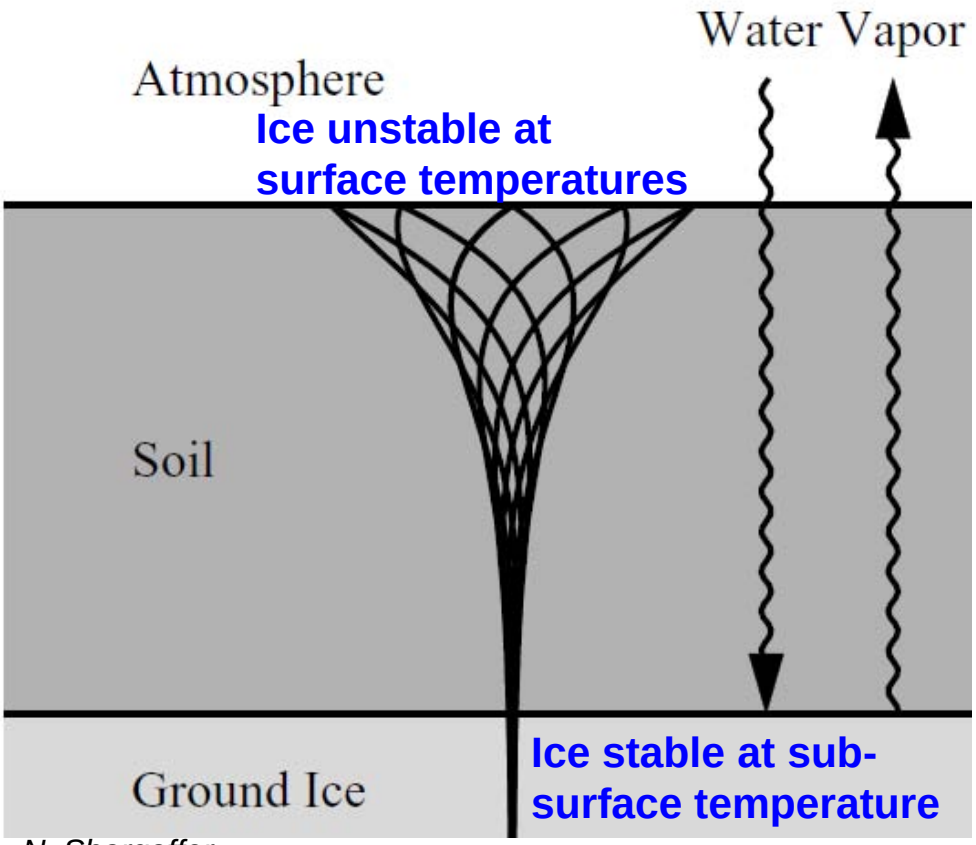
Ice stability
(<Tfrost> - <Tsurf>

(*Schorghofer 2007* criterion)

Forget et al. 2007



Stable subsurface ice on Mars



N. Shorgoffer

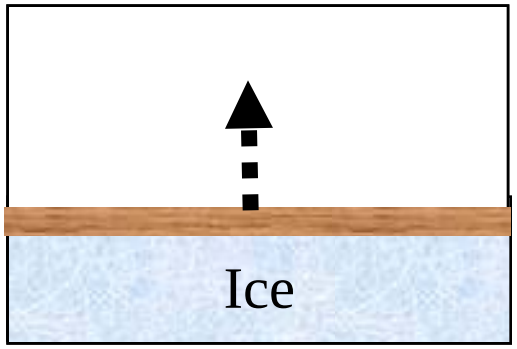
Subsurface Ice in equilibrium with the atmosphere

on present day Mars, down to ~50-60°lat on flat terrains, 25°lat on pole facing slope

1) Diffused water in the subsurface

2) "ice layer" buried to ice table depth below a sublimation lag:

•

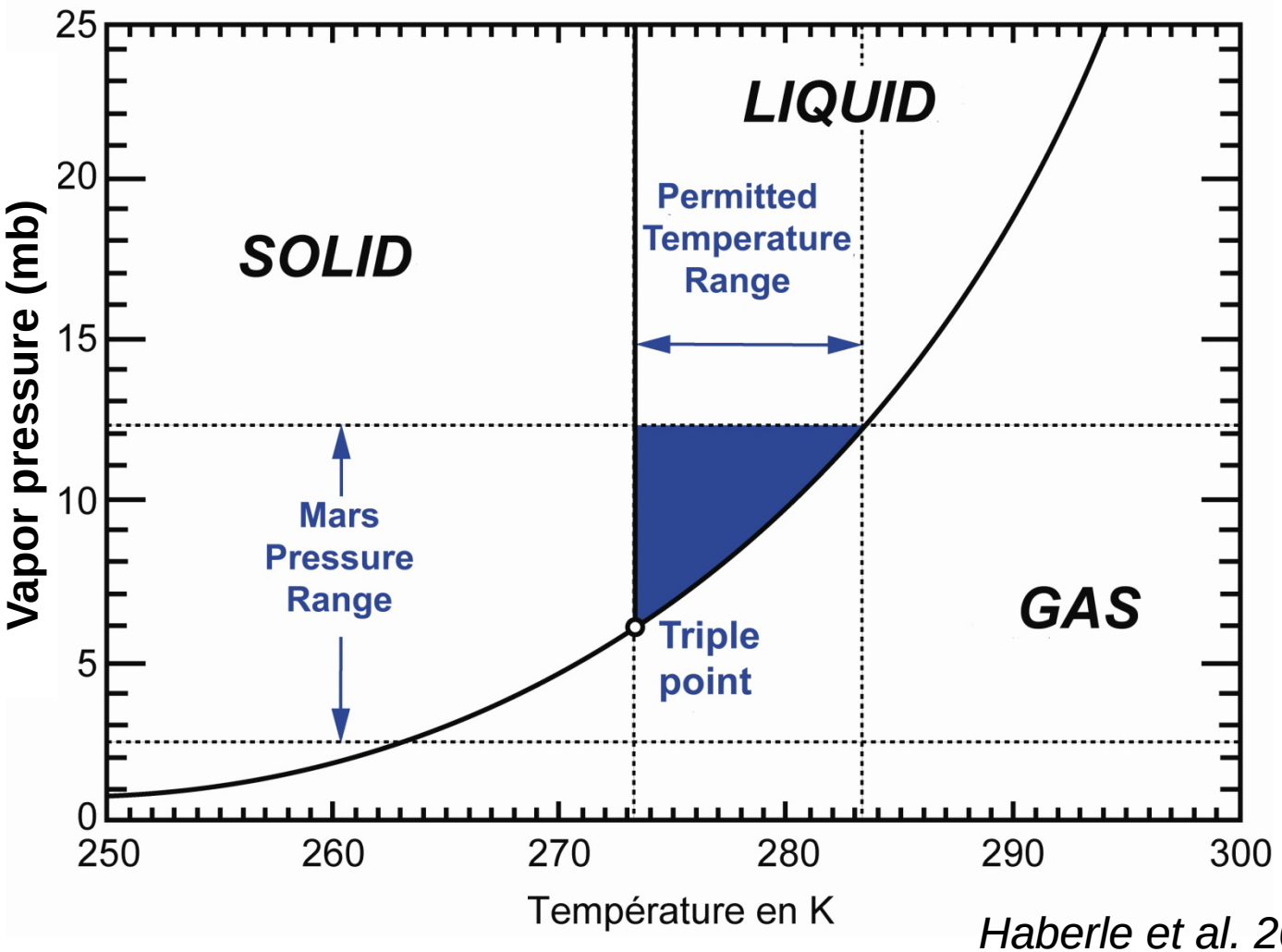


Basic facts learned from present-day water cycle observations and modelling :

1. A « closed » water cycle
2. Surface water ice cannot accumulate outside the polar regions
3. Subsurface water ice can be stable down to ~55° latitude (on flat surface)

What about surface liquid water ?

Liquid water on Mars



Haberle et al. 2003

Liquid water on Mars Mars ?

Pure water

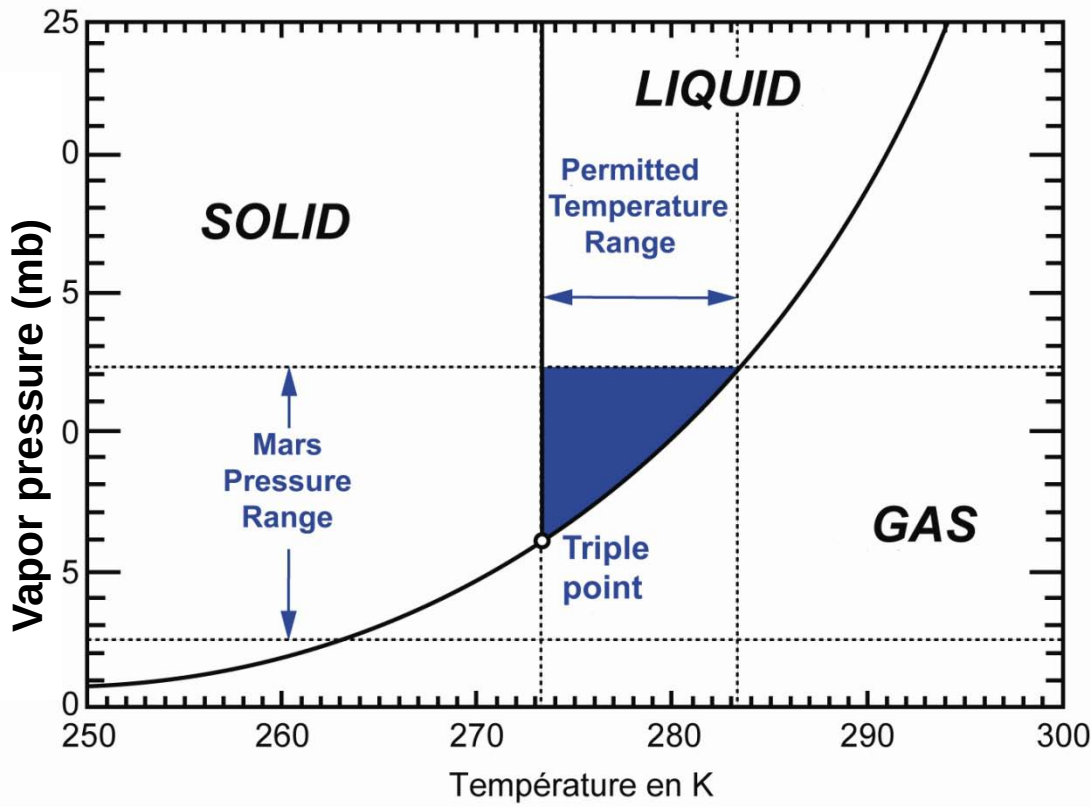
Only if T >0°C and

Ps > 610 Pa (triple point)

⇨ Reading phase diagram :

- Boiling : controlled by ABSOLUTE pressure (~atmospheric pressure)
- Evaporation : surface liquid water stability controlled by water vapor partial pressure in the air

P_{H2O} = Pabs x $[H_2O]$ << Pabs !



⇨Pure Liquid water impossible except in lower plains (Ps> 6.1mb) where it is very unstable

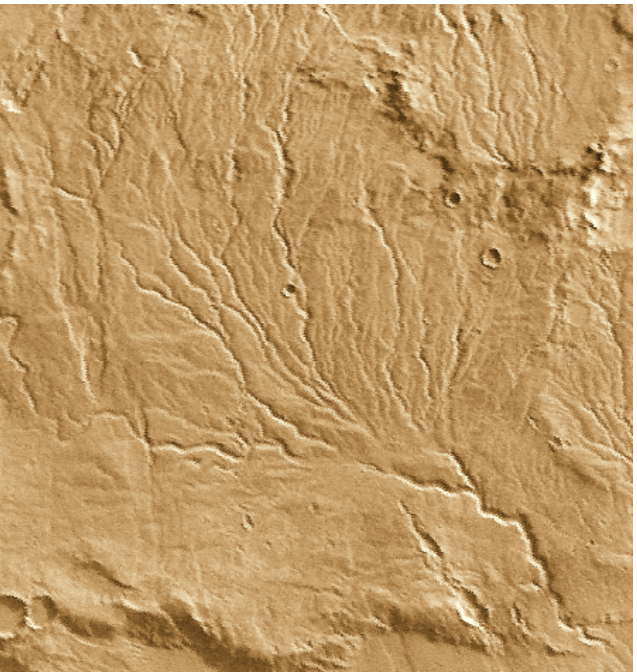
(Liquid brines possible at colder temperature ?)

On present-day Mars

- No accumulation of surface ice outside polar regions.
- No surface liquid water

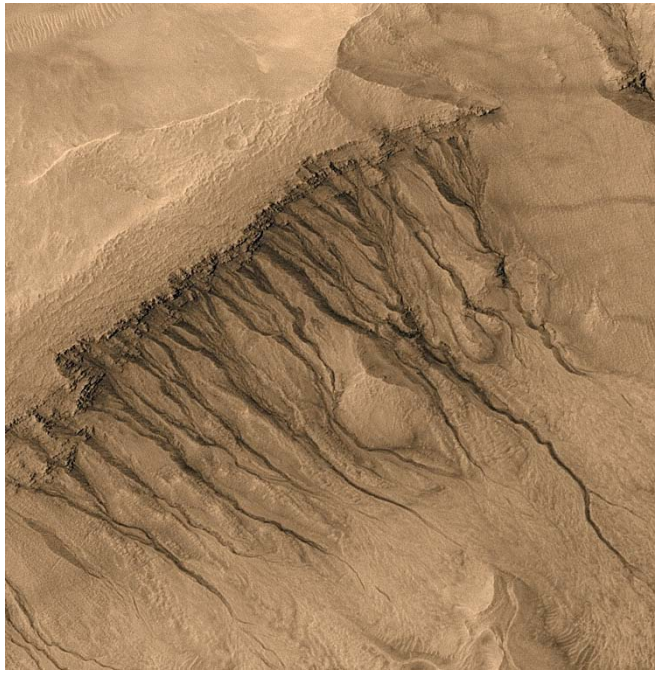
In the past ?

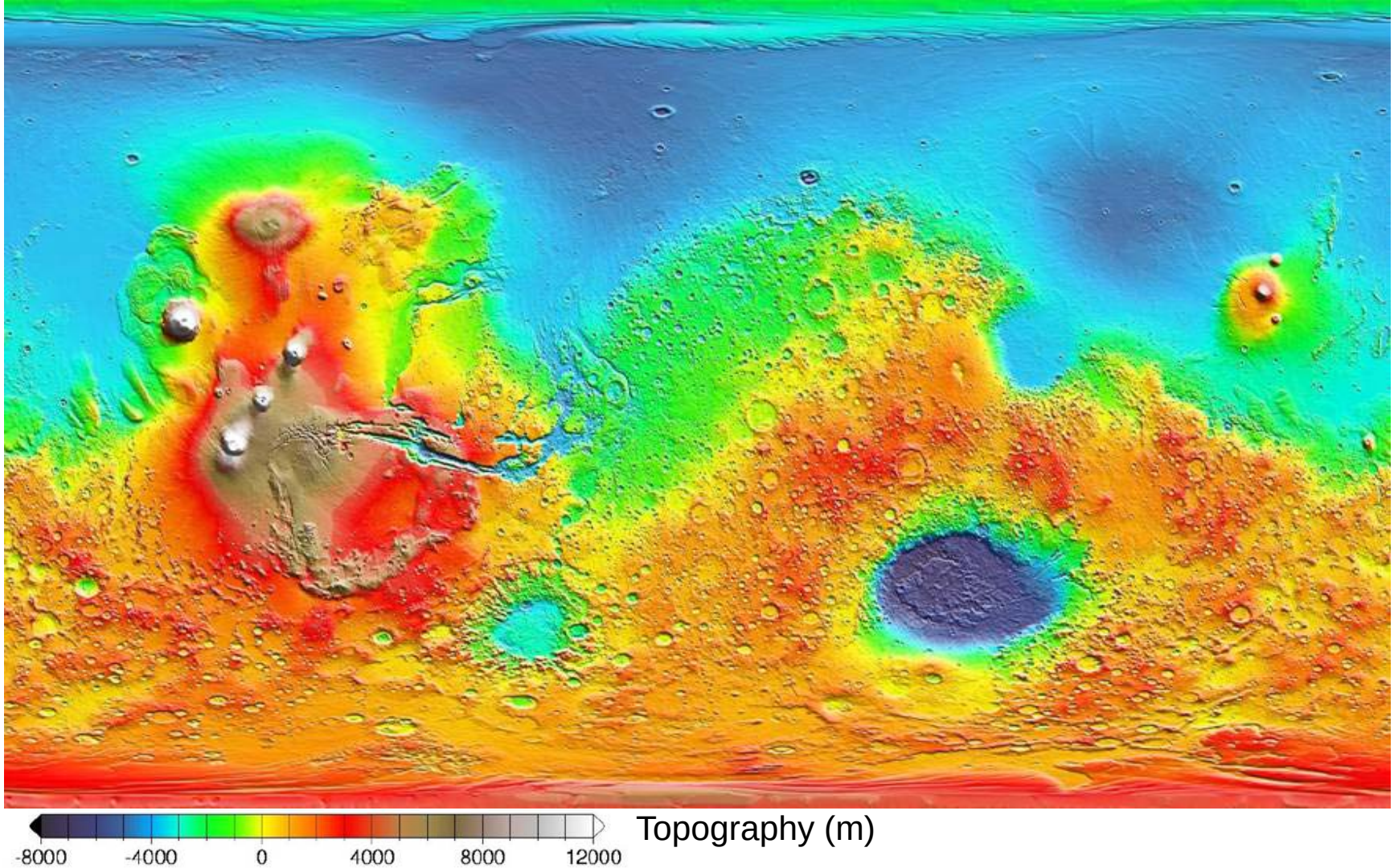
Very ancient terrains (>3.8 Ga)

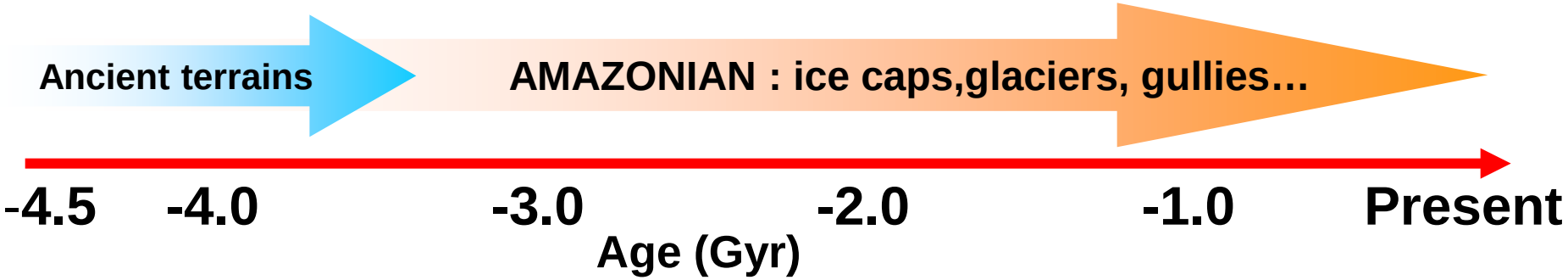


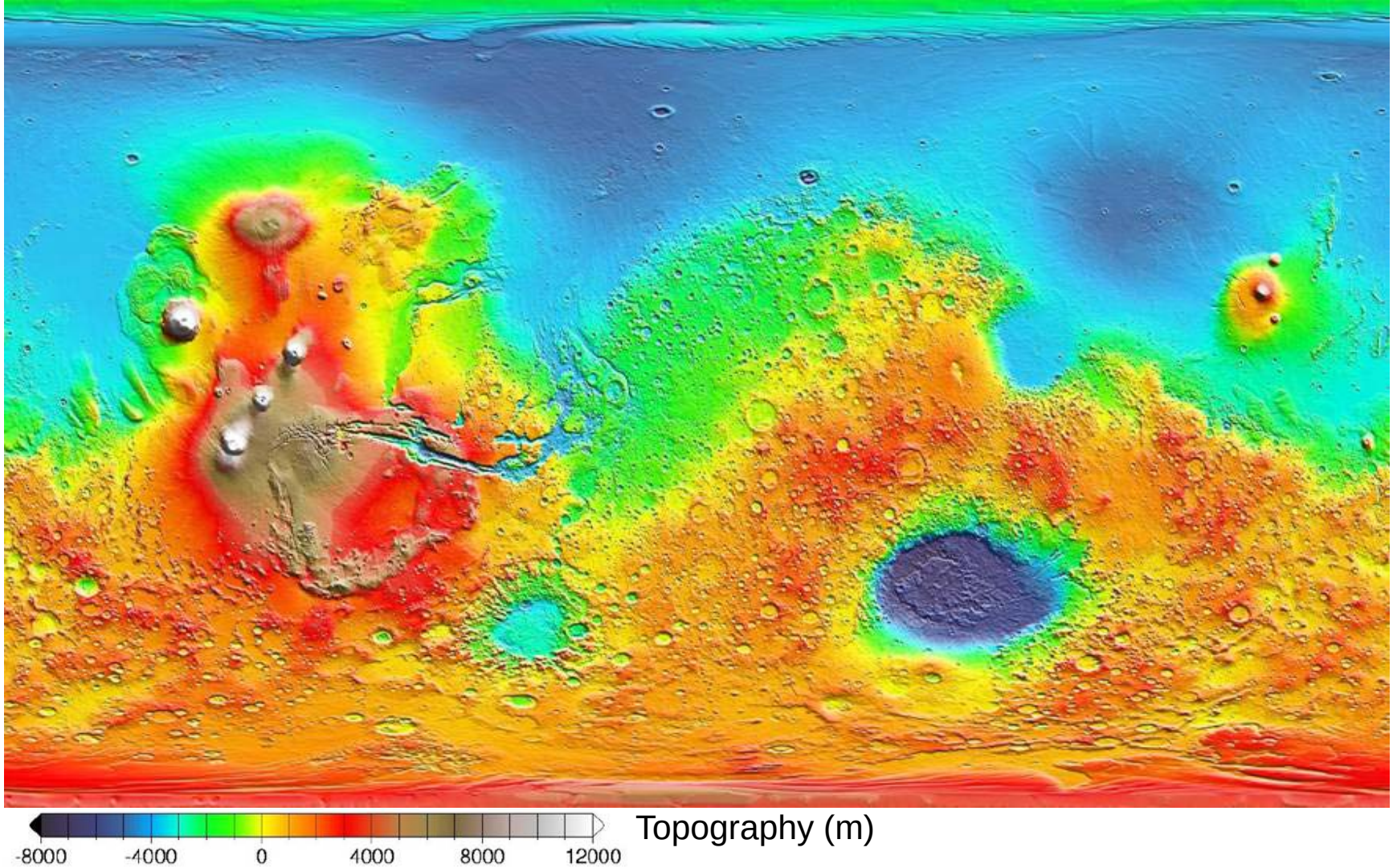
Recent terrain (-10^6 yr)

Recent terrain (-10^6 yr)

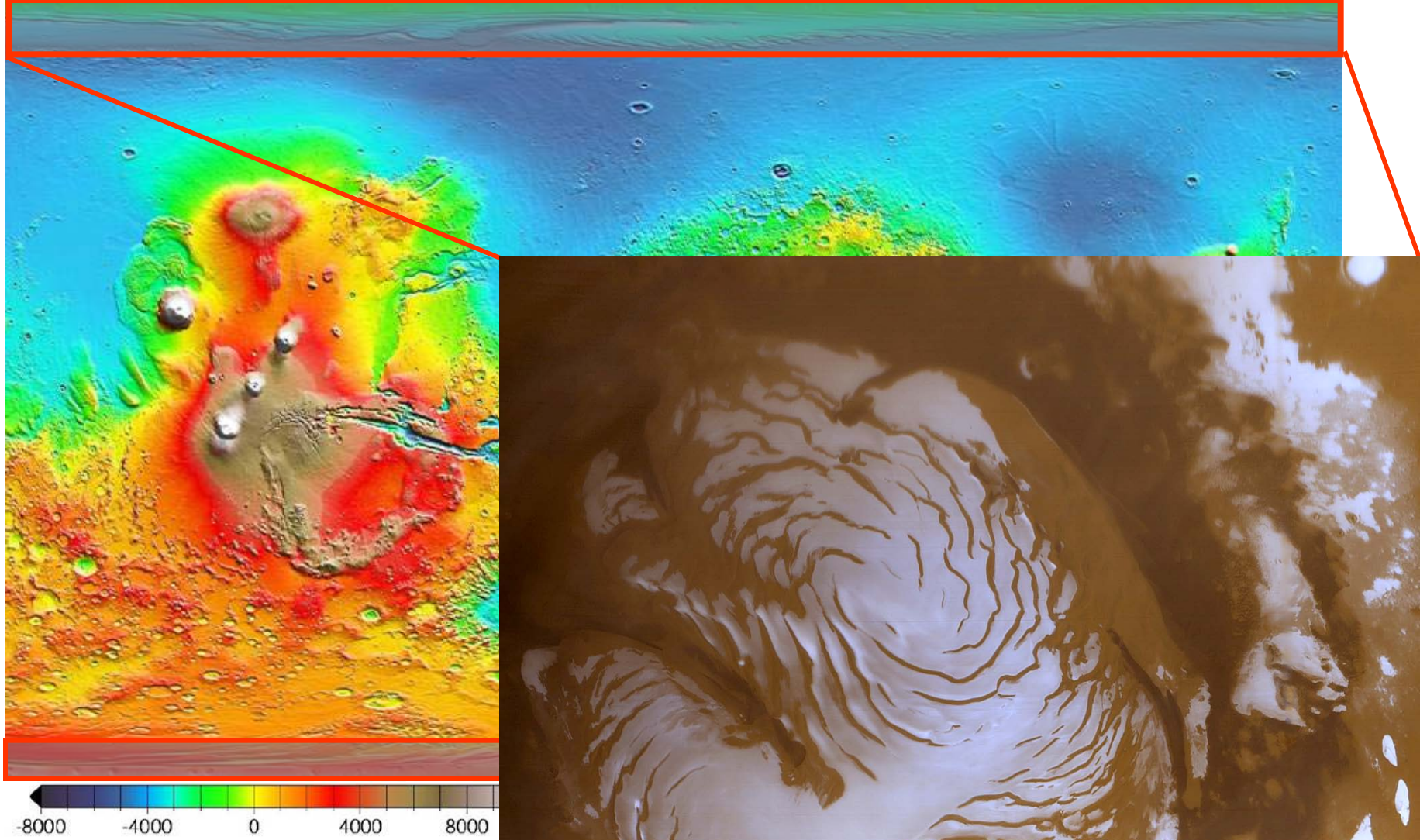



-8000
-4000
0
4000
8000
12000
Topography (m)

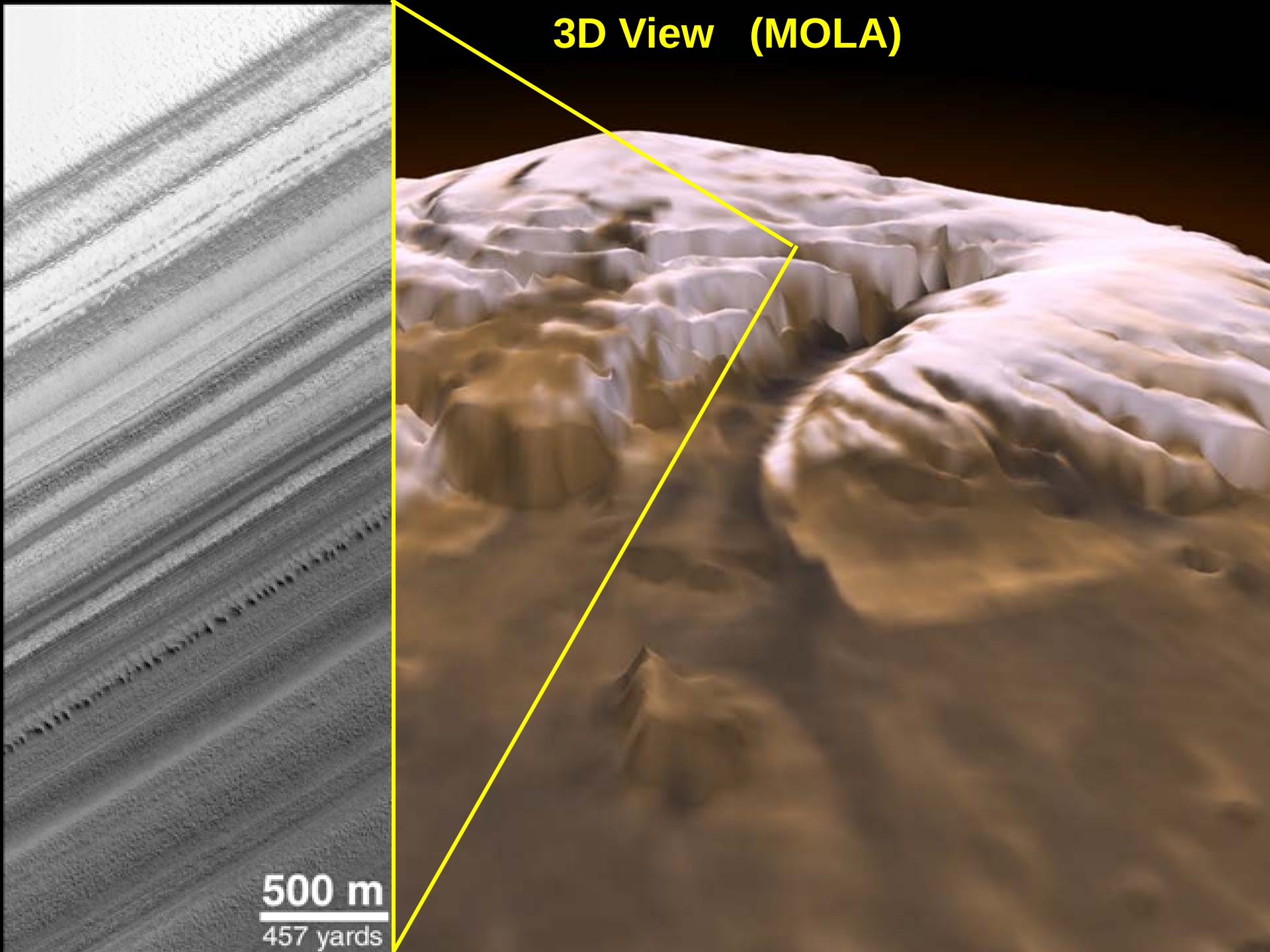

Ancient terrains
AMAZONIAN : ice caps,glaciers, gullies…
-4.5
-4.0
-3.0
-2.0
-1.0
Present
Age (Gyr)

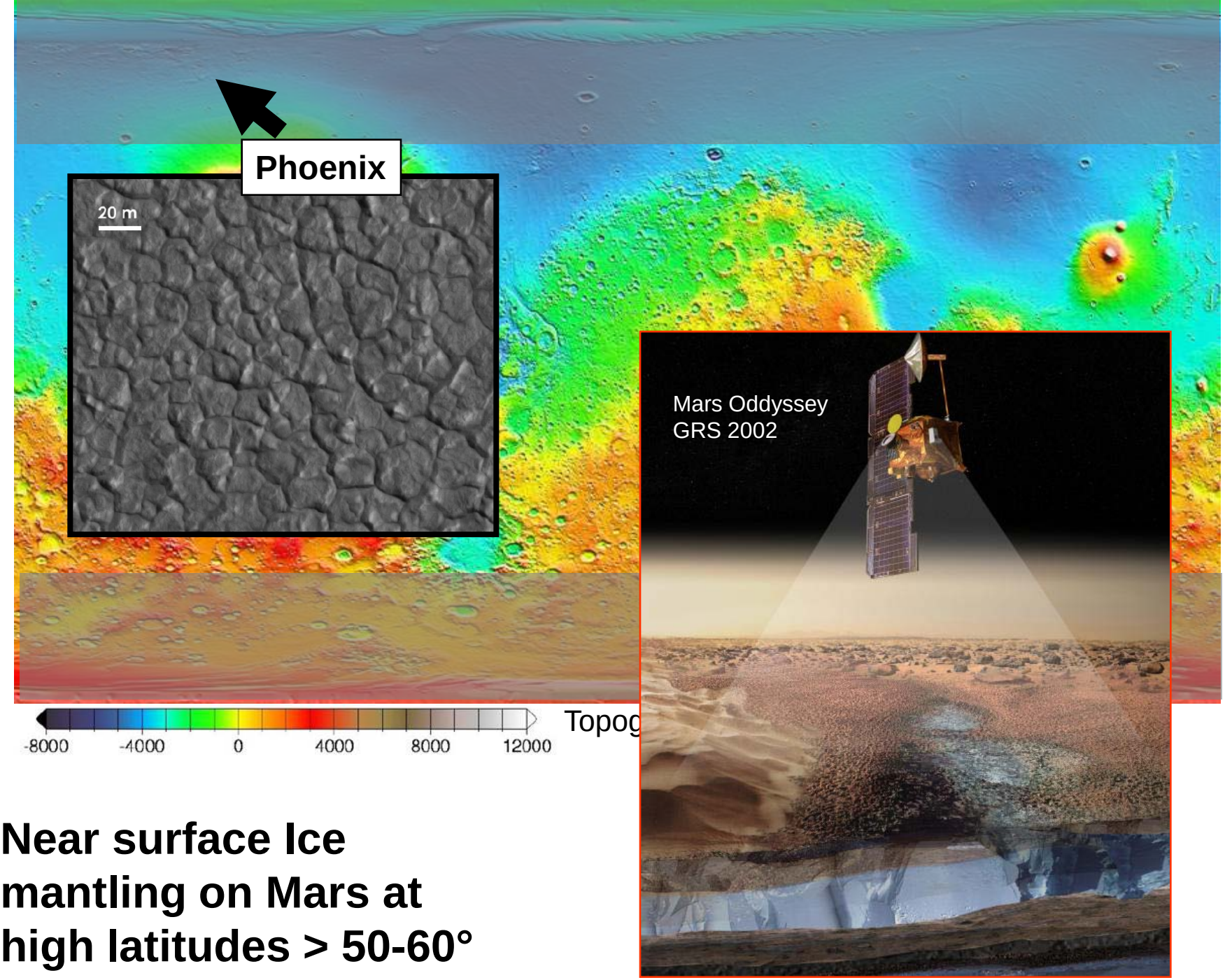


Near surface ice reservoir on Mars: clues on recent climate variations ?



Polar layered deposits (> ~80° lat)

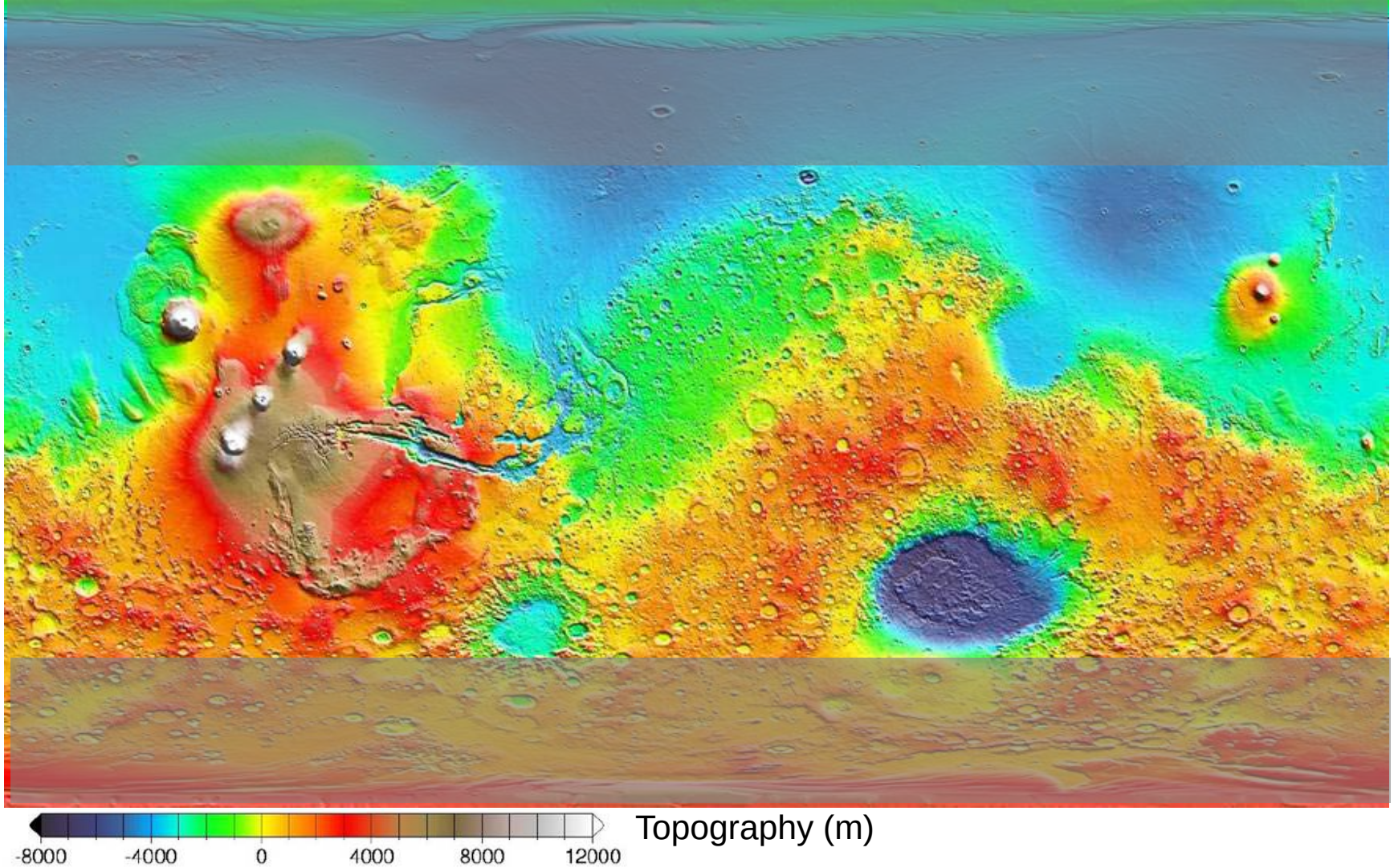

3D View (MOLA)
500 m
457 yards



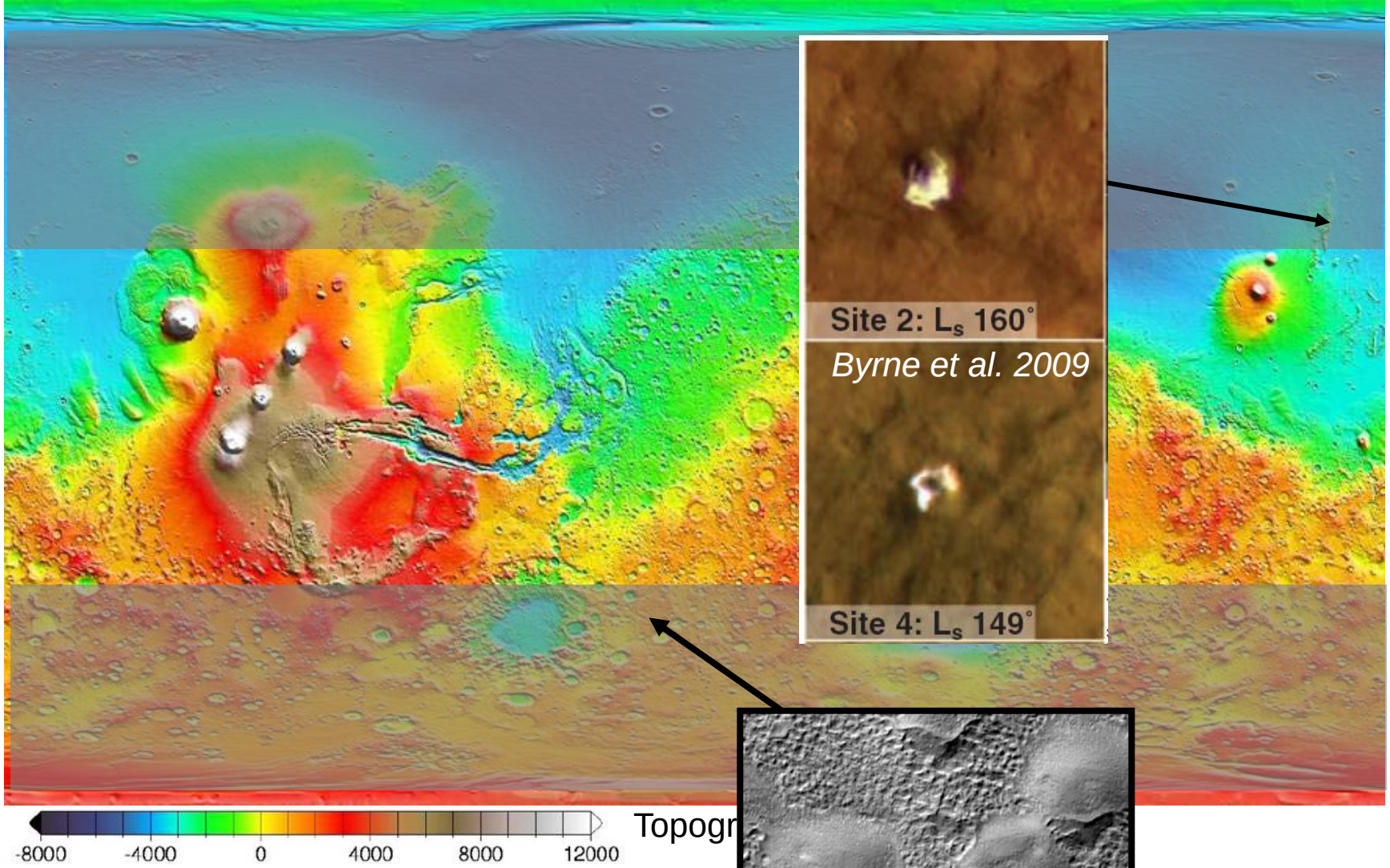
Near surface Ice mantling on Mars at high latitudes > 50-60°

Phoenix: May 25, 2008 68°N

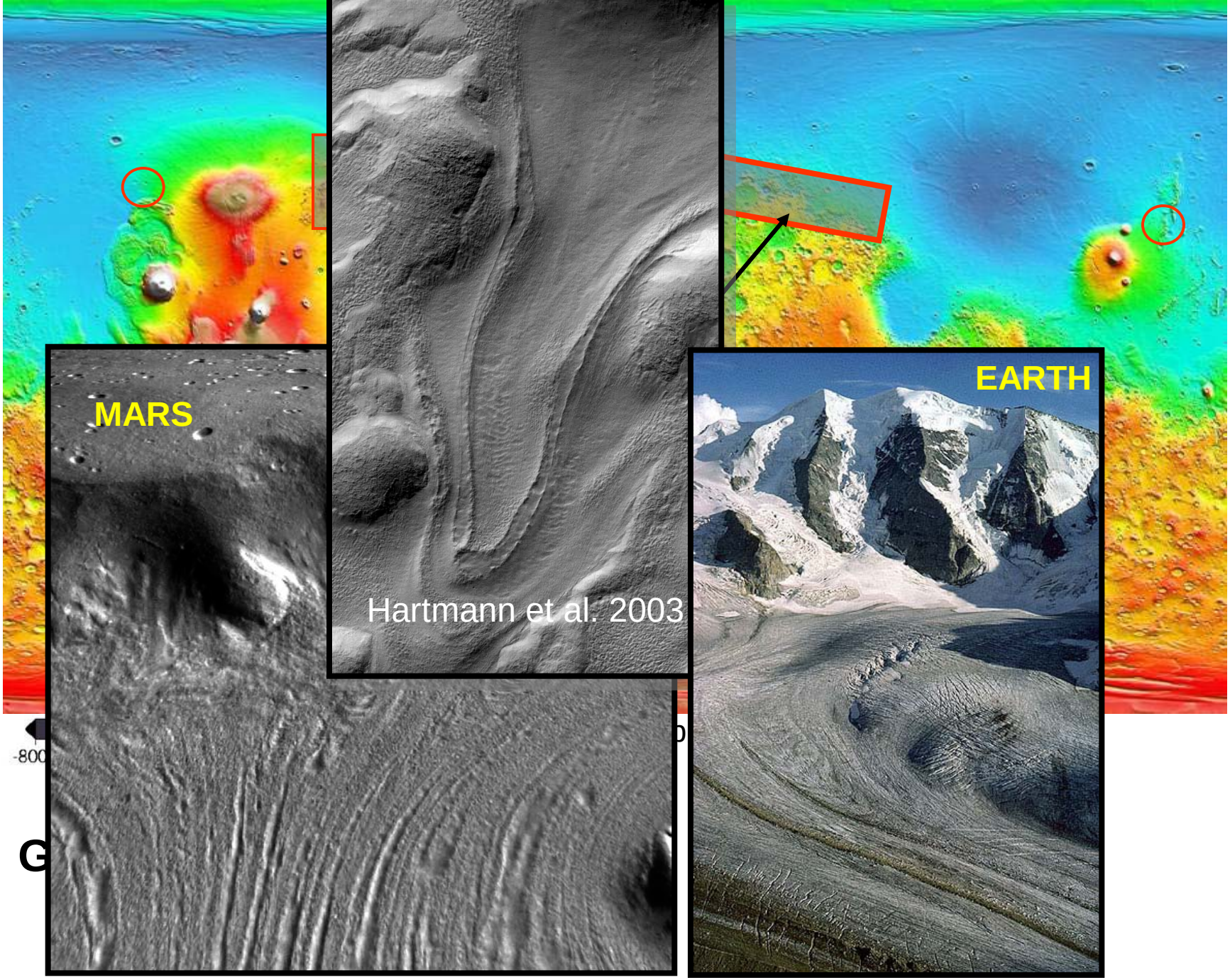
Below Phoenix : ice exposed by landing thrusters



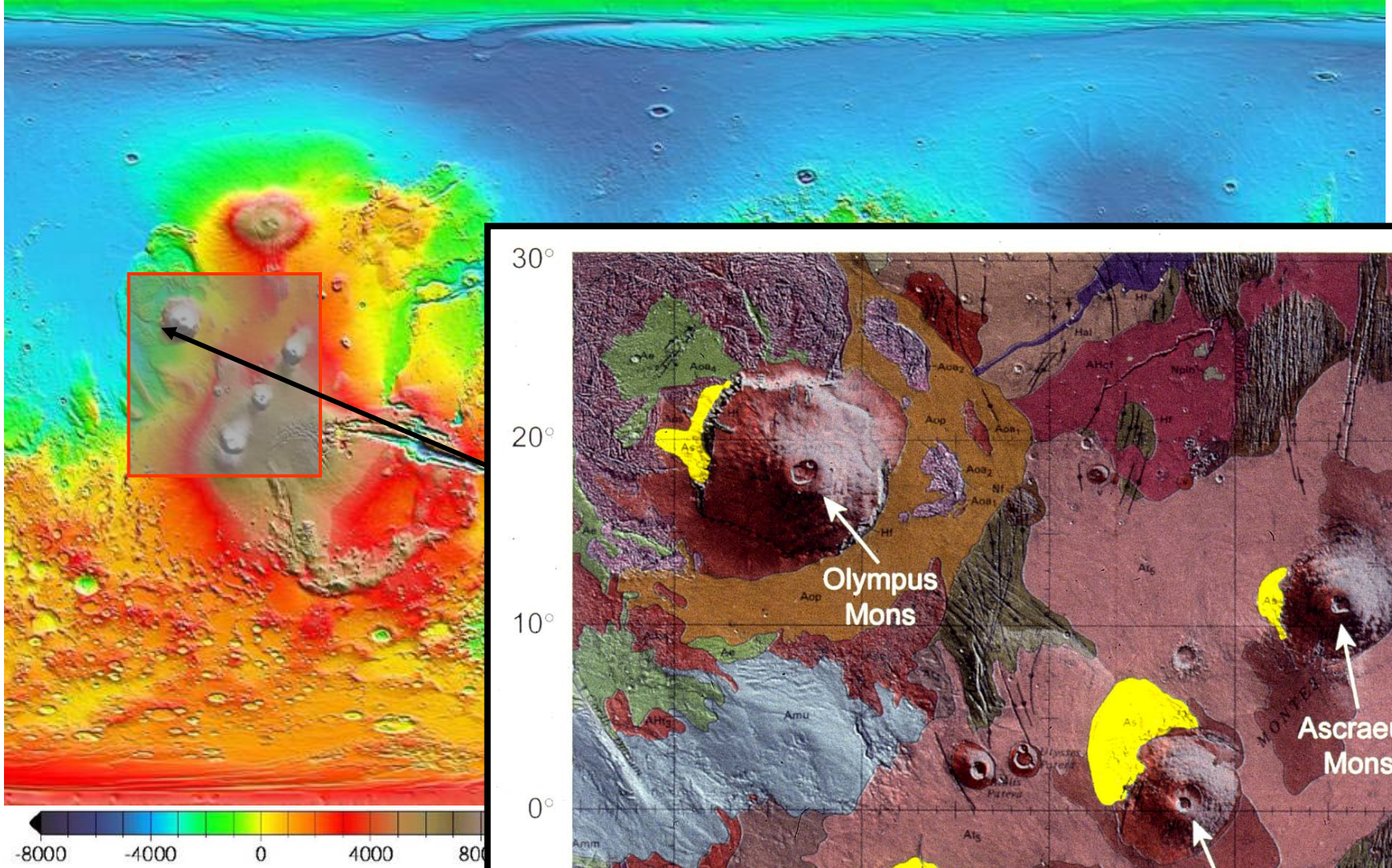
Near surface Ice mantling on Mars at high latitudes > 50-60°

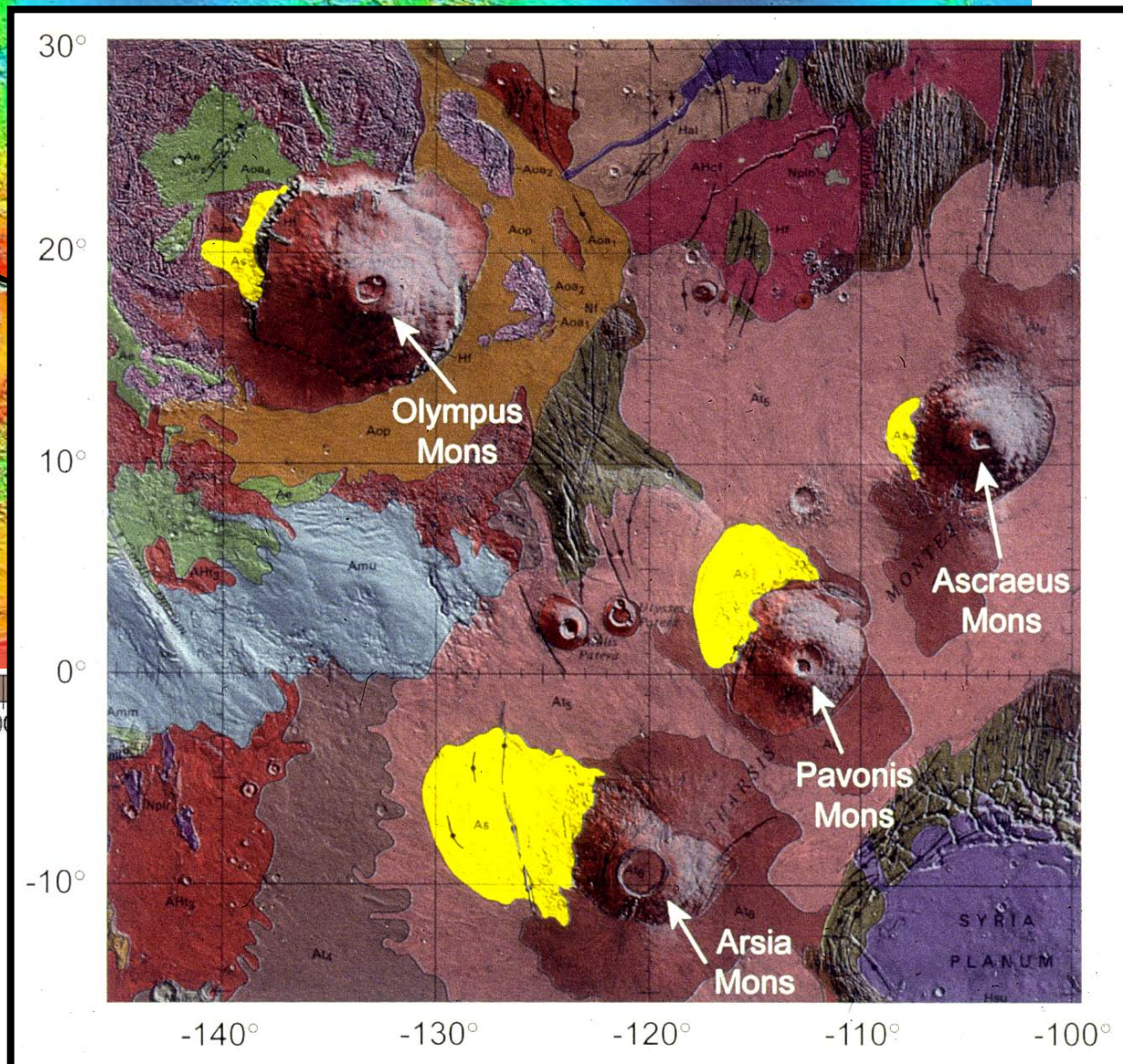


Near surface Ice mantling on Mars at high latitudes down to 30 ?°



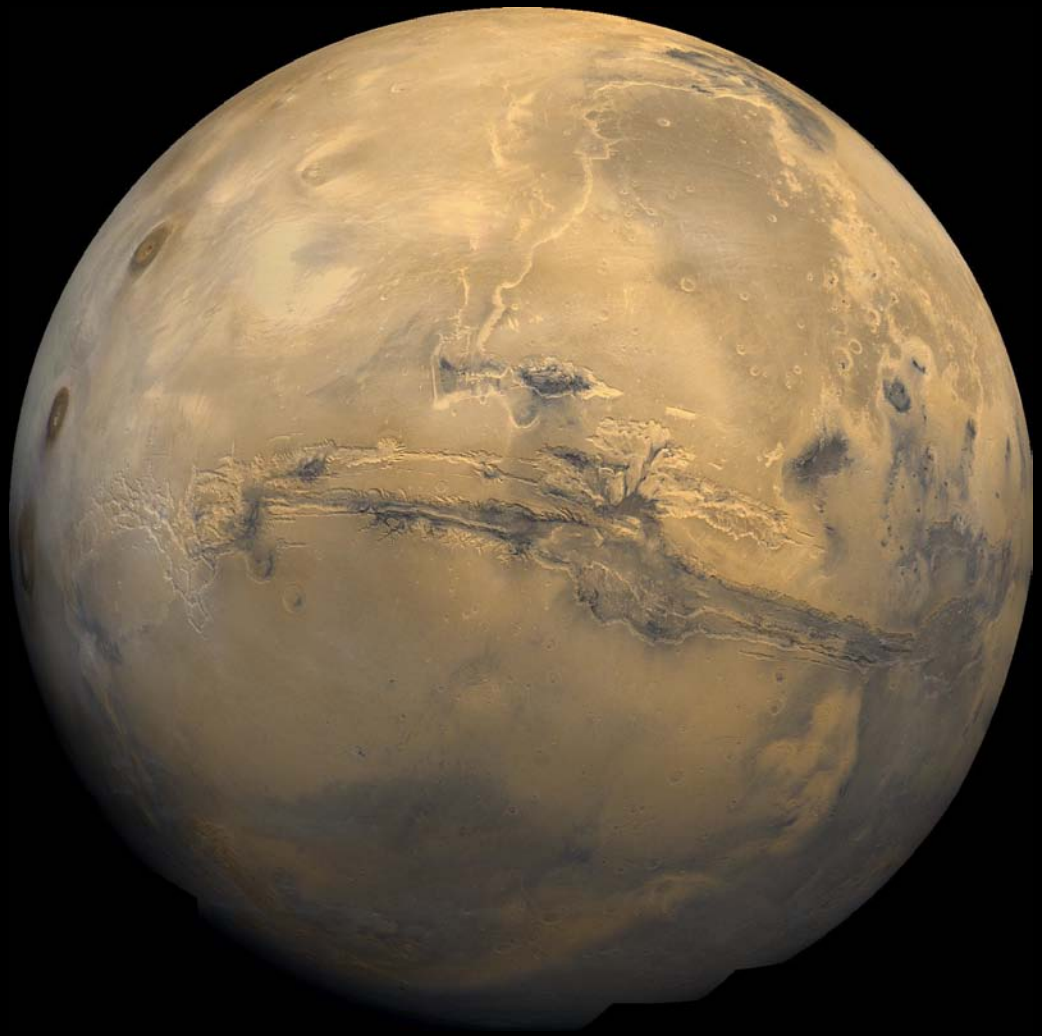
Head et al. 2003





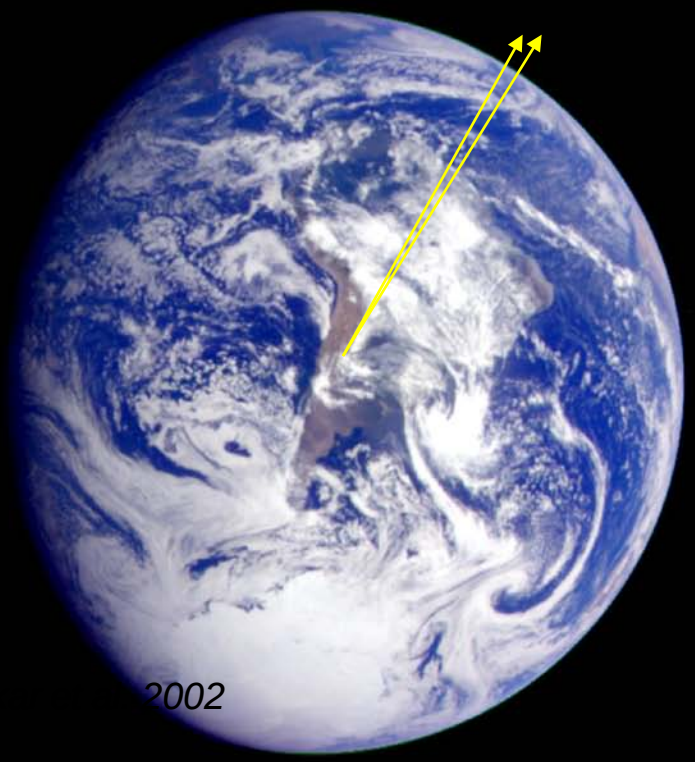
Glacier-like landforms in the tropics

How to form geologically recent glaciers on a such a dry planet ?

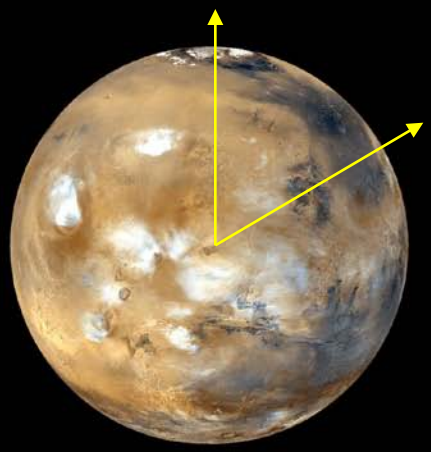


Climate changes resulting from obliquity variations

Earth obliquity: variations 1.3



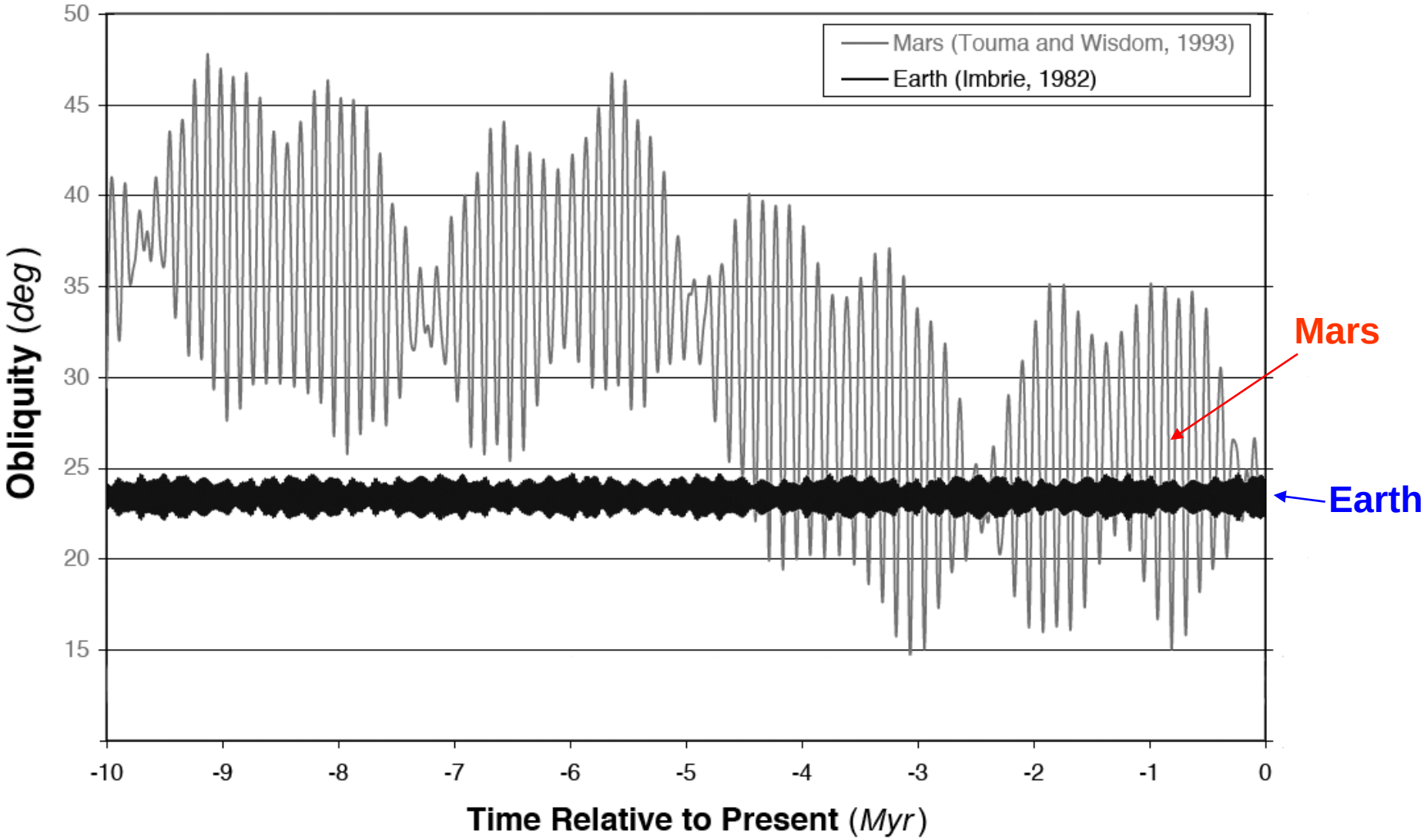
Mars: variations
between 0° et >60° !



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

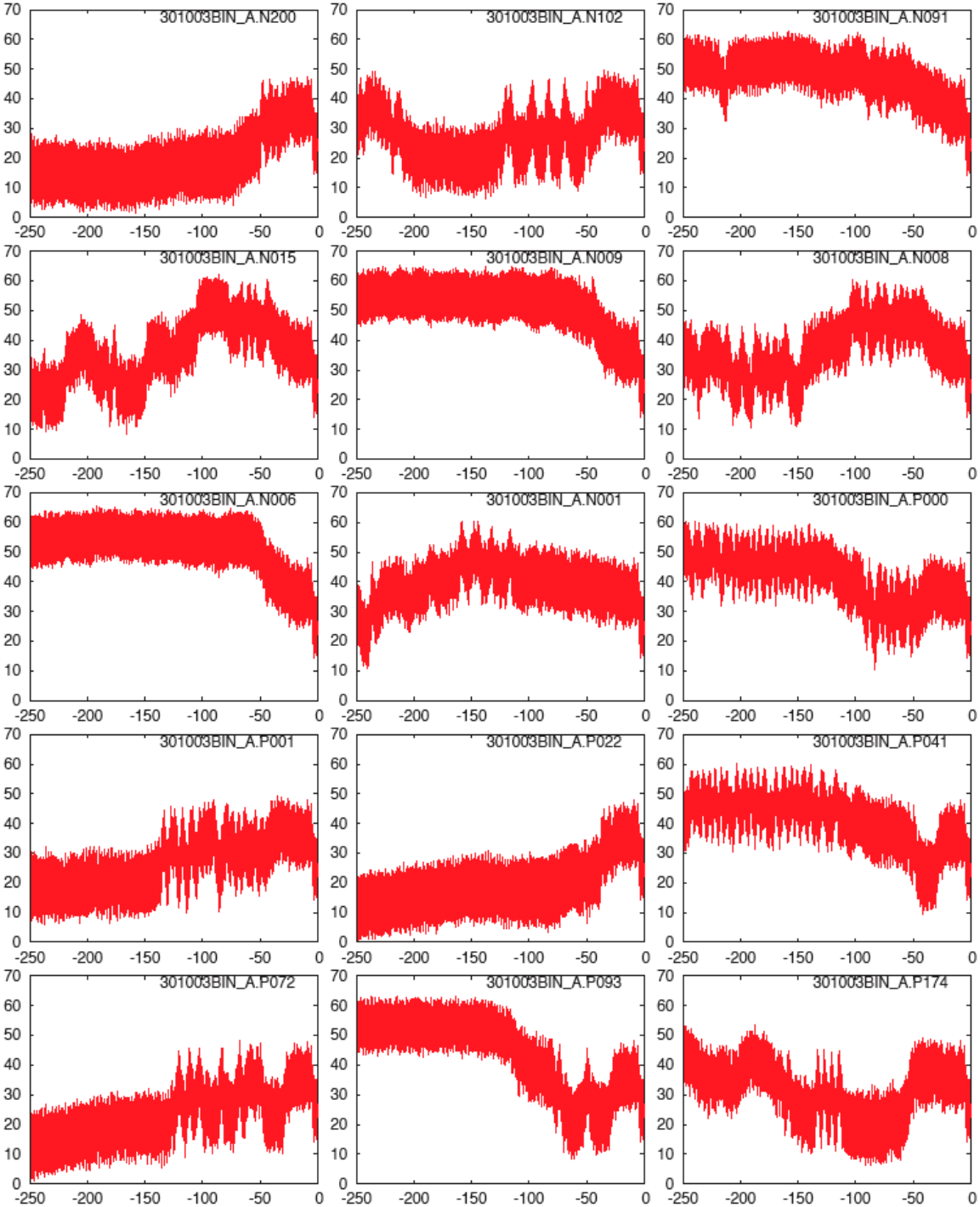


- 250 Myr – Now :

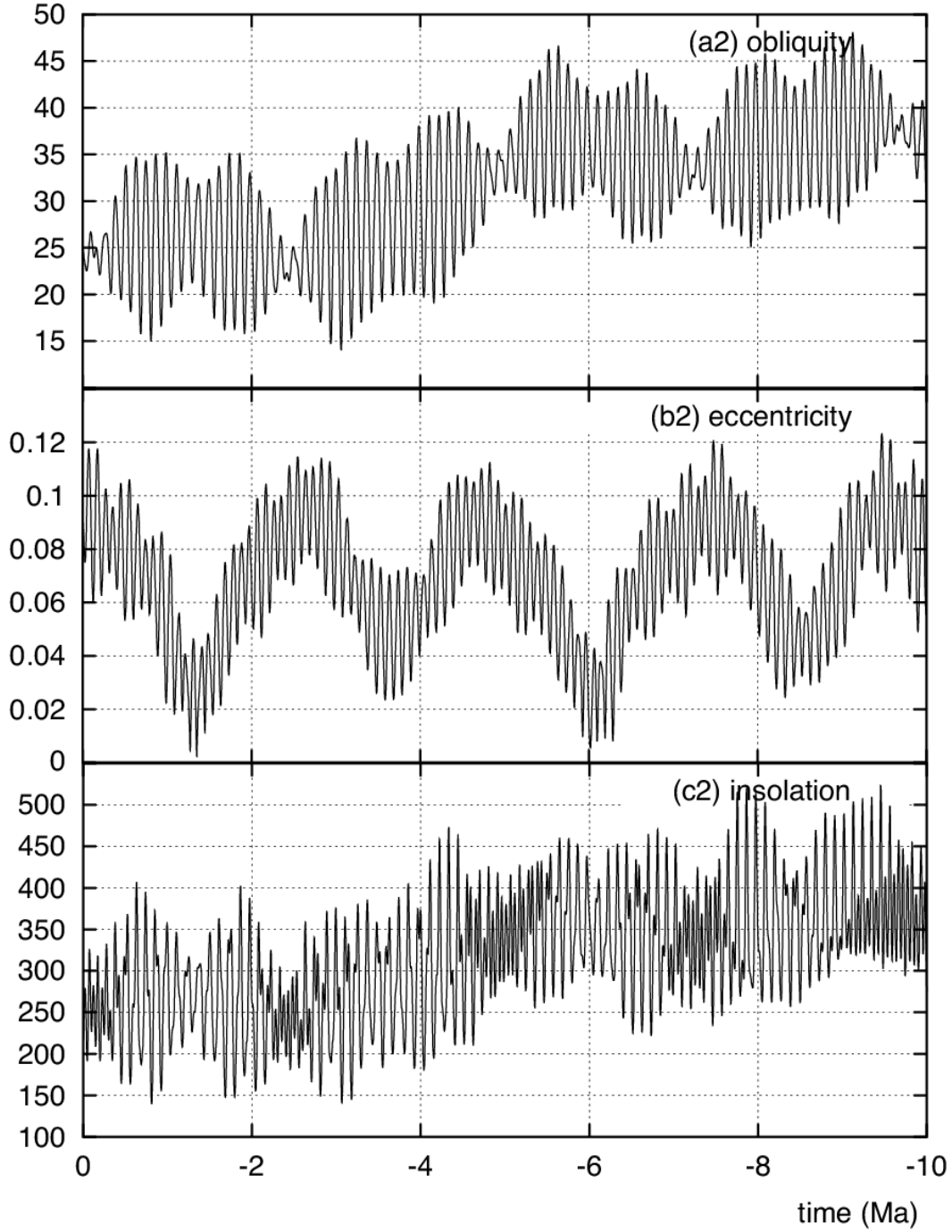
- Chaos : past evolution unknown before -10 Myr
- Possible variations of obliquity

(Laskar et al. 2004) :

⇨ Most likely obliquity was 42º.

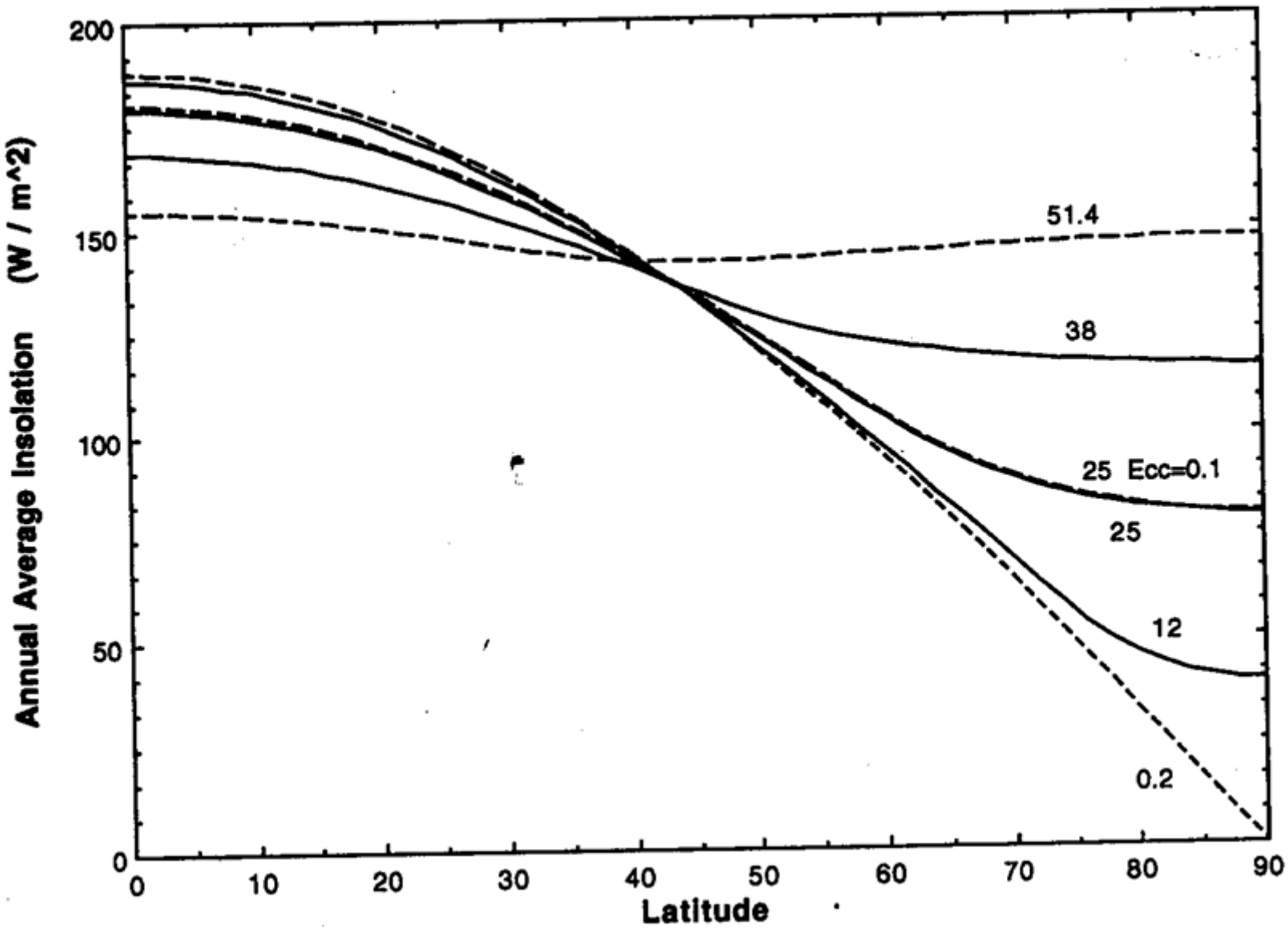


0 - 10 Myr



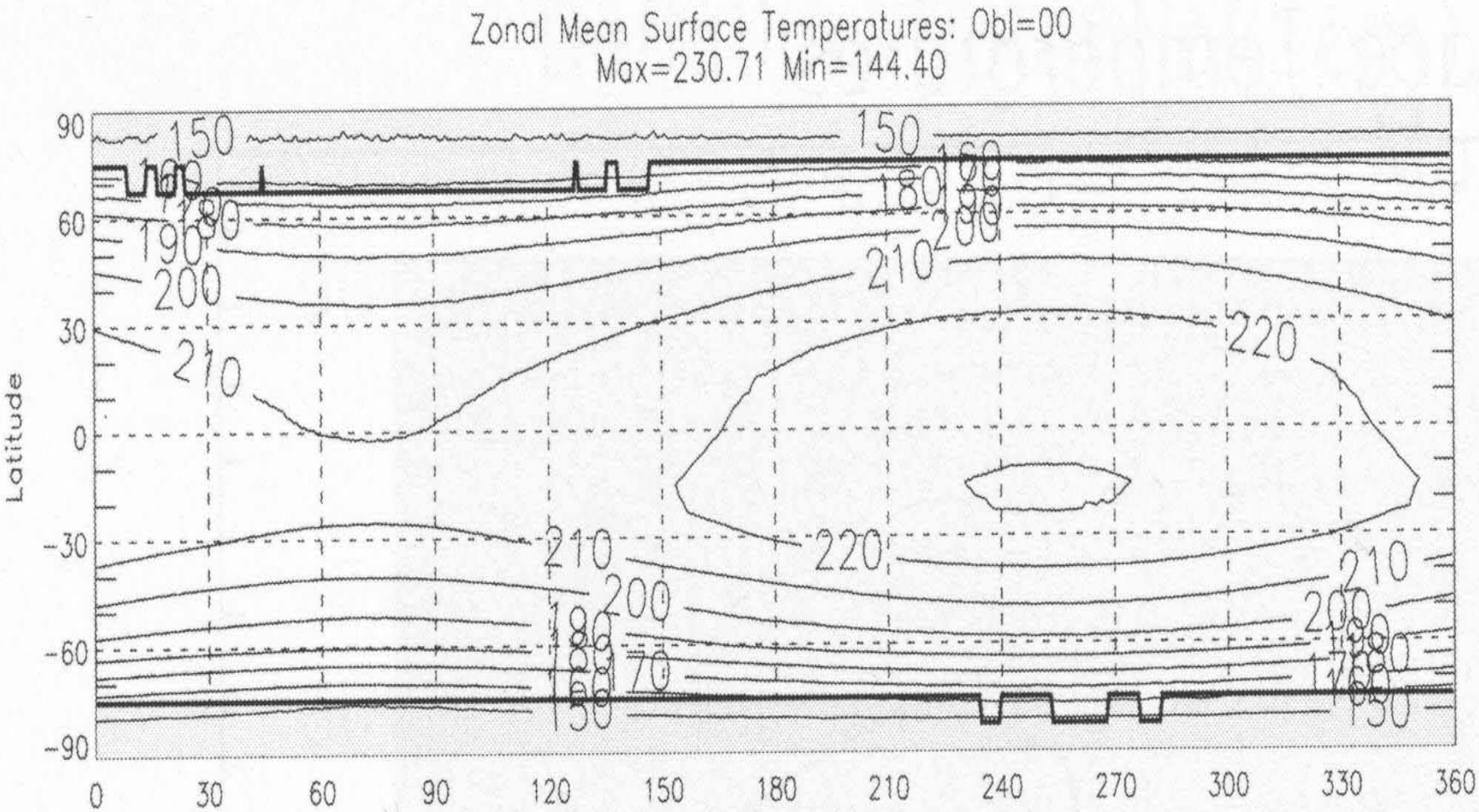
Laskar and Robutel (1993)

Annual mean insolation :



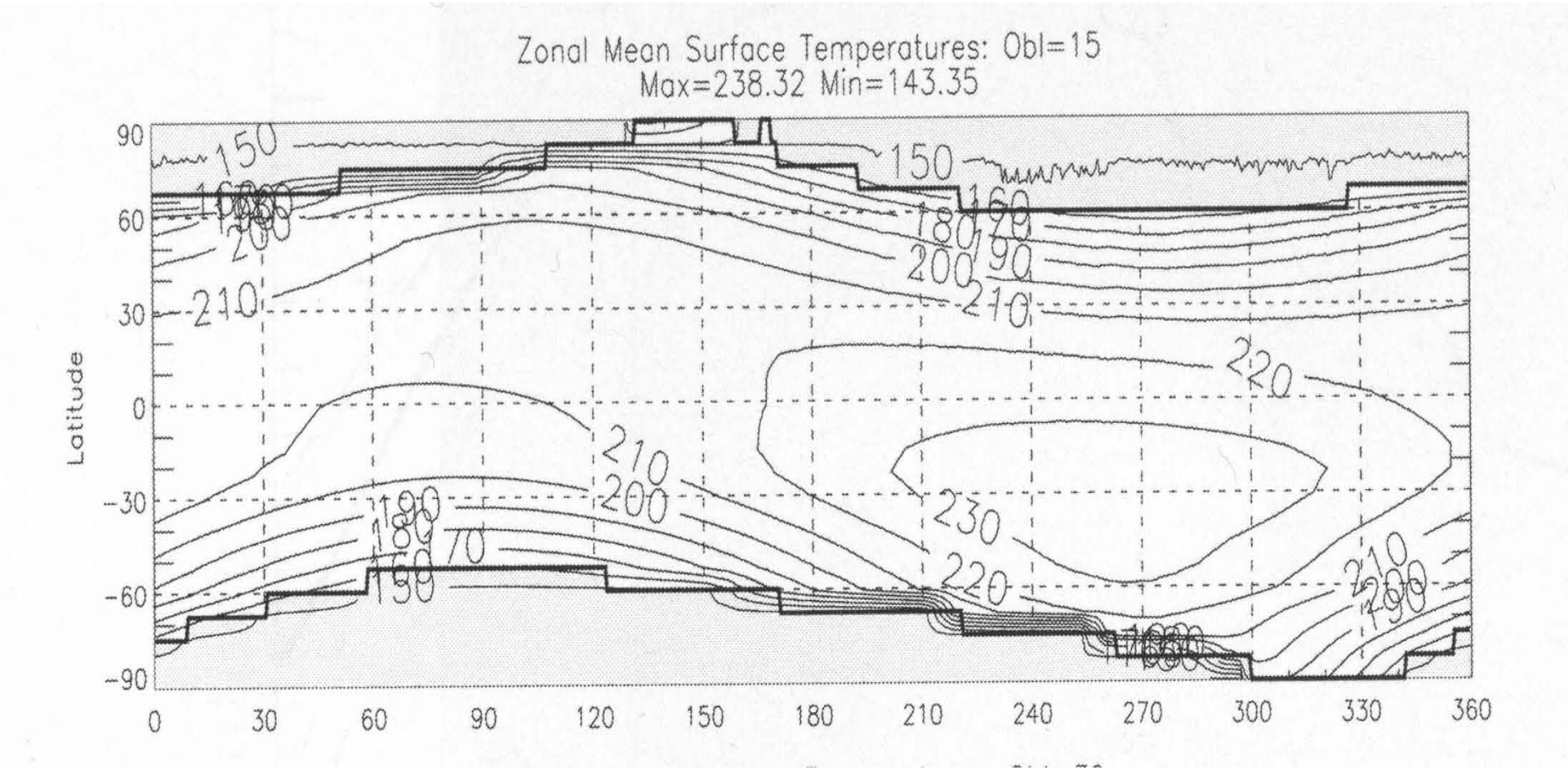
Zonal mean temperature (K) **Obliquity = 0°**

Haberle et al. 2003 , NASA Ames model



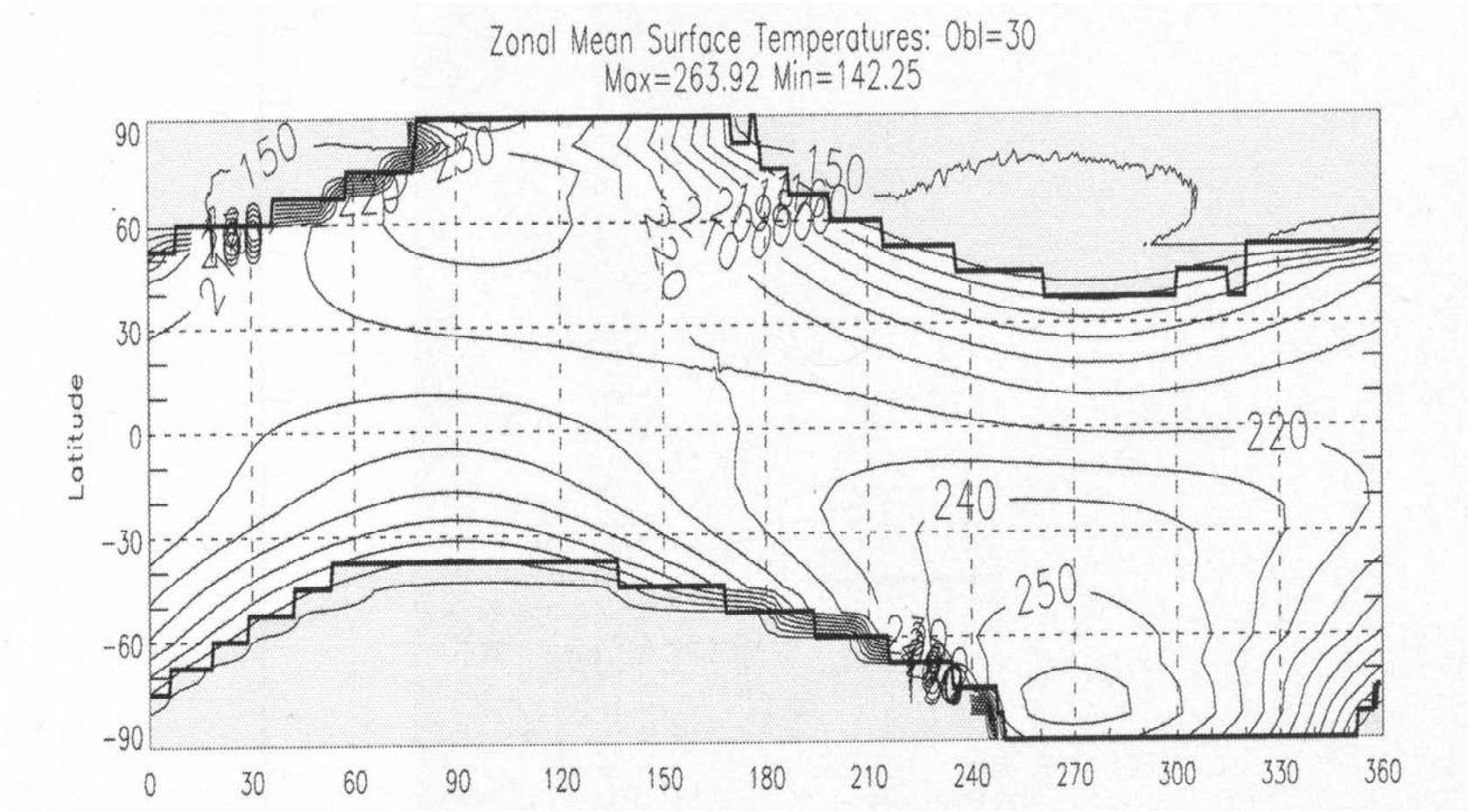
Zonal mean temperature (K) **Obliquity = 15°**

Haberle et al. 2003



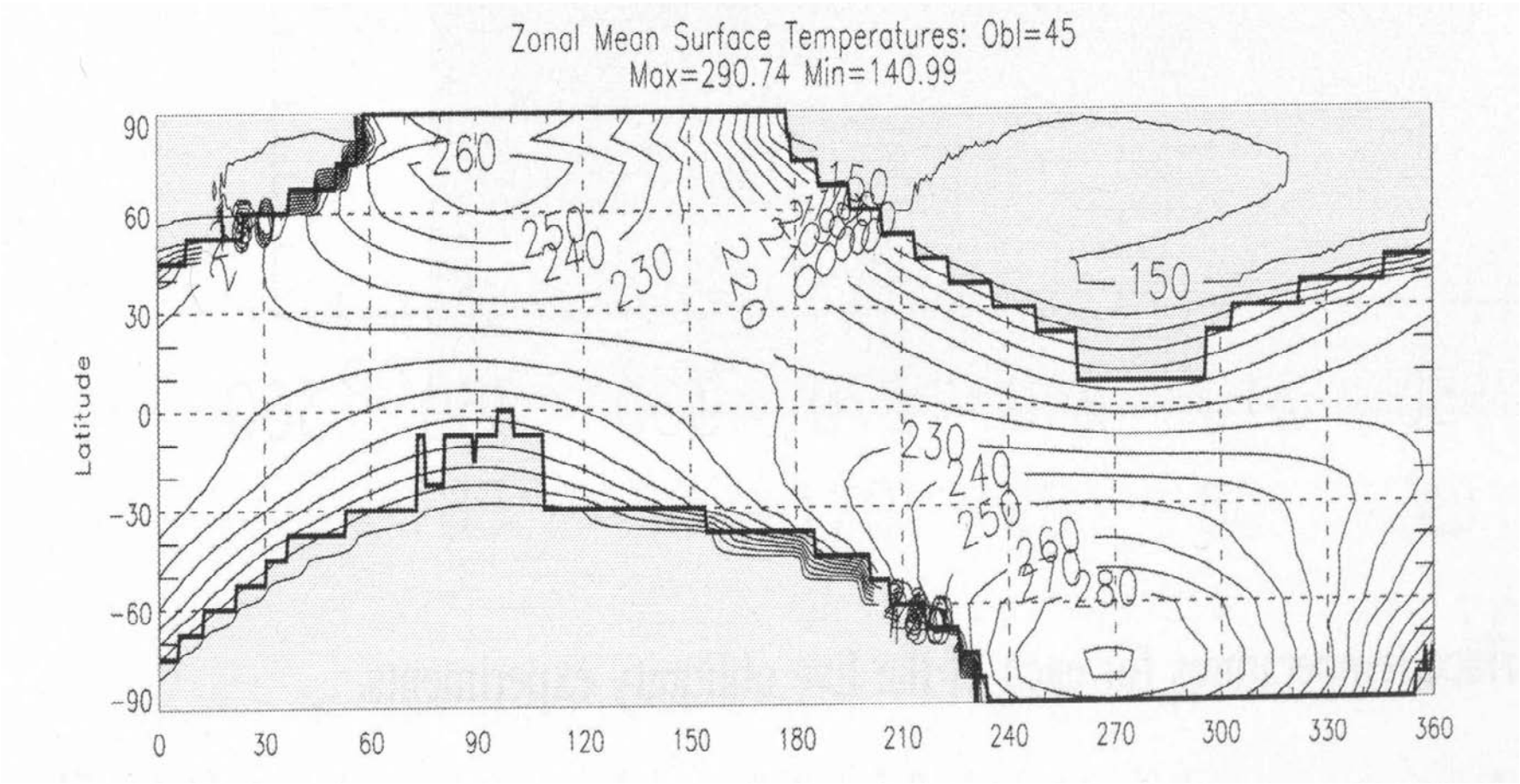
Zonal mean temperature (K) **Obliquity = 30°**

Haberle et al. 2003



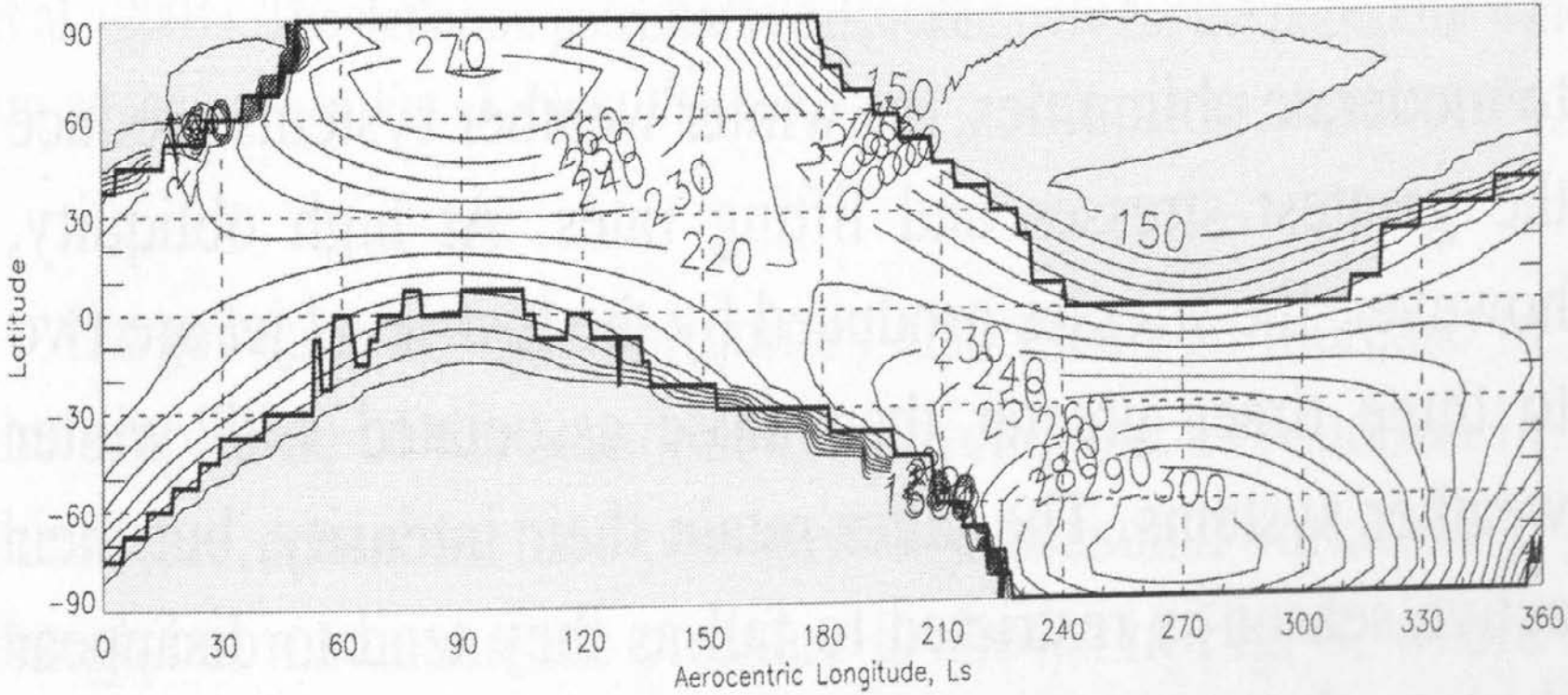
Zonal mean temperature (K) **Obliquity = 45°**

Haberle et al. 2003



Zonal mean temperature (K) **Obliquity = 60°**

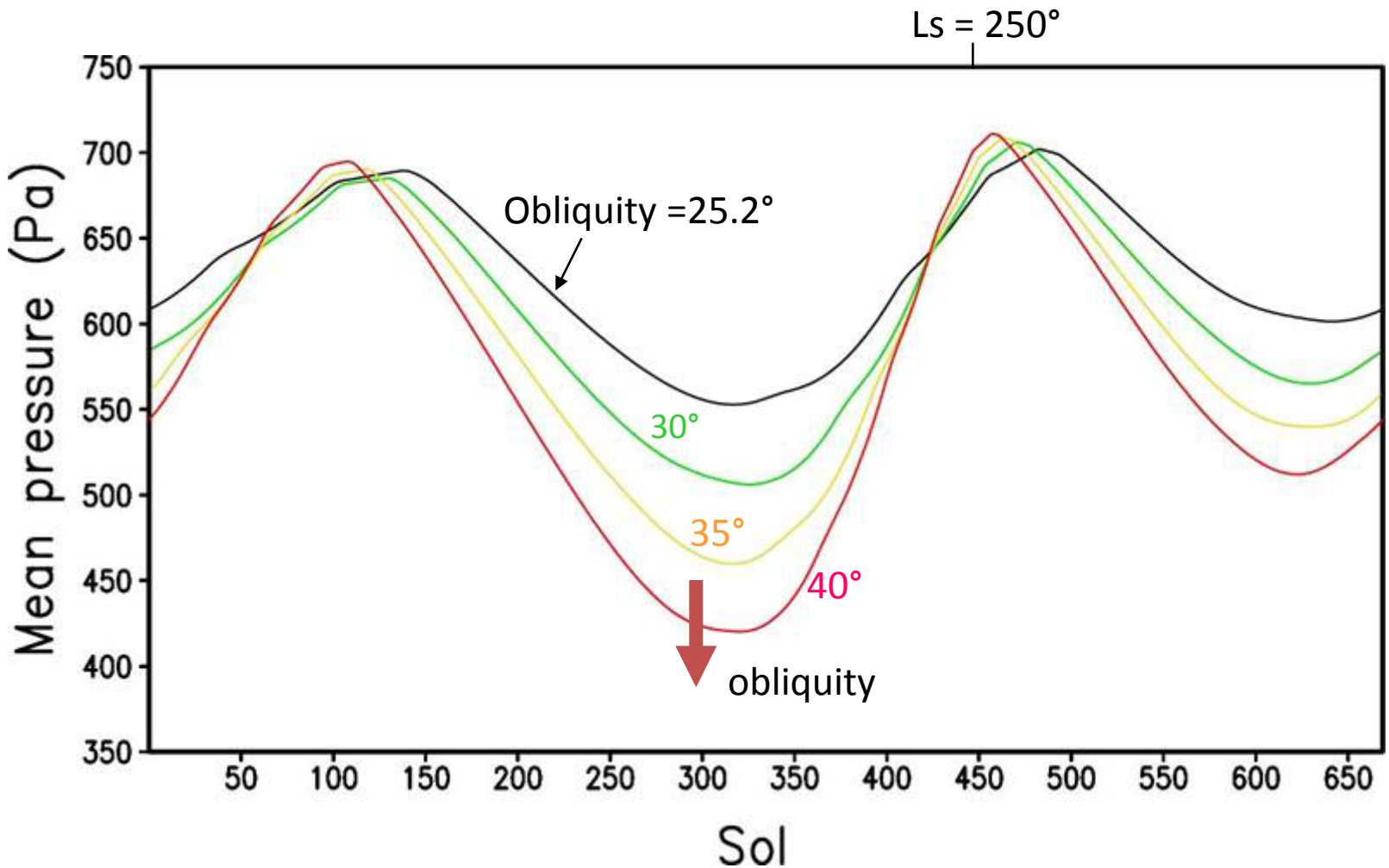
Haberle et al. 2003



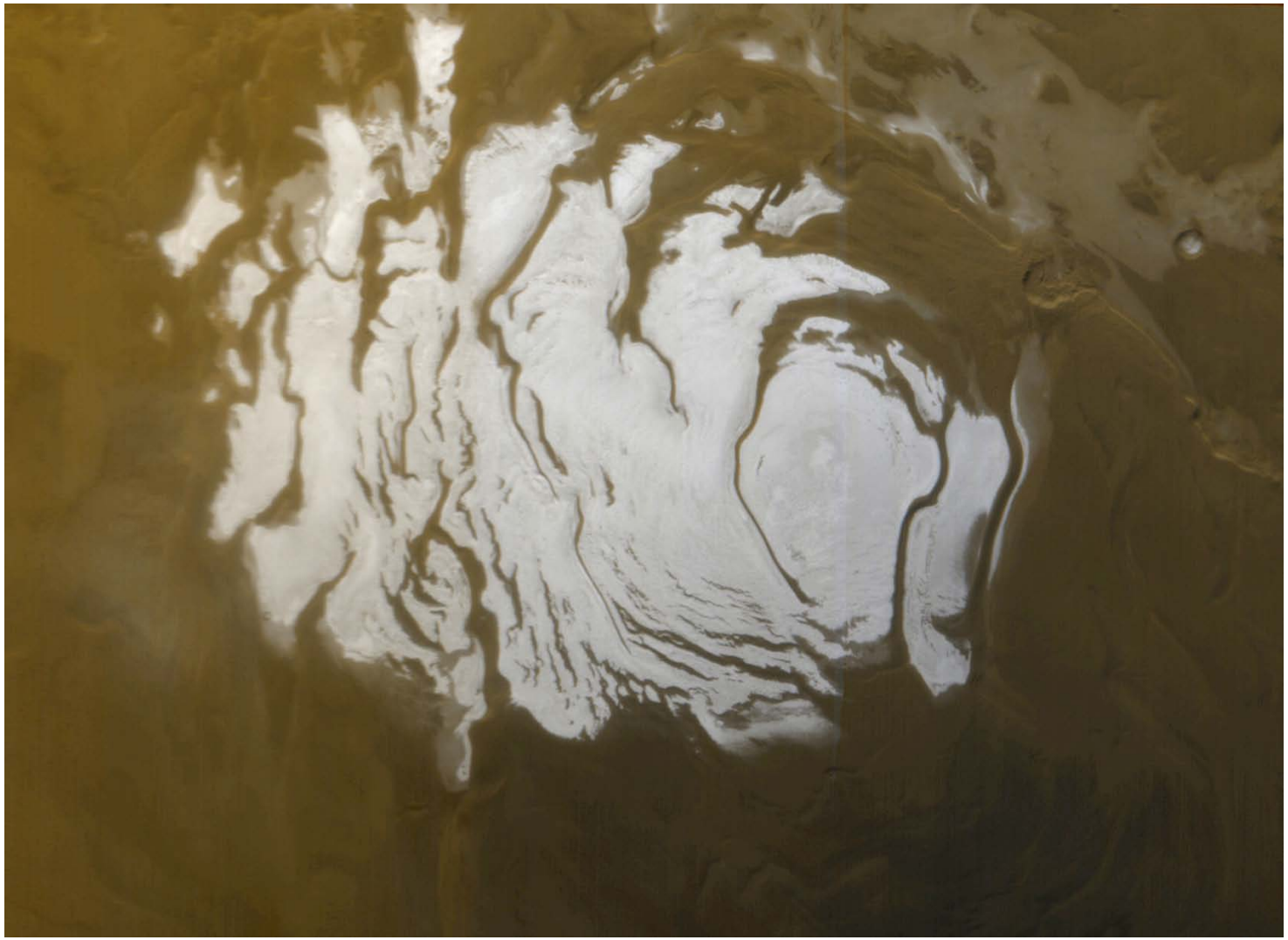
Change of surface pressure with obliquity

Seasonal variation of the mean pressure: higher obliquity ⇨ more massive seasonal CO_2 ice caps

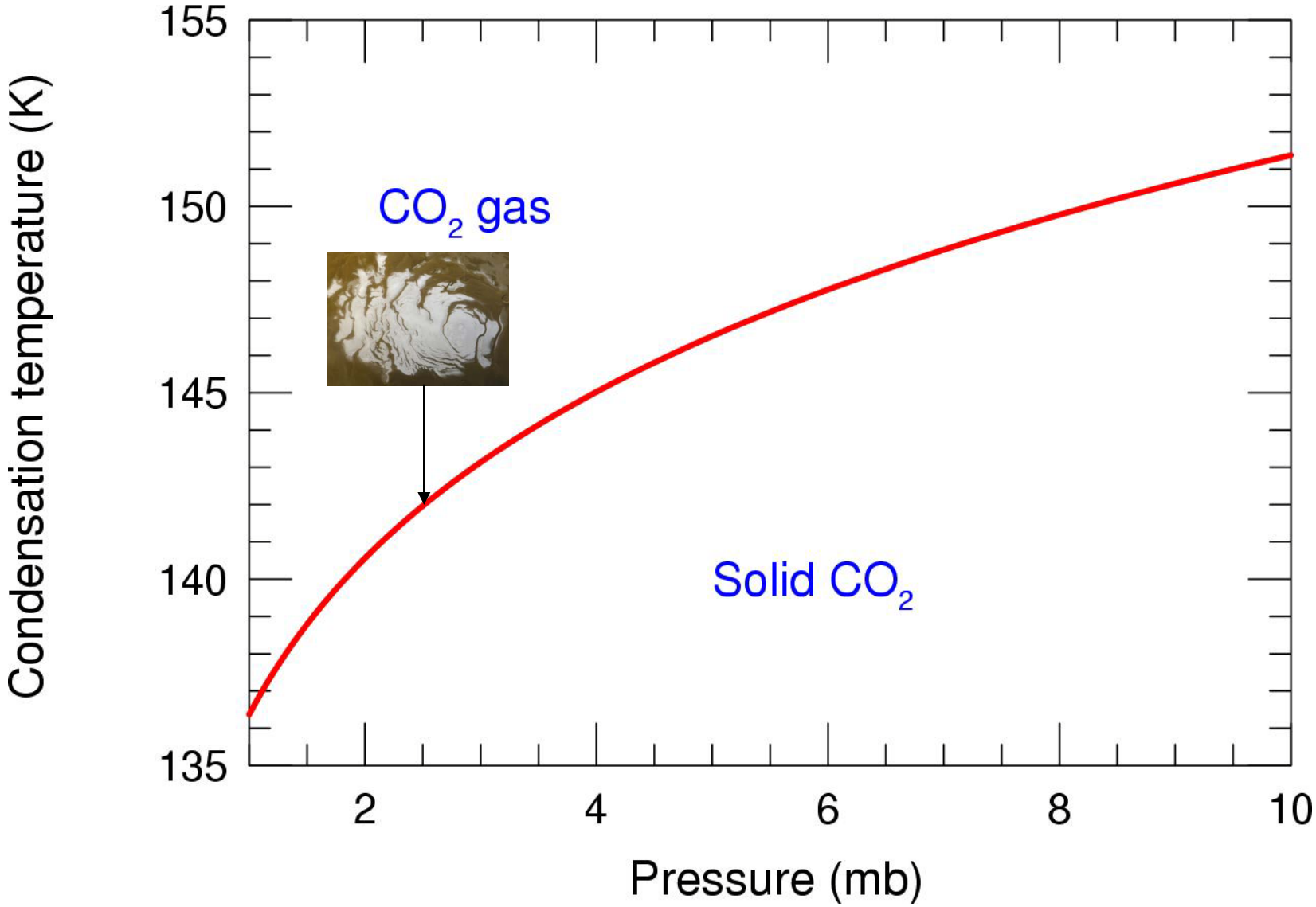
(LMD GCM calculations)



Perrenial CO2 ice cap near the south pole (300 km accross)



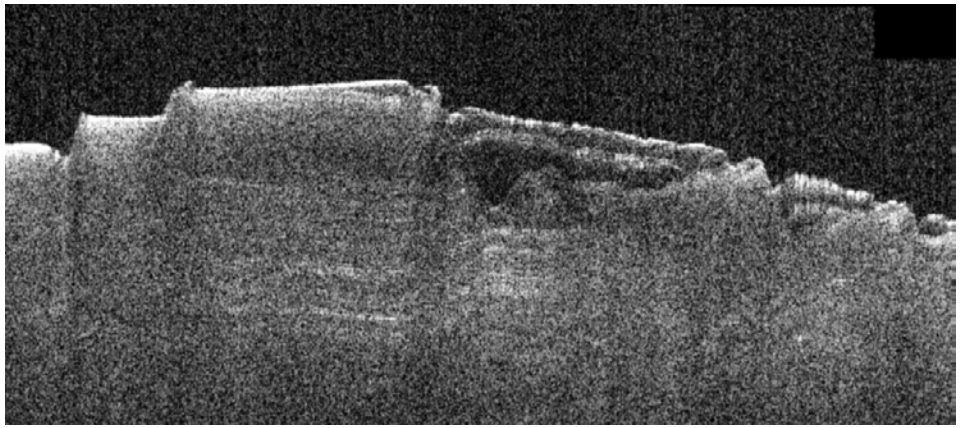
Total Atmospheric mass depends on the permanent CO2 ice cap temperature (unless exhausted)



CO_2 inventory at high obliquity

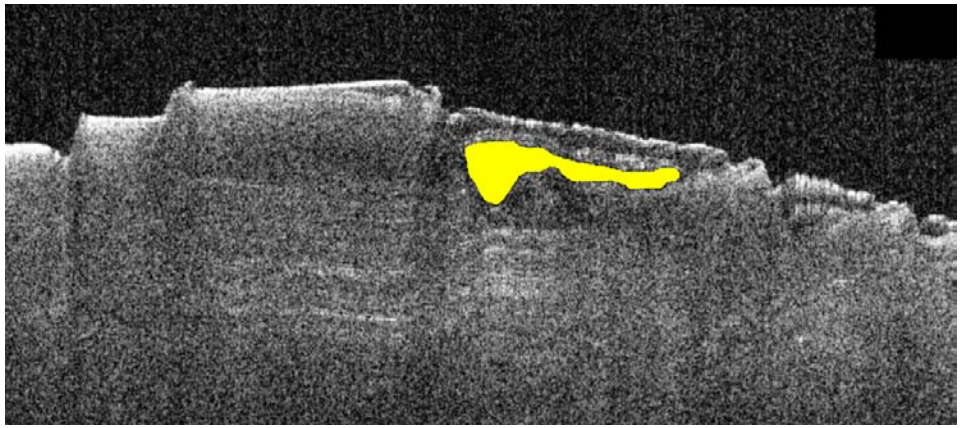
- Average insolation at the pole is proportional to the sine of the obliquity: strong warming.
  - Sublimation of the relatively thin south residual polar caps: < 0.2 mbar *[Thomas et al., 2009]*
  - Recently discovered ! : 4 – 5 mbar – deposit inside SPLD ? *[Phillips et al., 2010]*
  -

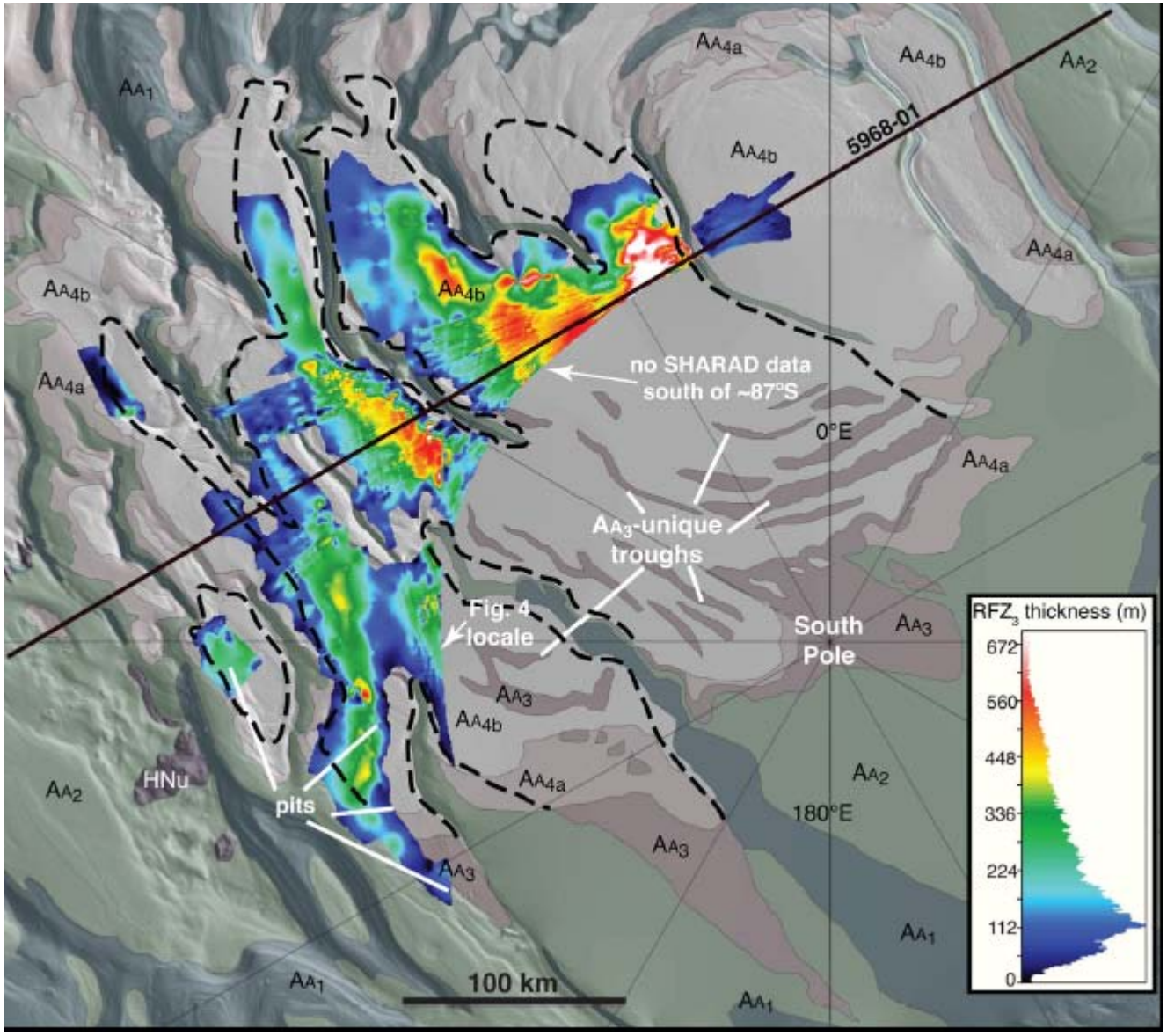
"SHARAD Finds Voluminous CO2 Ice Sequestered in the Martian South Polar Layered Deposits" (*Phillips et al.*, 2011)



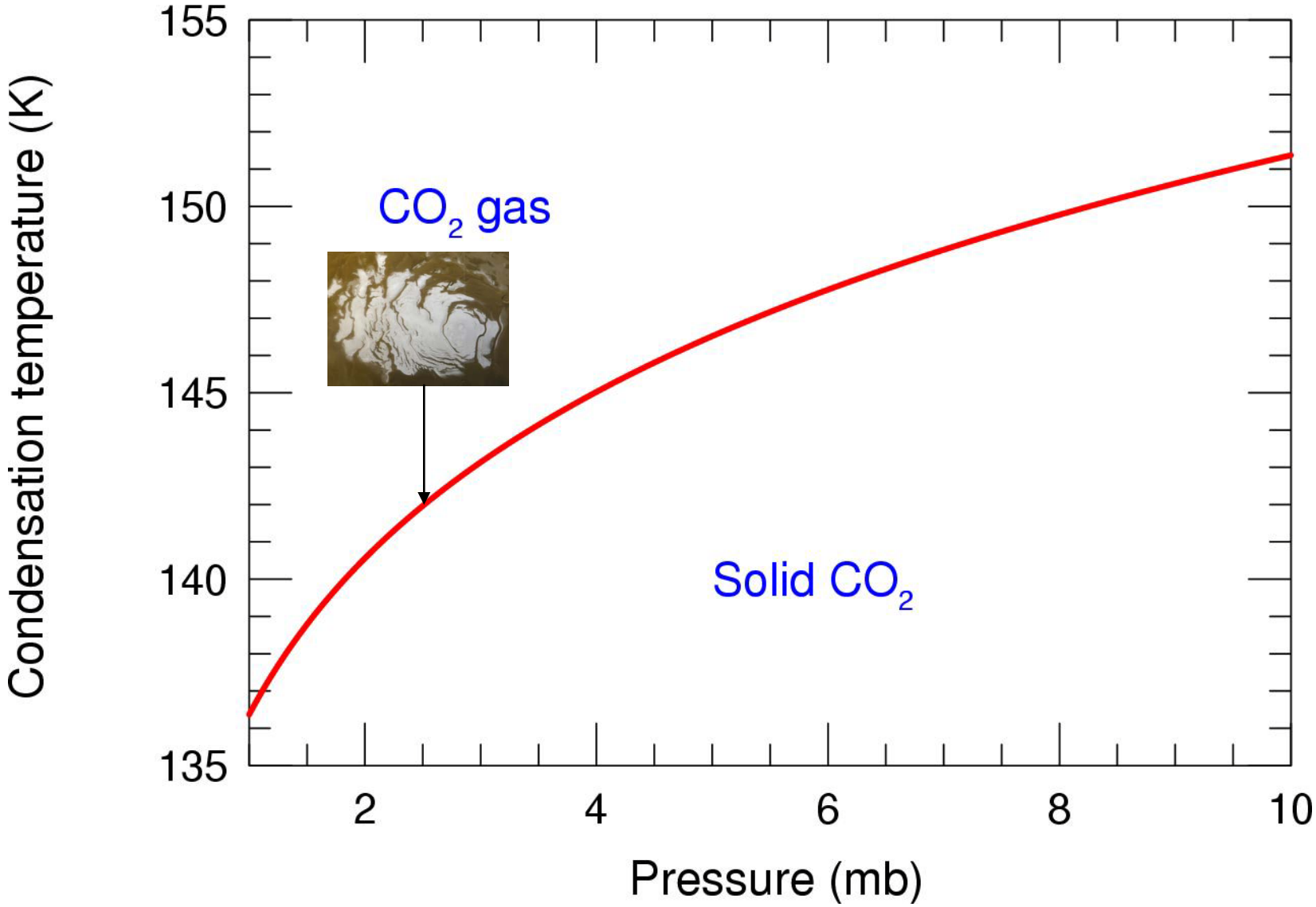
Additional 4 – 5 mbar, or more ?

(liquid water significantly more stable)




AA1
AA4a
AA4b
AA2
5968-01
AA4b
AA4a
AA4b
AA4b
AA4a
no SHARAD data
south of ~87°S
0°E
AA4a
AA3-unique
troughs
Fig. 4
locale
South
Pole
AA3
AA3
AA4b
AA4a
AA2
HNu
pits
180°E
AA3
AA3
AA1
AA1
100 km
AA1
RFZ3 thickness (m)
672
560
448
336
224
112
0

Total Atmospheric mass depends on the permanent CO2 ice cap temperature (unless exhausted)



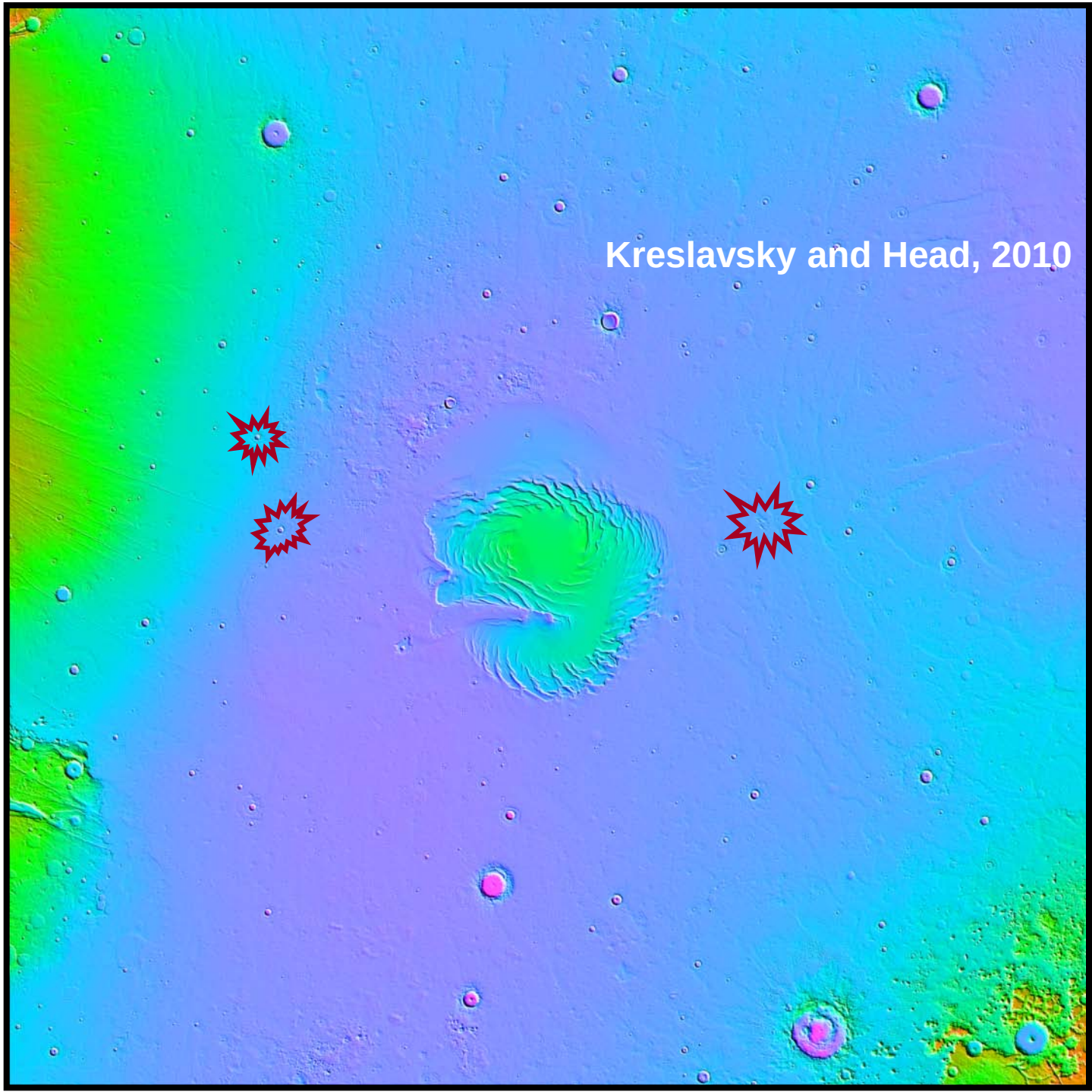
CO_2 inventory at high obliquity

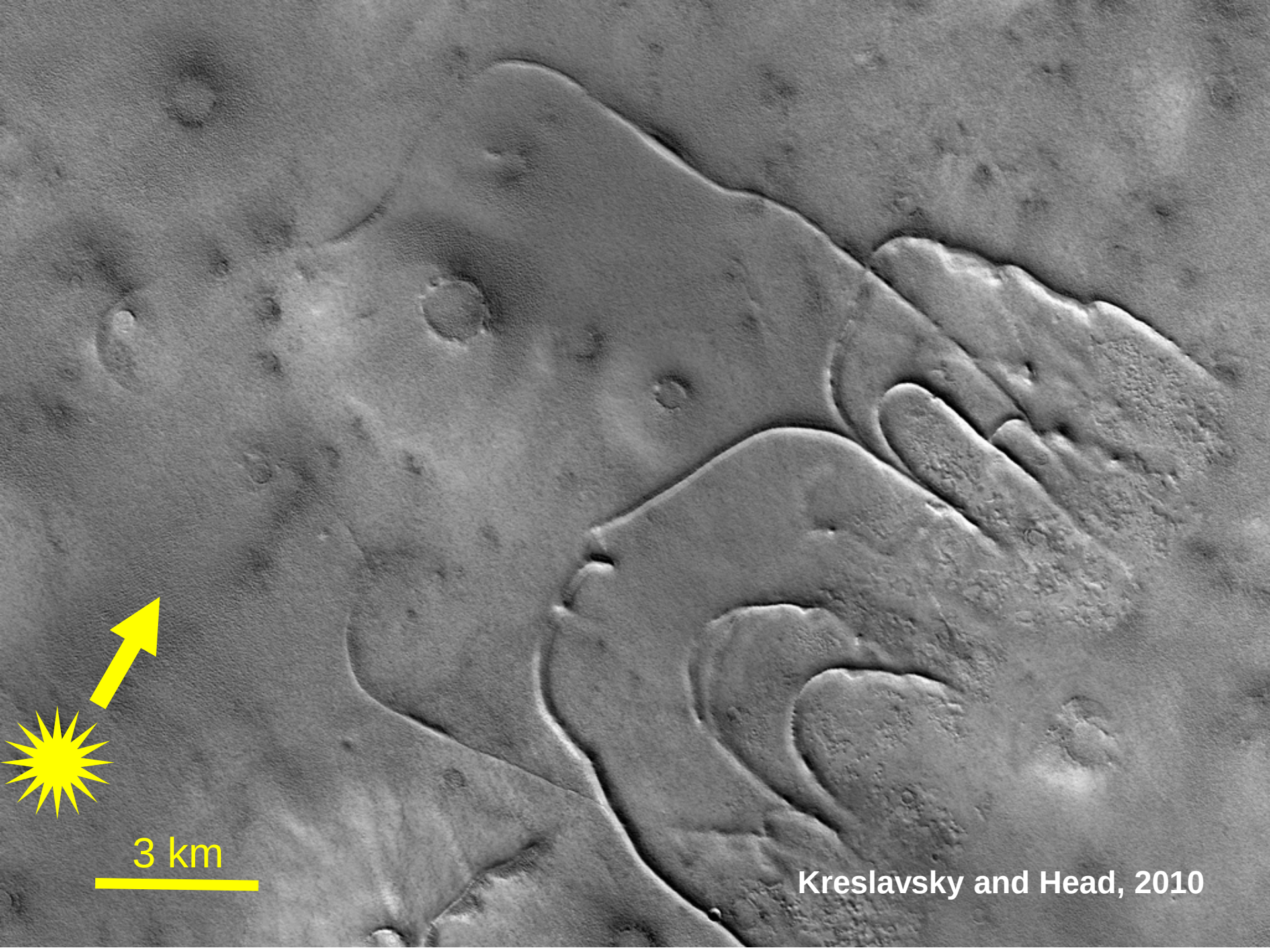
- Average insolation at the pole is proportional to the sine of the obliquity: strong warming.
  - Sublimation of the relatively thin south residual polar caps: < 0.2 mbar *[Thomas et al., 2009]*
  - Recently discovered ! : 4 – 5 mbar – deposit inside SPLD ? *[Phillips et al., 2010]*
  - Desorbed CO_2 from the high latitude ground (30 mbars ? e.g. *Zent et al.* 1992): less likely with all the H_2O ice detected by Mars Odyssey ?
  - < 20 mbar – mixed with H2O ice in the PLD ?

Atmospheric collapse at low obliquity

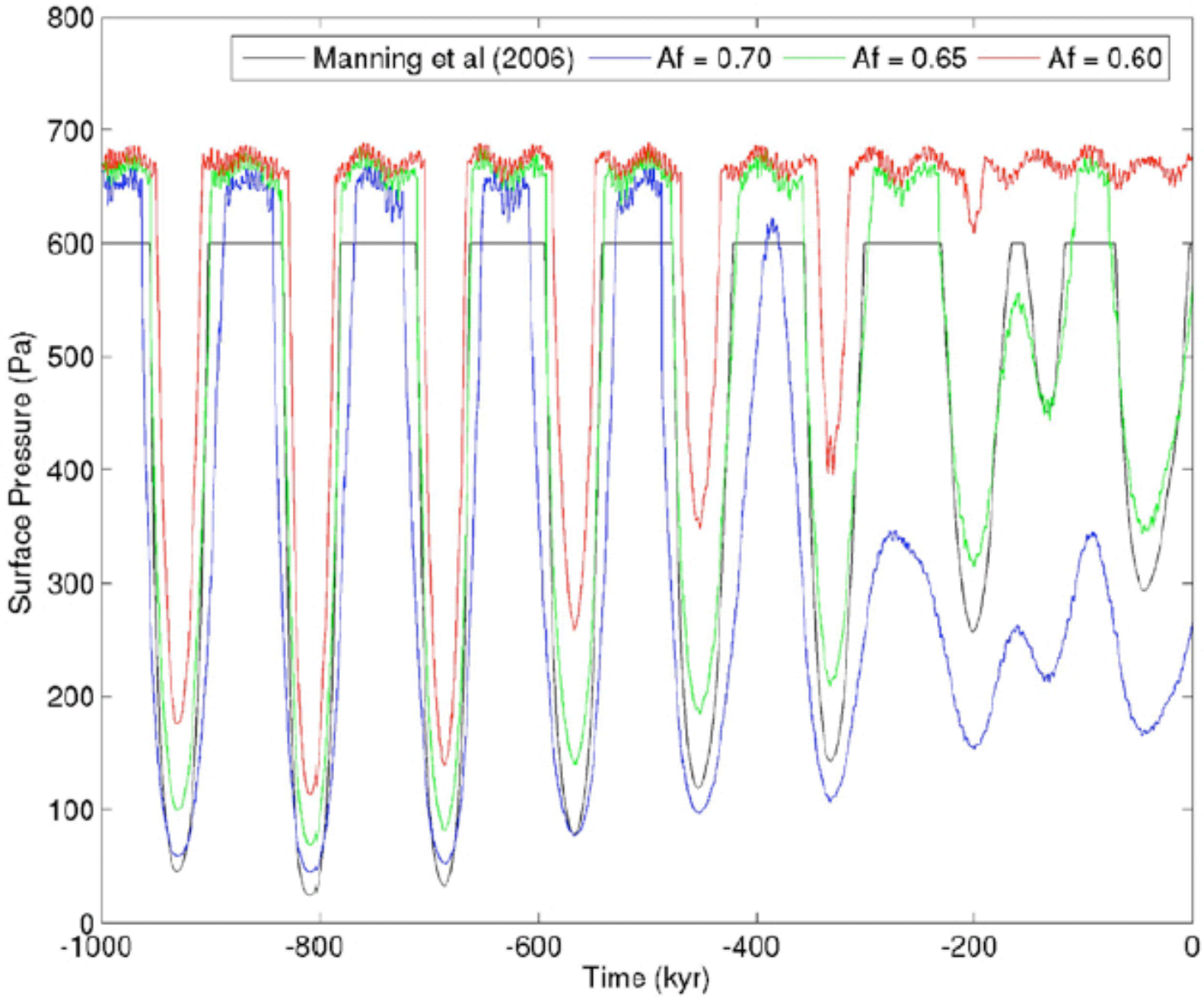
- Average insolation at the pole is proportional to the sine of the obliquity: massive permanent CO2 ice cap ? .
  - Preferential accumulation on steep pole-facing slopes at ~ 70 -80 latitude rather than at the pôles ? [Kreslavsky and Head, 2005]

CO_2 glaciers

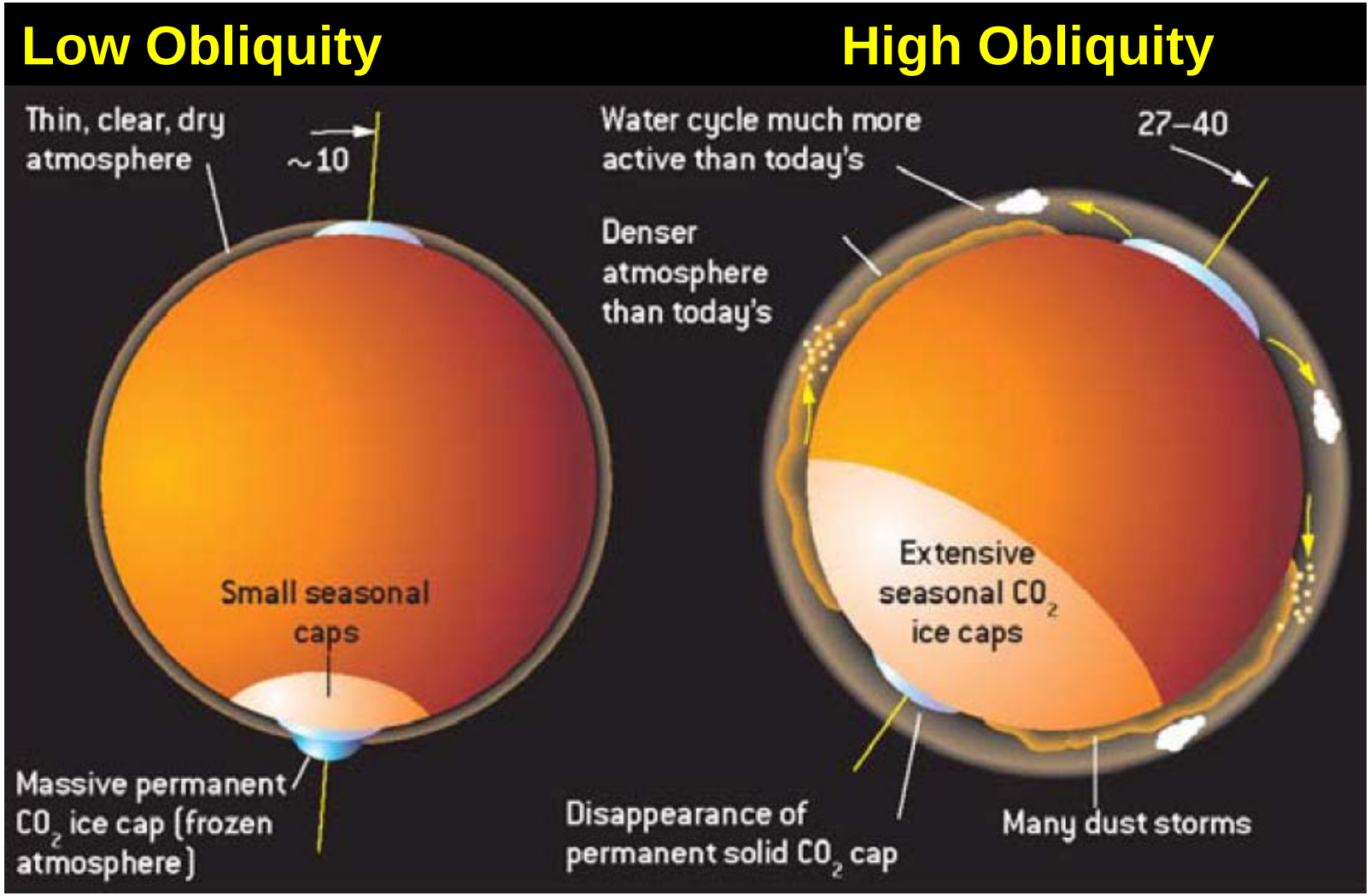



3 km
Kreslavsky and Head, 2010

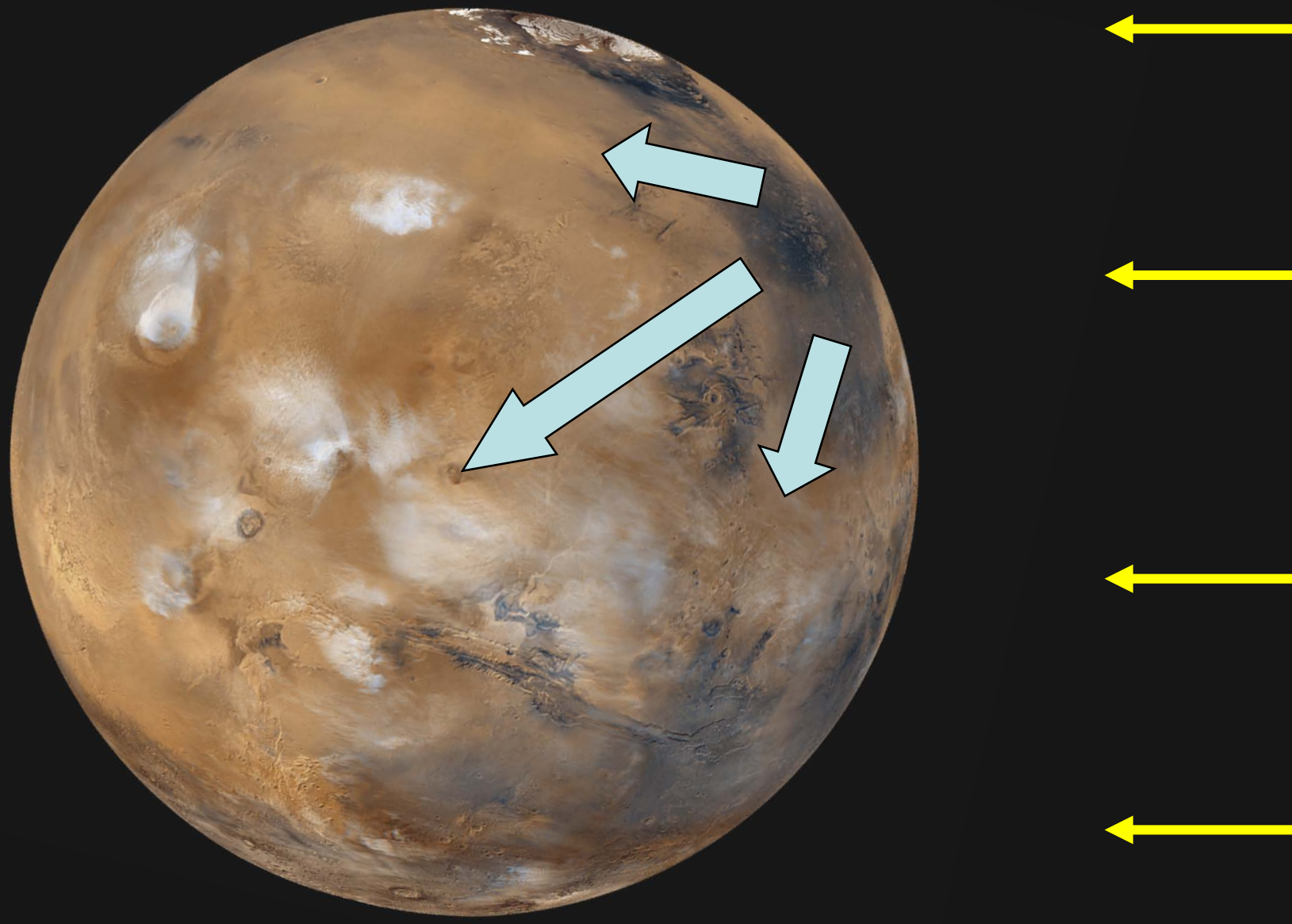
Wood and Griffiths (2009): mean pressure can drop to < 1 mbar



Summary: Impact of obliquity variations on Mars Climate



Mars water cycle at high obliquity

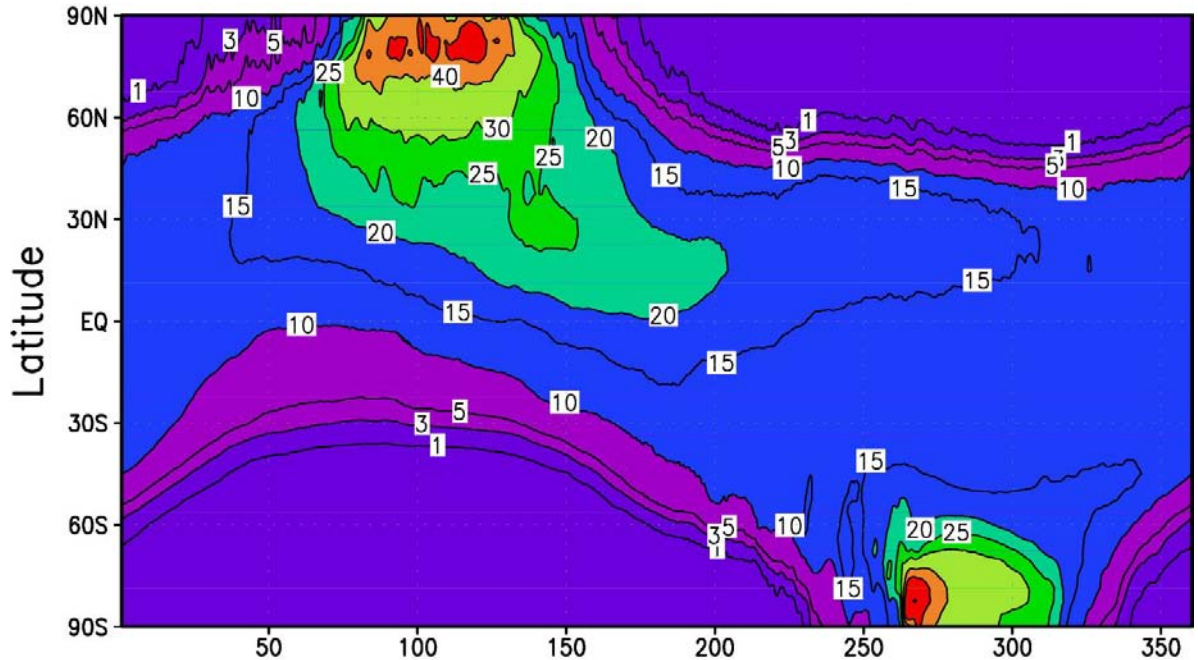


LMD GCM Simulations:

Water vapor column

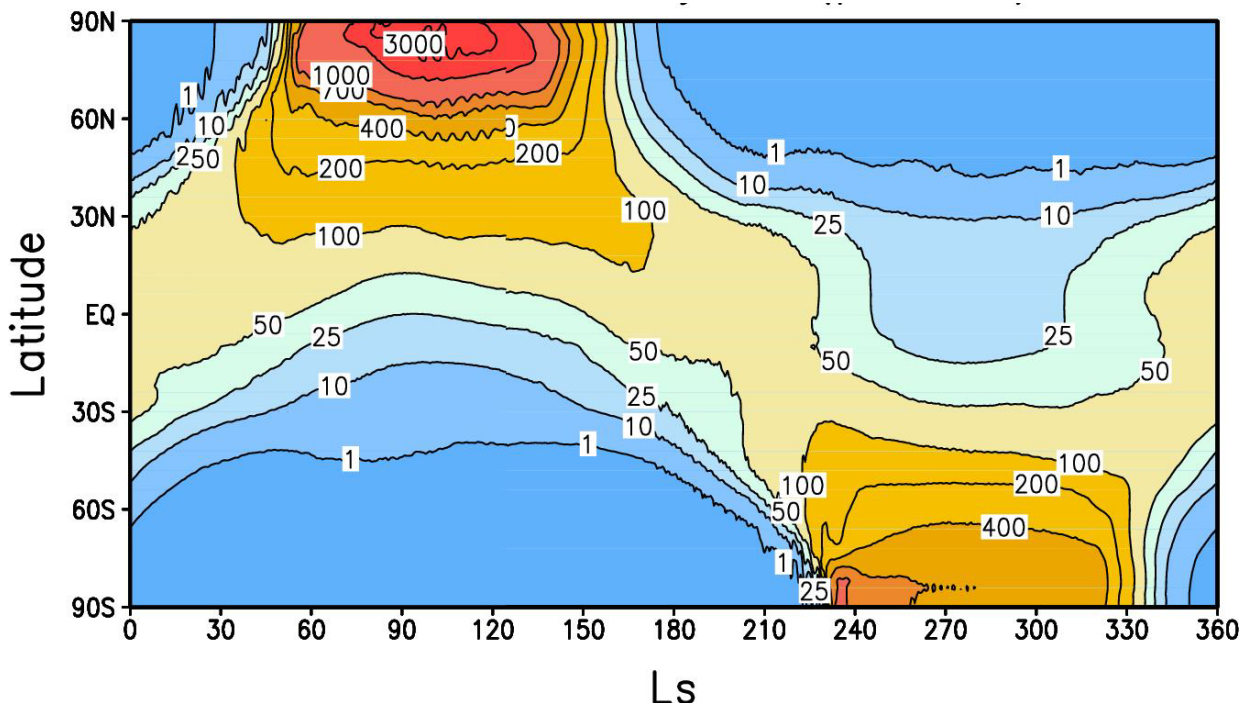
(*precipitable –microns*)

On present-day Mars :



Same, but 45° Obliquity

(Circular orbit)

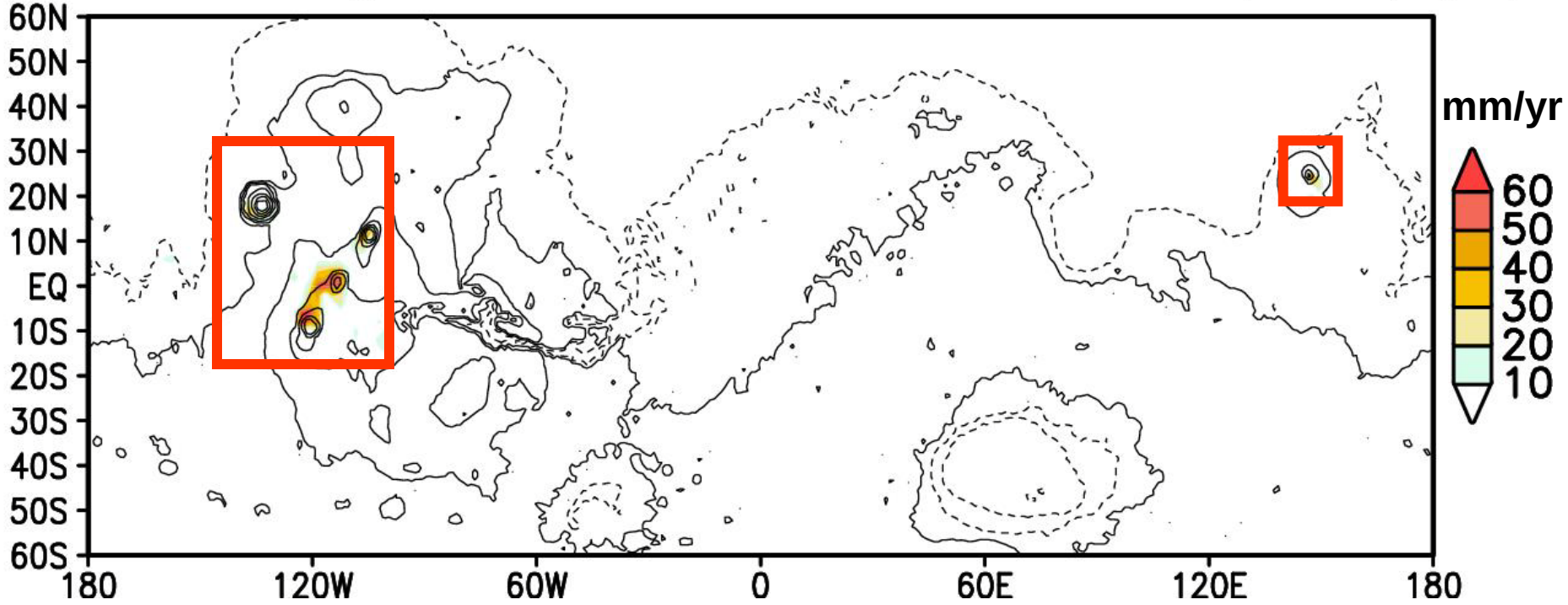


Ice accumulation rate (mm/yr)

high resolution simulation (2°x2°)

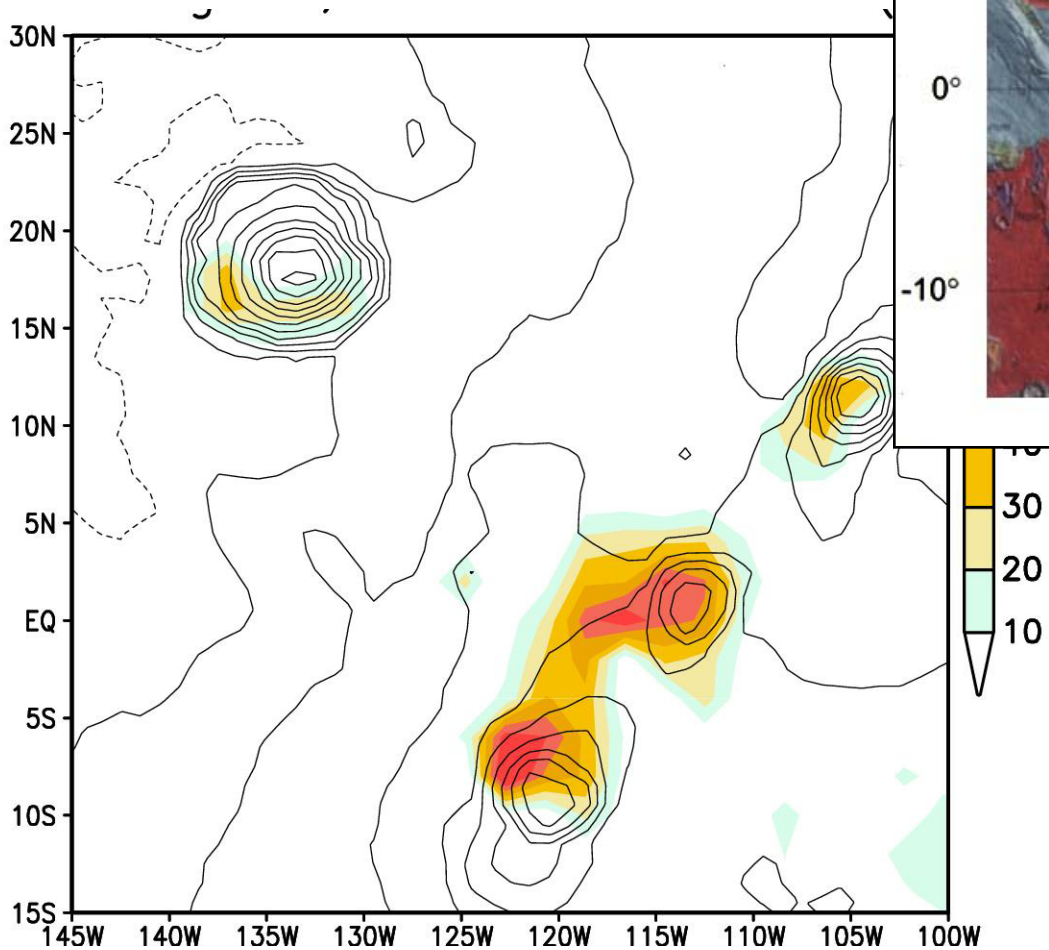
Obliquity = 45° , Excentricity = 0, Dust Opacity =0.2

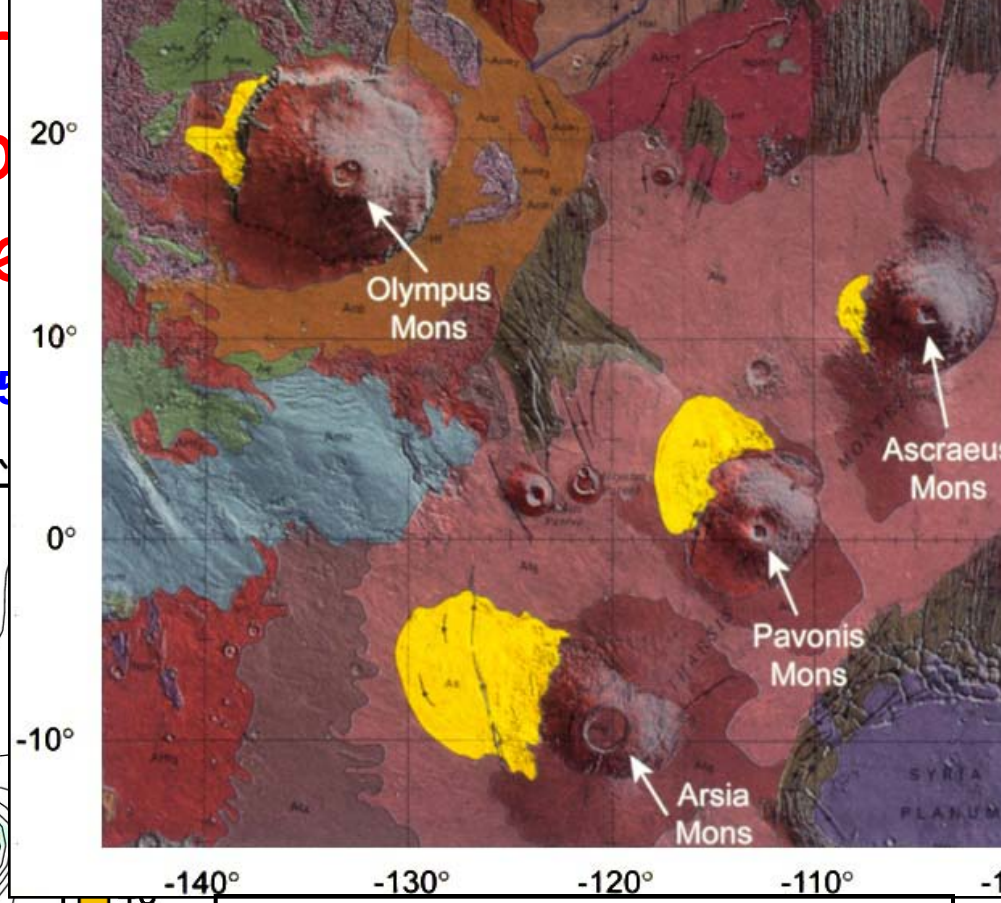
Forget et al. Science 311, p368, 2006



The format
accumulatio
very high re

Forget et al. 2006: Obliquity = 45

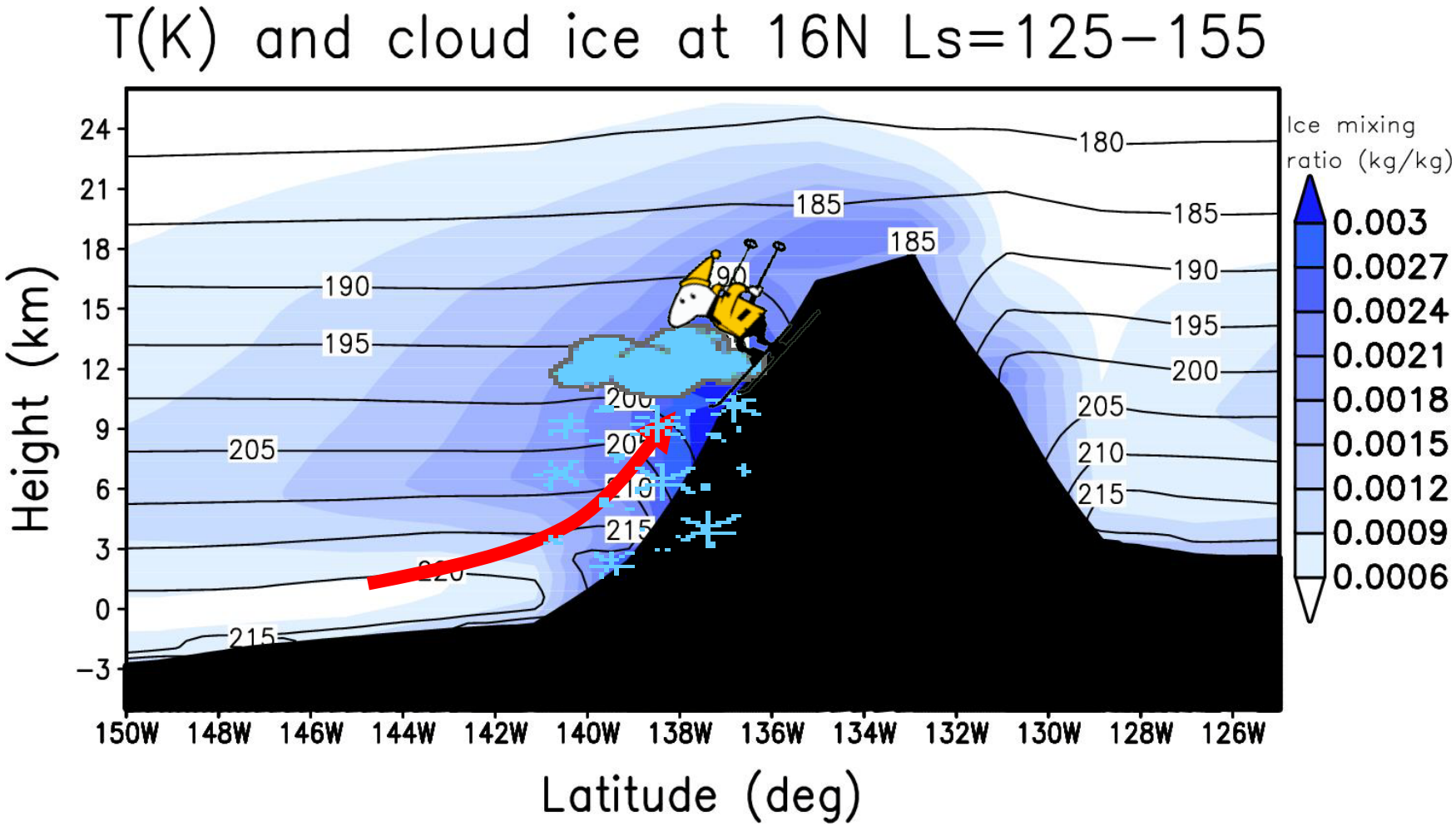




- **Fan shaped deposits, drop moraines characteristic of cold based glaciers.**
- **Rock glaciers**

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

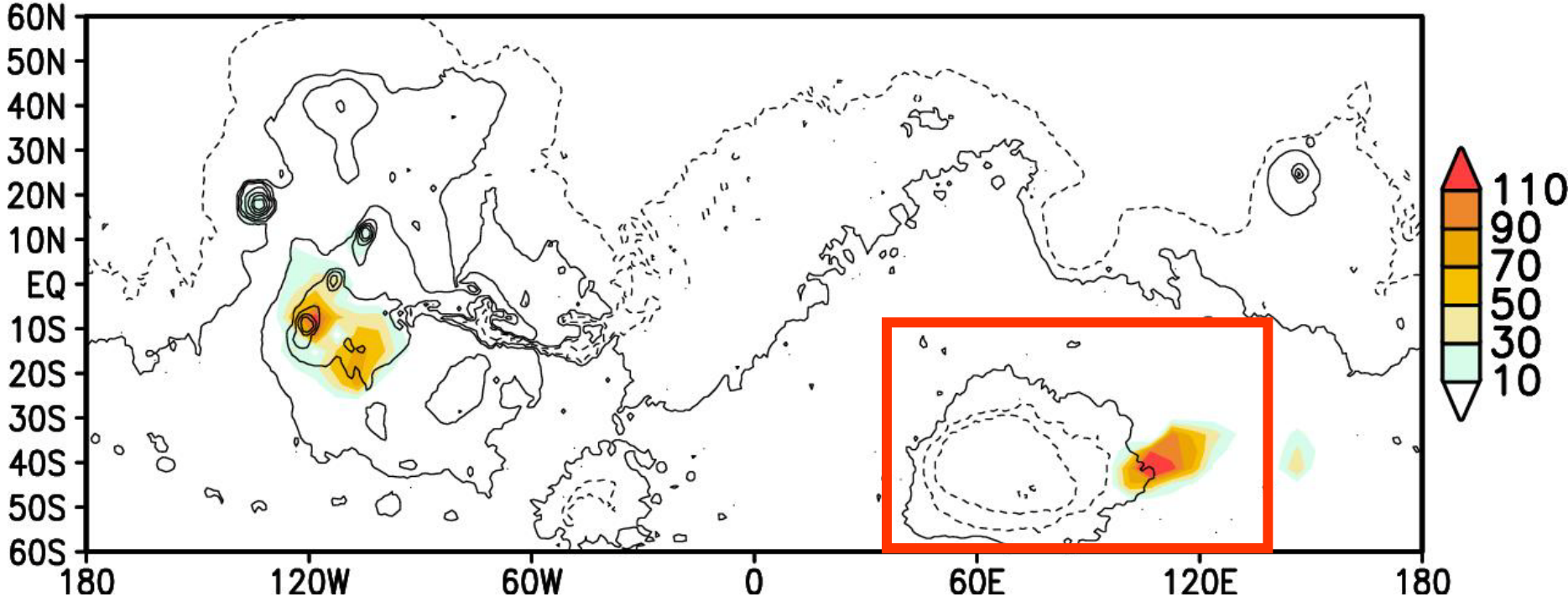


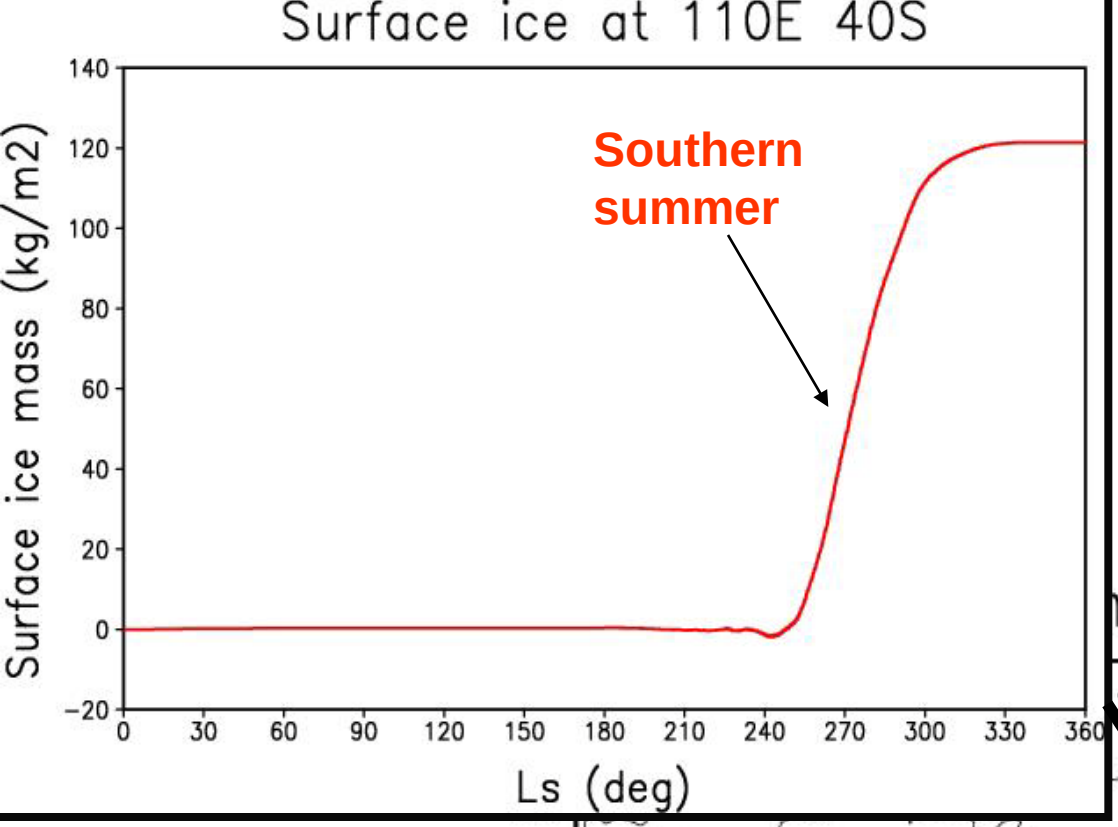
What if water ice is also available **at the south pole ?**

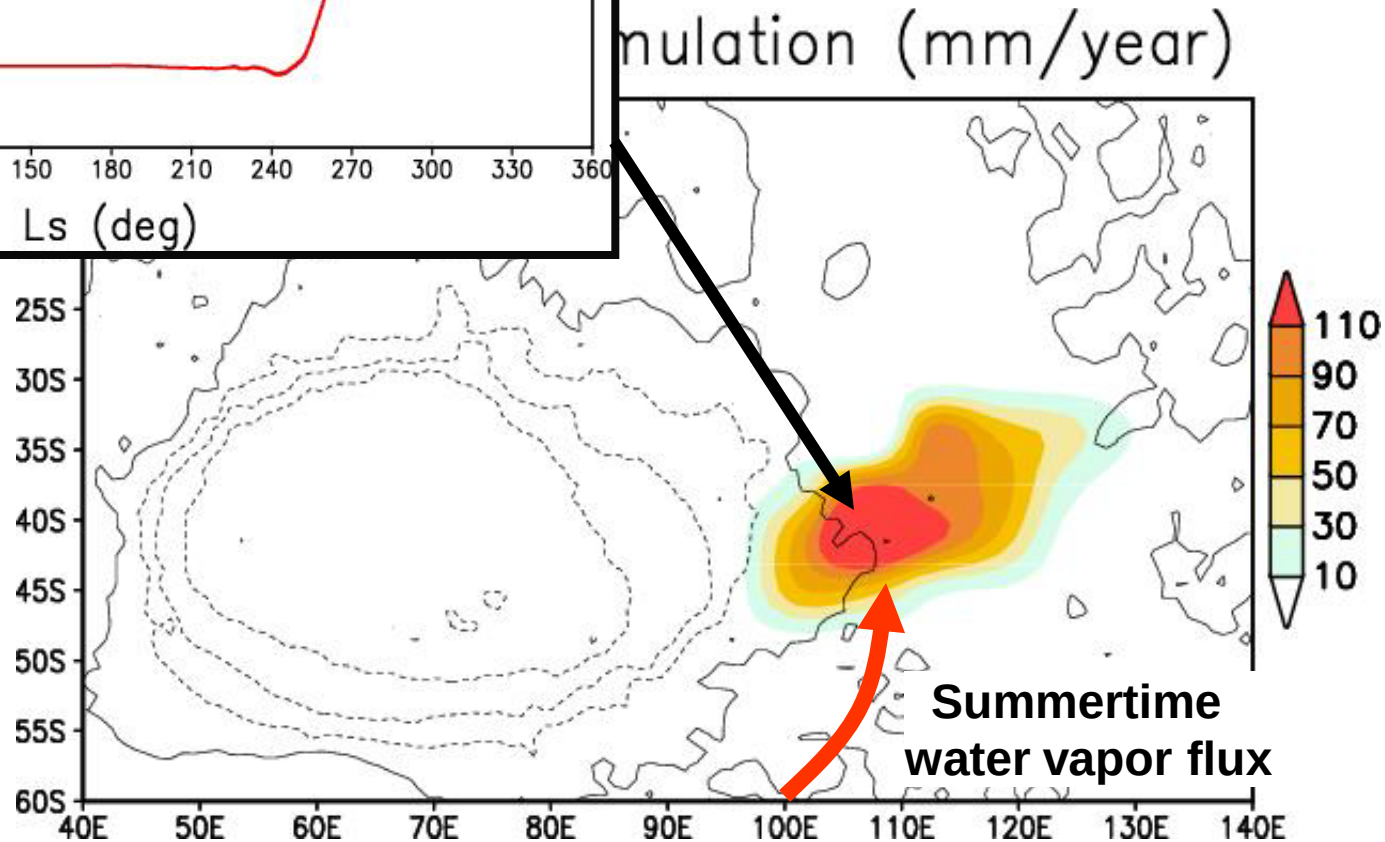
High Obliquity Simulation with a water ice cap **at the south pole**

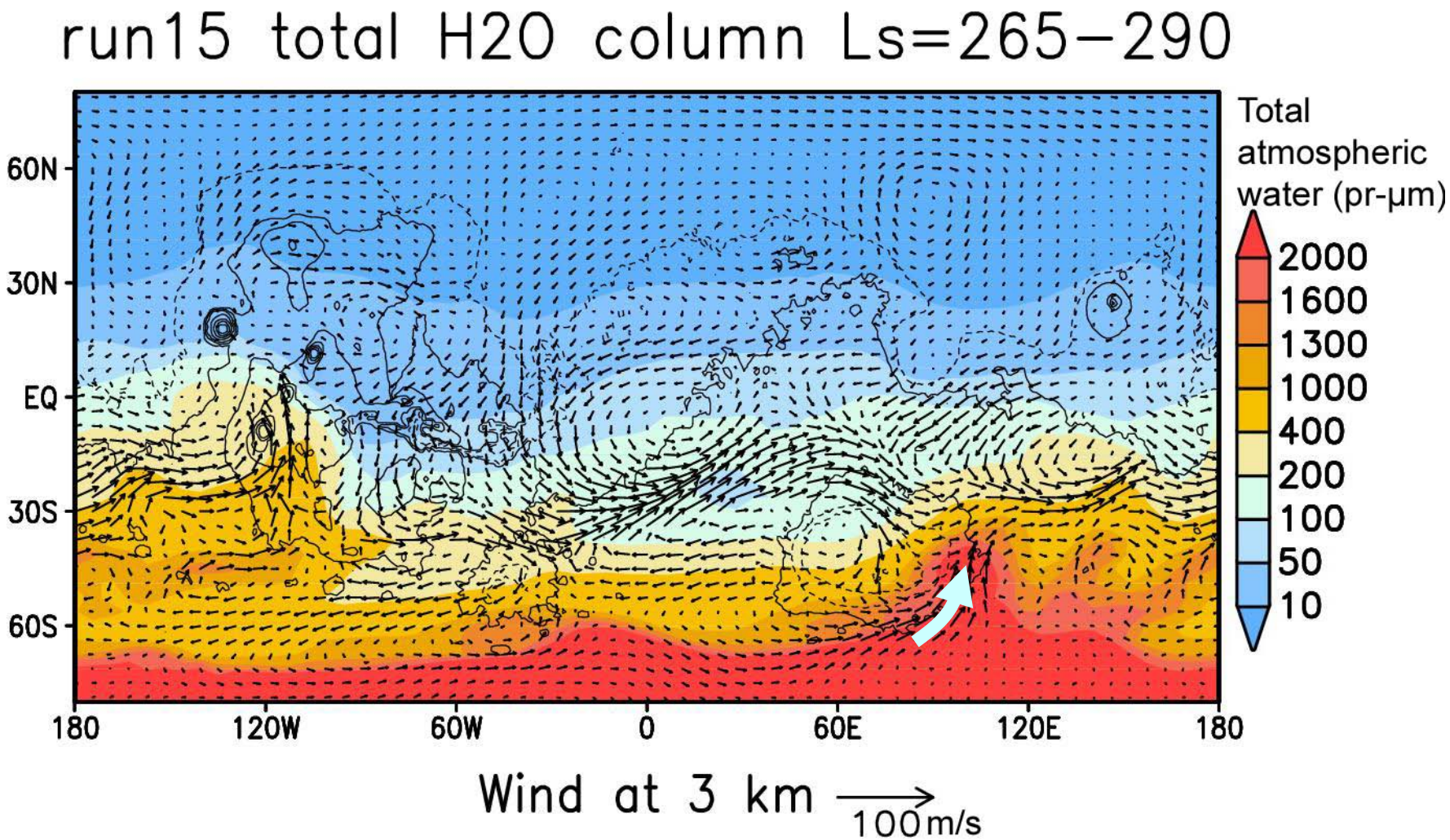
(Forget et al. science 2006)

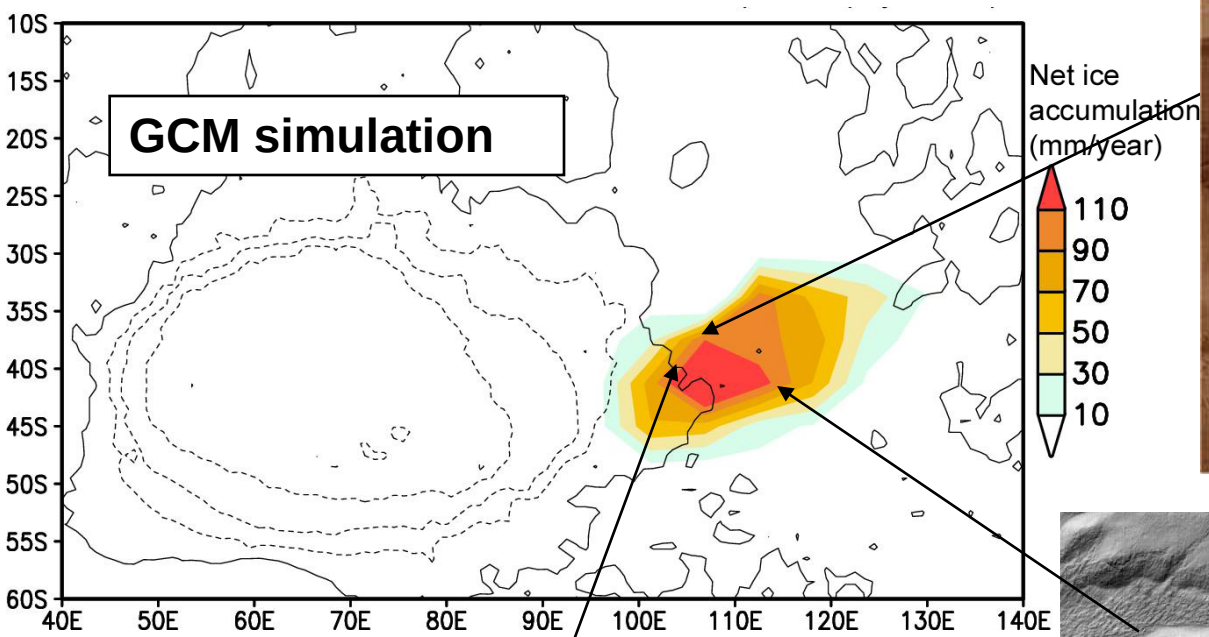
Yearly accumulation rate (mm/year) (1Oth year simulation)

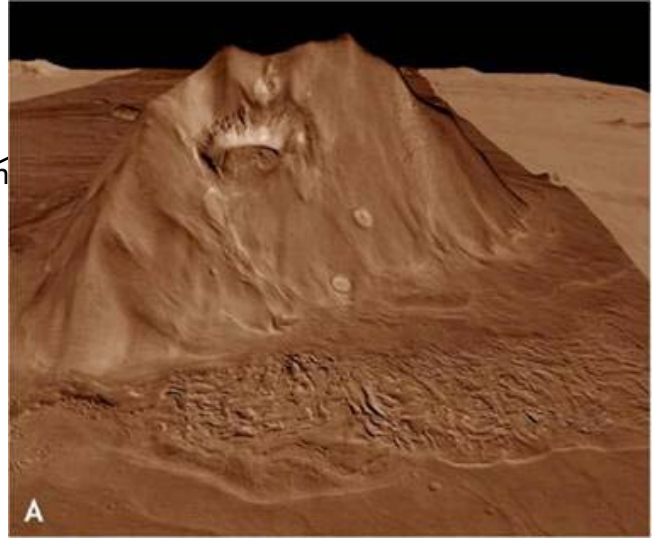


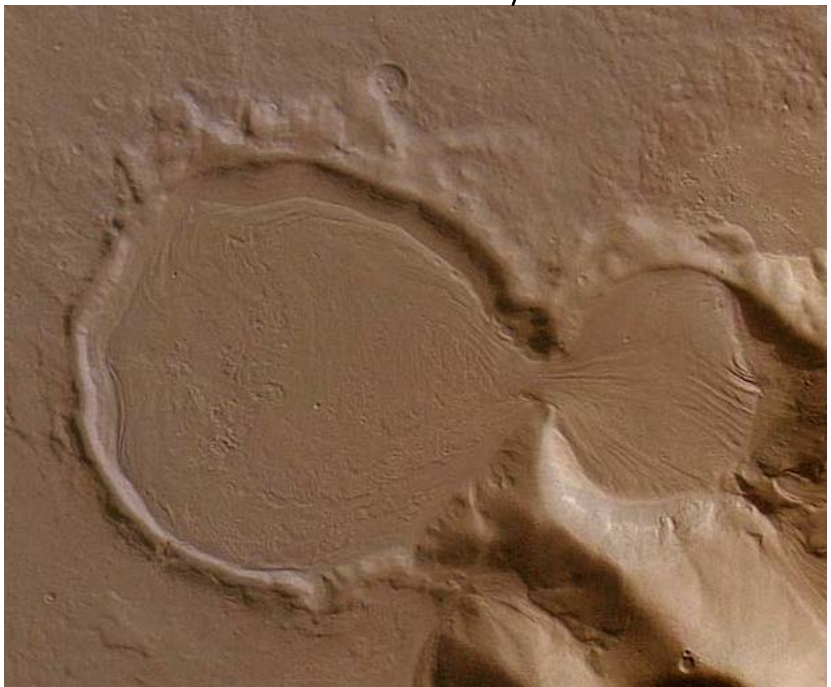

Surface ice at 110E 40S
Southern summer
Surface ice mass (kg/m2)
140
120
100
80
60
40
20
0
−20
0
30
60
90
120
150
180
210
240
270
300
330
360
Ls (deg)


mulation (mm/year)
25S
30S
35S
40S
45S
50S
55S
60S
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
110
90
70
50
30
10
Summertime water vapor flux


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

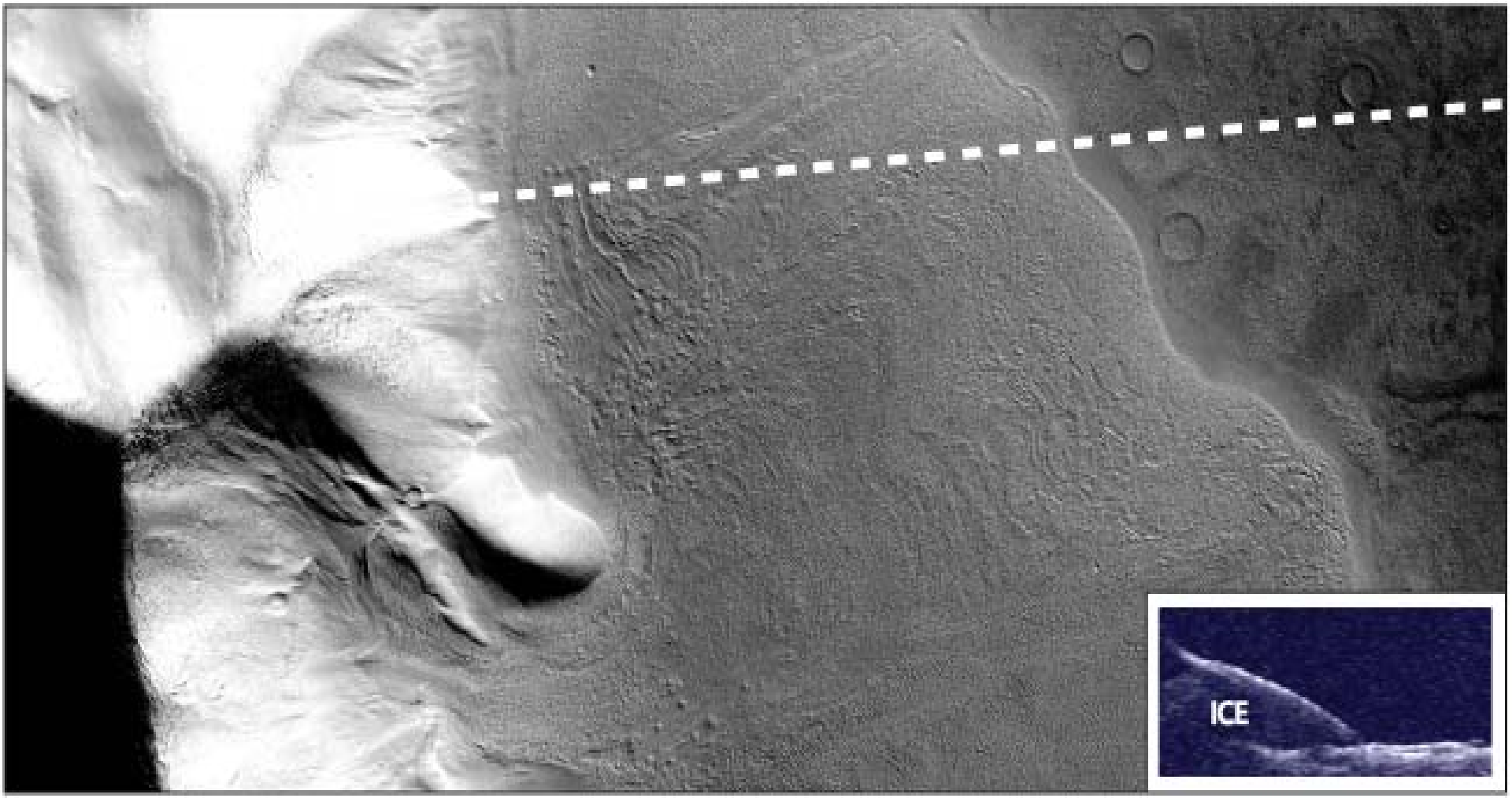




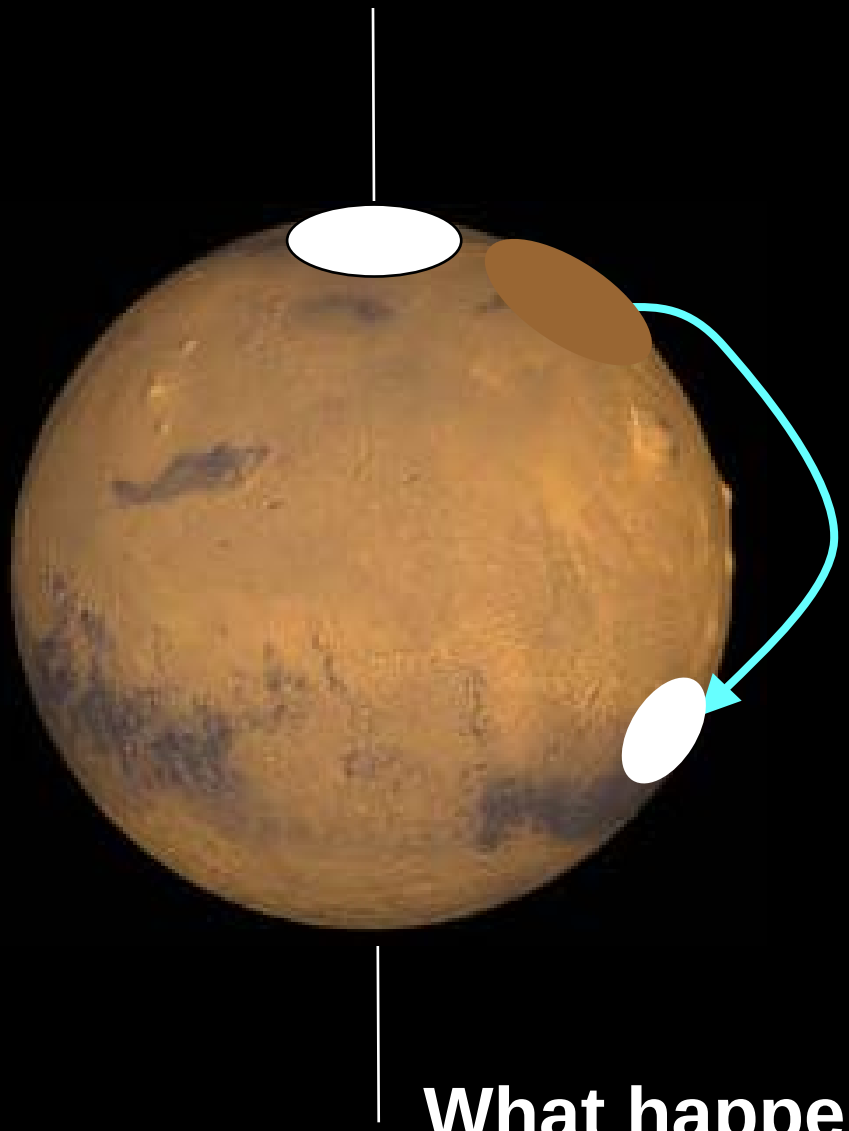


Head et al.
Hartmann et al.
Crown et al.
Etc…

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

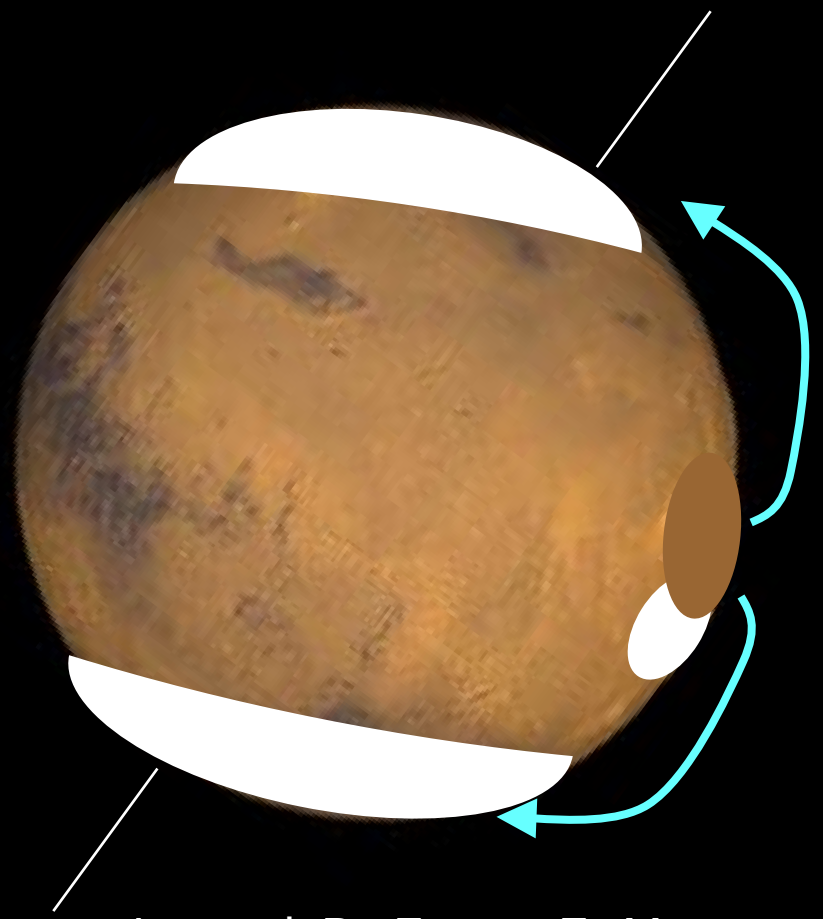


GCM simulation of high obliquity

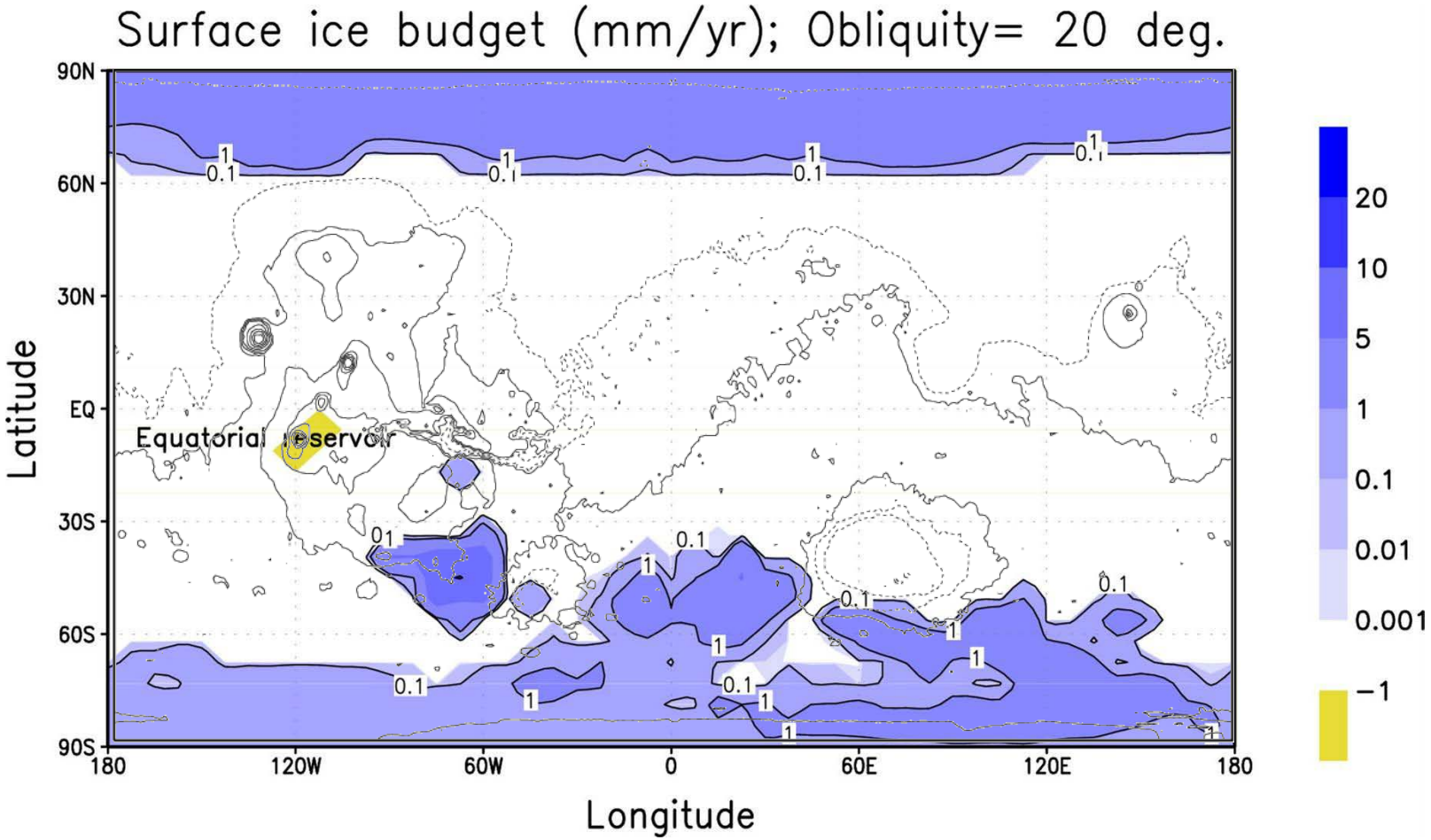


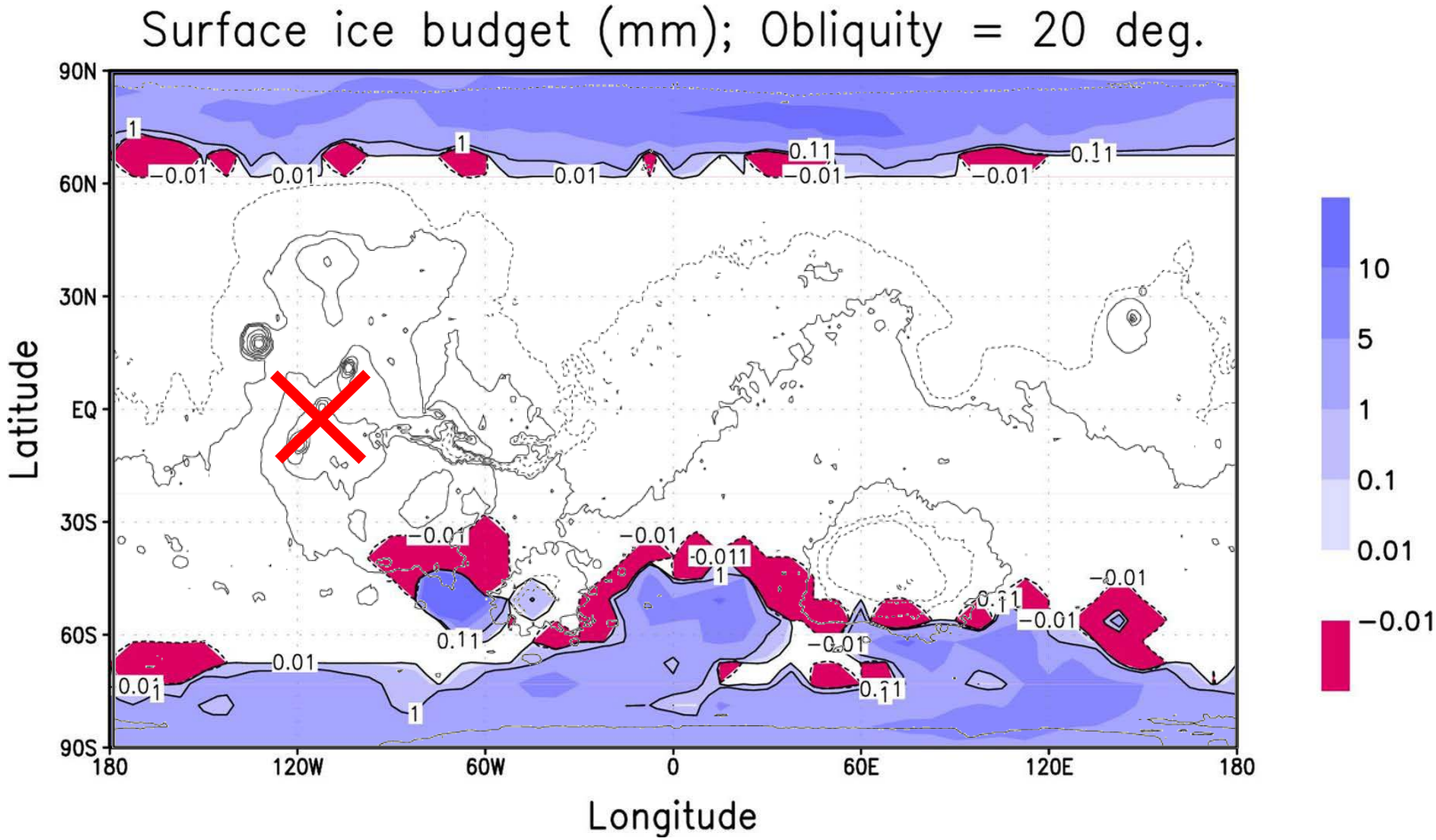
What happened next ?

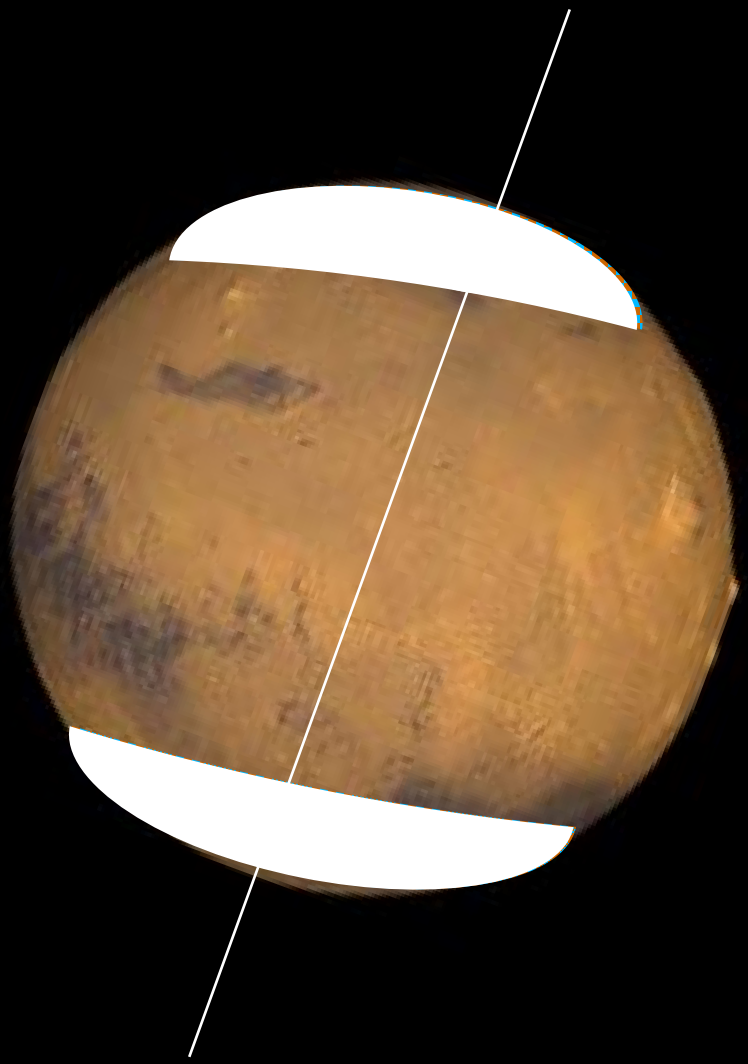
Back from high obliquity to low obliquity



•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
Equatorial reservoir
20
10
5
1
0.1
0.01
0.001
−1

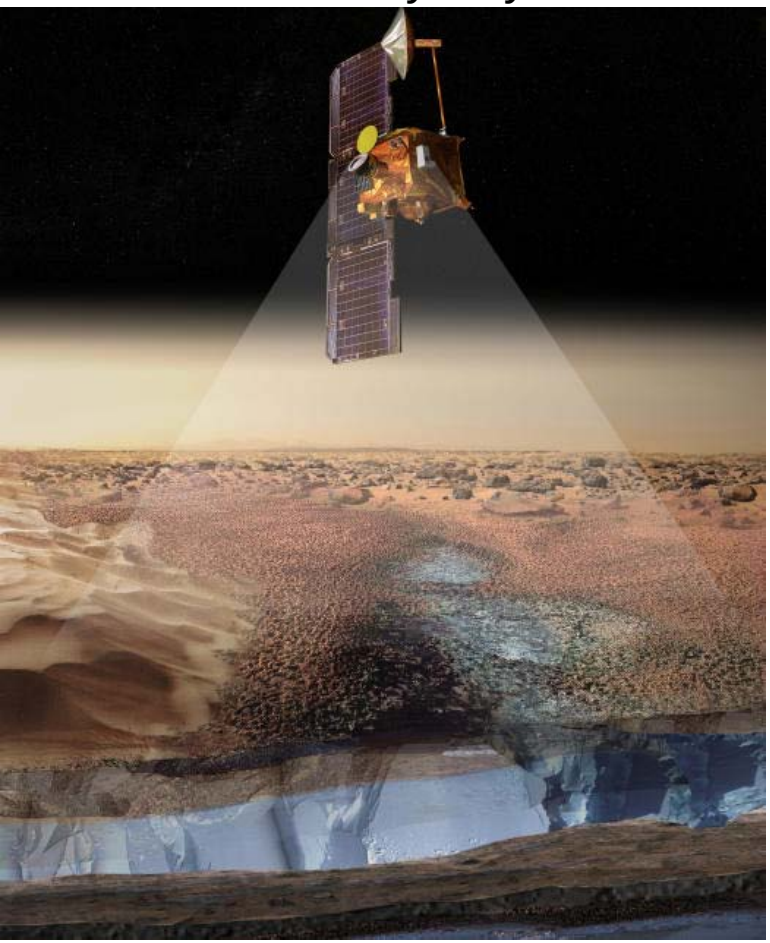

Surface ice budget (mm); Obliquity = 20 deg.
Latitude
Longitude
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
10
5
1
0.1
0.01
−0.01

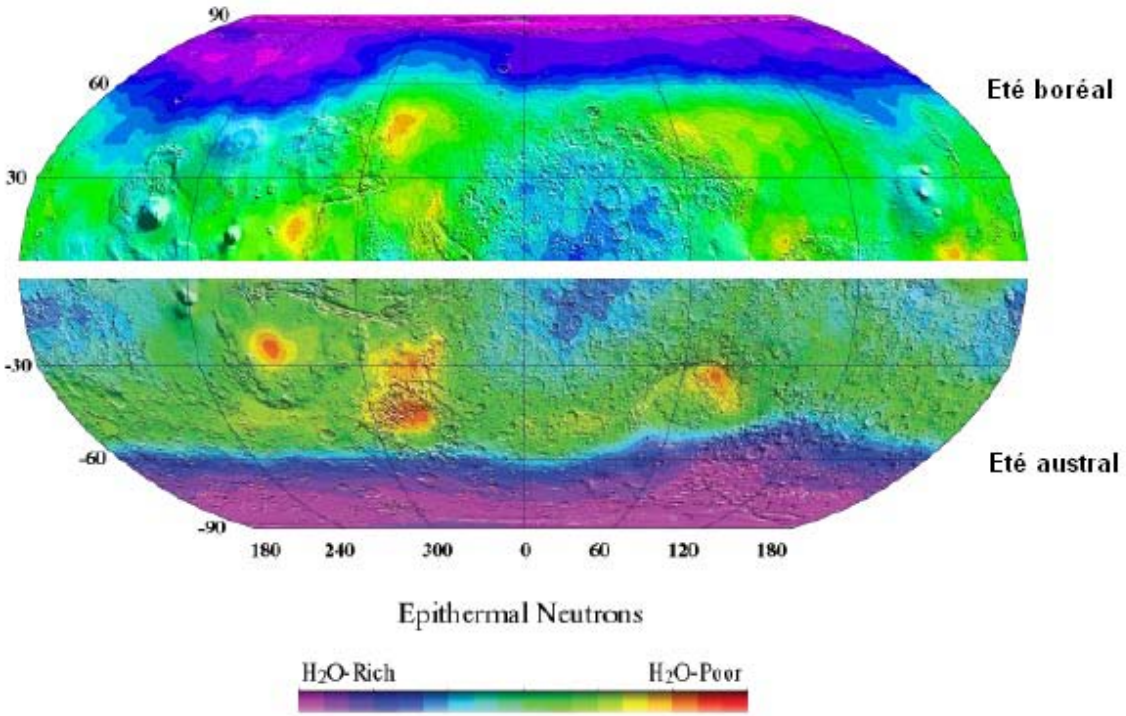


Near surface ice detected by Mars Odyssey GRS

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

NASA Mars Odyssey

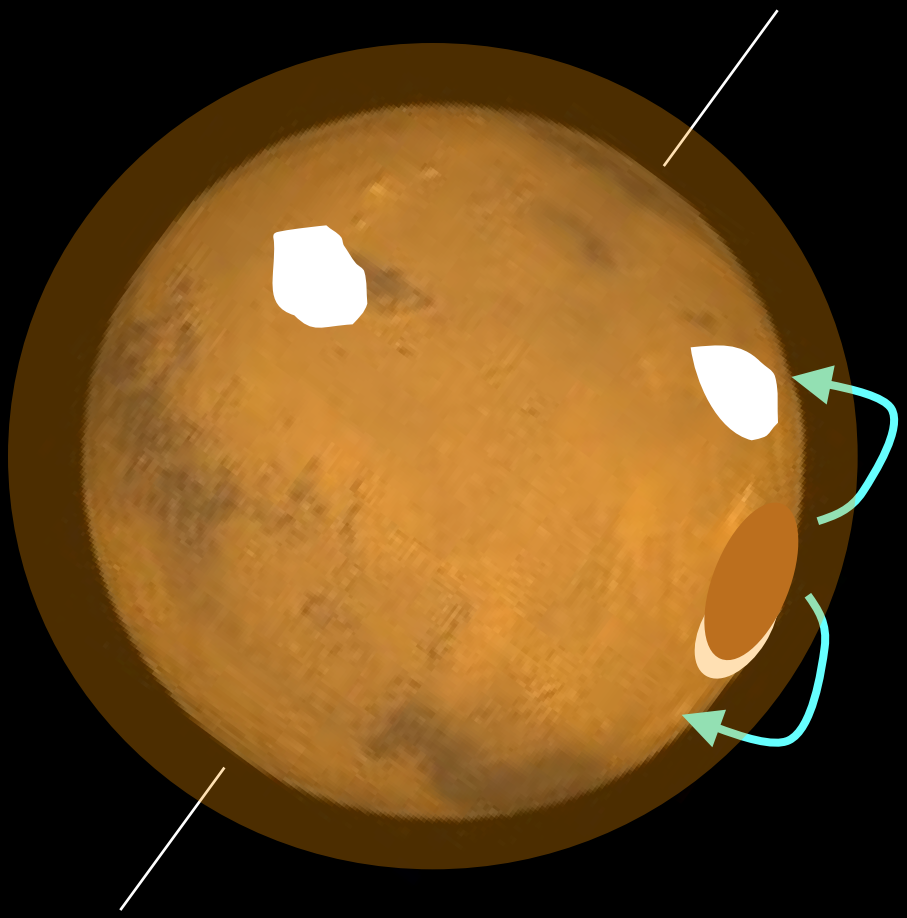




Back from high obliquity to low obliquity

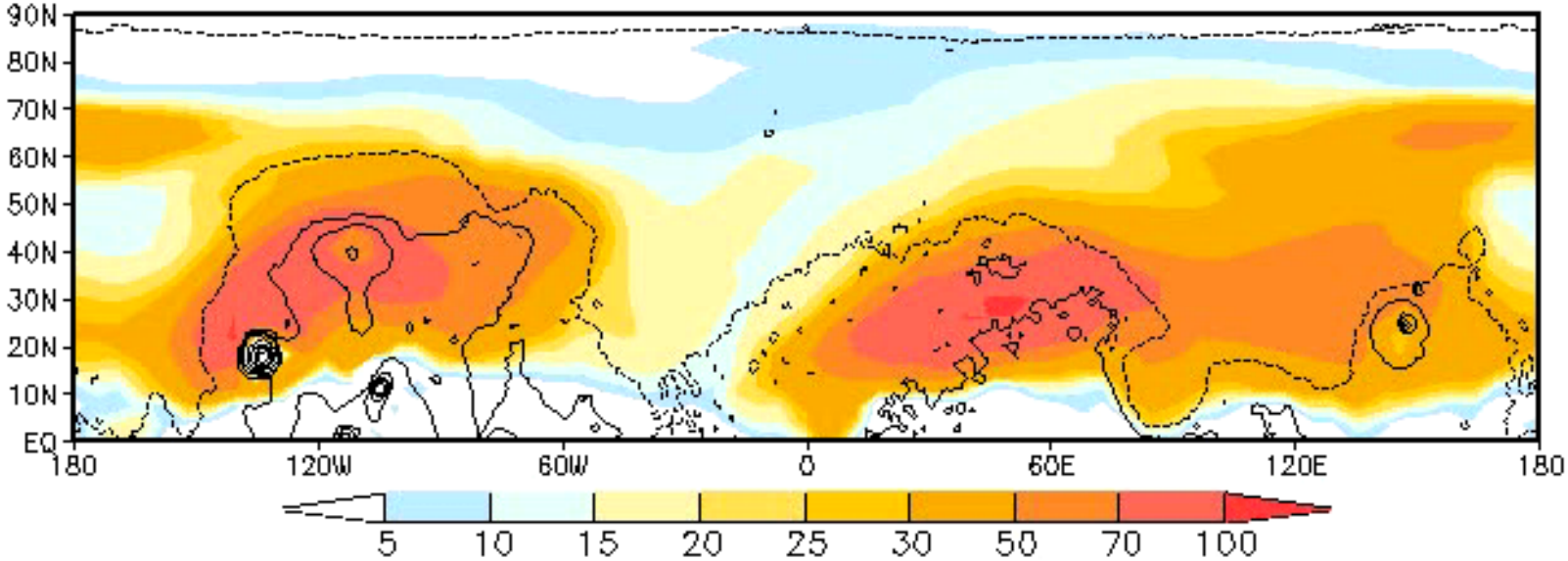
WITH HIGH ATMOSPHERIC DUST OPACITY

(Madeleine et al., Icarus 2009)



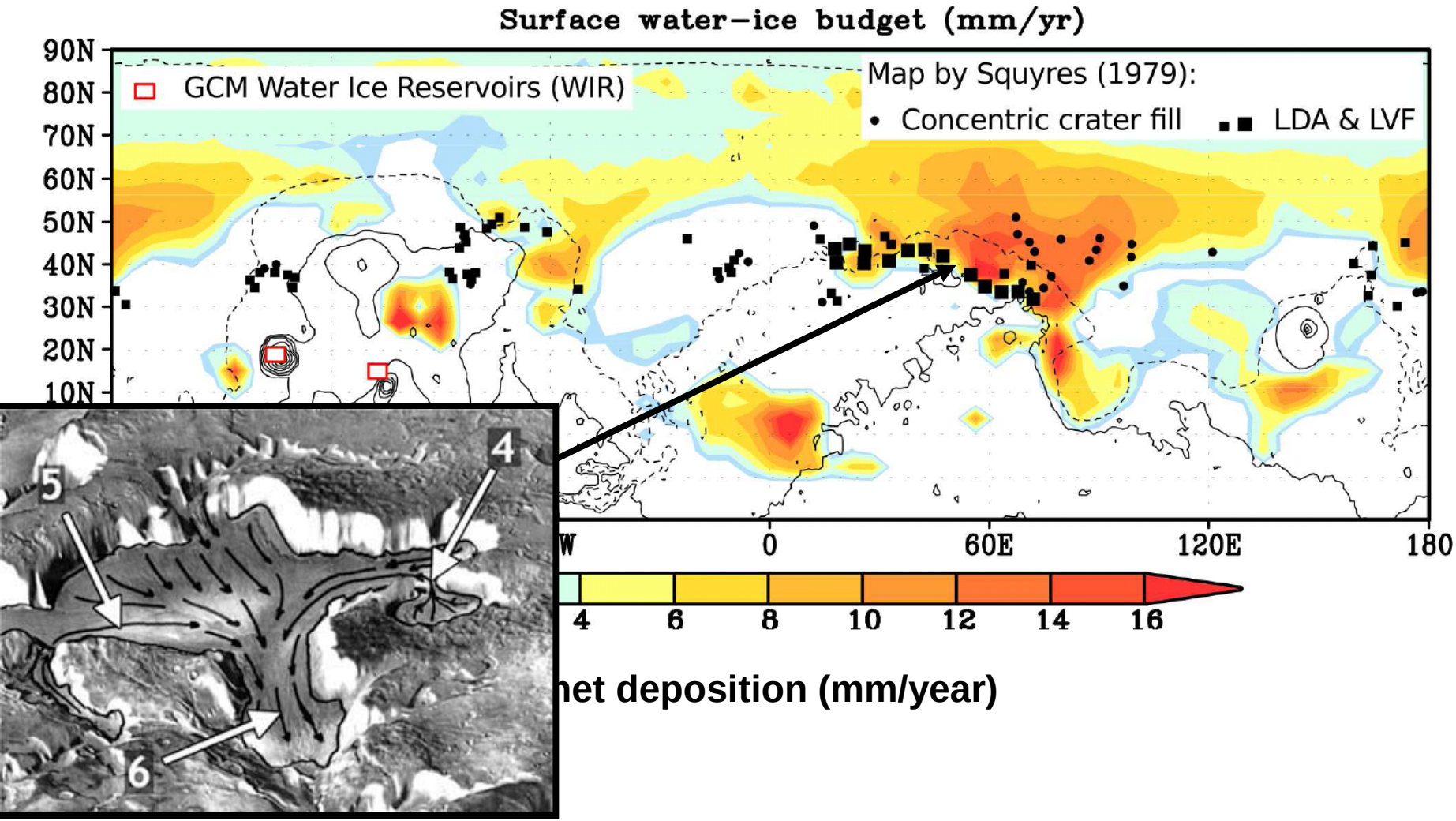
ICE ACCUMULATION RATE (dayly mean)

sol = 499 N. Fall



(g/m2/sol)

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

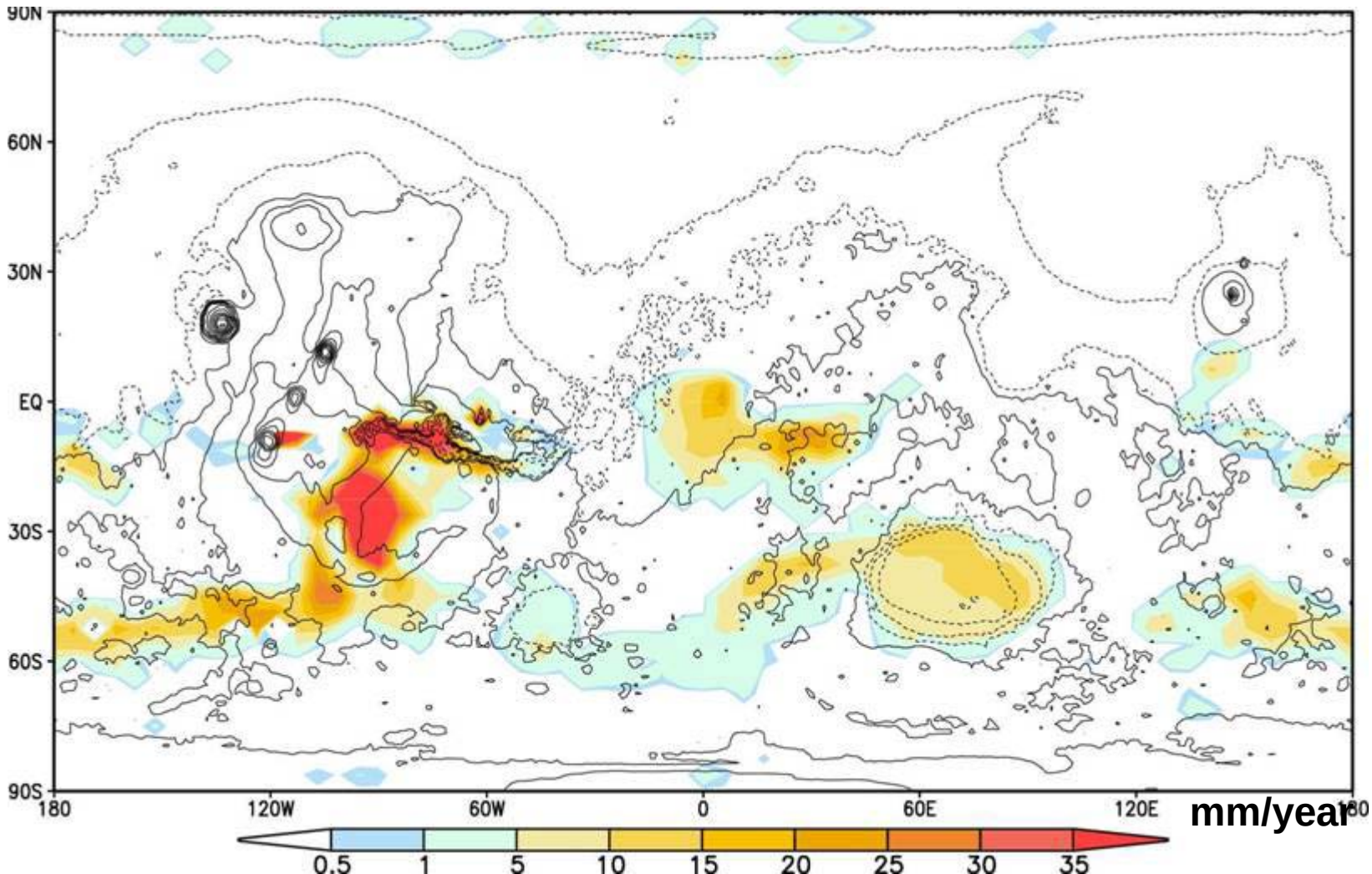


(Madeleine et al., Icarus 2009)

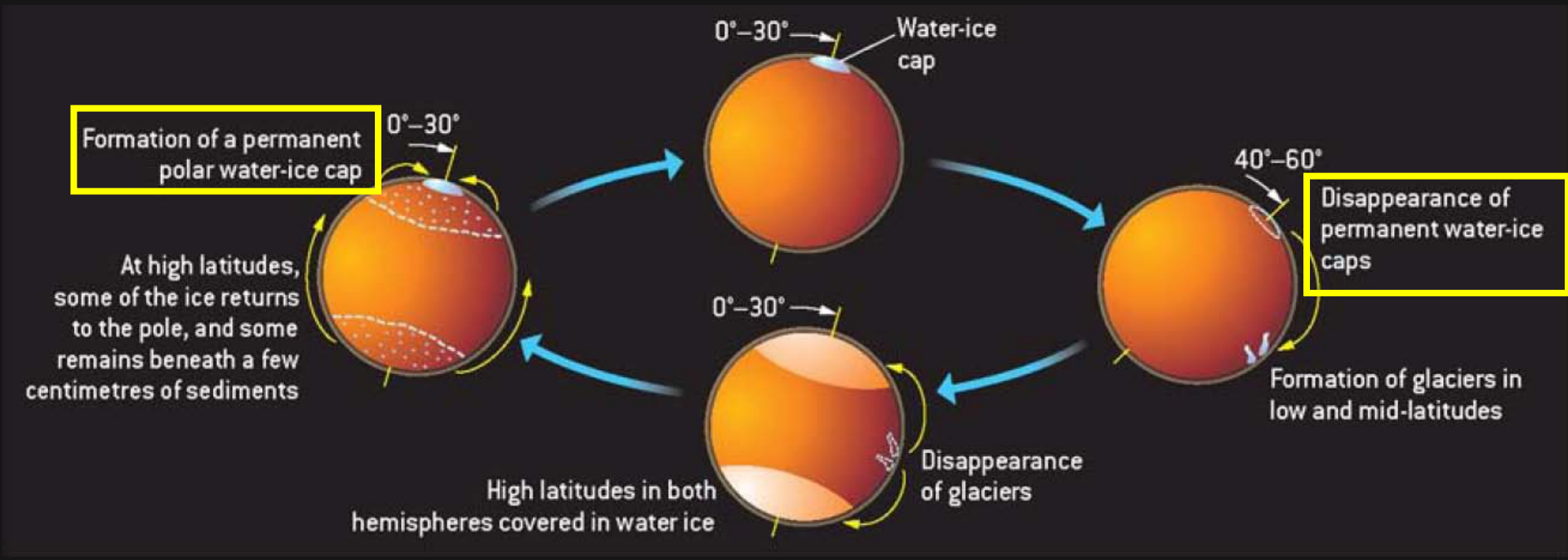
Dusty atmosphere (Madeleine et al., 2009)

Dust opacity = 2.5 **Obliquity = 35°** **Ls(perihelion)=90°**

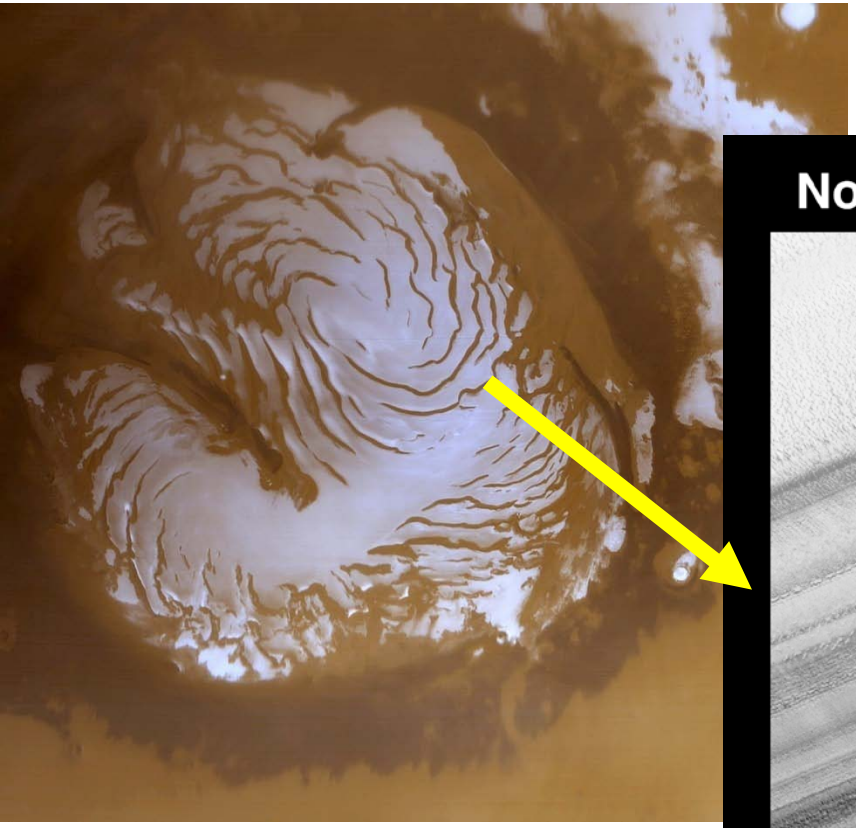
Water source = Tharsis Glaciers

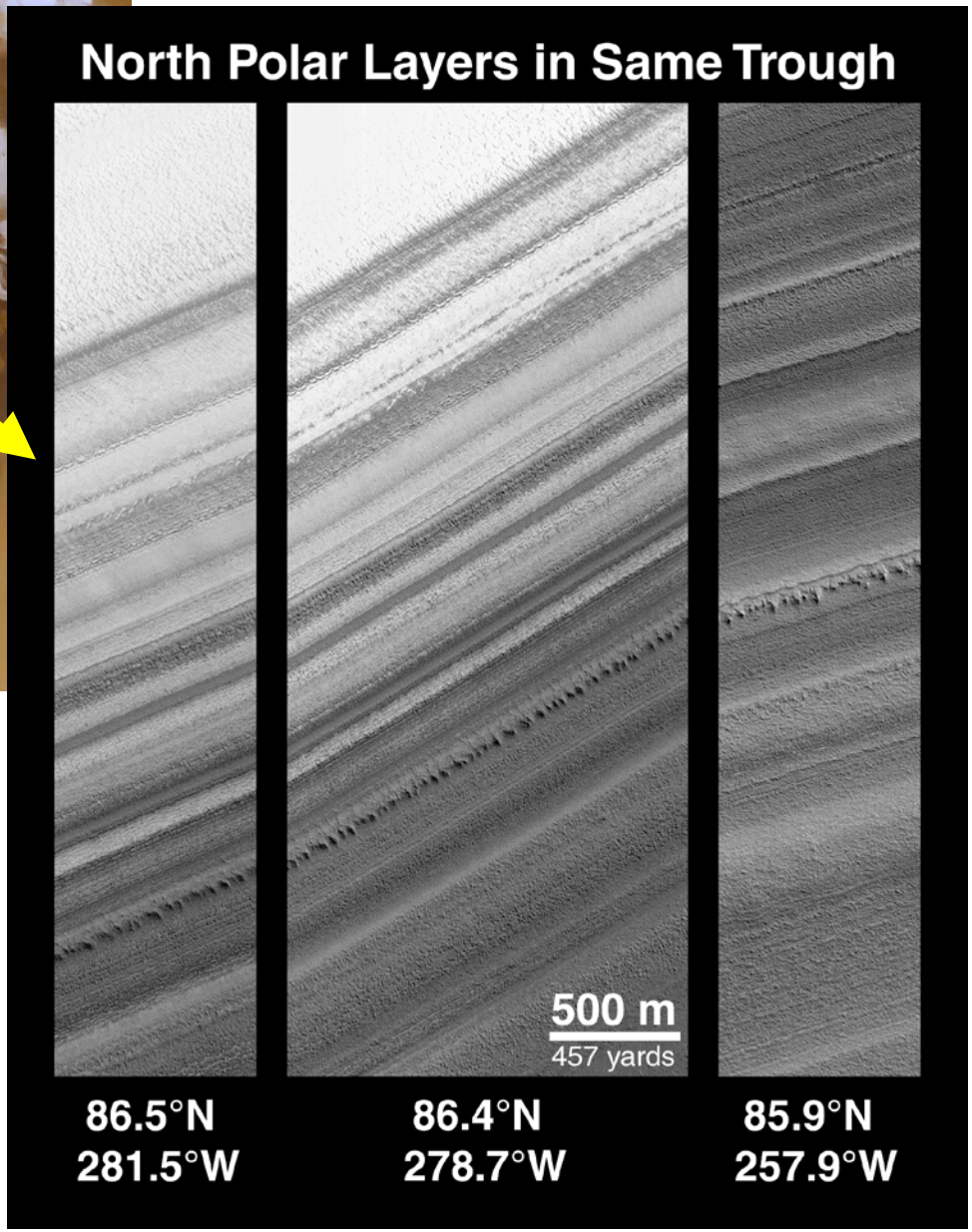


The Mars climate system has been able to transport water ice between various reservoirs in the past hundreds of millions years



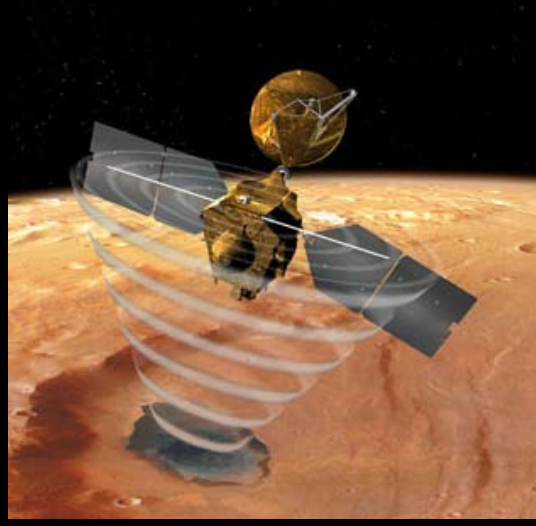
Can we use the modeled past climates to reconstruct the north polar layered deposits history ?

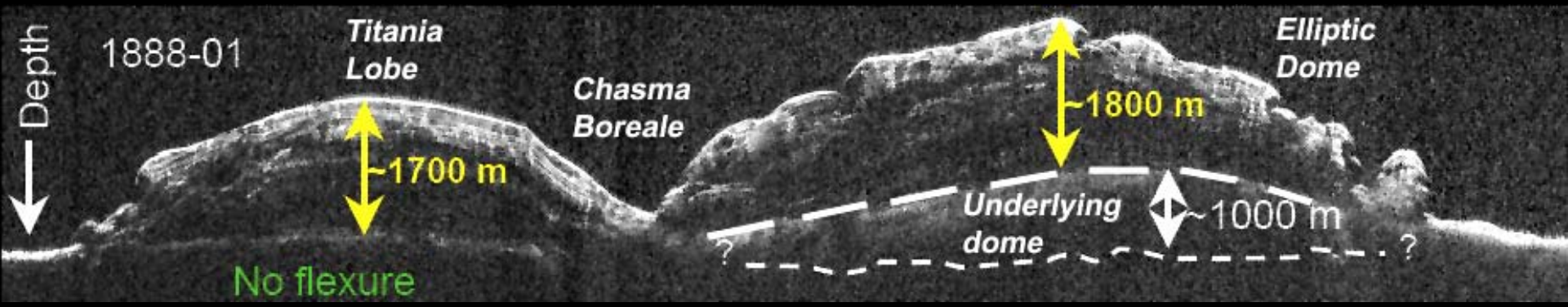


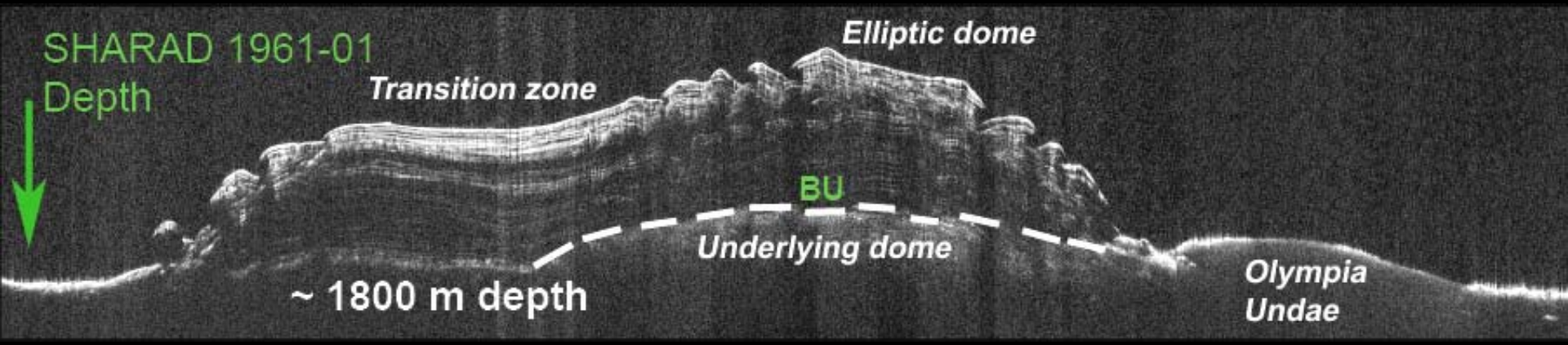


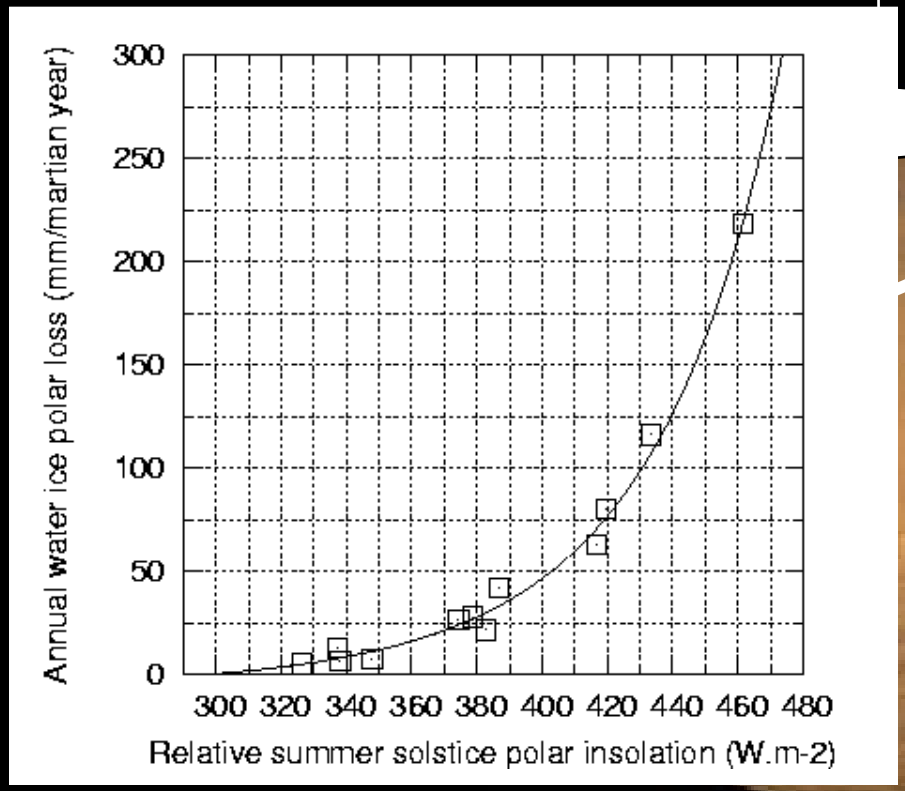
Record of climate variations in the polar layered terrain?

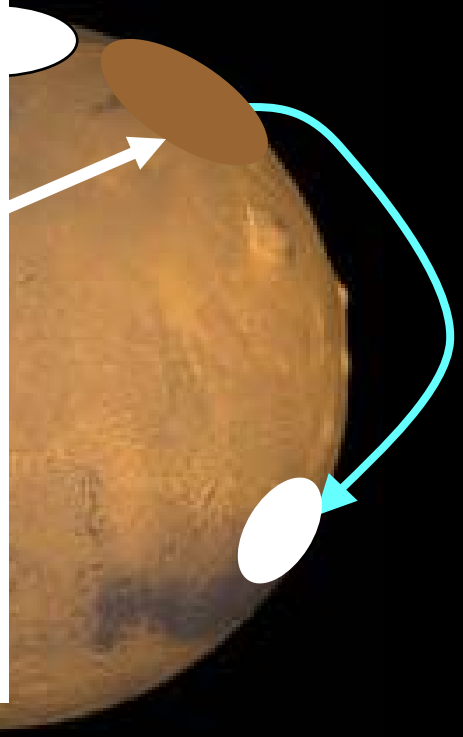
NPLD sounding with radar SHARAD on Mars Reconnaissance Orbiter



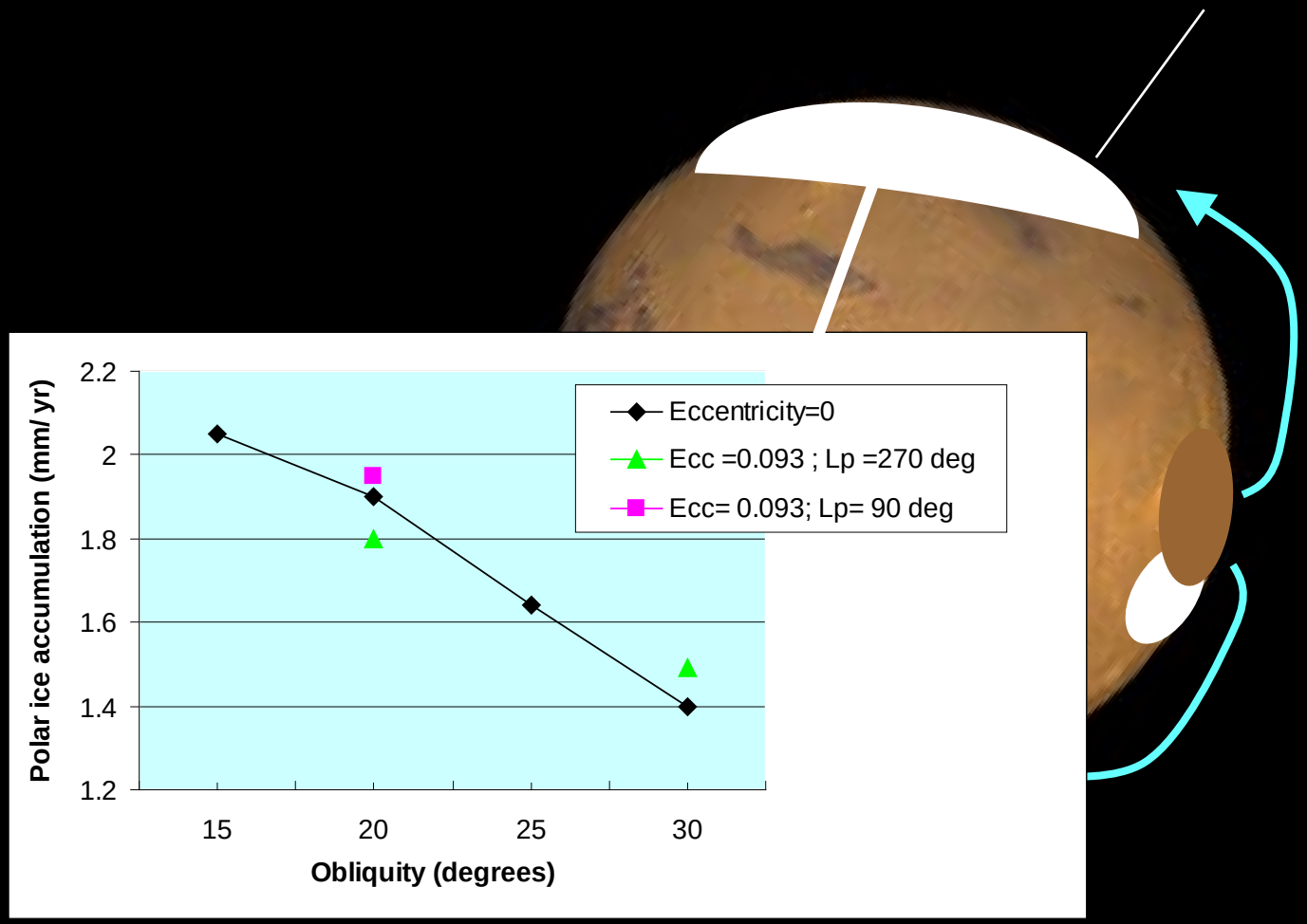








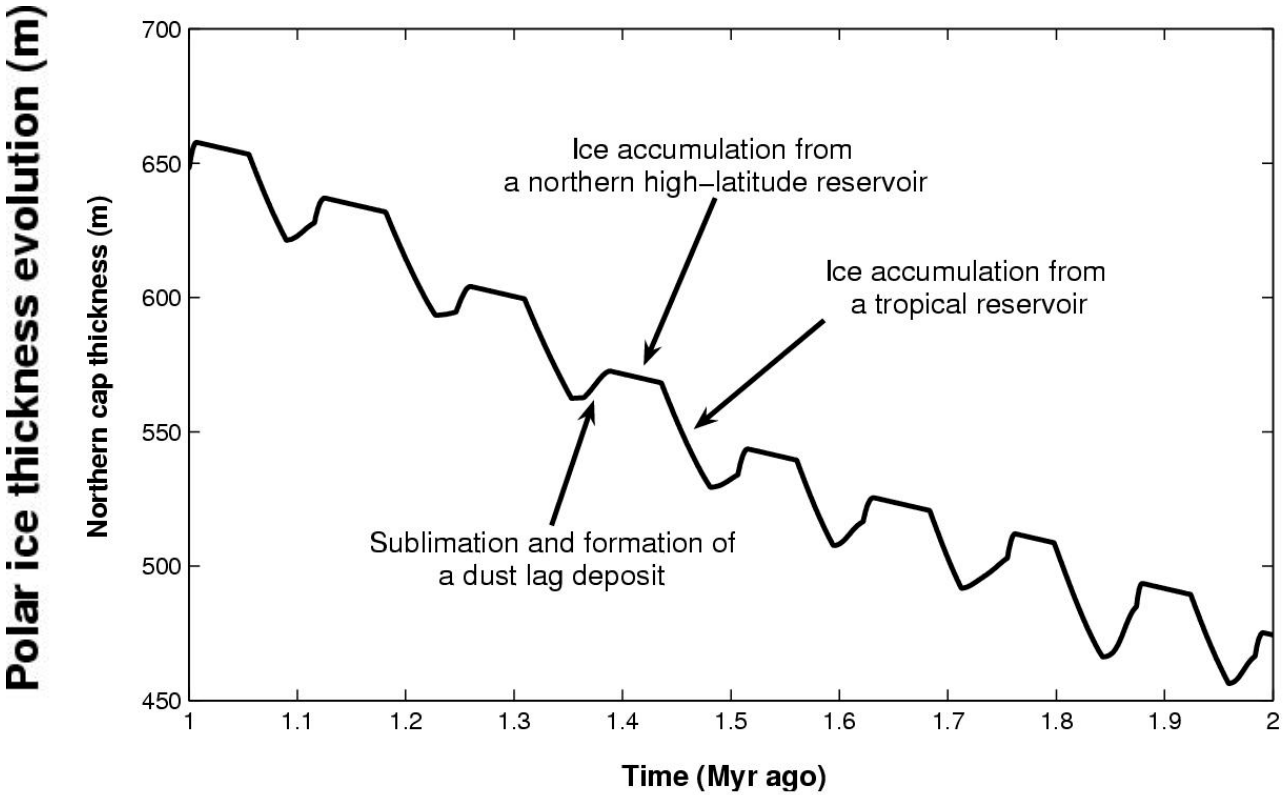
Levrard et al. 2007

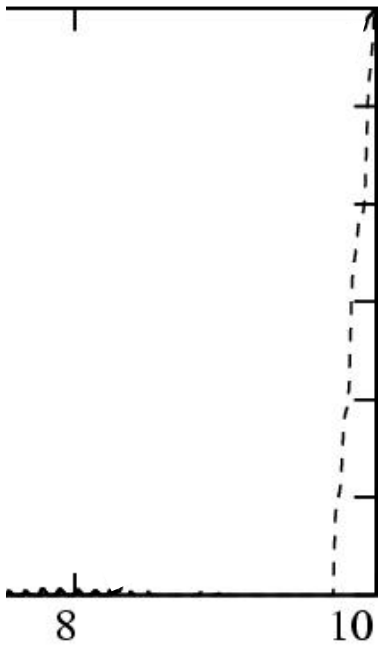


Levrard et al. 2007

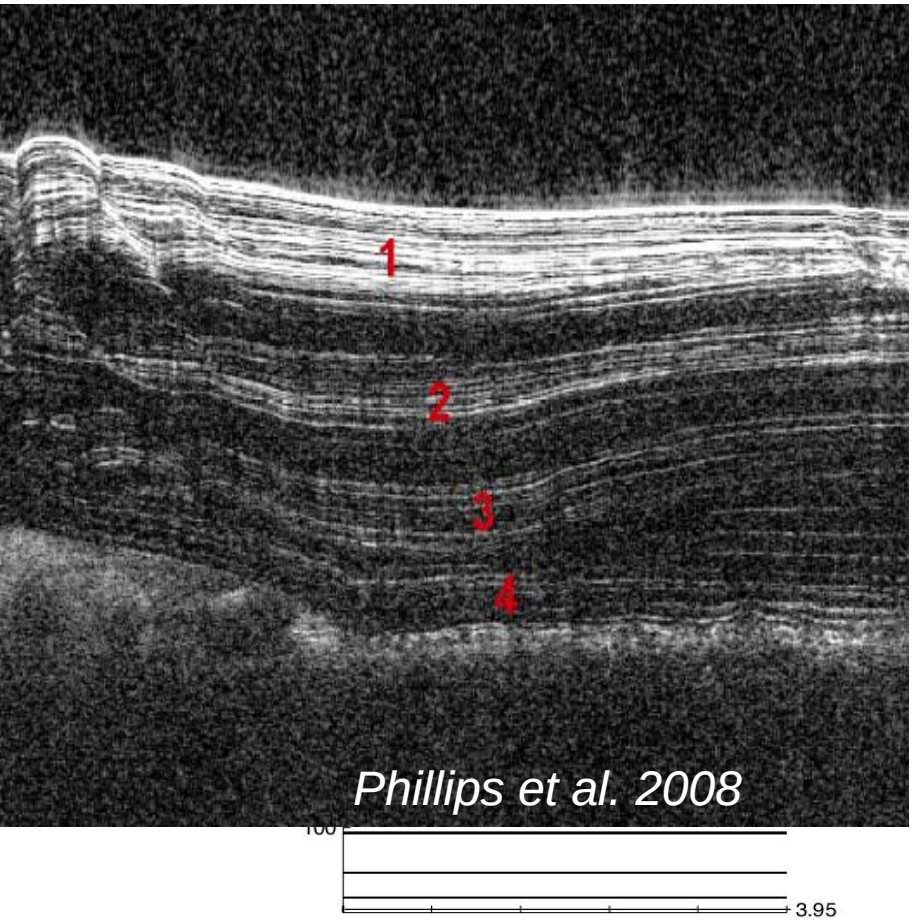
Simulation of the Northern polar deposits based on LMD GCM simulations

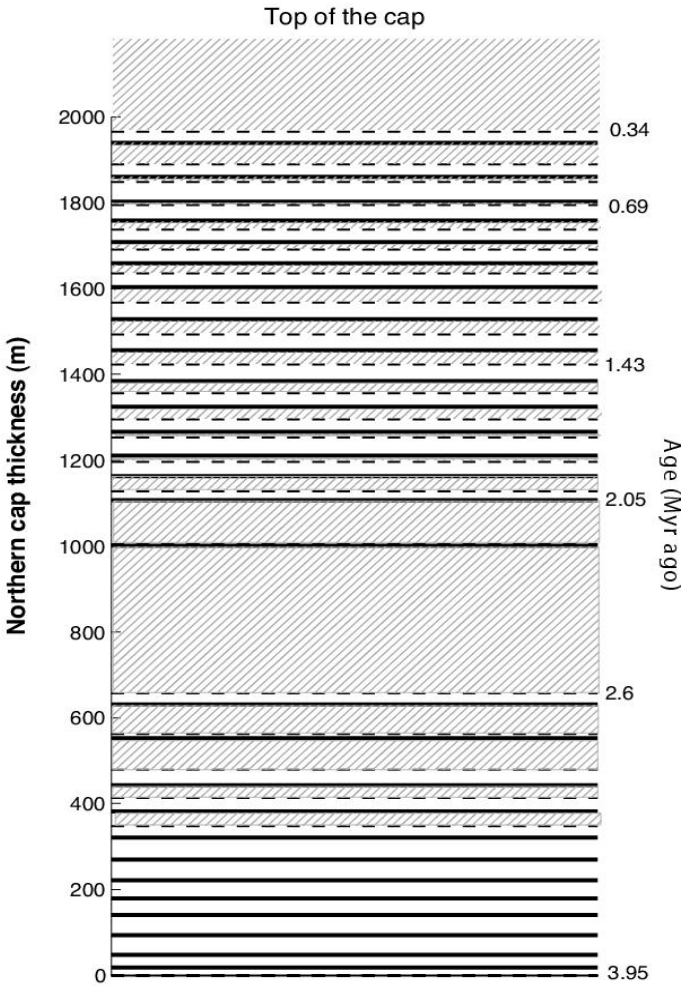
(*Levrard et al., JGR, in press, 2007*)





Structure of the modeled present day polar cap with a 3 reservoirs system :nnNorthern cap ; Tropics ; mid-latitudes





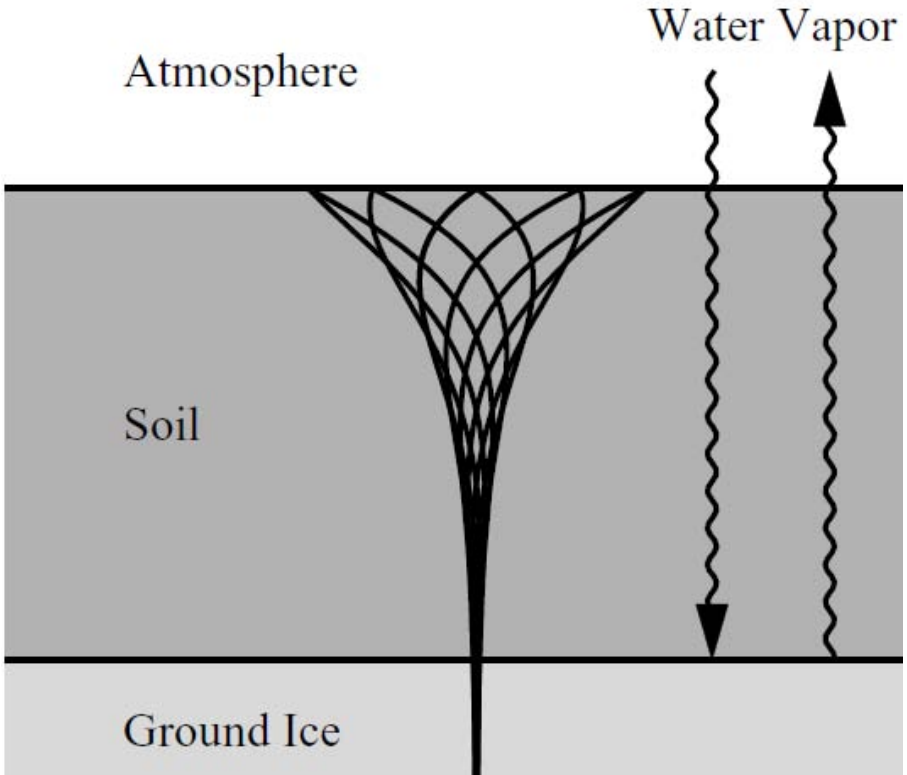
Case 1 : slow accumulation from mid-lat reservoirs : 0.17 mm/yr

Case 2 : fast accumulation from mid-lat reservoirs : 1.7 mm/yr

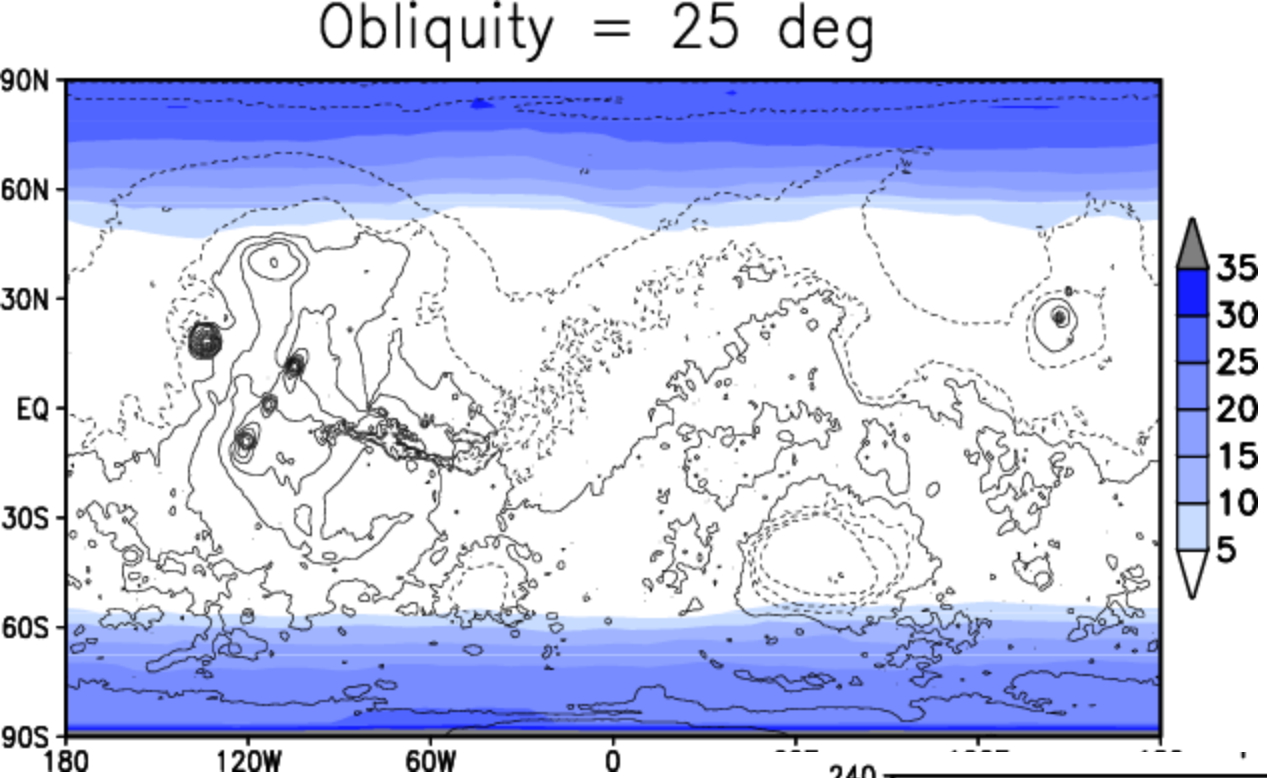
Stability of ice in the subsurface

Higher obliquity = more water vapor

⇨ Ice stable in the subsurface at lower latitude



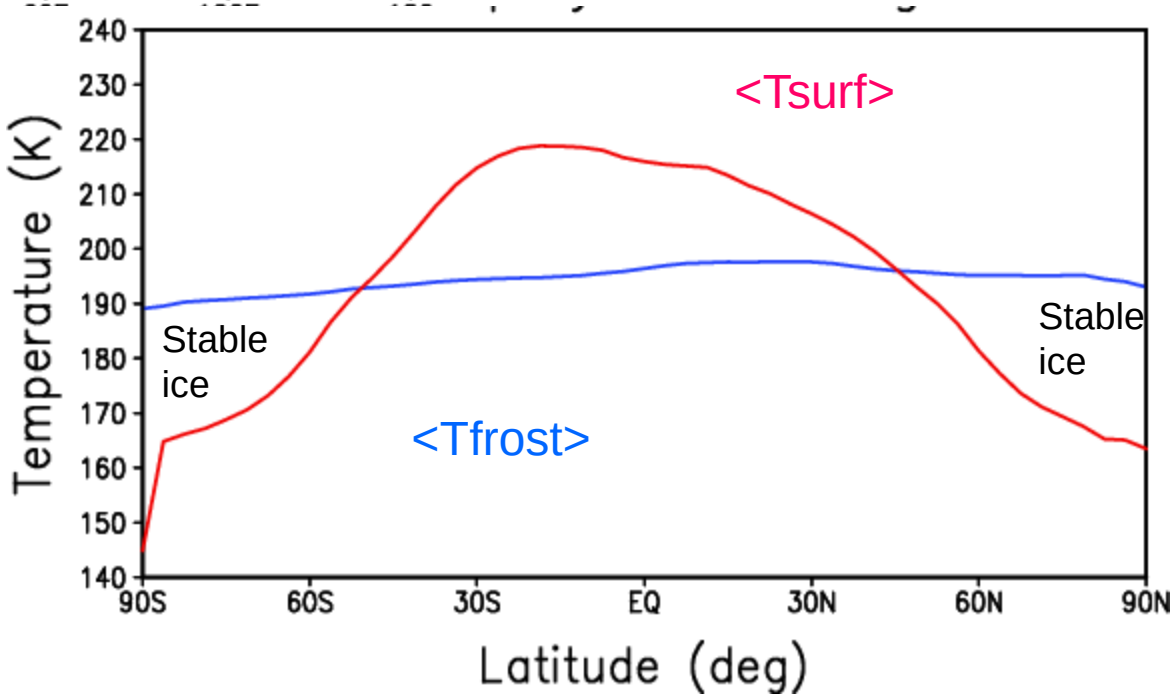
N. Shorgoffer

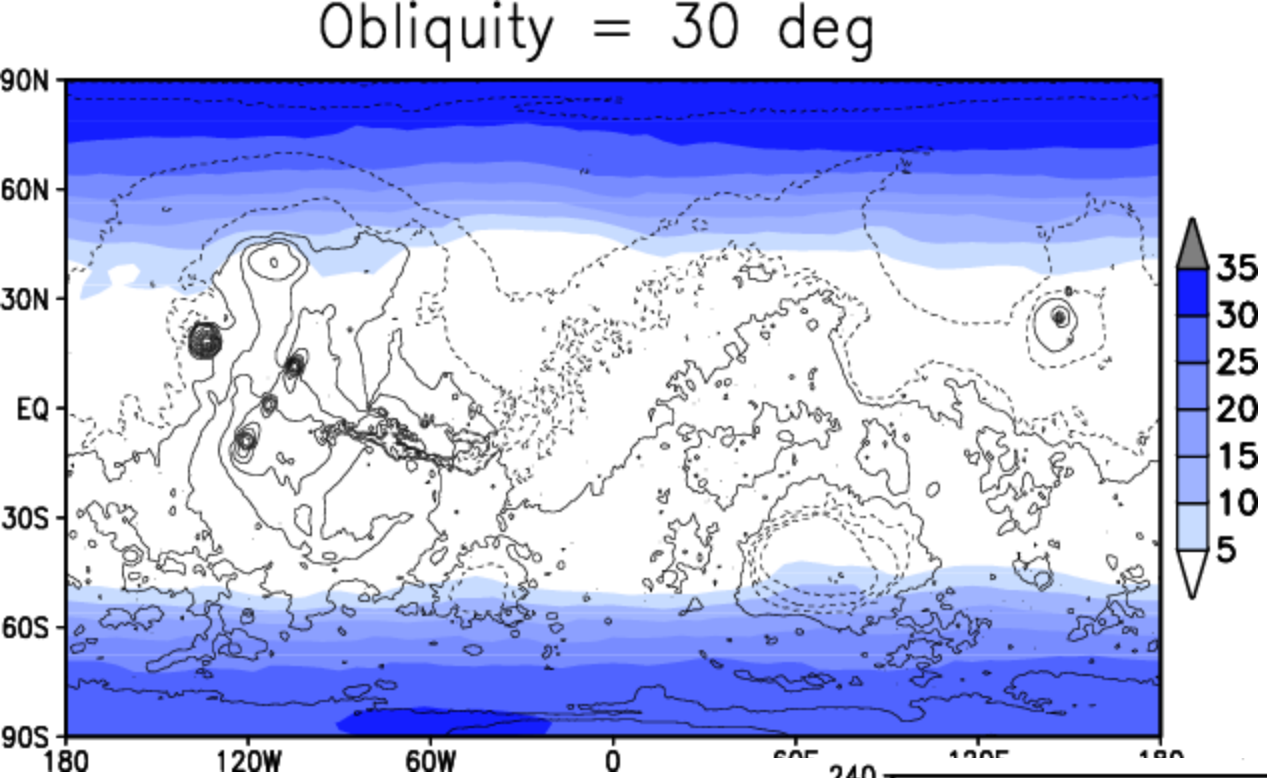


Ice stability
(<Tfrost> - <Tsurf>

(*Schorghofer 2007* criterion)

Forget et al. 2007

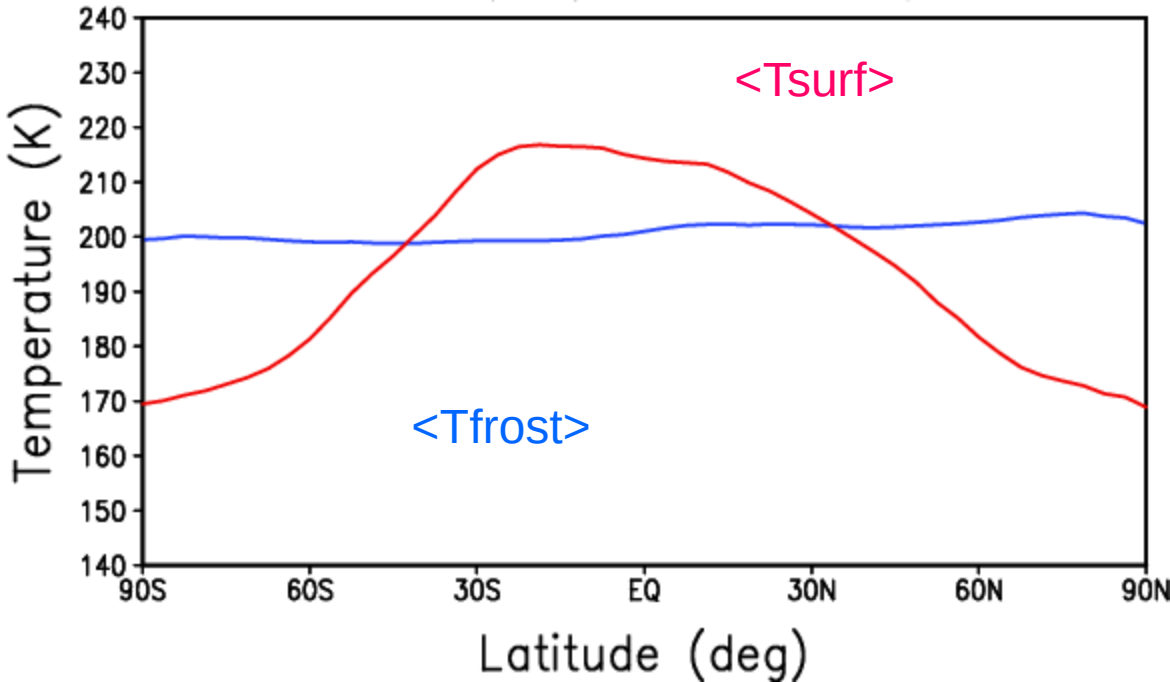


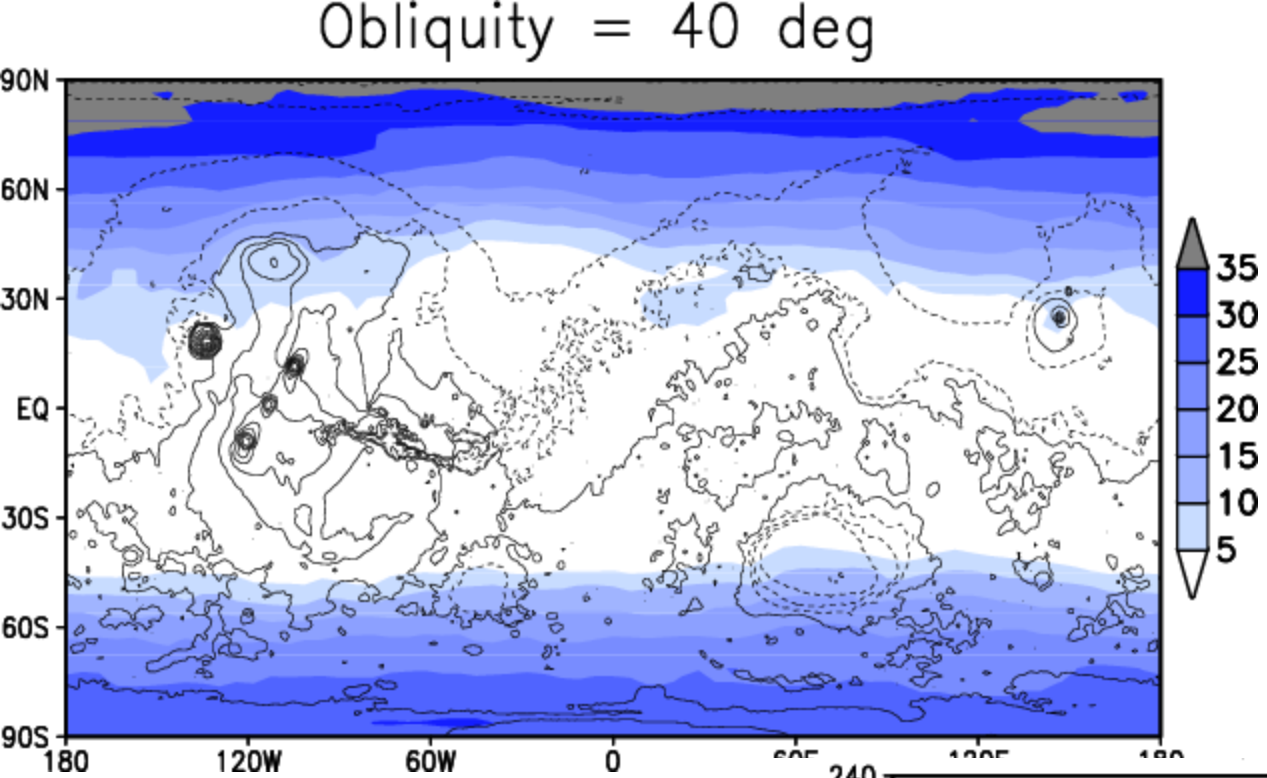


Ice stability
(<Tfrost> - <Tsurf>

(*Schorghofer 2007* criterion)

Forget et al. 2007

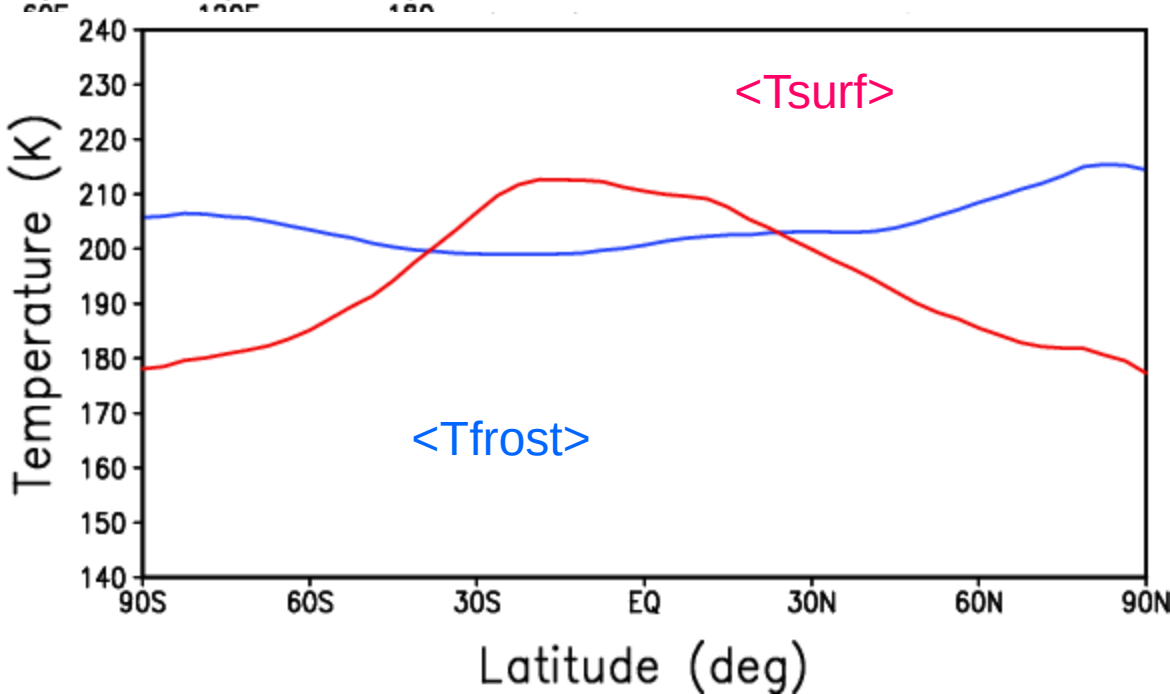


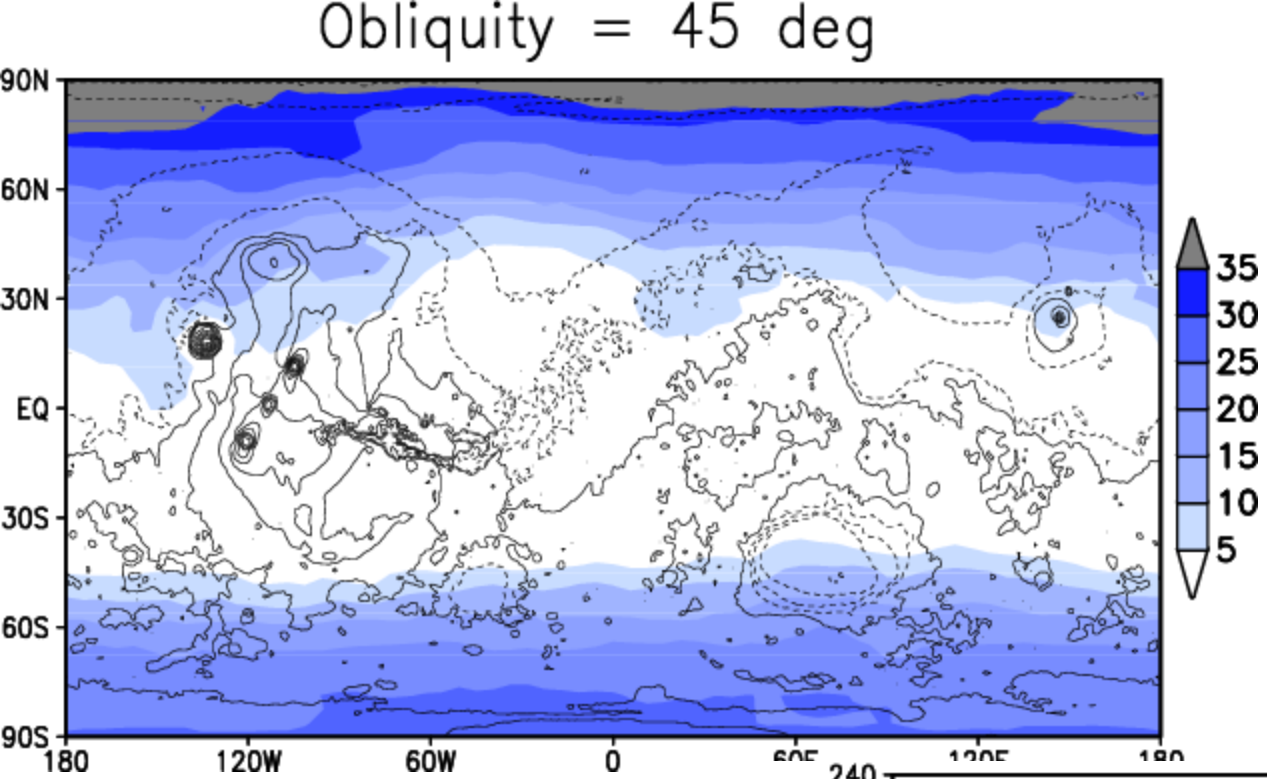


Ice stability
(<Tfrost> - <Tsurf>

(*Schorghofer 2007* criterion)

Forget et al. 2007

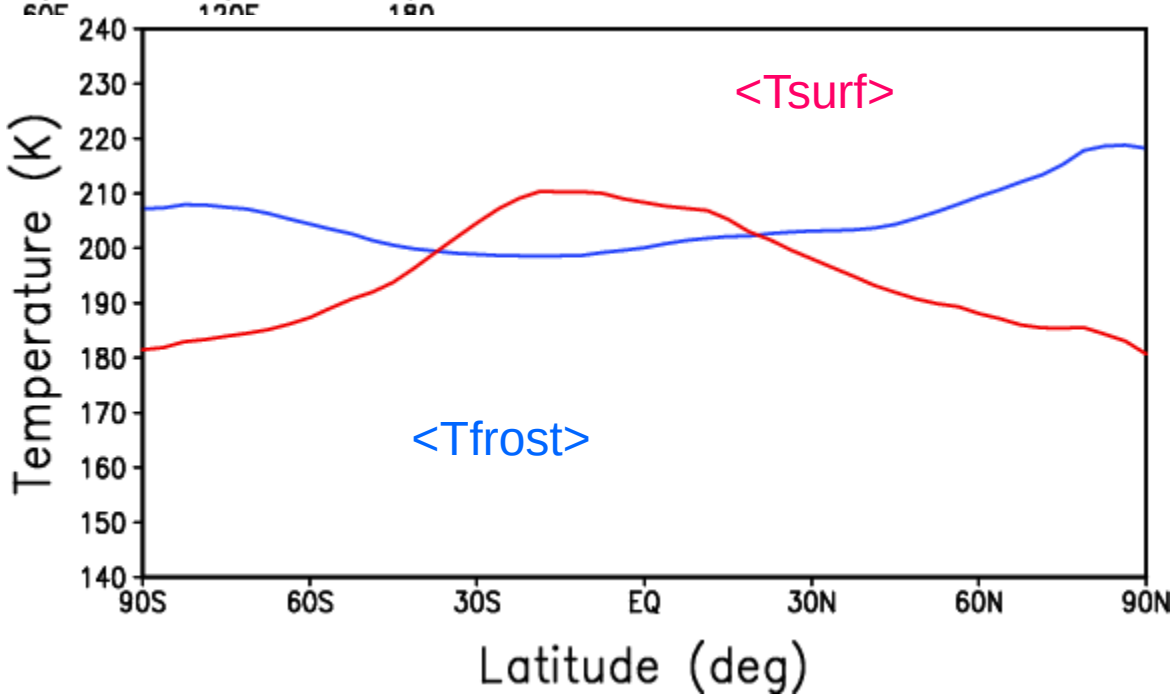


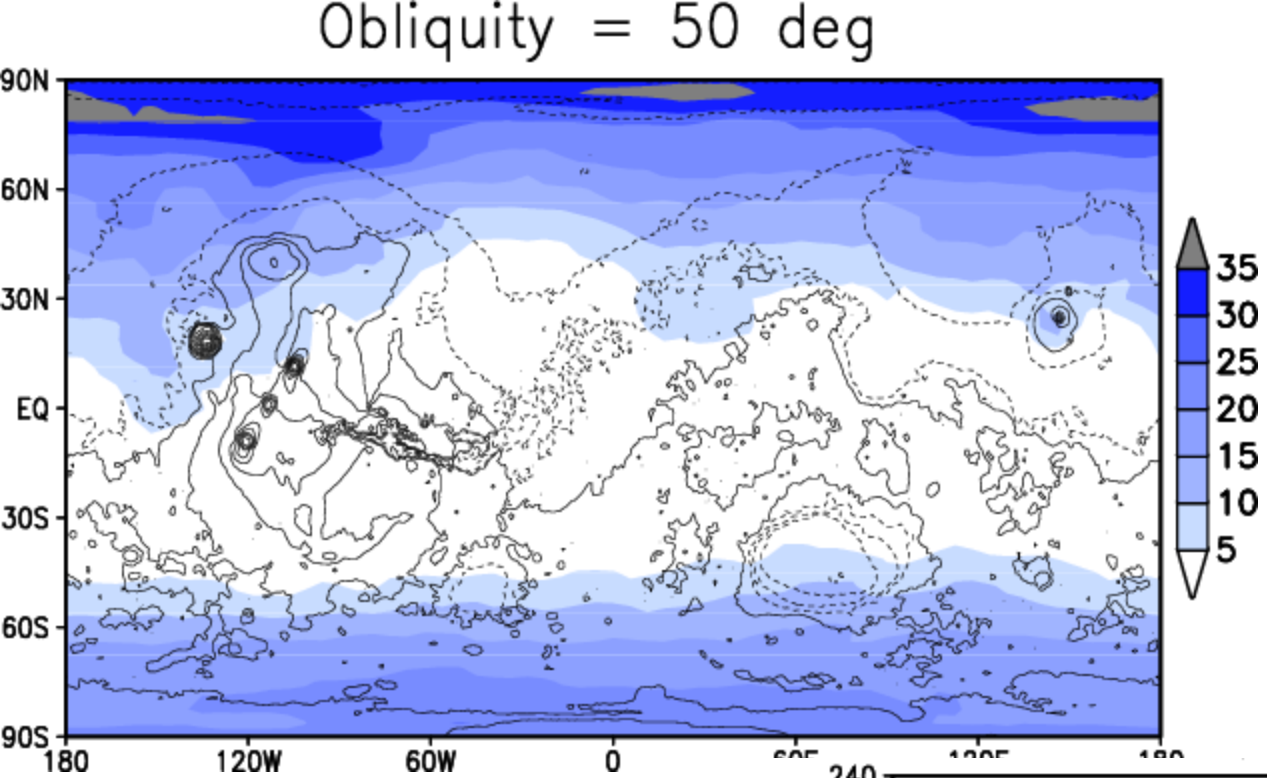


Ice stability
(<Tfrost> - <Tsurf>

(*Schorghofer 2007* criterion)

Forget et al. 2007

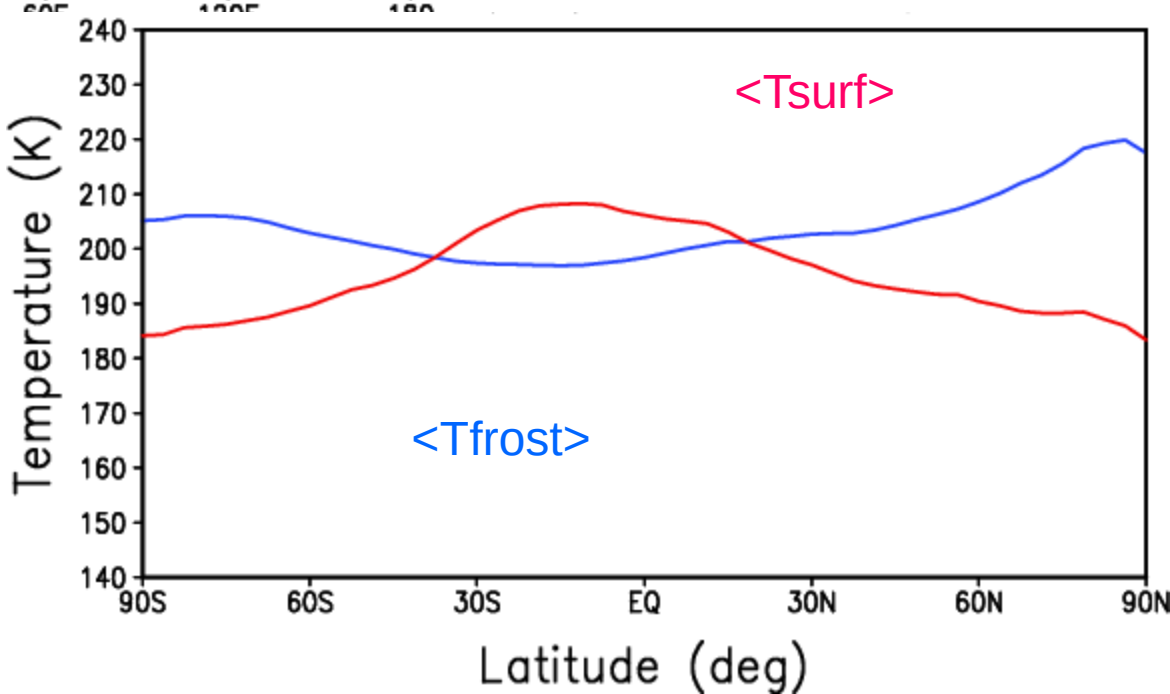


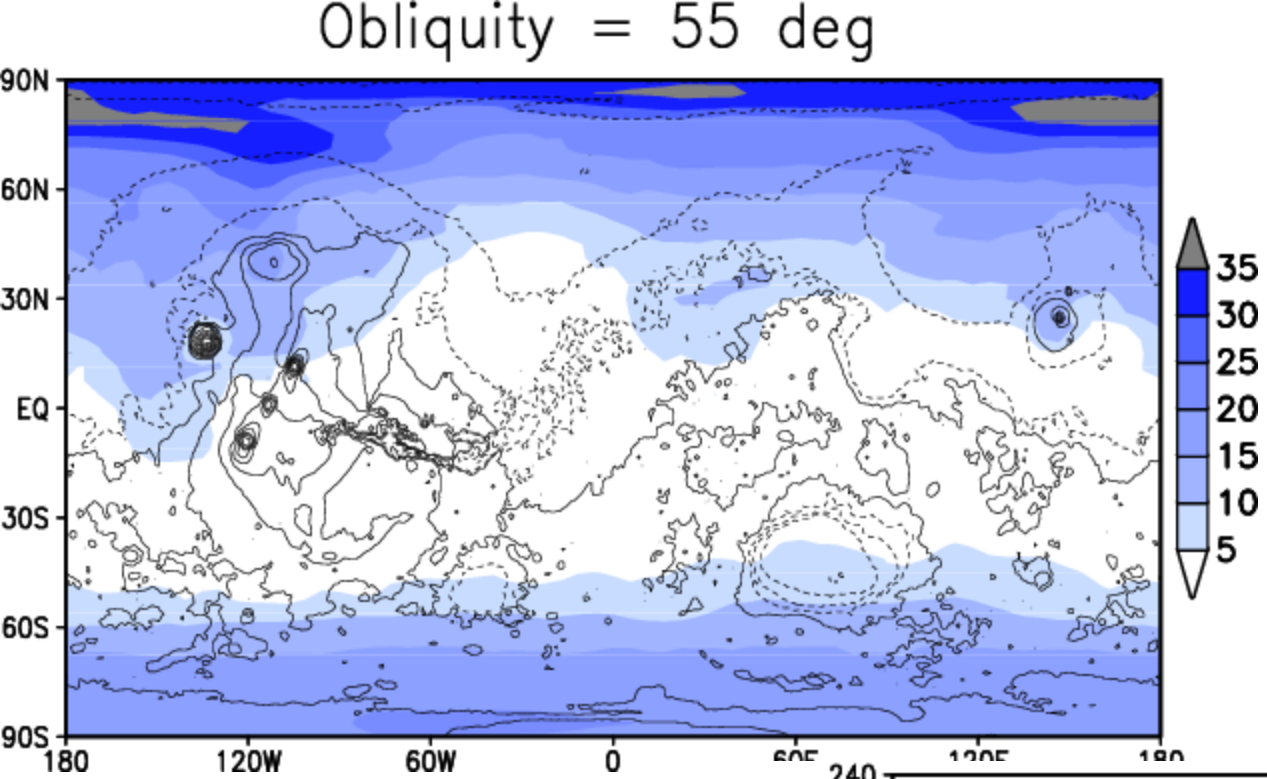


Ice stability
(<Tfrost> - <Tsurf>

(*Schorghofer 2007* criterion)

Forget et al. 2007

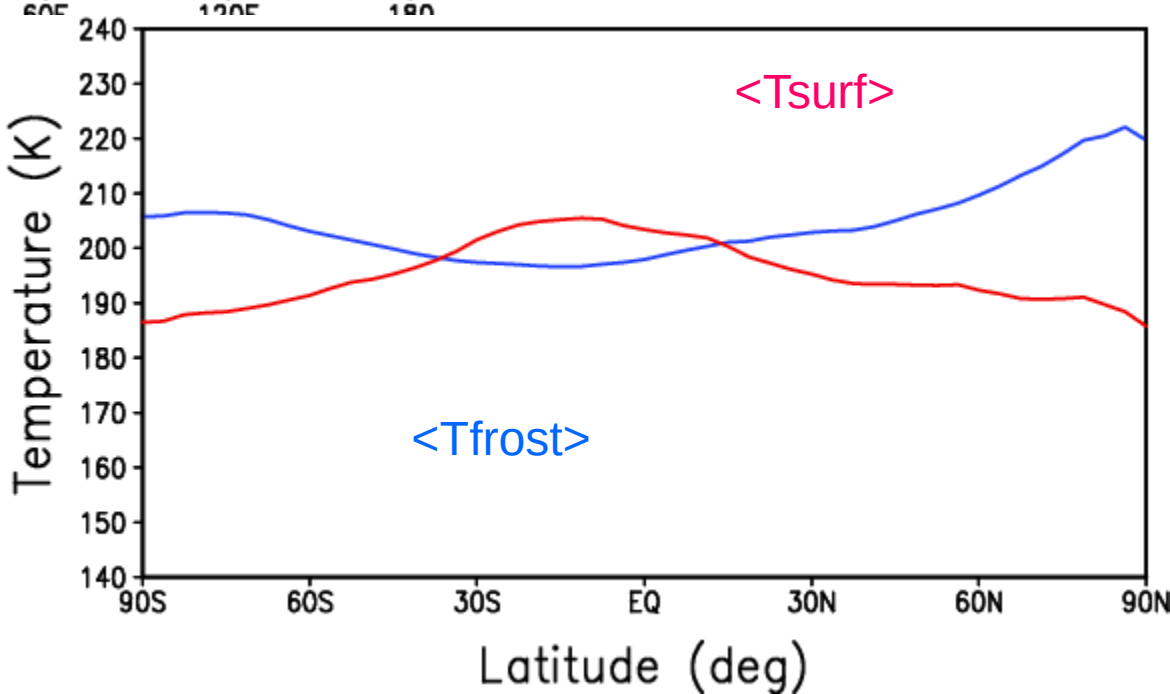




Ice stability
(<Tfrost> - <Tsurf>

(*Schorghofer 2007* criterion)

Forget et al. 2007

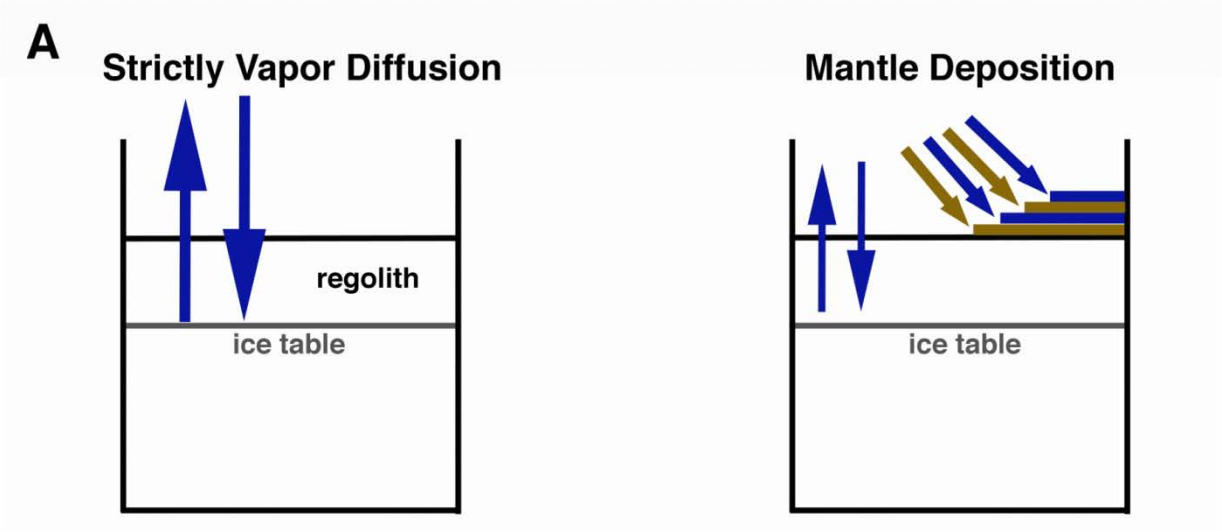


An ongoing debate on ice mantle

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)



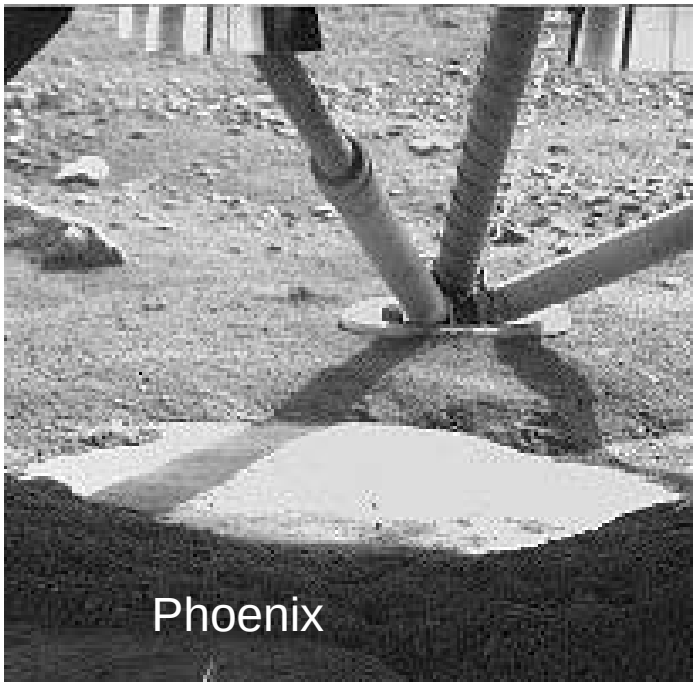
Head et al.

An ongoing debate on ice mantle

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.**

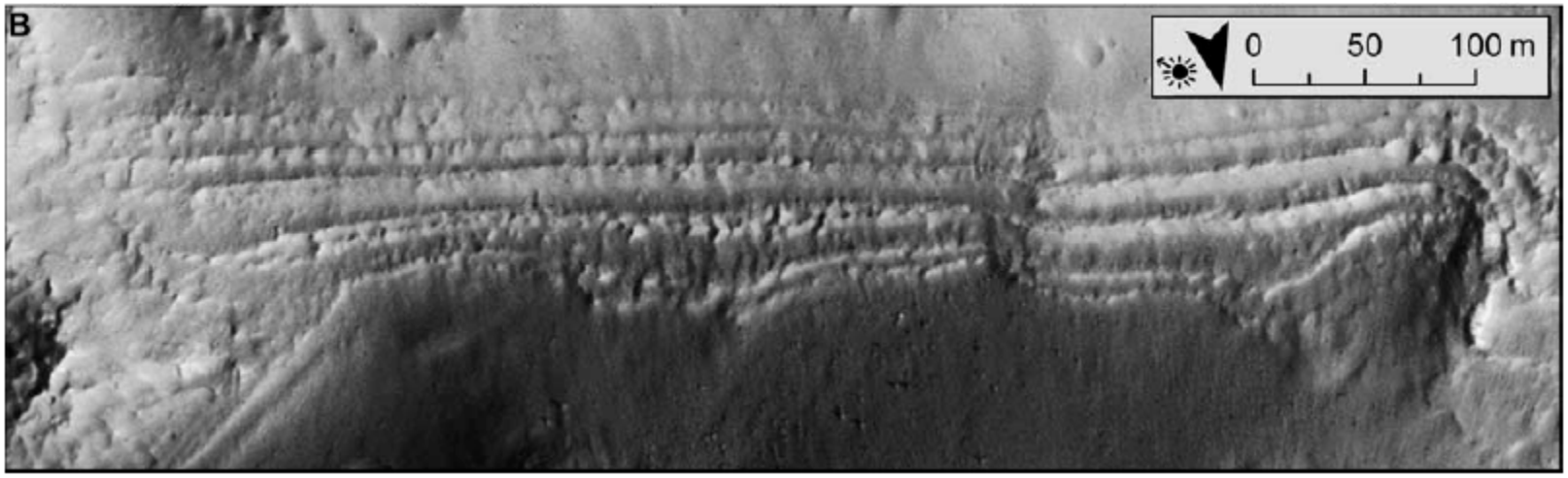
- Both are consistant with the fact that water ice is currently in equilibrium with the atmosphere *(Mellon et al. 2004, shorgoffer 2007)*
- **Pro snow**: Phoenix, GRS and new craters ice appear to be quite pure !
- **Pro diffusion**: Analysis of phoenix observations by *Mellon et al. (2009)* conclude : « 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 »



An ongoing debate on ice mantle

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
currently
(Mellon et a
- **Pro snov**
quite pur
- **Pro diffu**
by *Mellor*
these relati
with the fo
such as would occur by thin film migration and the formation of ice lenses, needle ice, or similar ice »
- **Pro snow** : outcrops of dessicated mantle at low latitudes show meters-thick layers *(Shon et al. 2007)*
-

An ongoing debate on ice mantle

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)*
- **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 »
- **Pro snow** : outcrops of dessicated mantle at low latitudes show meters-thick layers *(Shon et al. 2007)*
- **Pro diffusion :** Ice down to 30° latitude better explained than with snow with current climate models
- **Pro diffusion** : boulders are observed ON the surface

CONCLUSIONS (1) : « recent » climate

- Due to the variations of Mars orbital / rotational parameters, the **current** Mars climate system have mobilized large amount of water to form glaciers, ice caps until recently and in the future.
- Several **robust** mechanisms have been simulated by the Global Climate Model.
- Lots of issues remain in the model (radiative effect of ice and vapor, role of regolith and dust lag, dust cycle, dust-ice interaction, etc…) and to understand the relatives ages of the icy landforms
- What is the main process creating the ice mantling ???
- **Could we also simulate Mars climate ~4 billions years ago ?**