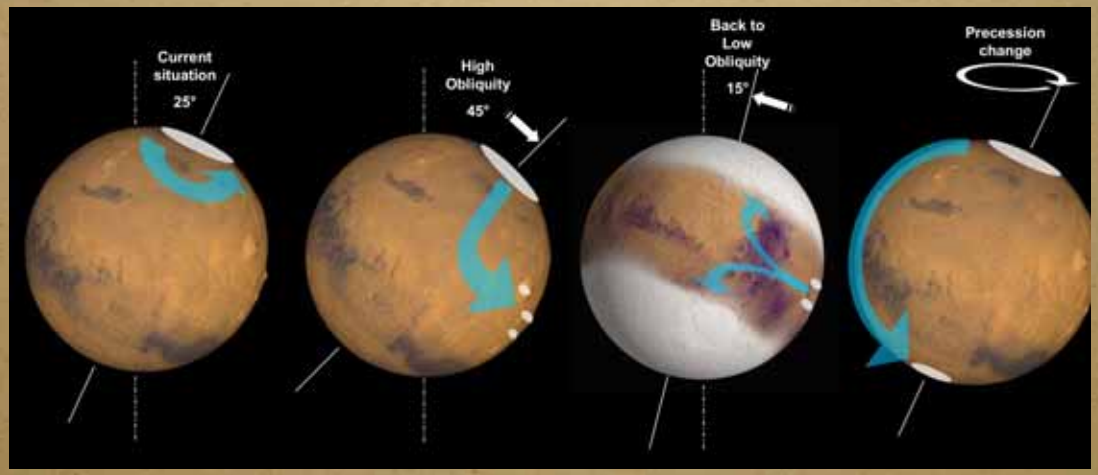
# The orbital forcing of climate changes on Mars



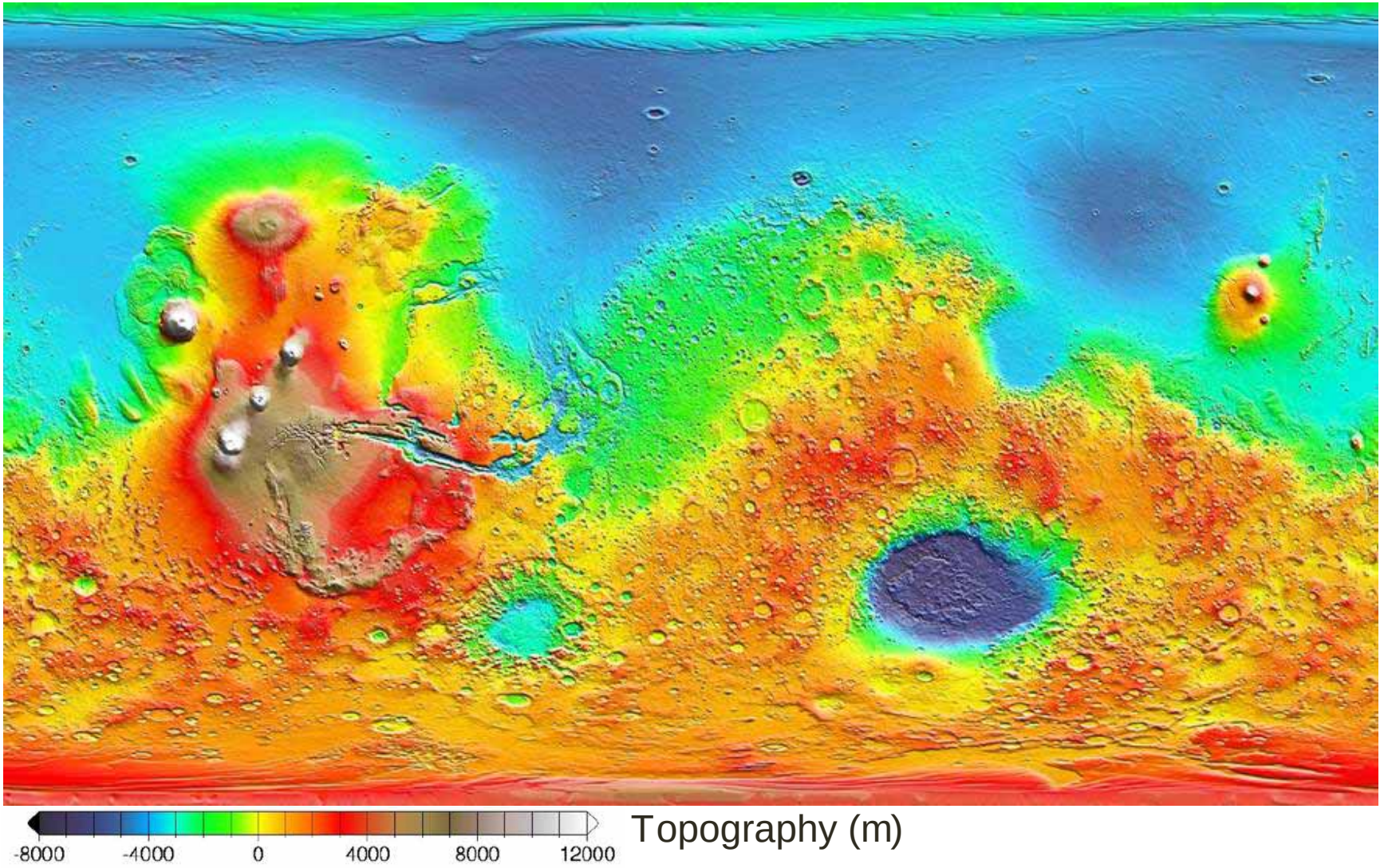

F. Montmessin

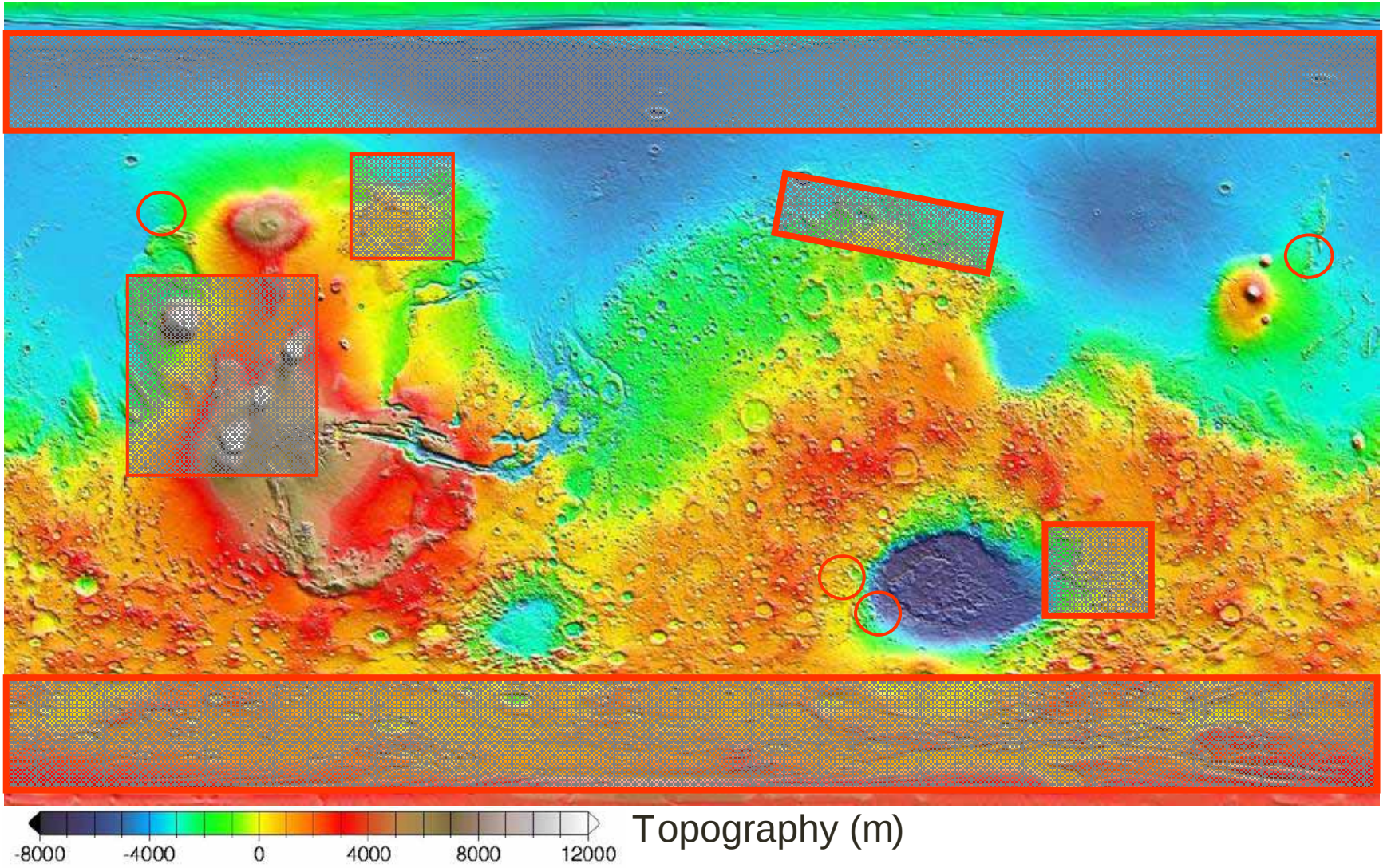
Service d'Aéronomie CNRS

*Solar System Exploration symposium*
*IKI 2007*

# Mars climate in brief

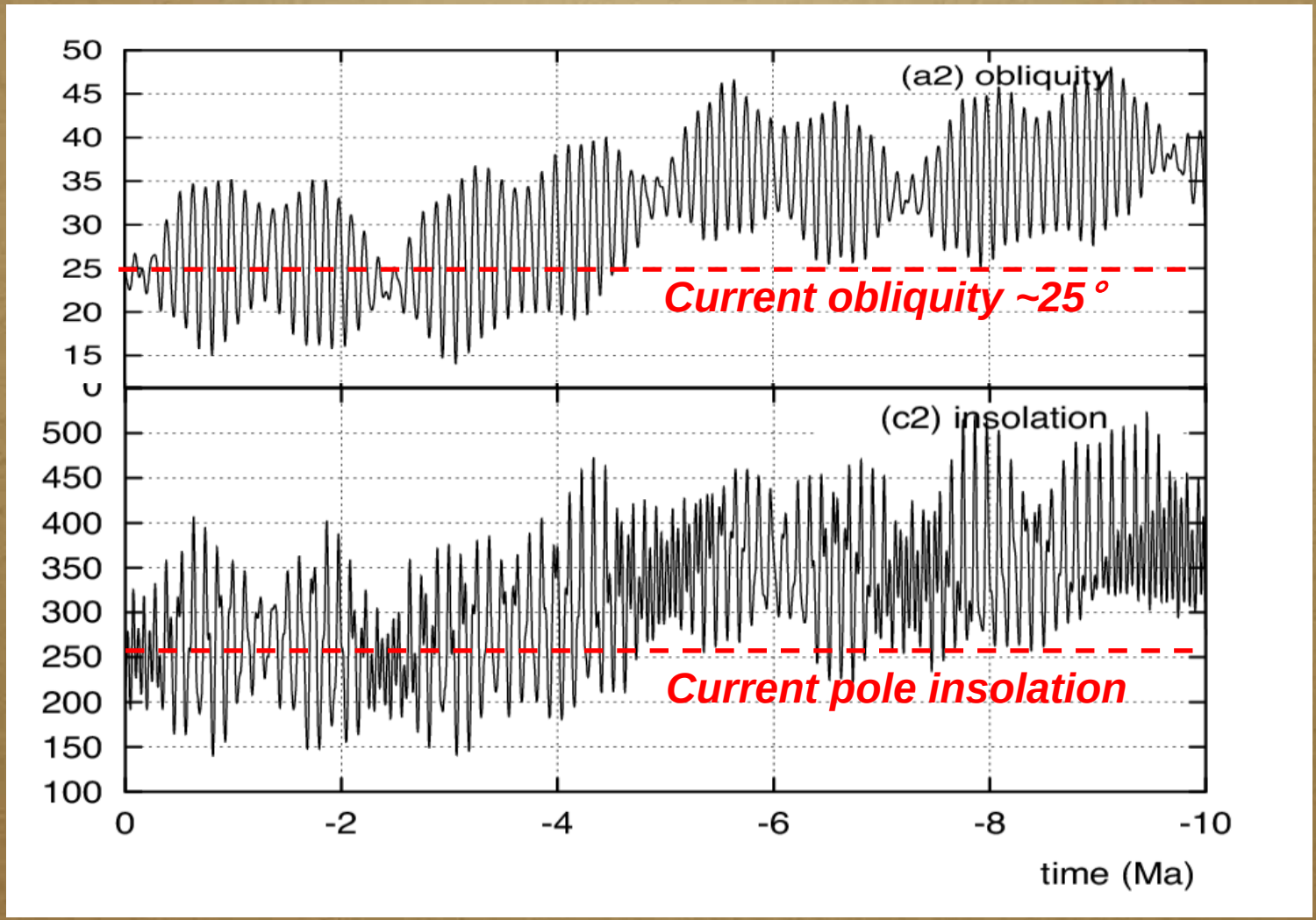
- **Pressure = 6 mbar , CO2 @ 95 %**
  **(varies w/season = condensation cycle)**
- **Mean Surface Temperature = -50°C**
- **Low water vapor content = ~10 pr. μm**
- **Extensive surface reservoirs (polar caps) and in the subsurface**
- **Suspended Particles (τ ~ 0.1 to >5) :**
  - **Dust from the regolith**
  - **Ice crystals from $H_2O$ & $CO_2$ condensation**
- **Earth-like Circulation:**
  - **Hadley Cell**
  - **Stationary and transient weather systems**


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

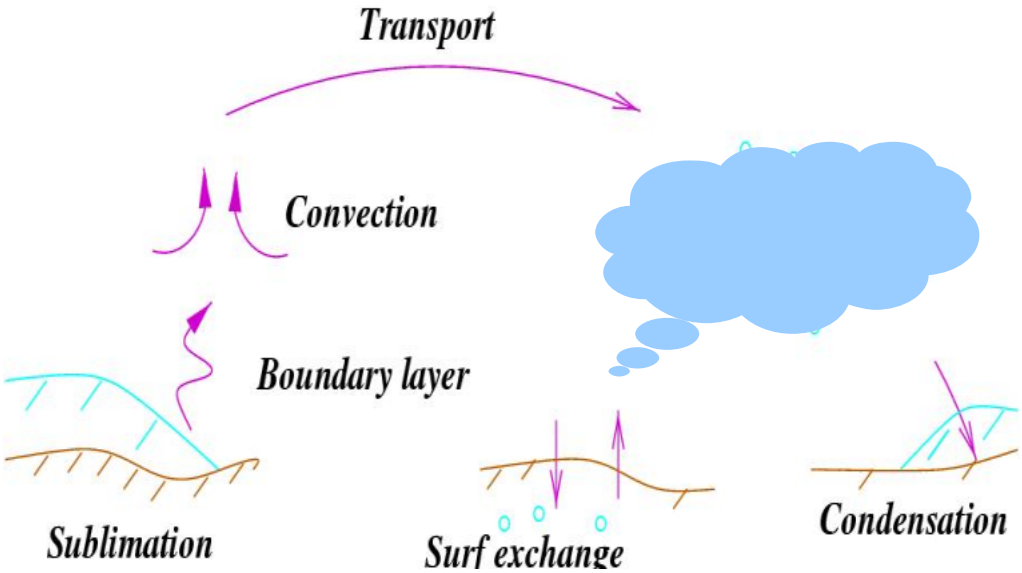


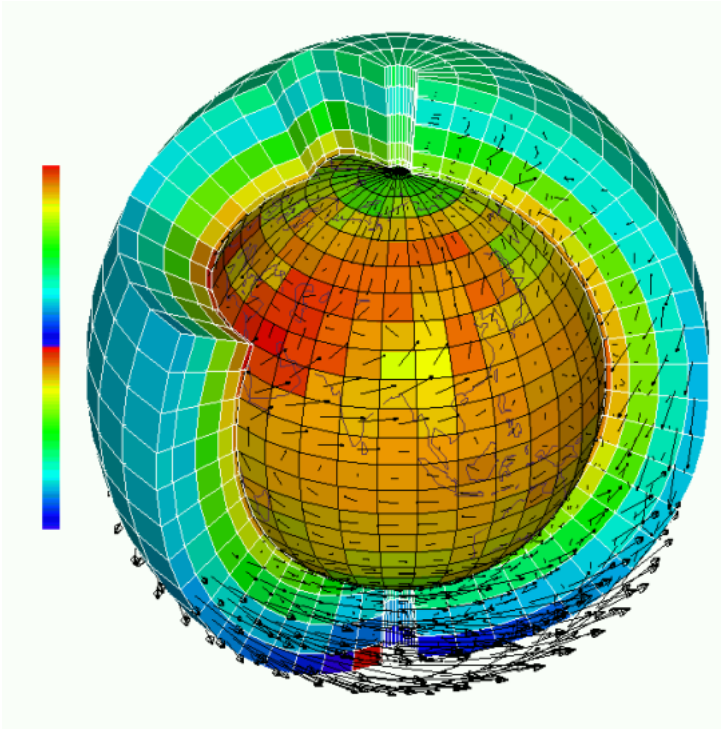

**Amazonian geology (last 1-2 $10^9$ years) :**
**ice related landforms where ice is NOT currently stable AT THE SURFACE**

# Mars orbit recent variations



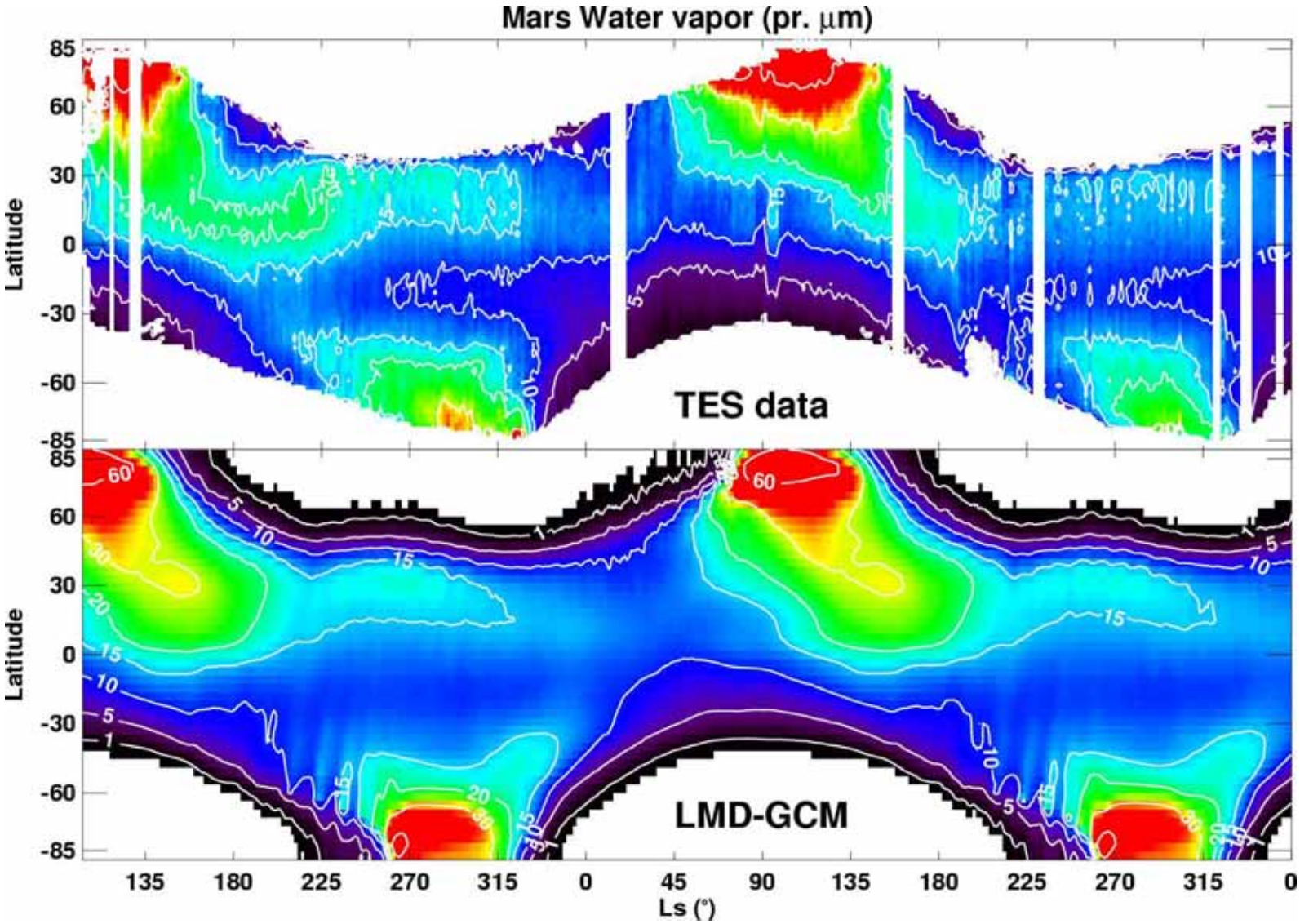
# The Mars GCM developed at IPSL



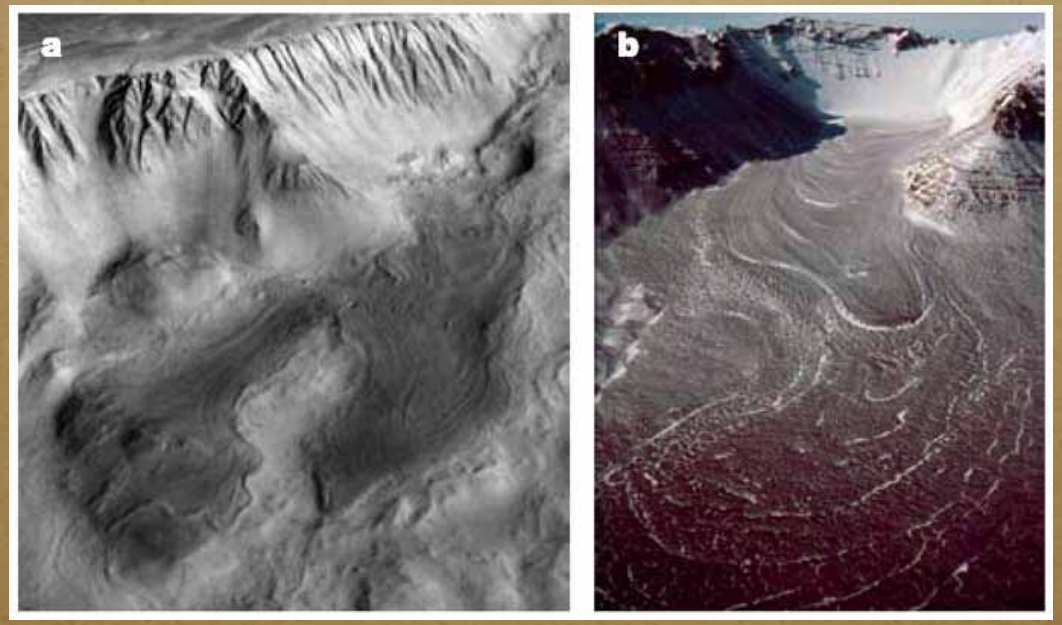
- ✓Dynamical core inherited from the LMD GCM Earth model
- ✓Chemistry & Microphysics developed at Service d'Aéronomie
- ✓Spatial resolution : 5.6° x 3.8° + 25 altitude levels

# Present day Mars




*Montmessin et al*. 2004

# *1st forcing of climate change:* obliquity




*Head et al.*, 2005

**Left : Olympus Mons (Mars) – Right : Antarctica (Earth)**

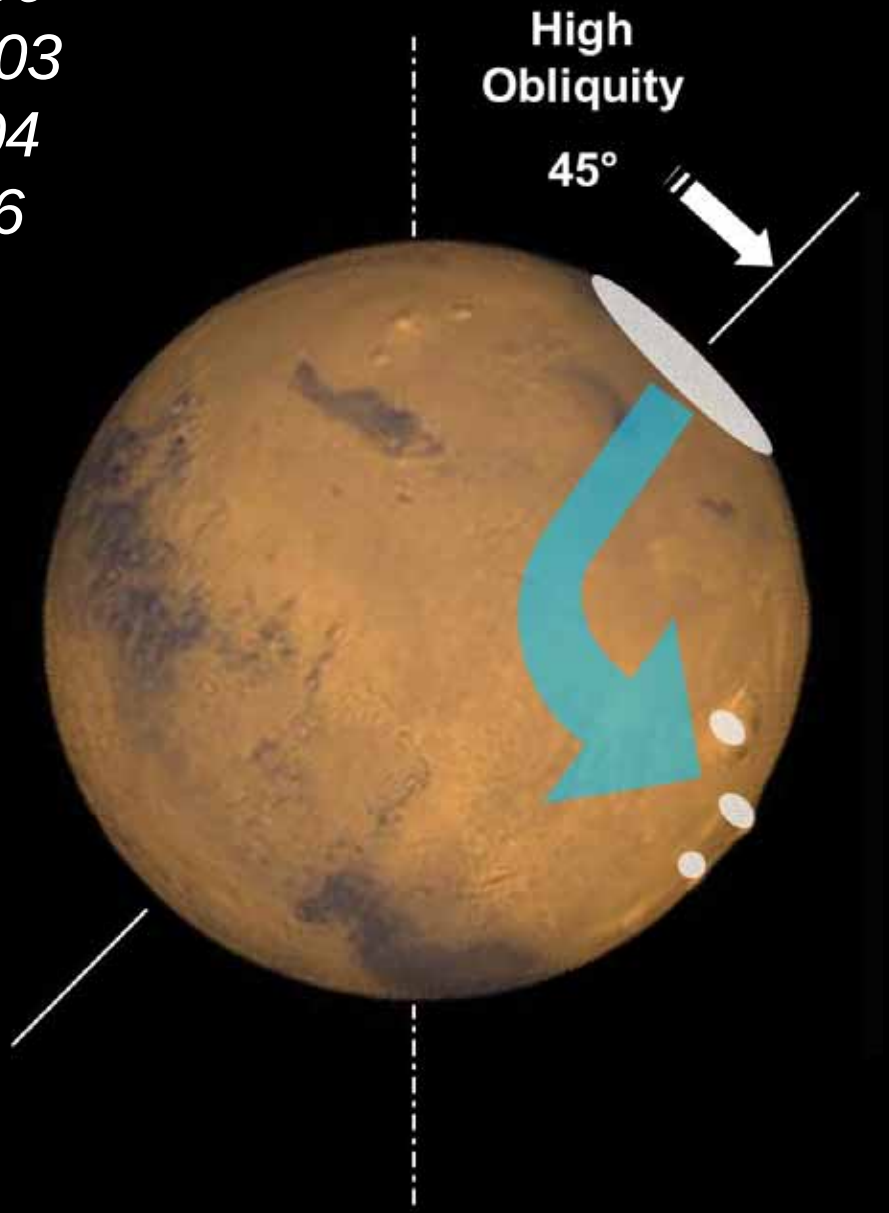
GCM simulations at high obliquity

*Haberle et al. 2000*

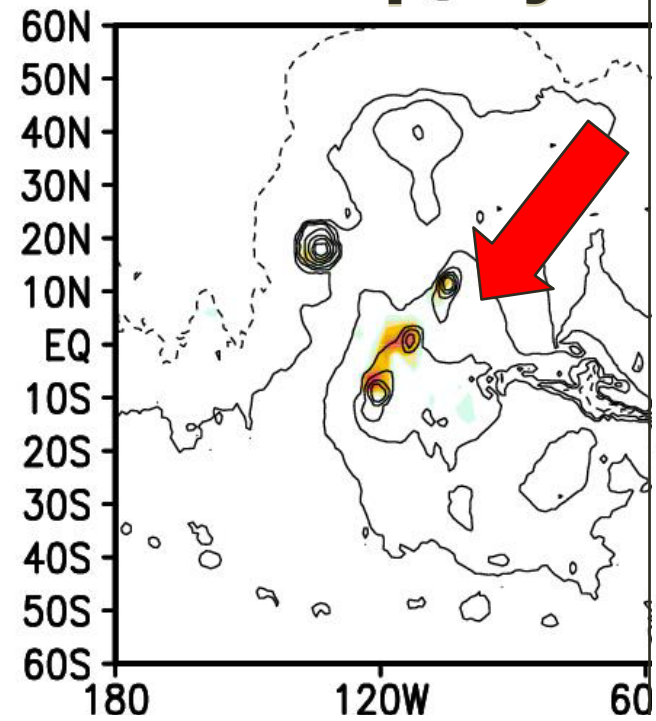
*Mischna et al. 2003*

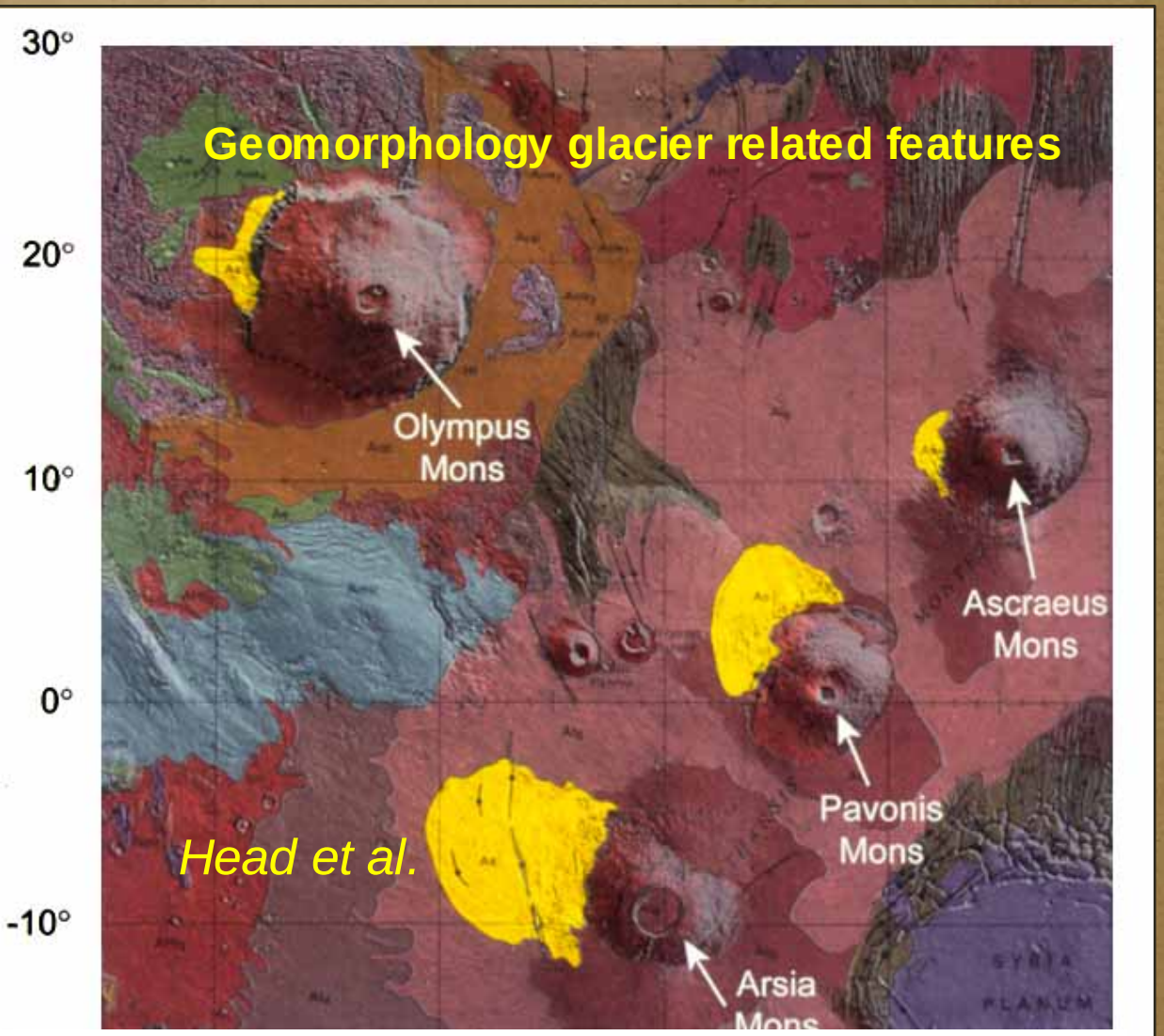
*Levrard et al. 2004*

*Forget et al., 2006*



# Glacier formation at high obliquity

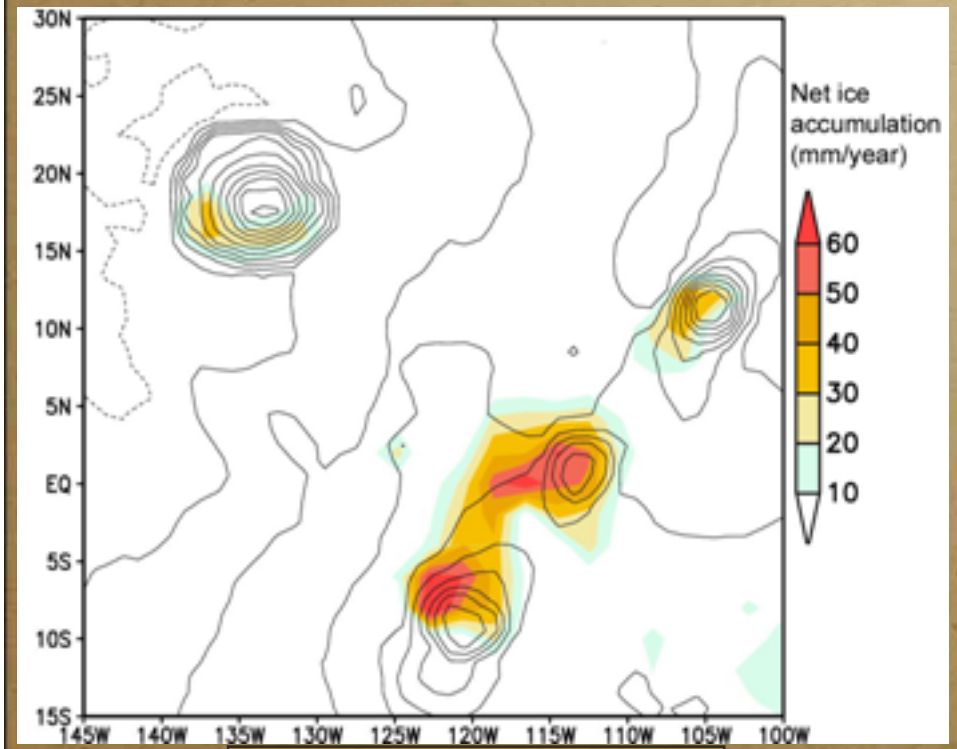


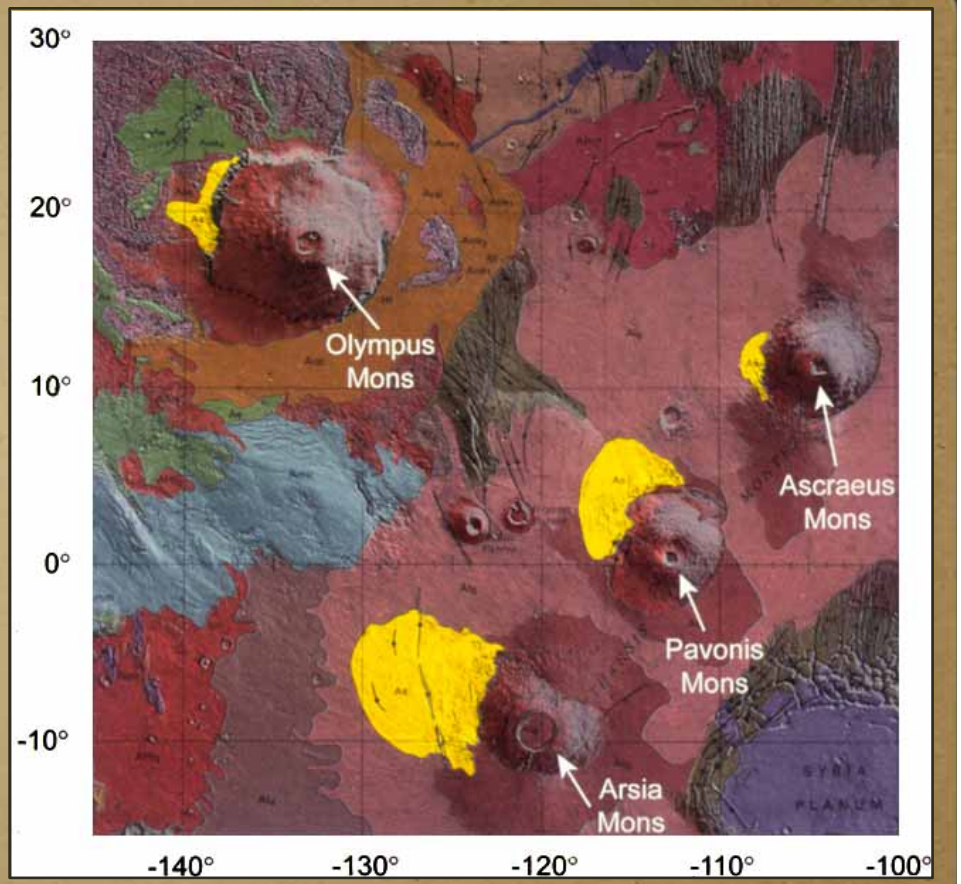

**Accumulation map (mm/yr)**

**GCM simulation**
***Forget et al., 2006***

# Comparison with Geomorphology glacier related features



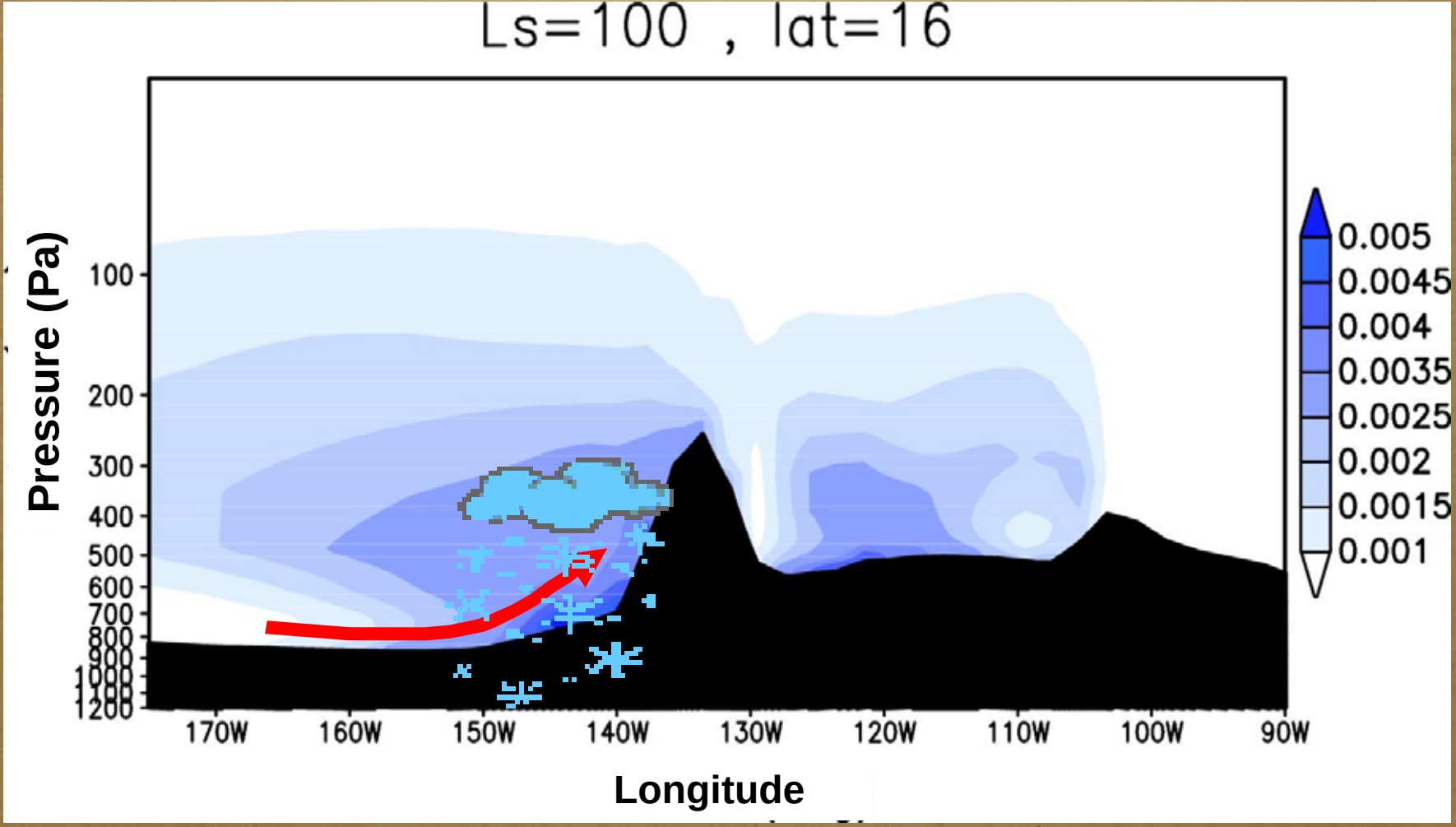

**GCM simulation**
*Forget et al., 2006*




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

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

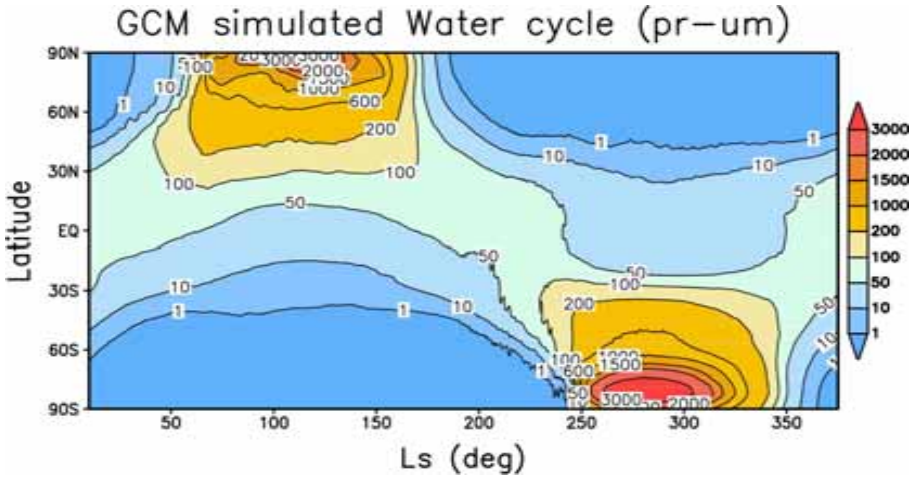
# Cloud mixing ratio (kg/kg)

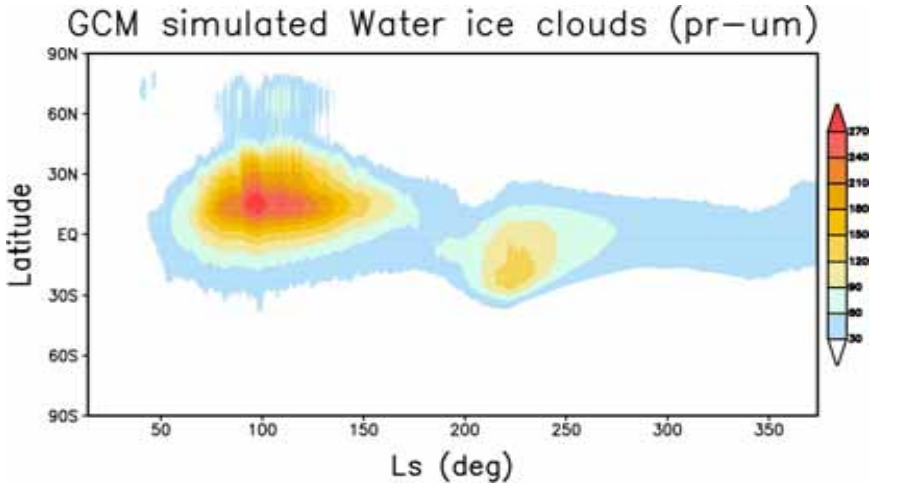


# The Martian climate at high obliquity

Higher pole insolation induces a stronger sublimation process and thus a **climate 30x wetter than today**

Circulation is also much stronger, especially the Hadley cell which forces a **more intense cycle of cloud formation, and thus more precipitation**, leading to water ice deposition in the tropics.



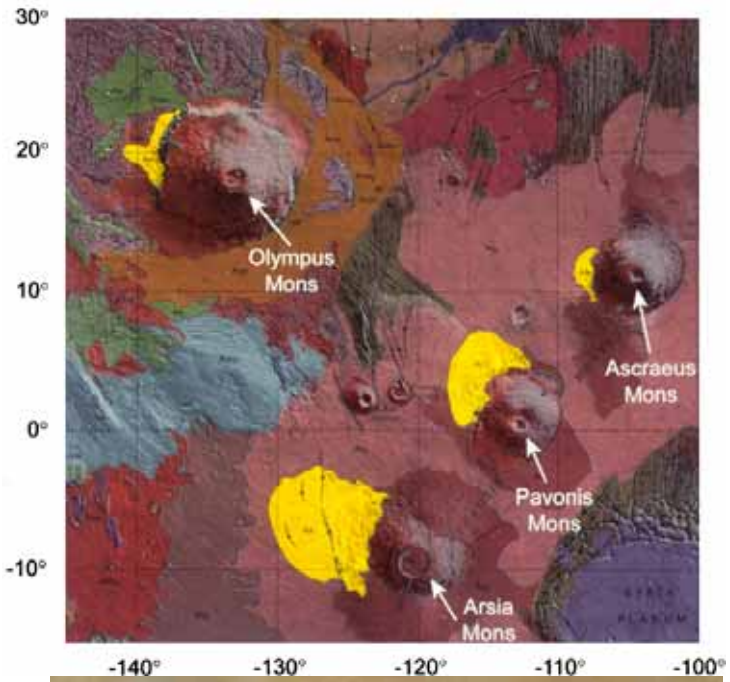



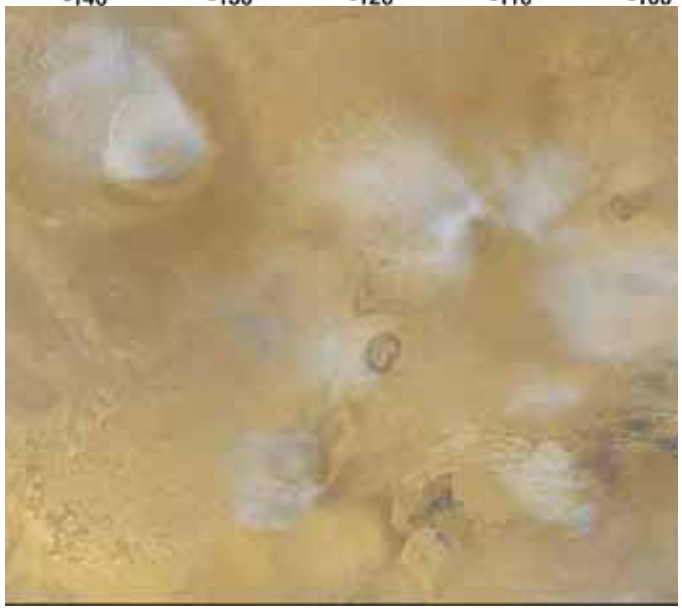
# Those "volcanic" glaciers…..

High obliquity periods have generated extremely wet climatic conditions…..

Precipitation & accumulation of ice on the windward side of tropical volcanoes

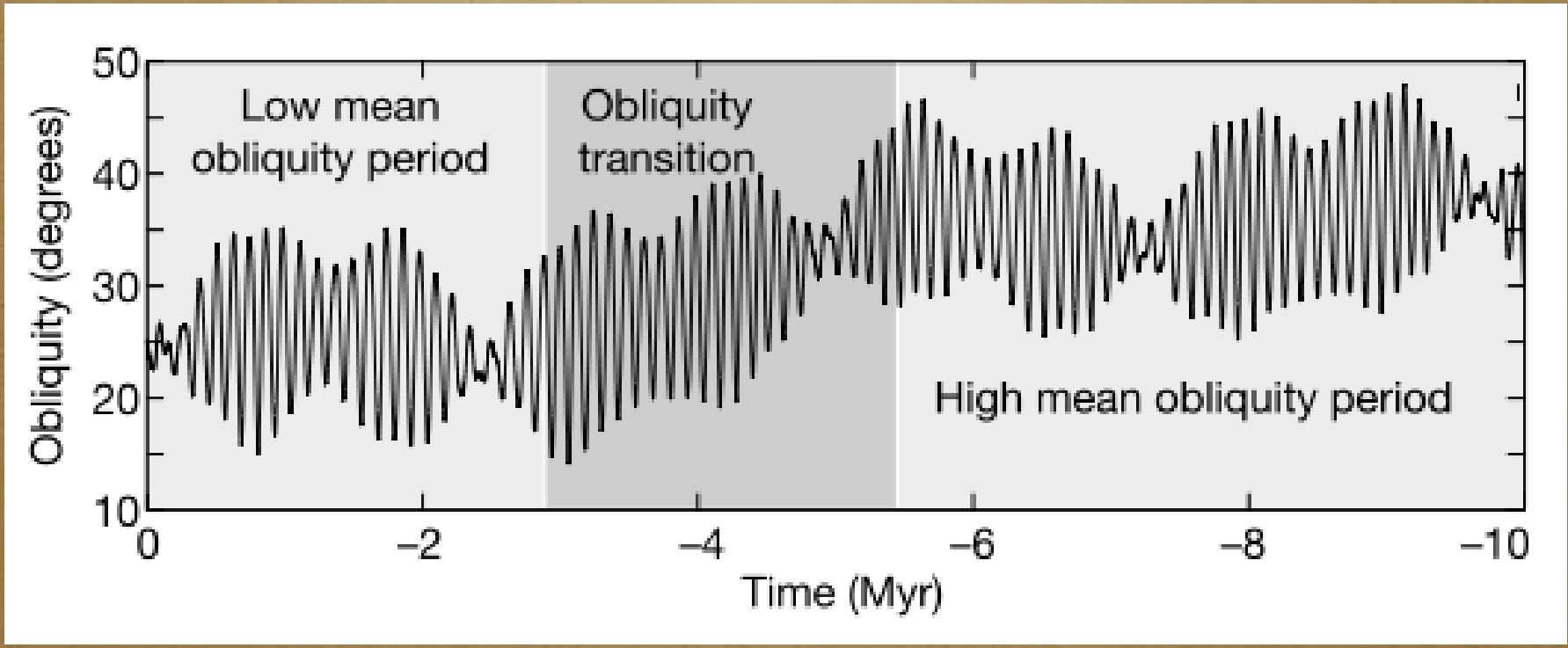
Yet, these meteorological conditions are not so different than today, only magnified



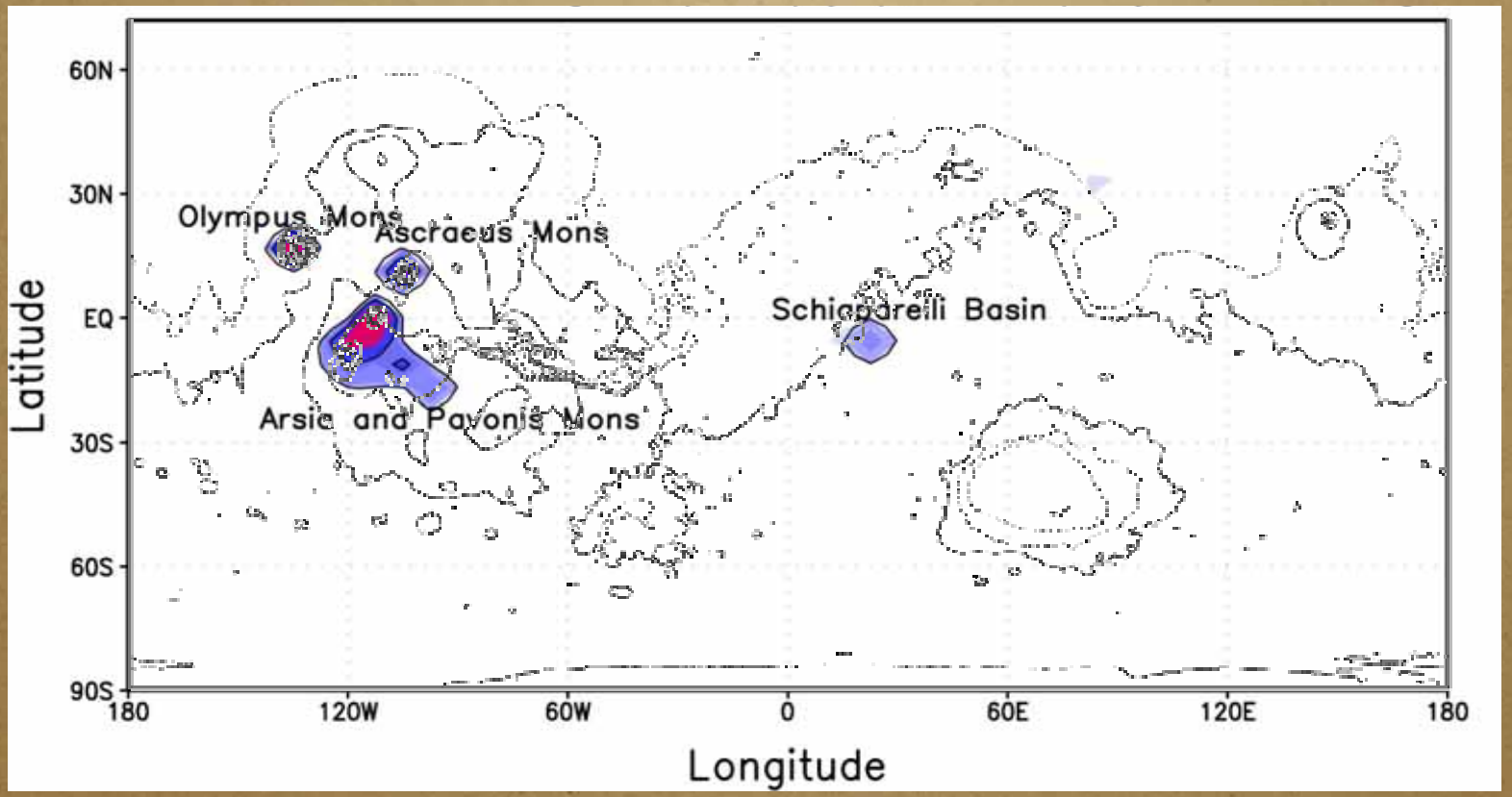
***Tropical clouds seen today near the summit of volcanoes***

# Transition from a high to a low obliquity regime

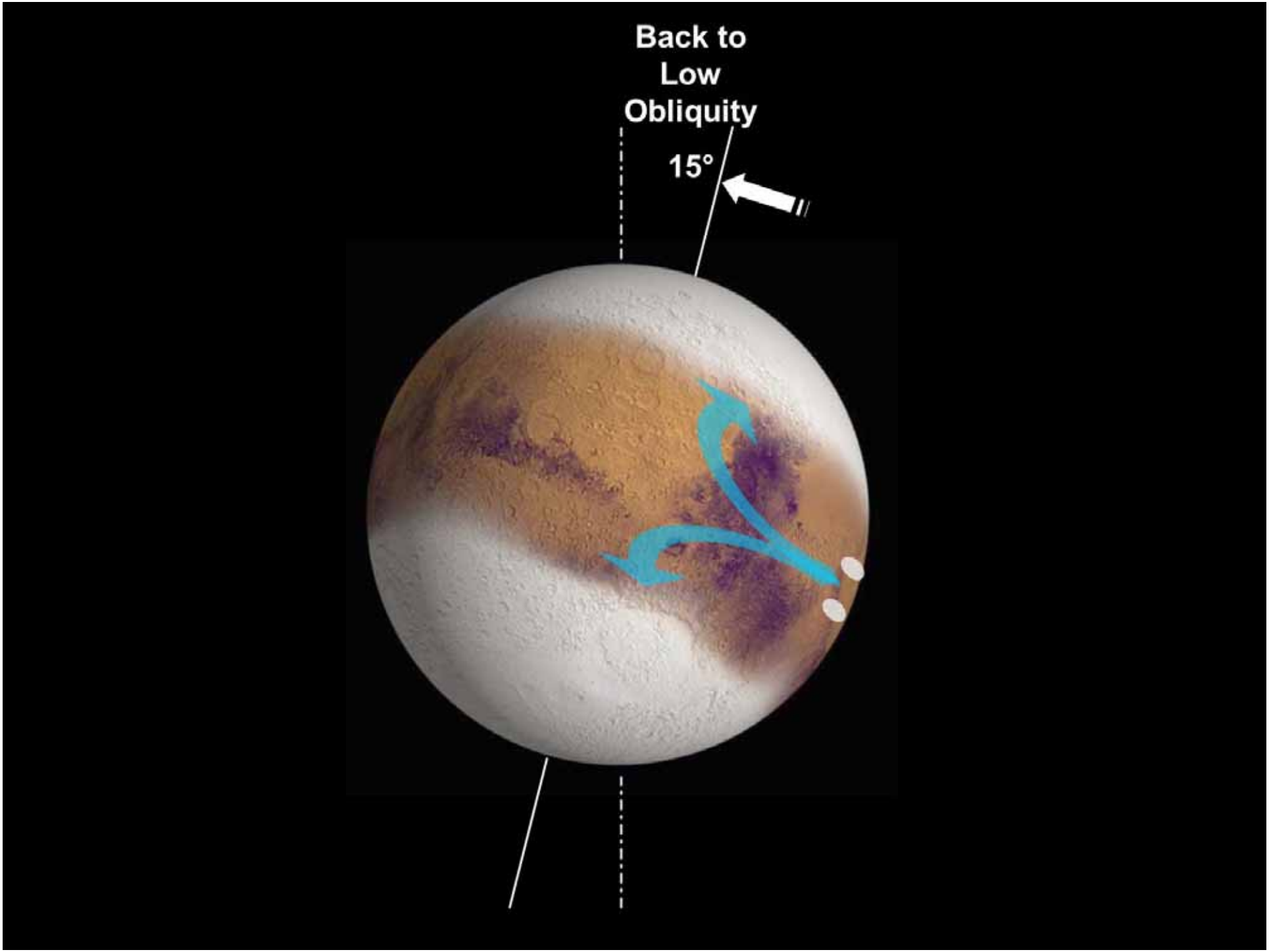



*Levrard et al. (Nature, 2004)*

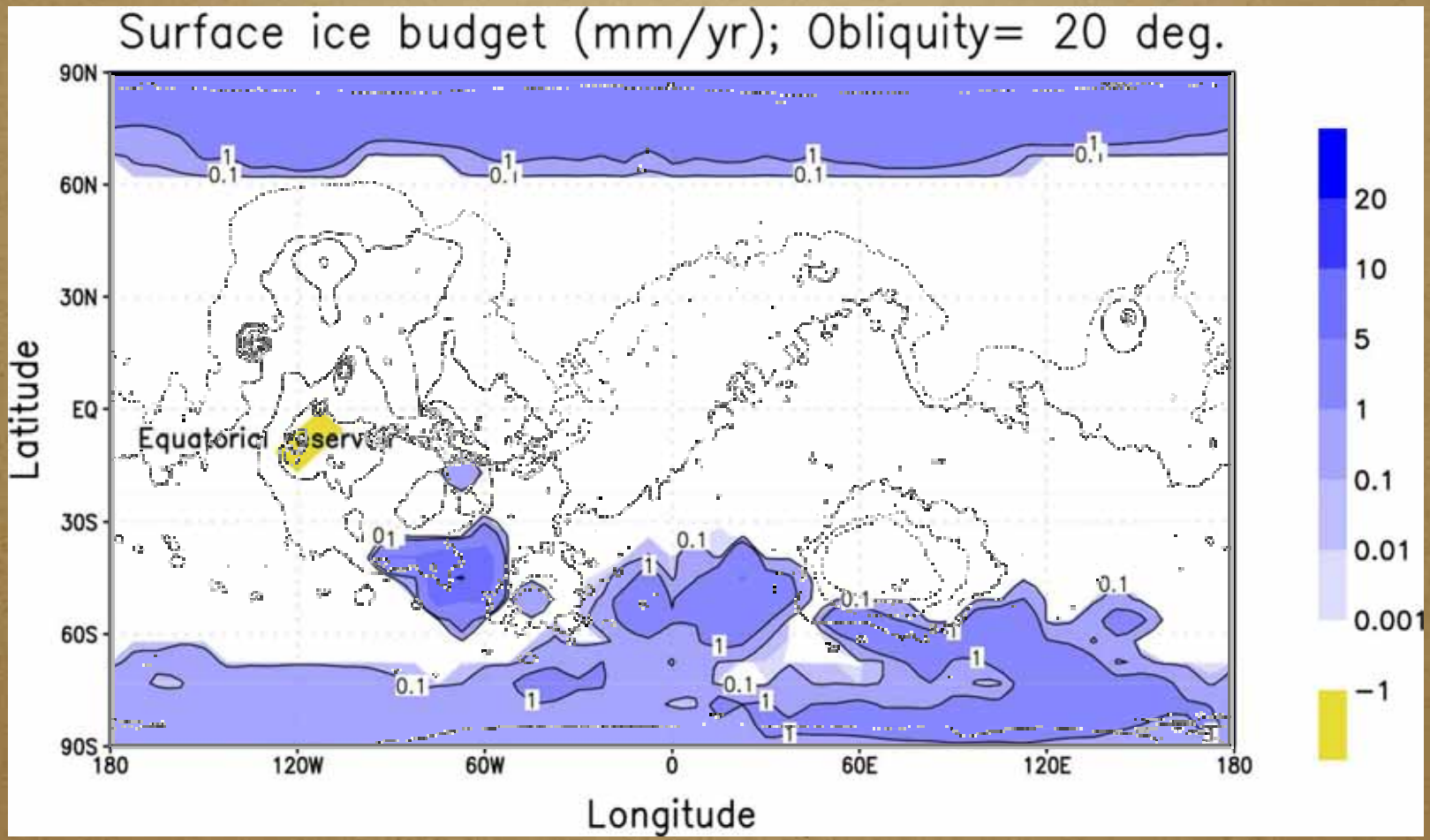
# **Initial situation** (5 Myr ago) = the reservoirs of water are in the tropics



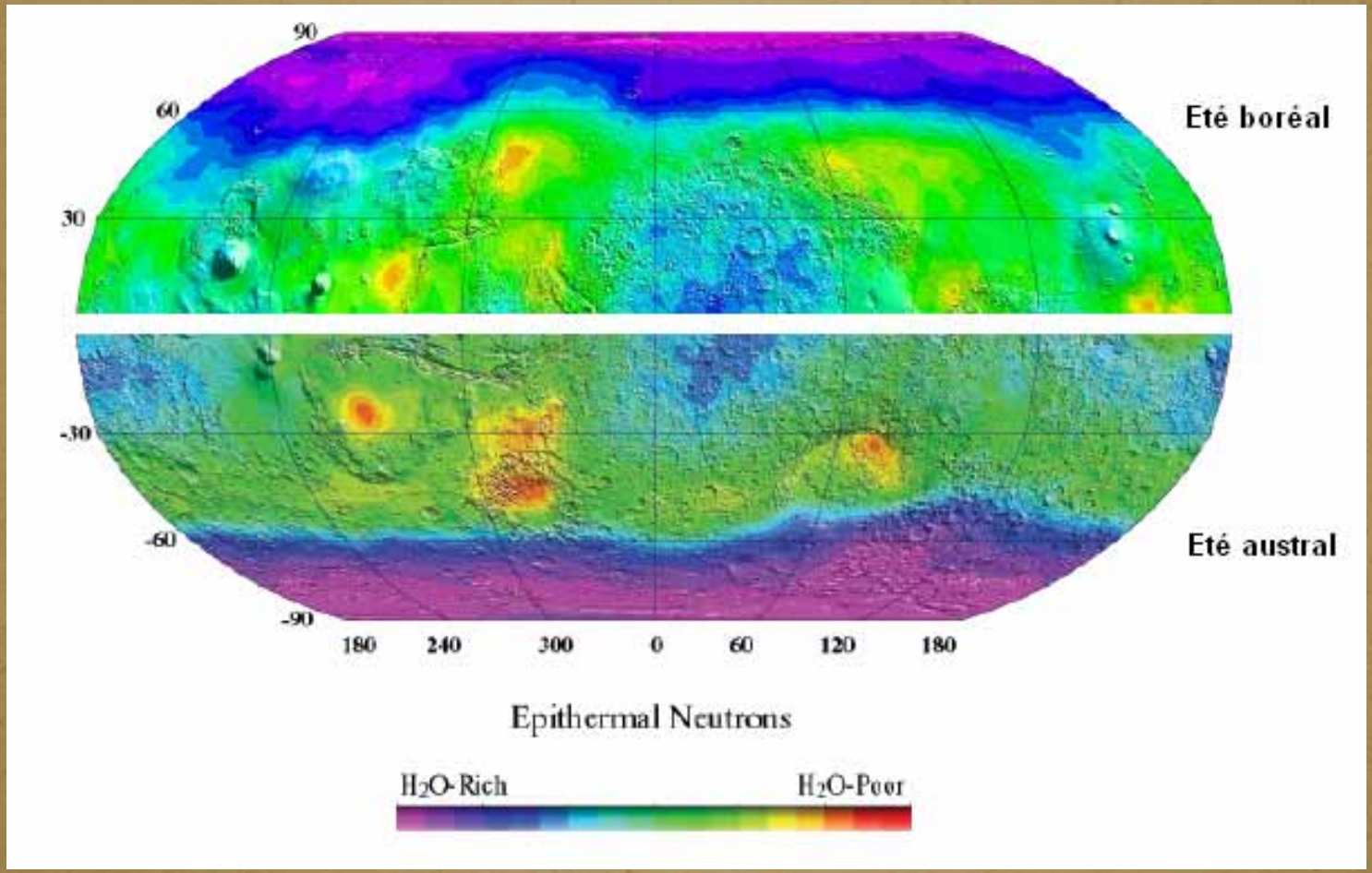

*Levrard et al. (Nature, 2004)*


Back to
Low
Obliquity
15°

# GCM simulations



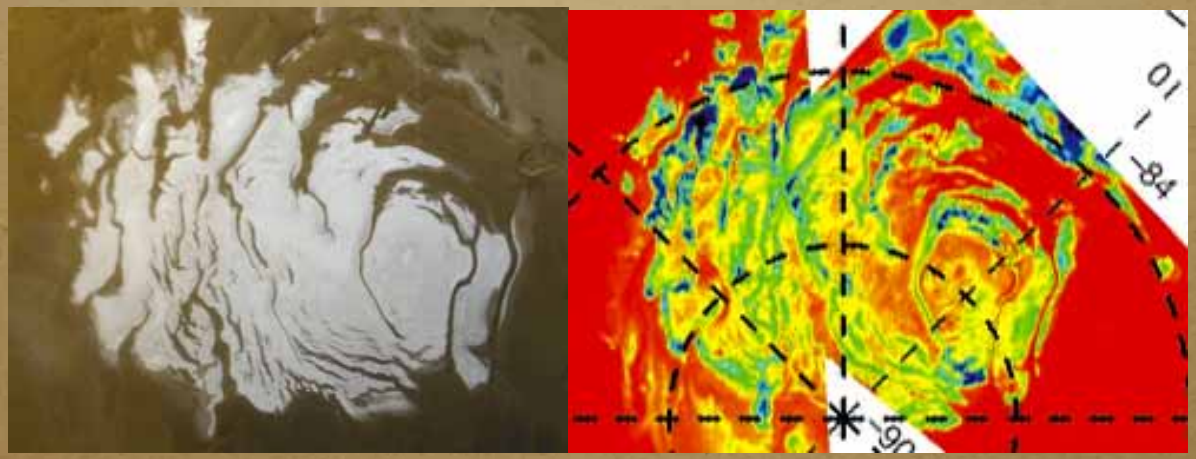

*Levrard et al., 2004*




## GRS water ice can be explained by the following event sequence:

1. Deposition of meters-thick layers of water ice poleward of 60° during the transition period to present low obliquity regime
2. Equatorial reservoir eventually exhausted
3. High latitude water ice became unstable, leading to upper mantle dessication and lag formation and then retreat of water ice to the pole

# *2nd forcing of climate change:* precession

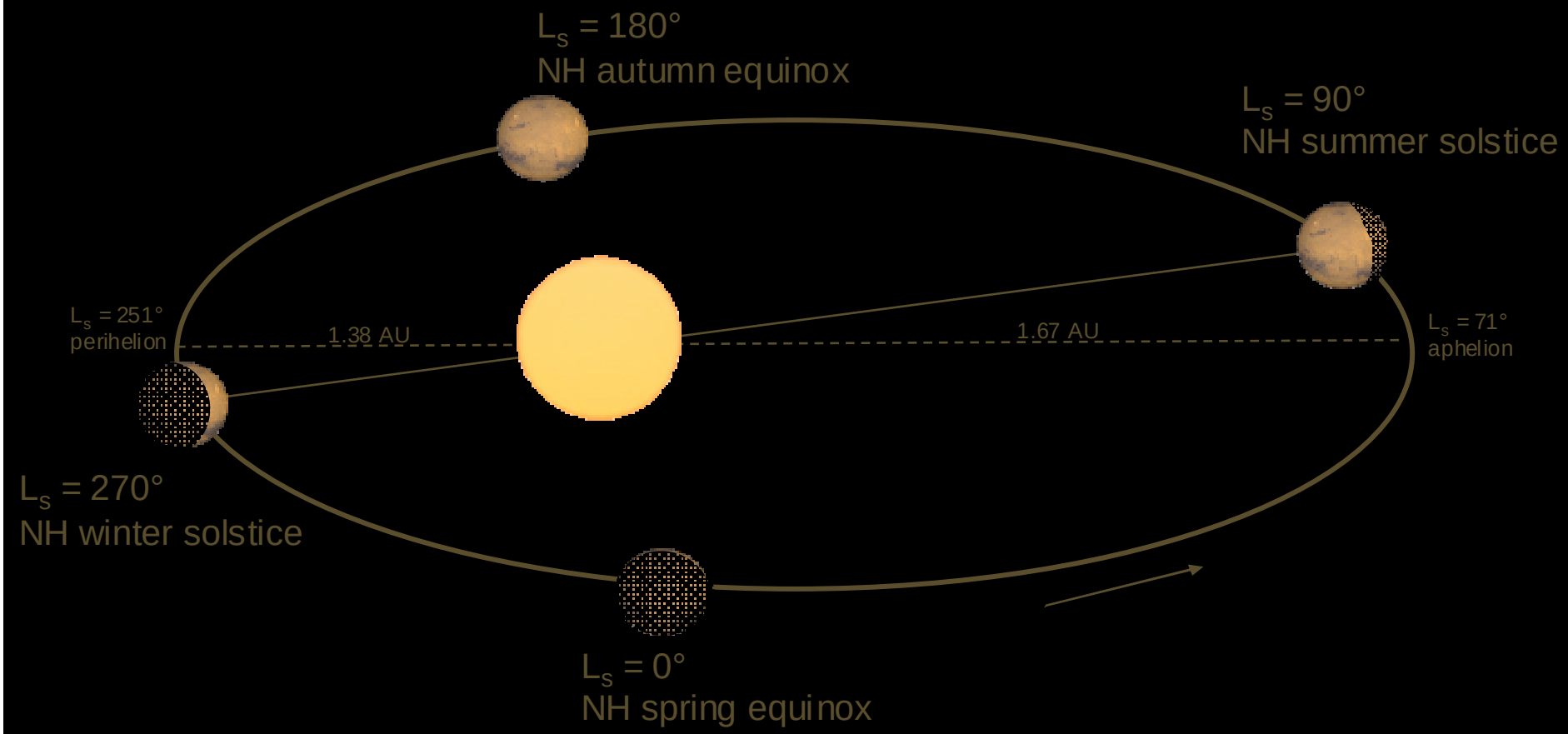


Discovery of water ice sheets at the south pole of Mars (Bibring et al., 2004)

# A few Facts and ideas

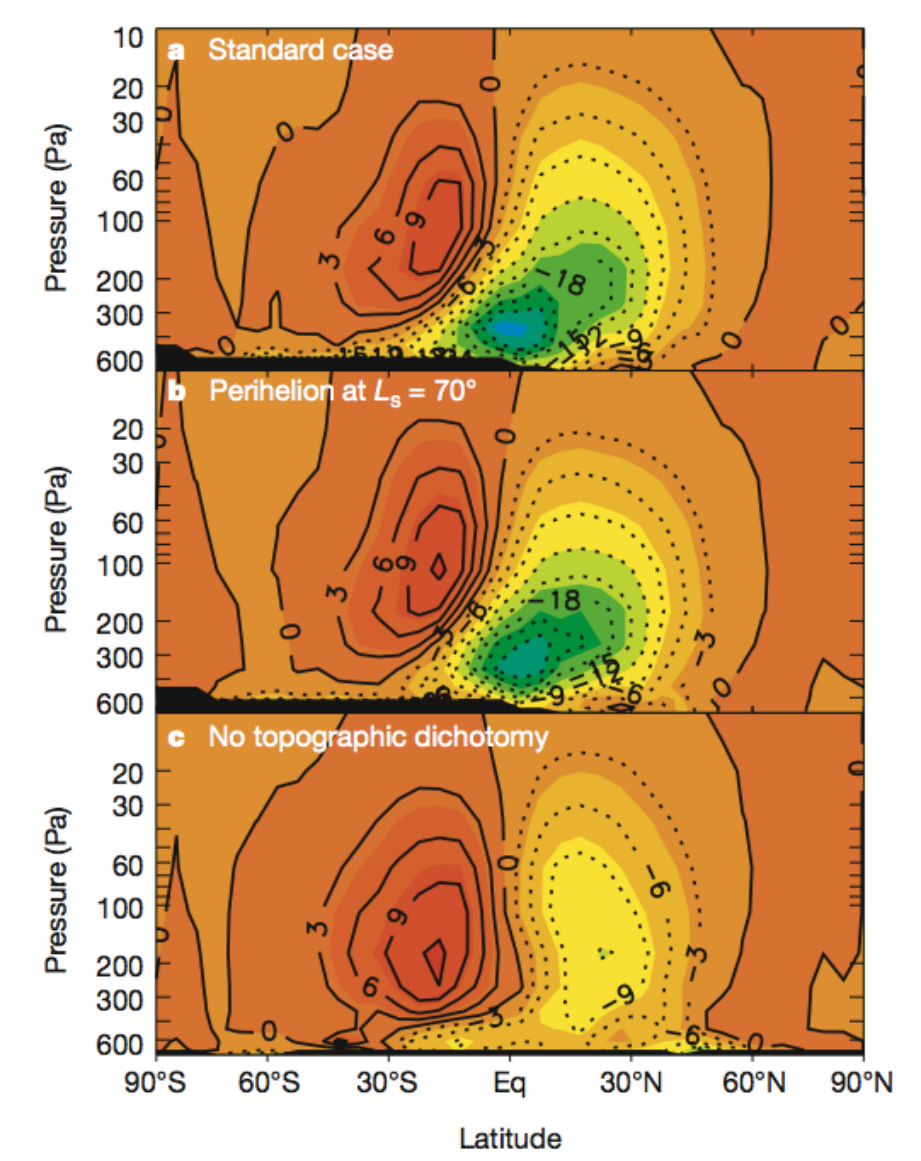
- N & S polar regions contain extensive water reservoir, but…
  $H_2O$ ice is only exposed in the north, $CO_2$ ice in the south
- Mars water cycle equilibrates with insolation conditions at the poles (*Davies,* 1981) and thus with orbit changes
- **Water ice is only stable at the north pole**, **why ??**

# 1. Mars Climate is asymmetric



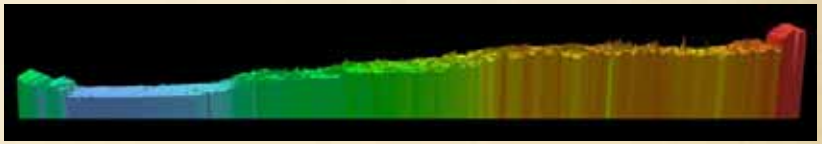

*Summer is shorter and warmer (+20K) in the south*

# 2. Circulation is asymmetric



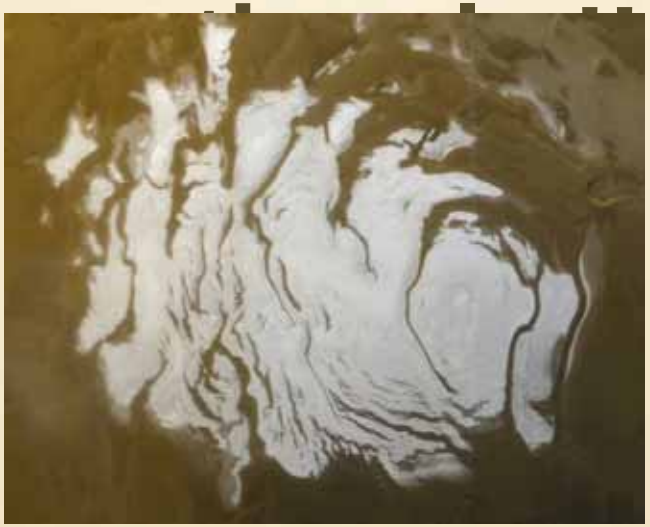

*Richardson and Wilson, 2002*

The north-to-south topographic dichotomy

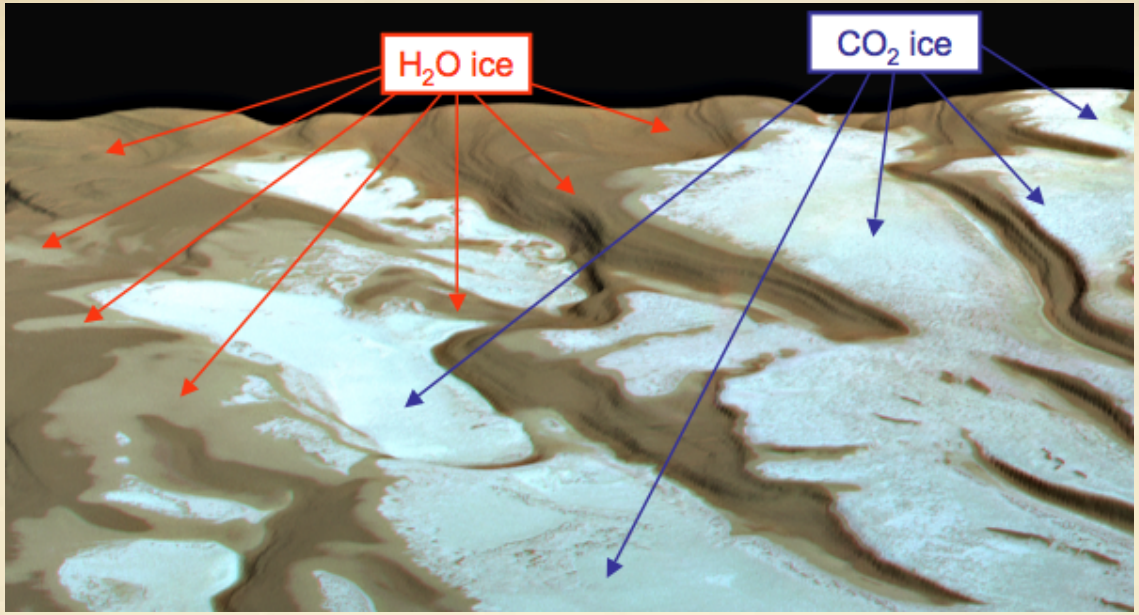


forces a stronger meridional advection during southern spring/summer.

# But recent observations say….
# Water ice also resides at the

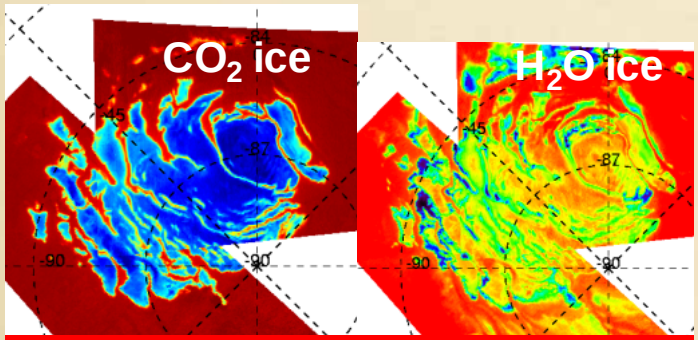


*The south residual cap. We used to think there was only $CO_2$ ice there…*




***HRSC image of the south pole***

# OMEGA mapping



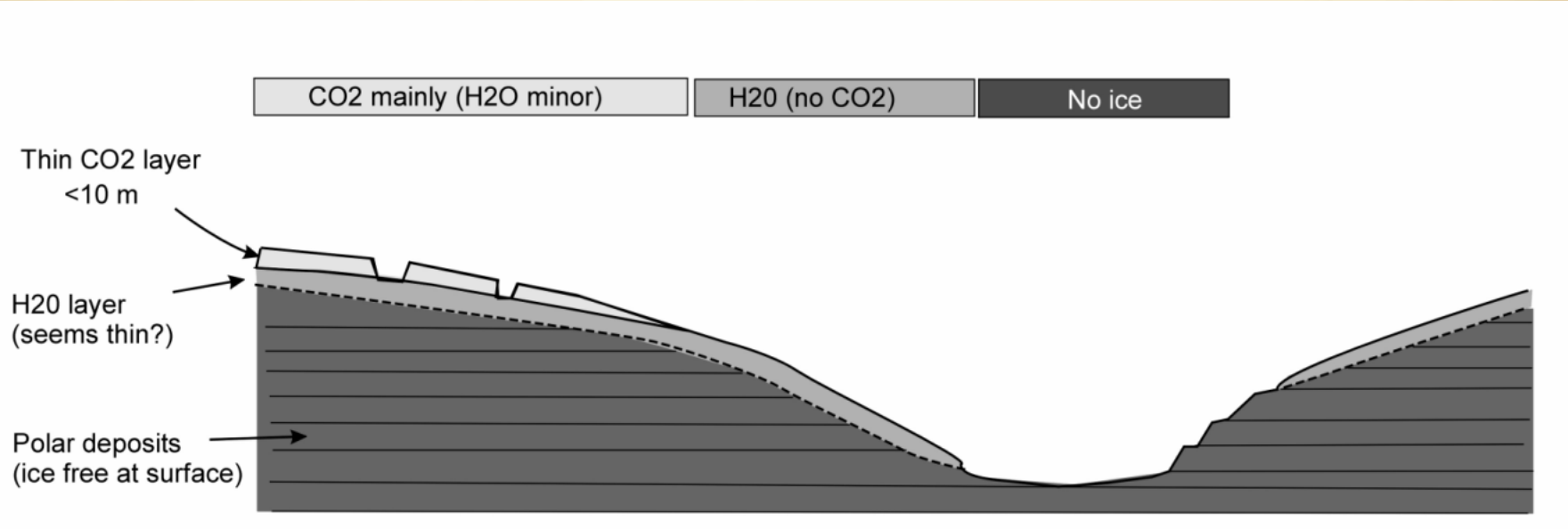

***Bibring et al. 2004***

- OMEGA has revealed the existence of **3 distinct units** of water ice:
  1. Mixed with $CO_2$ ice in the residual "bright" cap.
  2. Contour of the "bright" $CO_2$ cap.
  3. Isolated patches.
- The existence of Unit 1 is expected since:

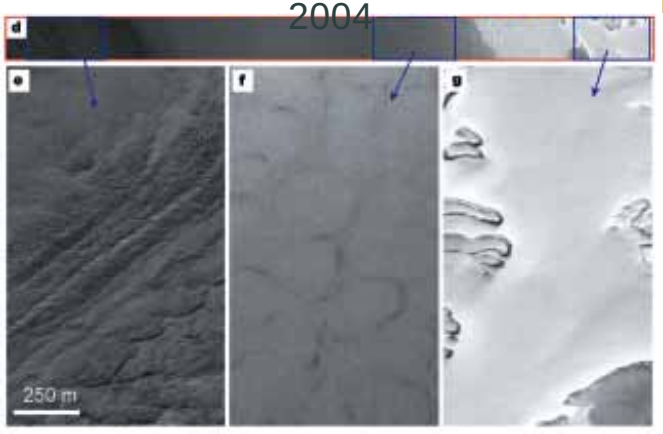
  $$T_{surf} < T_{sat}(H_2O)$$

  water gets trapped at the top of the $CO_2$ ice layer.
- The presence of Units 2 and 3 is unexplained.

# A new view of the South Polar Cap




*Bibring et al.*, 2004; *Mangold et al.*, 2004



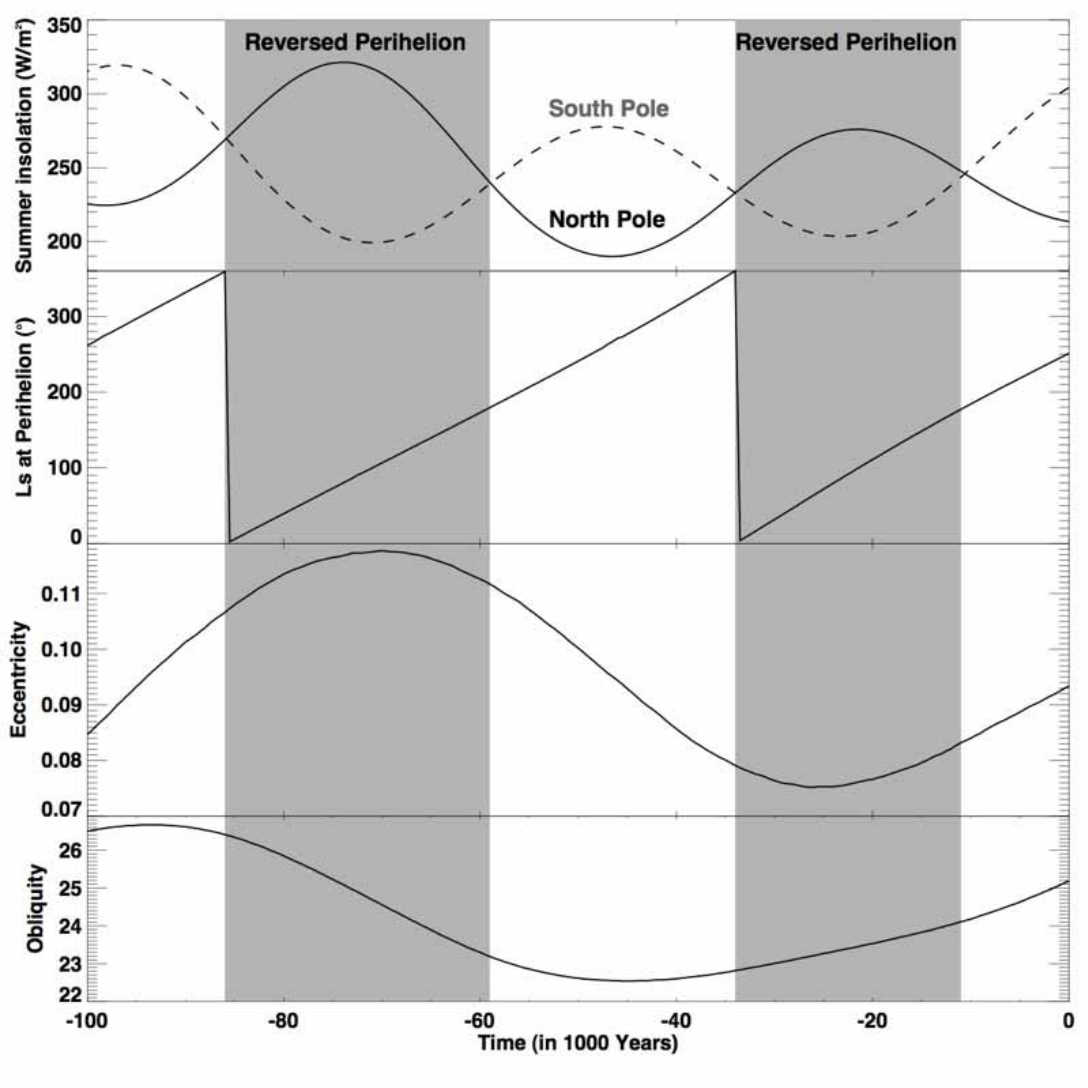

Polygonal features of Unit 2 are seen through the $CO_2$ ice layer, thus:

- A water ice layer sits below the thin (meters-thick) $CO_2$ ice veneer
- These water ice units predate the formation of the $CO_2$ veneer

……But, water ice is unstable wrt. current climate

**Water ice Units 2 & 3 are remnants of past climate conditions !**

# Mars orbit recent variations




*Obtained using Laskar et al. (2004) secular solution*

| | *Today* | *"Reversed Perihelion"* *(-21.5 kyr ago)* |
|---|---|---|
| **Circulation asymmetry** | ……*favors* ***North*** | ……*favors* ***North*** |
| **Climate asymmetry** | ……*favors* ***North*** | ……*favors* ***South*** |

**North wins !**

**? ?**

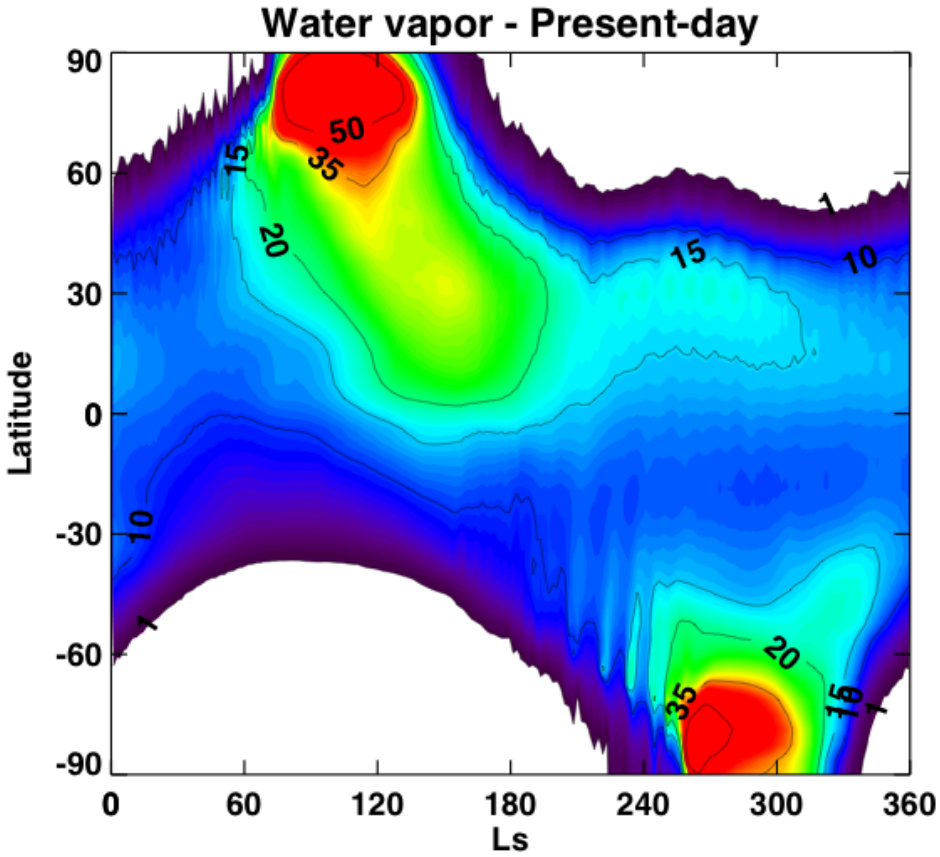
# “Reversed Perihelion” modeling study

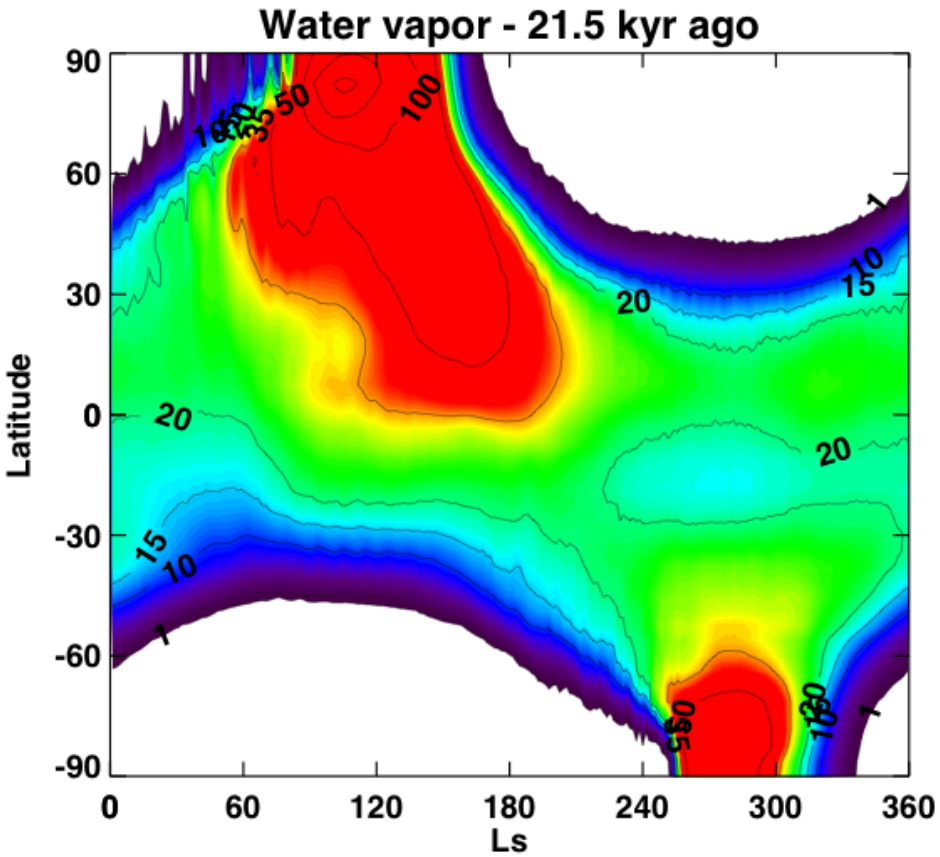
Question: Can we explain water ice at the south pole just by playing with precession ?

Answer: GCM simulations of Mars water cycle (*Montmessin et al*., 2004)

Model set with a -21.5 kyr orbital configuration:

- $L_p$~70° vs. 250° today (Lp = Solar Longitude at Perihelion)
- Obliquity - 23.5°
- No $CO_2$ cold trap at the south pole
- Various climatic scenarios (changing dust climatology)




**Lp = 251 °**

**"Today"**

***in pr. μm***

**Lp = 71 °**

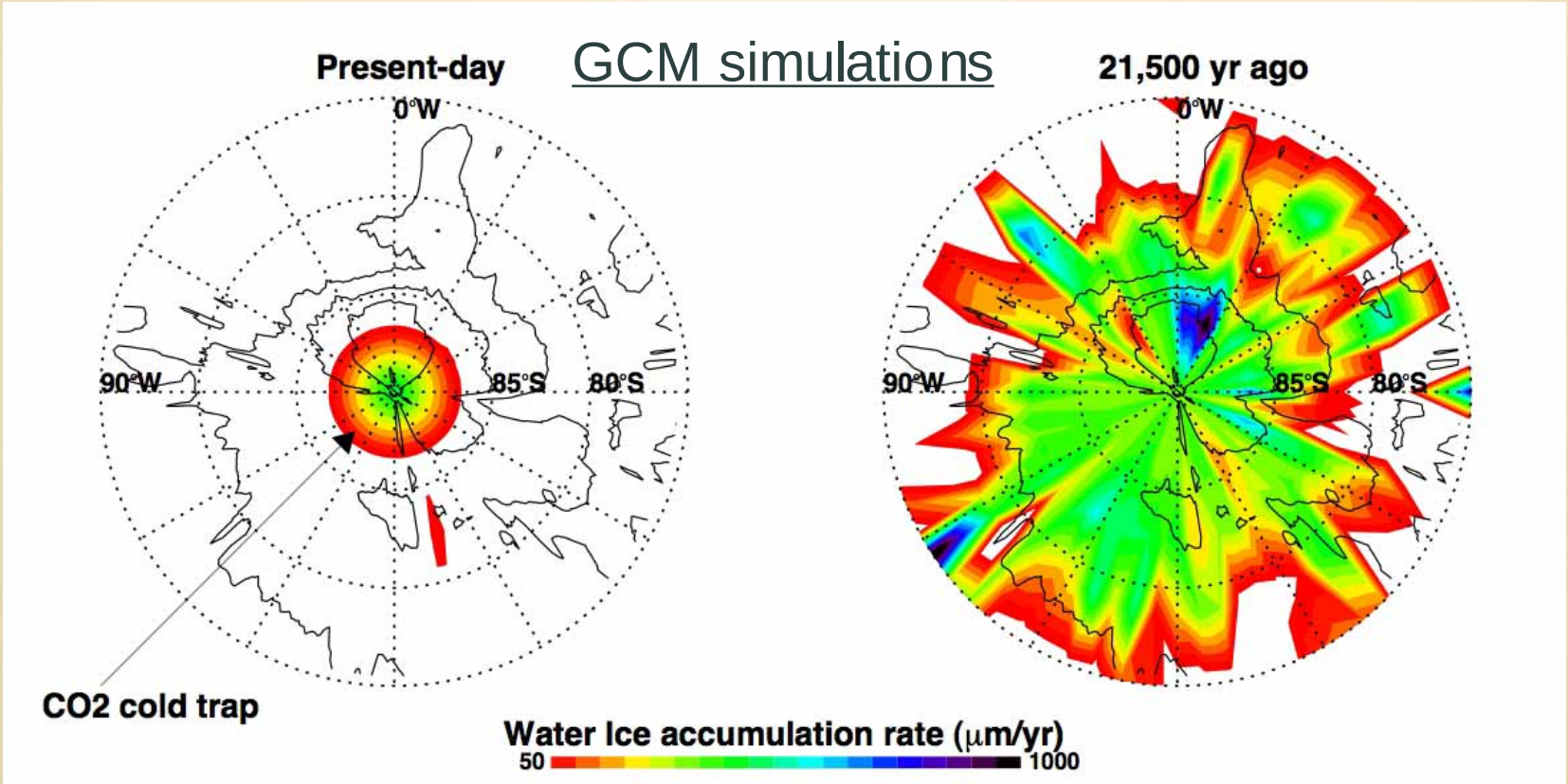
**"Reversed Perihelion"**

***Under a "reversed perihelion" climate, summer pole $T_{north}$ ⇗ > $T_{south}$***

- Sublimation flux is >2 times stronger
- Water cycle is globally 2 times wetter

**In “reversed perihelion” climate, GCM predicts that water ice is removed from the north polar cap and is transferred to the south pole every year where it accumulates.**

**Meters of water ice could have been deposited there during the last “reversed perihelion” regime, 25 000 years ago.**




*Montmessin et al*., 2007

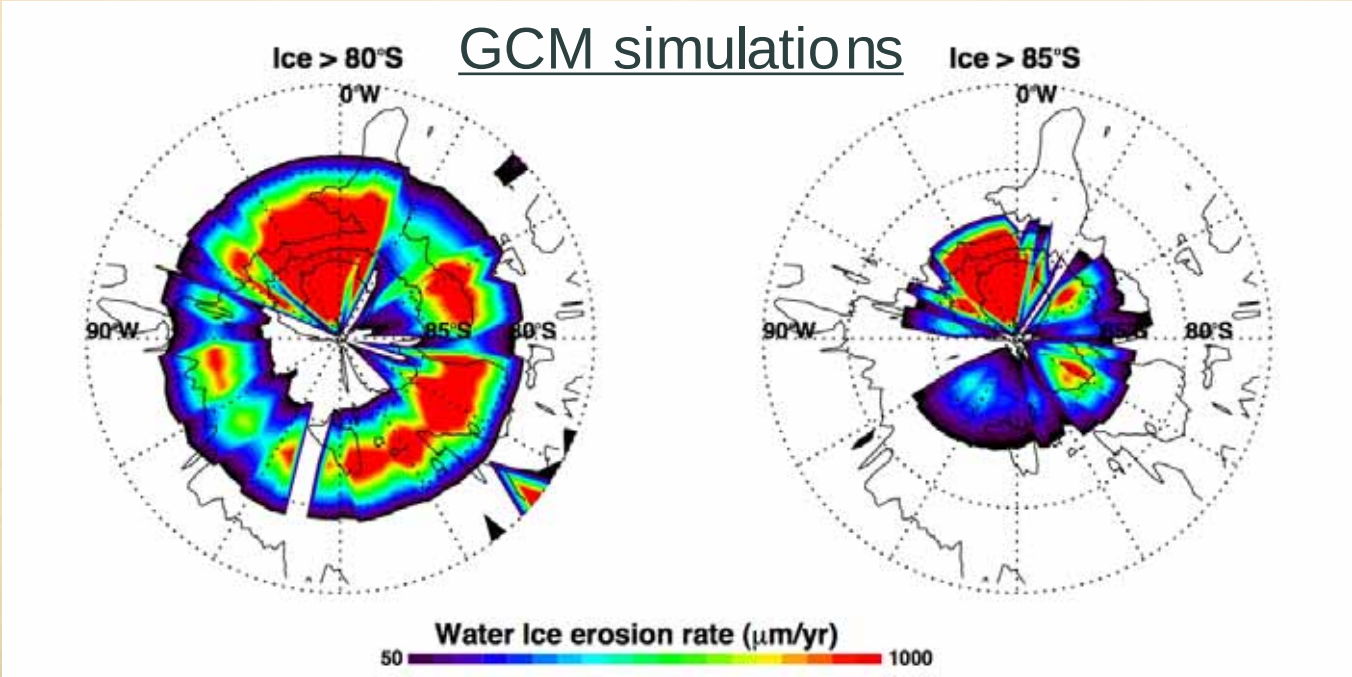
# What happened afterwards?

When precession returned into current regime (-10 kyr), **south polar water became unstable.**

Under current climatic regime, GCM simulations indicate that **south polar water is removed with rates as high as 1 mm.yr$^{-1}$.**

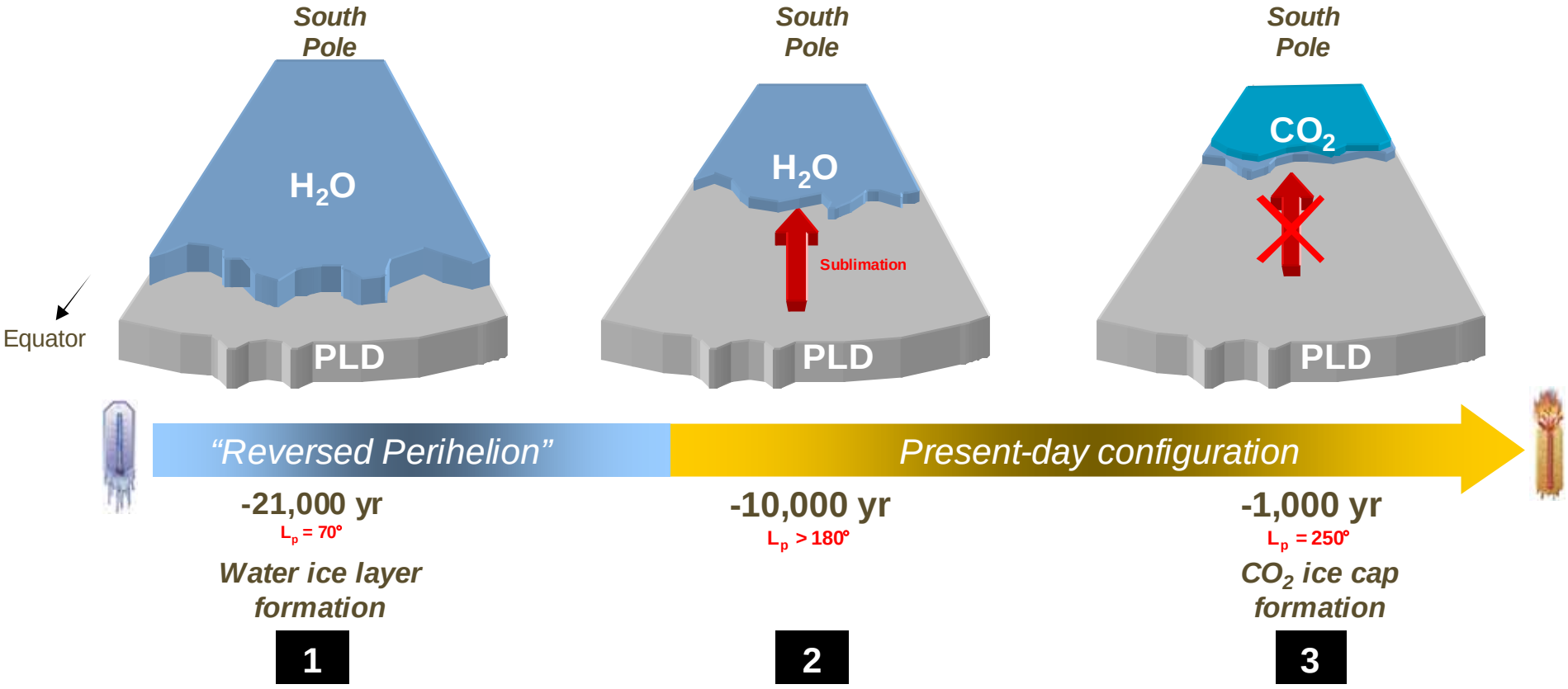
During the last 10 kyr, **water ice receded poleward in a concentric fashion** following the secular increase of summer insolation.

And then…?



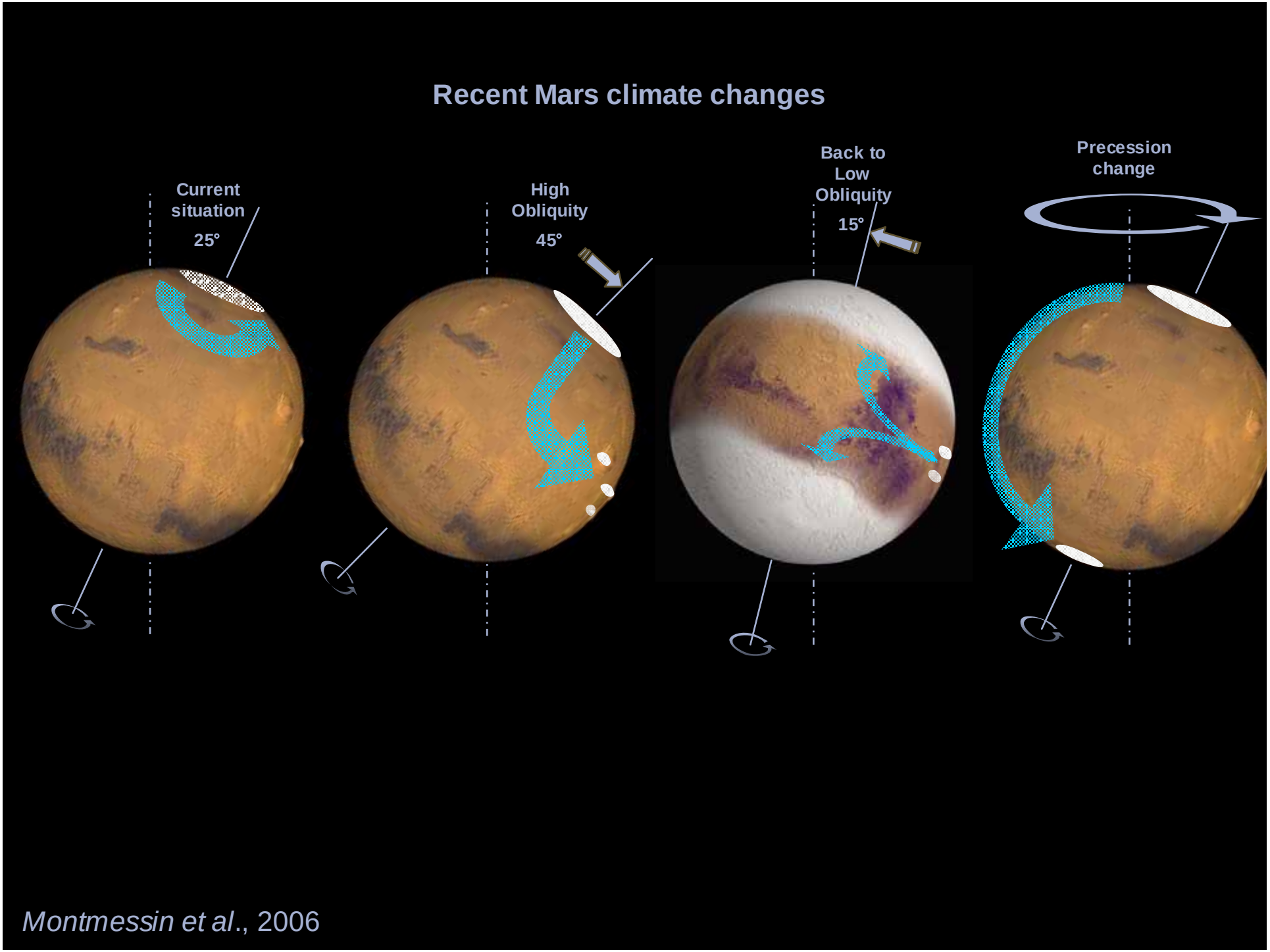

Montmessin et al., 2007

# A scenario for the recent evolution of water ice at the south pole



To summarize….

## Recent Mars climate changes




*Montmessin et al.*, 2006

# A little bit of Mars history….

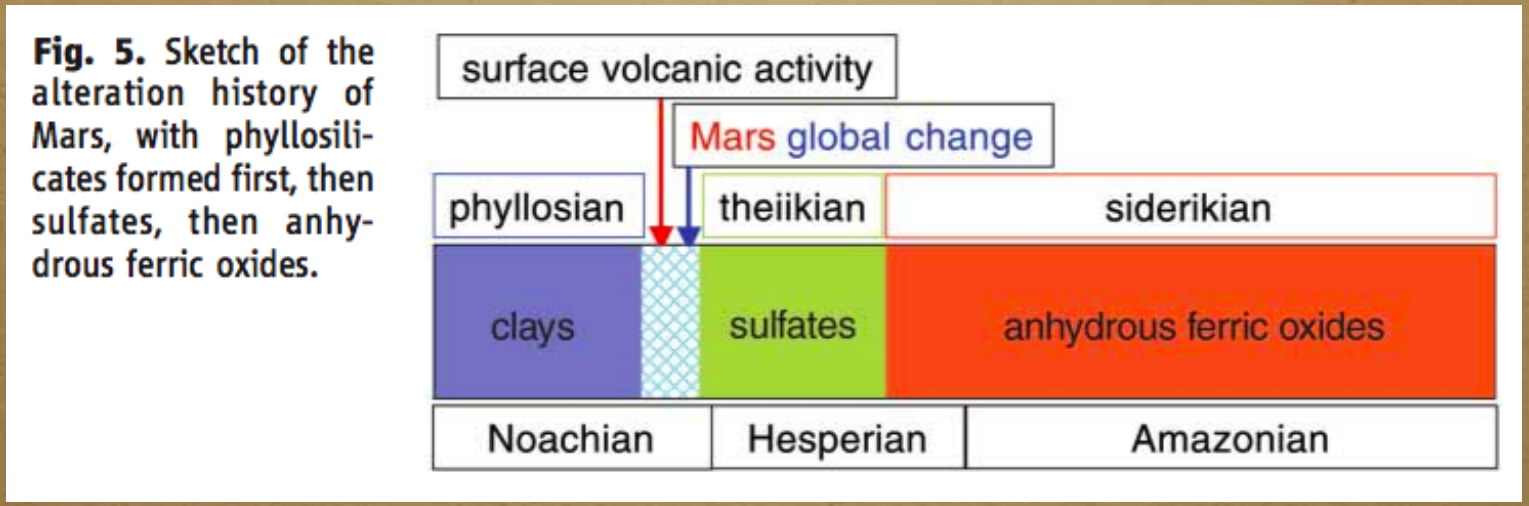
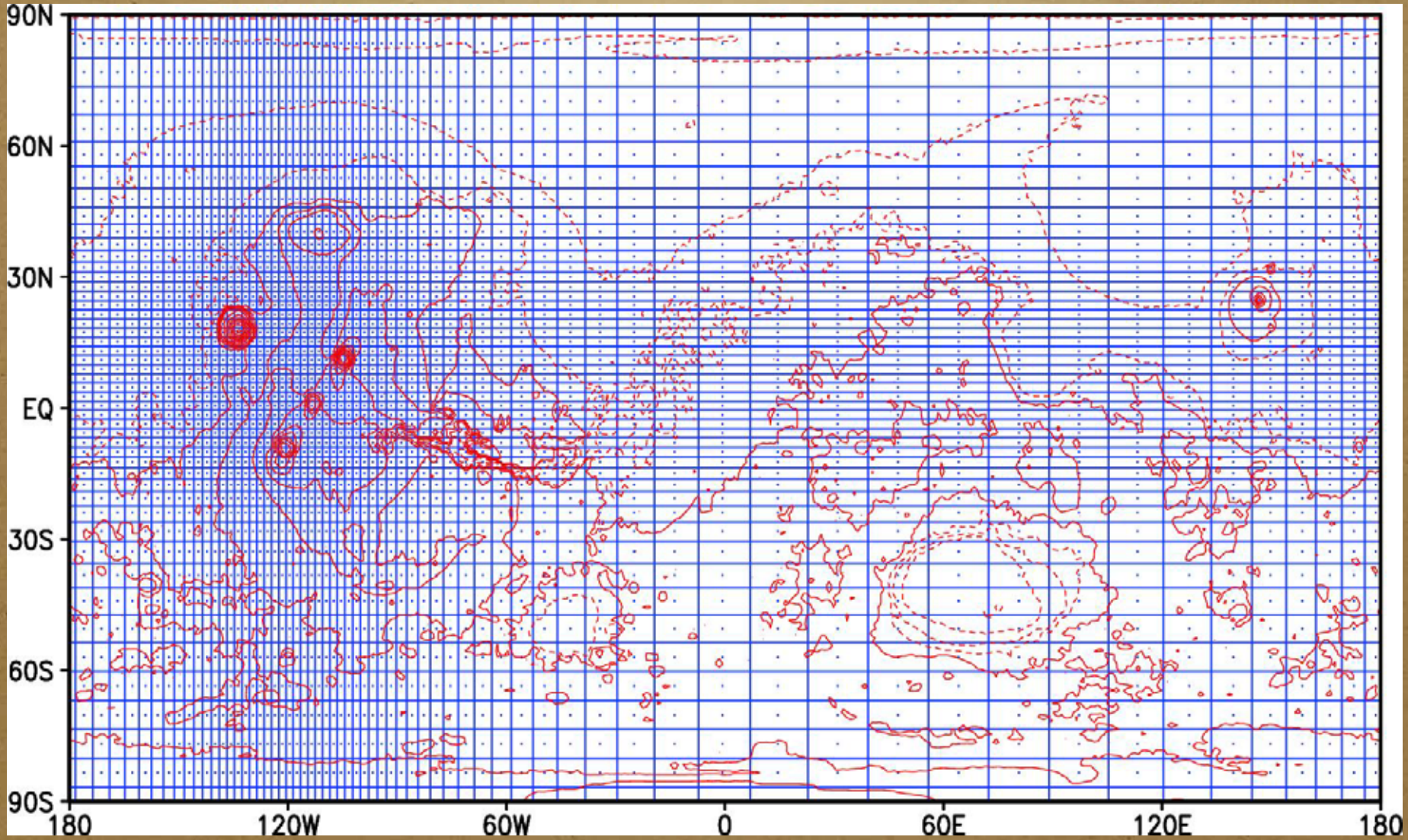
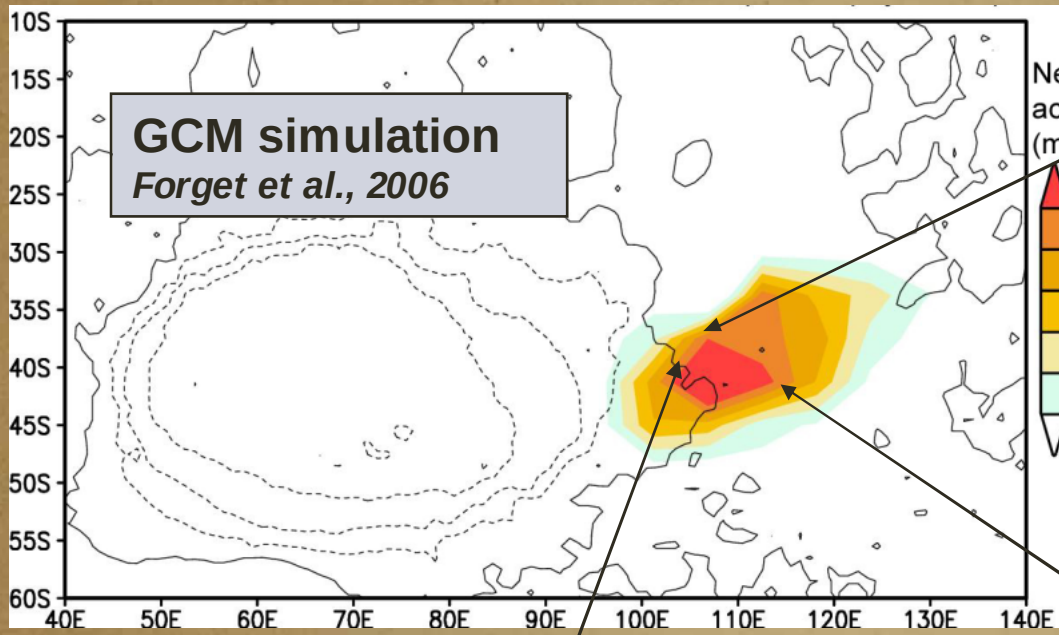


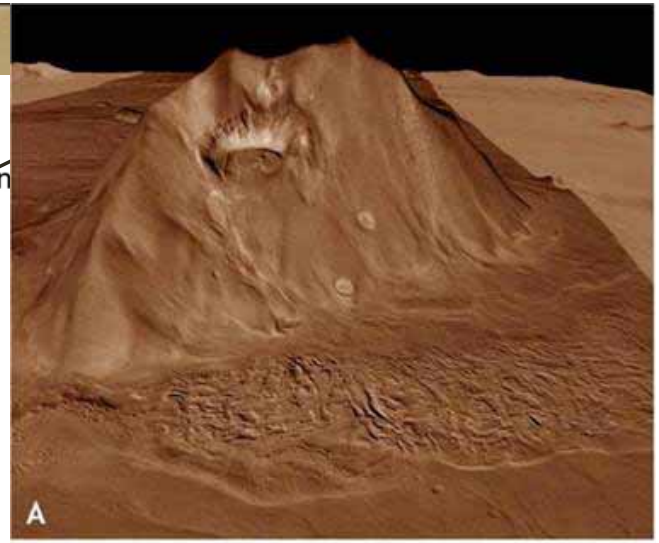

**Fig. 5.** Sketch of the alteration history of Mars, with phyllosilicates formed first, then sulfates, then anhydrous ferric oxides.

*Bibring et al.* , 2006

# High resolution simulation (res. 2°x2°)



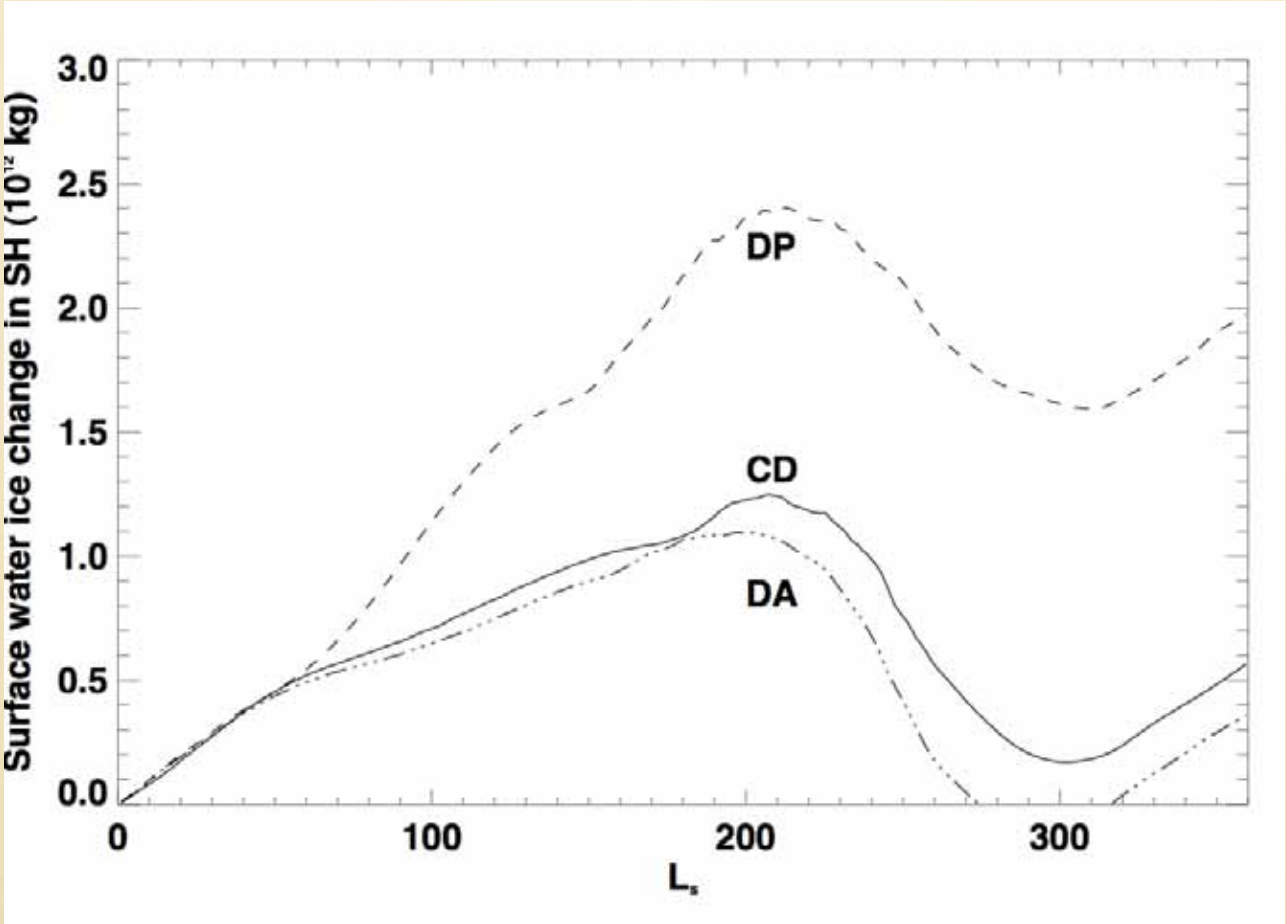


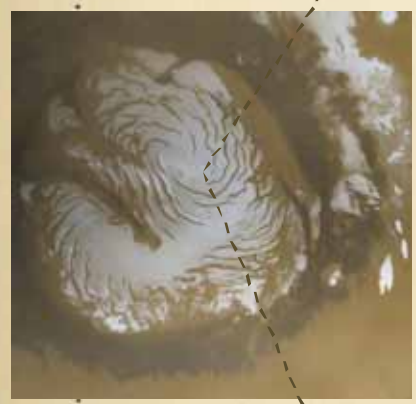

Head et al.
Hartmann et al.
Crown et al.
Etc…

- *Sorry for the delay…I knew I would exceed my allocated time*

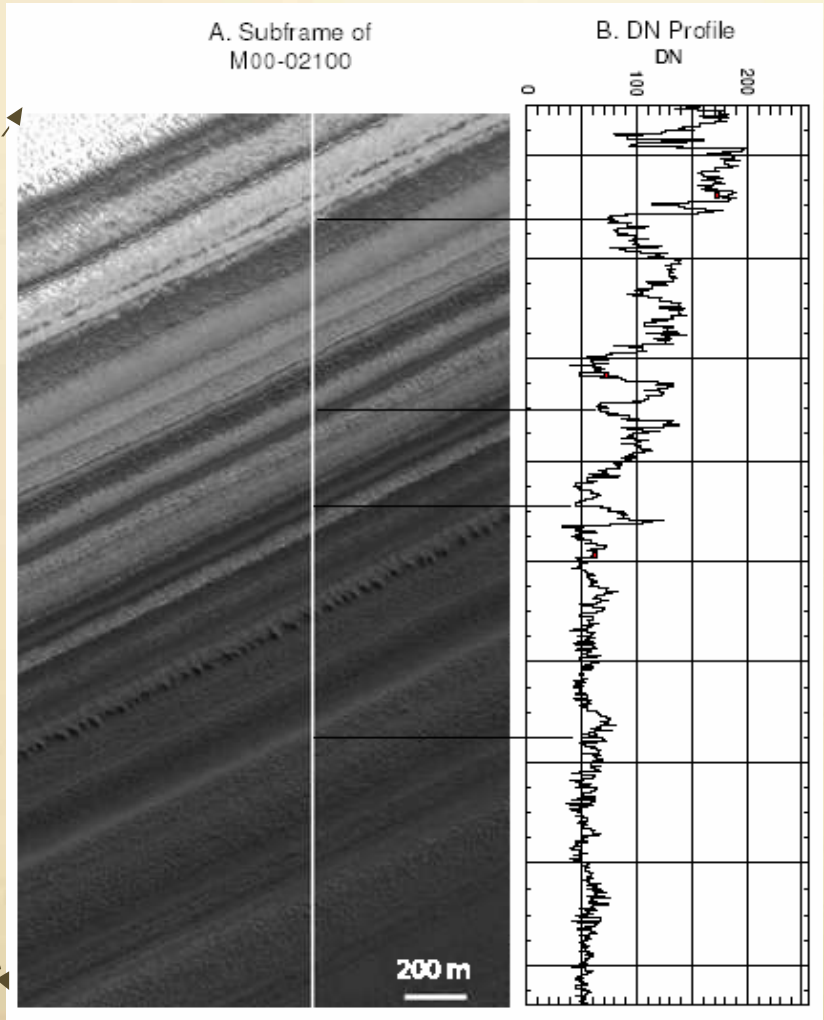
While the accumulation rate is sensitive to dust scenarios, **the NtoS nature of water transfer is a robust feature of the "reversed perihelion" regime.**



# Polar layered deposits



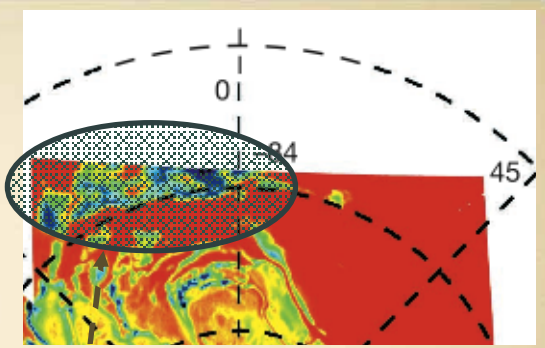
Milkovich and Head
(JGR, 2005)



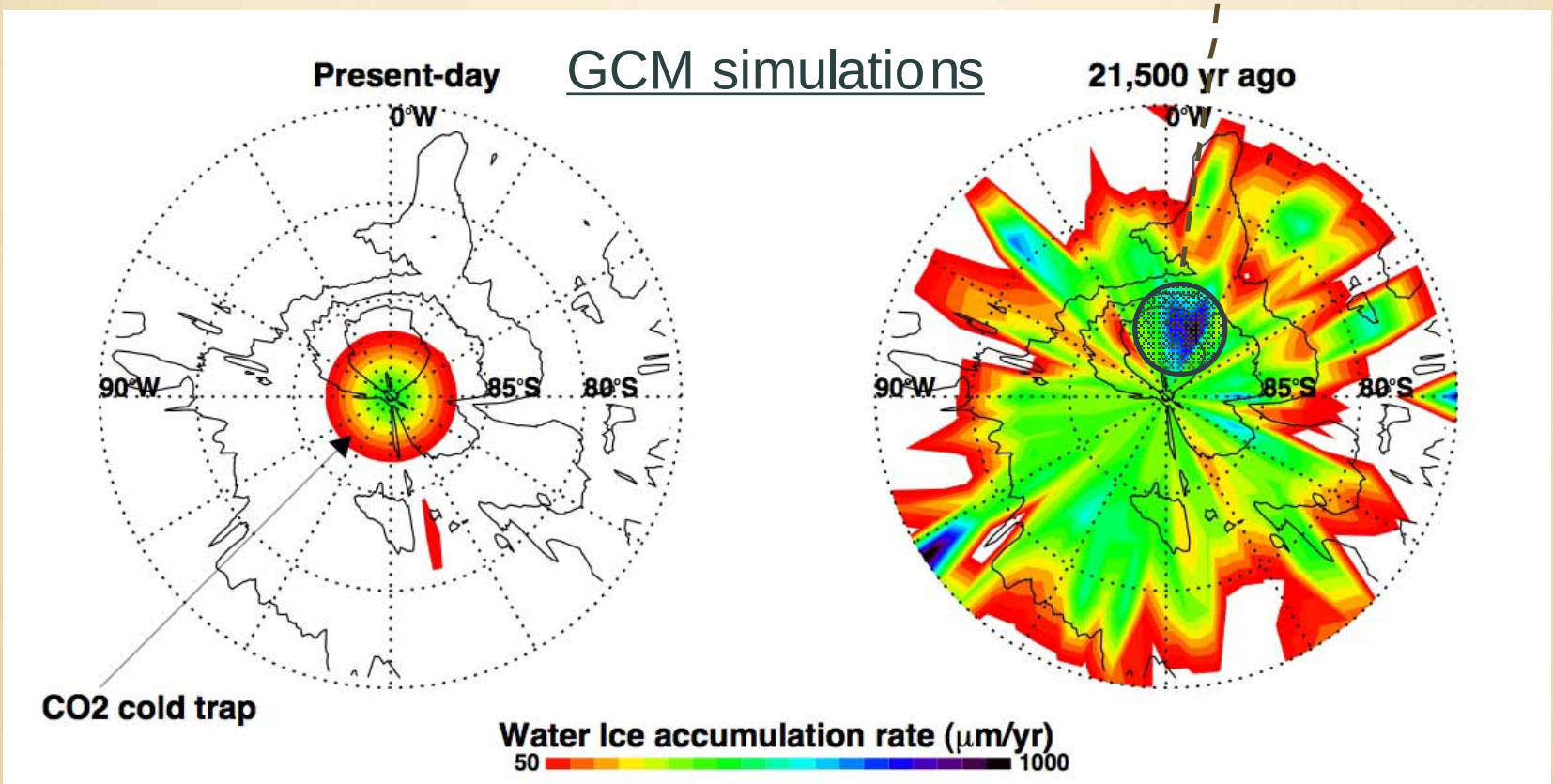

- Polar cap thickness
  - Accumulation of dark and light layers
- Photometric signal suggests =
  - A dominant frequency in the accumulation sequence (50 kyr)
  - Cycle related to precession period

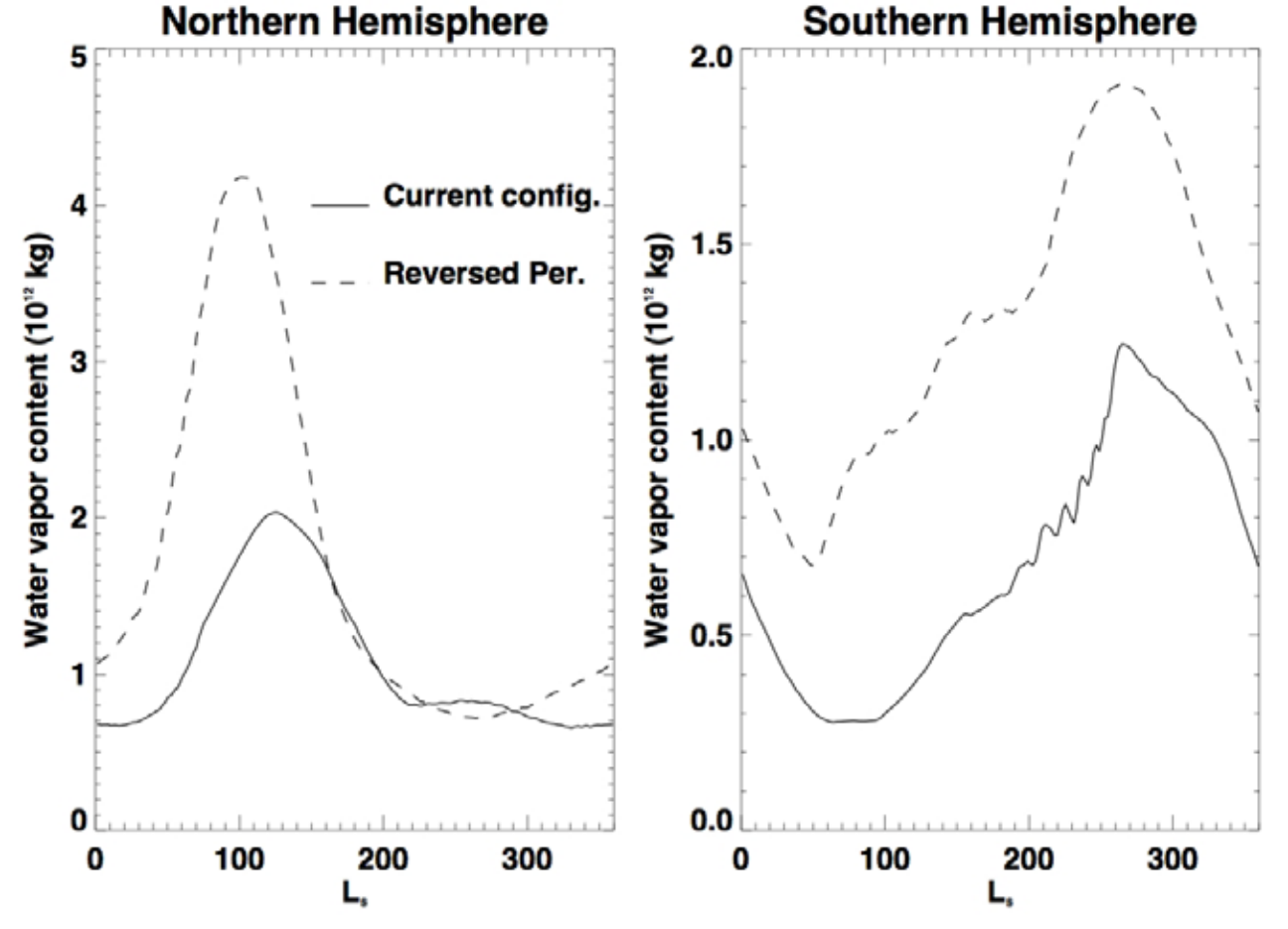
Locally, accumulation rates > 1 mm.yr$^{-1}$.

**Meters of water ice** could have been deposited at the south pole during the last “reversed perihelion” regime.




GCM simulations

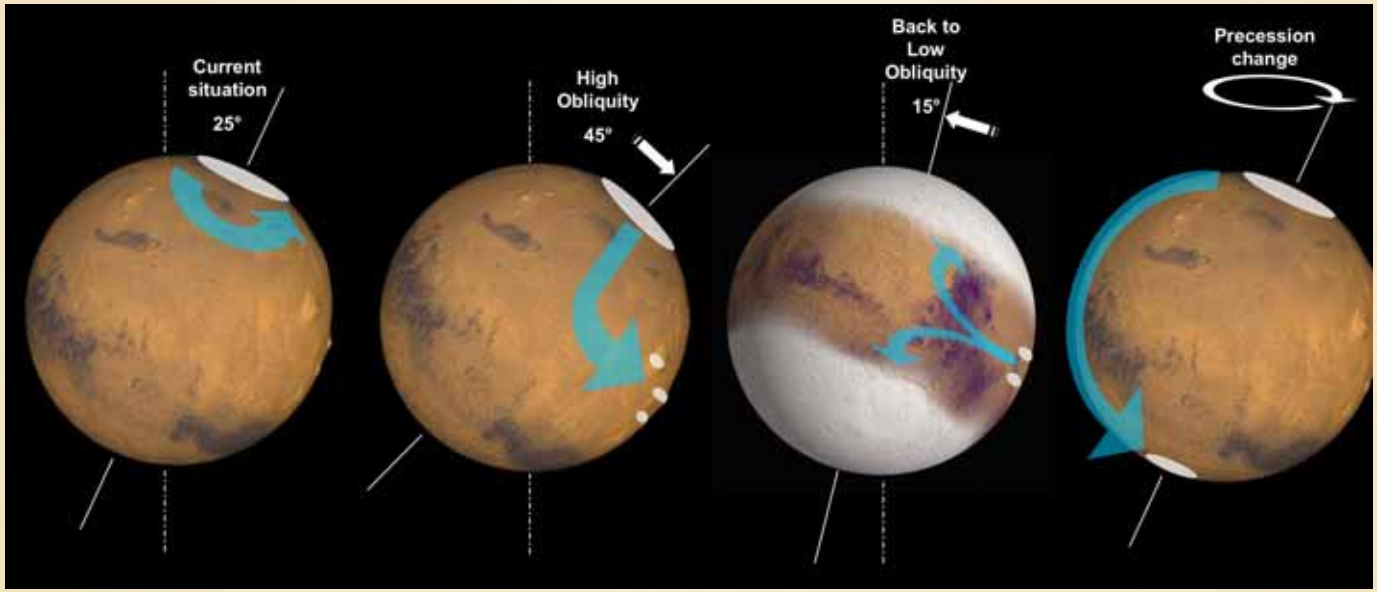





***Under a "reversed perihelion" climate, summer pole $T_{north}$ ⇗ > $T_{south}$***

- Sublimation flux is >2 times stronger
- Water cycle is globally 2 times wetter

# Conclusion




**Precession cycle generates pole-to-pole exchange of water**, the direction of which depends on the perihelion argument.

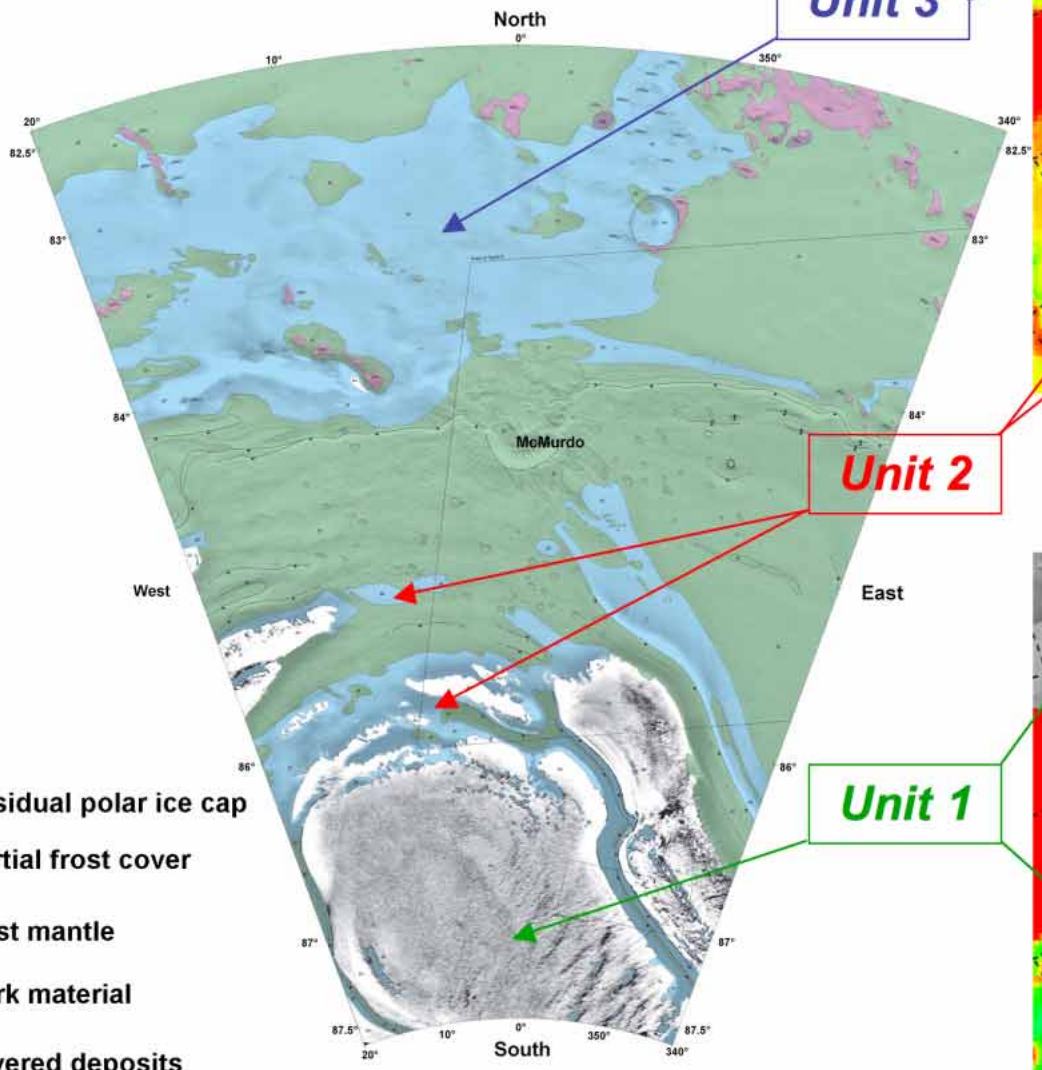
This mechanism has created the recently discovered **perennial water ice units of the south pole.**

A few thousands ago, the **$CO_2$ ice residual layer formed and protected these units from complete removal.**

However, due to complex interactions between dust and water cycles, this transfer of water **should favor the North Pole on the long term**.

Ref.: Montmessin et al. (2007), JGR Planets, *in press*

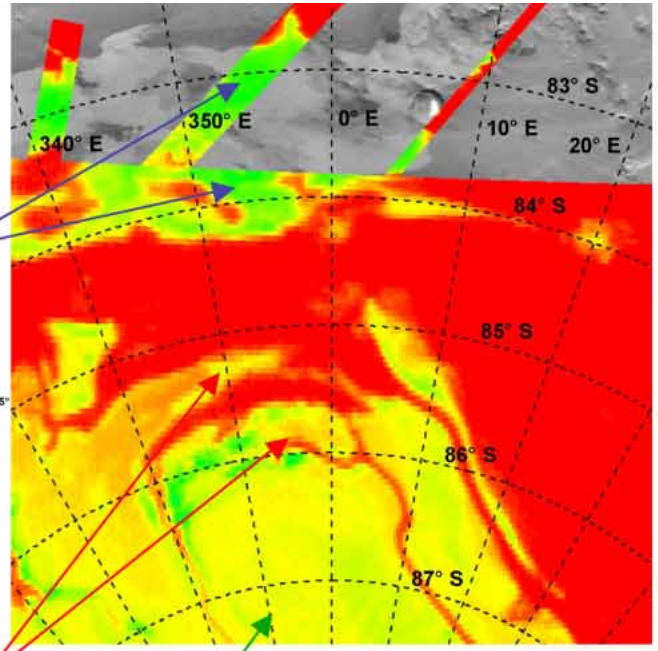
# USGS I-2886




Unit 3

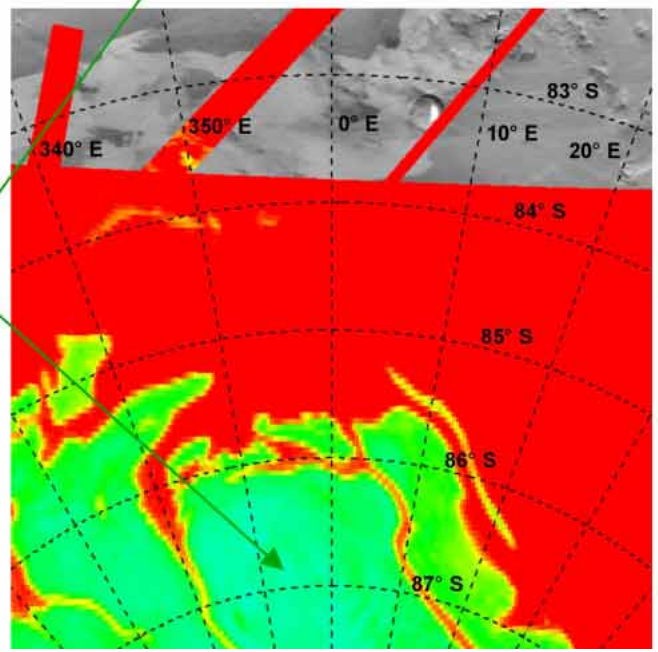
Unit 2

Unit 1




$H_2O$ ice

OMEGA observations




$CO_2$ ice

# Discovery of a thick water ice unit near the south pole of Mars: TES/THEMIS detection

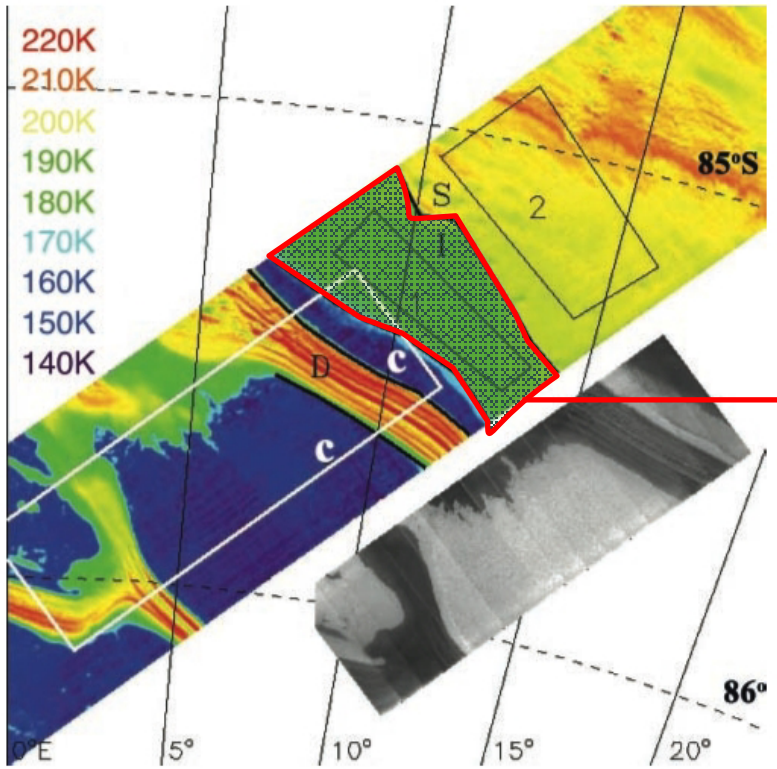
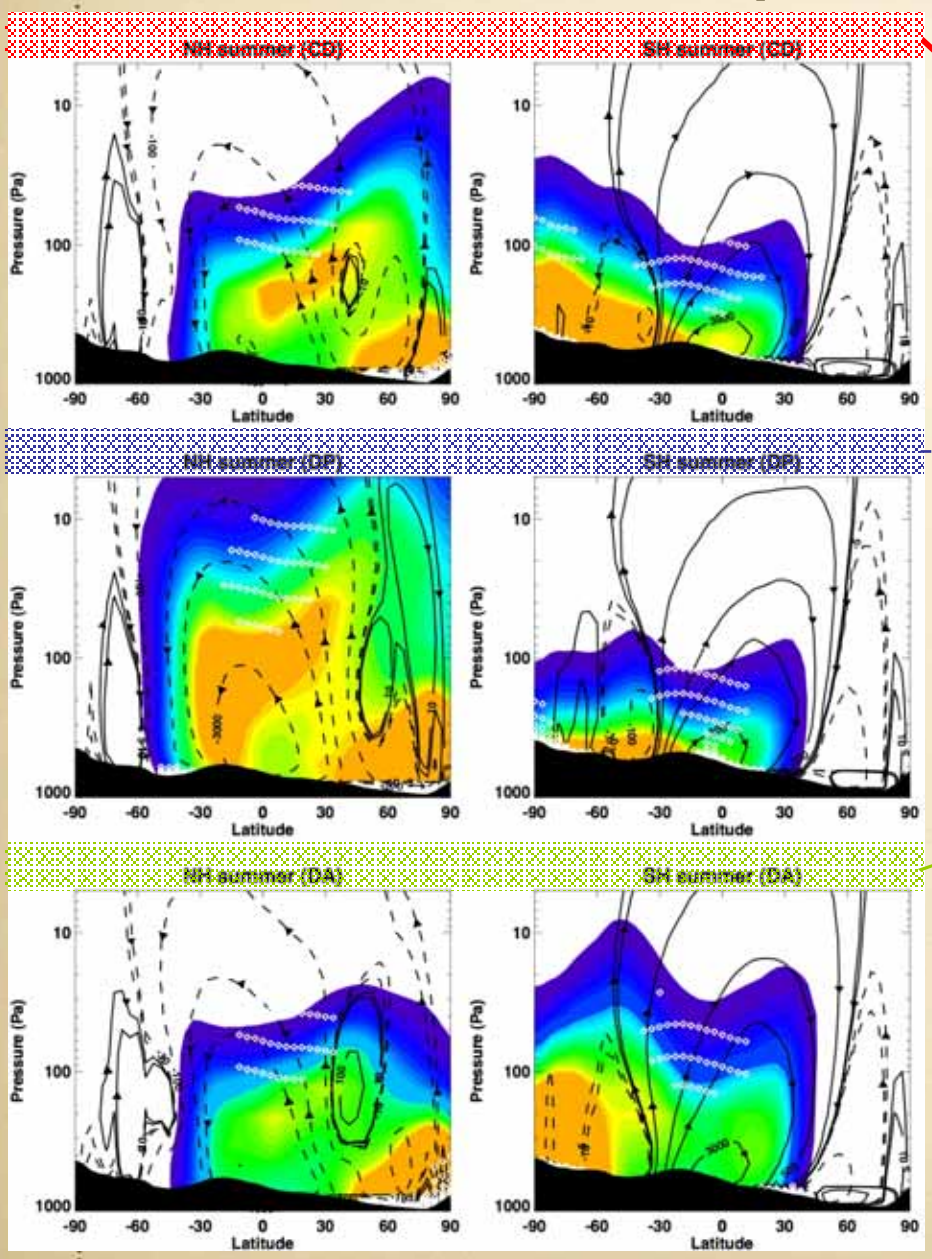


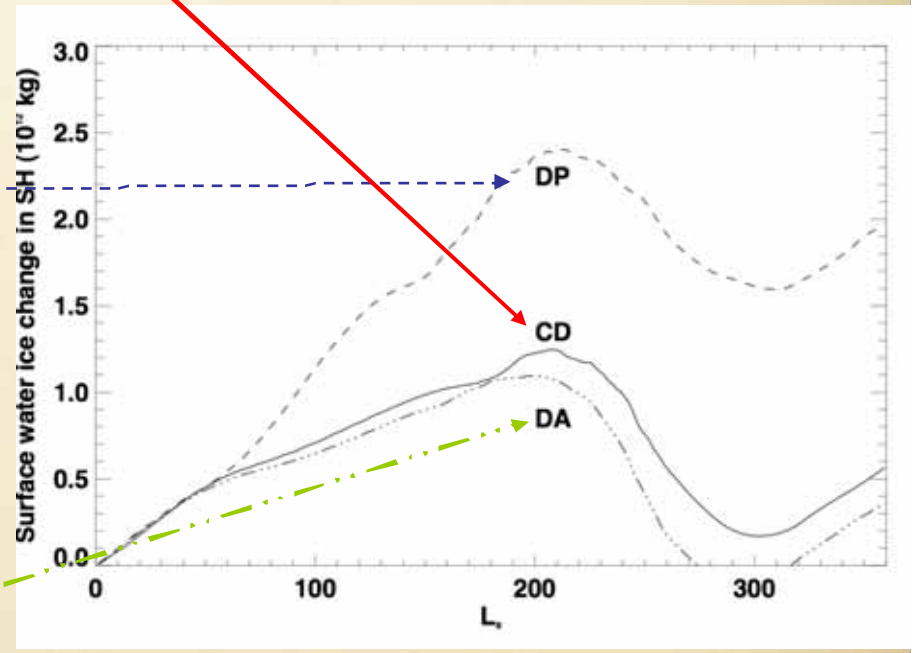

**Fig. 1.** Simultaneous THEMIS infrared (IR) and VIS images near the south polar cap at $L_S$ = 334°; illumination is from the top. The false-color image is THEMIS IR image I00910002 (band 9, 12.6 μm). The darkest areas in the image are near 145 K, and the brightest, near 220 K; the strip is 32 km wide. The gray insert is THEMIS VIS image V00910003 (band 3, 654 nm). The thermal image is overlaid with a sketch of the individual thermal units: C, solid $CO_2$ on the surface; D, a dry, gently sloping unit that is dark and hot (the classic "dark lanes" through the perennial cap); I, the flat-lying unit of intermediate albedo and temperature (water ice); S, a warmer and darker flat-lying unit (soil). The numbered black rectangles are regions of interest (ROIs) used to accumulate seasonal data. The white rectangle outlines the position of the VIS image, shown to the right as the grayscale image.

***High thermal inertia area = water ice !!***

***Titus et al., 2003***

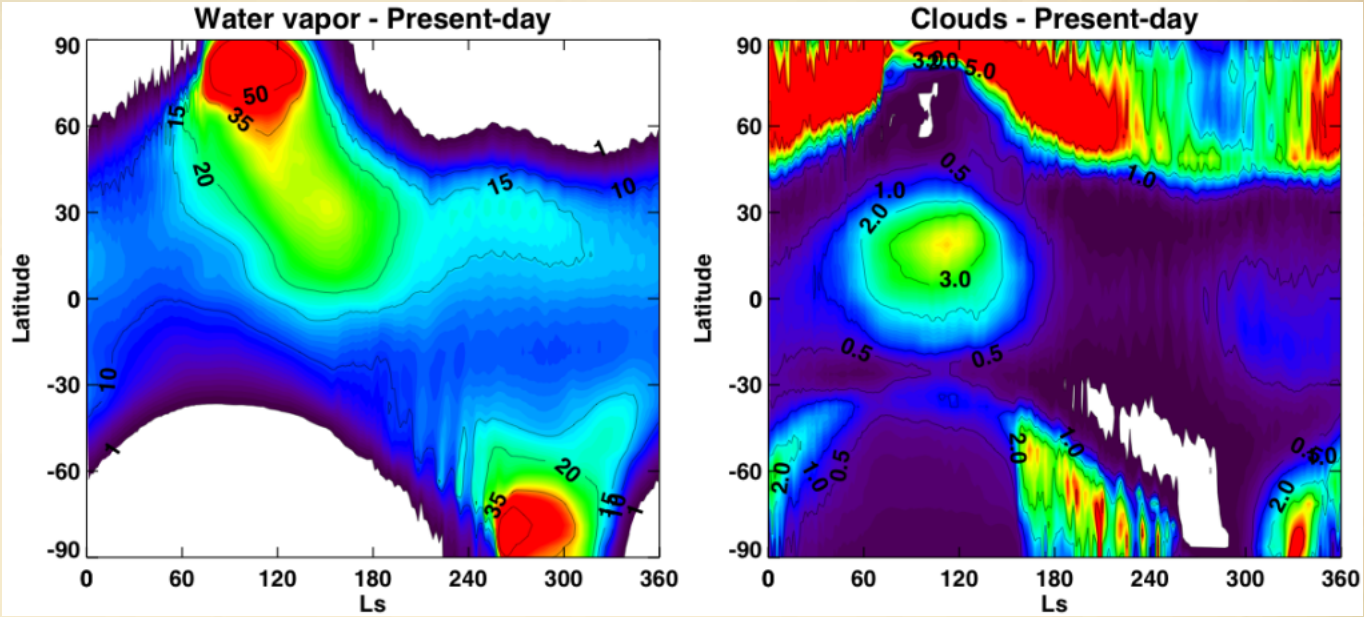
# The equatorial “valve”



Lp = 251°

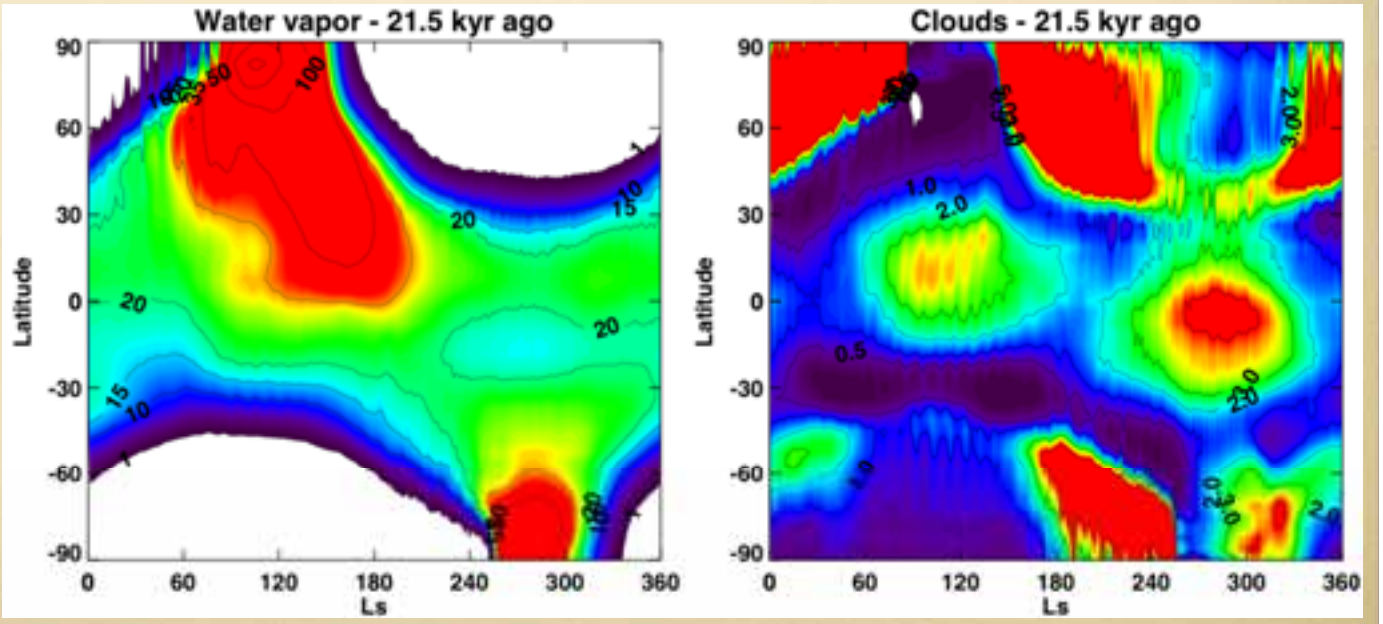
today




***in pr. $\mu$m***

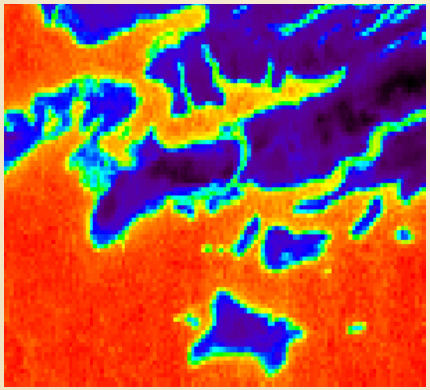
Lp = 71°

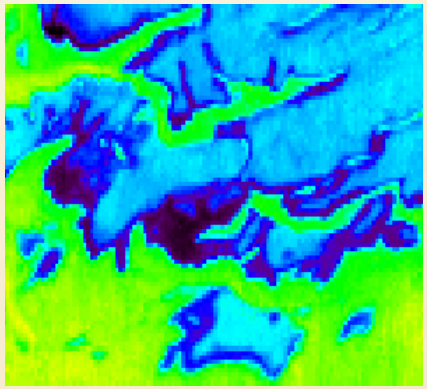
"reversed perihelion"



# New facts

$CO_2$ OMEGA $H_2O$ HRSC



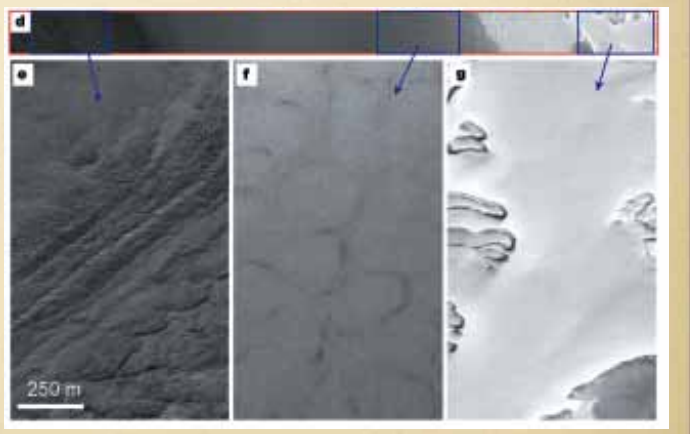


Polygonal features within the water ice contour expand below the $CO_2$ ice layer (*Bibring et al.*, 2004), this implies that :

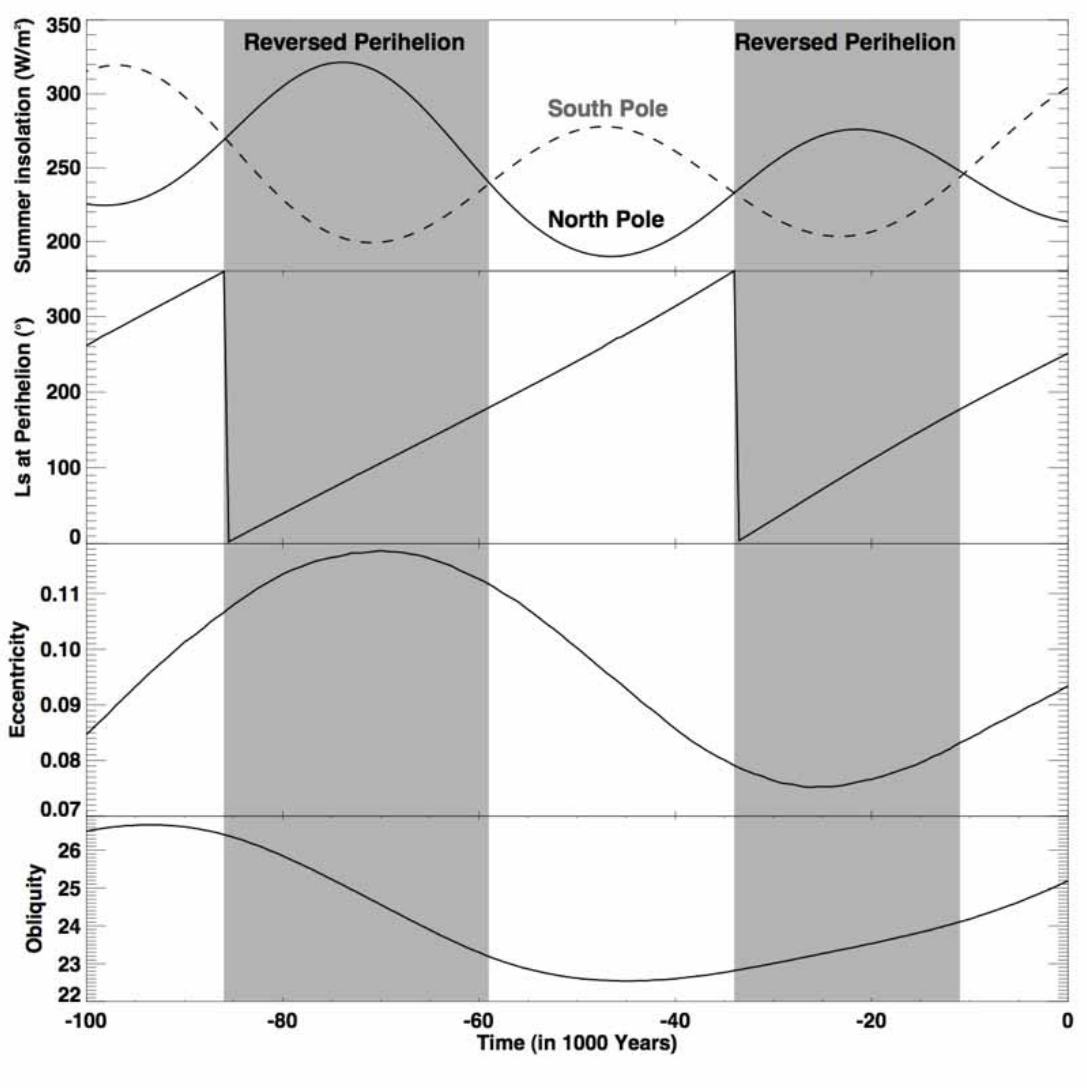
- A water ice layer sits below the thin (meters-thick) $CO_2$ ice veneer
- These water ice units predate the formation of residual $CO_2$

……But, water ice is unstable wrt current climate

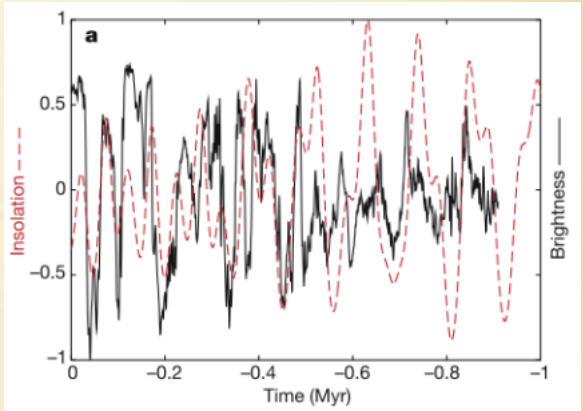
**Remnants of past climate conditions**



# Mars orbit recent variations




*Obtained using Laskar et al. (2004) secular solution*




*Correlation between computed insolation variations at the north pole and brightness variations observed in a cross-section of the north layered deposits (Laskar et al., 2002)*

***Dominant period = 51 kyr = precession***

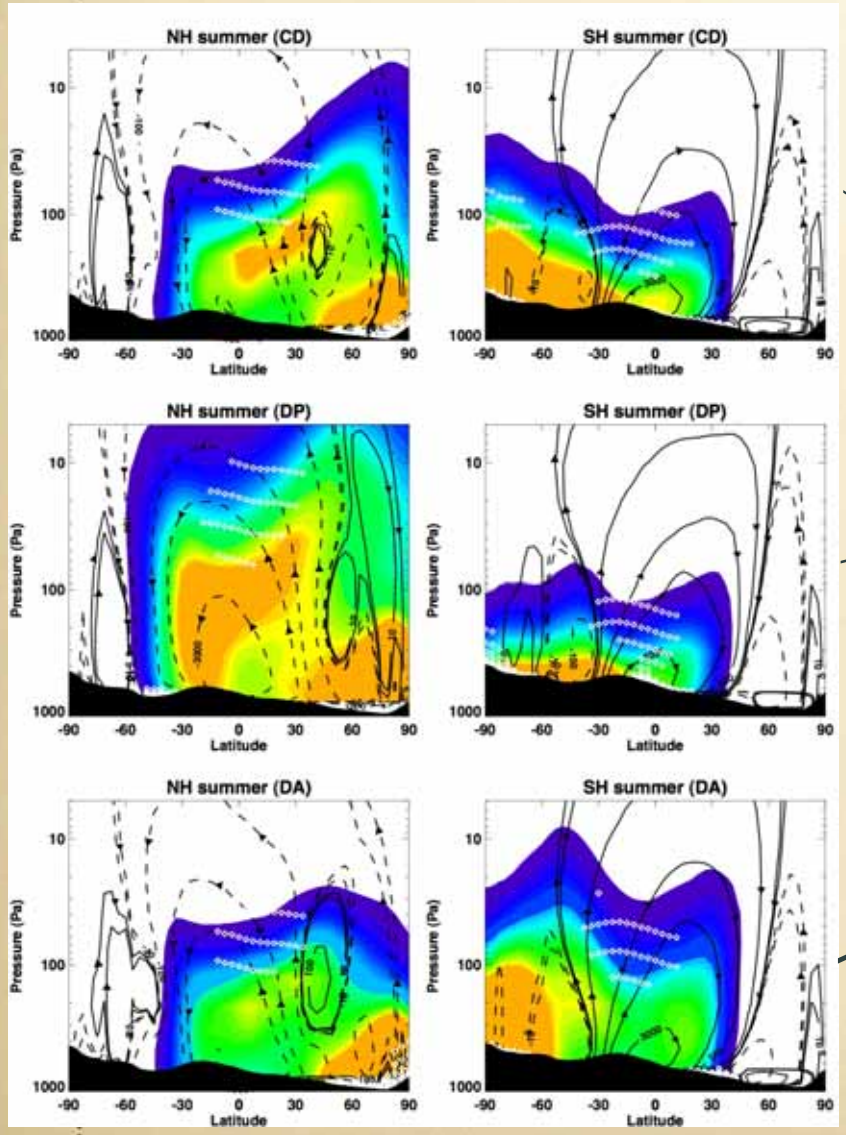
# The “Clancy effect”

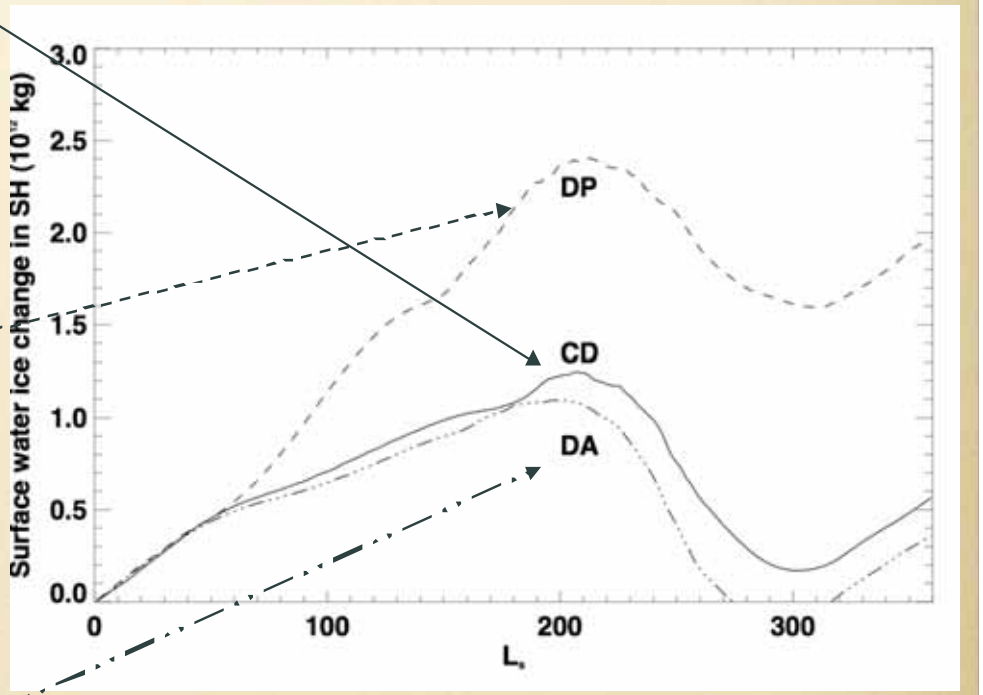
(*Clancy et al*., Icarus 1996)

key to understanding the large north–south hemispheric asymmetries of Mars water vapor and the residual polar ice caps. The orbital dependence of the altitude of water vapor saturation can couple with the solstice Hadley circulations of the Mars atmosphere to create a non-linear atmospheric water pump toward the aphelion summer hemisphere. It is even possible that this process accounts for the origin of the polar layered deposits, as the hemispheric direction of this

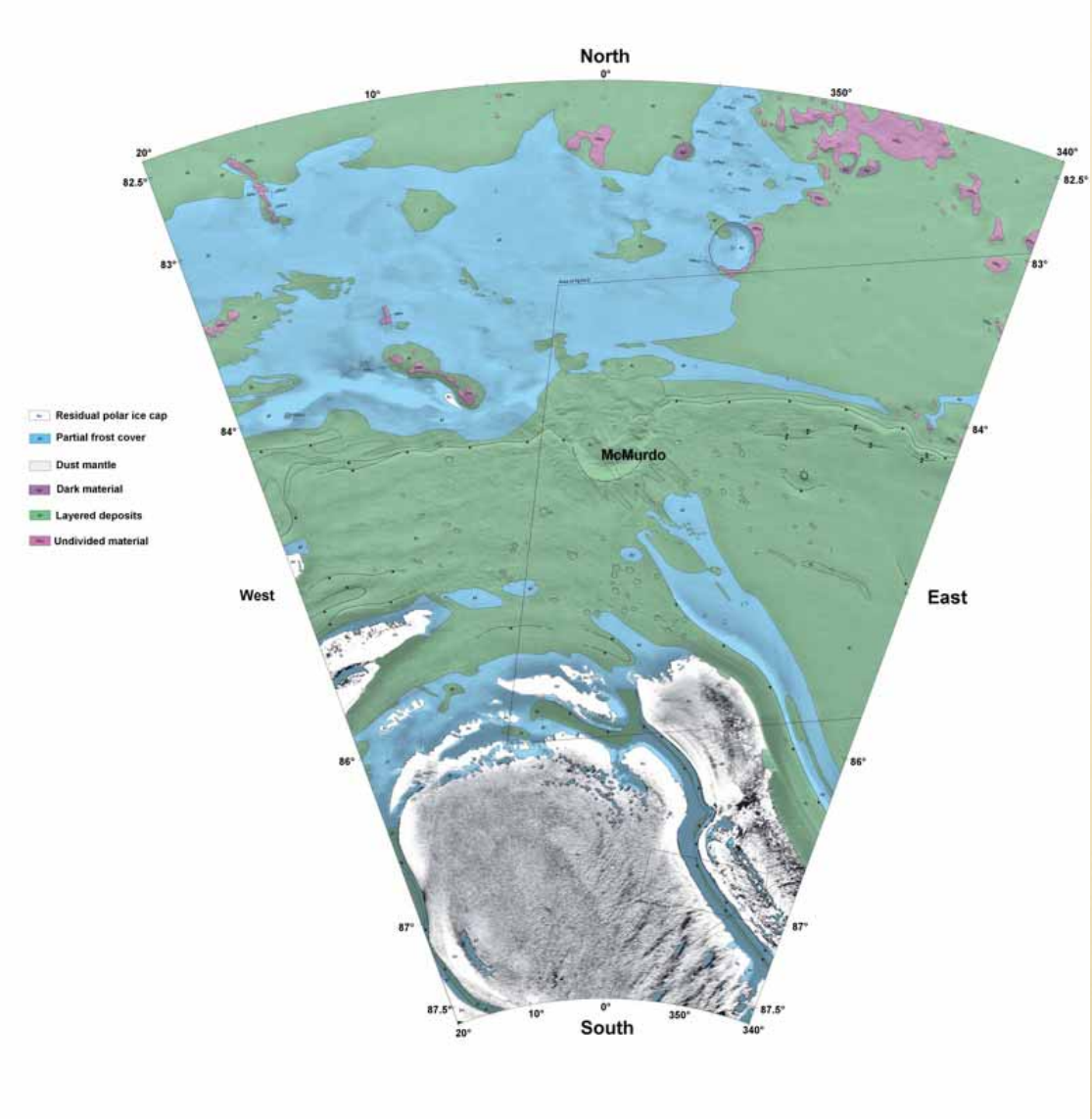
- Meridional transport of water is forced assymetric about the equator not only because of topography but also because of orbit eccentricity.
- The Clancy effect relates to the ability of the aphelion summer hemisphere to gain and retain water due to coupling between general circulation and cloud-induced (sedimentation) vertical redistribution of water.
- Today, the north is the aphelion synchronized summer hemisphere, half a precession cycle ago (-21.5 kyr), it was the south…..
- Clancy et al. suggest this mechanism holds a key to the north-south geological differentiation.

# Quantifying the “Clancy effect”



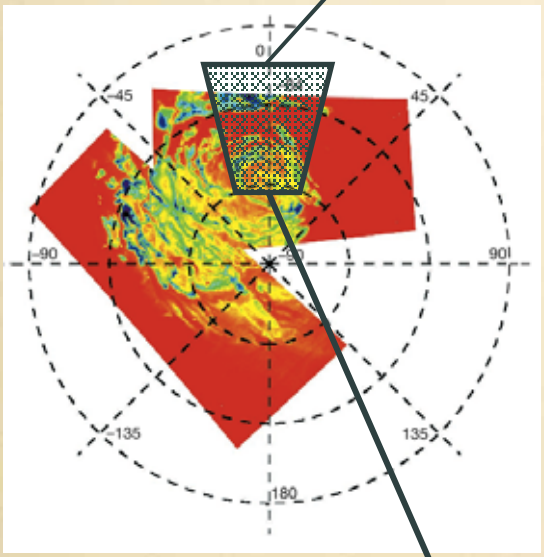



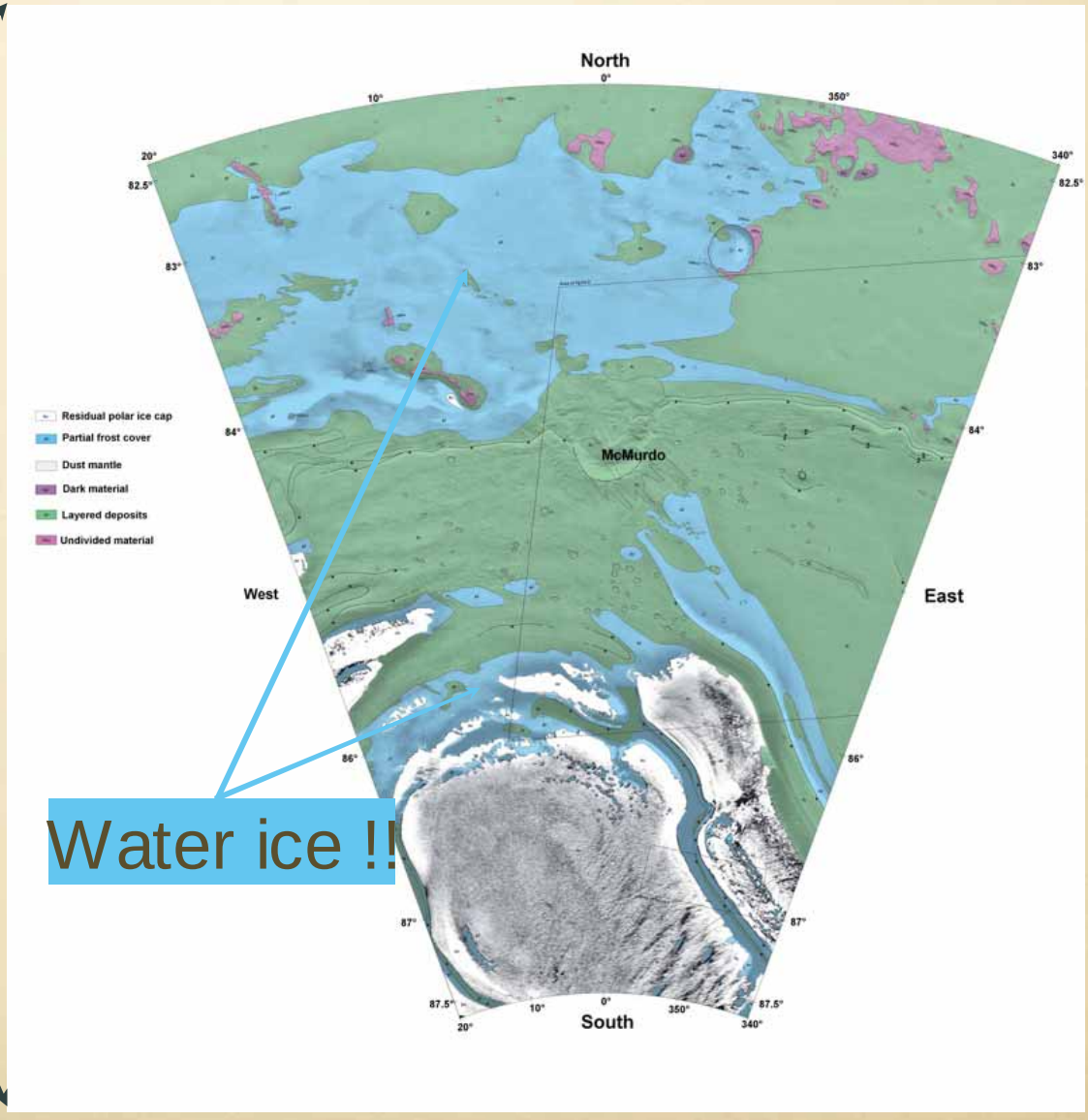
# USGS I-2886 map (by K. Herkenhoff)



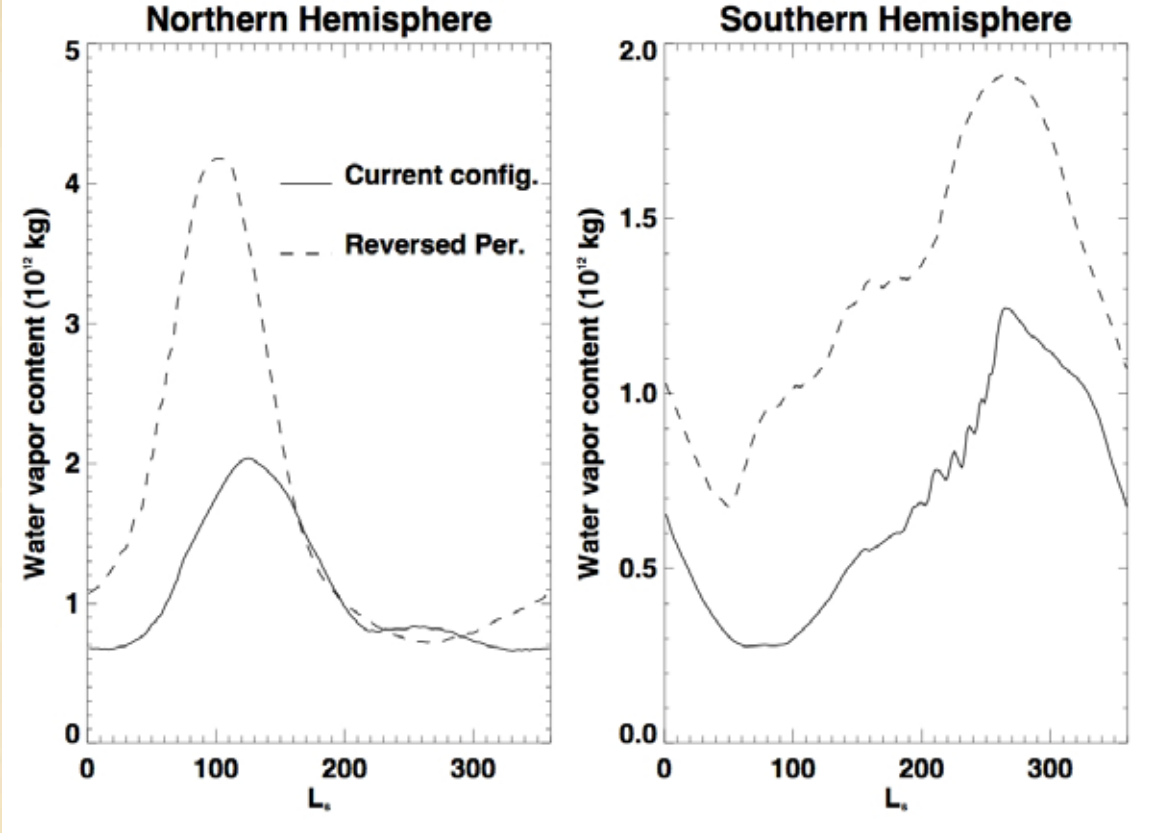
## USGS I-2886 map
(by K. Herkenhoff, Viking era)

## OMEGA map
(Bibring et al., 2004)

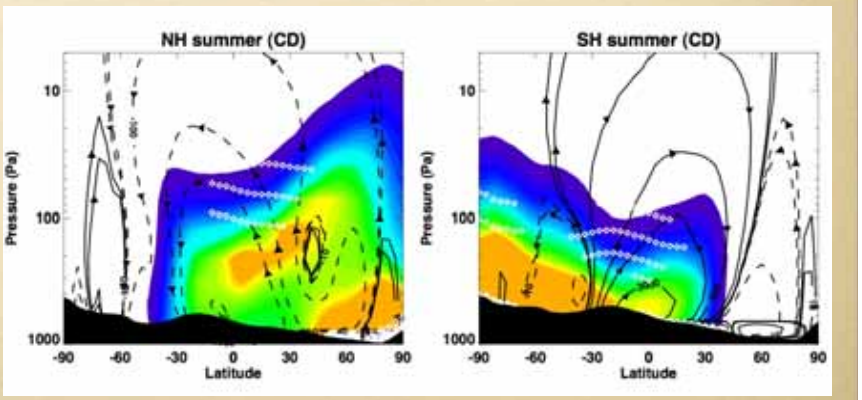


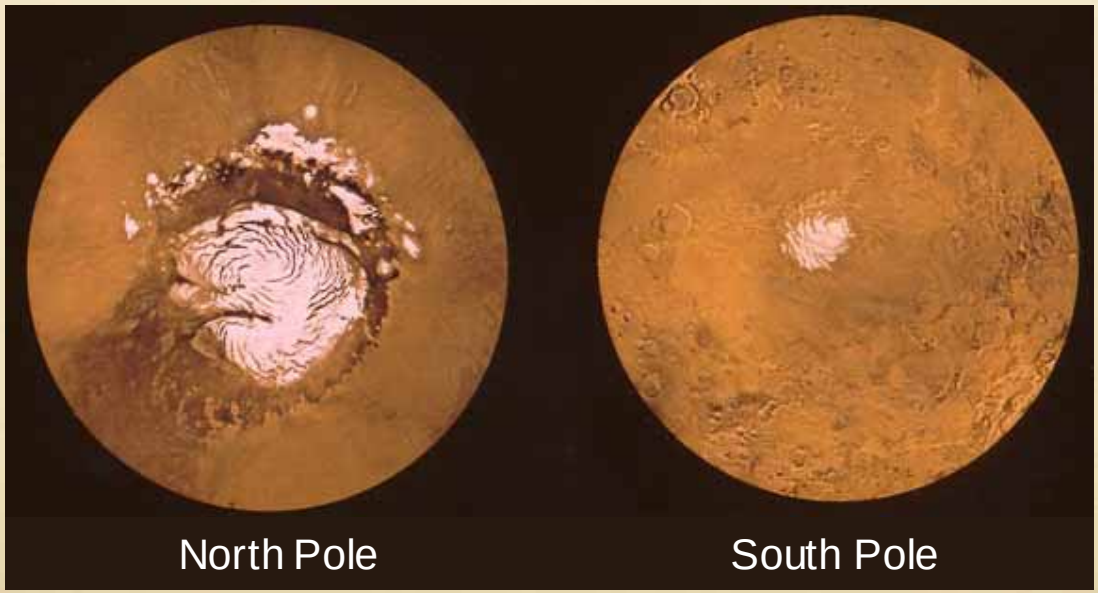

Water ice !!




- Lp shift to northern spring/summer induces increase of insolation = Ts + 20 K
- Sublimation flux is 2 to 3 times stronger
- Water cycle is globally 2 times wetter
- Some water is lost in the south polar region…

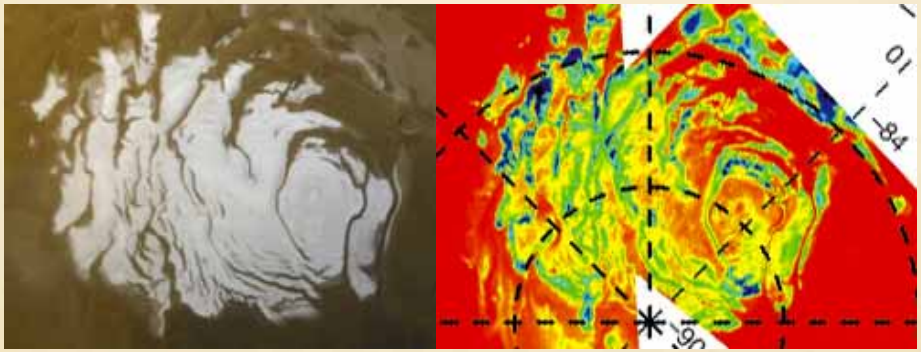


…..all these factors favor accumulation and storage of volatiles (water, dust) in the North



# The origin of perennial water ice at the south pole

- a story about “uncontrolled” migration on Mars...



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