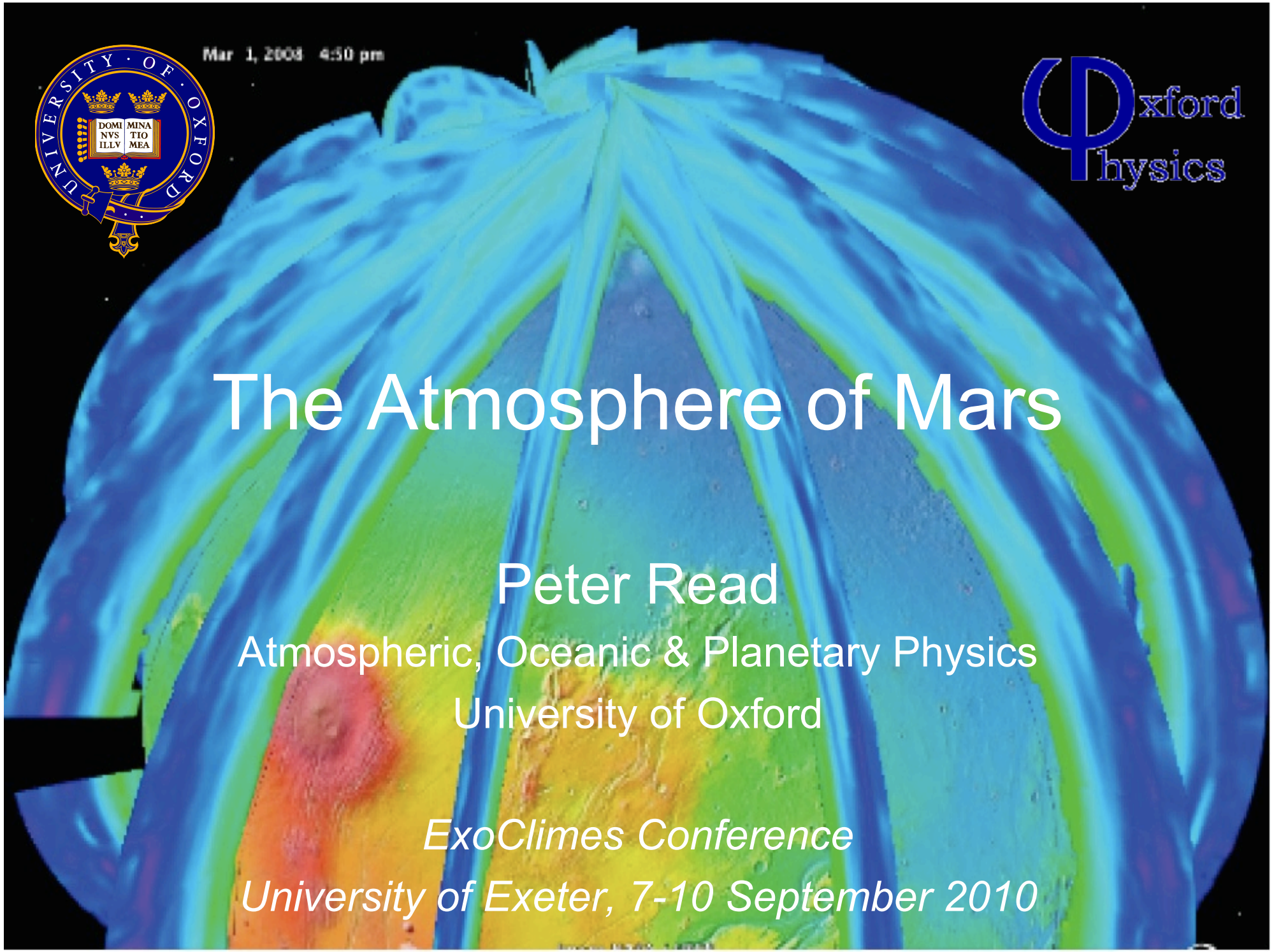


The Atmosphere of Mars

Peter Read

Atmospheric, Oceanic & Planetary Physics

University of Oxford

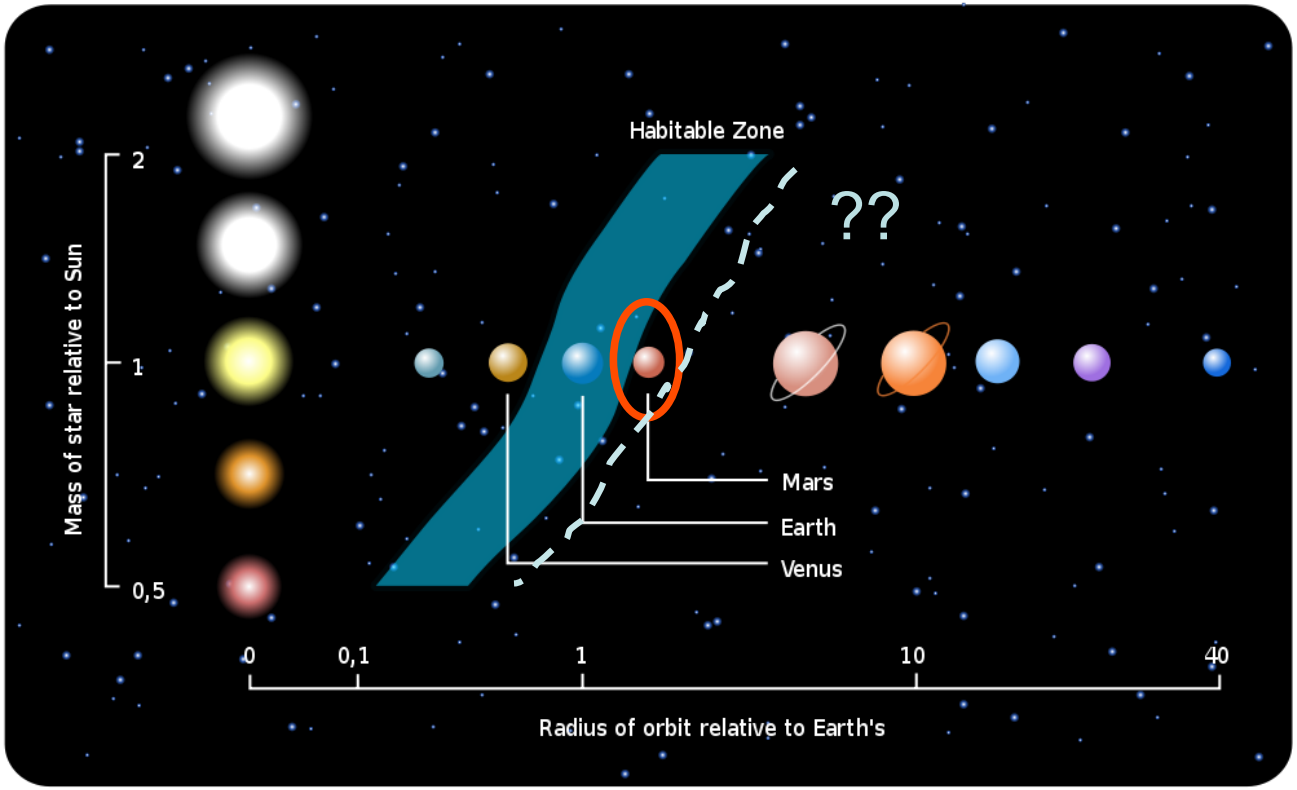
ExoClimes Conference

University of Exeter, 7-10 September 2010

Themes

- Mars as an Earth-like planet
  - Present day atmospheric circulation
  - Meteorology and climate
- Mars in the ‘habitable zone’….?
  - Water and the hydrological cycle
- Mars’ dynamically changing climate
  - Astronomically-controlled cyclic changes
  - Wet and warm(er) in the past….?
- Mars atmosphere in context
  - Circulation regimes and climatological parameter space

Mars in the ‘habitable zone’?



- Locations supporting sustained presence of liquid water [Kasting et al. 1993…]
- Inner boundary determined by runaway greenhouse
- Outer boundary…..?

Themes

- Mars as an Earth-like planet
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  - Astronomically-controlled cyclic changes
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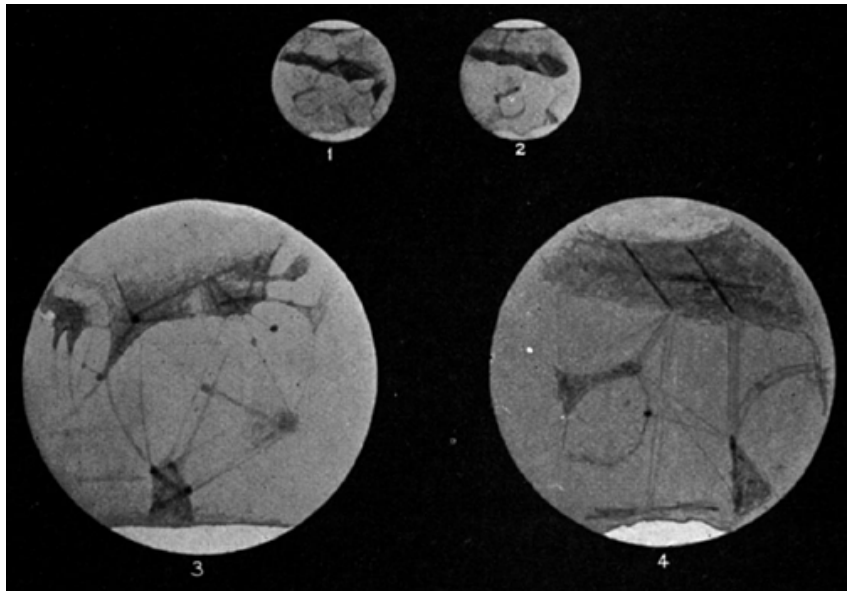
Earth & Mars: facts & figures

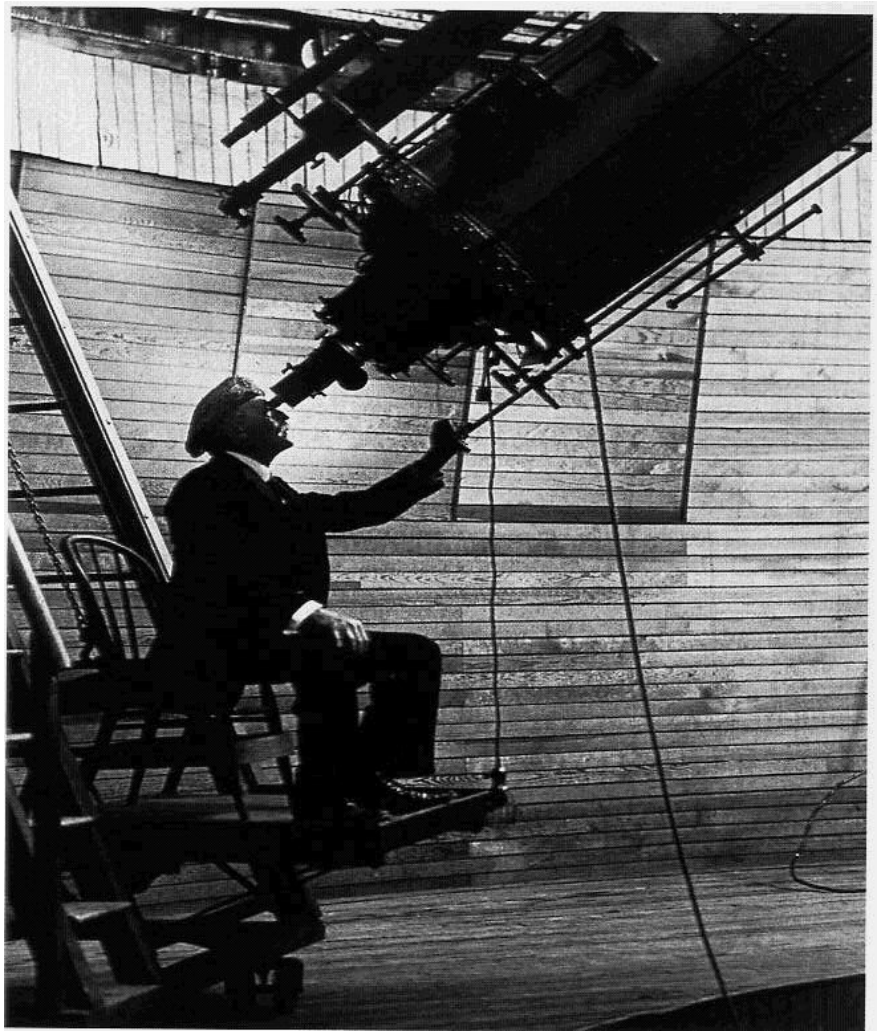
	Mars	Earth
• Equatorial radius (km)	3390	6380
• Rotation period (hrs)	24.62	23.93
• Obliquity (degs)	25.2	23.5
• Orbital period (sols)	668.6	365.24
• Distance from Sun (AU)	1.38-1.67	0.98-1.02
• Atmospheric composition	CO_2 (95%) N_2 (2.7%)	N_2 (78%) O_2 (21%)
• Surface pressure (hPa)	6-10	1013
• Surface temperature (K)	140-290	230-320

Ground-based observations

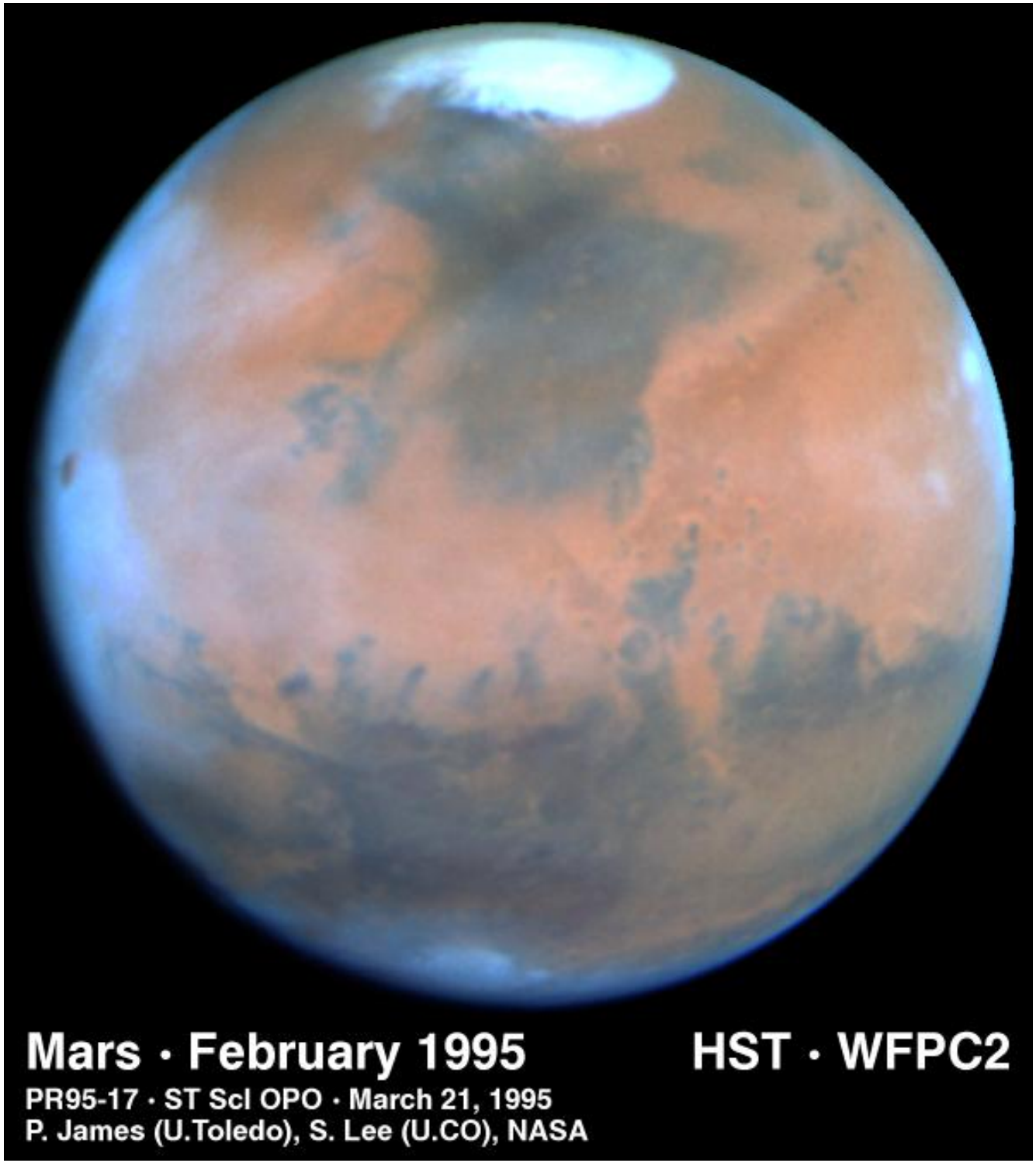
Percival Lowell

Lowell Observatory
(Arizona)



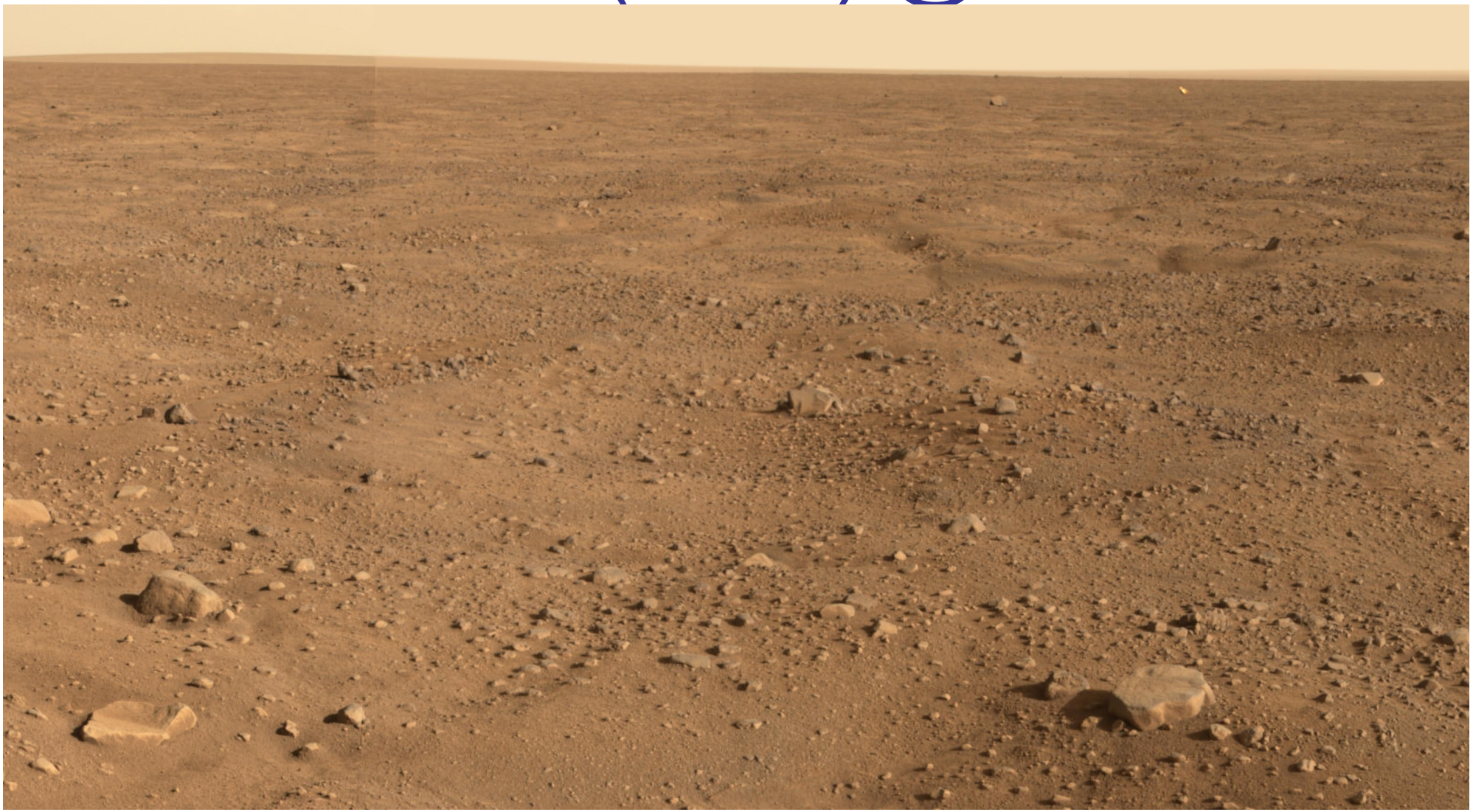


Mars from Hubble Space Telescope



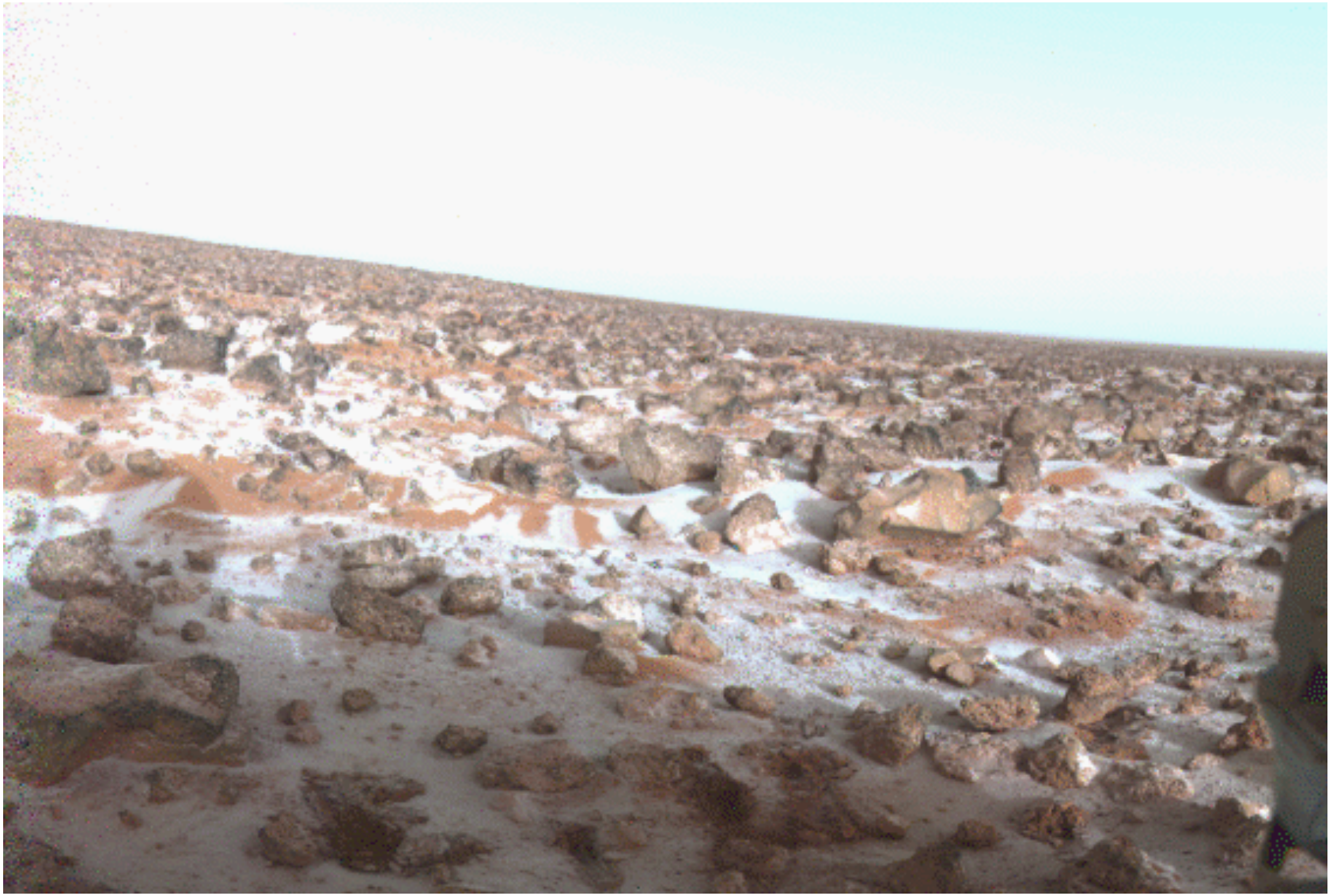
‘Twin peaks’ from Pathfinder Lander (1997) @19ºN

Northward view from Phoenix Lander (2008) @68ºN

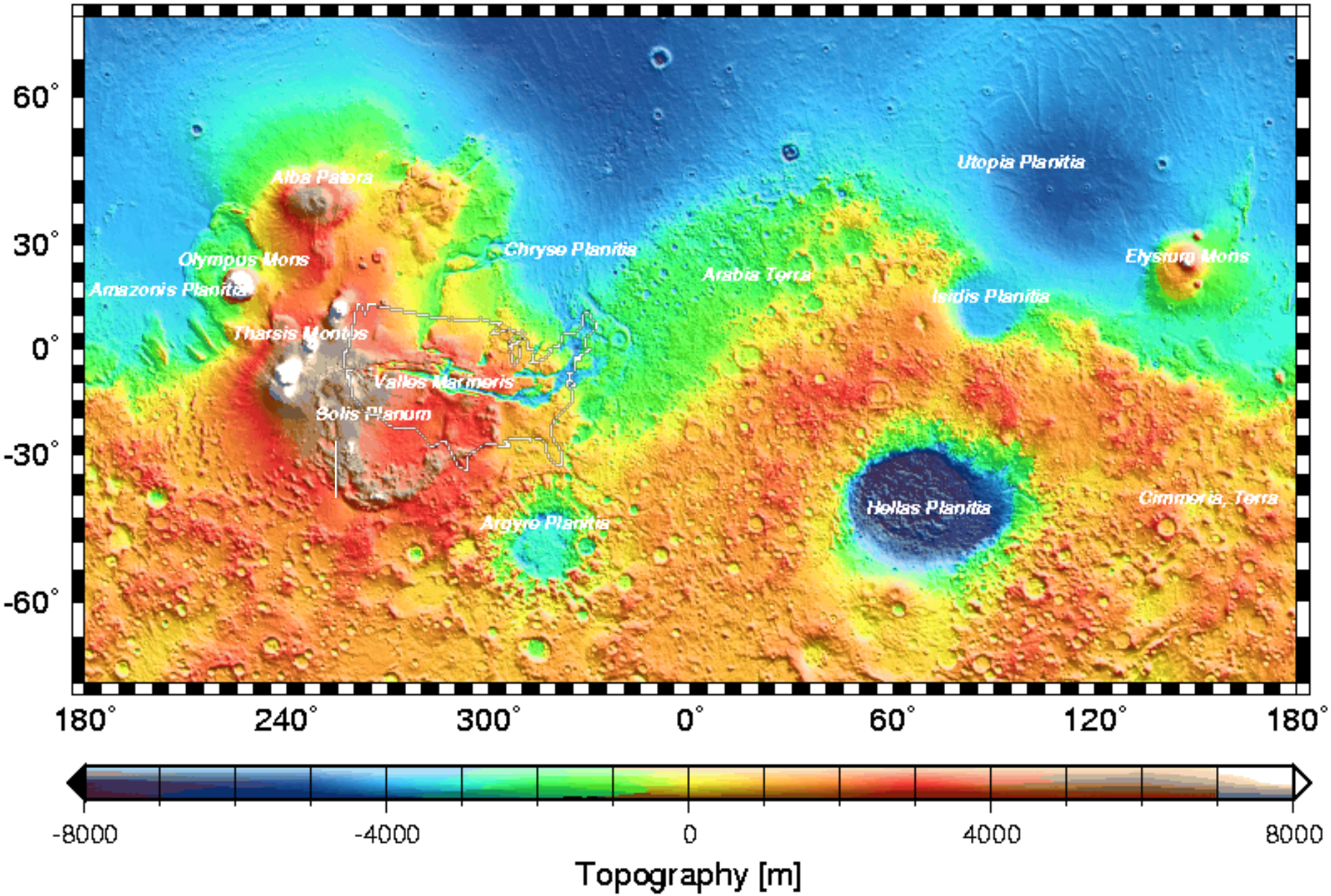


Surface frosts

Viking Lander (1978) @48^{o}N

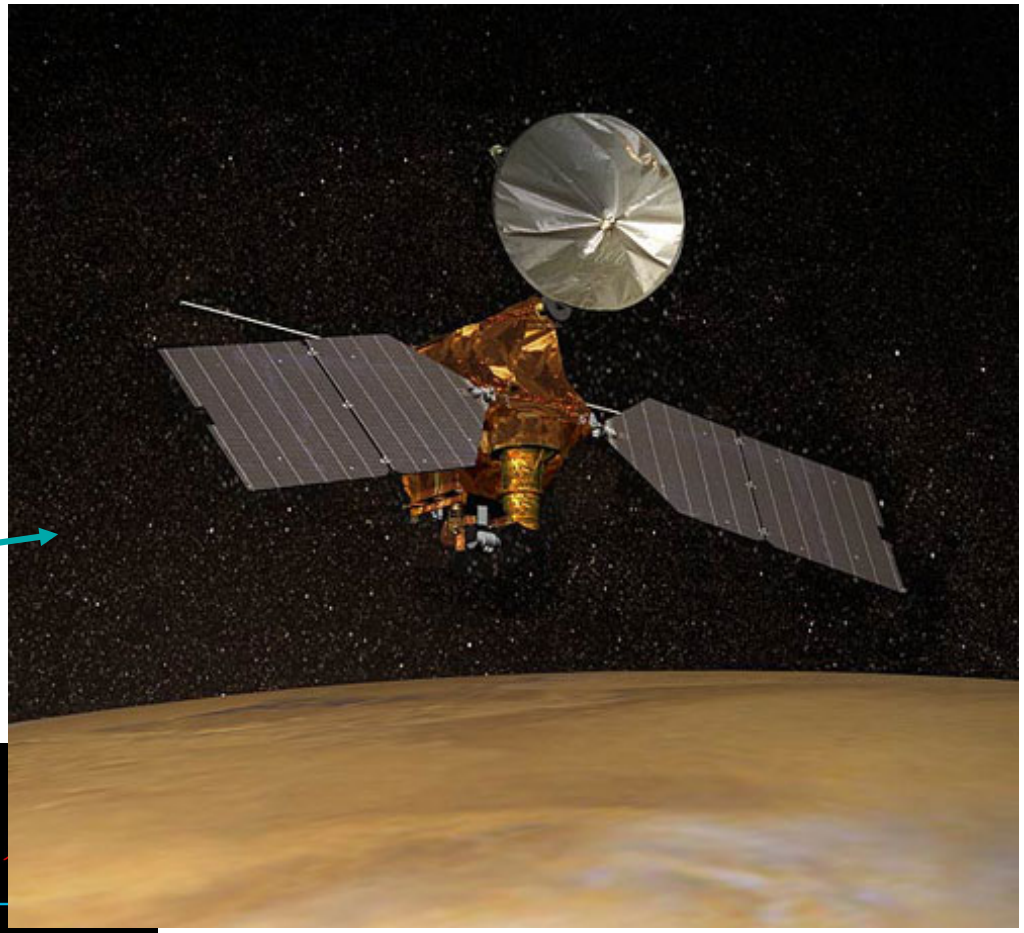


MOLA Topography



Orbiting spacecraft:

Mars Reconnaissance Orbiter (NASA)



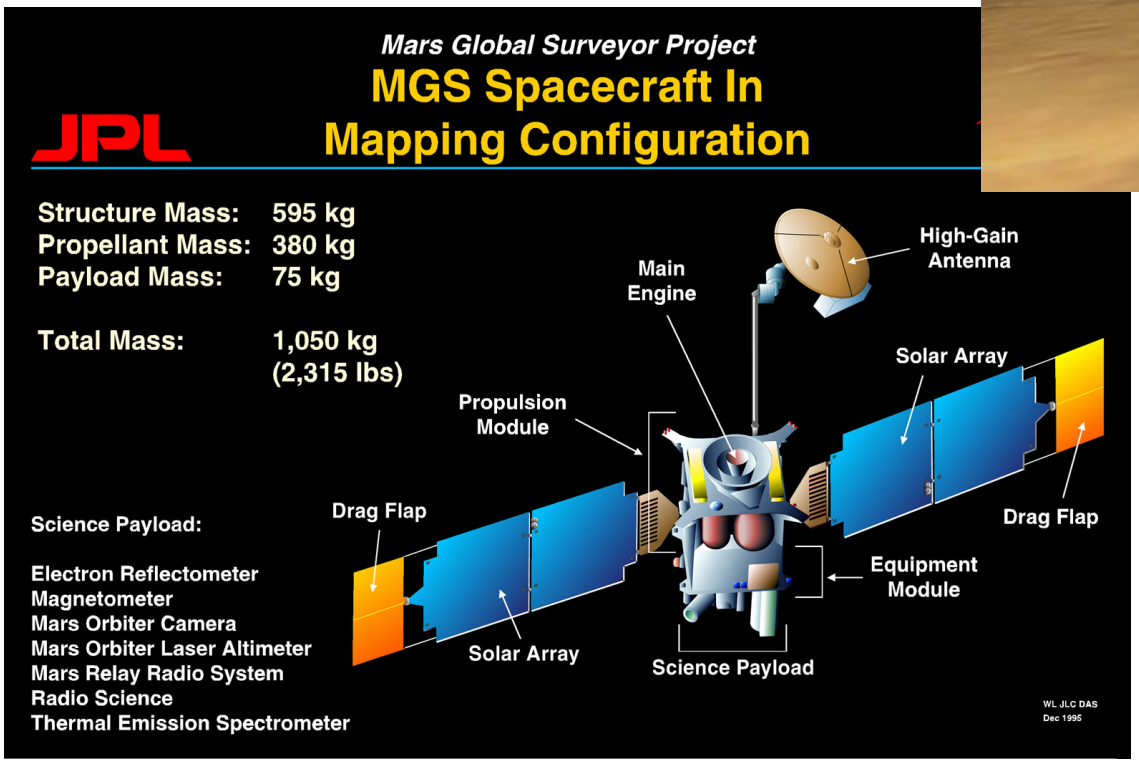


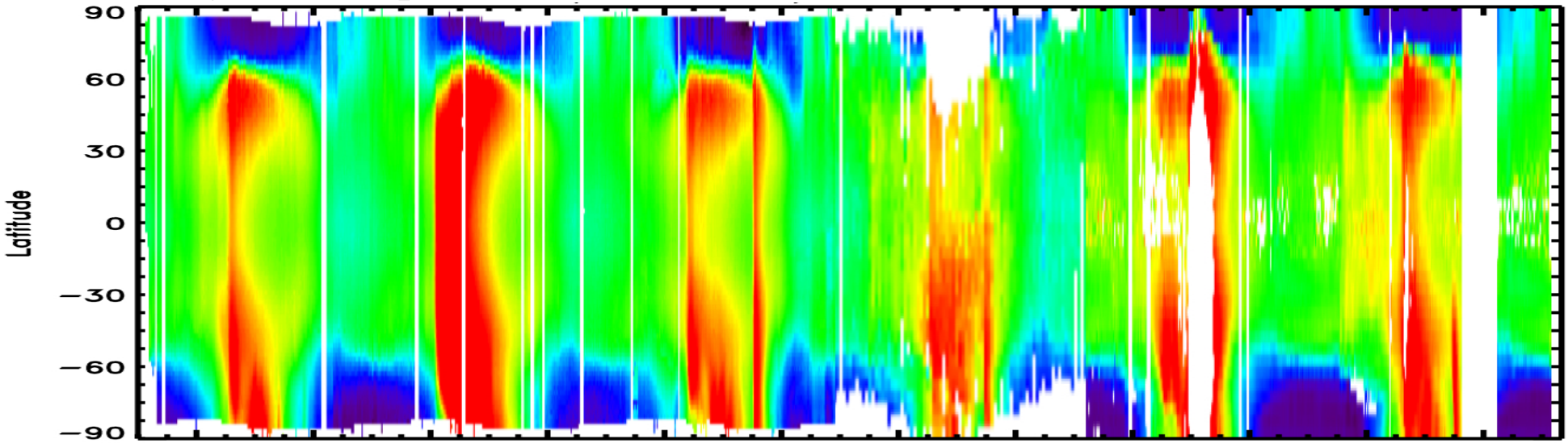
Image credits: NASA/JPL/Caltech

MRO Data Extends Martian Climatology

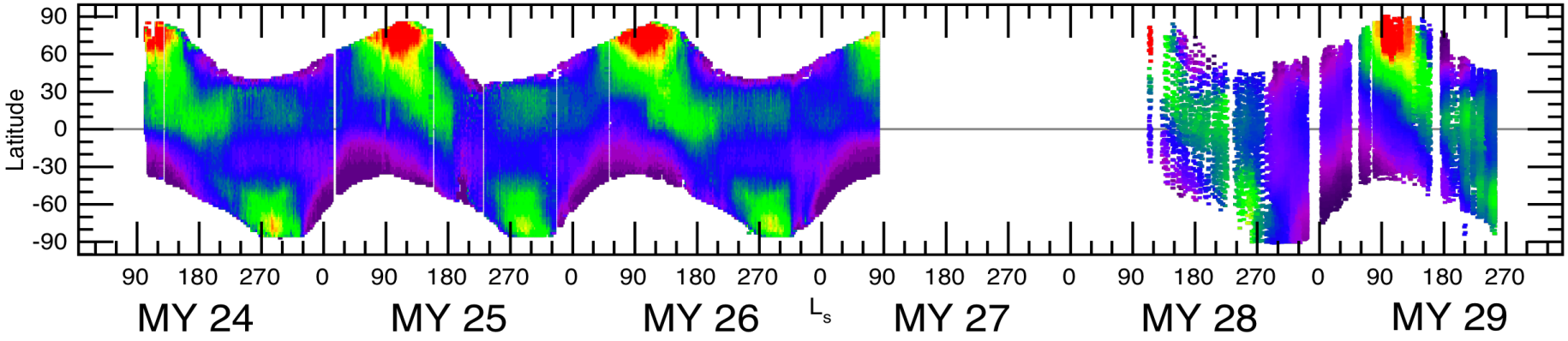
Combined Climatology of 6 Mars Years

MGS/TES | ODY/ THEMIS | MRO MCS & CRISM

Daytime Temperature at 50 Pa

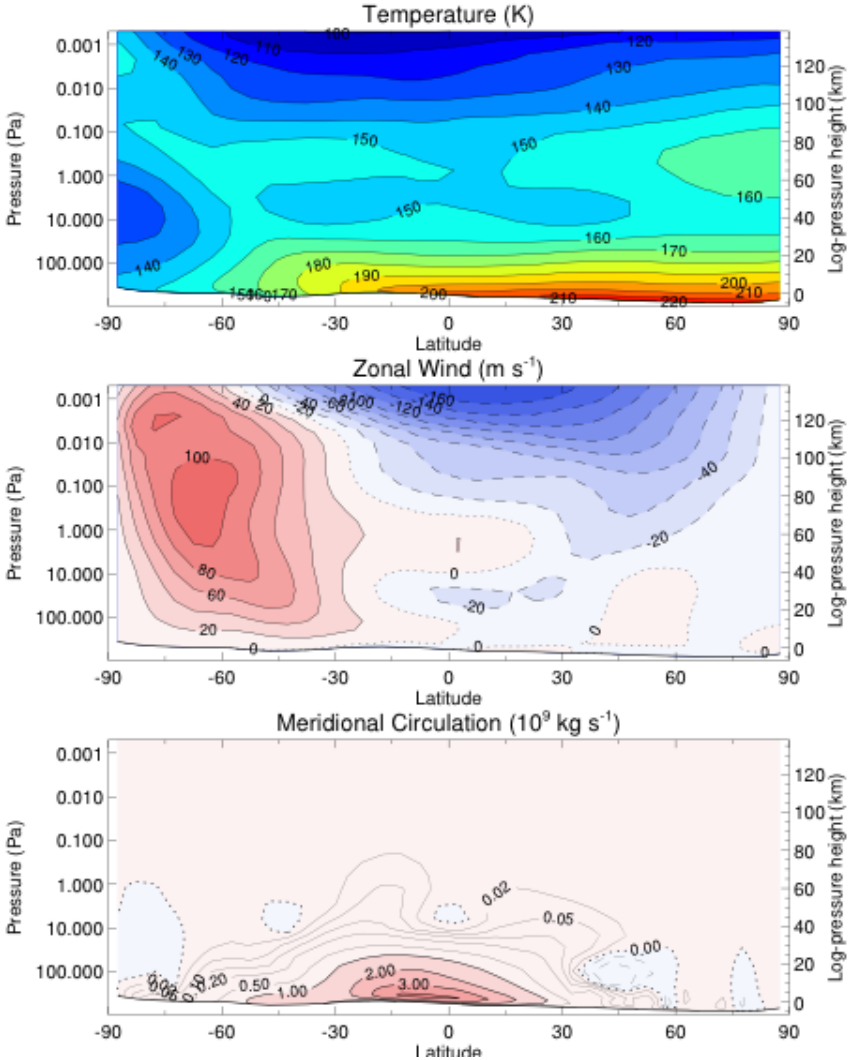


Daytime Column Water Vapor



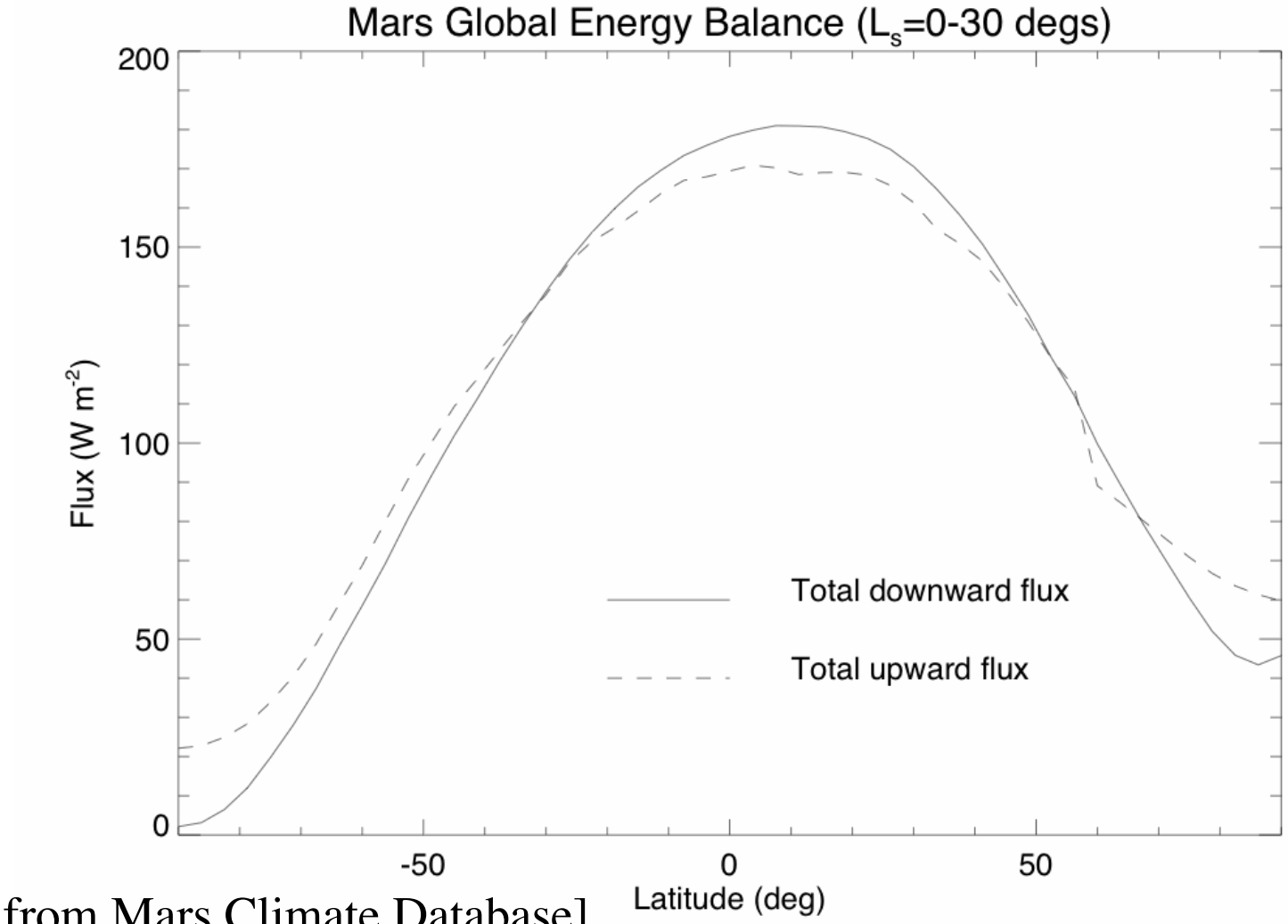
TES: Smith (2006); THEMIS: Smith (2009);
CRISM: Smith *et al*. (2009); MCS: Kass *et al*.

LMD-Oxford/OU-IAA European Mars Climate model



- Global numerical model of Martian atmospheric circulation (cf Met Office, NCEP, ECMWF…)
- High resolution dynamics
  - Typically T31 (3.75° x 3.75°)
  - Most recently up to T170 (512 x 256)
  - 32 vertical levels stretched to ~120 km alt. ($s = p/p_s$)
  - Surface topography & thermal properties
- Radiative transfer (solar heating and IR cooling)
- Seasonal and diurnal cycles
- CO_2, dust and H_2O transport
- Boundary layer mixing
- Sub-gridscale orographic drag

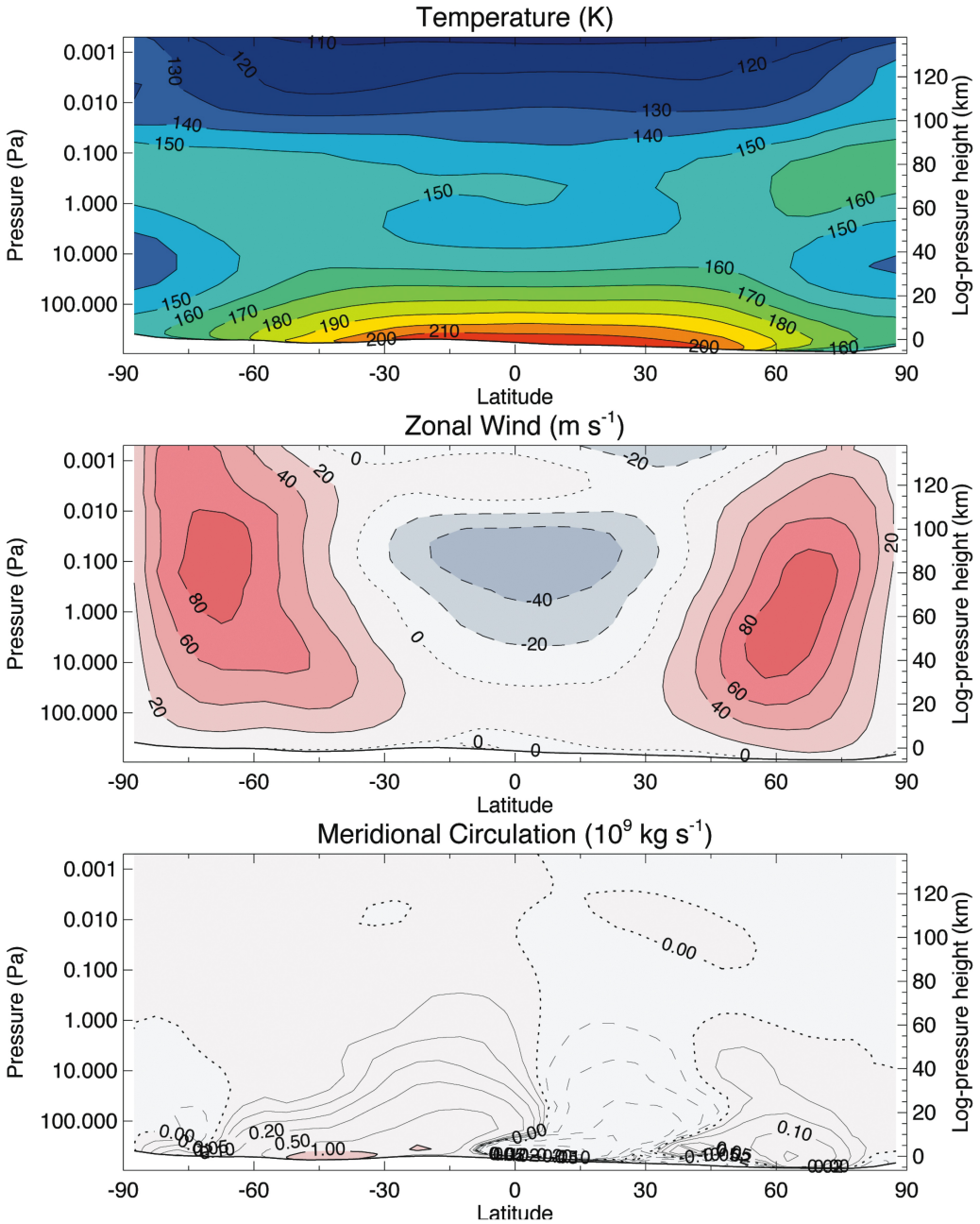
Global Energy Budget



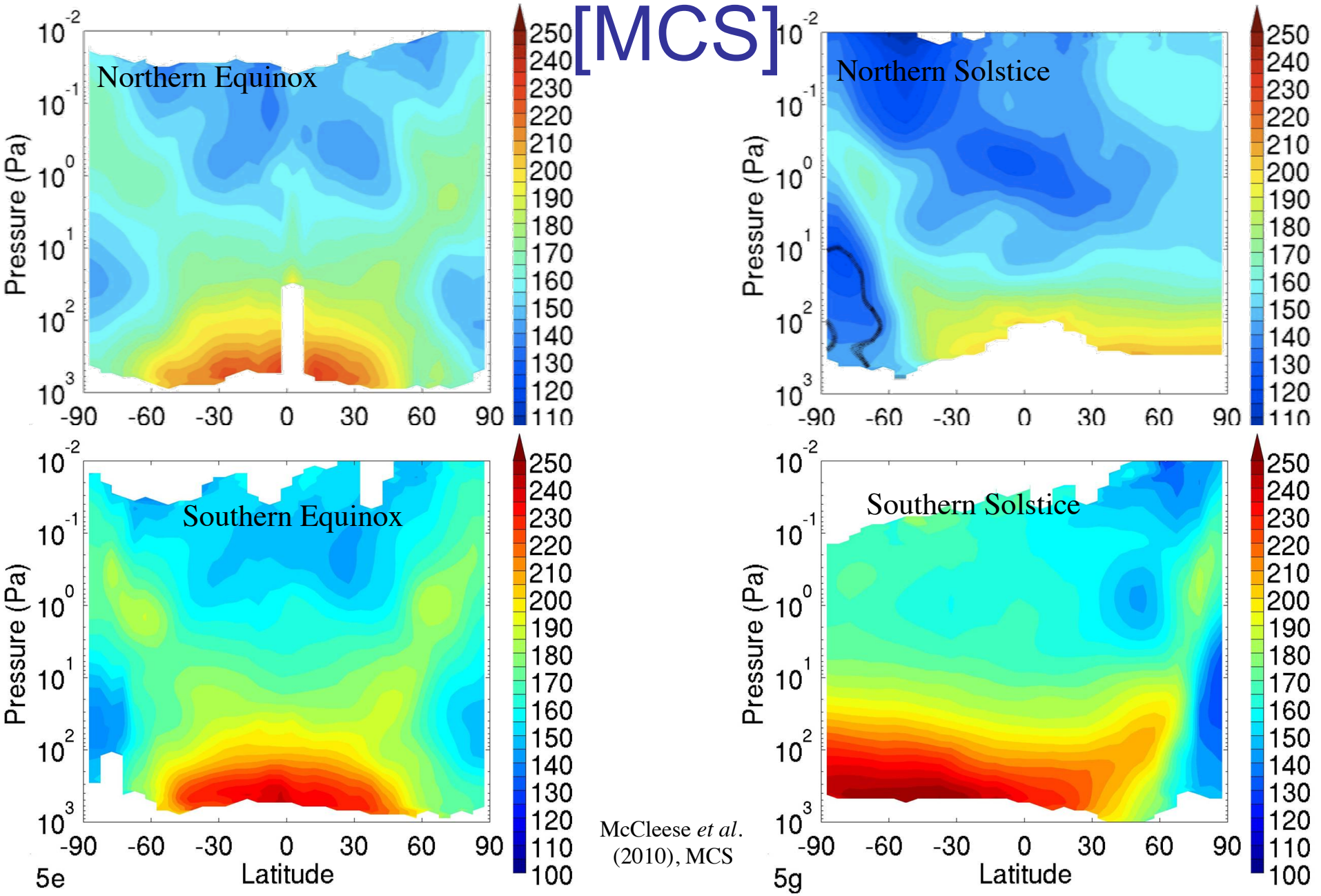
[Data from Mars Climate Database]

Mars Annual mean circulation

[Read & Lewis 2004]

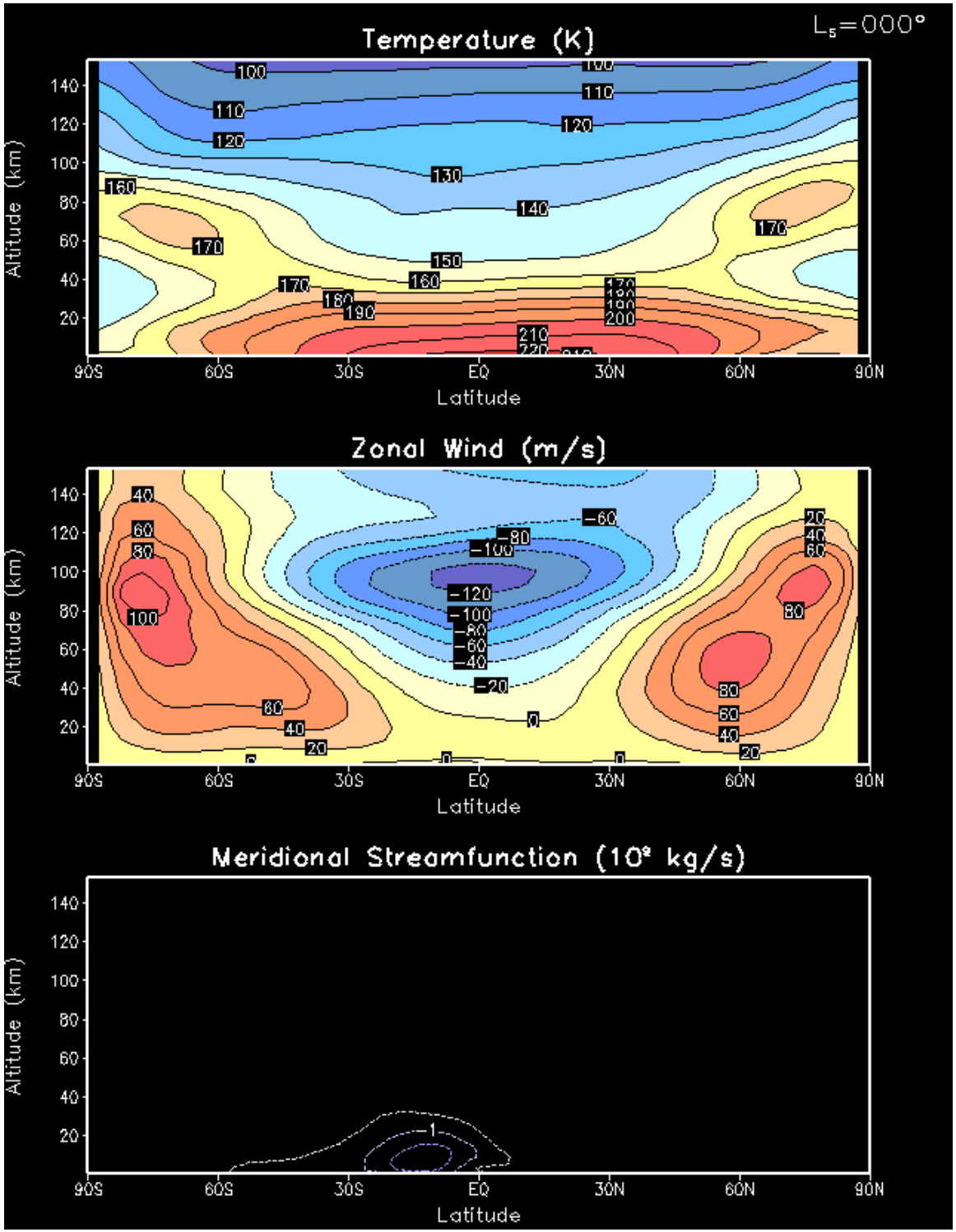


Global Atmospheric Structure [MCS]

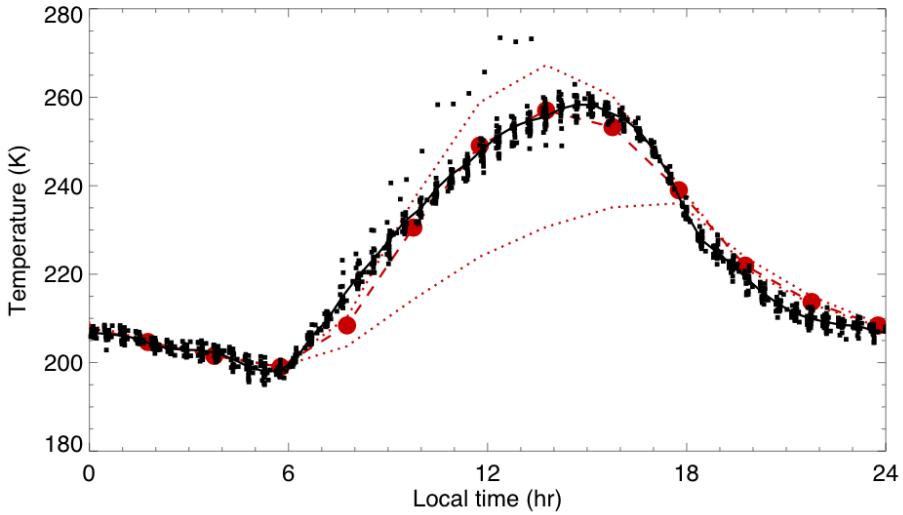


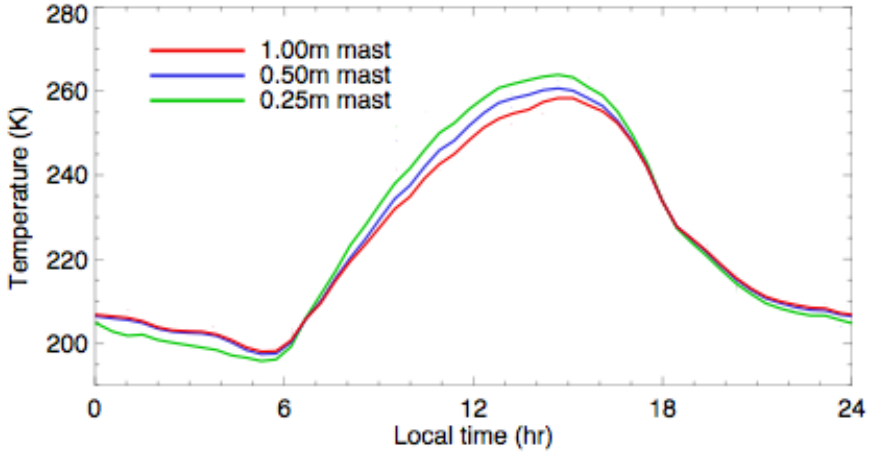
McCleese *et al.* (2010), MCS

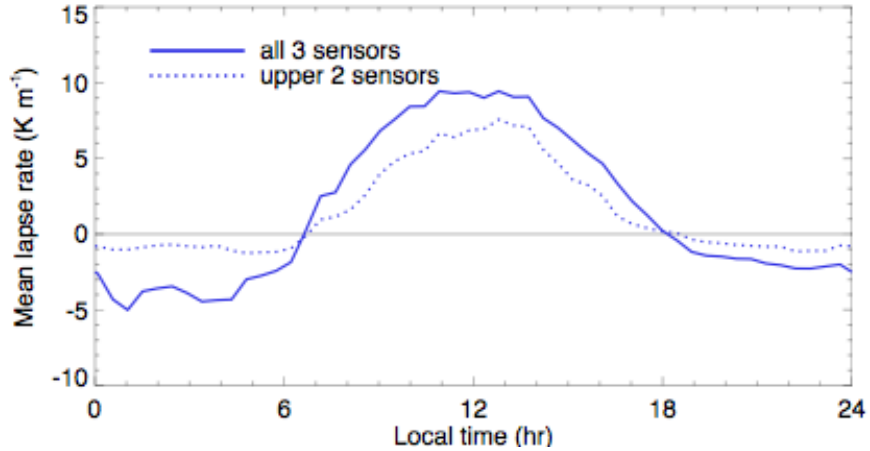
Seasonal variations of the zonal mean circulation on Mars (UK MGCM)



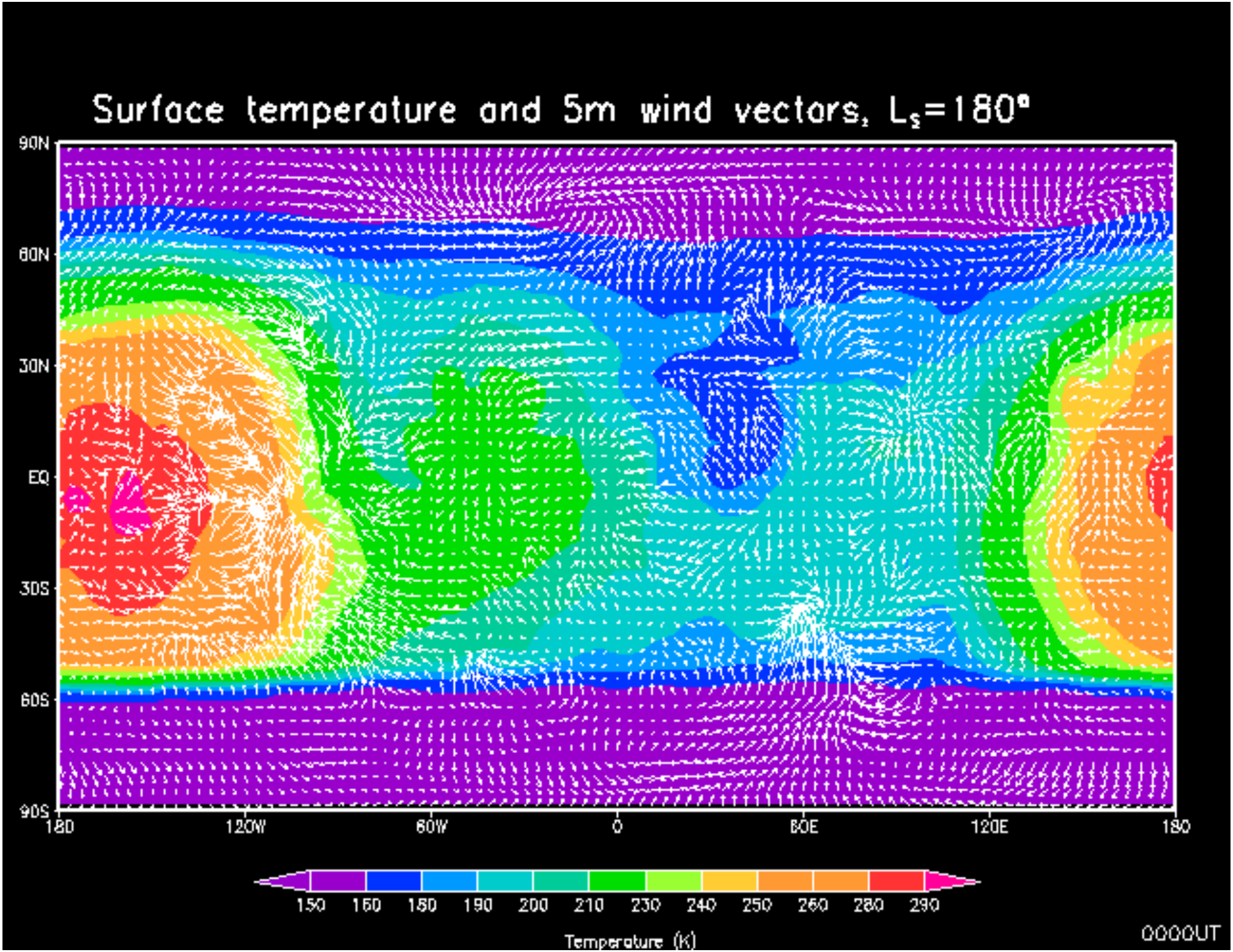
Diurnal cycles (MPF)





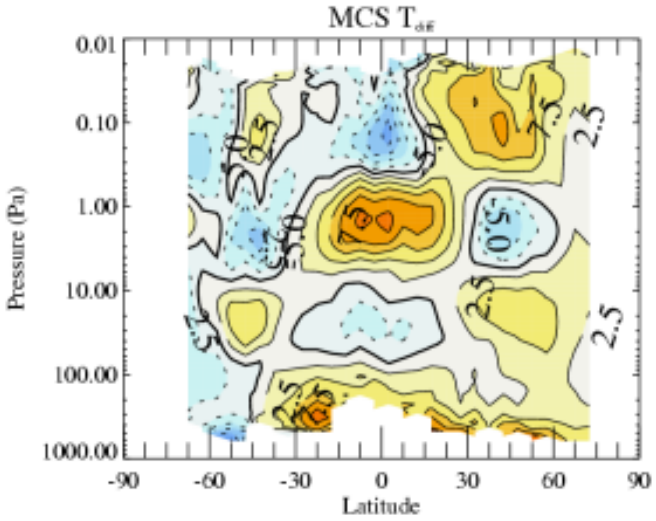


- Very repeatable variation of T (t) each day
- Diurnal tide dominant in NH summer

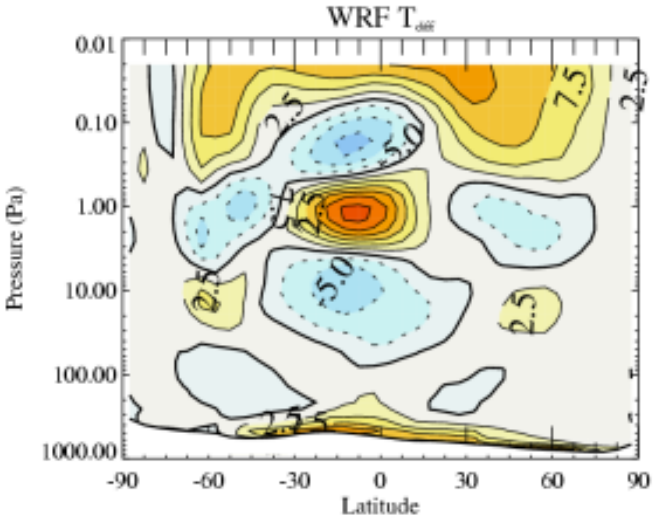

Surface temperature and 5m wind vectors, L_s=180°
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
150
160
180
190
200
210
230
240
250
260
280
290
Temperature (K)
OOOOUT

Character of Atmospheric Tides

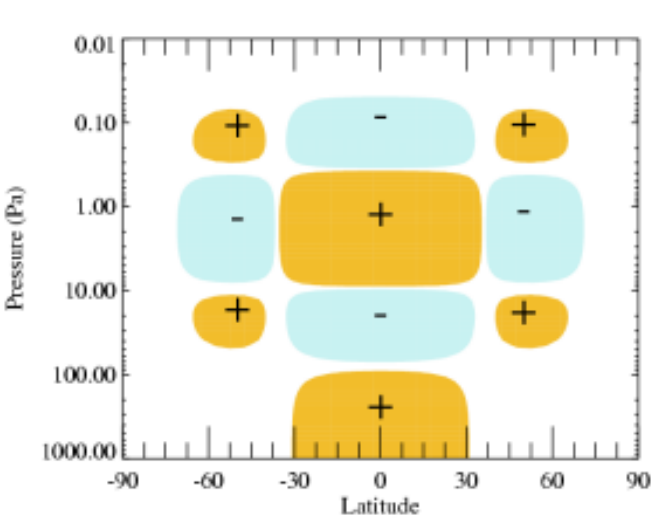
MCS



WRF MGCM

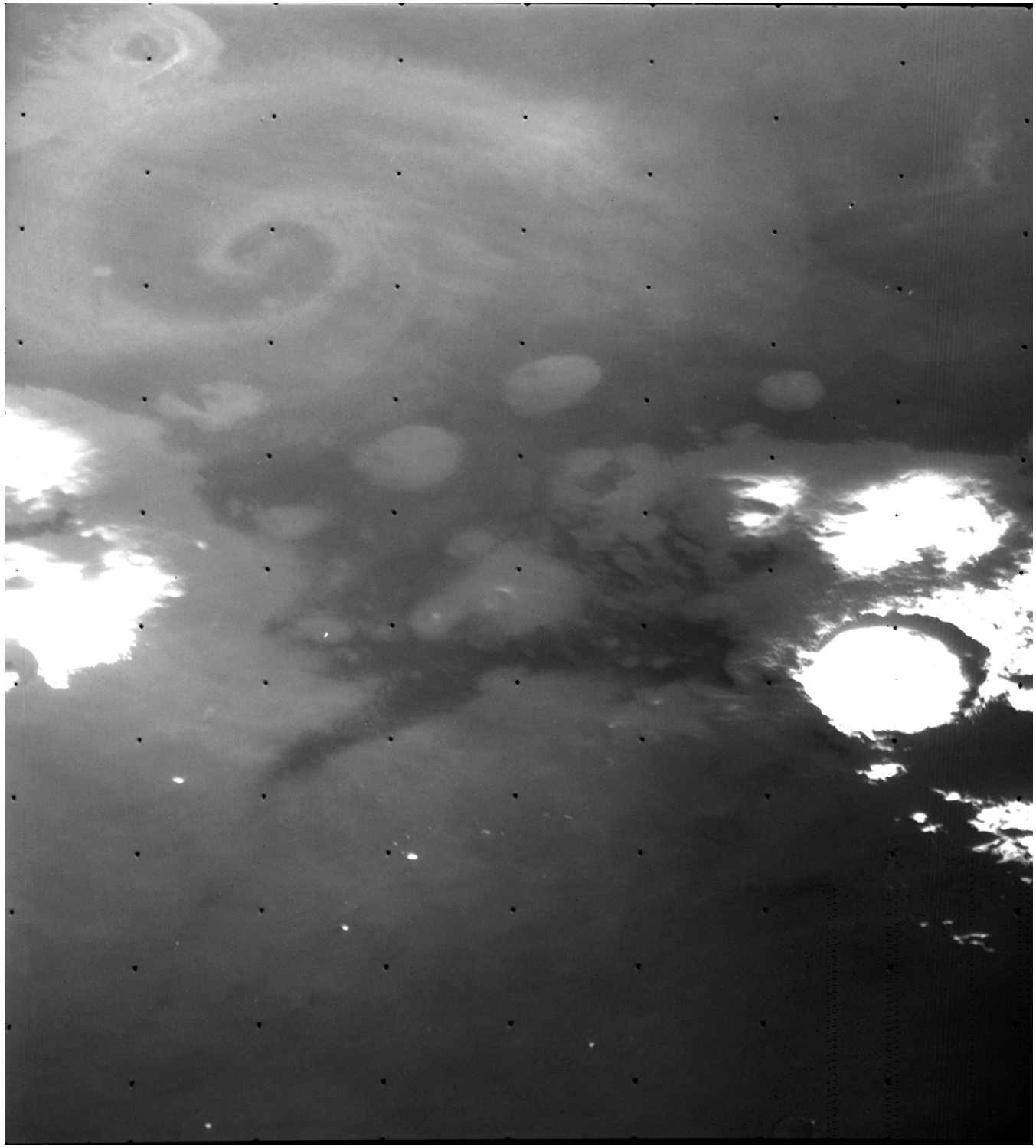


Tide Schematic



Temperature difference: Day - Night

Lee *et al*. (2009)

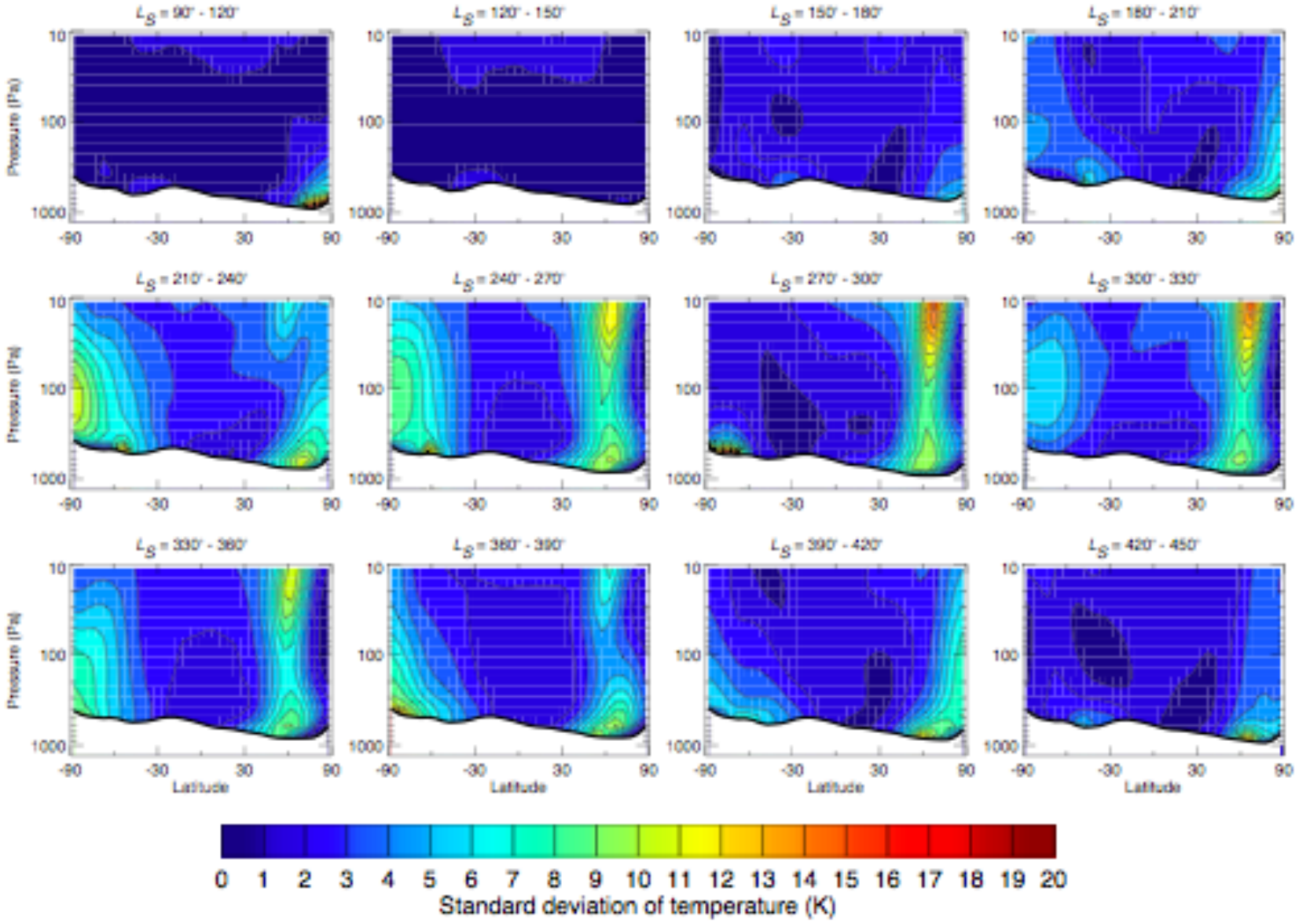


Cyclone : clouds and fog

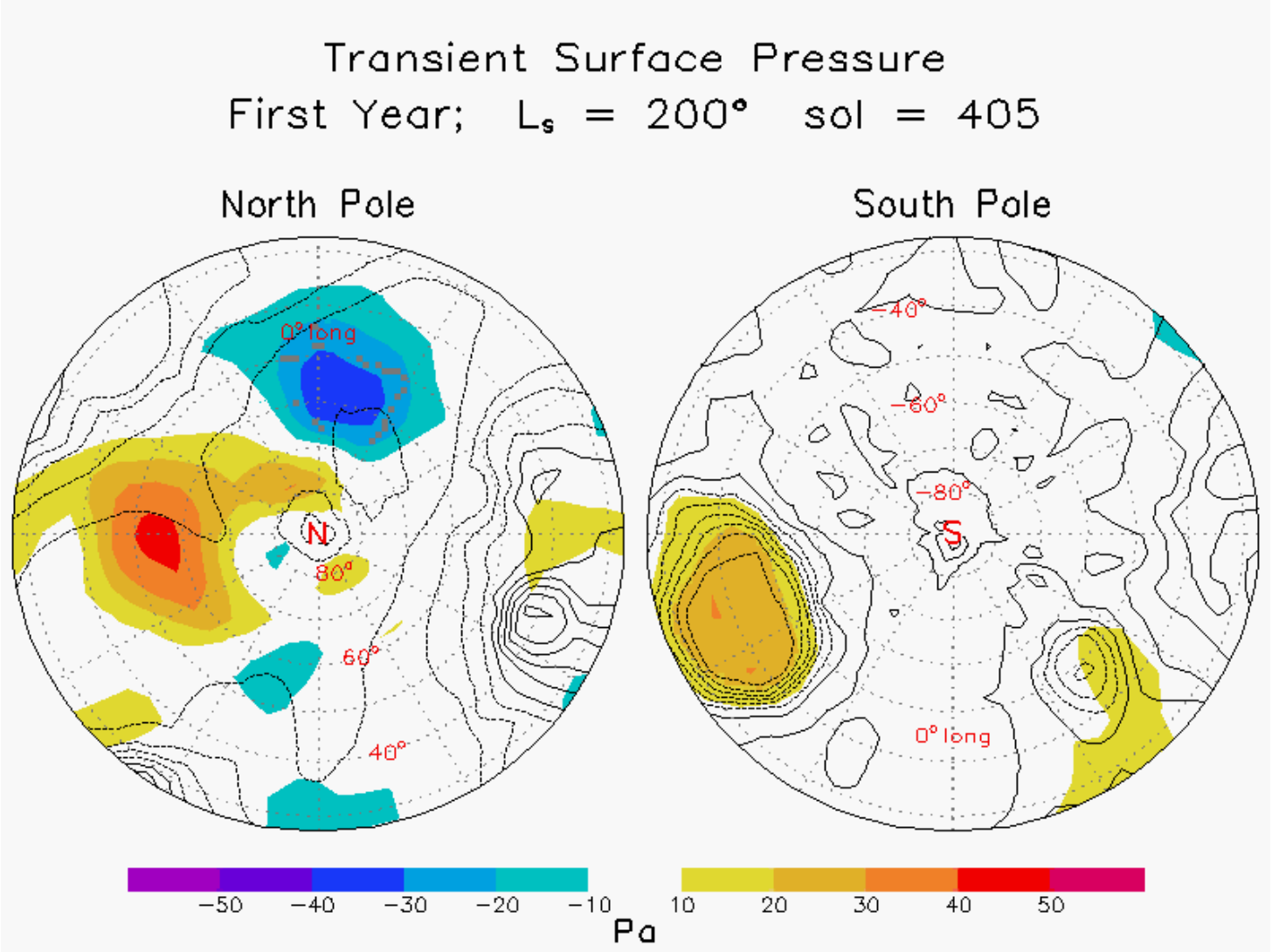
Baroclinic storms on Mars

- Active and strong in autumn-winter-spring seasons
- Weak/shallow or absent in summer
- Dominated by planetary wavenumbers 1-3
  - Deep ‘internal’ baroclinic modes?
- Almost regular & persistent in time cf chaotic & short-lived on Earth
- Closer to marginal stability than Earth?

Baroclinic <T'^{2}>$^{1/2}$ vs season

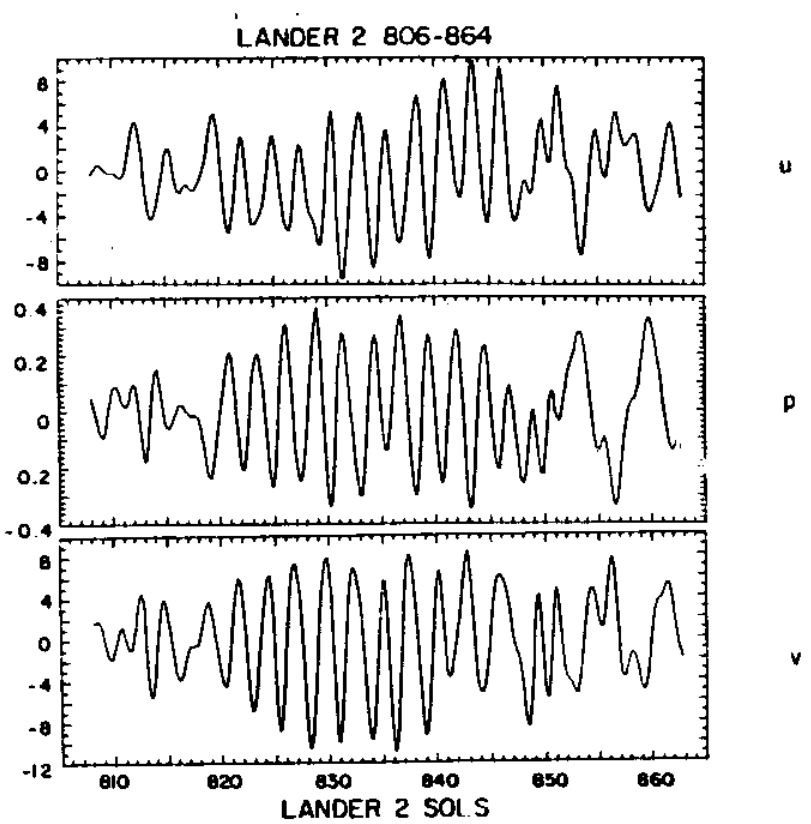


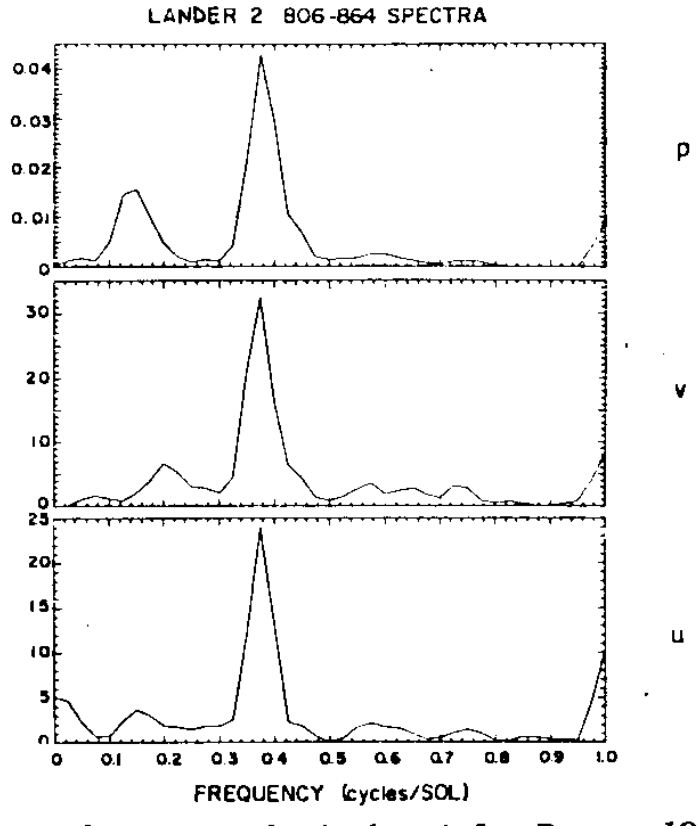
Mars GCM: transient patterns in surface pressure



Mars: surface variations

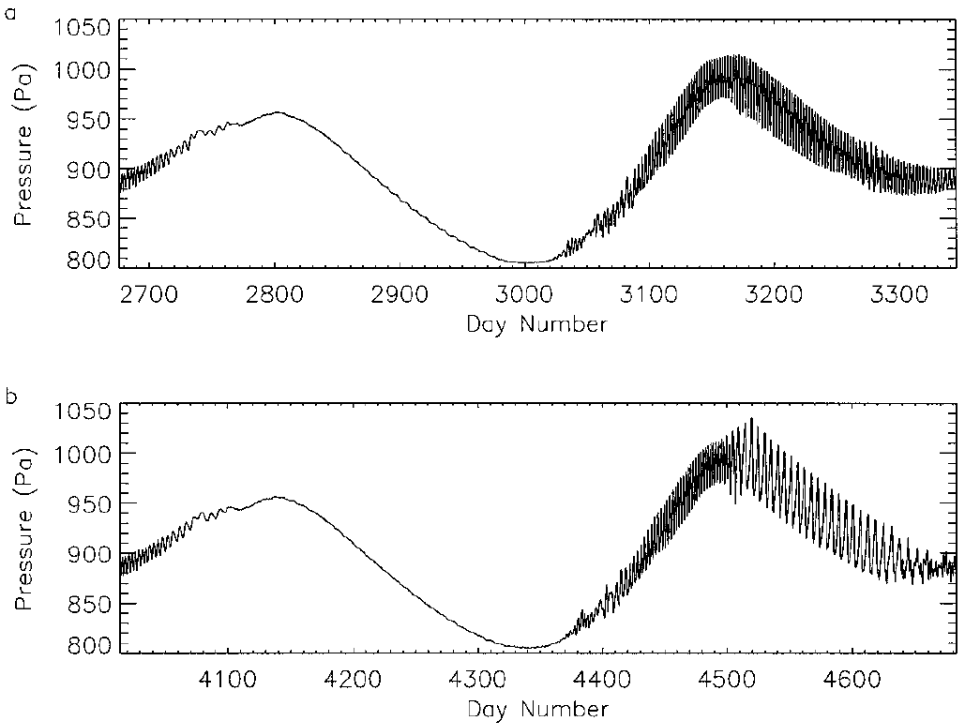
Viking Lander 2





- p_s,u,v band-passed filtered (2-20 sol period)
- Spectral analysis of 60 sol records

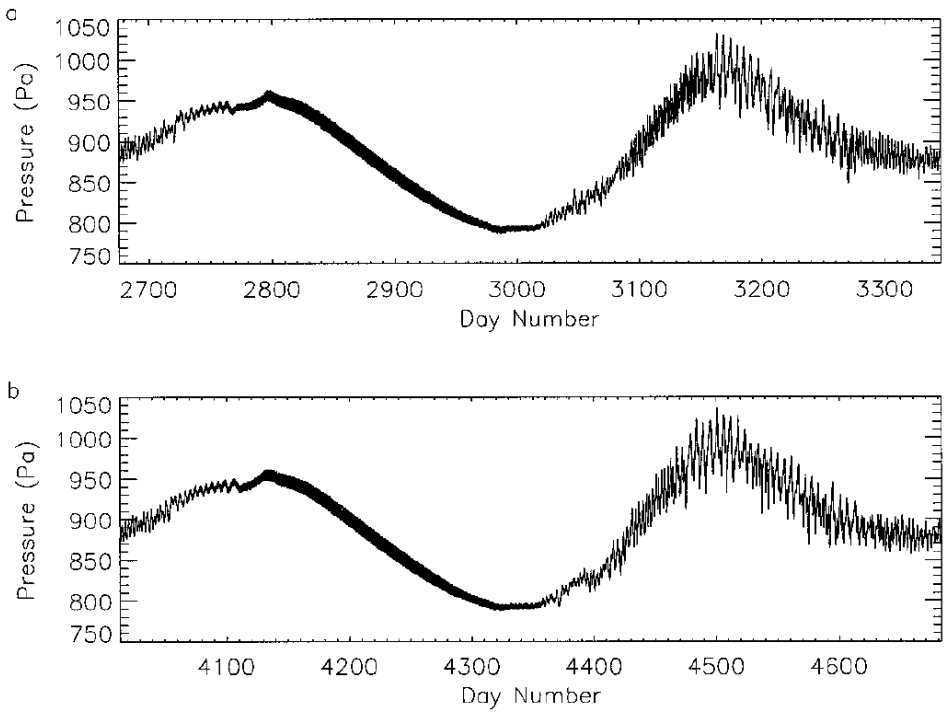
Low-dimensional dynamics?



- 'Thought experiment' using a GCM
  - Simulation of Martian circulation
    - WITH seasonal variations
    - WITHOUT diurnal variations
- Baroclinic instability absent in summer
- Baroclinic waves ~perfectly periodic in winter…

Collins et al. *Icarus* (1996)

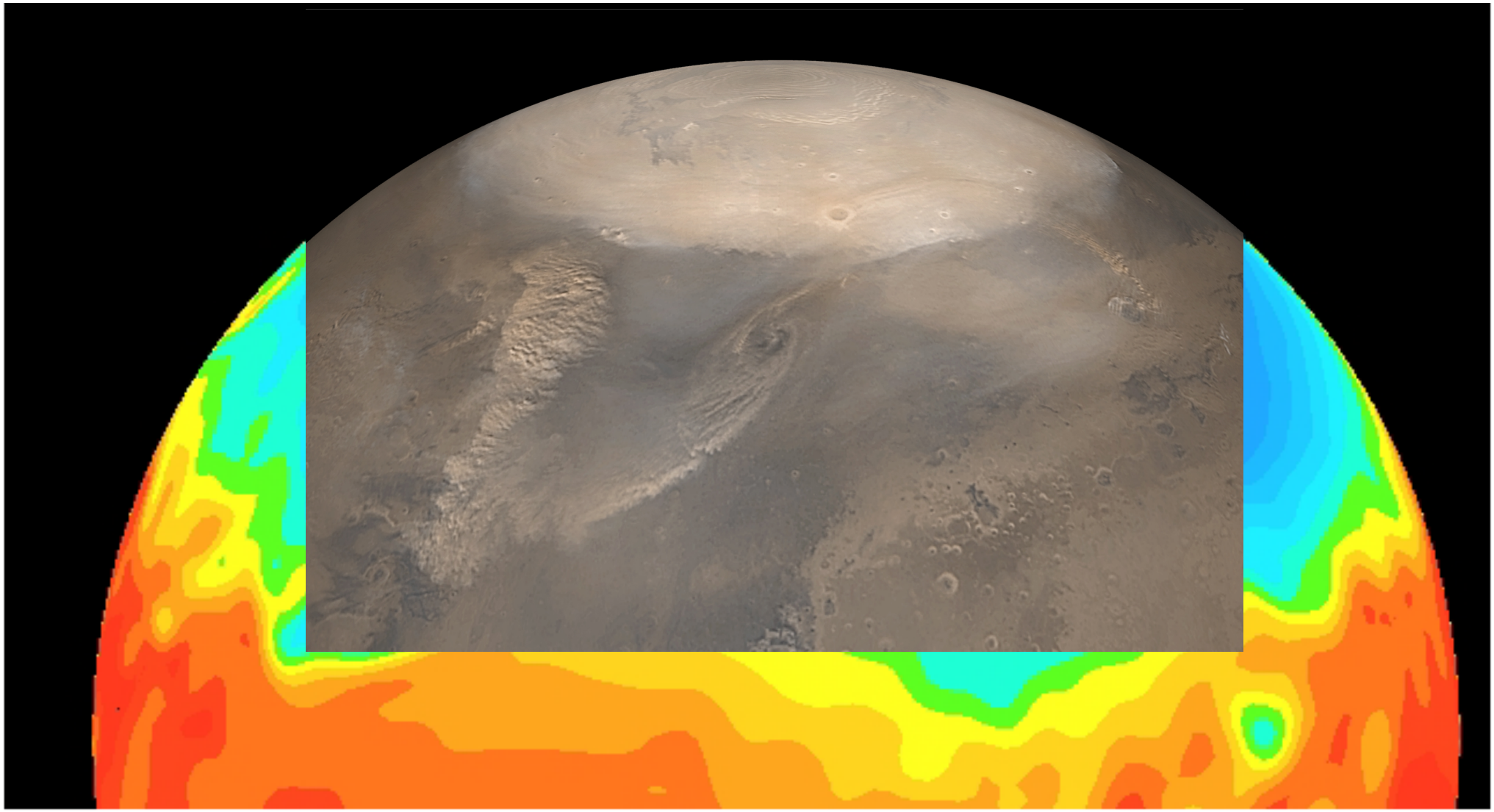
Low-dimensional dynamics?



- 'Thought experiment' using a GCM
  - Simulation of Martian circulation
    - WITH seasonal variations
    - WITH diurnal variations
- Baroclinic instability absent in summer
- Baroclinic waves now CHAOTIC in winter…

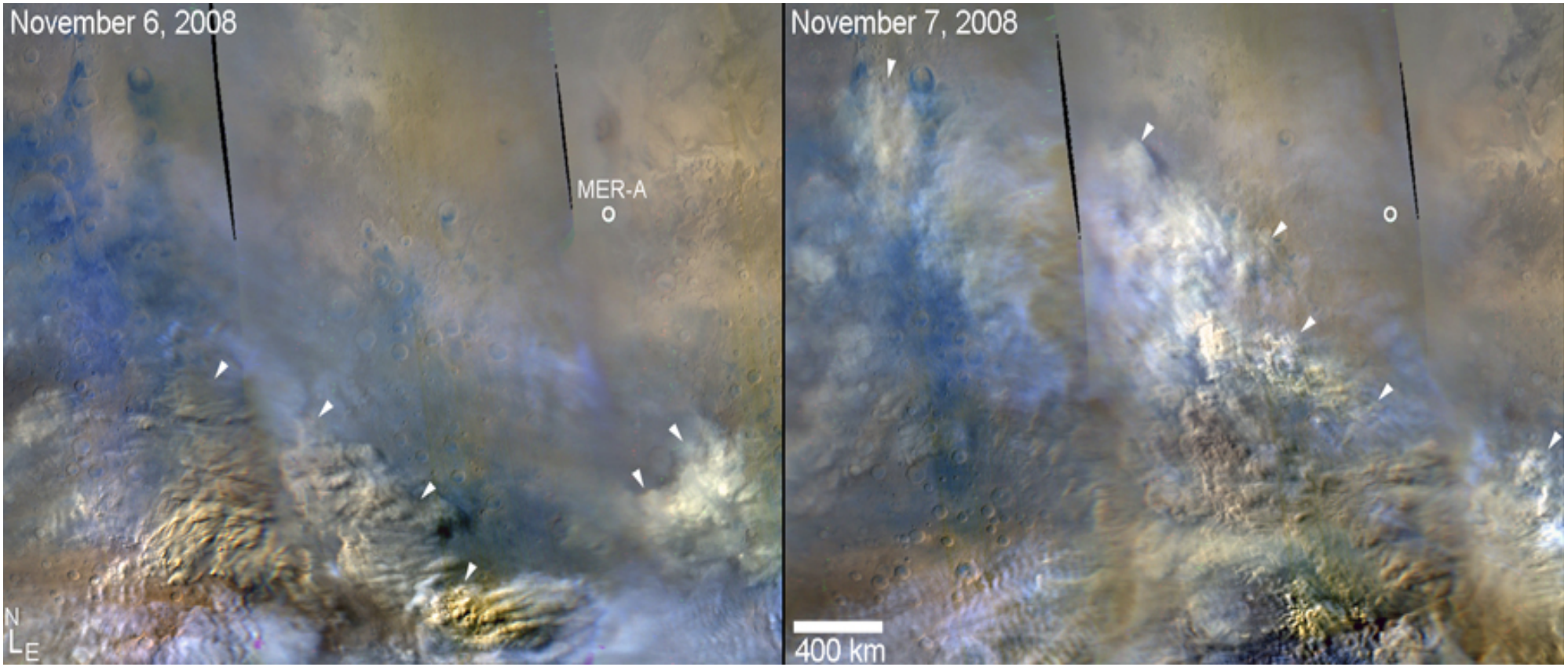
Collins et al. *Icarus* (1996)

Fronts and cyclones



Dust Storm Activity Near Spirit

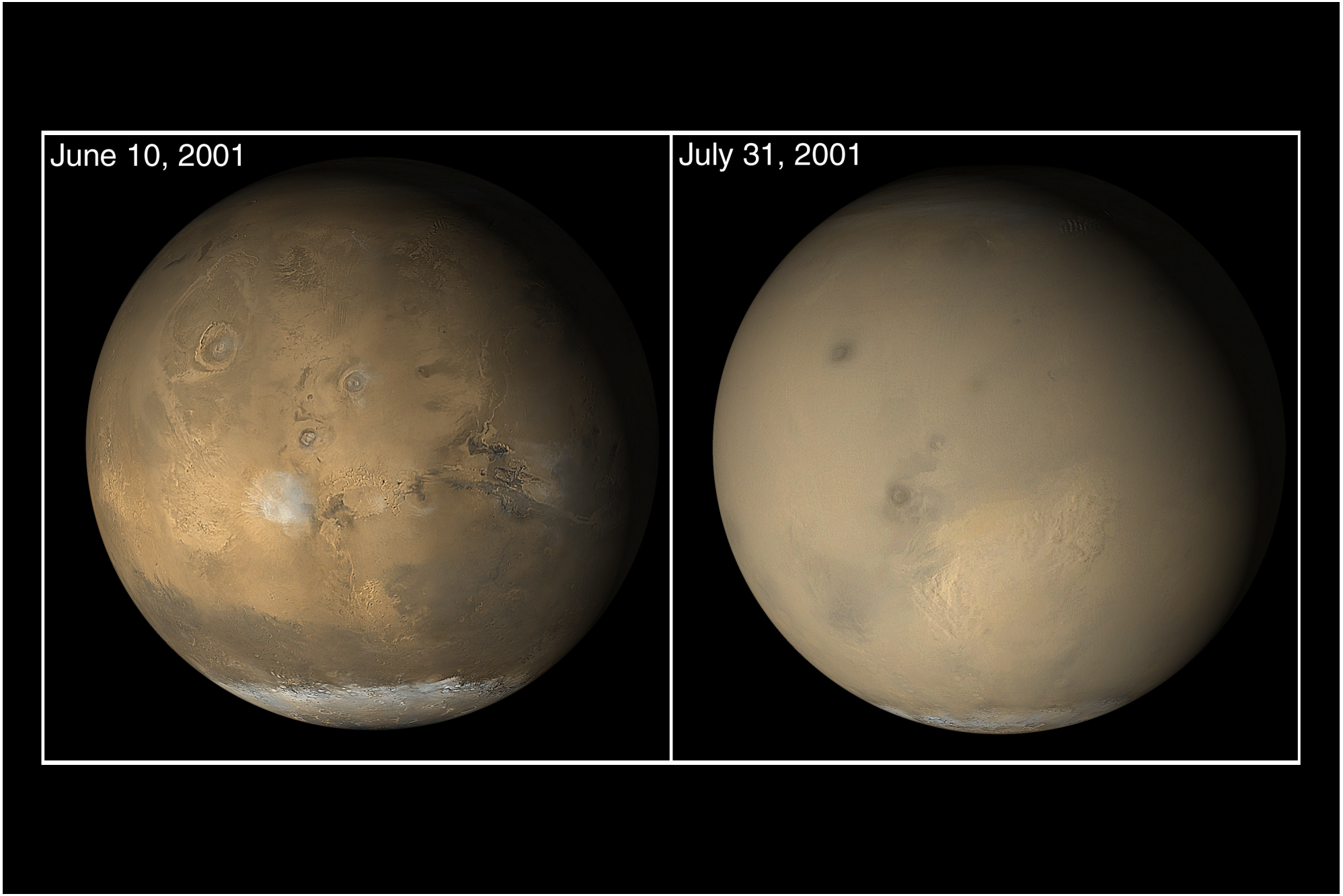
November 2008, L_s = 153.6



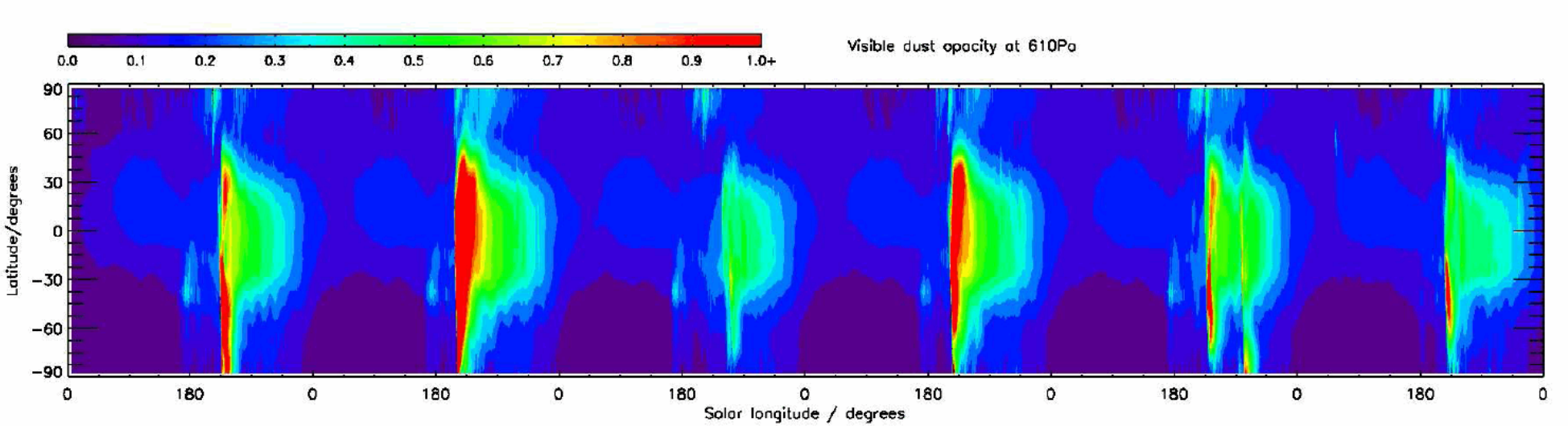
Cantor *et al*., MARCI

Dust Storms on Earth & Mars

Global Dust Storm of 2001 (MGS/MOC)



Chaotic dust storms in GCMs



Mulholland (2010)

- Parametrized dust lifting
  - Critical stress threshold for saltation
- Dust transported by circulation
- Deposition via sedimentation

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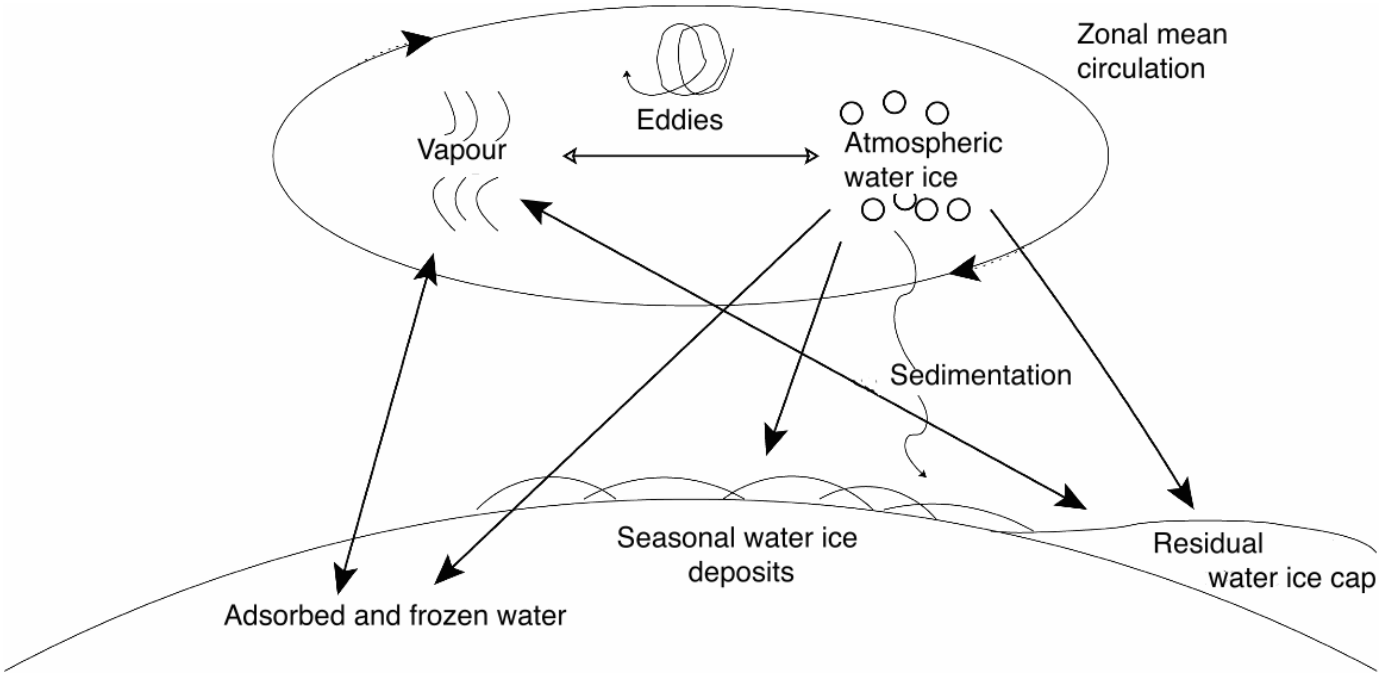
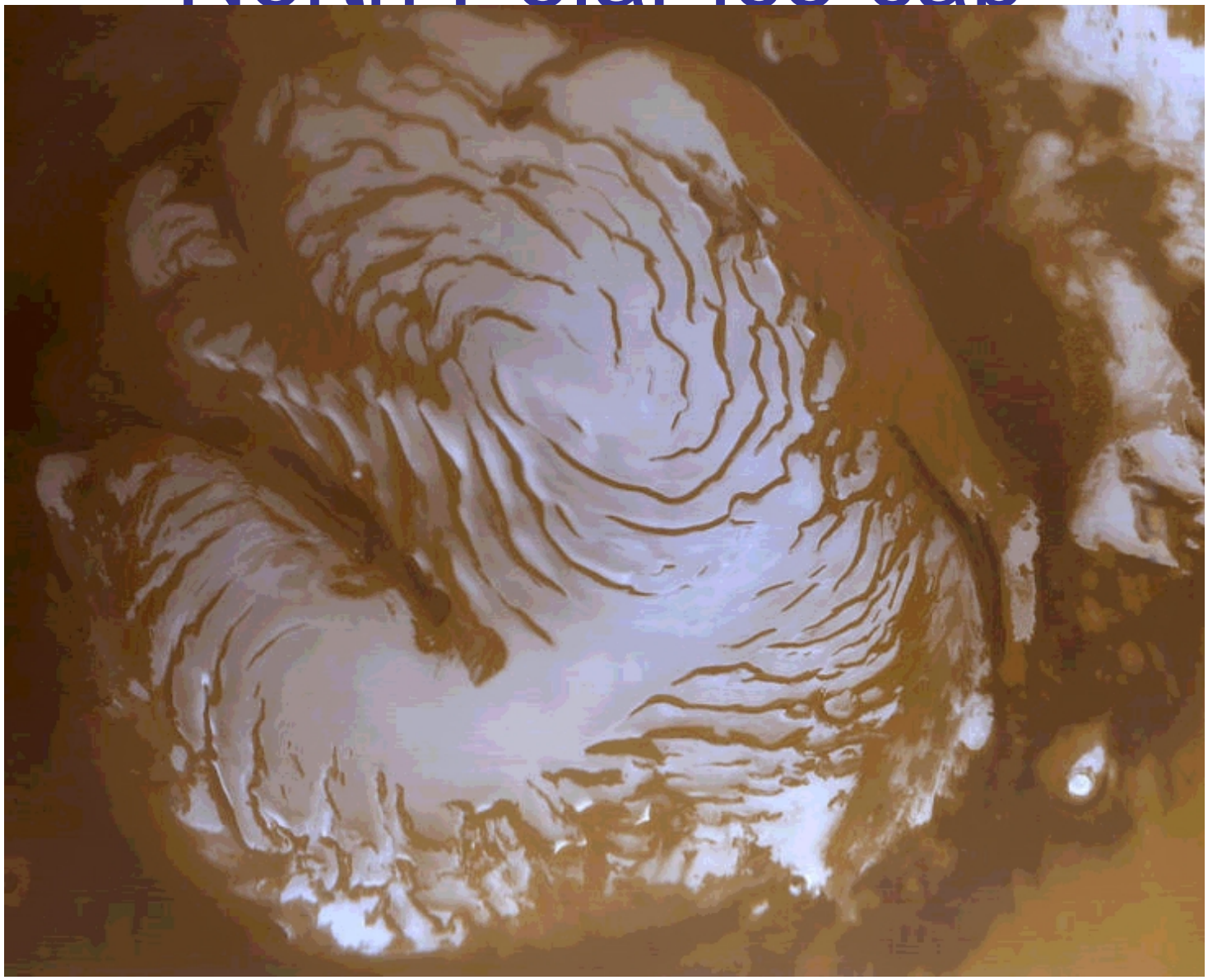
Mars Water Cycle

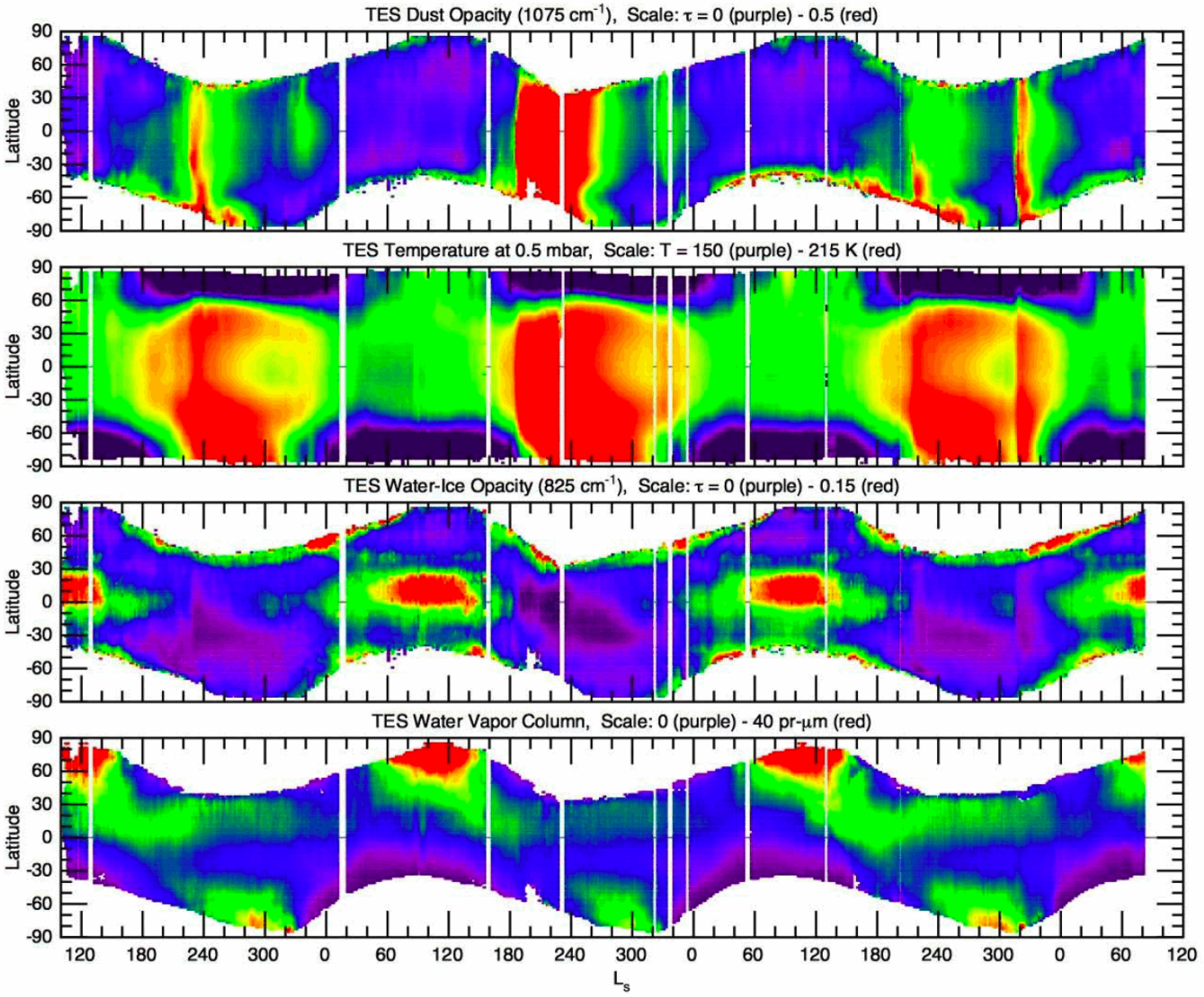


- Water mostly in frozen form at the surface (NB p < p[triple point])
- Seasonal exchanges with the atmosphere
  - Water vapour (measured in precipitable microns!)
  - Very low ABSOLUTE humidity…..BUT
  - **RELATIVE humidity can rise to 100%** -->Ice clouds, frosts, fogs…

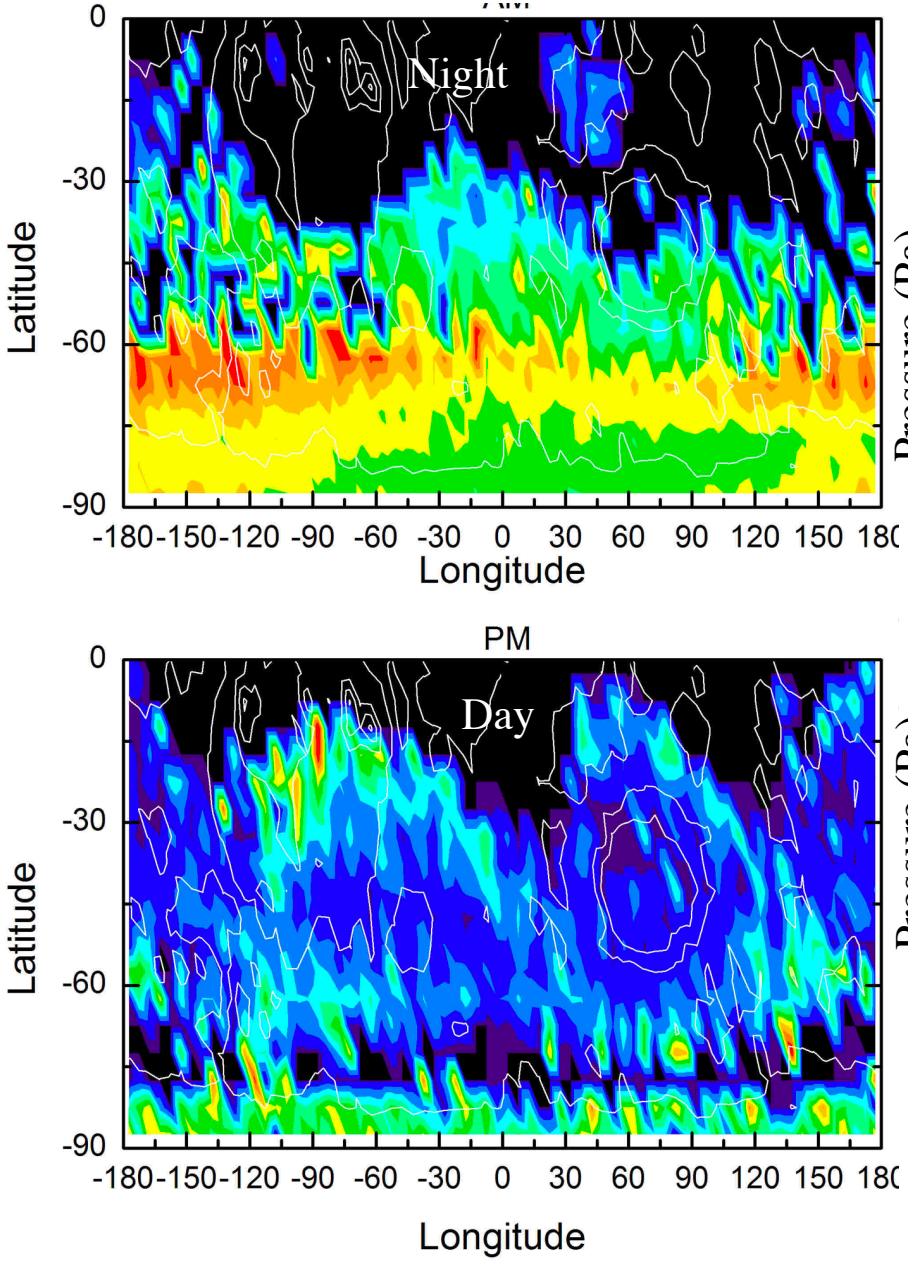
Water on present-day Mars - North Polar ice cap



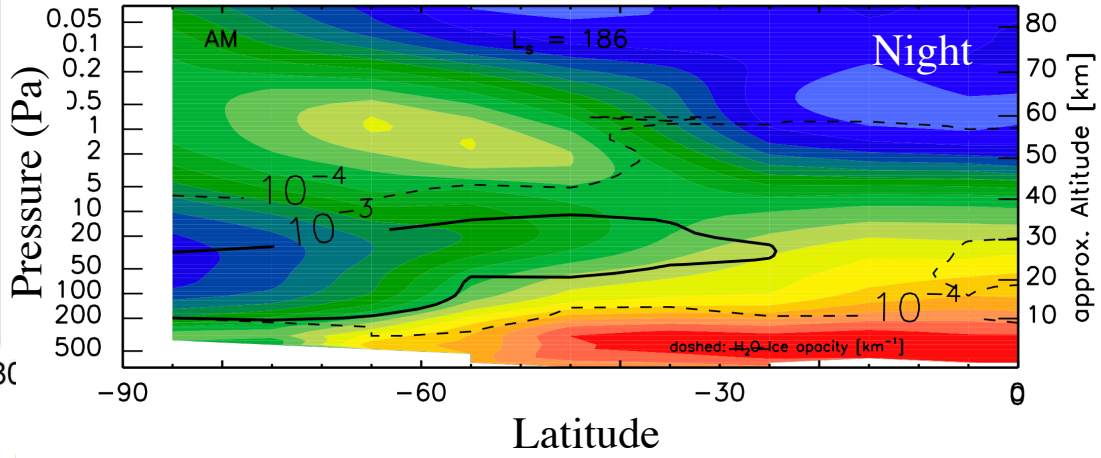
Mars dust and water cycles

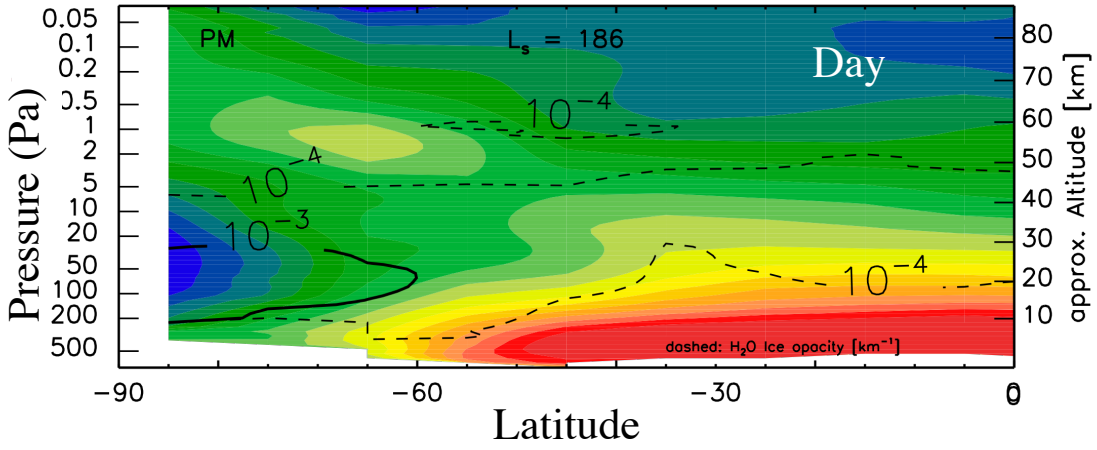


Polar Hood Clouds



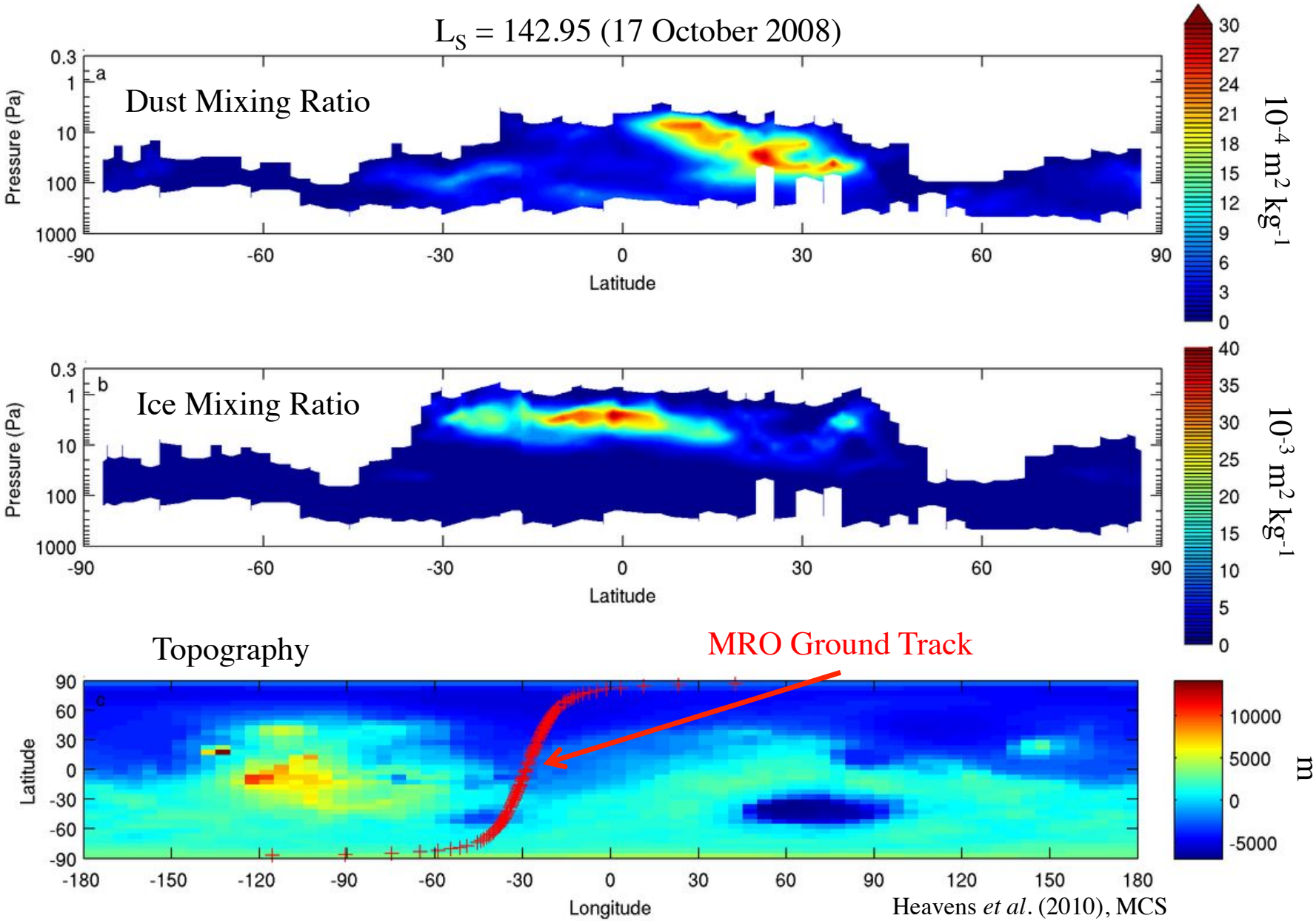
Southern Equinox





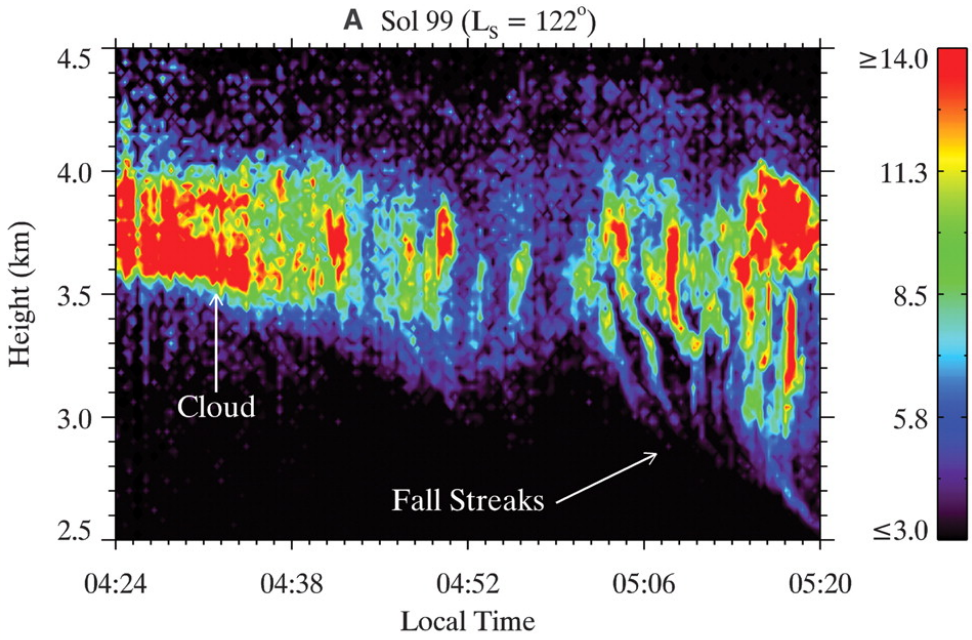
Benson *et al*. (2010), MCS

Dust and Ice Layers



Heavens *et al*. (2010), MCS

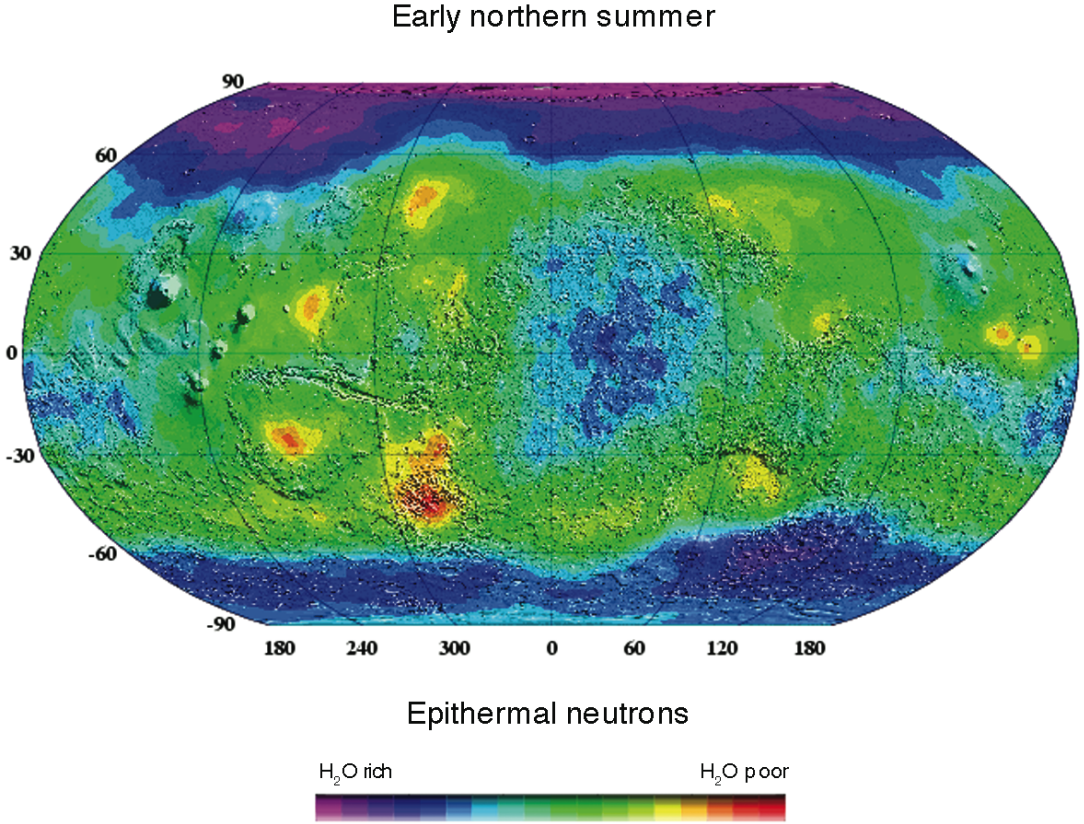
H_2O Ice clouds at Phoenix landing site

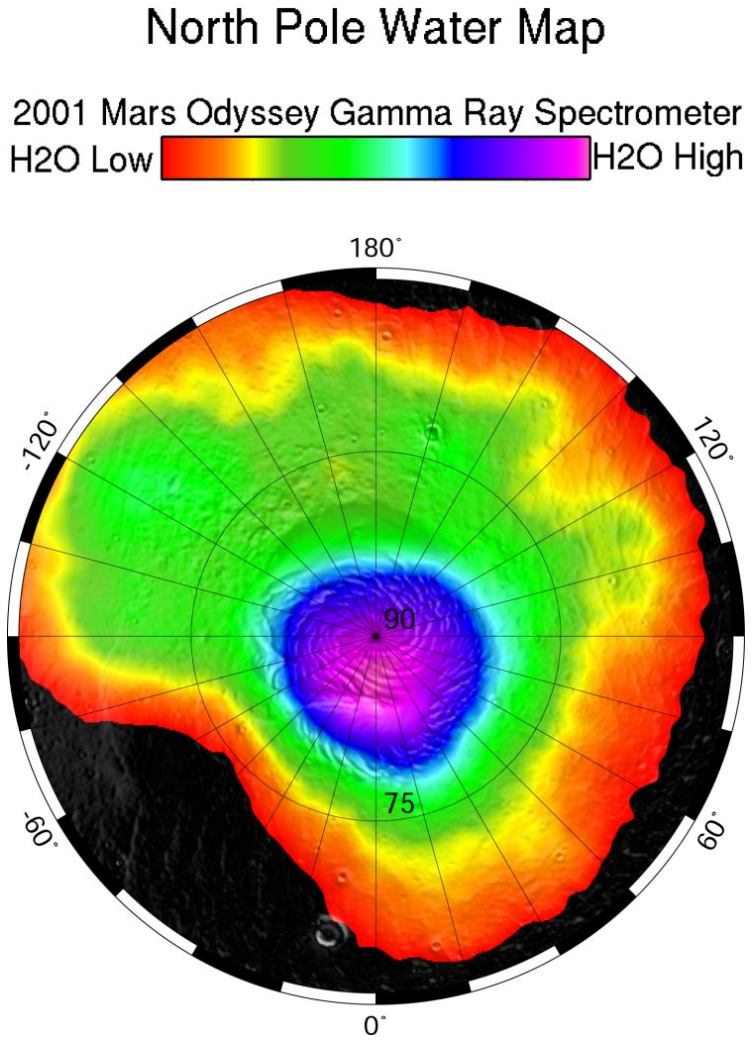


- Ice condensation commonly forms clouds ~4 km altitude
- Precipitation….?

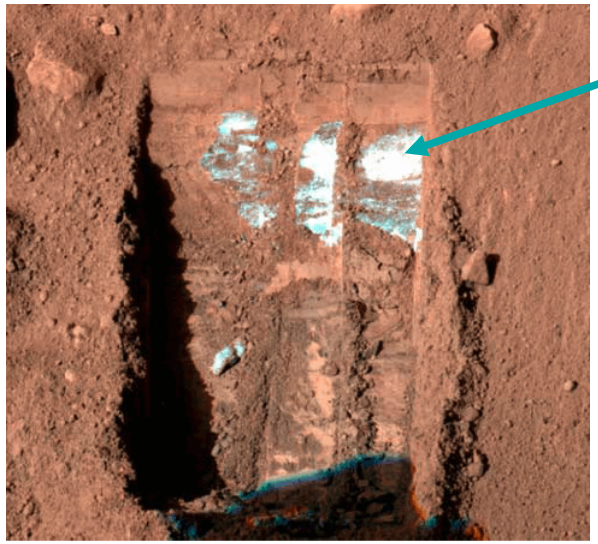
Sub-surface Water Ice

(Mars Odyssey: gamma-ray spectrometer)

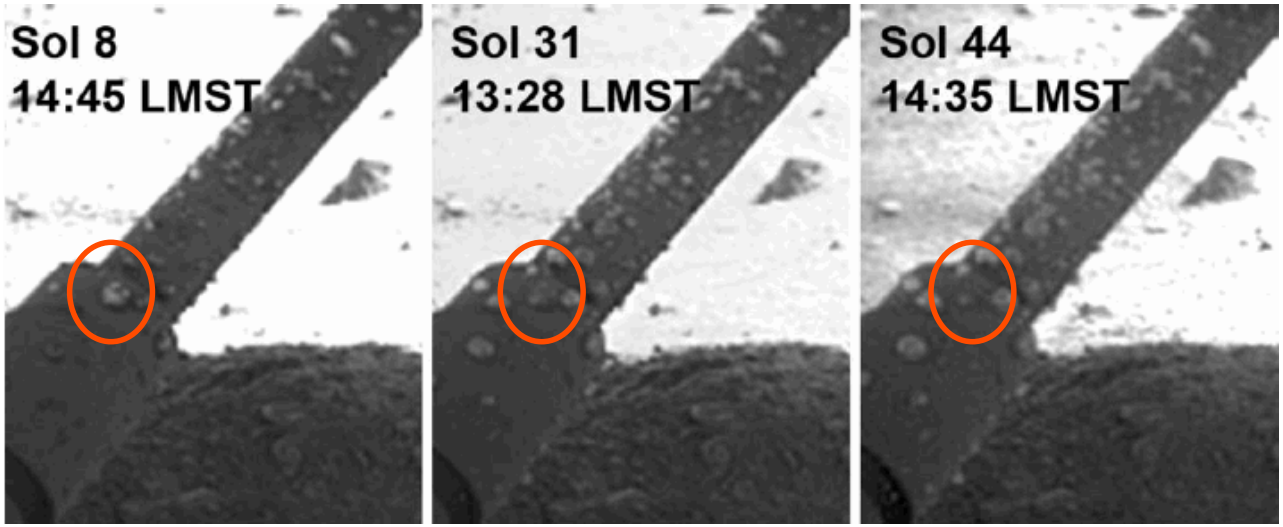




Sub-surface ice & liquid water at Phoenix landing site



- Soft (saline?) ice exposed in shallow trench
  - Fragments sublimed quickly
- Liquid droplets (saline?) splashed onto spacecraft strut when landing
  - Some subsequently rolled off



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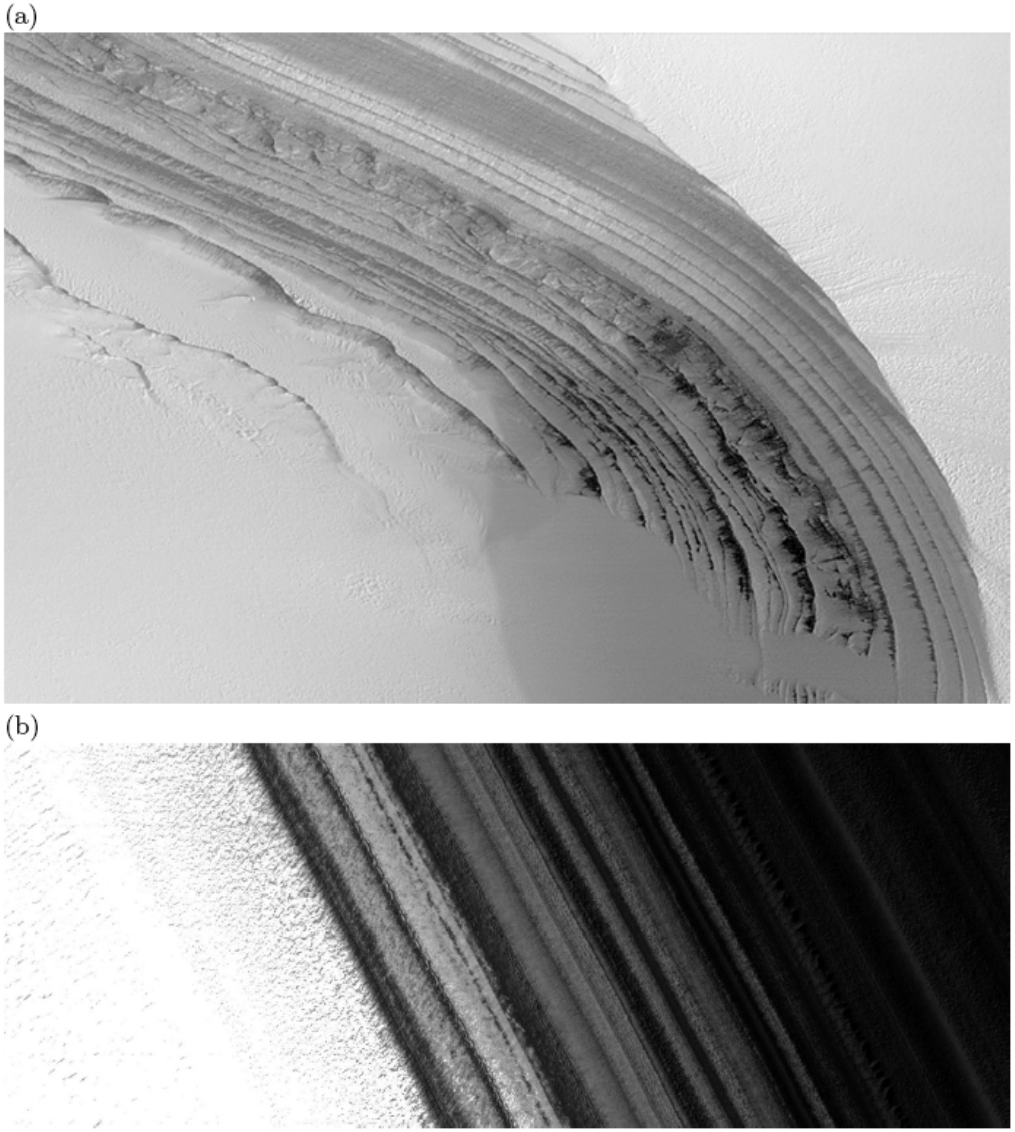
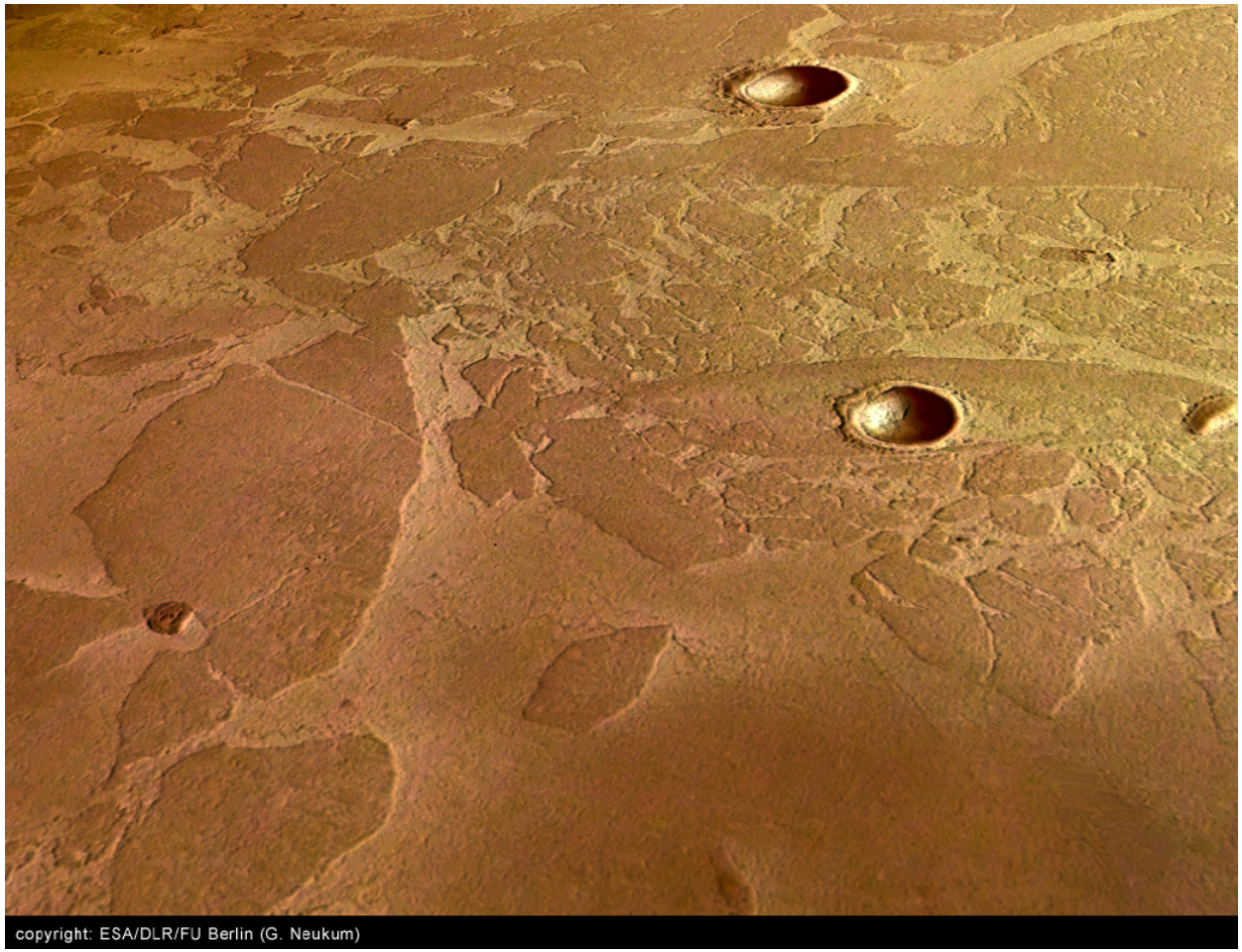
  - Circulation regimes and climatological parameter space

Recent climate change: polar layered terrains



- Layered deposits of water ice and dust
- Extensive terrains equatorward of polar caps
- Evidence of cyclic climate change…?

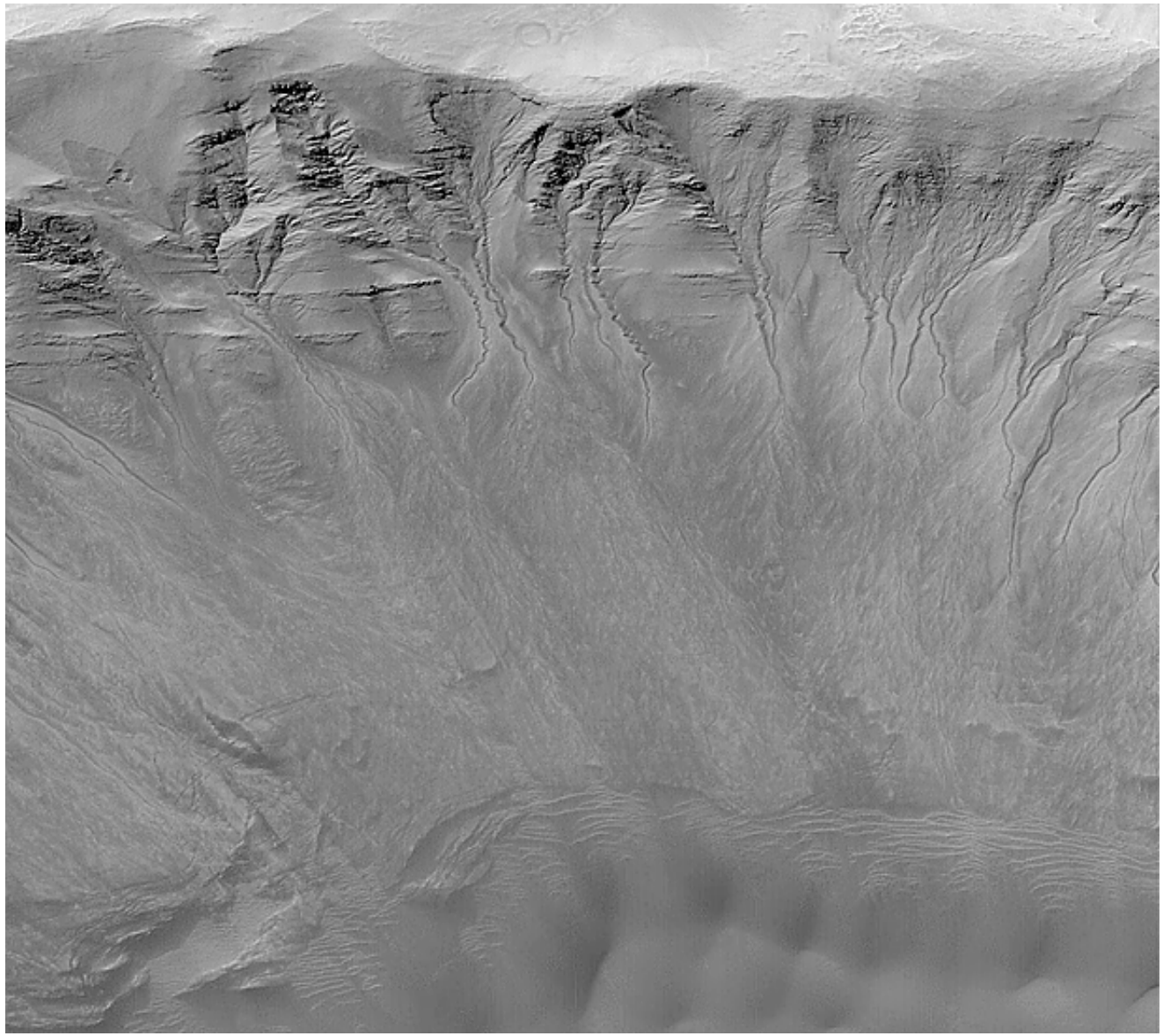
Changing climate on Mars

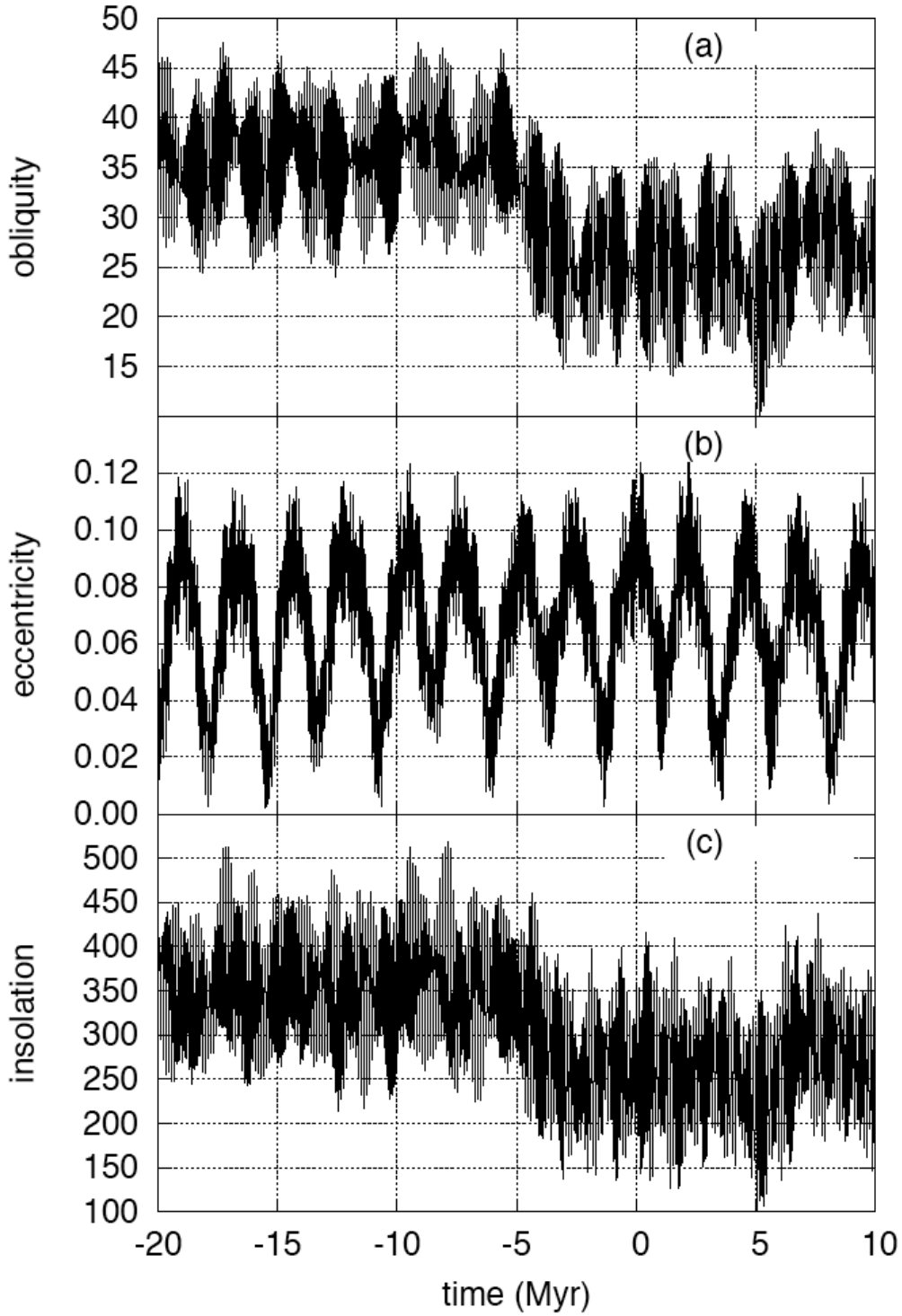


- Dust-covered frozen sea….?
- NB - at 5^{o}N latitude! - UNSTABLE?

Martian Gullies

- recent (<10Myr BP) water erosion?

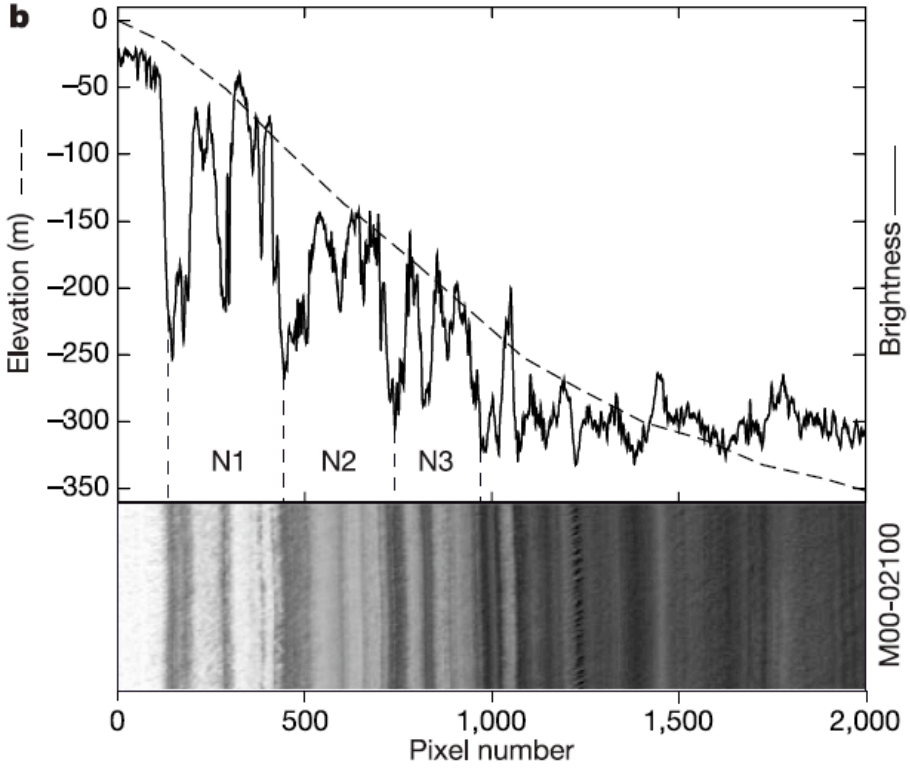


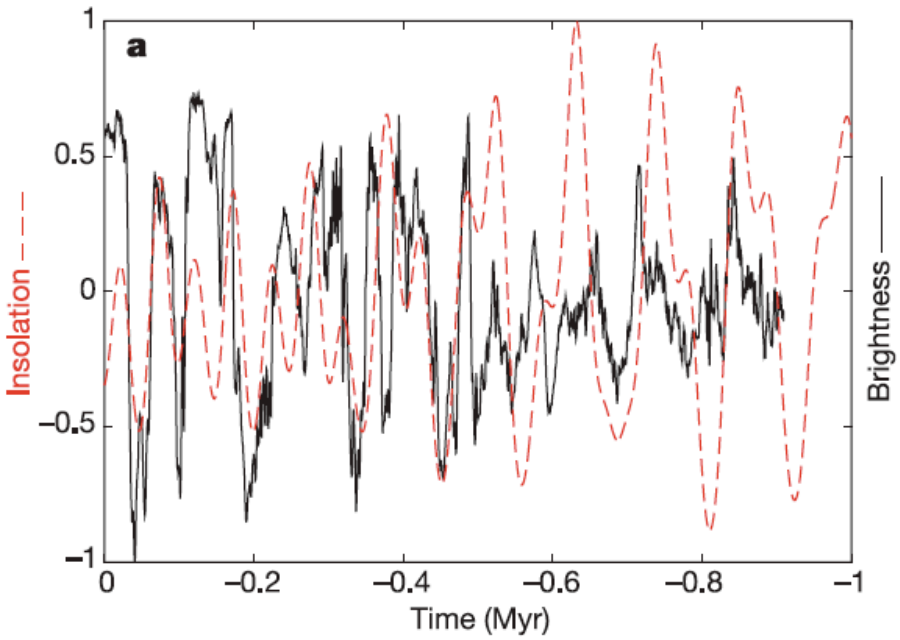


Cyclic (chaotic!) variations in Mars' obliquity

- Perturbations to Mars' orbit and rotation due to other planets
- Cyclic (but chaotic) variations in obliquity and orbital eccentricity
- Cyclic changes in solar insolation at poles

[From Laskar et al. 2004]

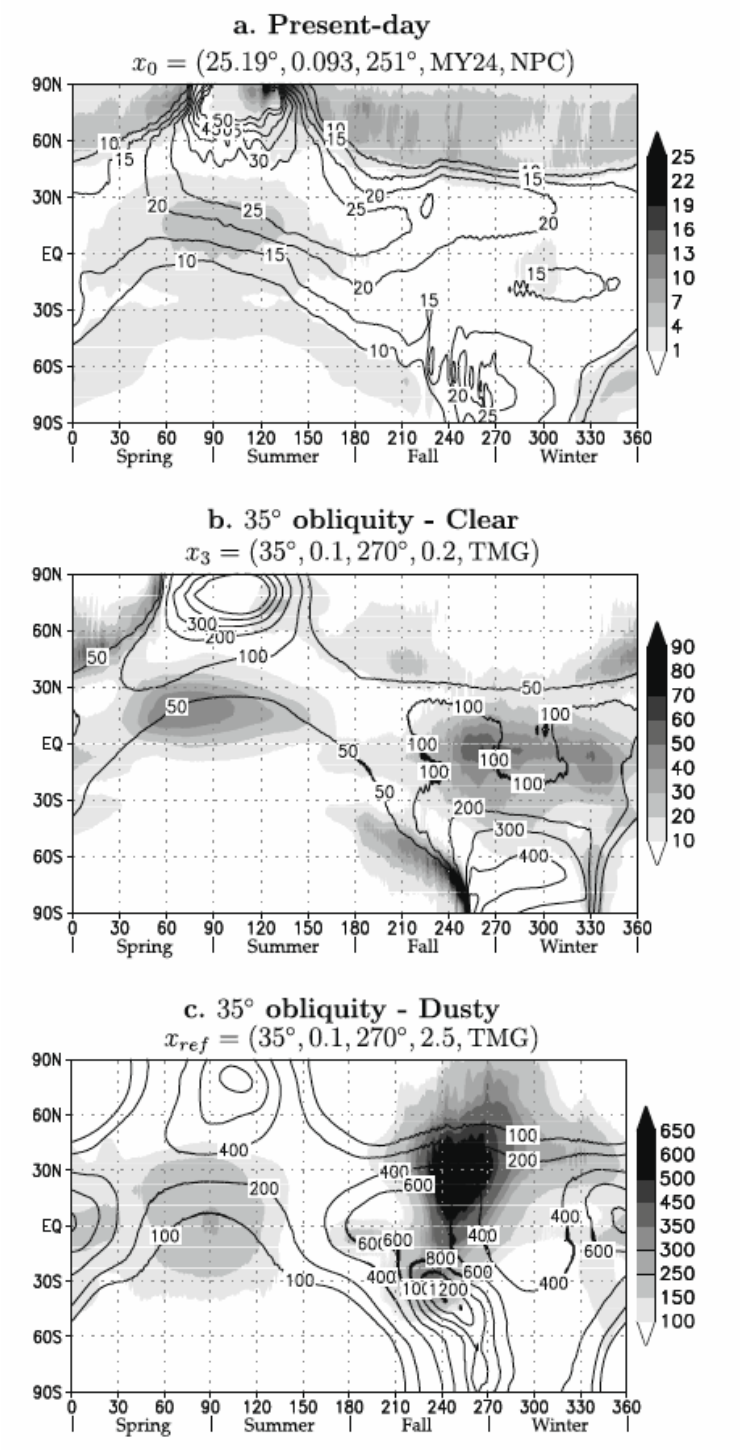




Cyclic variations in solar heating and Mars' polar layered terrains

- Measured brightness profiles across polar layers
- Best-fit correlation with solar heating at the poles

From Laskar et al. (2002; *Nature*)

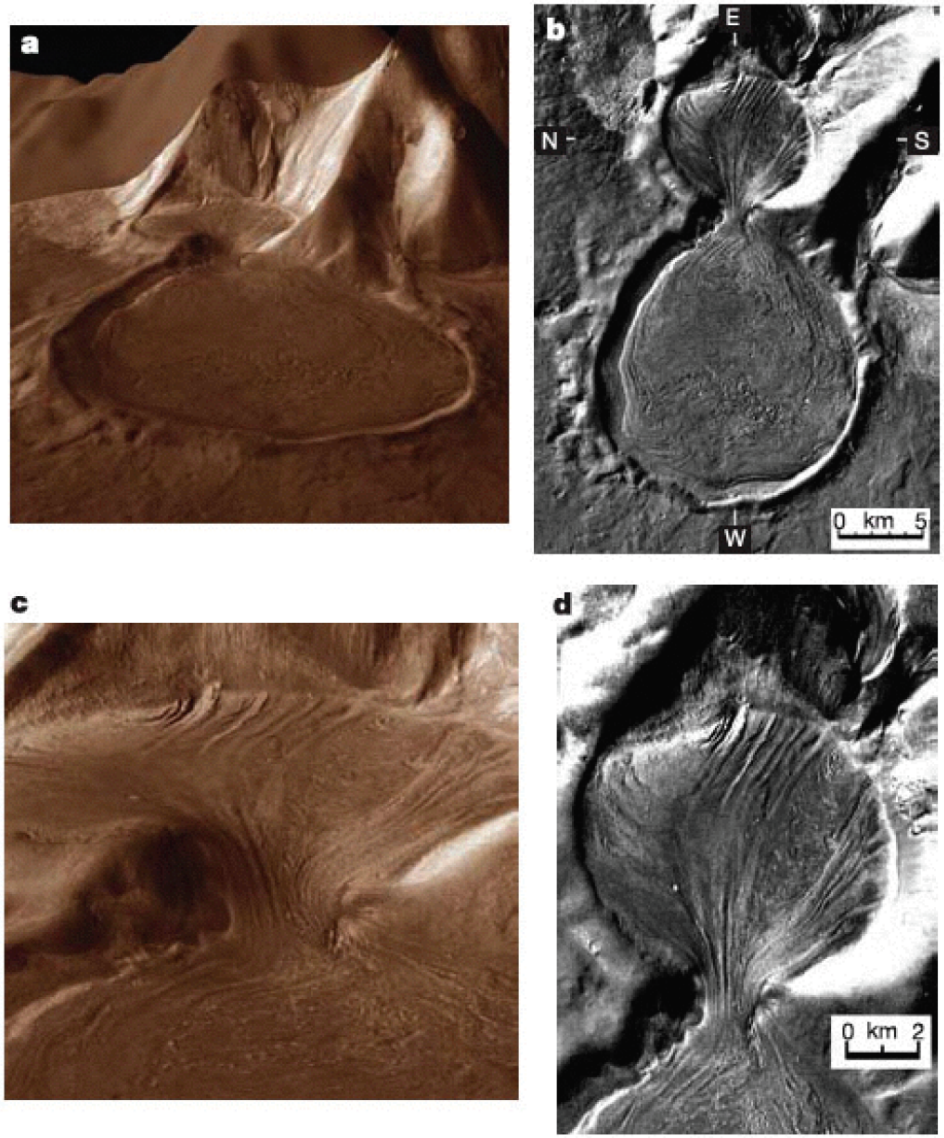


Water cycle at high obliquity

- Evaporation of permanent H_2O ice cap
- Increased absolute humidity (x 10)
  - Sustained H_2O snowfall possible?
- Increased winds and dustiness

Madeleine et al. (2009)

~(100°E, 40°S)

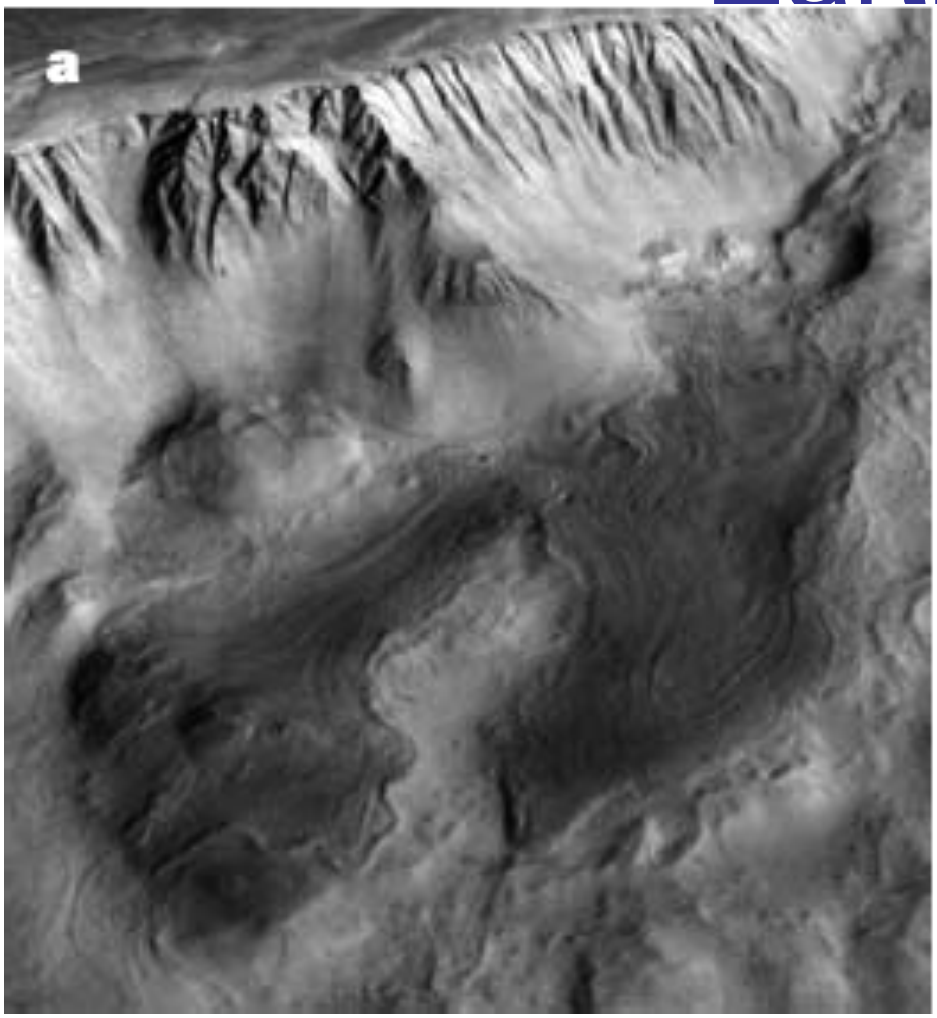


Low/mid-latitude water-ice glaciers on Mars

- Ice-filled craters
- Evidence of ice-flow down slopes and between depressions
- Origin of water ice?
  - Sub-surface…..?
  - Precipitation….?

Credit: Mex HRSC - Head et al. 2005)

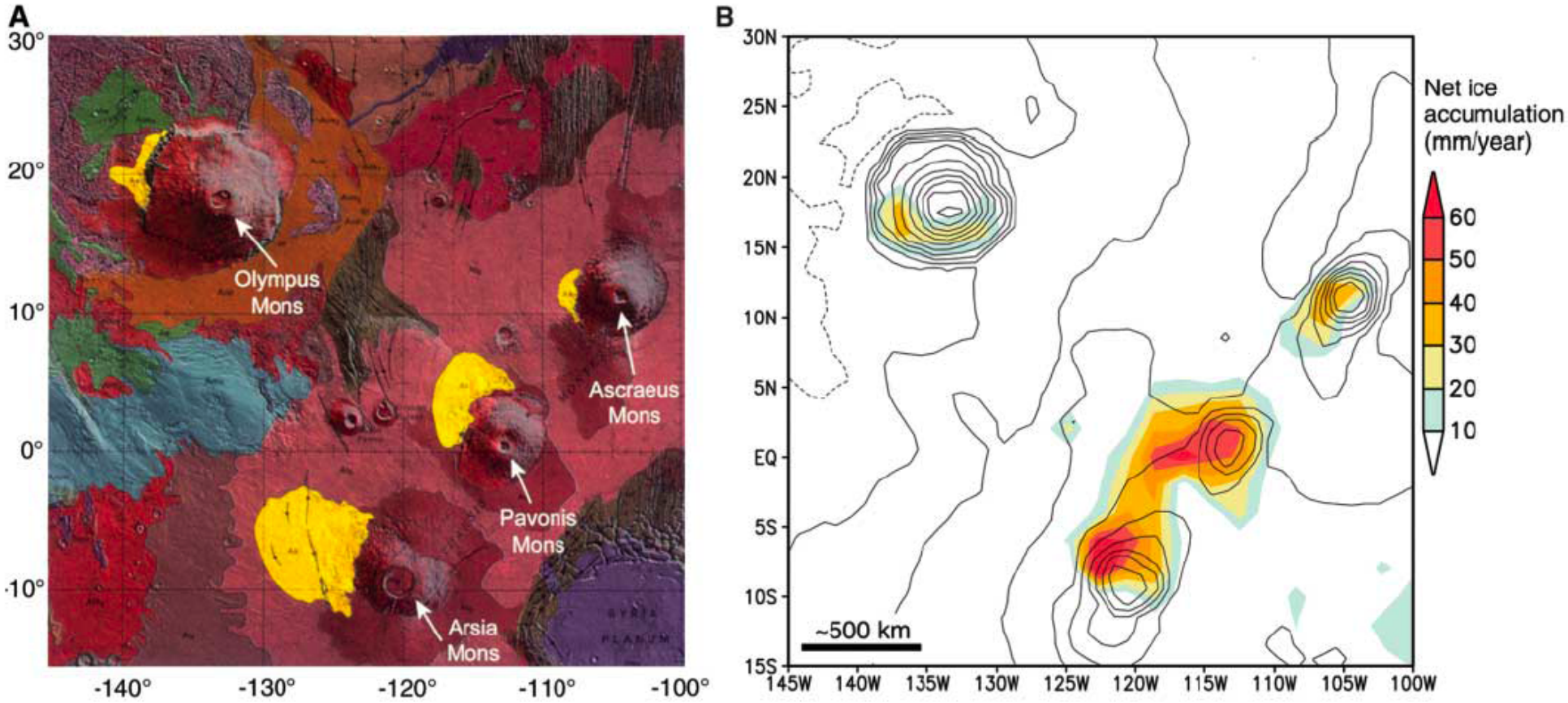
Rock glaciers on Mars and Earth



Olympus Mons (Mars)

Antarctic Dry Valleys (Mullins)

H_2O Snowfall on Tharsis at high obliquity (o > 40°)?

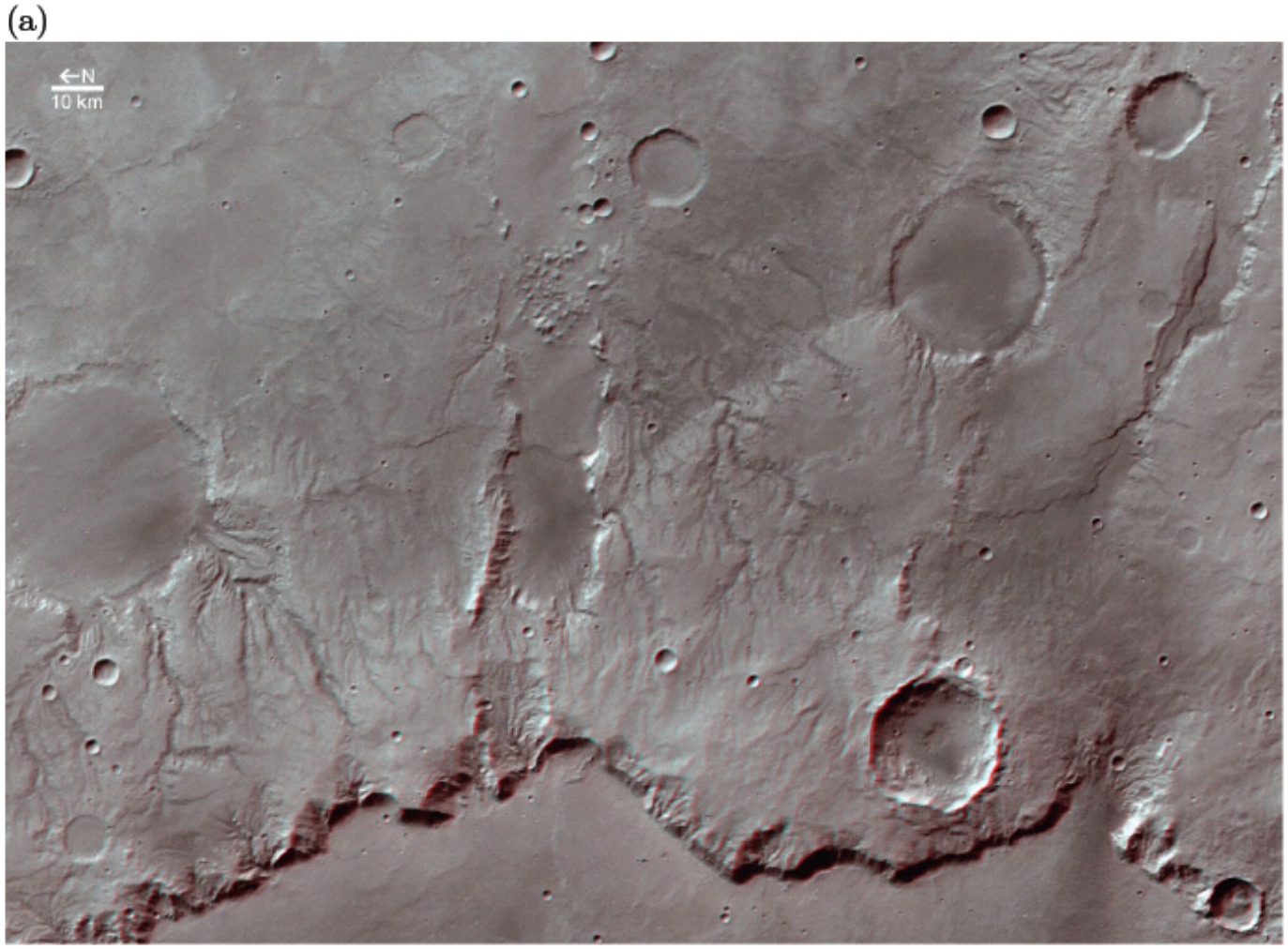


From Forget et al. *Science* (2006) - LMD GCM at o=45°

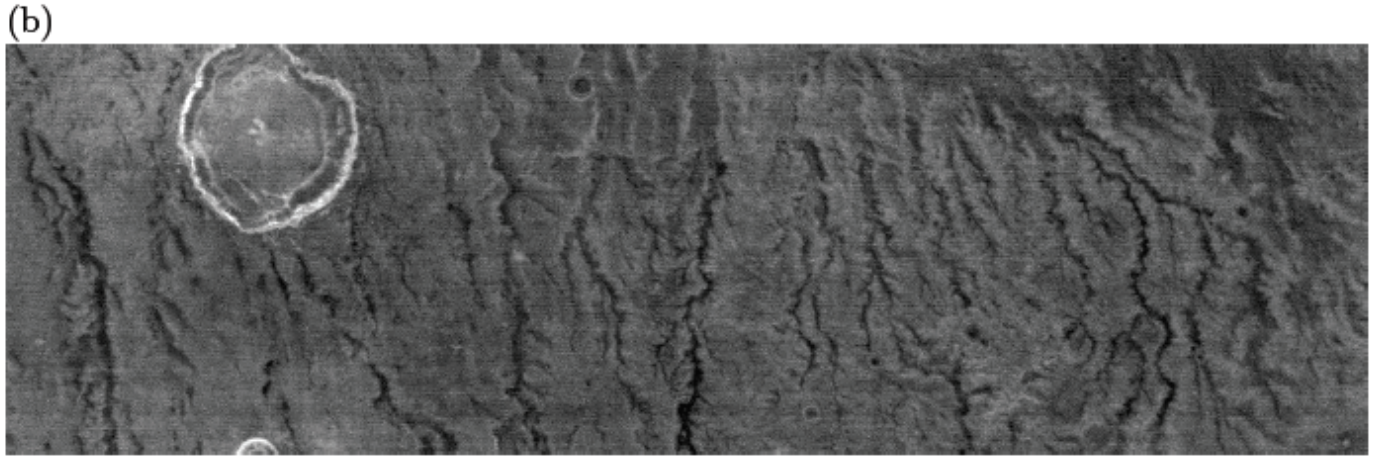
Water on Mars in the (distant - >3 Gyrs) past?

- sinuous channel networks

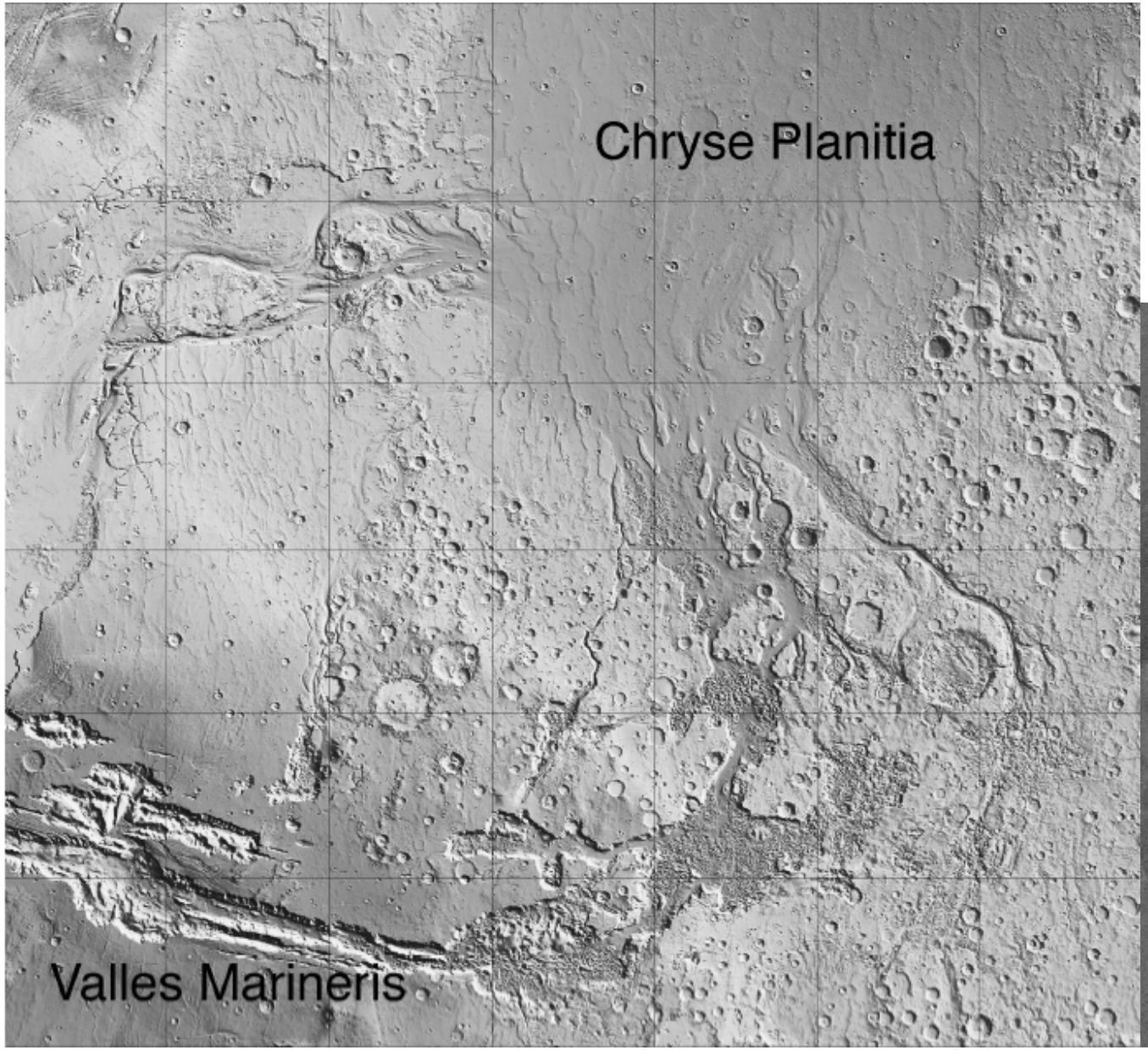
MEx
HRSC



MOd
THEMIS

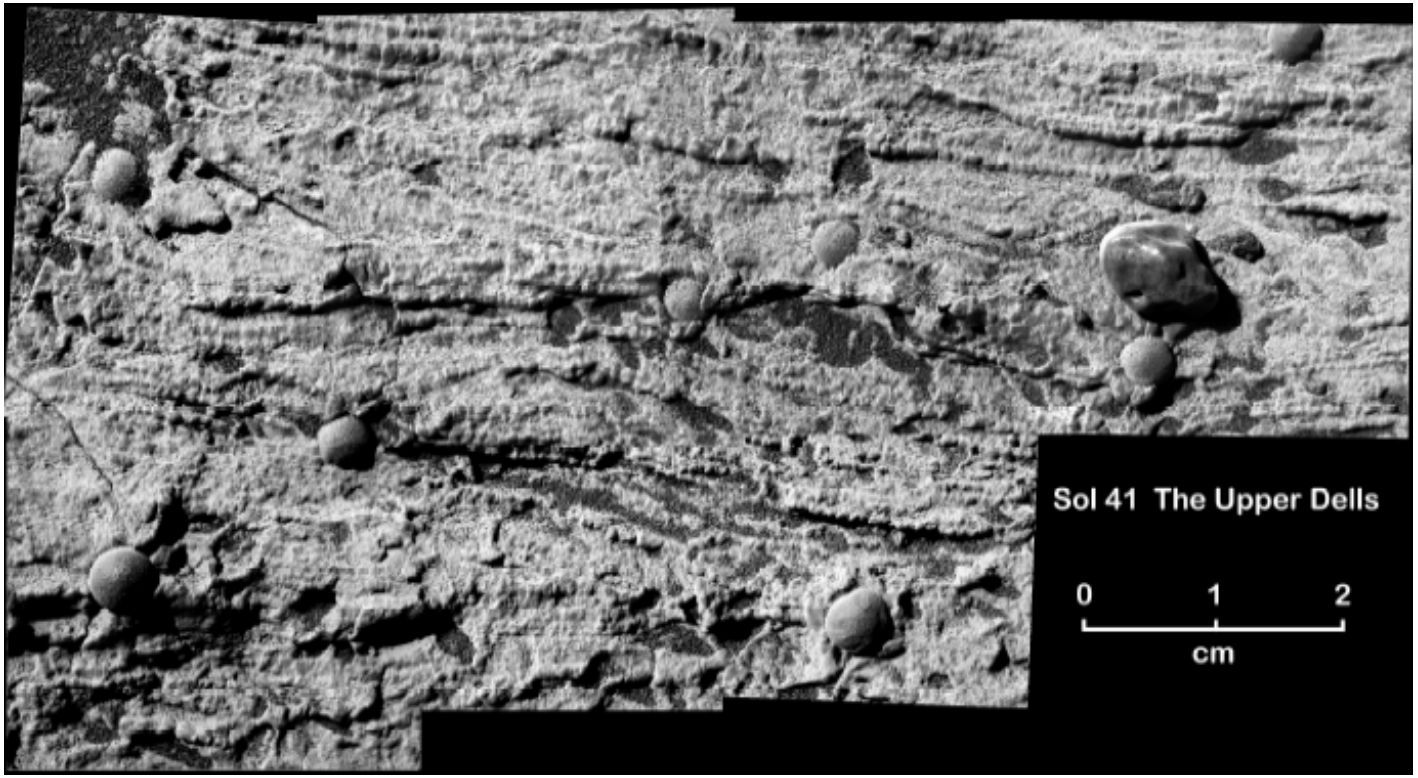


Catastrophic flood plains



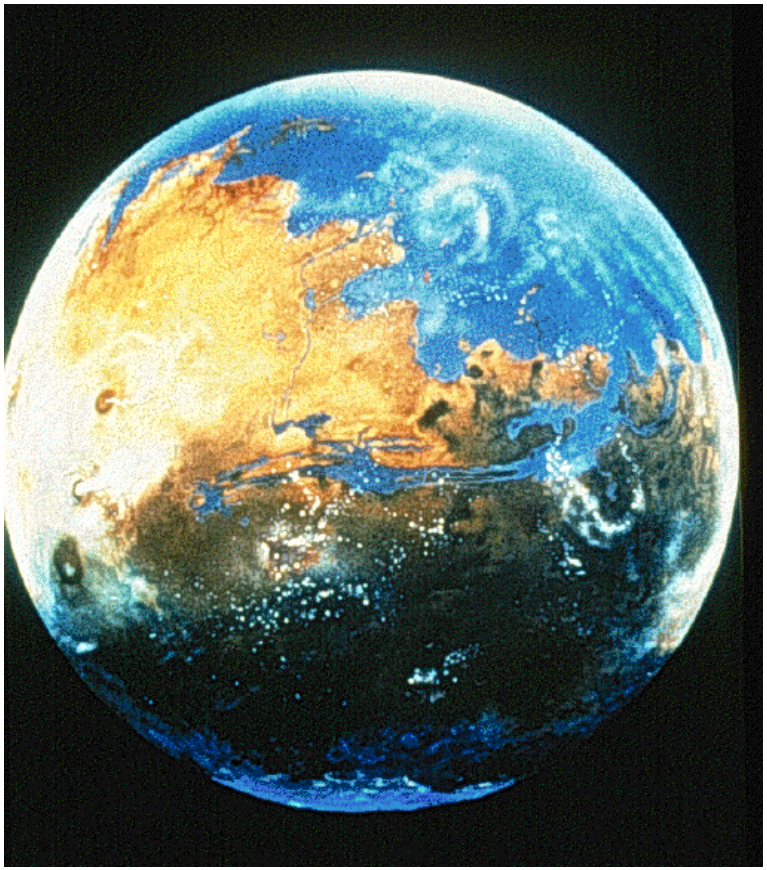
- Outflow channels
- Streamlined islands and craters

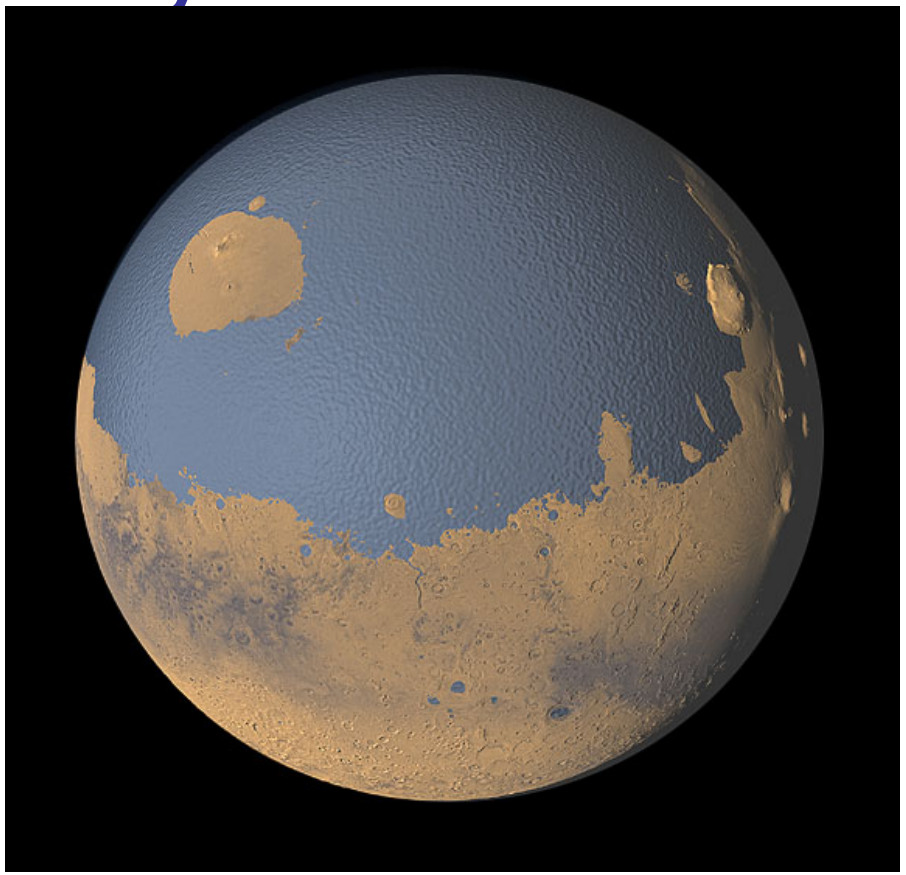
Evidence for past water on Mars



- ‘Blueberry’ spherules of haematite in rock deposits found at Opportunity landing site
- Requires liquid water to form…..

Water on early Mars?



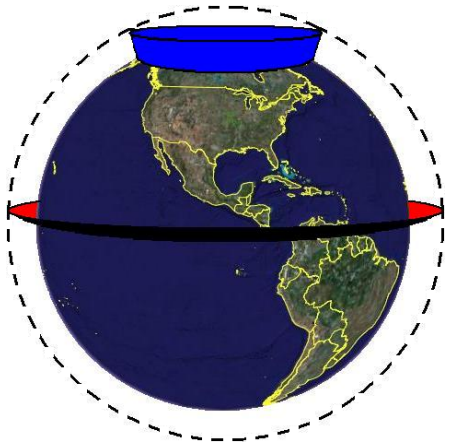


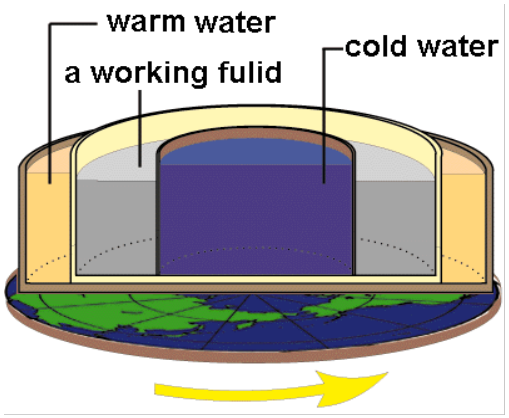
- Early ocean >3.5 Gyrs ago?
- Depth up to 500m, mainly in low-lying N Hem.
- **How were conditions maintained…?**

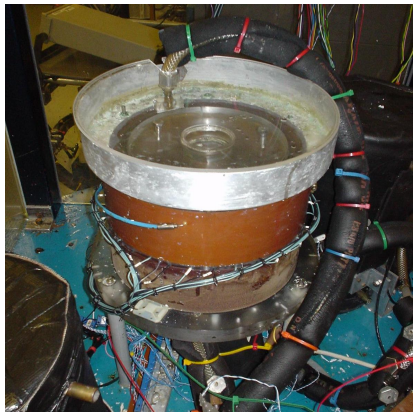
Themes

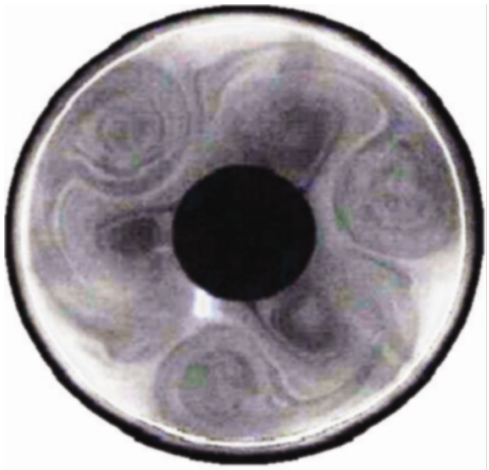
- Mars as an Earth-like planet
  - Present day atmospheric circulation
  - Meteorology and climate
- Mars in the ‘habitable zone’….?
  - Water and the hydrological cycle
- Mars’ dynamically changing climate
  - Astronomically-controlled cyclic changes
  - Wet and warm(er) in the past….?
- Mars atmosphere in context
  - Circulation regimes and climatological parameter space

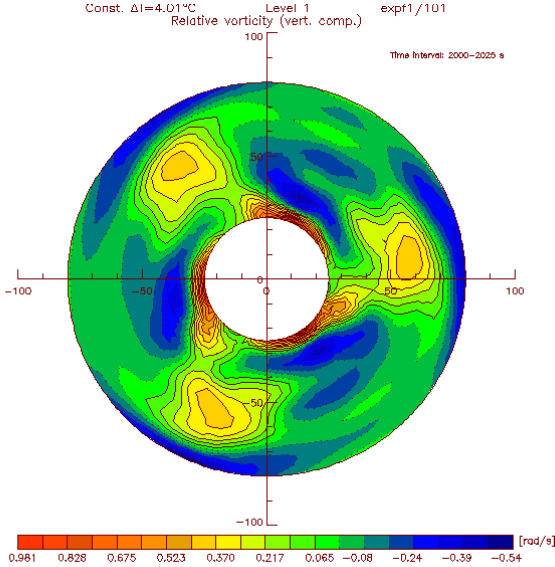
Laboratory Analogues of Planetary Atmospheric Circulation Systems











- *Baroclinic instability*

- a potential energy releasing instability in the atmosphere and oceans

Key parameters

Many possible dimensionless combinations (Pi theorem) - BUT dynamical similarity depends PRIMARILY on only a few

- Force scaling
  - Coriolis to viscous

$$\frac{4\Omega^2 L^4}{\nu^2}$$

$$Ta = \frac{4\Omega^2 (b-a)^5}{\nu^2 \quad d}$$

- Taylor Number

  - Inertial to Coriolis

$$\frac{U}{2\Omega L}$$

- Using geometry and geostrophic thermal wind

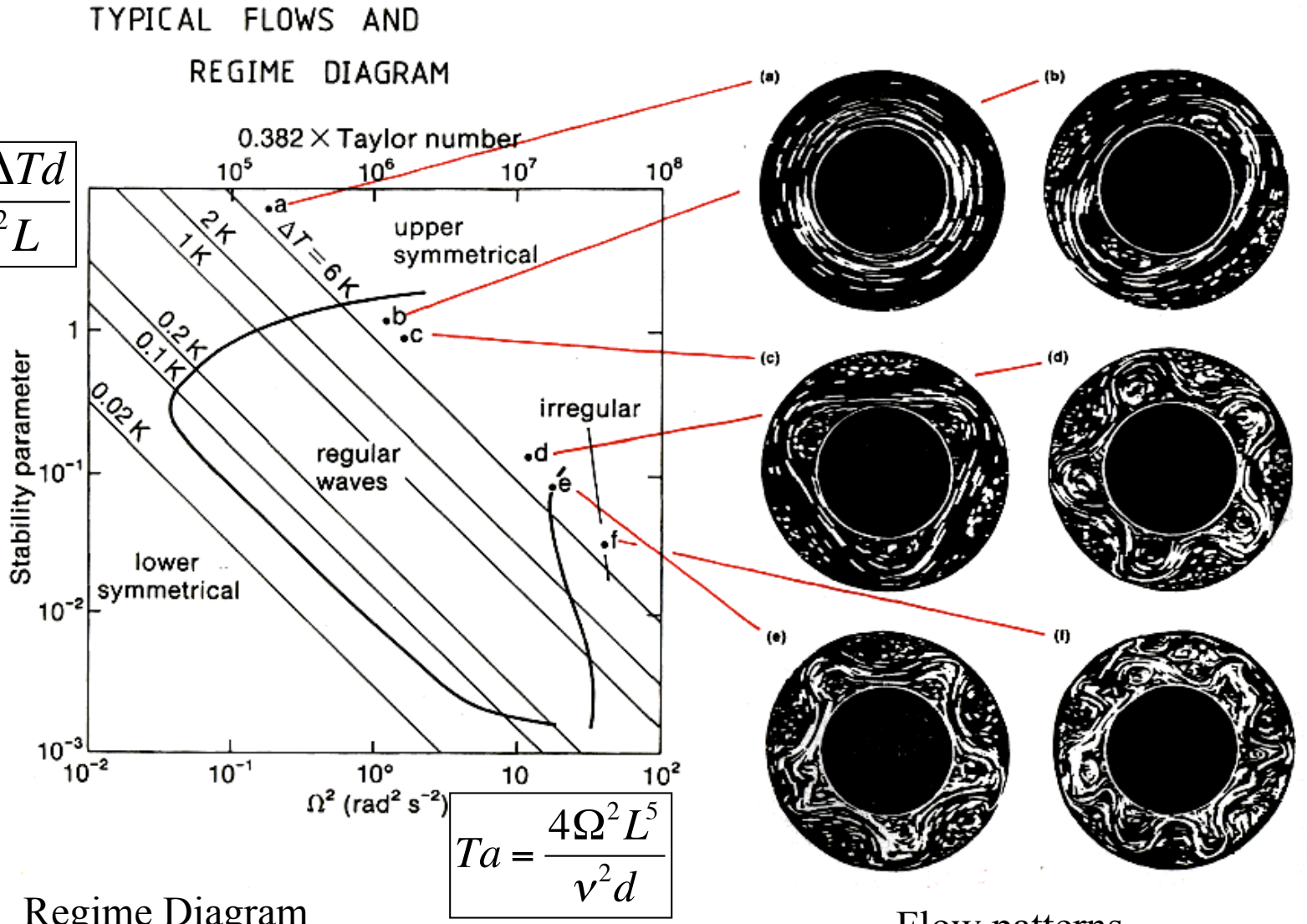
$$\Theta = \frac{g\alpha \Delta T \; d}{\Omega^2 (b-a)^2}$$

- Θ (thermal Rossby number)

CIRCULATION REGIMES

The baroclinic annulus experiment

$$\Theta = \frac{g\alpha\Delta T d}{\Omega^2 L}$$



$$Ta = \frac{4\Omega^2 L^5}{\nu^2 d}$$

Regime Diagram

Flow patterns

Planetary parameters

- Thermal Rossby and/or Burger number

$$\Theta = \frac{g\Delta\theta_y H}{\Omega^2 R^2 \theta_0} \quad \text{or} \quad Bu = \frac{N^2 H^2}{\Omega^2 R^2}; \; [N^2 = (g\,\partial\theta/\partial z)/\theta_0]$$

- Rhines lengthscale (based on thermal wind)

$$L_{Rh} = \pi\left(\frac{g\Delta\theta_y H}{2\Omega^2\theta_0}\right)^{1/2} = \pi R\sqrt{\frac{\Theta}{2}}$$

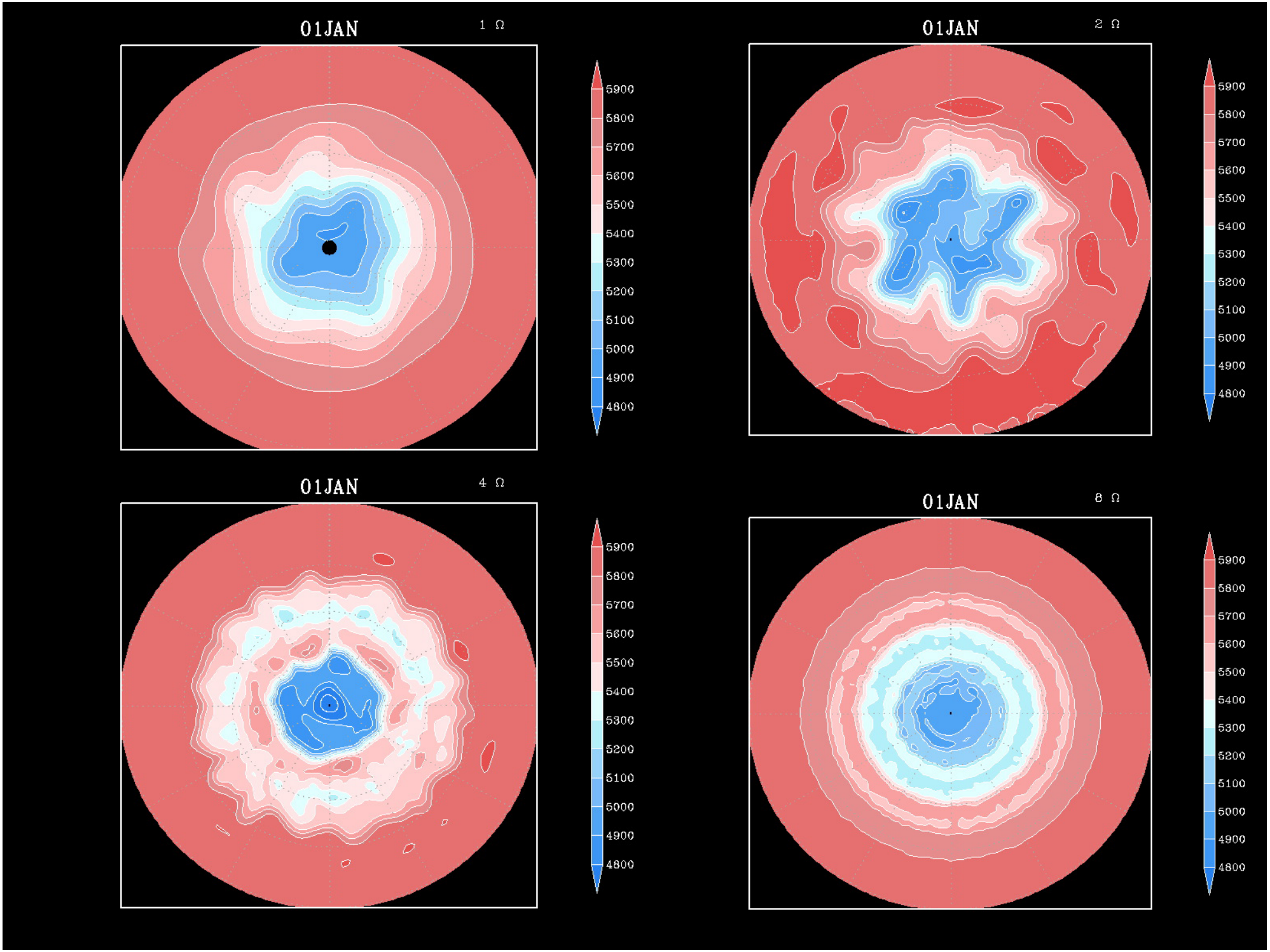
- Jet number

$$N_J \approx \frac{R\Omega}{\pi}\left(\frac{2\theta_0}{g\Delta\theta_y H}\right)^{1/2} = \frac{1}{\pi}\sqrt{\frac{2}{\Theta}}$$

NB - How to estimate/***predict*** $\Delta\theta_y$ & $\partial_z\theta$?

- Dissipation parameter[?]

$$F_r = 4\Omega^2 \min(\tau_{rad}^2, \tau_{fr}^2); \;\; [\text{cf } Ta = 4\Omega^2\tau_{visc}^2]$$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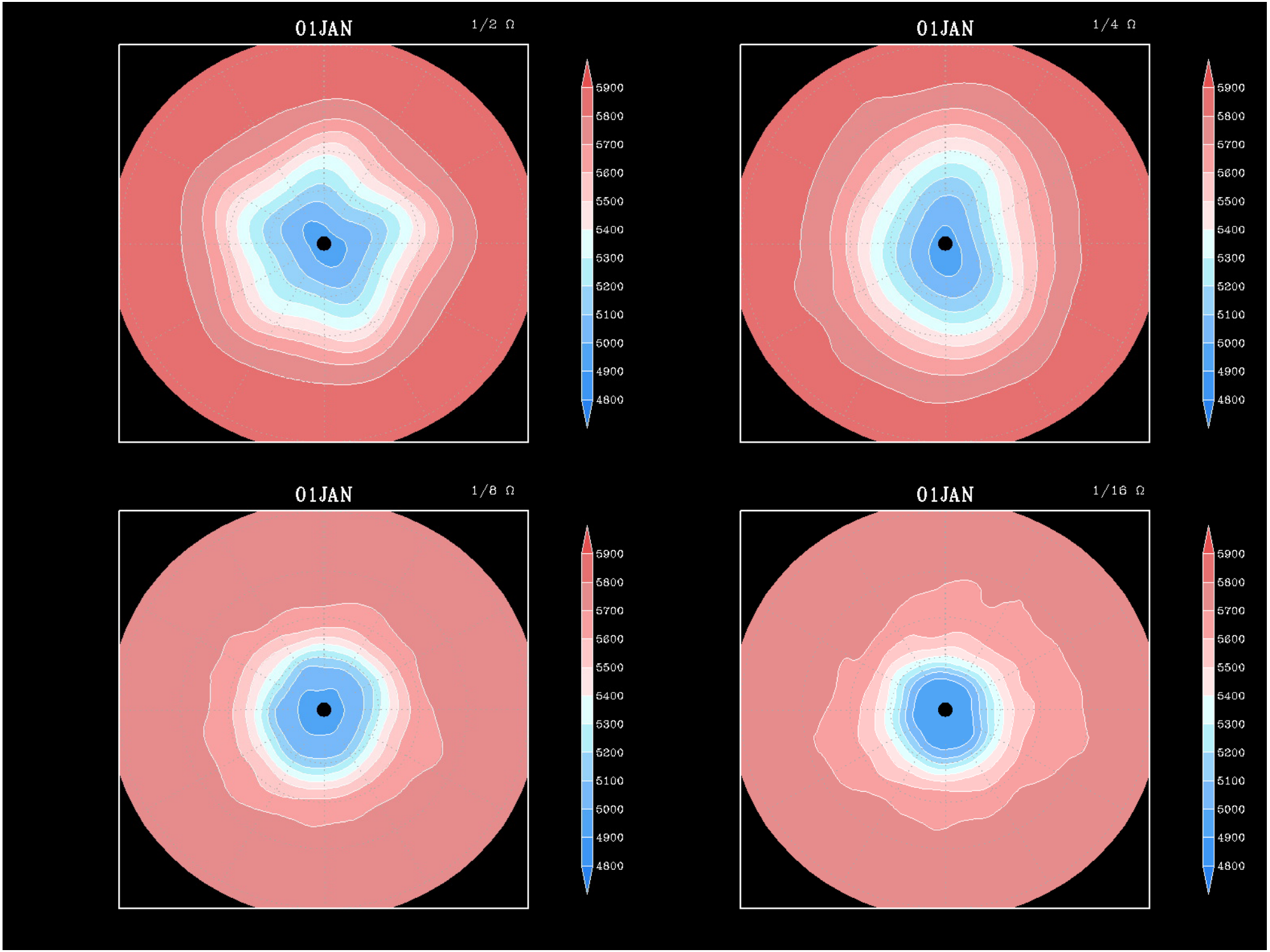
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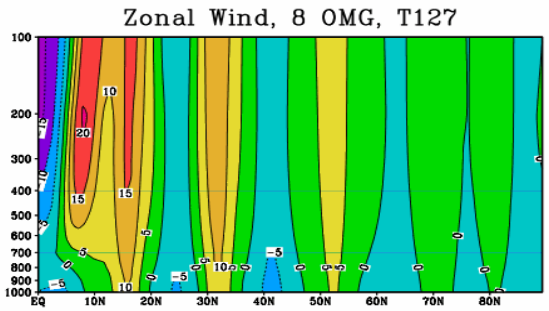
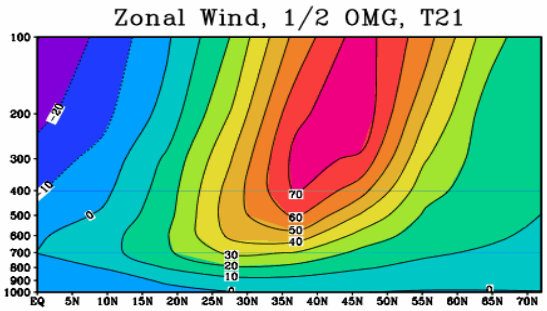
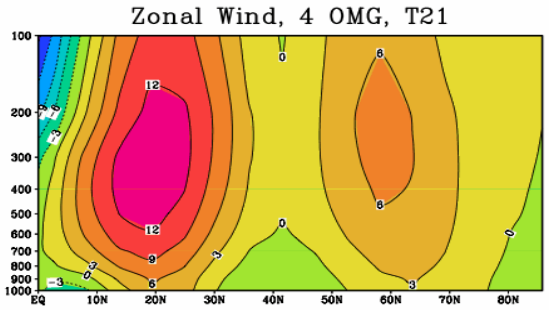
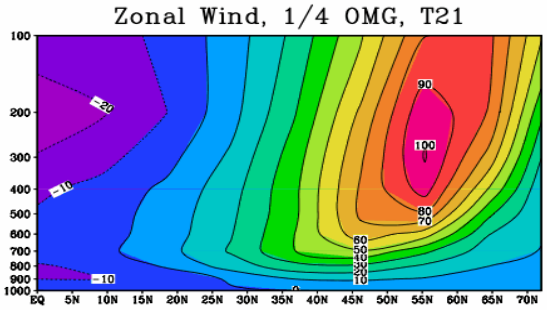
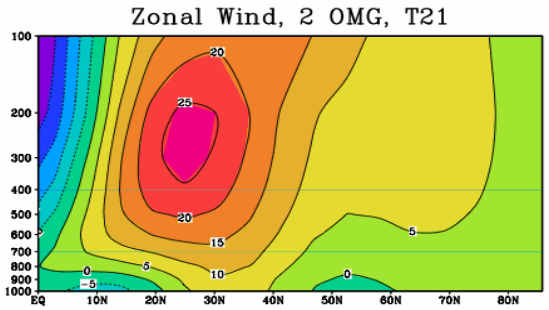
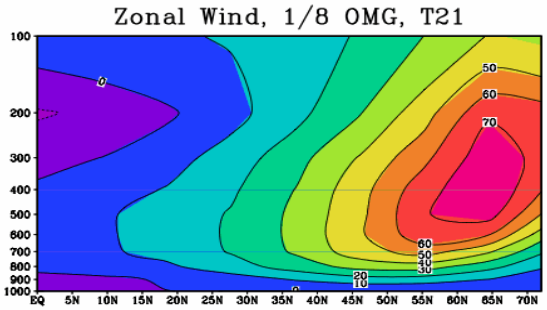


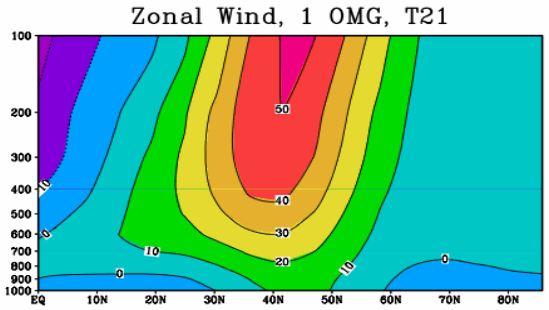


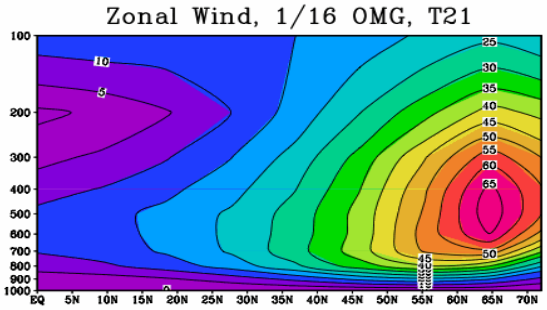












Varying Ω in a terrestrial GCM (Wang & Read 2010)

(T21-127L10)

From previous considerations

- $N_J \sim R\Omega$ (if $\Delta\theta_y$~constant)

Planetary parameters

Ω/Ω^*	Θ	N_J	$4\Omega^2\tau_R^2$
1/16	20	0.04	62
1/8	5	0.07	247
1/4	1.3	0.14	992
1/2	0.32	0.28	4000
1	0.08	1.57	1.5e4
2	0.02	2.1	6.3e4
4	0.005	3.3	2.5e5
8	0.001	5.5	1.0e6

Cf Venus?

Cf Mars?

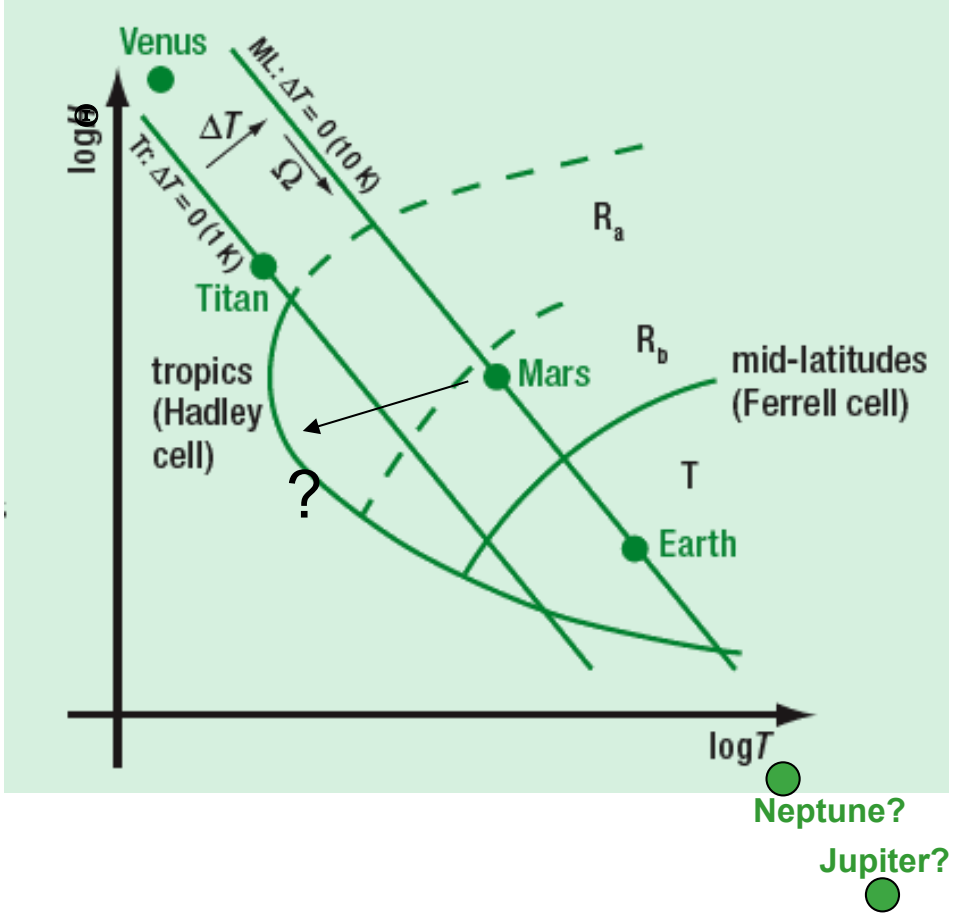
Cf Earth

Planetary parameters

Planet	**Θ**	**Bu**	**N_J**	**$4\Omega^2\tau_R^2$**
Earth	0.08	0.02	1.6	16000
Mars	0.17	0.04	1.0	44
Venus	370	140	0.02	16450
Titan	18	11.8	0.11	75000

Planetary circulation regimes

- Large-scale structure & style of circulation is determined largely by a few key (dimensionless) parameters
  - *Θ, Bu, T_r, T_f, obliquity, optical depths….*
  - Multiple (eddy-driven) jets, super-rotation, polar vortices, waves and eddies…..
- *Dynamical regimes separated by clear bifurcations at specific parameter values*
  - "Sudden" climate change…?
  - Multiple climate equilibria…?



Themes

- Mars as an Earth-like planet
  - Present day atmospheric circulation
  - Meteorology and climate ***remarkably Earth-like (with some notable exceptions!)***
- Mars in the 'habitable zone'….?
  - Water and the hydrological cycle
  - ***Role of brines?***
- Mars' dynamically changing climate
  - Astronomically-controlled cyclic changes ***- major climatic changes, including ppn, snowfall and local glaciation***
  - Wet and warm(er) in the past….?
- Mars atmosphere in context
  - Circulation regimes and climatological parameter space
  - ***Circulation style and climate determined by a small number of key parameters [Θ and τ_R]?***

Drawing together the results of recent spacecraft studies and the very latest techniques of atmospheric modelling, *The Martian Climate Revisited* provides a comprehensive summary of our knowledge and current understanding of the meteorology and climate of Mars from the viewpoint of atmospheric scientists. Such knowledge is based not only upon direct observations of the structure of the atmosphere and the daily and seasonal evolution of the Martian weather systems and atmospheric circulation, but also on techniques such as numerical simulation and meteorological data assimilation, a topic in which the authors are currently pioneers in its application to Mars.

The Martian Climate Revisited contains:

- a detailed discussion of Mars' climate models, including topics such as general circulation models (GCMs), mesoscale modelling, upper atmosphere modelling and the applications of meteorological data assimilation
- a review of Mars' global-scale atmospheric structure, circulation and seasonal cycles
- descriptions of topographical influences on Martian atmospheric circulation, diurnal phenomena and transient weather systems
- clear explanations of the importance of dust in the Martian climate, detailing the role of dust storms and dust transport in circulation models
- a discussion of the role of water on Mars, both in the formation of the ancient Martian landscape and in its present climate
- informed speculation on the long-term human exploration and colonisation of Mars and possibilities for terraforming Mars

With its extensive section of colour plates and a comprehensive list of bibliographic material, *The Martian Climate revisited* is an invaluable source of reference.

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Read and Lewis

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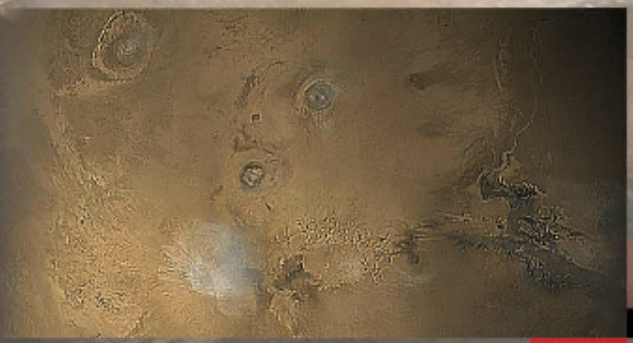
Peter L. Read and Stephen R. Lewis

THE MARTIAN CLIMATE REVISITED

Atmosphere and Environment of a Desert Planet



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