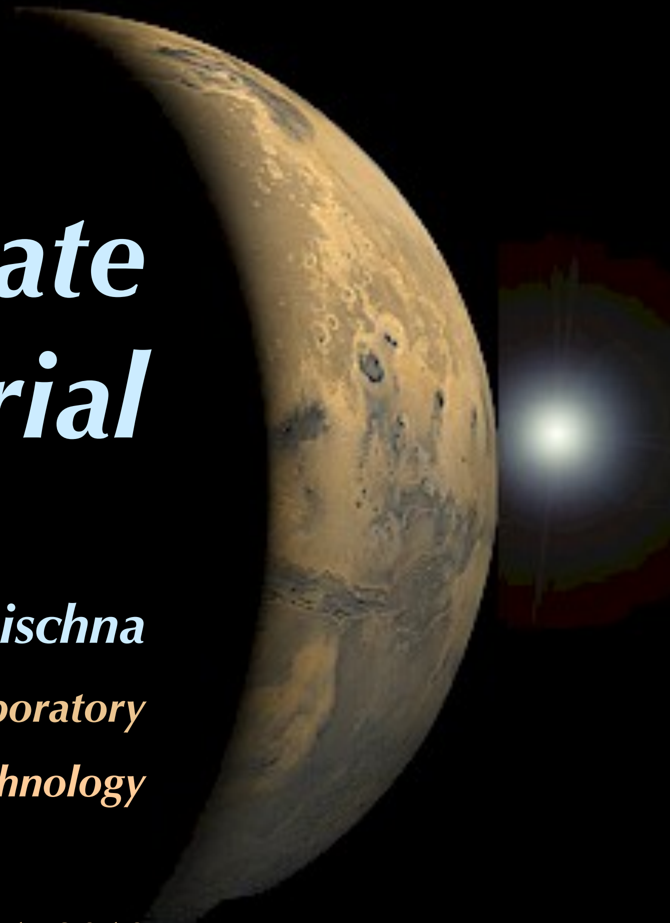


A Mars Climate Tutorial

Michael A. Mischna

Jet Propulsion Laboratory

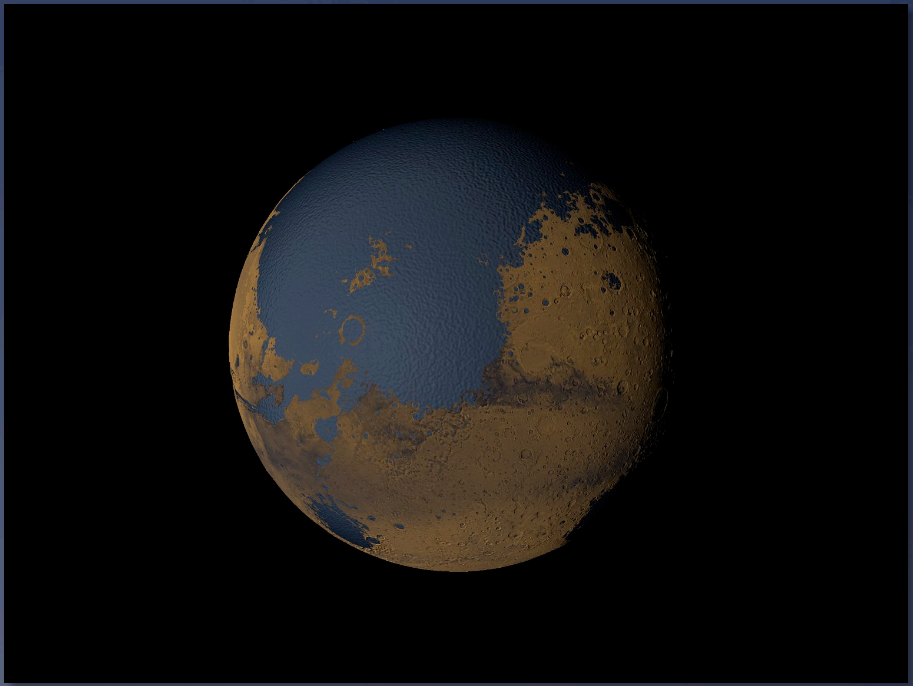
California Institute of Technology

March 31, 2010

Mars III Workshop, Les Houches, France

Introduction

- Trends in the martian atmosphere over many timescales alter the behavior of the atmosphere
  - "Warm/wet"
  - Global oceans
  - Orbital climate change
  - Greenhouse warming

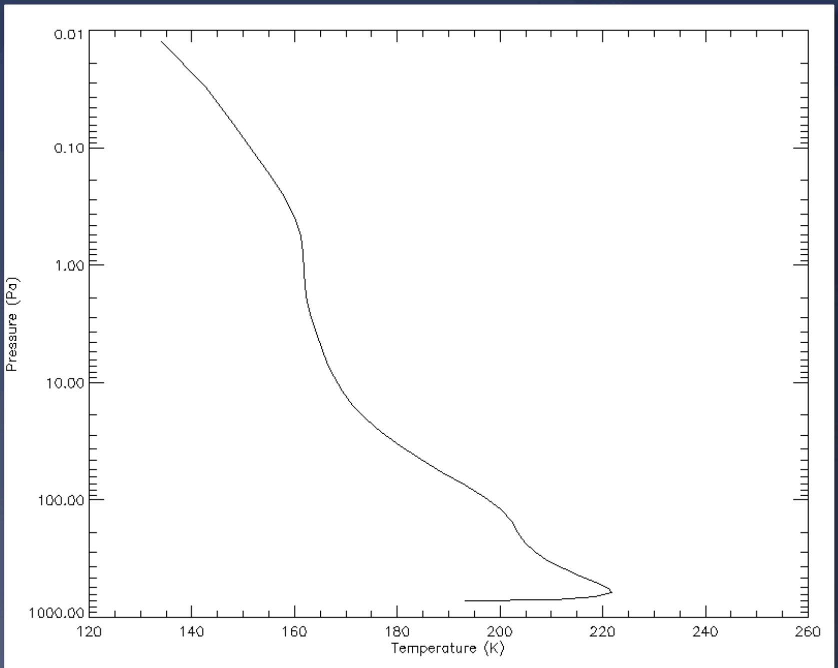


Introduction

- Provide a comprehensive overview of martian climate, past and present
- Companion talk to that of F. Forget this afternoon
- Theory
- Observations
- Modeling
- Mission applications

Outline

- Introduction
- The present-day climate system
  - Thermal structure
  - Basic meteorology
  - Dust cycle
- Past climate
  - Clues from observations
  - Addressing the early Mars climate enigma

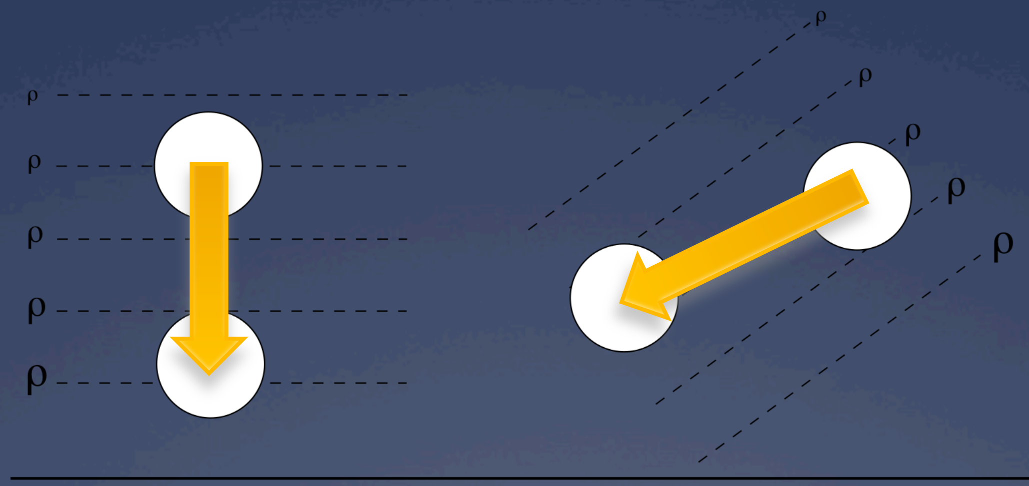


Outline

- Discussion geared towards the scientist who is *familiar* with physical principles, but perhaps *unfamiliar* with properties of the martian atmosphere/atmospheric circulation.
- We will address:
  - Temperature
  - Pressure (only brief mentions—defer until François's talk)
  - Winds
  - Dust

Modern Climate

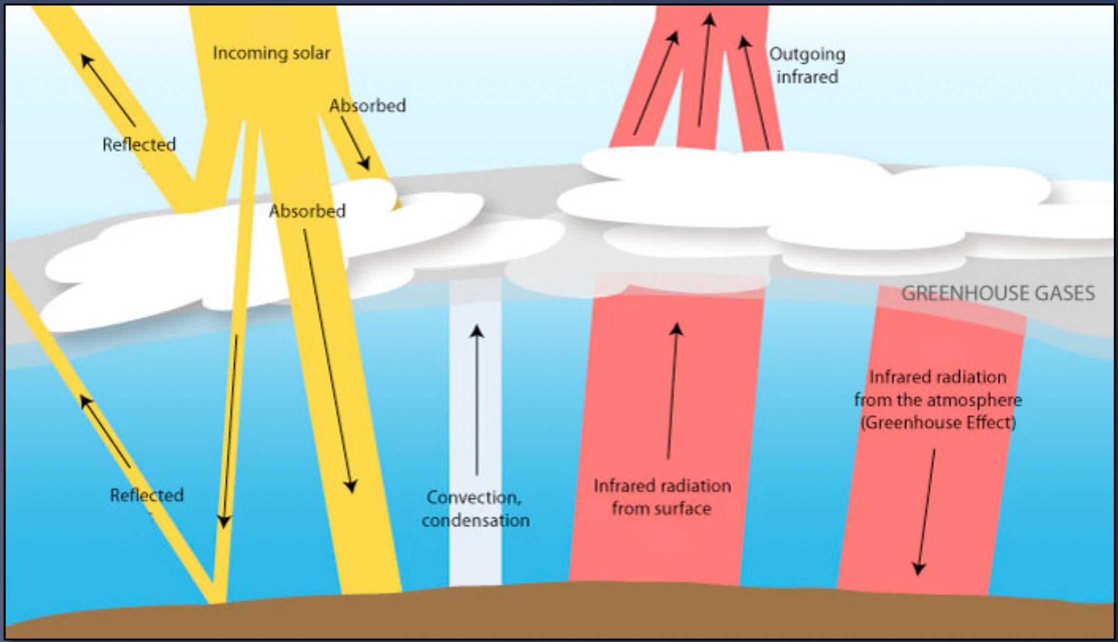
- Thermal structure of the martian atmosphere:
  - Density contrasts



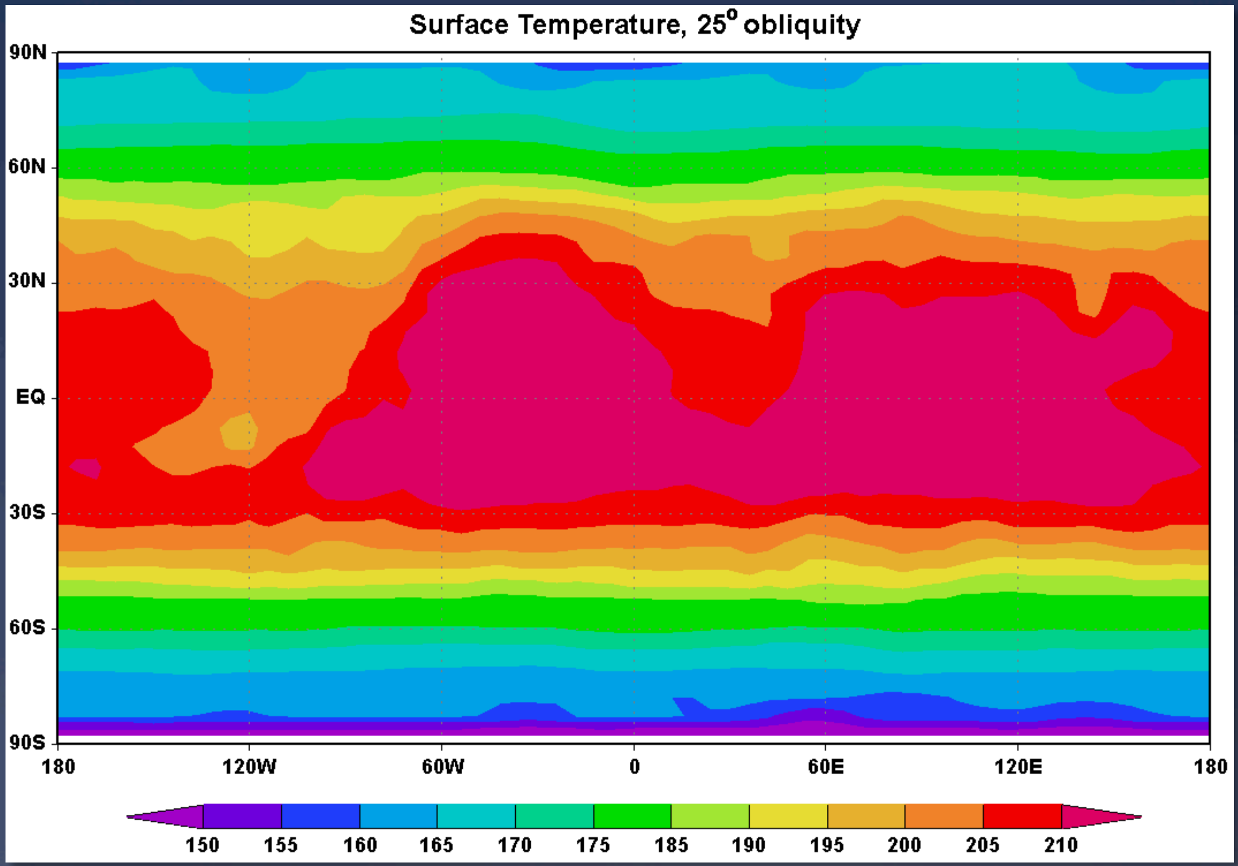
Adapted from Read and Lewis (2004)

Modern Climate

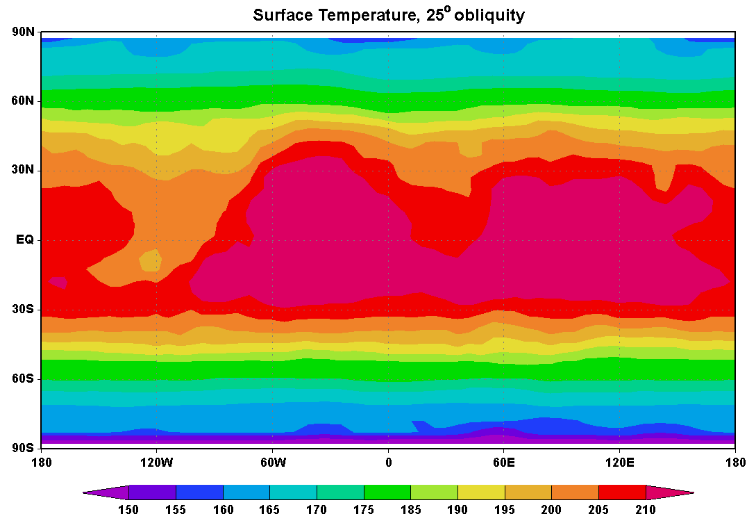
- Energy which drives circulation comes from the Sun
  - Absorption in atmosphere (gas/dust)
  - Absorption by surface
  - Re-radiation from surface/atmosphere
  - Dust scattering

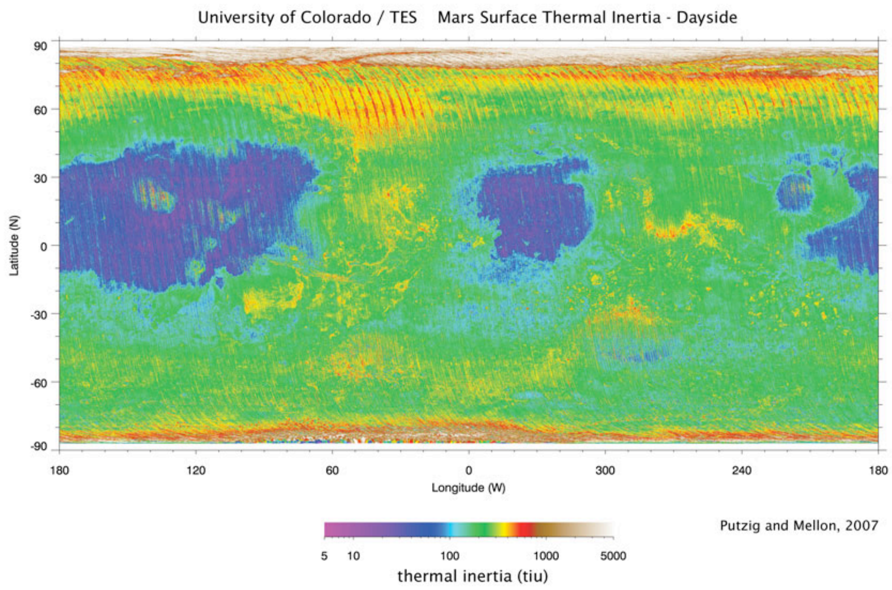


Surface Temperature

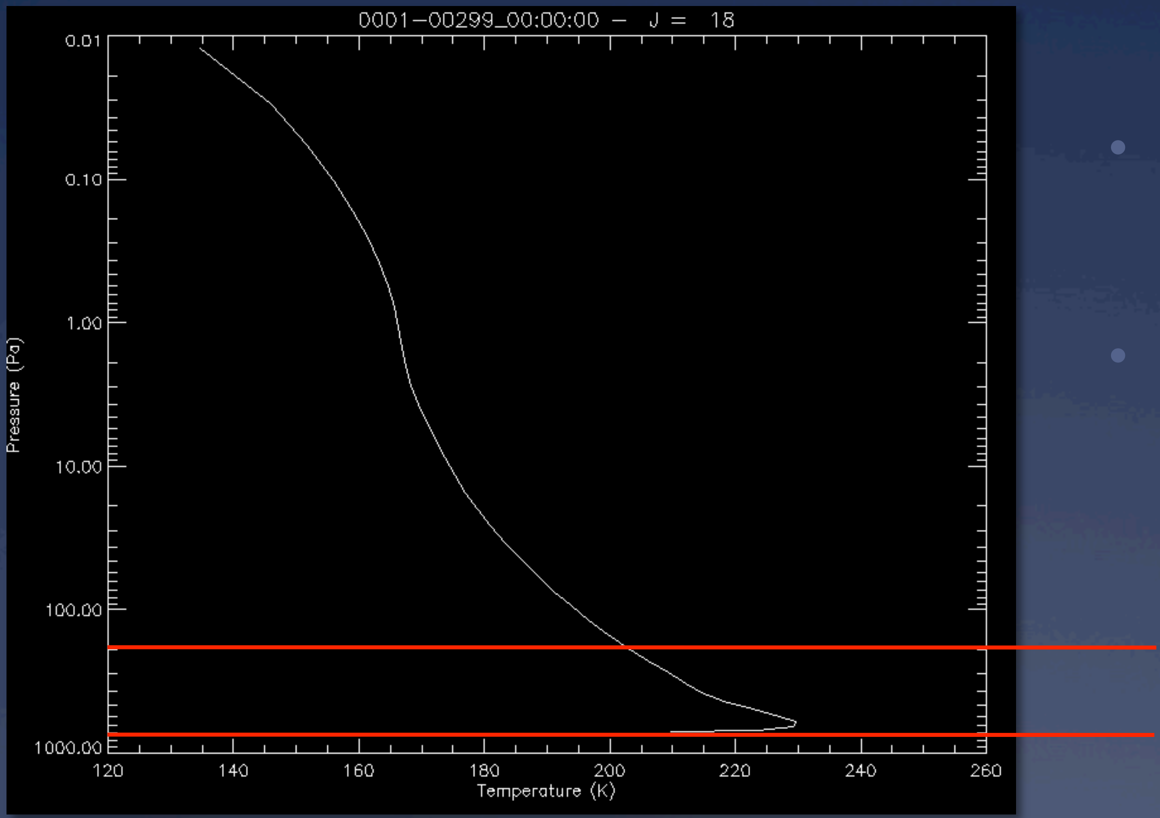


Surface Temperature





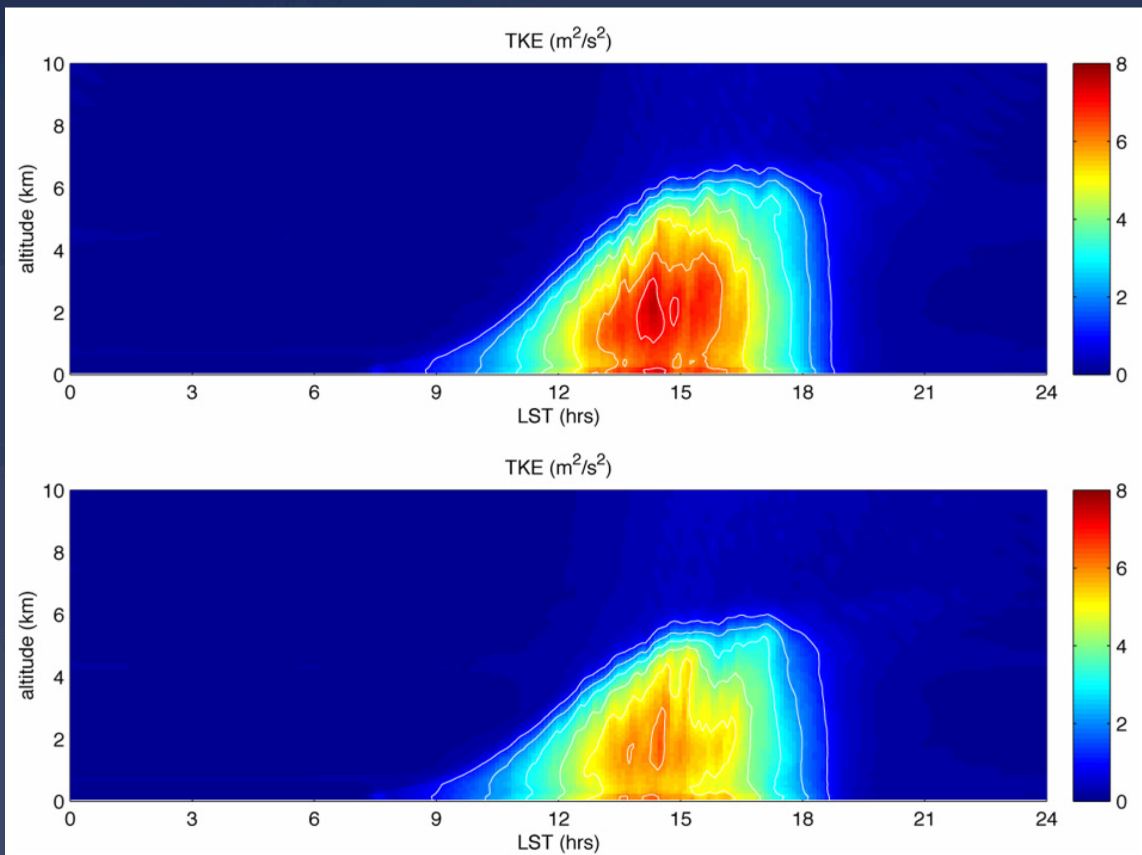
Vertical Profile



- Equatorial profile, 1 day, mid-summer
- Rapid sfc. heating/ cooling

Boundary layer,
~10 km

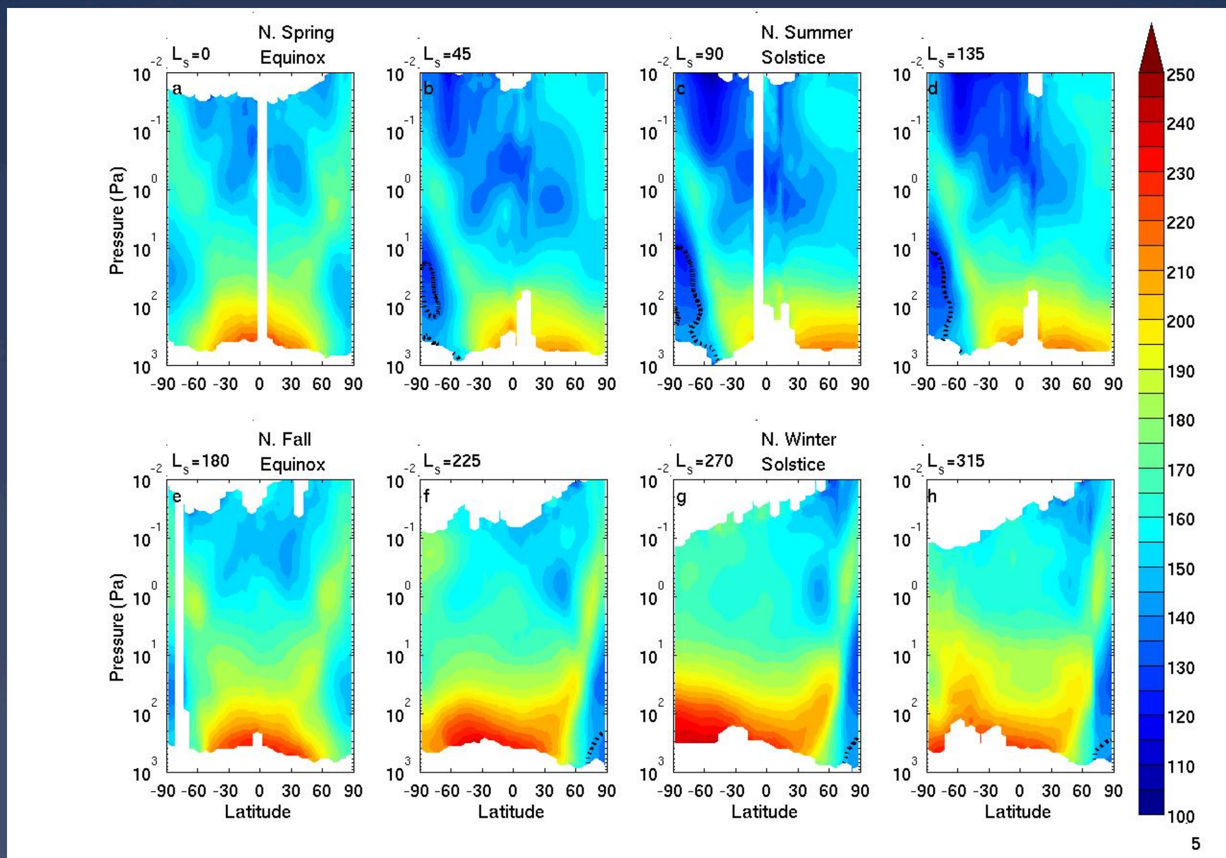
Turbulence



- Sub gridscale energy captured as turbulence
- Think of this as convective energy

Zonal Average Temperatures

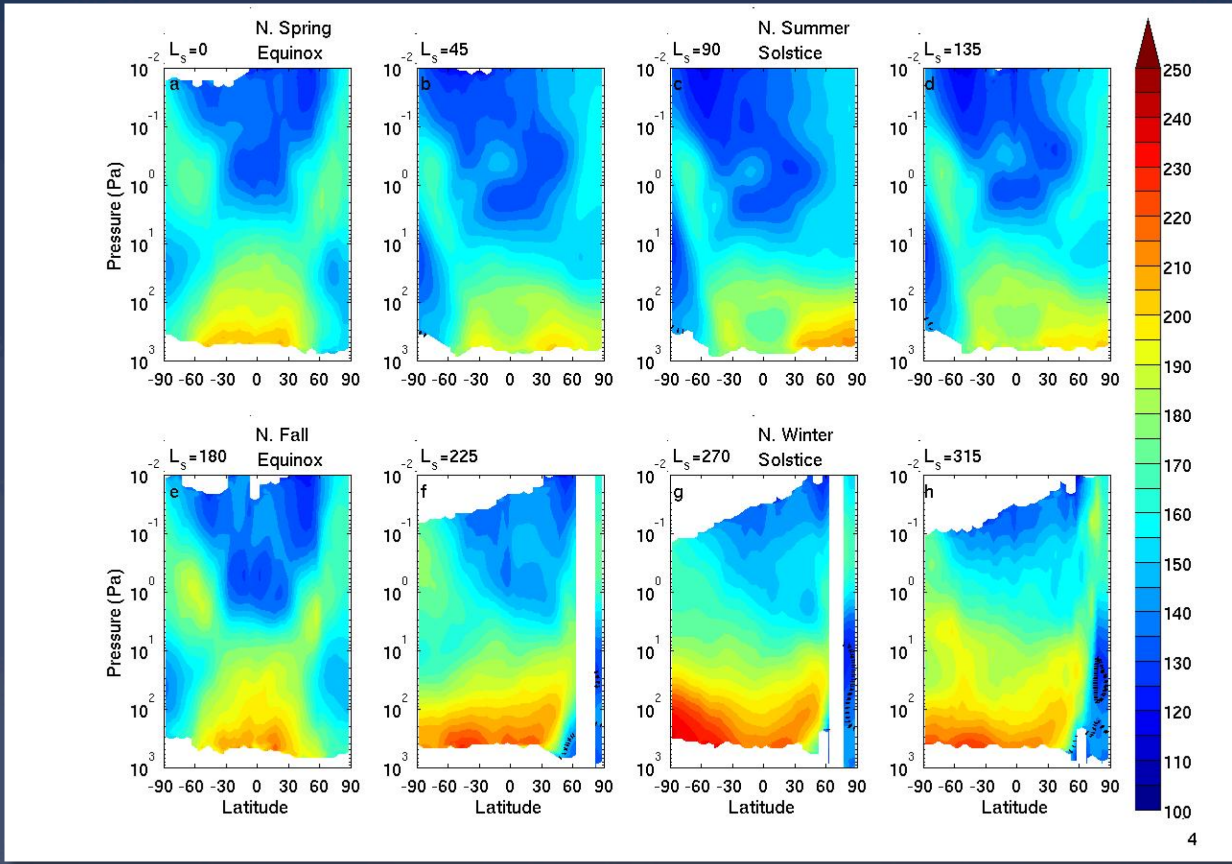
MCS temperatures, PM



from Heavens et al, *in prep.*

Modern Climate

MCS temperatures, AM



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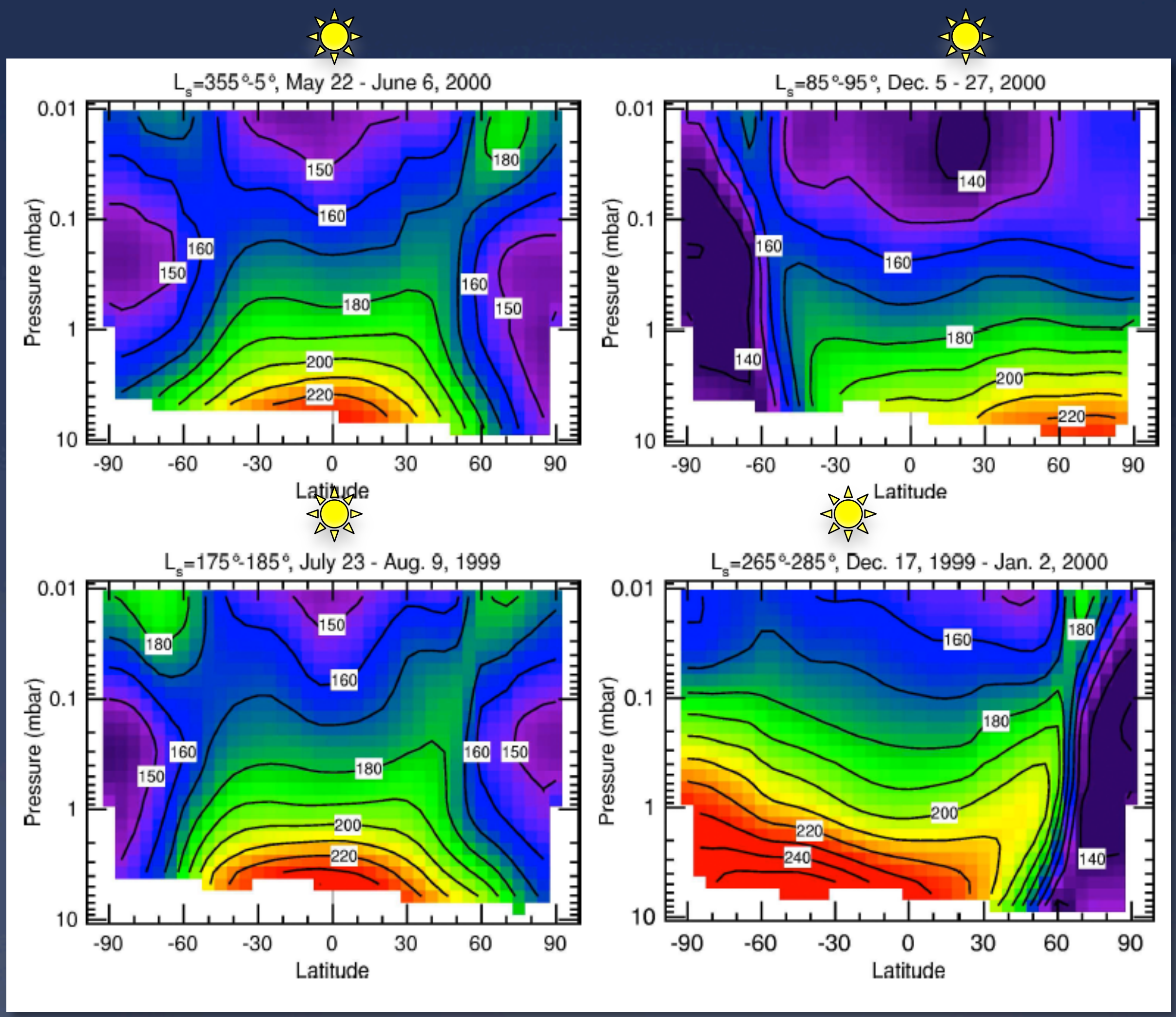
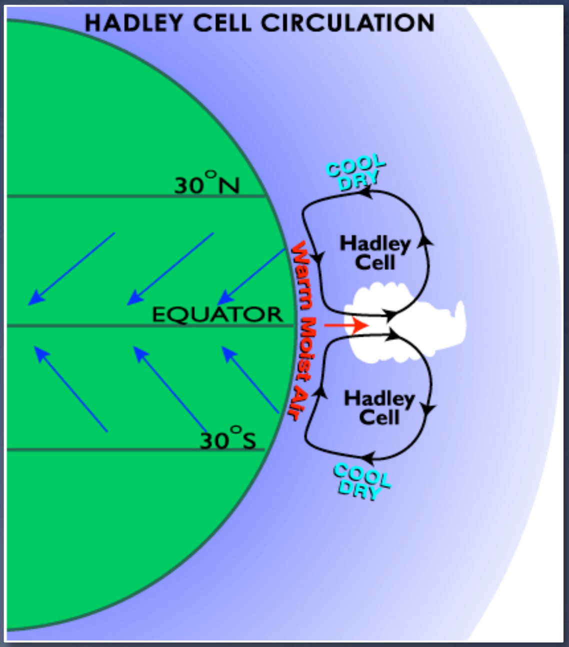
Zonal Average Temperatures



from Smith et al., (1999)

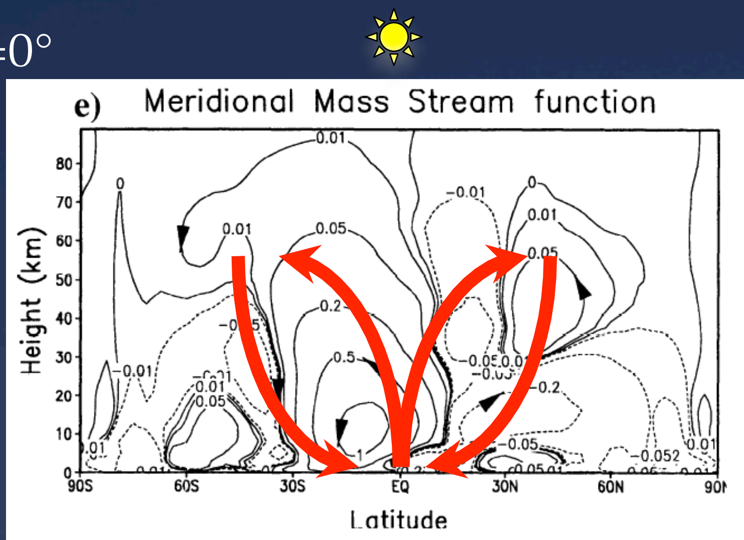
Winds and Circulation

- Hadley Circulation
  - Thermally direct overturning circulation
  - Imbalance of heating at equator and high latitudes
  - Similar to Earth

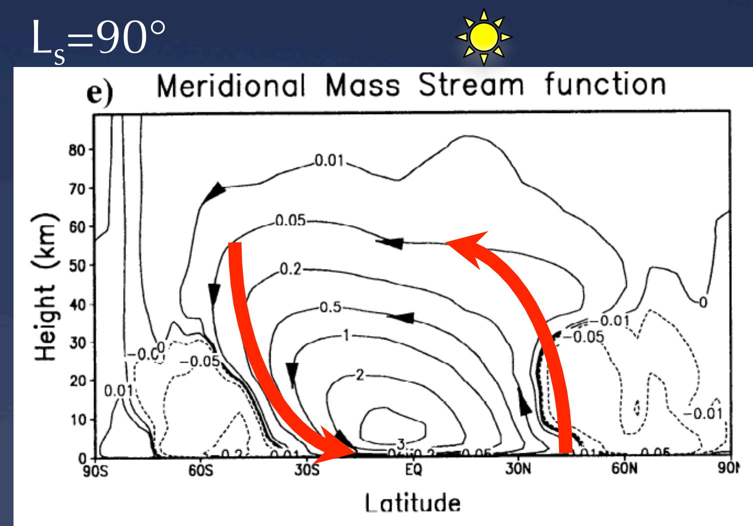


Mars Circulation

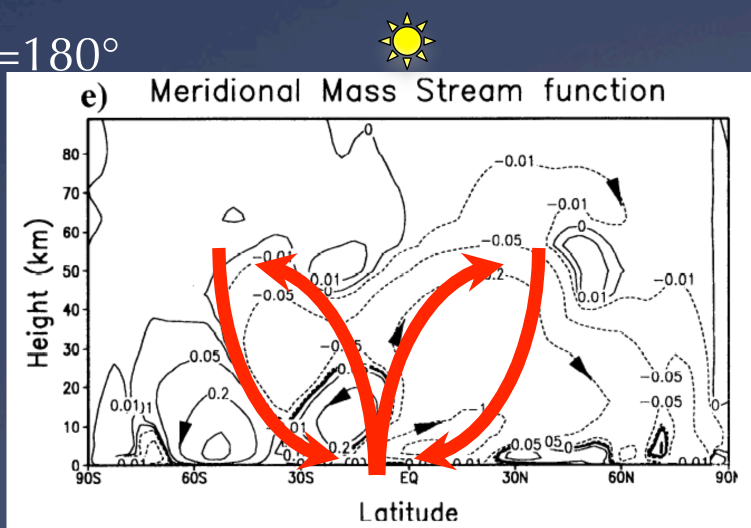
L_s=0°



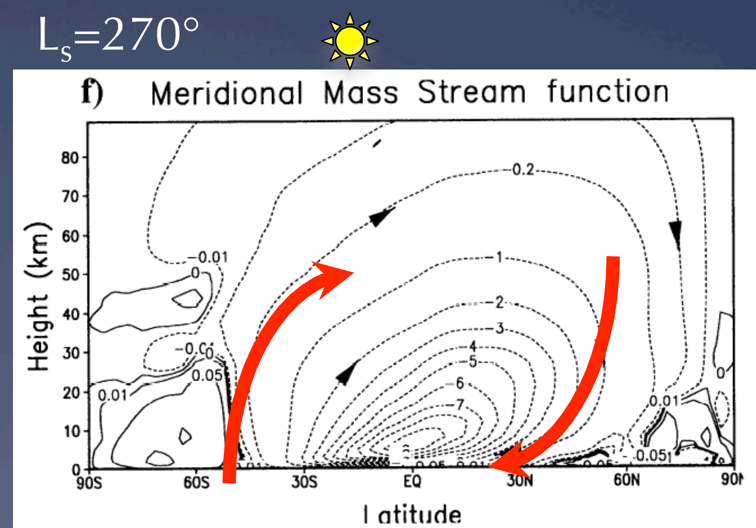
L_s=90°



L_s=180°



L_s=270°



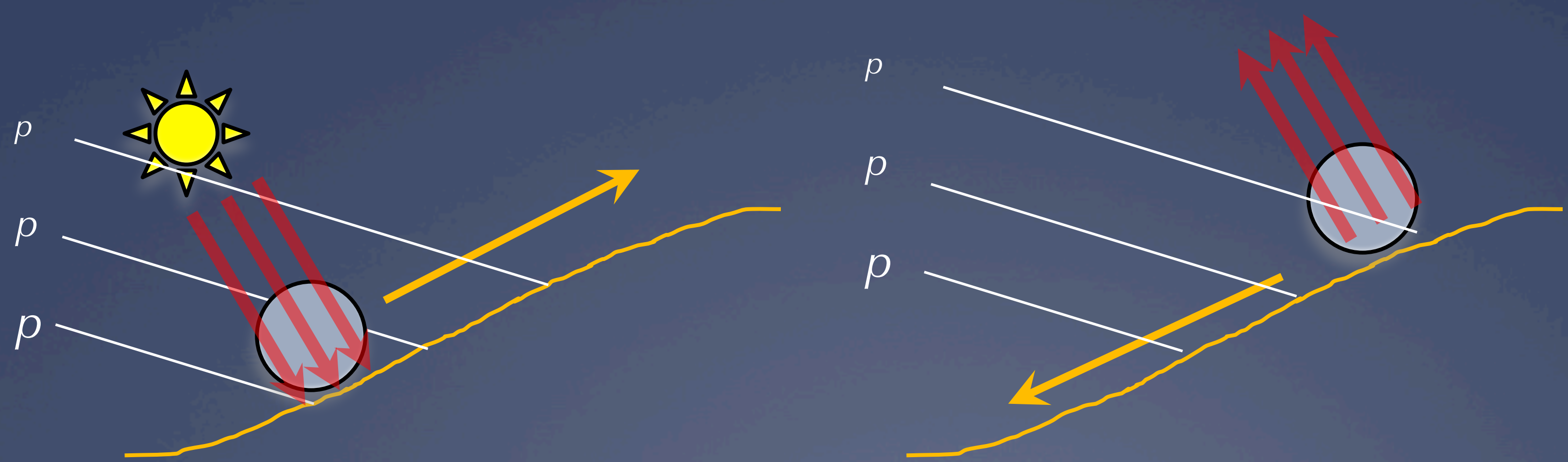
from Forget et al., (1999)

Local Circulation

- Modifiers of general circulation
  - Topography
  - Lack of oceans
  - Thermal contrast winds
  - Dust
- Tharsis height exceeds atmospheric scale height
  - Significant impact on atmospheric structure/stratification
- Topography is responsible for generating *waves* in the atmosphere, and restricting some wind patterns

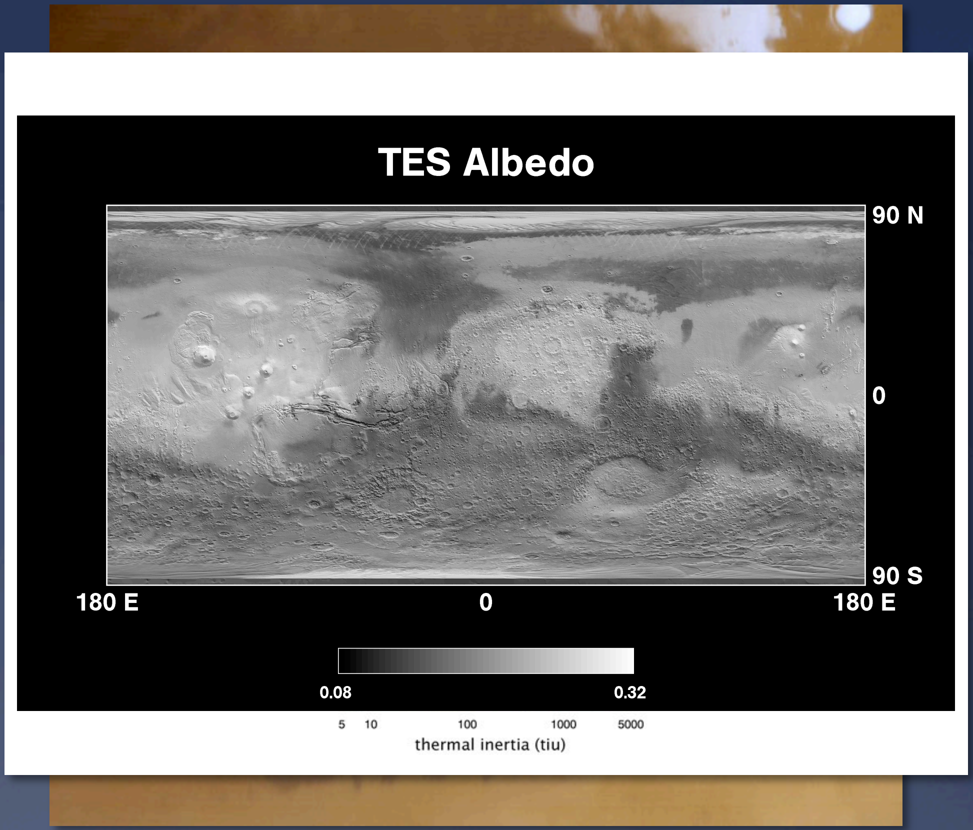
Local Circulation

- Slope winds
  - Driven on many different scales
  - Familiar to us on Earth, upslope/downslope winds
  - Buoyant air ascends, dense air descends



Local Circulation

- Thermal Contrast Winds
  - Similar in nature to slope winds
  - Also familiar to us, land/sea breezes
  - On Mars, driven by albedo/ TI differences
  - Polar cap edge winds



Winds on Mars

What we have directly measured

Winds on Mars

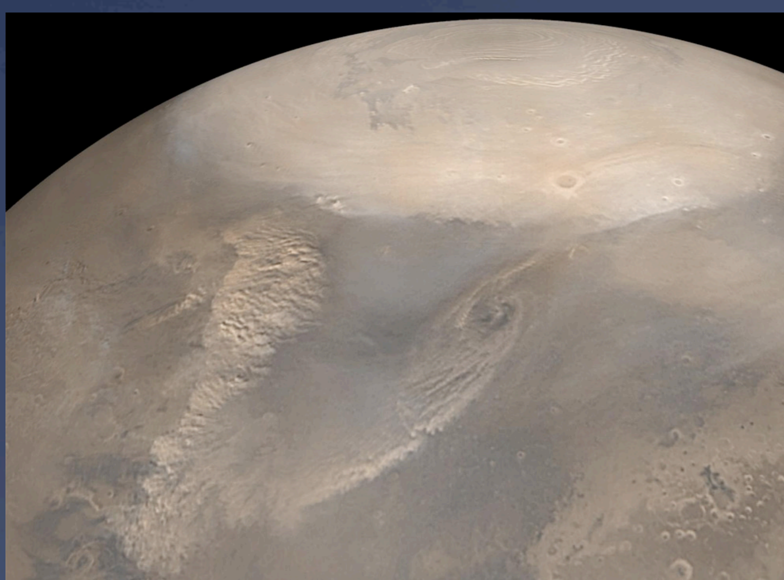
<u>What we have directly measured</u>

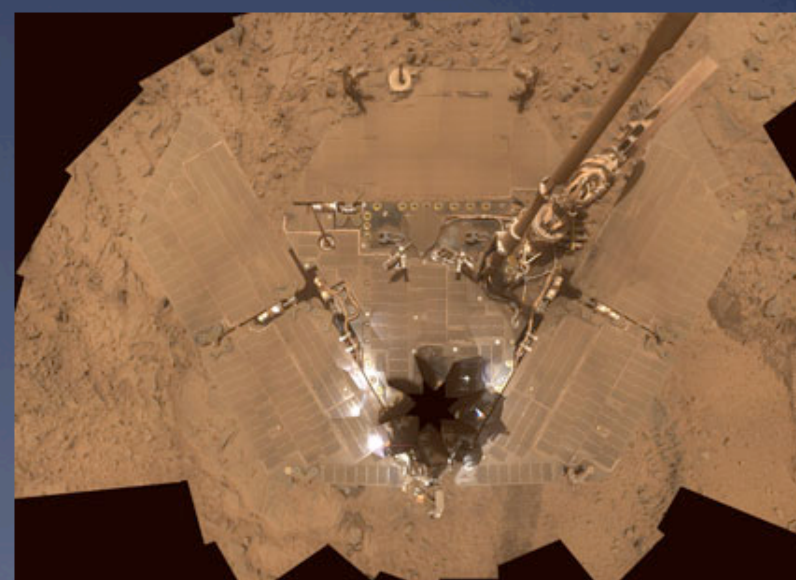
- Descent profiles (VL1, VL2, MPF, MER, PHX)
- Lander time series (VL1, VL2, MPF, PHX)
  - But they are poorly calibrated and somewhat qualitative
- Cloud tracking from sfc/orbit/Earth

Despite their critical importance to safe EDL, and being a lynchpin of the whole climate system, we have never obtained adequate wind measurements, and there are no plans to accommodate such instruments on future missions.

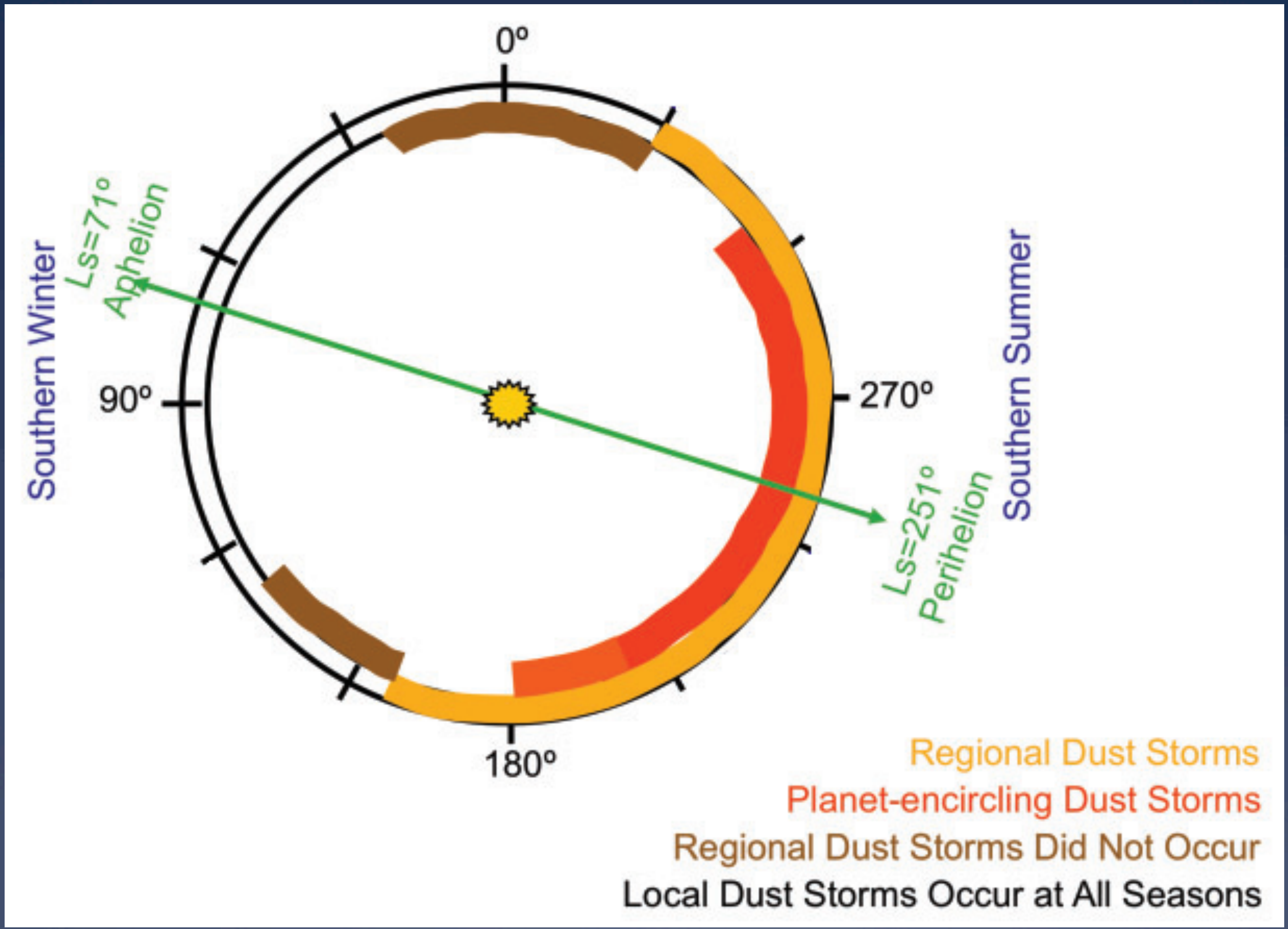
Dust

- What is it good for?
- Absolutely nothing! Say it again… (apologies to Edwin Starr)





Seasonal Dust Cycle



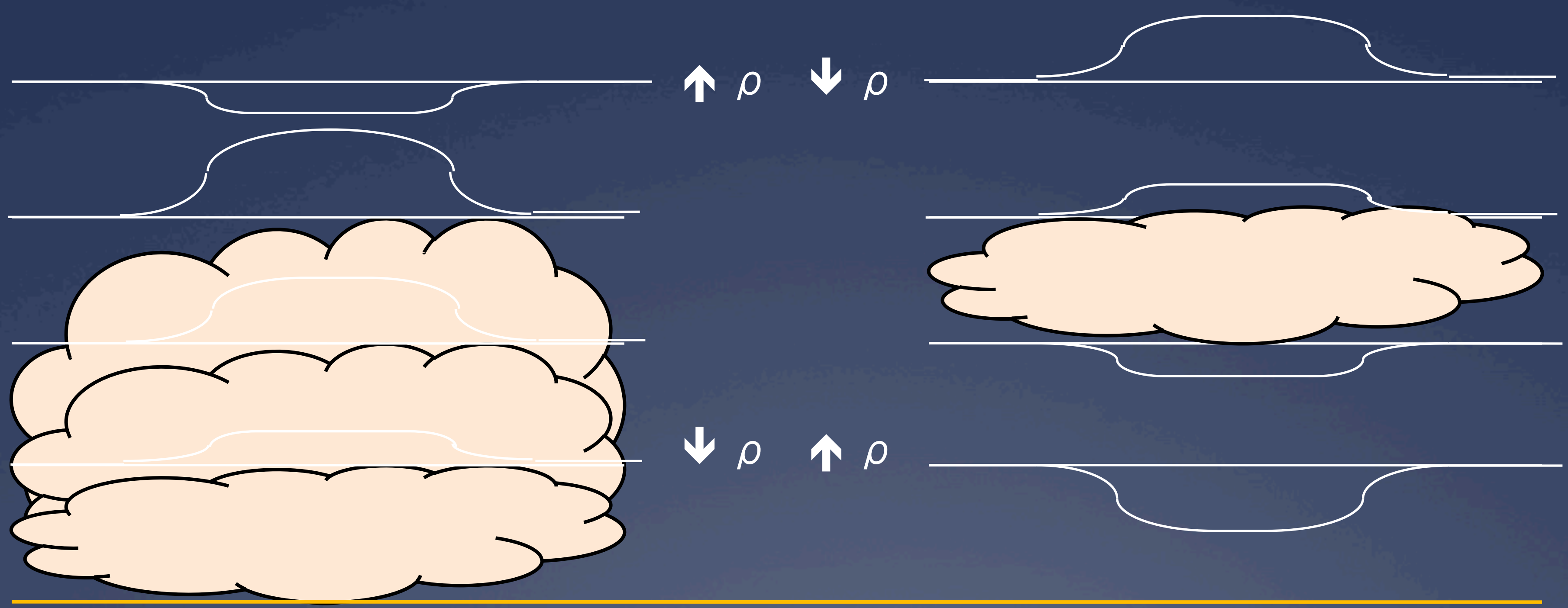
Dust Effects

- At larger scales, most major circulation components are strengthened by increased dust loading in the atmosphere
  - The zonal-mean circulation (i.e. Hadley circulation) is strengthened and expanded in both latitude and height.

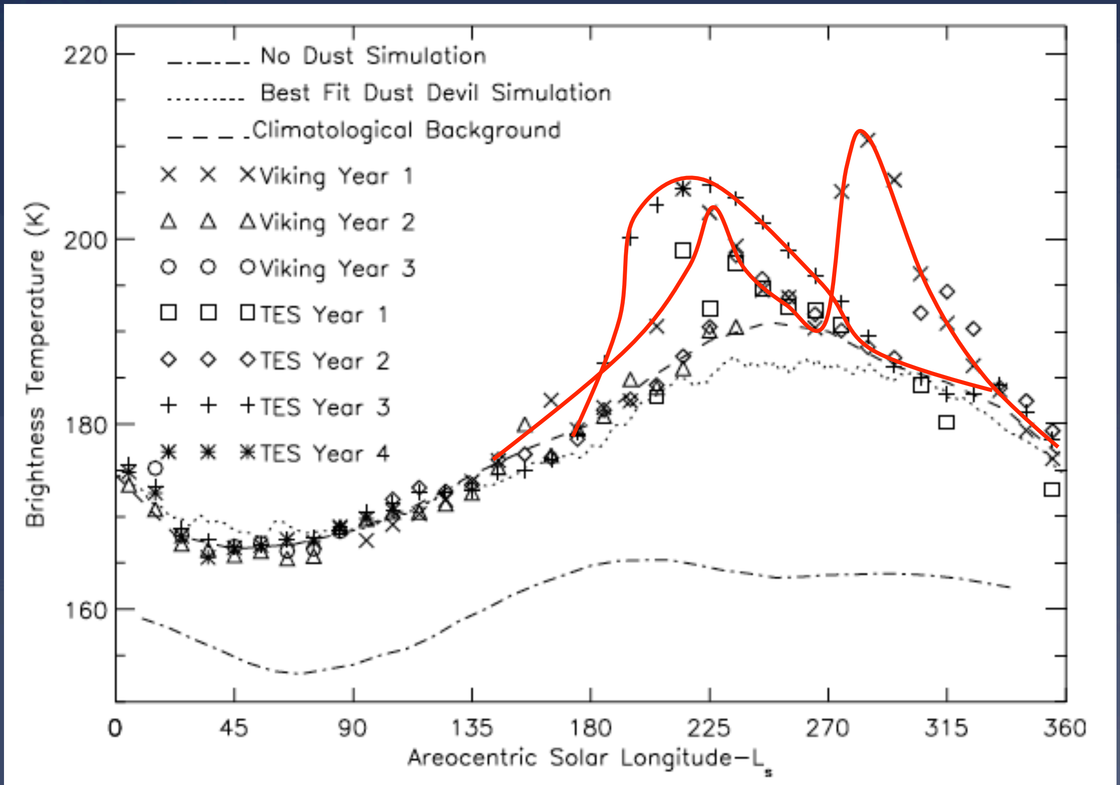
Dust Effects

- Circulations forced by solar heating of the ground are generally weakened due to the reduction in insolation at the ground
  - Increase in the downward IR at night reduces amplitude of the diurnal thermal cycle.
- Examples of such circulations as we have seen include
  - diurnal slope flows
  - polar cap edge “sea-breeze” circulations
  - canyon/valley winds
  - daytime turbulent convection in the boundary layer

Dust Heating

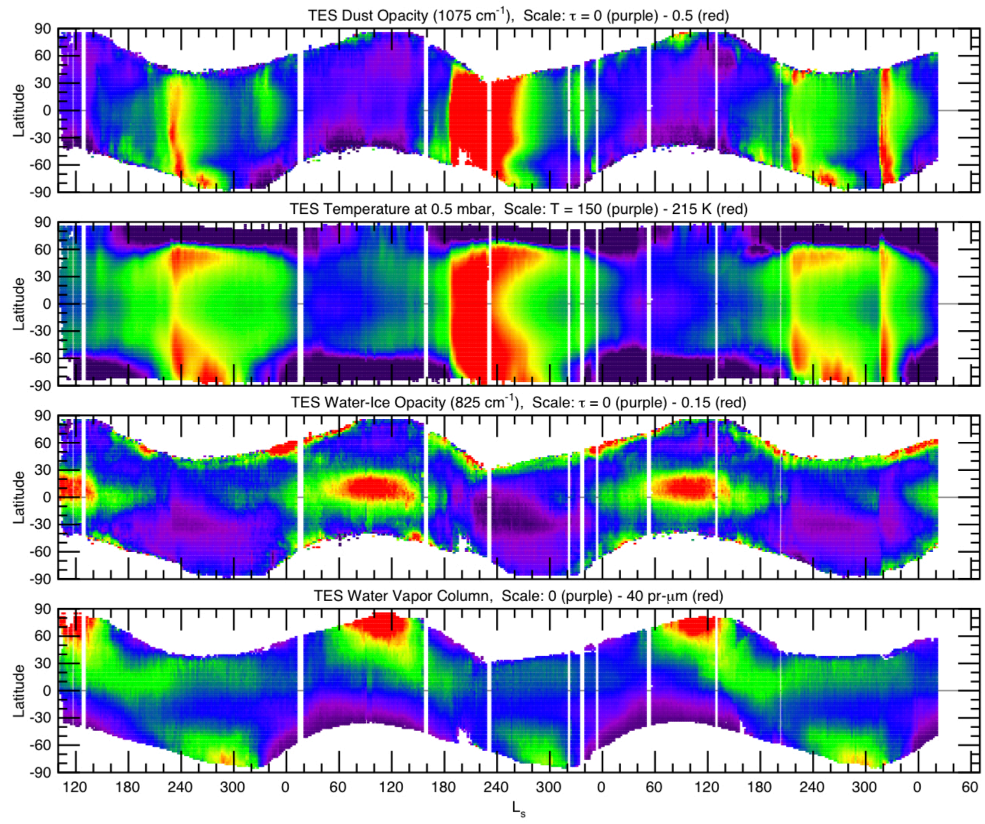


Interannual Variability



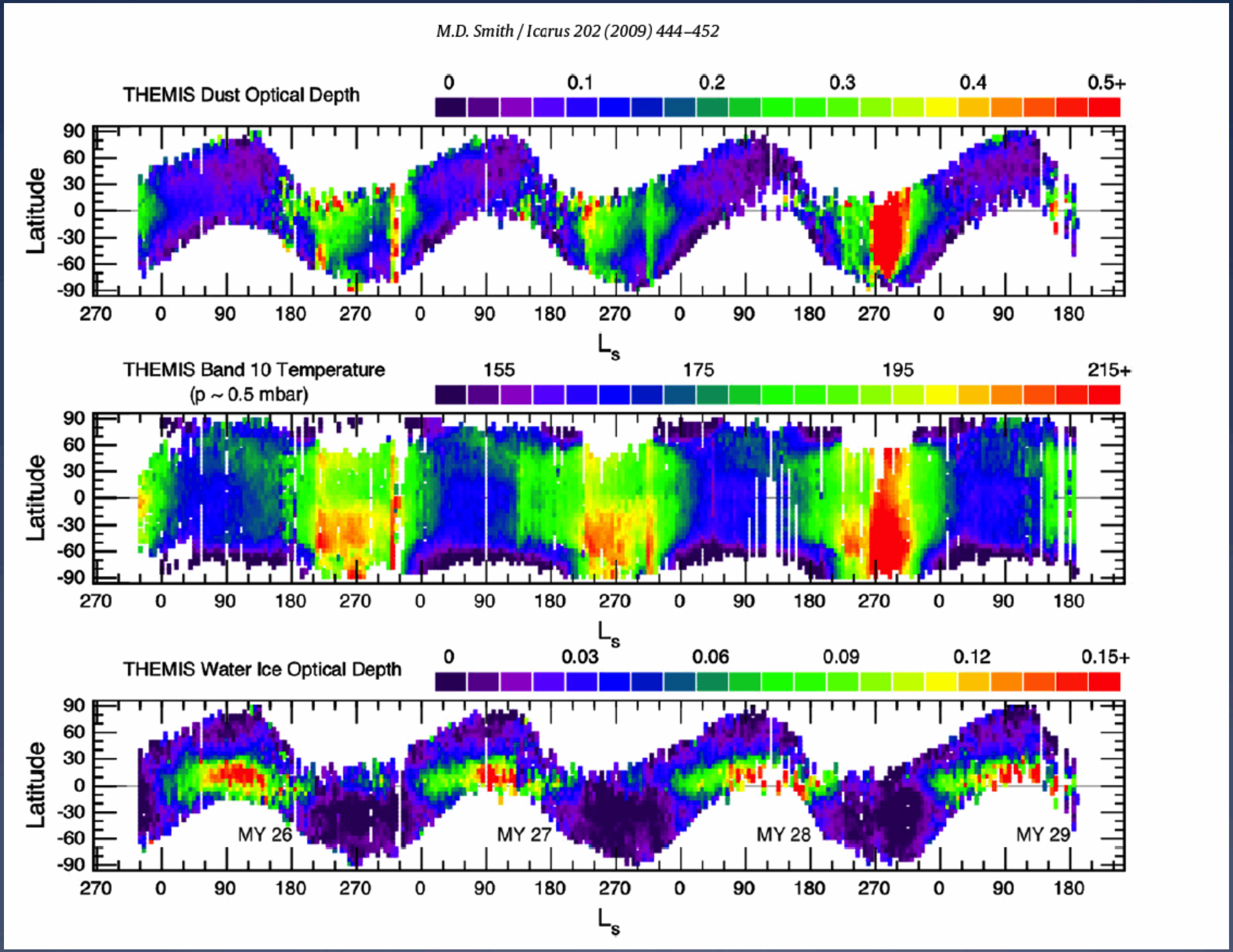
- Dust storms generally warm the atmosphere
- Clear seasonality to dust activity
- Storms do not occur every year

TES Measurements



from Smith (1999) and cited every workshop/conference since

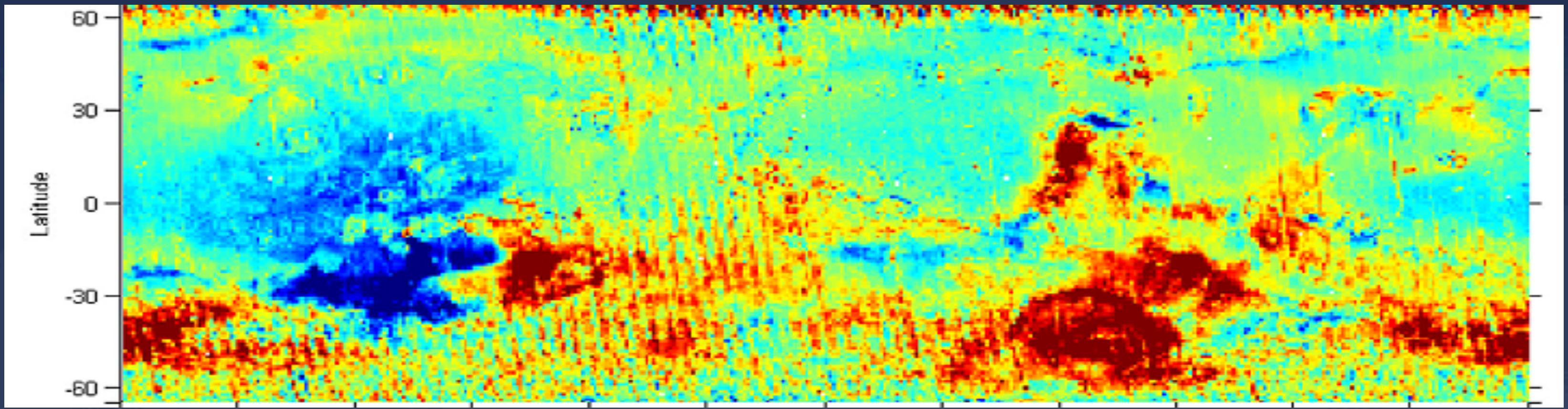
THEMIS Measurements



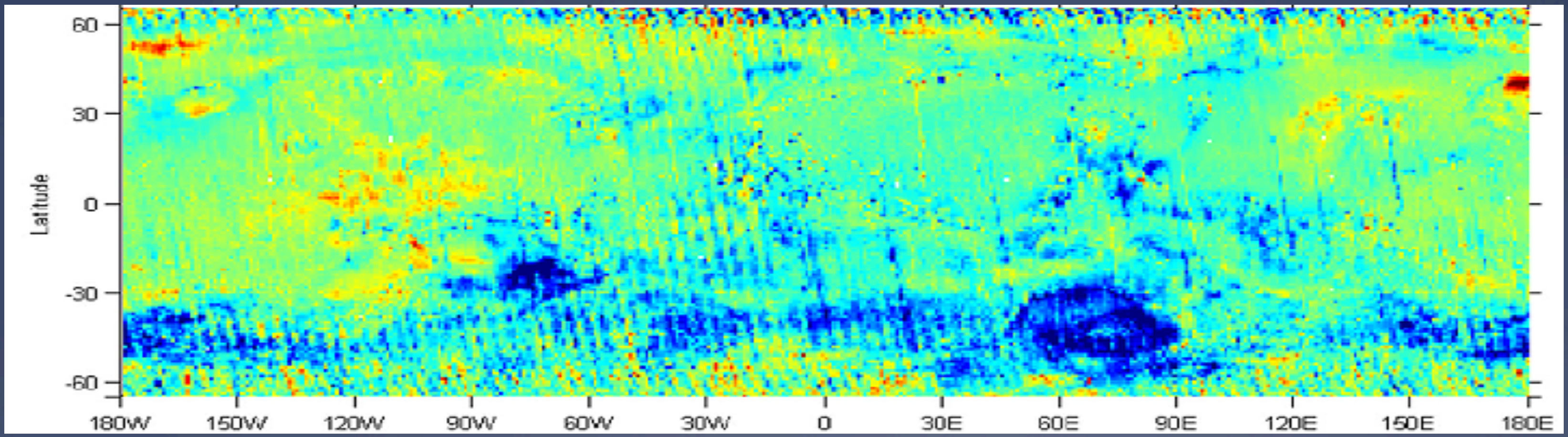
from Smith (2002)

Dust Sources and Sinks

(Yr 3 spring)-(Yr 2 spring): **Hellas, Hesperia, Sirenum and Solis gain**; **Daedalia loses**

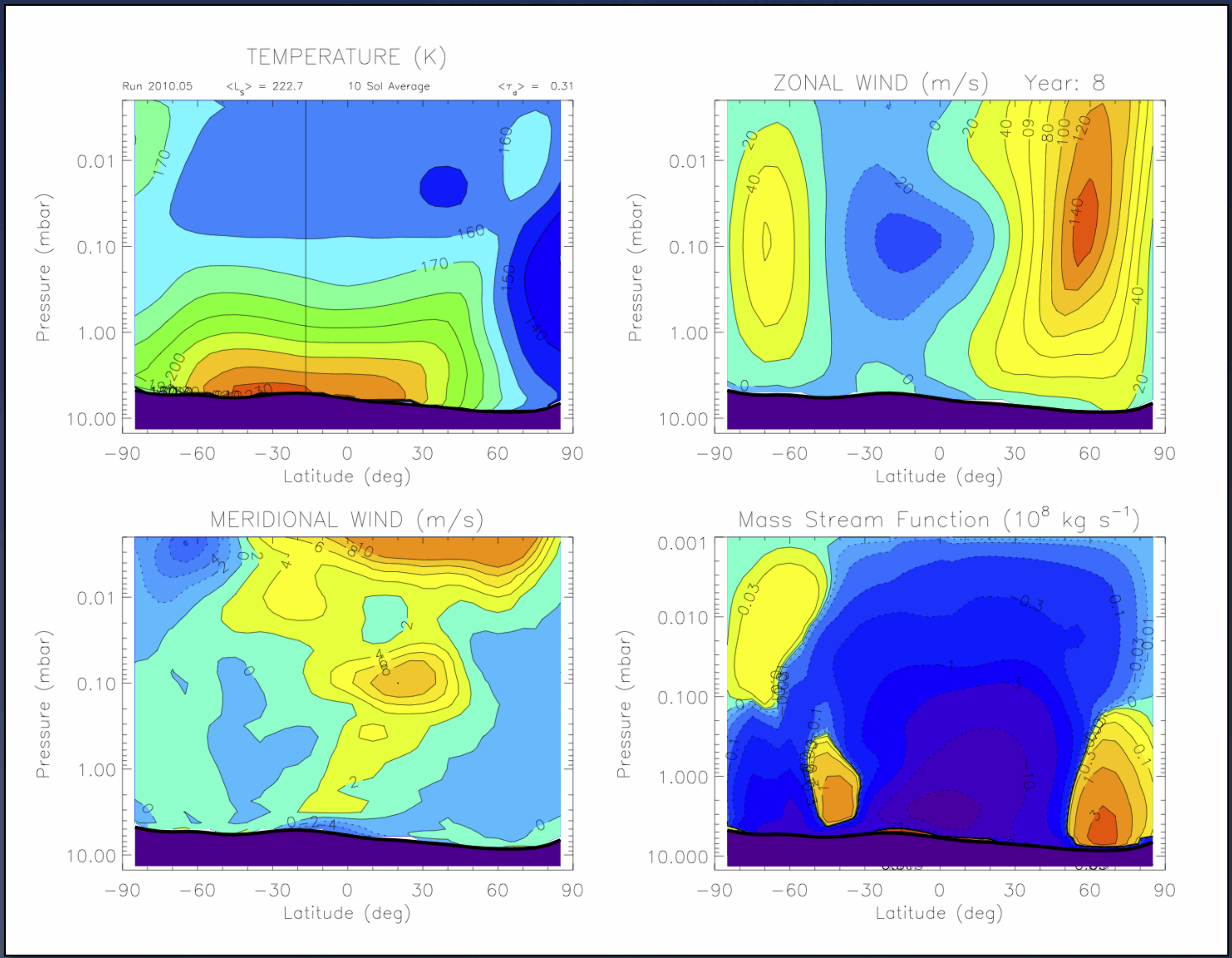


(Yr 4 spring)-(Yr 3 spring): **Hellas, Sirenum and Solis lose dust**

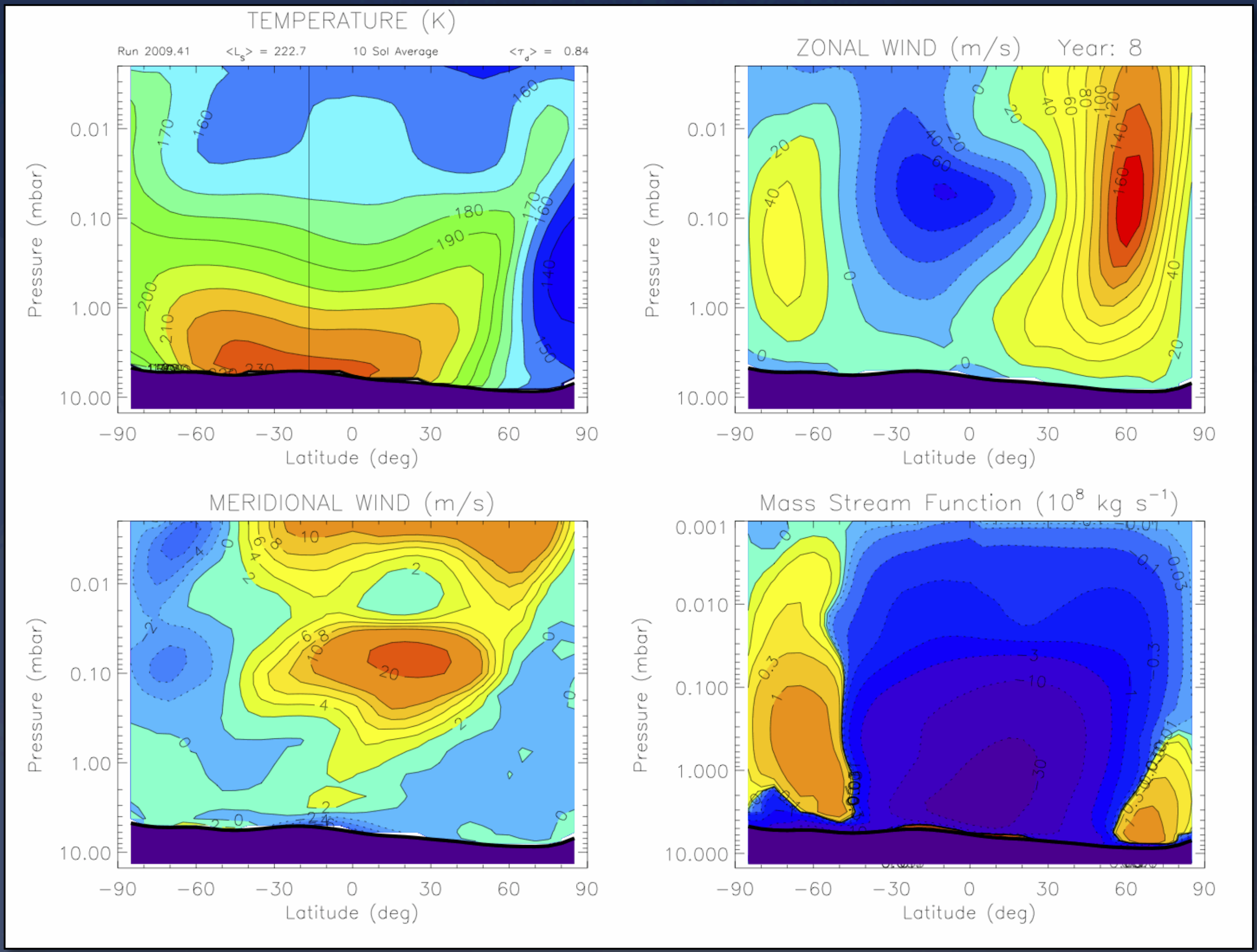


from Szwast *et al.*, 2006

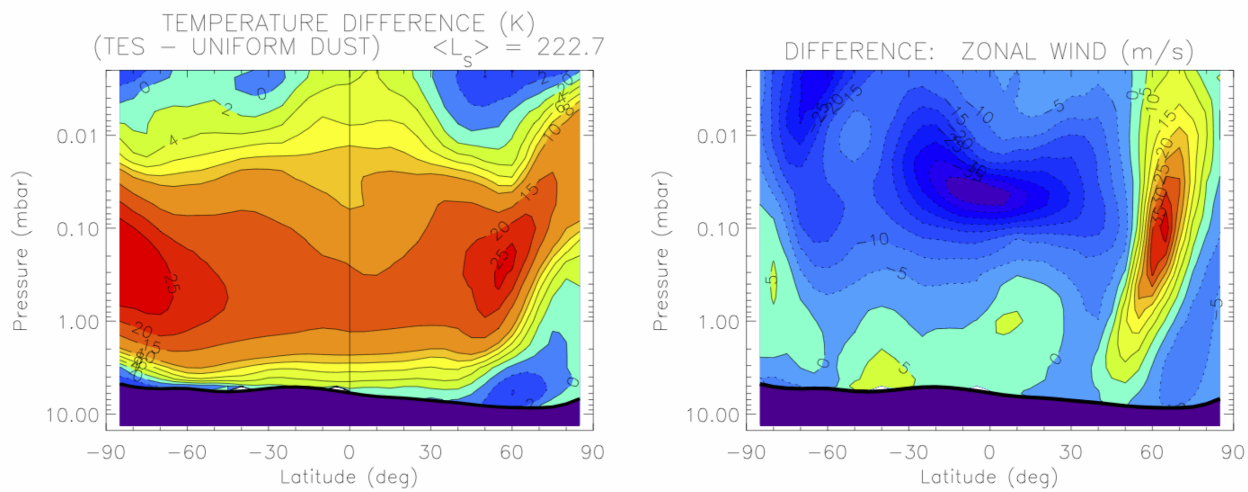
Clear Atmosphere

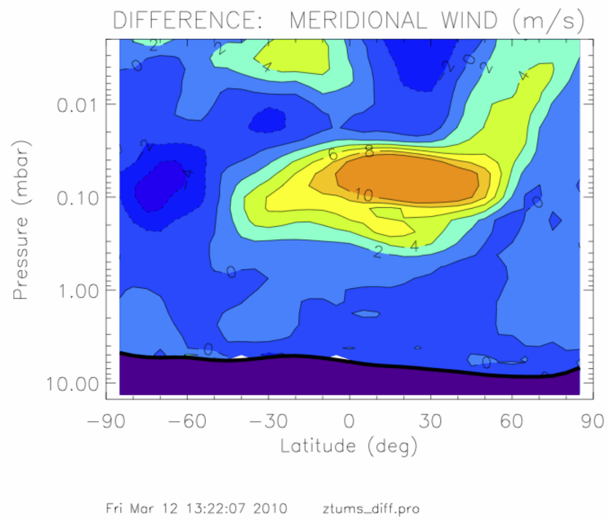


Dusty Atmosphere



Difference





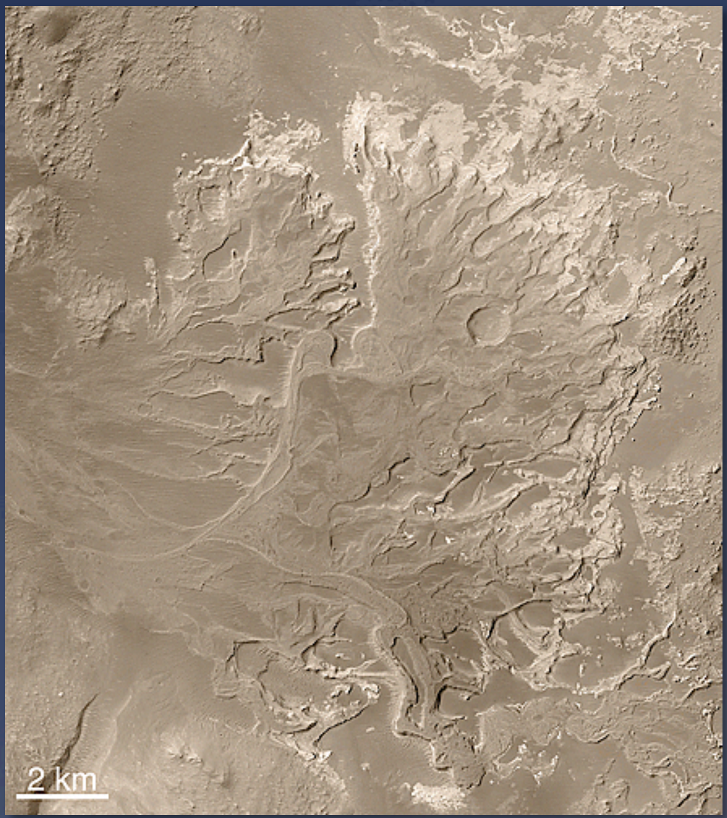
- Dust acts to push Hadley cell poleward and strengthen winds.
- Think of it as pushing the jet stream poleward

Summary (Pt 1)

- Martian atmosphere similar to Earth's
- Temperature largely controlled by surface absorption/reradiation
- Dust is complicated
  - Absorbs radiation—warming
  - Shields surface insolation—cooling
- Large scale circulation drives winds
  - Smaller-scale modifier

Early Mars Climate

- Why do we care?



Warm temperatures (>273 K?) + Faint young sun

=

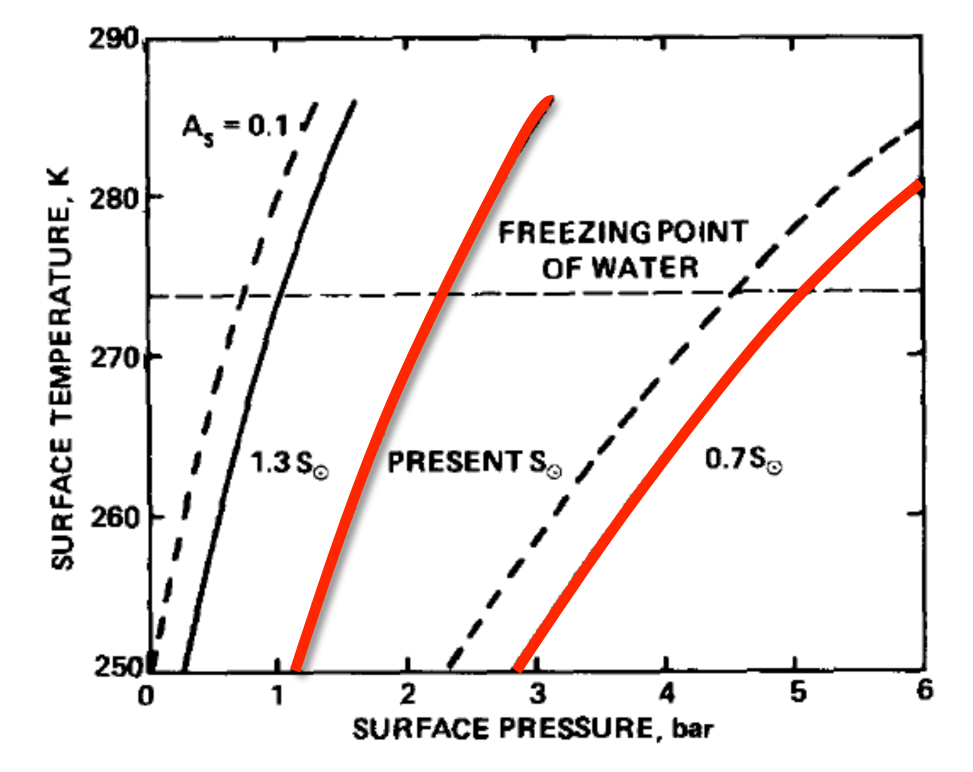
Freezing point moderator | Atmospheric 'enhancement'

→ Drastic shift in climate in Mars history

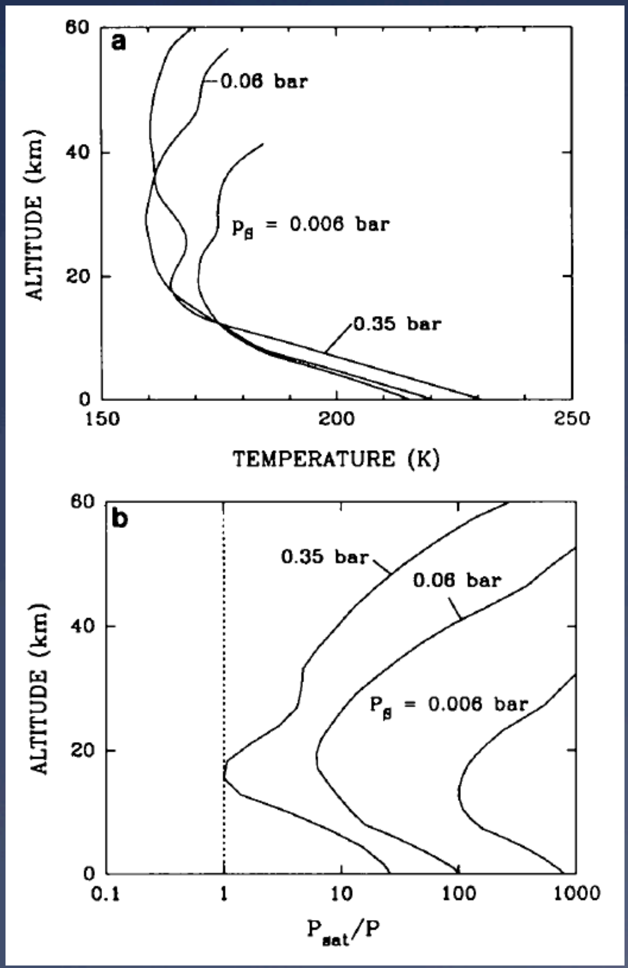
The 'faint young Sun' paradox

Reconciling the 'paradox'

- First Attempt (circa 1980s)
- Thick CO_2 atmosphere (1-5 bar)
- Assumes *reduced solar luminosity* (75%)
    - Comparatively easy to reach 273 K at present solar luminosity.



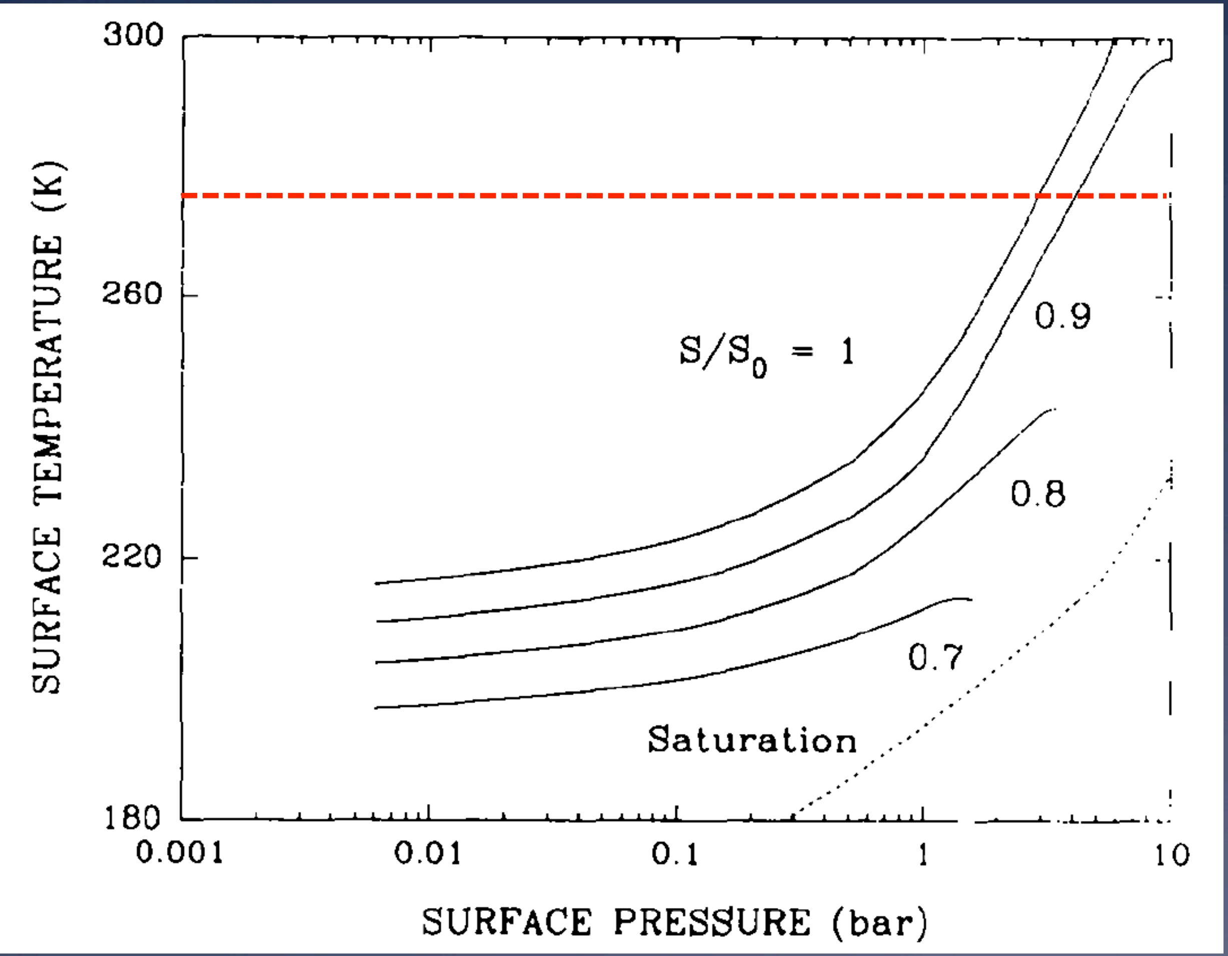
CO_2 Atmosphere



- Jim Kasting identified a critical flaw in the CO_2-only model
- Above 350 mb, CO_2 will saturate in the atmosphere, reducing warming previously estimated.

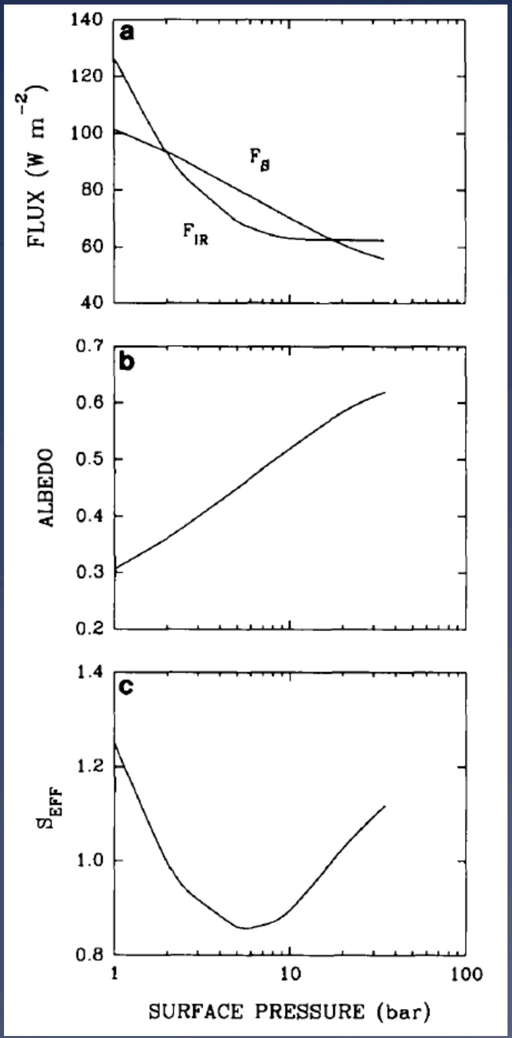
CO_2 Atmosphere

With CO_2 Saturation



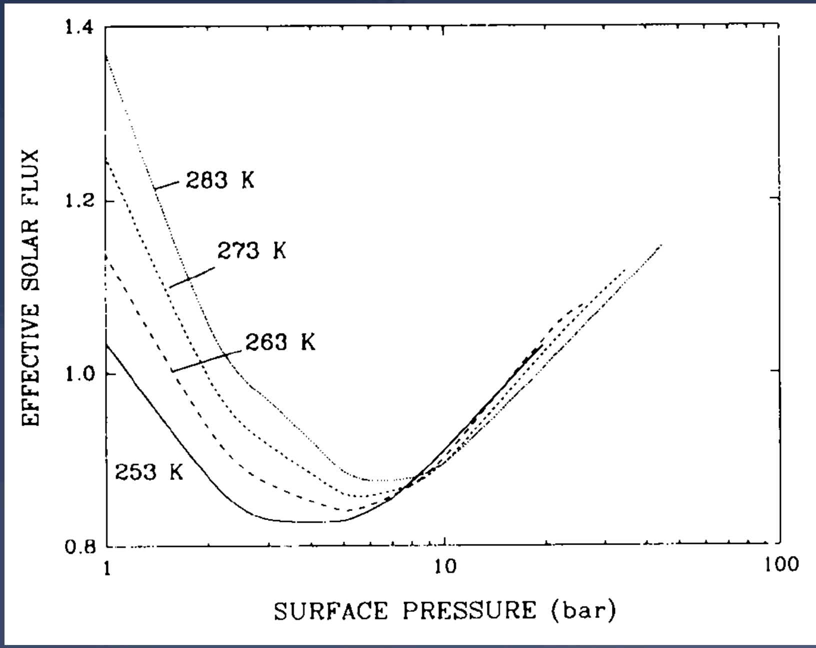
Think of this ratio as a proxy for time in martian history

CO_2 Atmosphere



- As surface pressure increases:
  1. Planetary albedo rises due to atmospheric scattering (planet gets "brighter")
  2. IR emission levels off
  3. Warm temperatures become increasingly hard to obtain

CO_2 Atmosphere



- Even reduced melting point temperatures (e.g. brine solutions) cannot help early Mars with CO_2 alone
- Prior to ~2 Ga, liquid water not sustainable by CO_2.

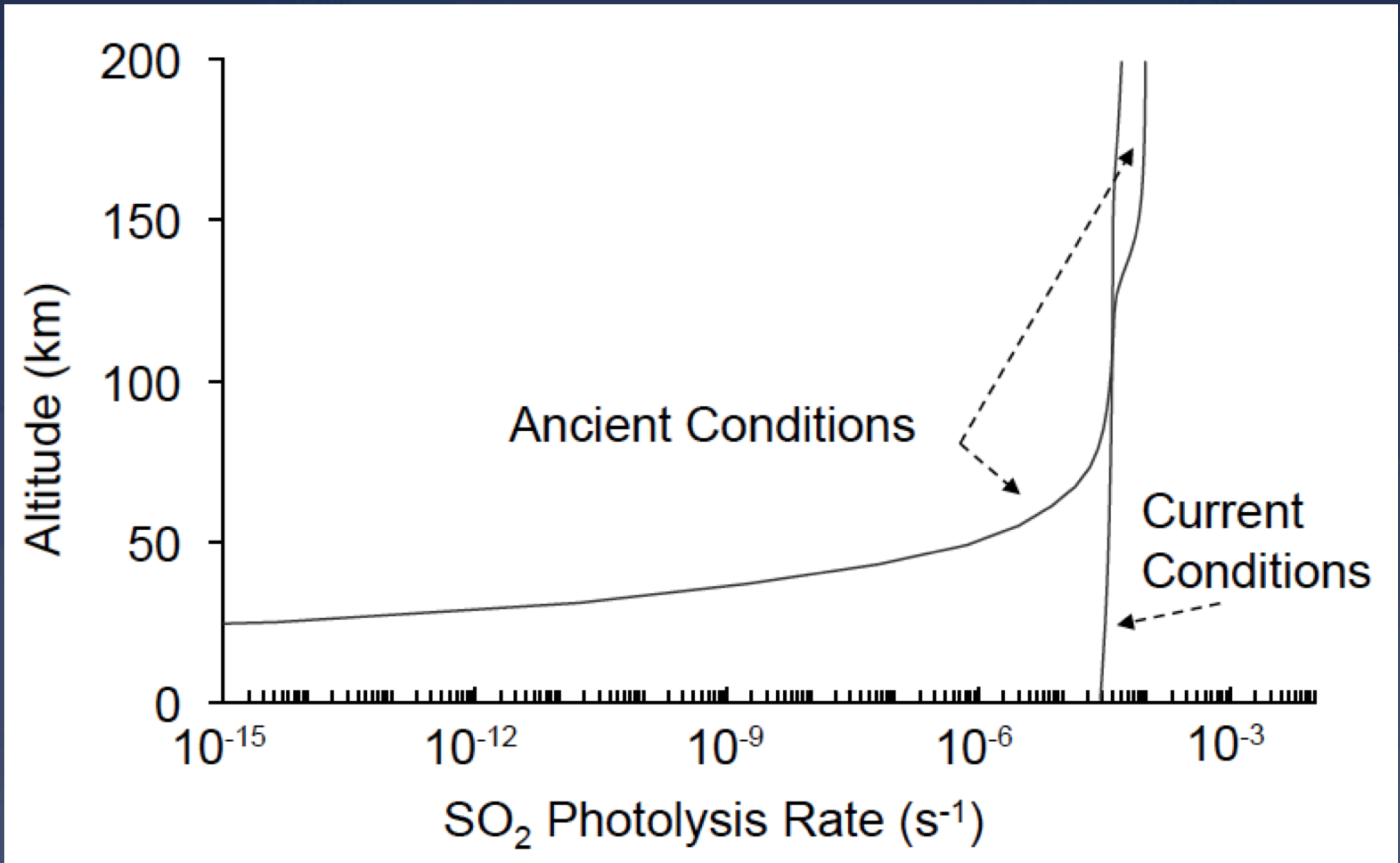
Reconciling the 'paradox'

- Second Attempt (circa 1980s-1990s)
- Trace greenhouse species
- NH_3, SO_2, CH_4, H_2S, H_2O, etc.
- Plausible, but each have drawbacks
- Let's take SO_2 as a common example

Reconciling the ‘paradox’

- Sulfur compounds have been frequently suggested.
- Readily abundant volcanic source
- Widespread surface distribution
- Water soluble and short photochemical lifetime
  - But perhaps not as much as once assumed…

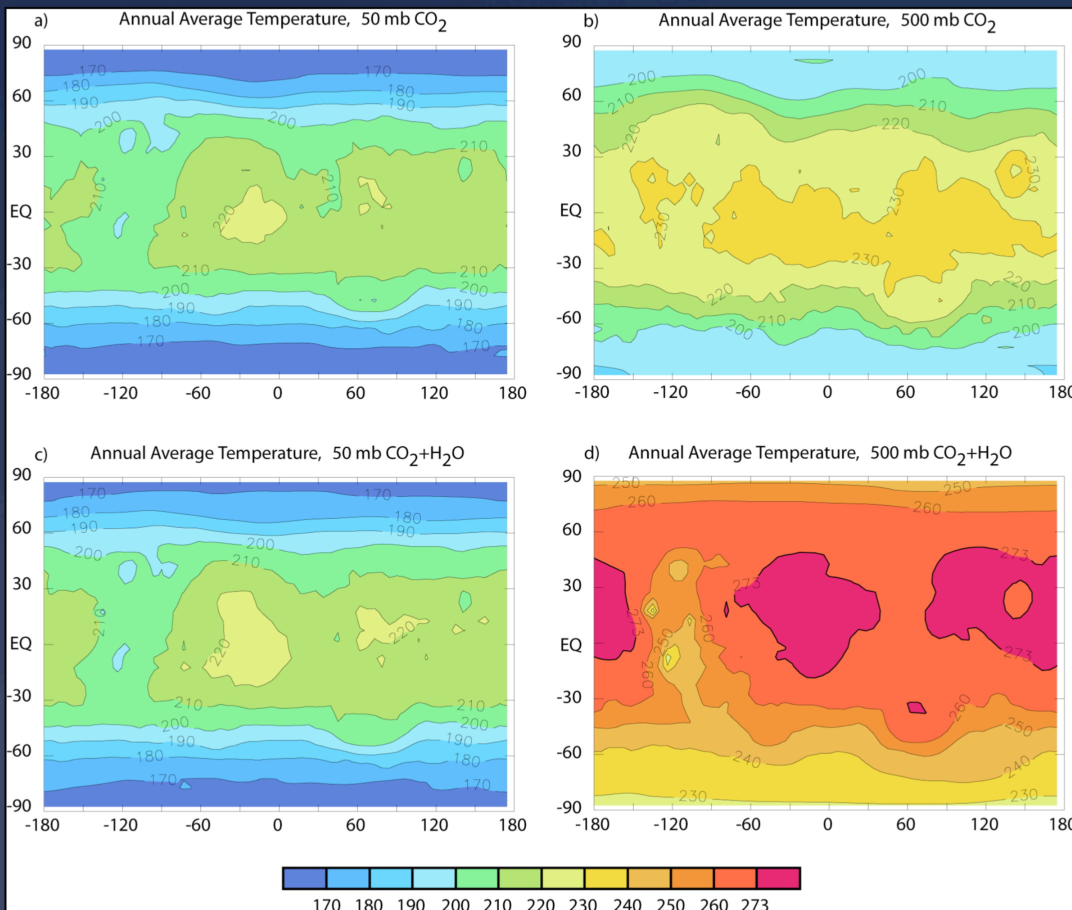
Addressing the Drawbacks



Addressing the Drawbacks

Initial $f(SO_2)$	*e*-folding time (in Earth years*)
Base code calculations	
10^{-8}	333
10^{-7}	381
10^{-6}	793
Sensitivity studies	
10^{-6} (higher temperature)	751
10^{-6} (higher precipitation)	81
10^{-6} (lower precipitation)	1550
10^{-6} (higher *K*)	783

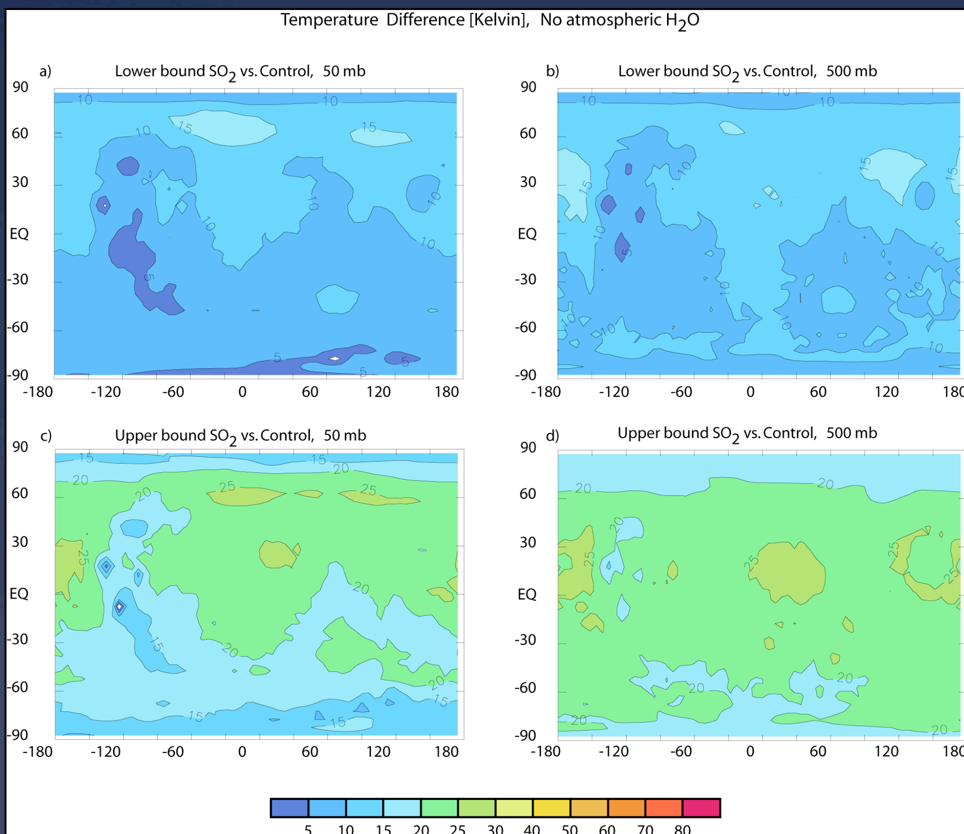
Trace Gases



- Trace gases like SO_2 can fill 'gaps' in the absorption spectrum that allow radiation to escape.
- CO_2 actually quite limited!

from Johnson et al., (2008)

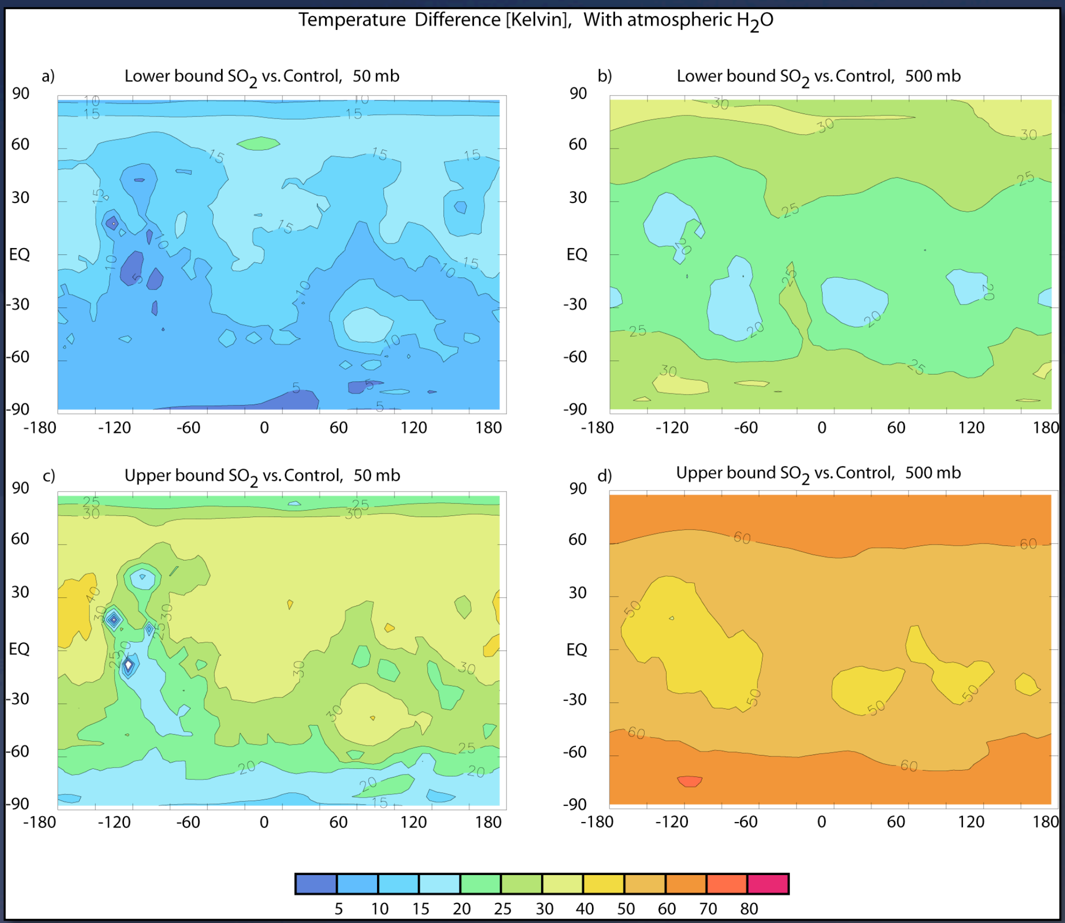
Trace Gases



- Sulfur may have periodically been injected in large quantities via volcanic outgassing.
  - Other gases, too
- By itself, it's a mediocre greenhouse agent. (~5-15 K for mixing ratios of 10^{-5}-10^{-3})

from Johnson et al., (2008)

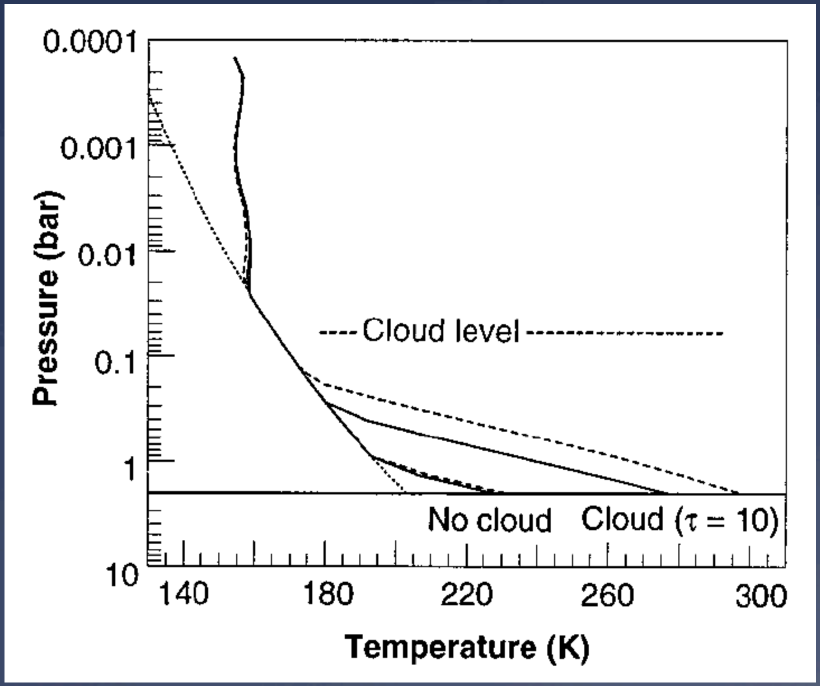
Trace Gases



- In tandem, multiple gases can be a powerful greenhouse force.
- CO_2, SO_2 and H_2O, for example

from Johnson et al., (2008)

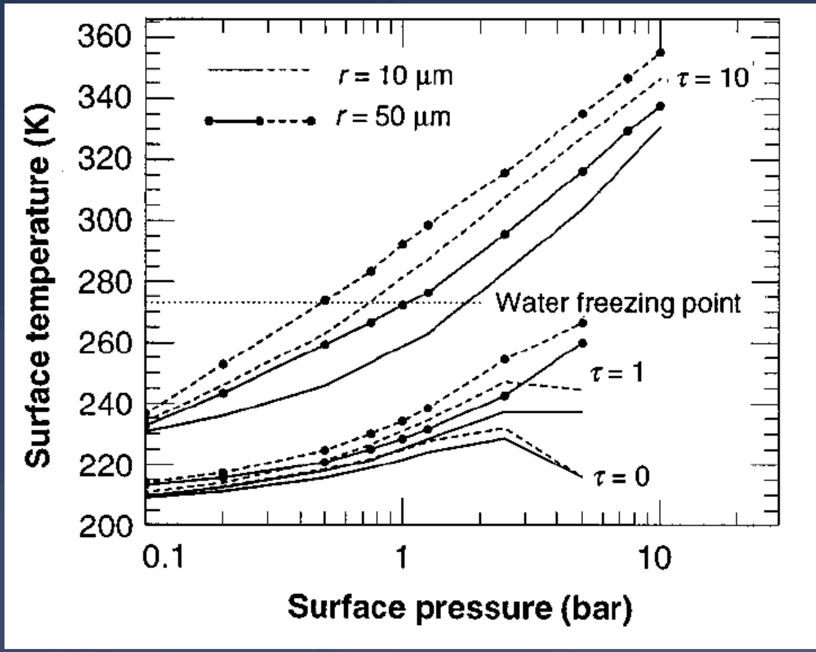
Clouds



- Carbon dioxide ice clouds can be effective scatterers of upwelling IR.
- An alternative idea to greenhouse gases

from Forget and Pierrehumbert (1997)

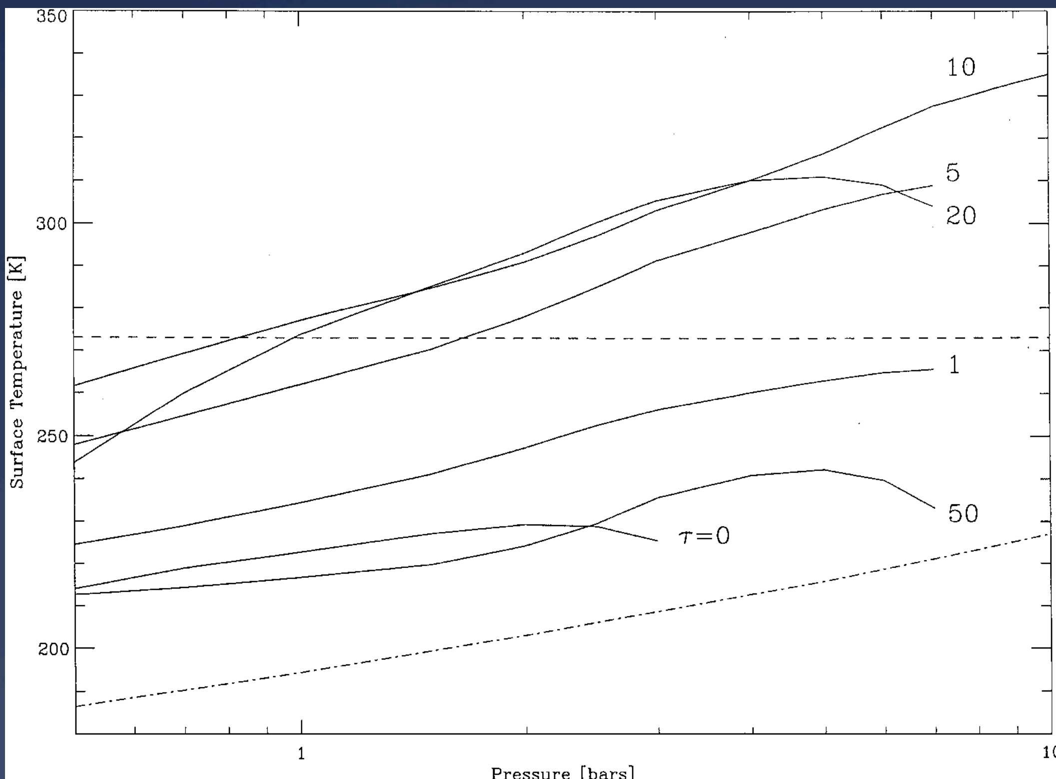
Clouds



- Substantial cloud cover required
- <1 bar CO_2 for small ice crystals.

from Forget and Pierrehumbert (1997)

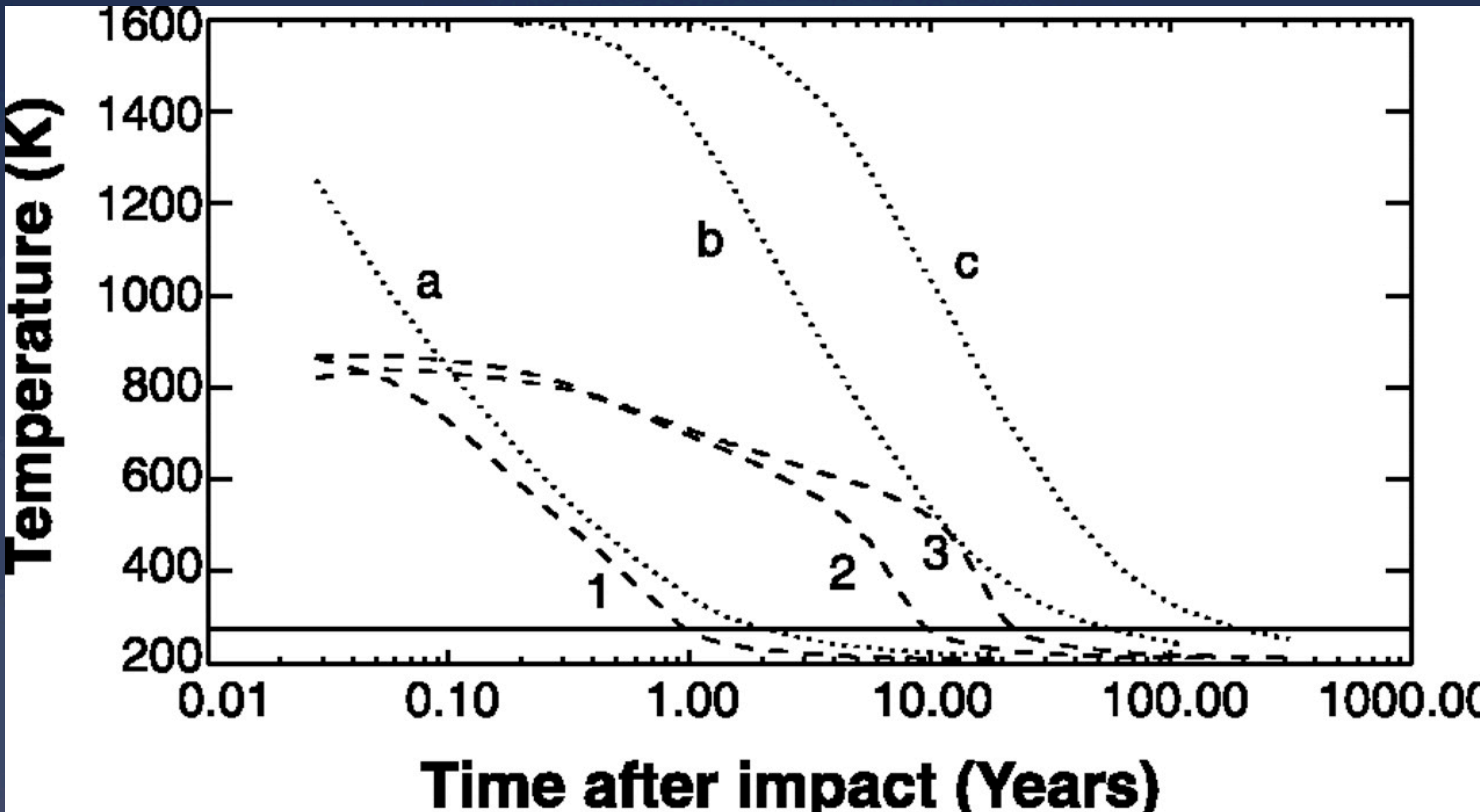
Clouds



- Very thick clouds are more effective reflectors of incoming solar than scatterers of IR.
- τ 1-5 is not a very thick cloud.

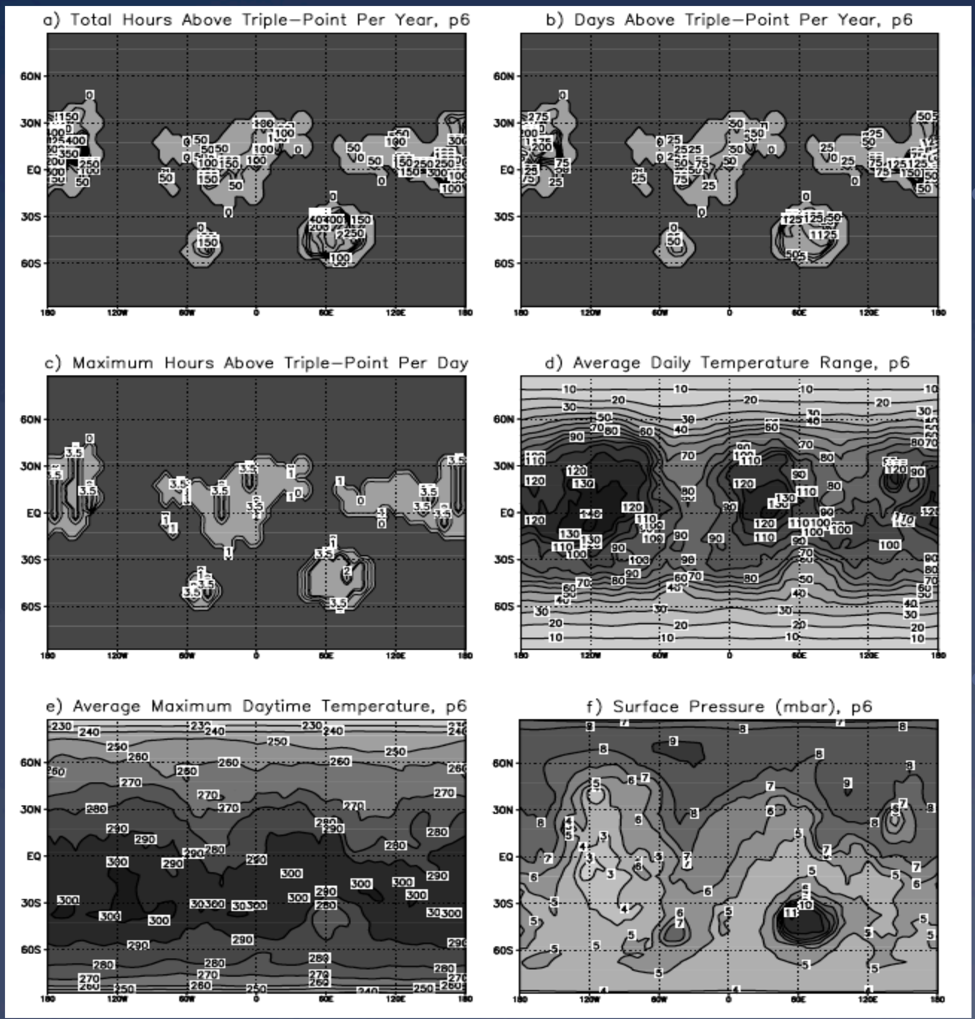
from Mischna et al., (2003)

Impact Warming



from Segura et al., (2002)

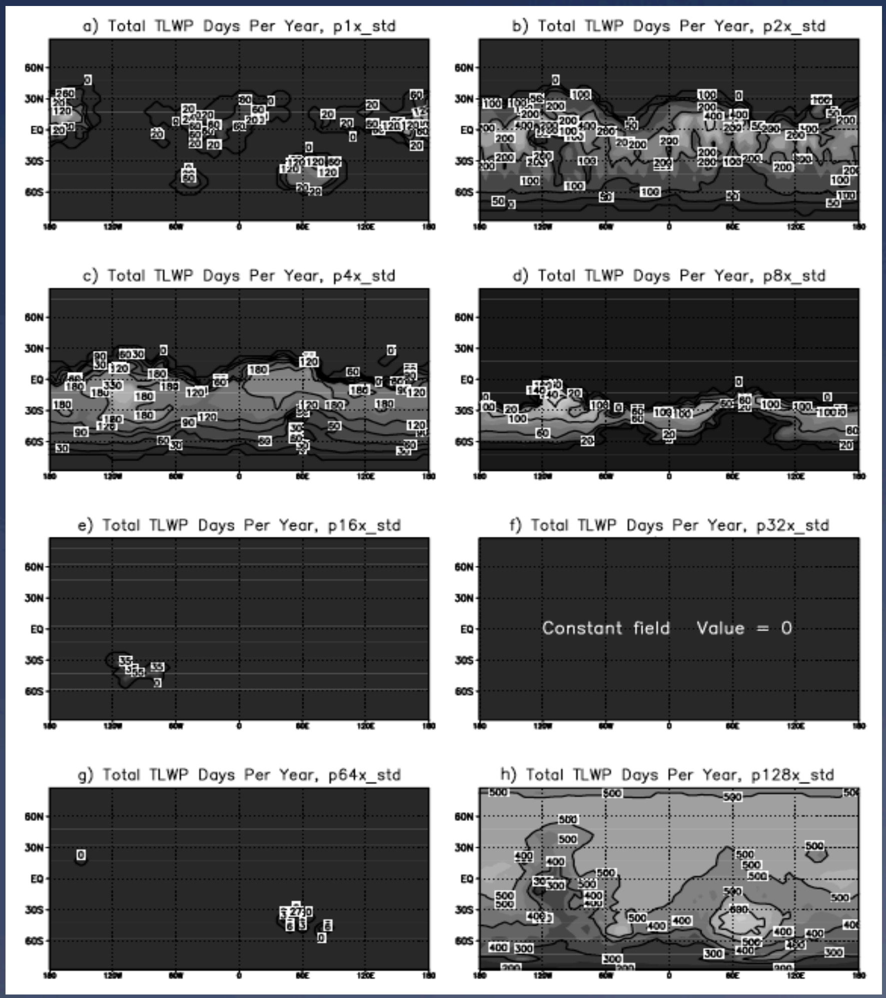
Questioning the 'Paradox'



- To have liquid water today:
  - Temperature range
  - Pressure condition
- On present-day Mars, there are very restricted regions that meet these requirements.

from Richardson and Mischna., (2005)

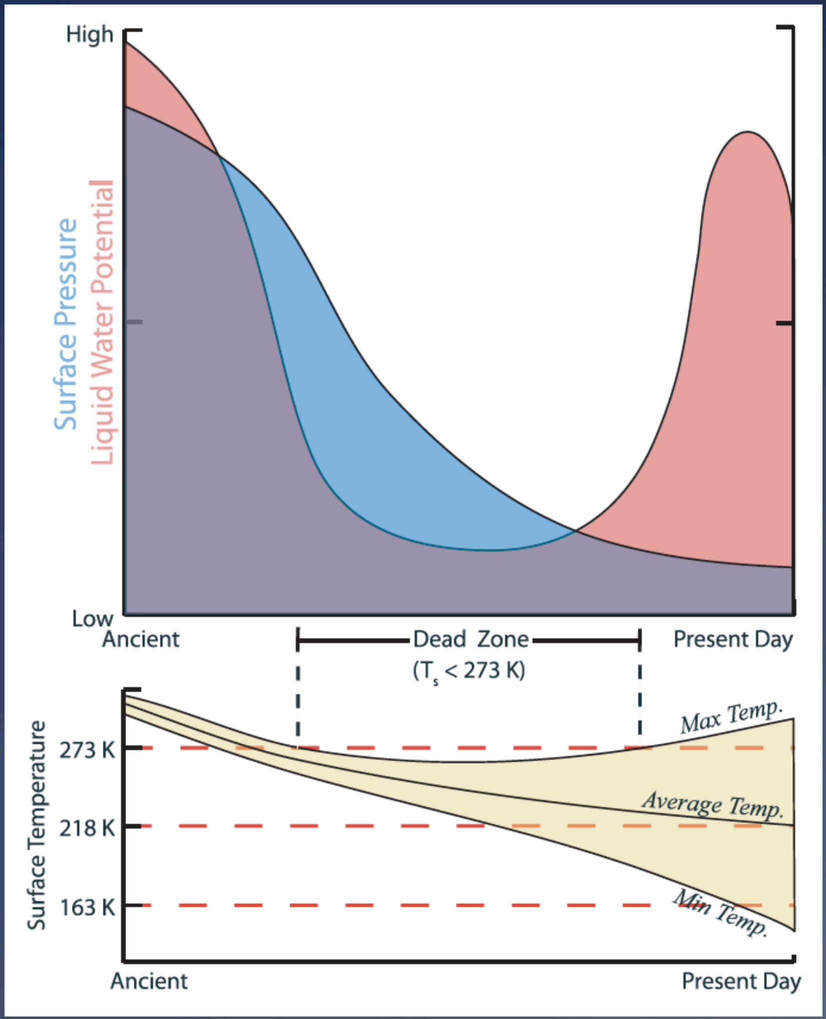
Questioning the 'Paradox'



from Richardson and Mischna, (2005)

- A thicker atmosphere tends to 'mute' diurnal temperature cycle.

Questioning the 'Paradox'



from Richardson and Mischna (2005)

- Assume the atmosphere has gotten thinner over time.
- While mean T has decreased, temperature range has increased
- Potential to have liquid water today.

Summary (Pt 2)

- Geochemical evidence suggests a wet early Mars
- Need to greatly warm early Mars (FYS paradox)
- CO_2-only is difficult
- Possible alternatives
  - Sulfur species, methane, water vapor,
  - CO_2 ice clouds
  - Impacts?
- Liquid water possible today in transient state