Atmospheric Dynamics: Martian Climate History

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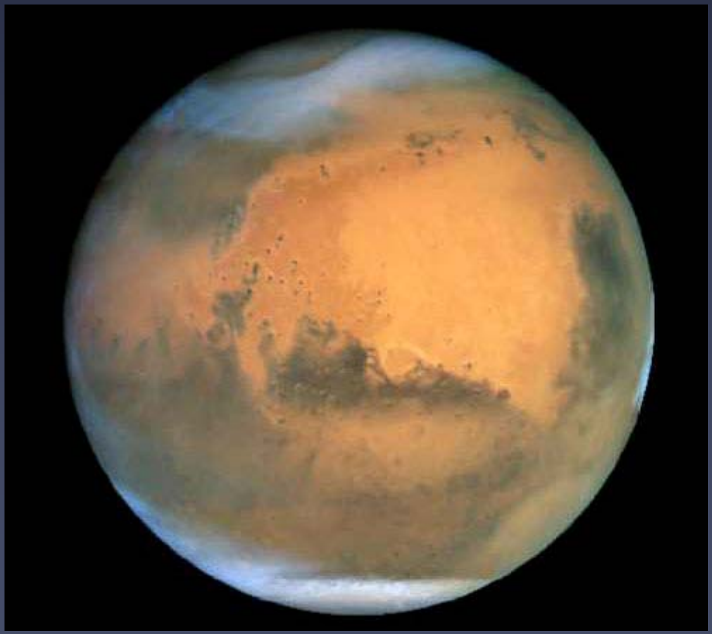
Methane on Mars KISS Workshop

Mars Atmospheric Dynamics

Outline

- Discussion geared towards the scientist/engineer who is *familiar* with physical principles, but perhaps *unfamiliar* with properties of the martian atmosphere/atmospheric circulation.
- A slant towards how the atmosphere influences methane production, transport, decay.
- We will address:
  - Temperature
  - Pressure
  - Winds
  - Dust

The Martian Atmosphere

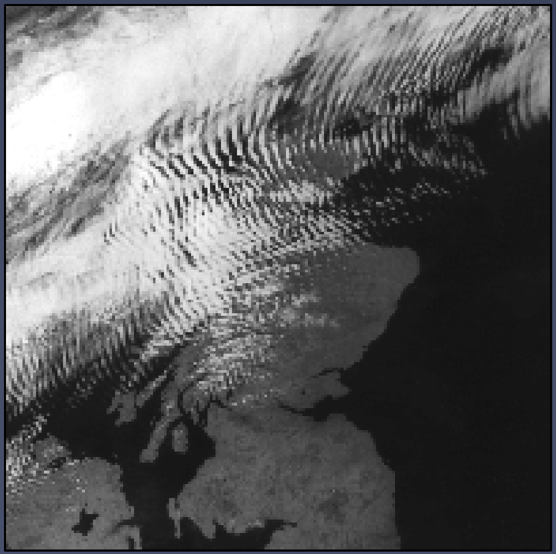


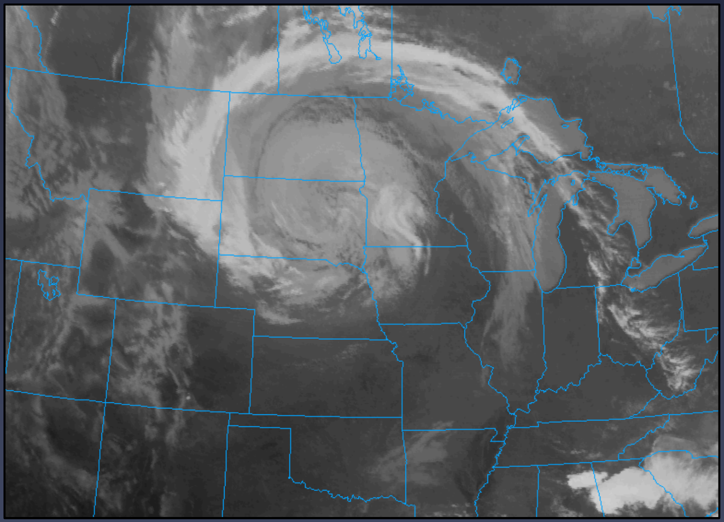
Comparing Mars and Earth Environments

	Earth	Mars
Composition	78% N_2 21% O_2	95% CO_2
Atmospheric Water	1-4%	Virtually none
Surface pressure	1 atm.	~0.01 atm.
Surface temperature	-85 to 57ºC	-128 to 27ºC
Polar Caps	Yes	Yes
Days in Year	365	669

The Martian Atmosphere

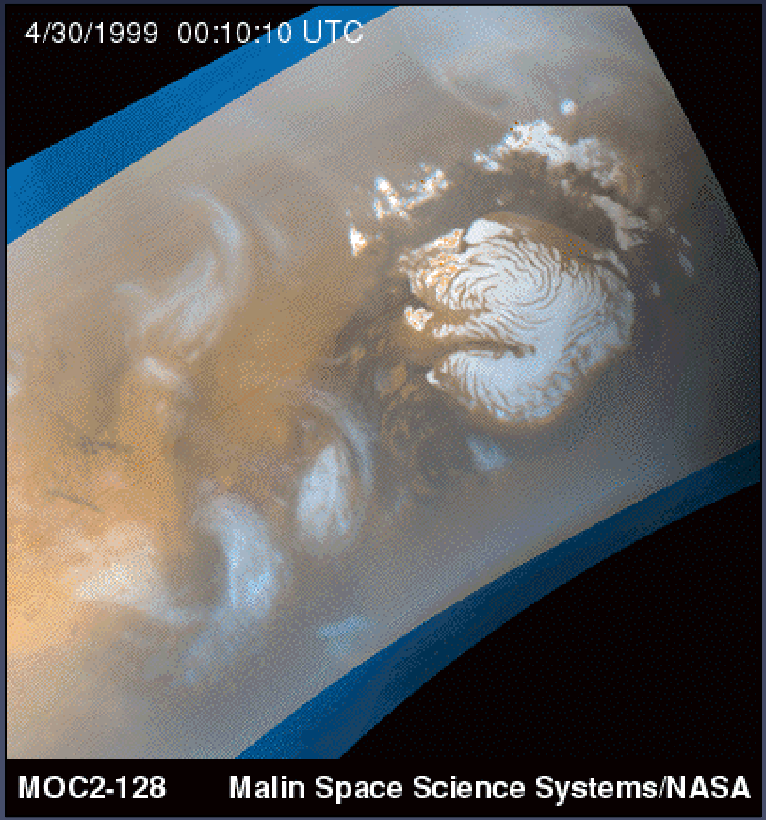
EARTH VS. MARS WEATHER

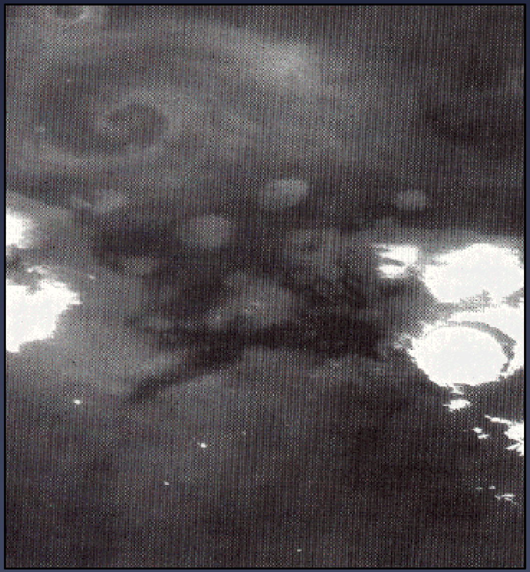




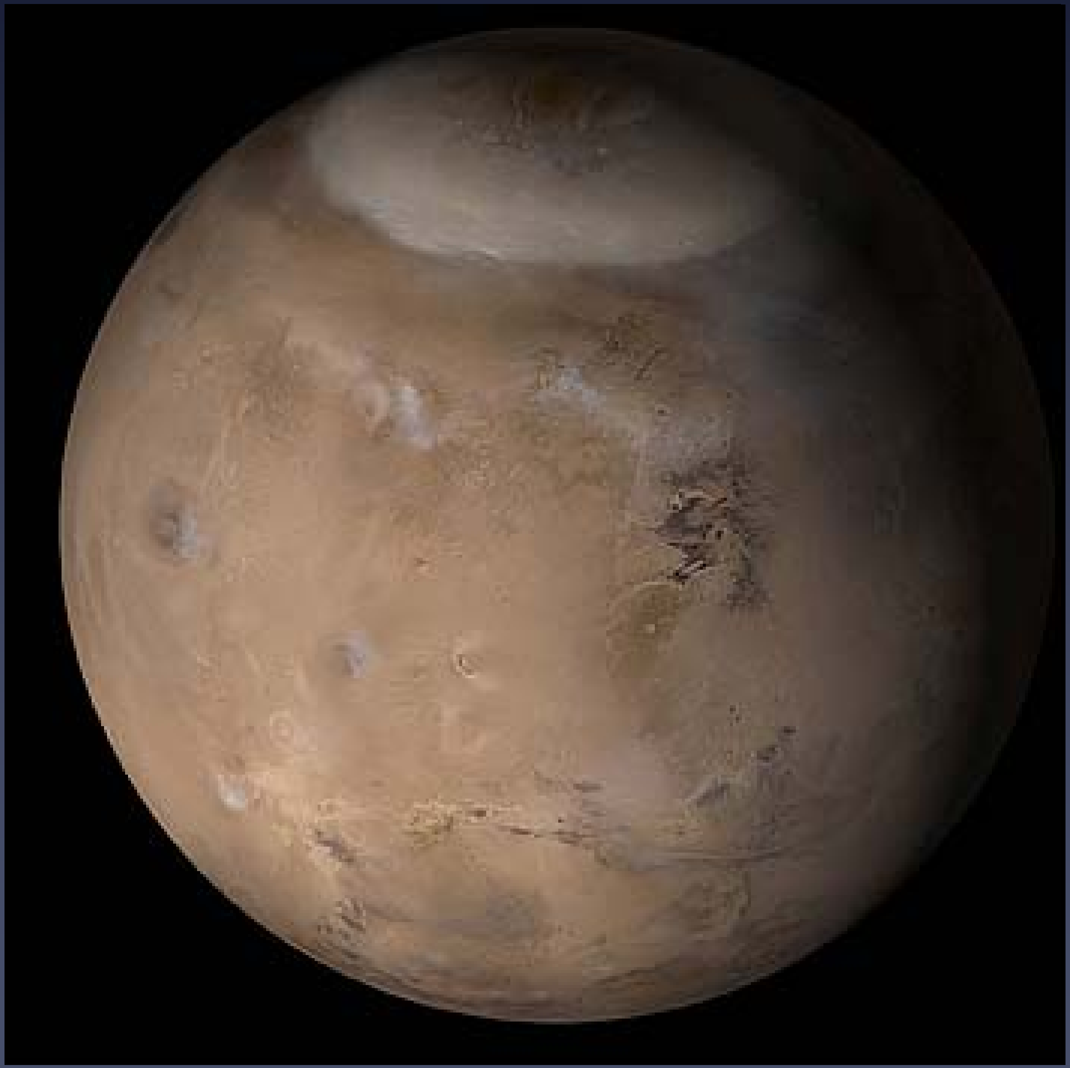
The Martian Atmosphere

EARTH VS. MARS WEATHER



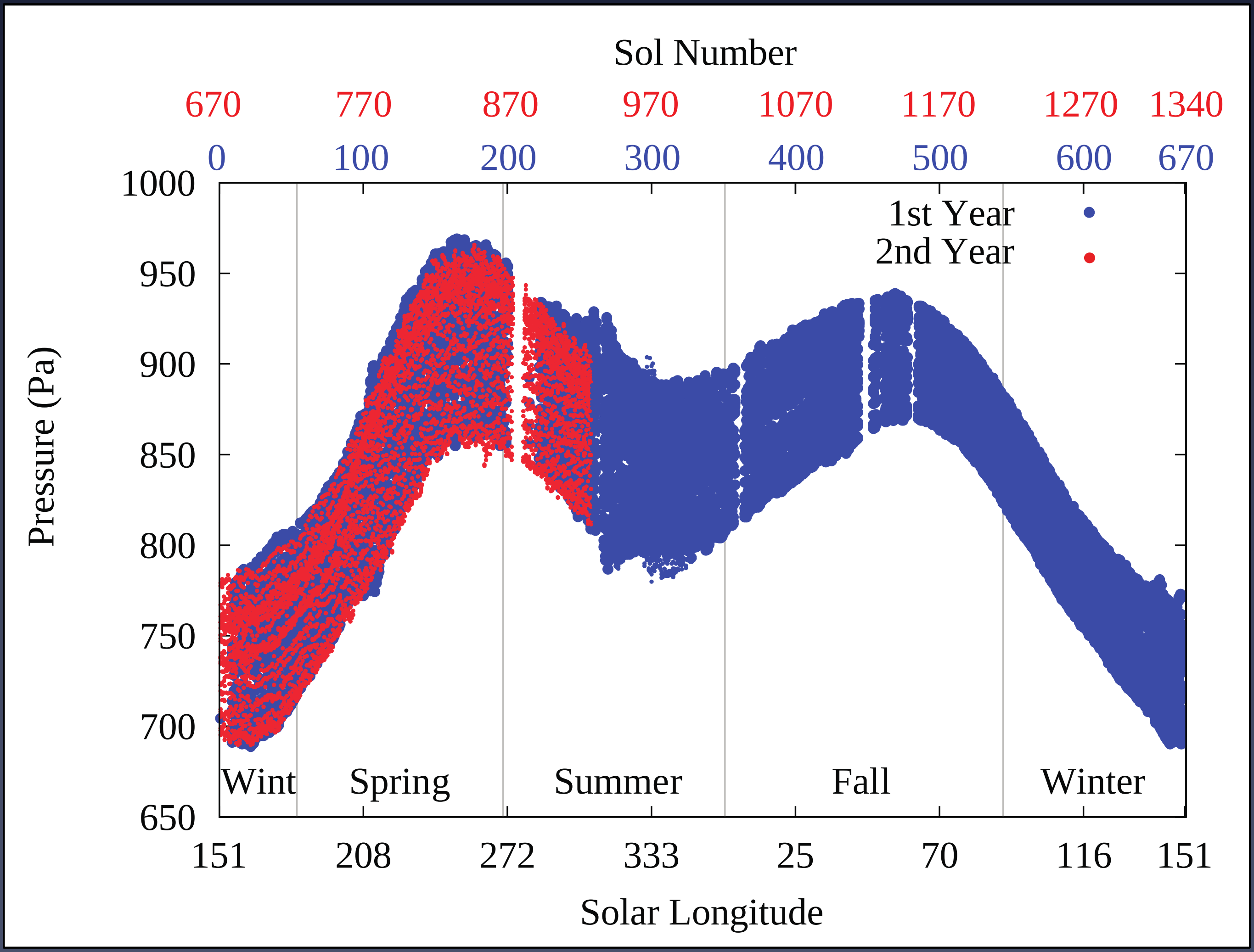


Surface Pressure



- Because of the distance from the Sun, and Mars' atmospheric composition, the atmosphere itself freezes out.
- This causes substantial variations in martian surface pressure over the course of a year.

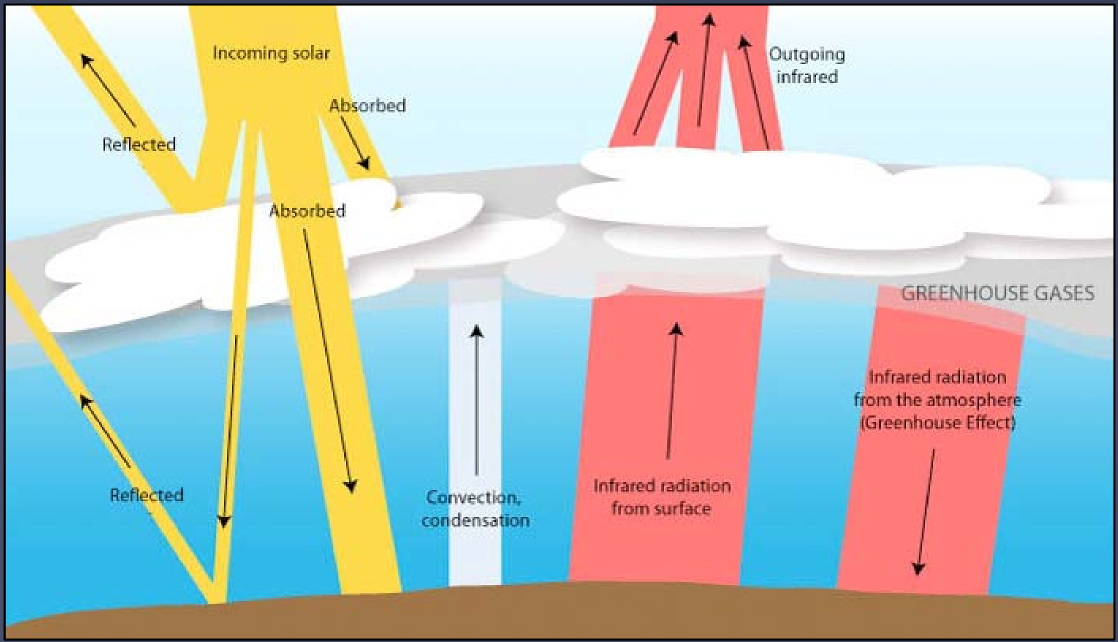
Surface Pressure



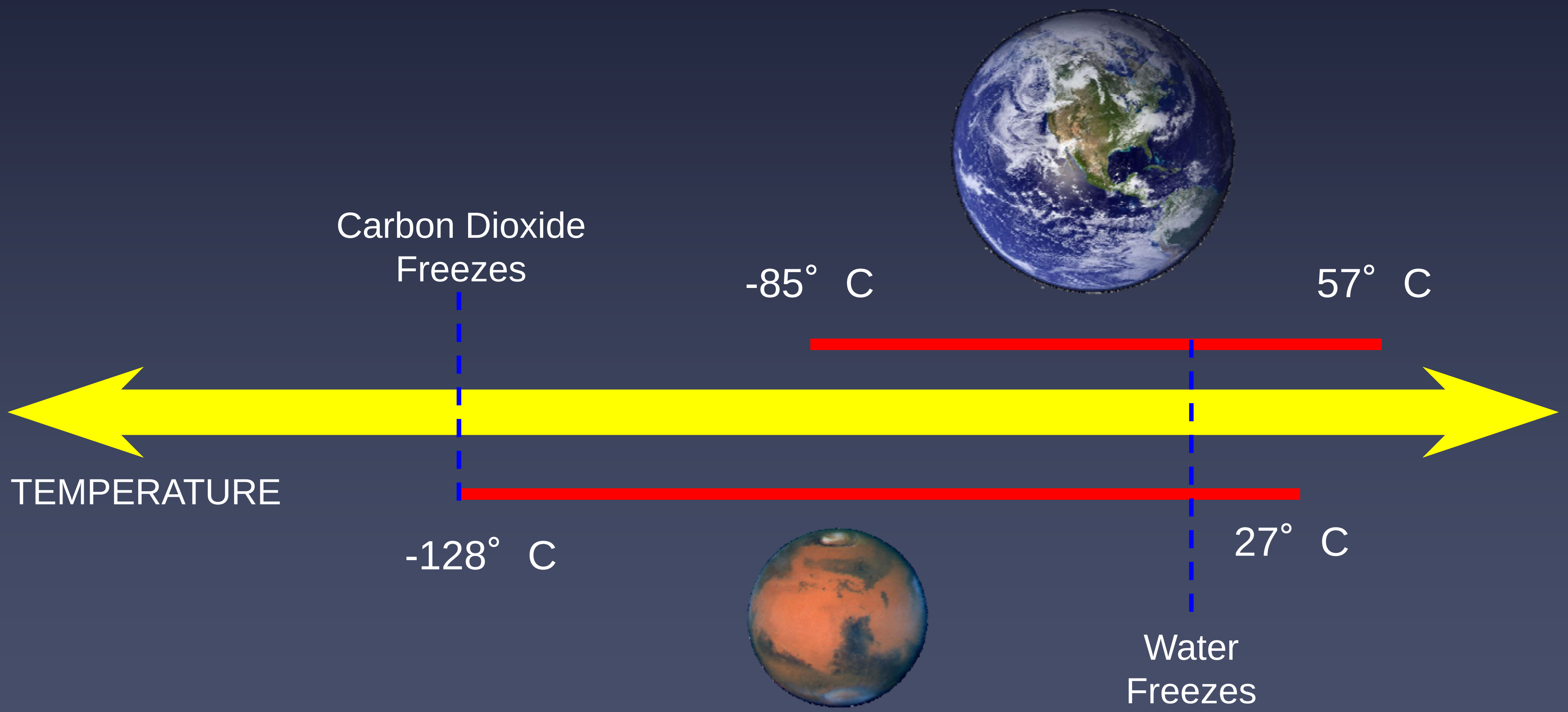
REMS data through sol 938, from G. Martinez

The Martian Atmosphere

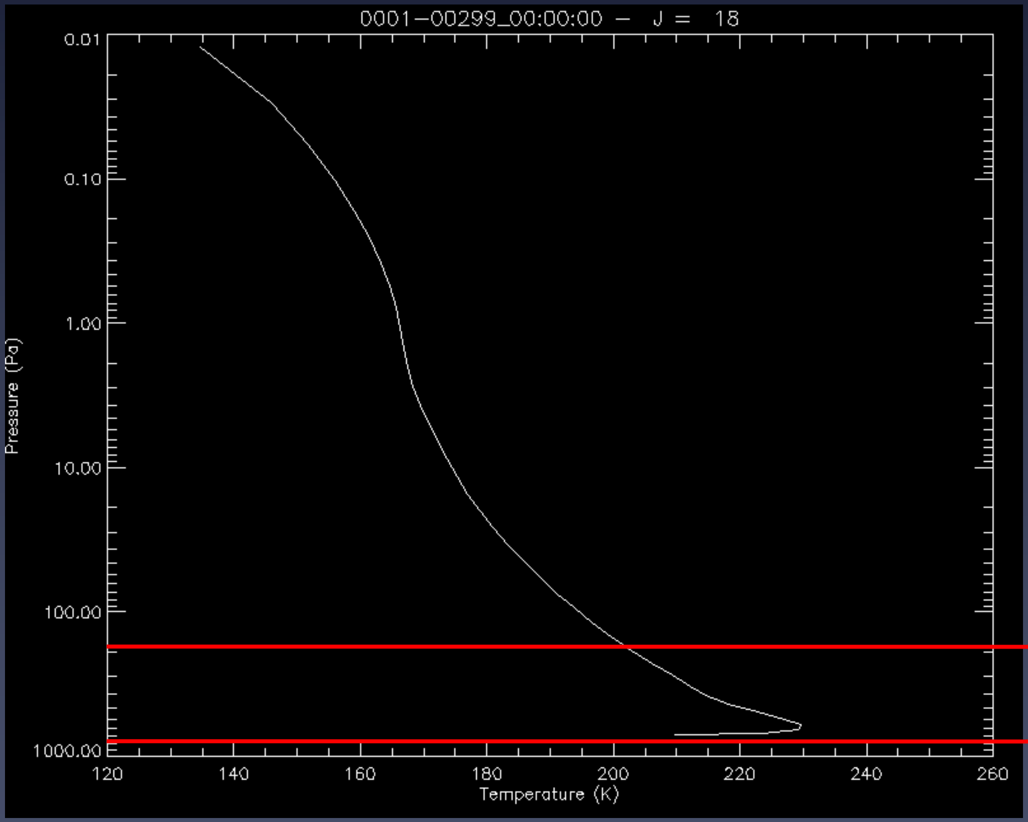
- Energy which drives circulation comes from the Sun
  - Absorption in atmosphere (gas/dust)
  - Absorption by surface
  - Re-radiation from surface/atmosphere
  - Dust scattering
  - Latent heat at poles



Temperature



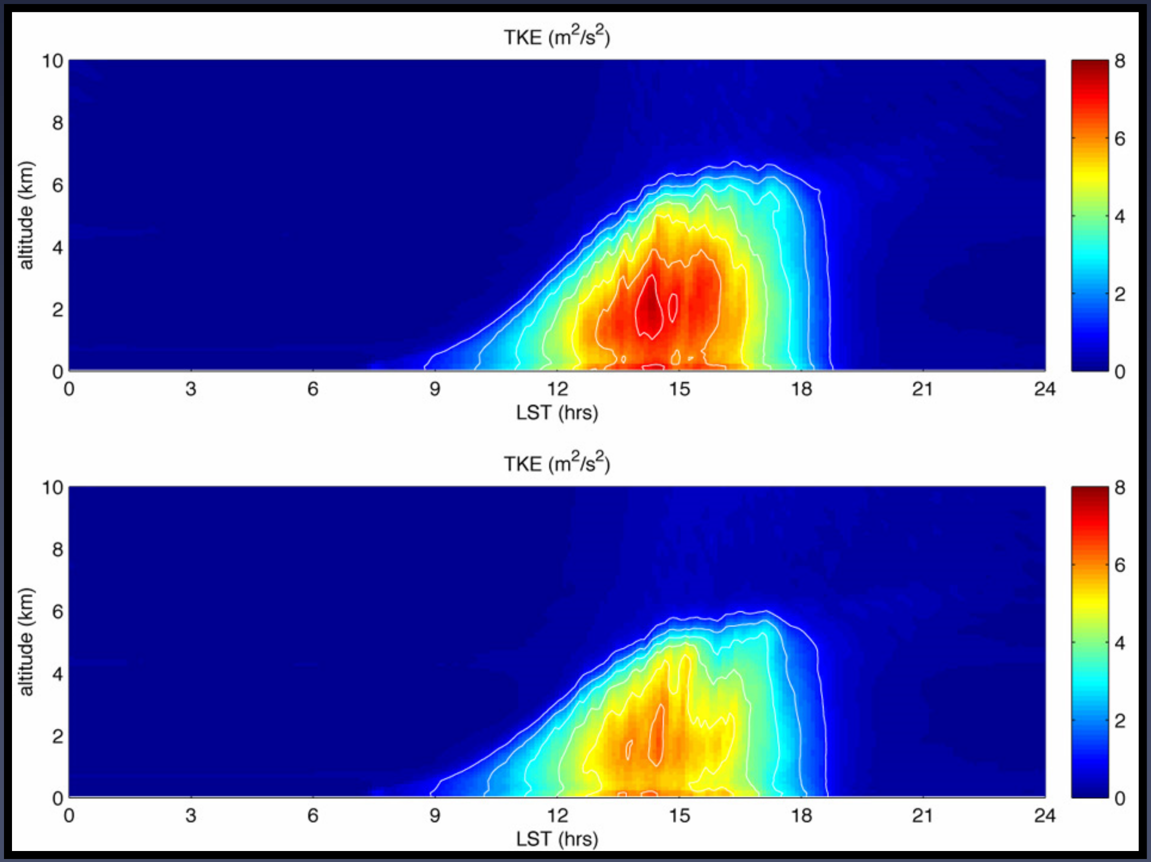
Temperature



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

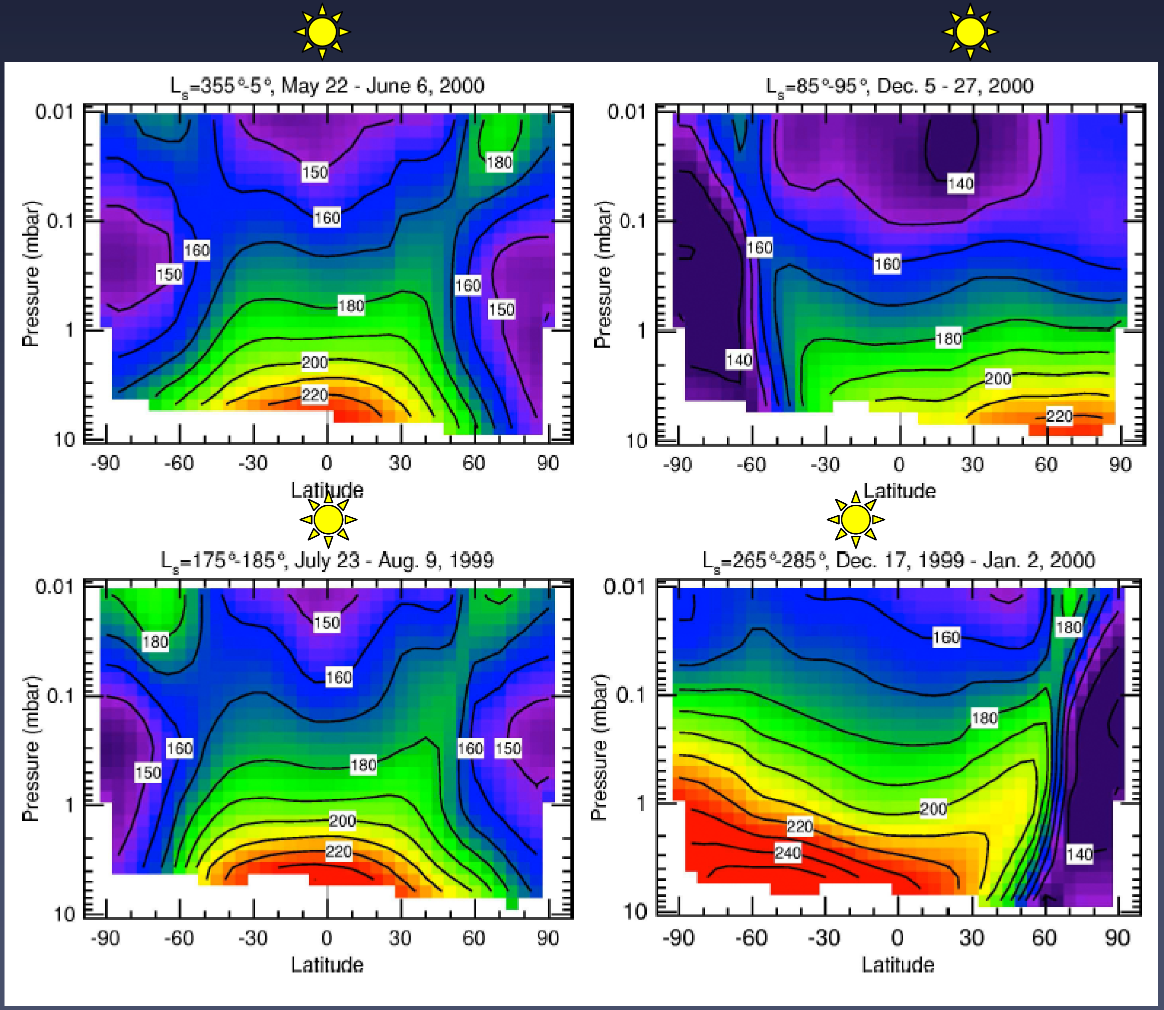
Boundary layer, ~10 km

Turbulence



- Energy at small scales is turbulent energy.
- Think of this as convective energy

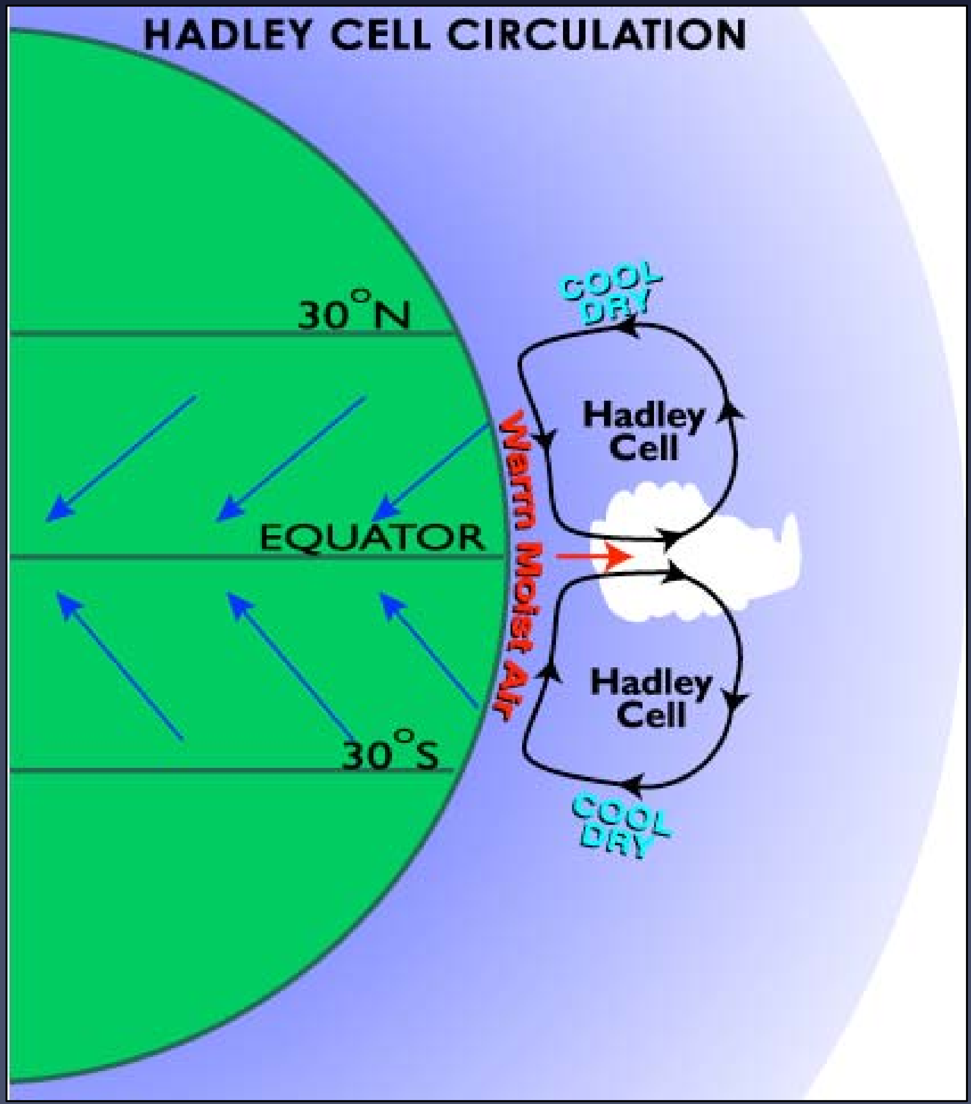
Zonal Average Temperatures



from Smith et al., (1999)

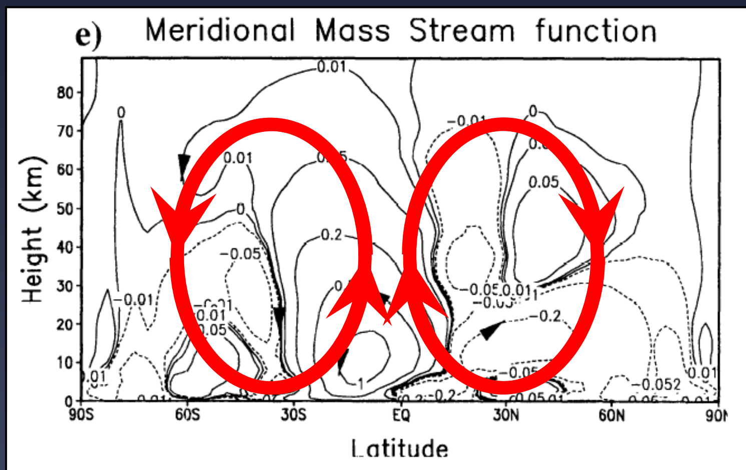
Global Circulation

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

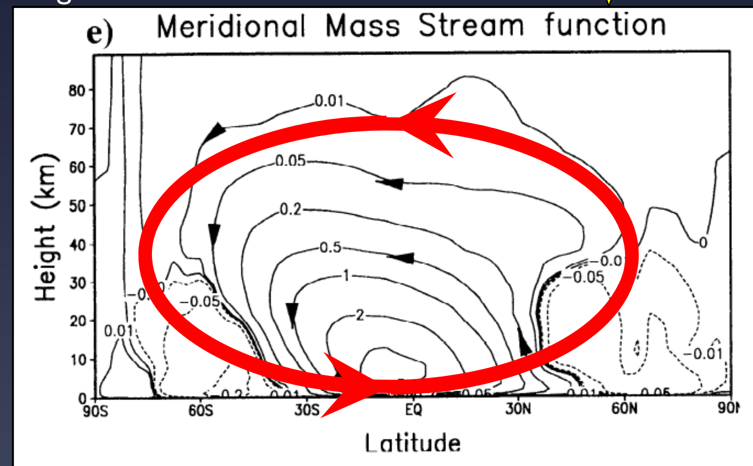


Global Circulation

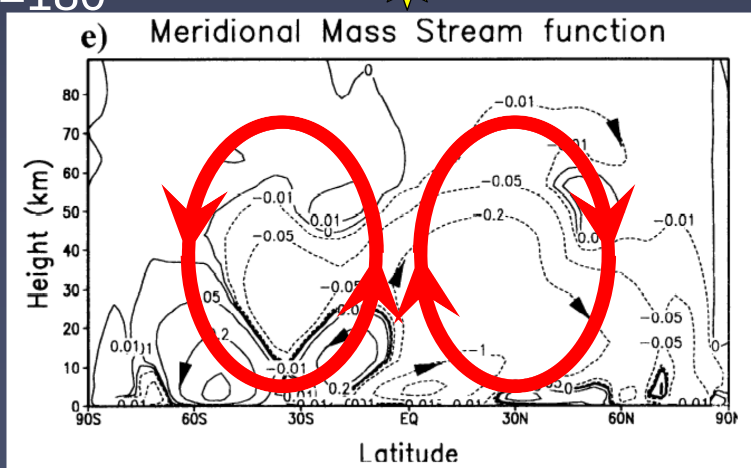
$L_S=0°$



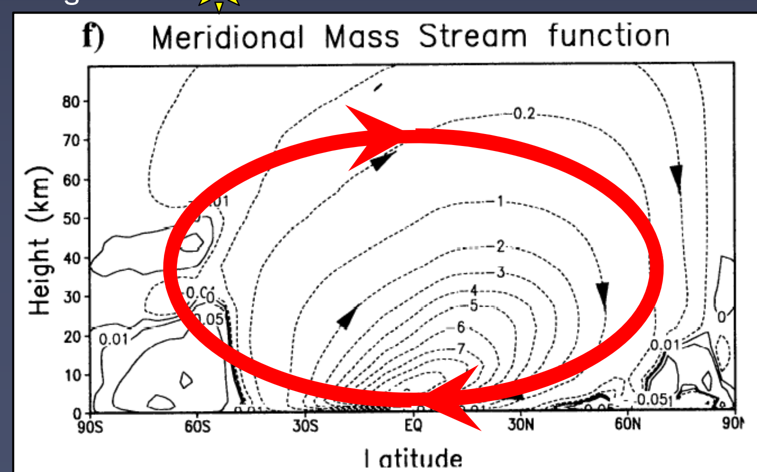
$L_S=90°$



$L_S=180°$



$L_S=270°$



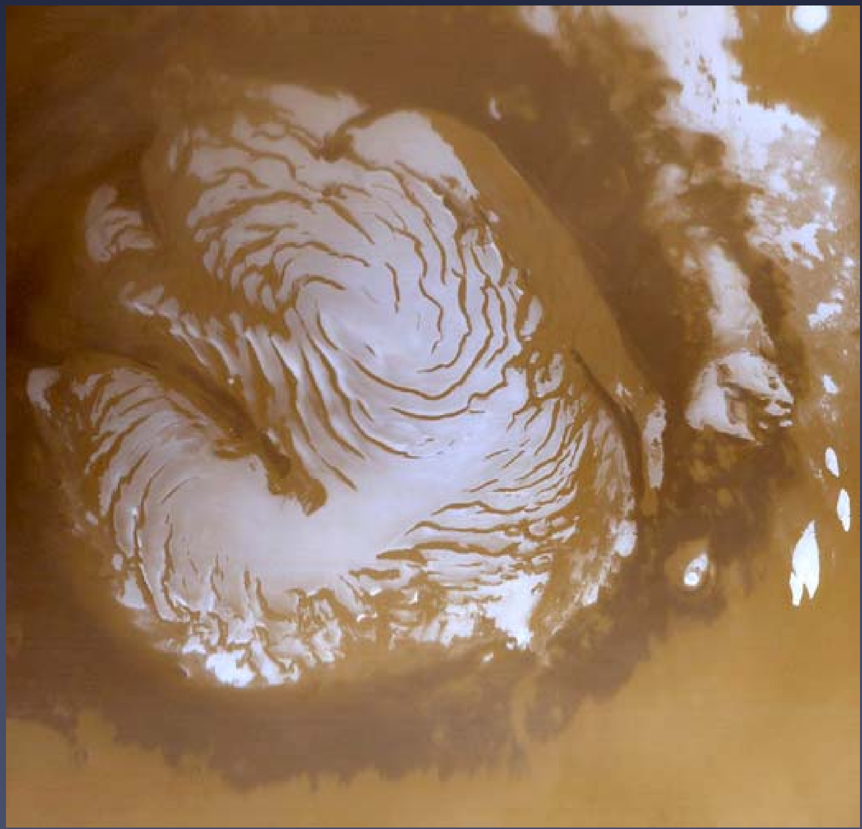
from Forget et al., (1999)

Local Circulation

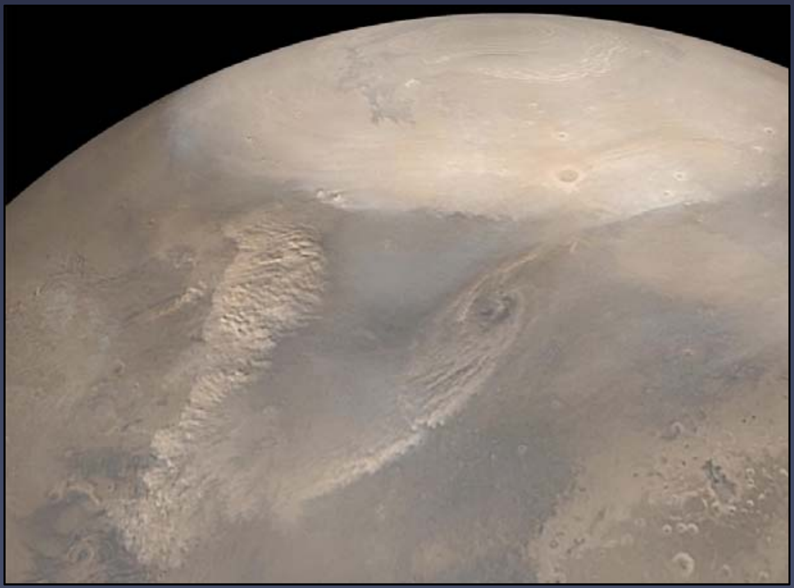
- Modifiers of general circulation
  - Topography
  - Thermal contrast (poles, albedo/TI variations)
  - Dust
- Topography is responsible for generating *waves* in the atmosphere, and restricting some wind patterns
- Slope winds
  - Driven on many different scales
  - Familiar to us on Earth, upslope/downslope winds
  - Buoyant air ascends, dense air descends

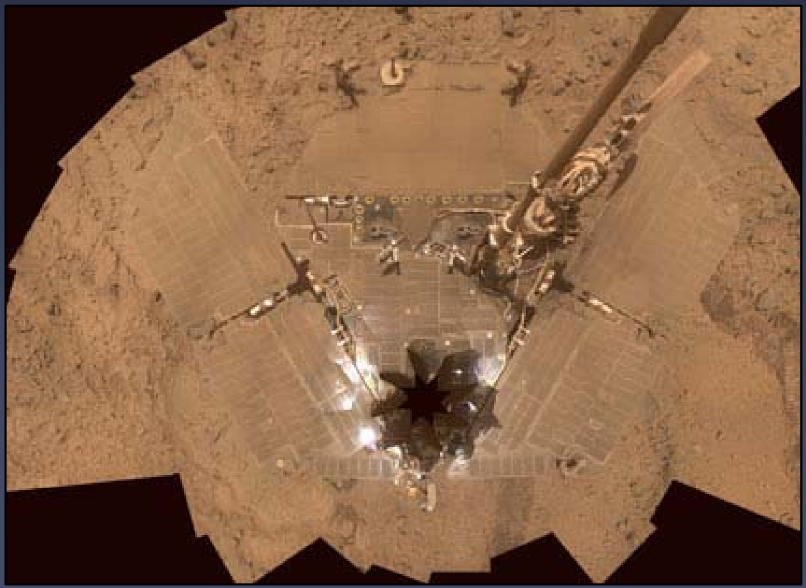
Local Circulation

- 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



Atmospheric Dust





Atmospheric Dust

- At larger scales, most major circulation components are strengthened by increased dust loading in the atmosphere
    - e.g. Hadley circulation
- Circulations forced by solar heating of the ground are generally weakened due to the reduction in insolation at the ground
    - e.g. diurnal slope flows, cap edge circulation, boundary layer convection

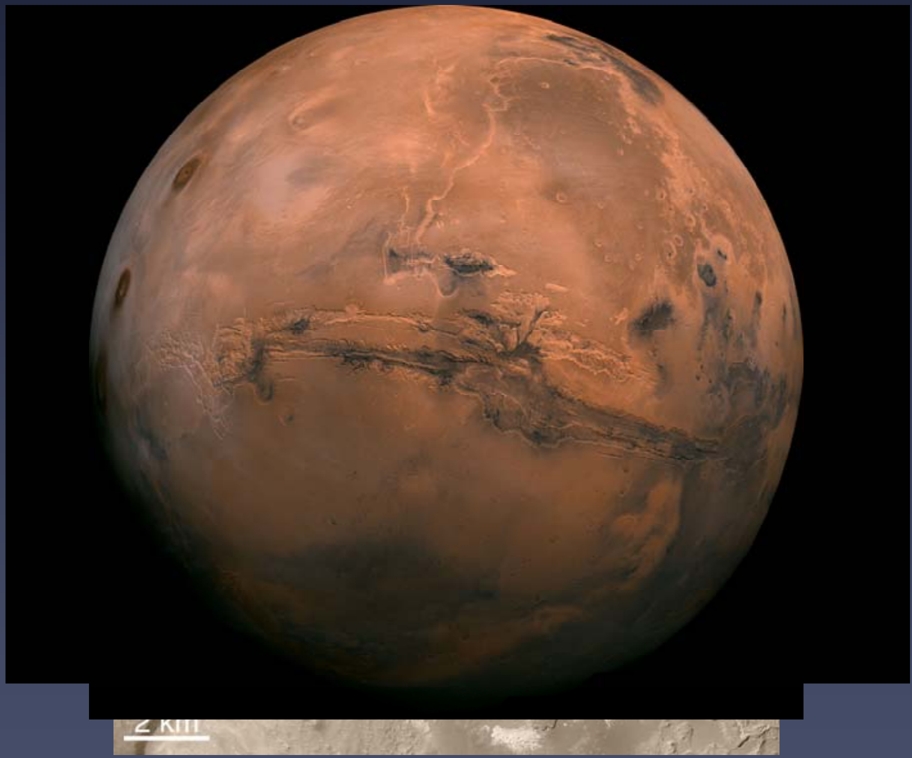
Summary (Pt 1)

- Temperature
  - Largely controlled by surface absorption/re-radiation
  - Diurnal cycle (stable vs. unstable); mixing
- Pressure
  - Seasonal condensation cycle, non-condensable enrichment
- Dust
  - Affects strength of global circulation
  - Potential chemistry effects (not discussed here)
- Wind
  - Multiple scales
  - Globally mixes in ~30 days
  - Global circulation strongly affected by local conditions

Mars Climate History

Introduction

- Geological and geochemical evidence points to a vastly different, early climate on Mars.
  - Fluvial features (rivers, channels, shorelines, aqueous signatures) suggest a planet warmer and wetter than present
  - An atmosphere of 100’s mb pressure
  - Temperatures near or above melting point of water
- What happened?

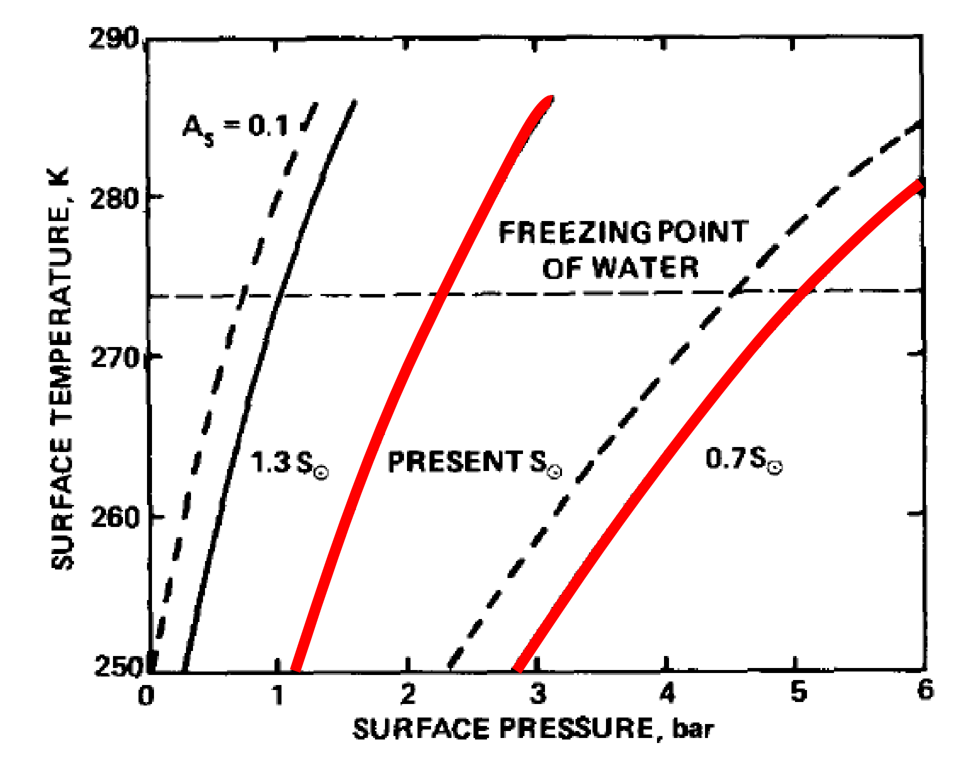


Introduction

- Early Mars atmosphere had to be thicker
  - Liquid water has pressure *and* temperature constraints
- Early solar luminosity was ~25% lower than present
  - Starting from a colder place
- The “Faint Young Sun” paradox
- Can it be reconciled?

CO_2 Atmosphere

- 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

- Add enough CO_2 to make the planet warm (~5 bar)
- But CO_2 will saturate at pressures lower than this.
- Furthermore…as surface pressure increases, planetary albedo rises due to atmospheric scattering (planet gets "brighter")

In other words, CO_2 is not always a greenhouse warmer.

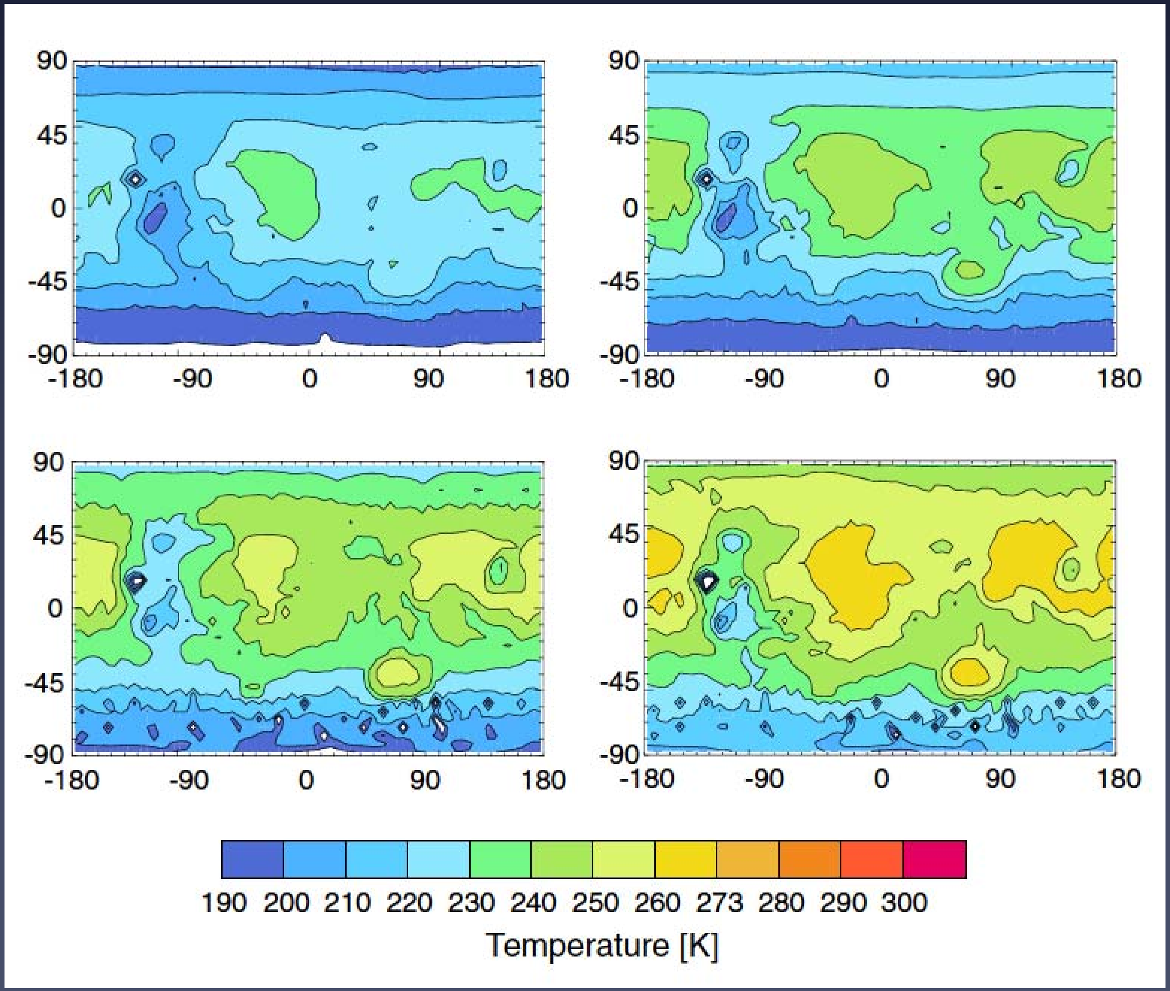
Trace Gases

- Still assume CO_2 was abundant long ago.
- Trace greenhouse species
  - NH_3, SO_2, CH_4, H_2S, H_2O, etc.
- Each has drawbacks
  - Solubility
  - Redox chemistry
  - Photochemical lifetime
  - Abundance
  - Etc…

Trace Gases

500 mb CO_2 only

500 mb CO_2 + SO_2



500 mb CO_2 + saturated atm.

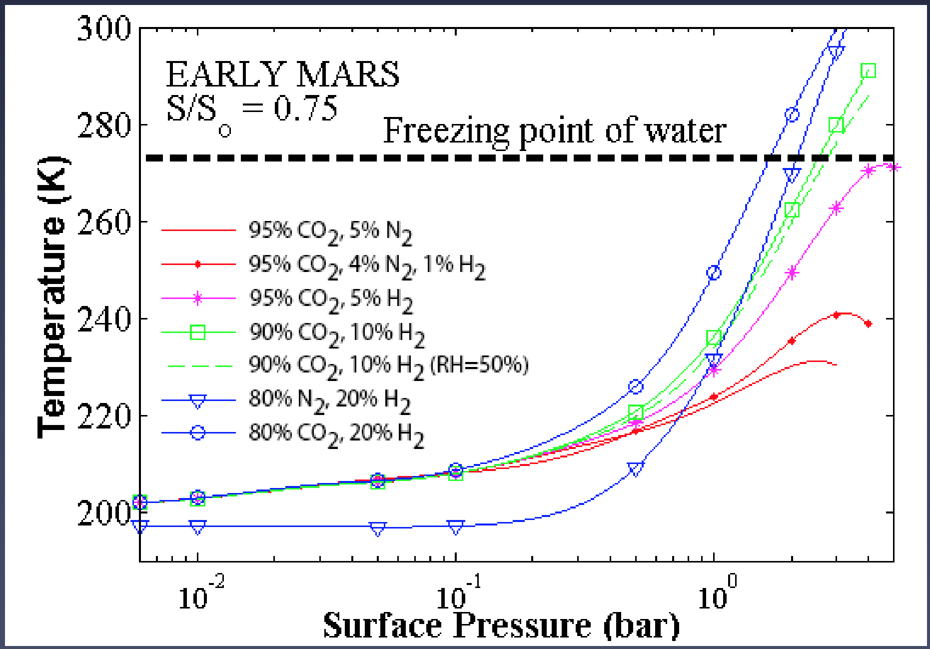
500 mb CO_2 + SO_2 + saturated atm.

Annual average surface temperatures

from Mischna et al., (2013)

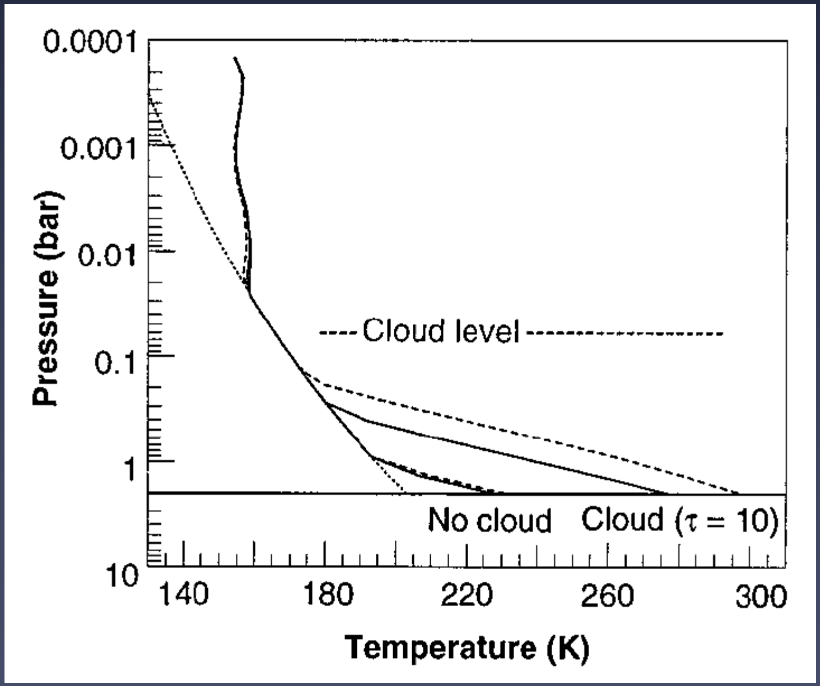
Trace Gases

- Greenhouse warming due to CIA by H_2 with CO_2.
- Significant only for background atmospheres > ~500 mb.
- Requires 10% H_2 atmosphere and saturated atmosphere



work by Ramirez et al. (2014)

Clouds

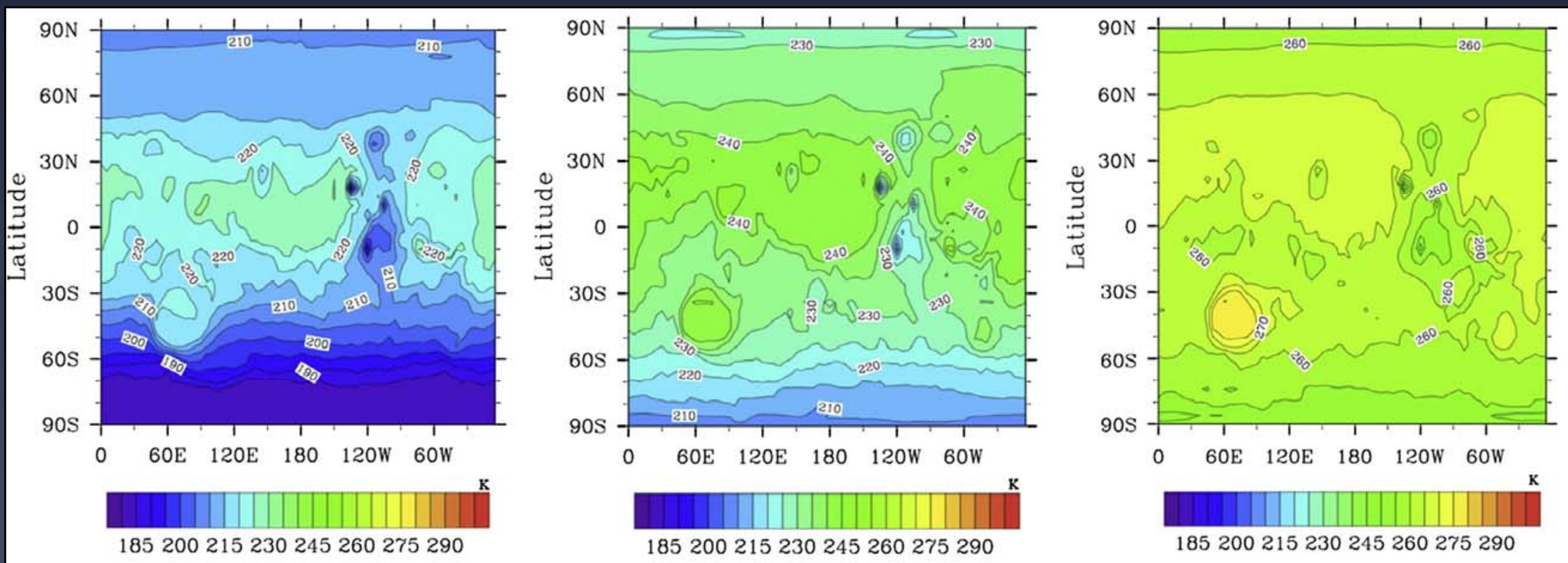


- Carbon dioxide ice clouds can be effective scatterers of upwelling IR.
- An alternative idea to greenhouse gases

from Forget and Pierrehumbert (1997)

Cloud Cover

- Water ice clouds can also act as warming agents in the atmosphere.



Urata and Toon, (2013)

More cloud / Higher cloud / Bigger cloud particles / <u>More warming</u>

- Even CO_2 ice clouds can be warming agents from IR scattering

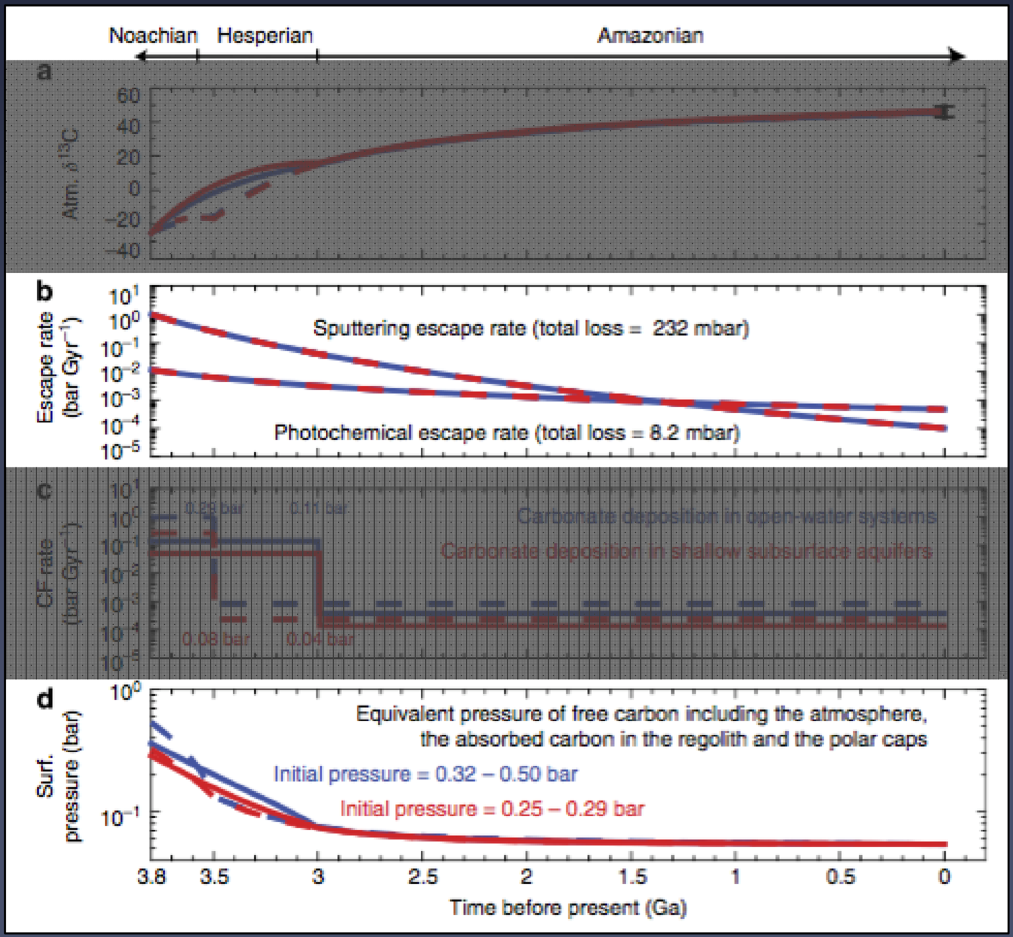
Impact Warming

- Impact-induced warming:
  - Introduction of significant heat and water to the climate system
- Big impactors (10's km)
  - Smaller impactors have negligible influence
  - Results in <u>global</u> influence
- Large impacts occur with less frequency later in Mars history

Impact Warming

- Impact climate change is <u>not</u> local
  - These are large impacts (~Hellas-forming size)
  - Precipitation could/would be global
- Cratering history limitation on how late in geological time such climate change could be
  - Large impacts occur with less frequency later in Mars history, largely restricting this to early times

Sputtering / Photochemical Escape

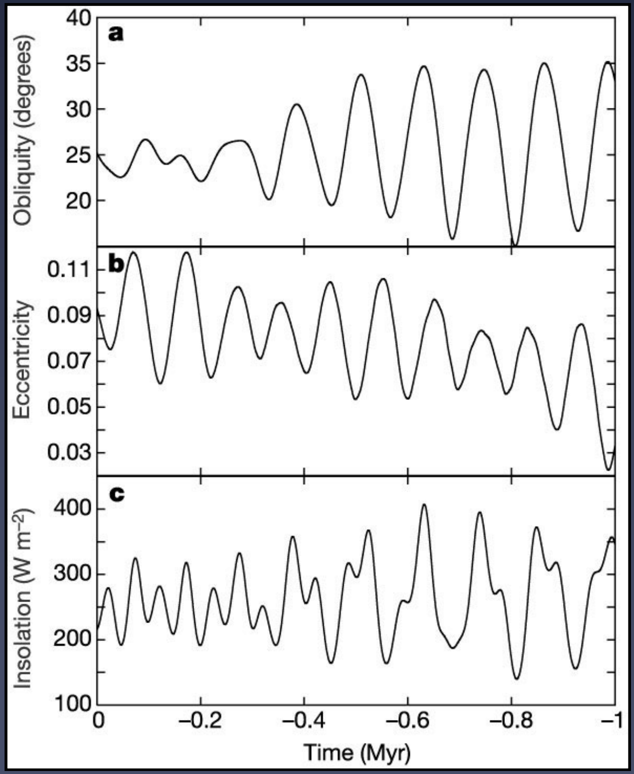


From Hu et al., (2015)

- Sputtering and moderate carbonate formation act as the decay process.
- Requires <1 bar CO_2 initially.
- Probably <100 mb since ~3 Ga
- Mostly cold and dry throughout history

Orbital Change

- Orbitally driven climate change
  - Obliquity
  - Eccentricity
  - Perihelion
- Does not modify overall global insolation
  - Only modest change to surface pressure
  - Primary effect is to water cycle/redistribution of surface ice



from Laskar et al., (2002)

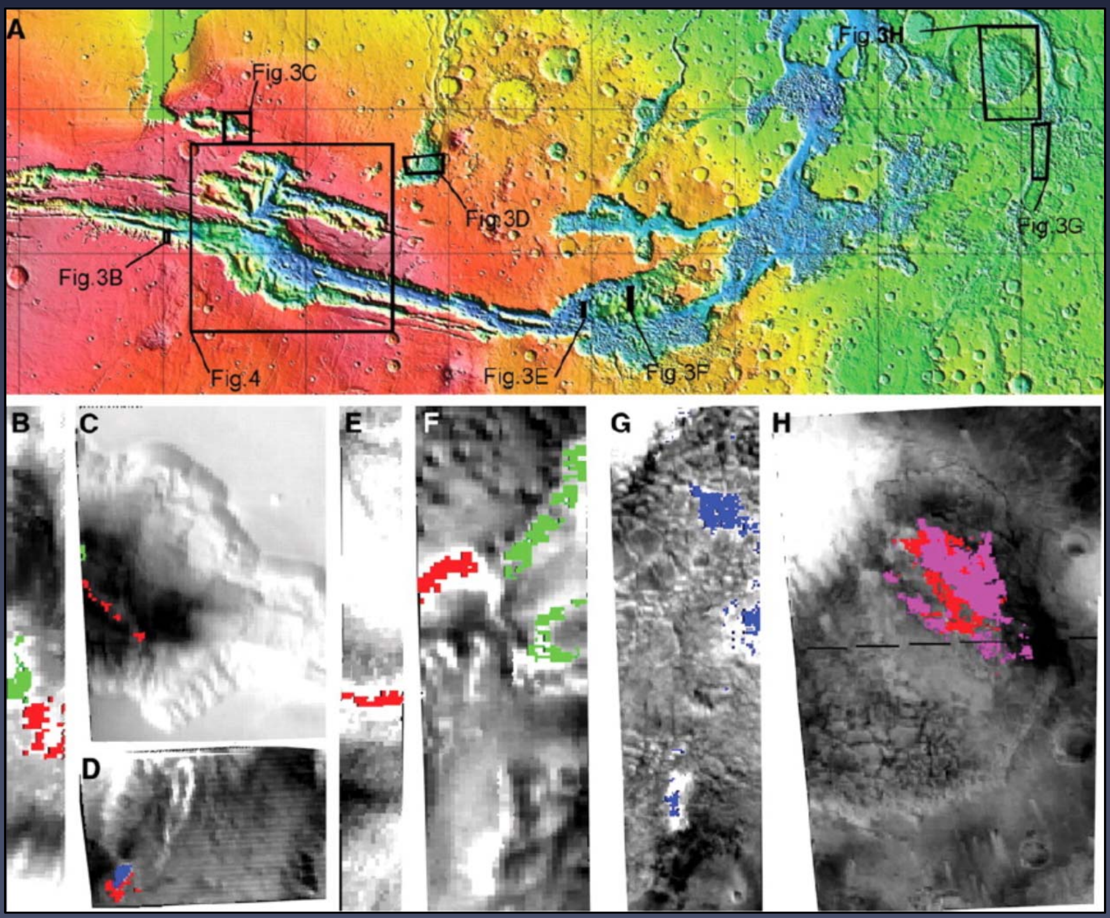
Orbital Change

- Rise in obliquity moves ice to tropics → increase in planetary albedo

- Change in eccentricity/precession phasing can control cloud distribution and polar cap size

- As obliquity approaches zero, atmosphere will collapse at poles

Alternatives to pure water melt



Kieserite ($MgSO_4 \cdot H_2O$)

Polyhydrated sulfates

(*e.g.* $MgSO_4 \cdot 7H_2O$)

Gypsum ($CaSO_4 \cdot 2H_2O$)

Other hydrates

Gendrin *et al.* (2005)

Summary (Pt 2)

- Geochemical and geological evidence suggests a wet early Mars
- Need to significantly warm early Mars (FYS paradox)
- Many mechanisms have been proposed, none wholly satisfactorily
  - Sulfur species, methane, water vapor,
  - CO_2/H_2O ice clouds
  - Impacts?
  - Brines
- Most prevailing theories estimate 100's mb initially