The Climate and Paleoclimates of Mars

Claire E. Newman

working with Mark Richardson at the

Division of Geological and
Planetary Sciences,
California Institute of Technology

Overview

- Investigative tools and techniques

- Review of the present climate
- Climate variability - mechanisms and simulations

- Paleoclimates of the past few tens of Myrs - the impact of Mars's changing orbit

- The climate of ancient Mars - the evidence and the theories

Overview

- **Investigative tools and techniques**

- Review of the present climate
- Climate variability - mechanisms and simulations

- Paleoclimates of the past few tens of Myrs - the impact of Mars's changing orbit

- The climate of ancient Mars - the evidence and the theories

Tools for examing Mars's climate(s): observations

- Current climate observations
- Geomorphological observations and interpretations
- Solid rock geochemistry observations and inferences about past weathering
- Isotope ratios and noble gases - implications for atmospheric loss

Tools for examing Mars's climate(s): models

- Geochemical evolutionary models of the atmosphere
- Radiative-convective models
- General circulation/climate models (GCMs)

Geochemical Evolutionary Models

Box” models that take rates of chemical creation/loss from theory or observation and use them to predict the time evolution of a set of chemical species: for example, the trend in CO_2 pressure

Processes considered for Mars:

- Loss of CO_2 to carbonate formation
- Loss of CO_2 through photochemical dissociation and loss from the top of the atmosphere
- Gain/loss of CO_2 from/to adsorption within the regolith
- Gain/loss of CO_2 from/to ice
- Gain of CO_2 from volcanism / outgassing
- Gain of CO_2 from impactors

Radiative Convective Climate Modeling

- Consider radiative heating of the surface and atmosphere and parameterized convection: used to determine global mean surface temperatures as a function of atmospheric composition and forcing

- Typically used to investigate the atmospheric composition and surface pressure needed to yield a “warm wet” early climate

- Applicable to processes operating on long timescales - assumes that horizontal variations are of negligible fundamental importance

Mars general circulation models

Useful for:

- understanding observations of variables for which we *have* data (e.g. temperature)
- looking at the circulation as a whole, including variables *not* measured directly (e.g. winds aloft)
- investigating the mechanisms behind processes such as dust storm initiation and water ice build-up
- exploring possible *past* climates (e.g. those which might have existed under different orbital conditions)

Mars general circulation models

Typically include:

- dynamical core (solves momentum equations)
- parameterized sub-grid scale physics, including:

  radiative transfer in a dusty CO_2 atmosphere
  10 layer soil scheme
  CO_2 condensation/sublimation flow
  boundary layer turbulence
  dust and water transport schemes

- observed surface properties (e.g. MOLA topography)

Overview

- Investigative tools and techniques

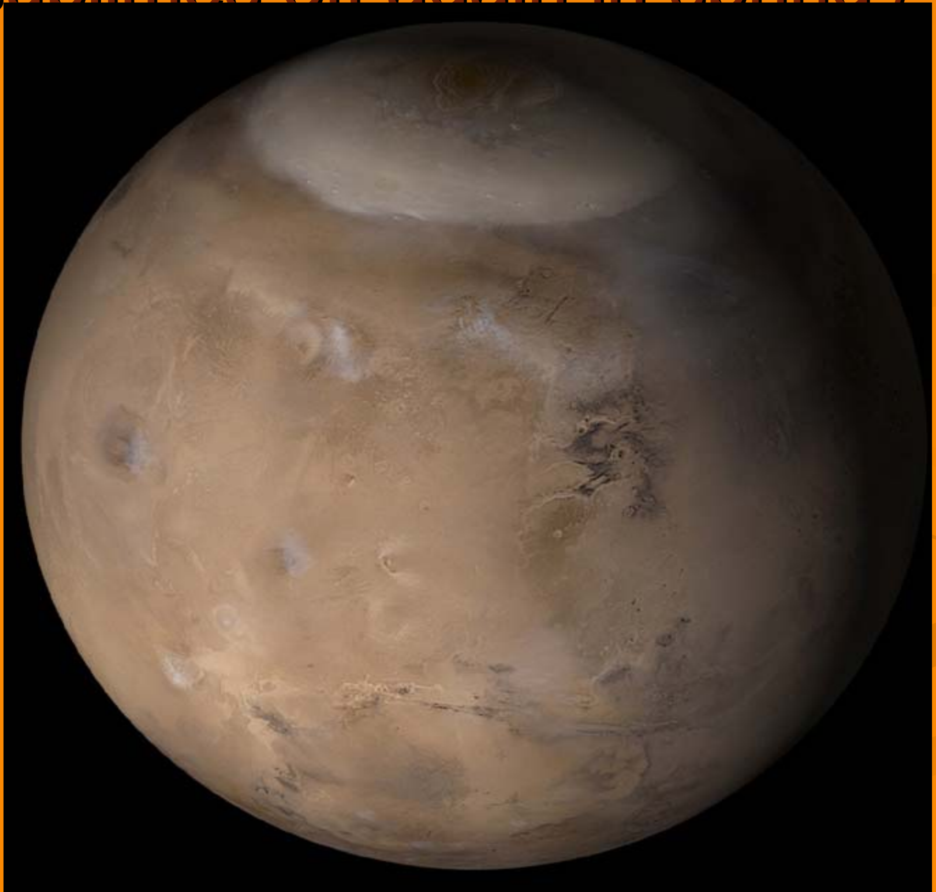
- **Review of the present climate**
- Climate variability - mechanisms and simulations

- Paleoclimates of the past few tens of Myrs - the impact of Mars’s changing orbit

- The climate of ancient Mars - the evidence and the theories

The Martian atmosphere

- CO_2 atmosphere with surface temperatures ~150-300K
- => ~1/3 of atmosphere condenses onto polar caps in fall / winter, sublimes off again in spring / summer



The Martian atmosphere (continued)

- Eccentric orbit => far more solar heating near perihelion (during northern winter)
- Thin atmosphere (~1% Earth’s) and fast radiative timescales
- Dust has a huge impact on atmospheric absorption of solar radiation
- ‘Dust storm season’ lasts from southern spring through summer

Why are we interested in dust and water transport when looking at climate?

- Dust has a big effect on heating rates in the Martian atmosphere (see previous talk) and is very important to present day climate variability

- The surface of Mars contains a record of dust and water deposition in the past (see later!)

- We need to understand the present dust and water cycles, including deposition

- Then we can try to use the surface record to infer wha the past dust and water cycles - and the past climates - were like

Overview

- Investigative tools and techniques

- Review of the present climate
- **Climate variability - mechanisms and simulations**

- Paleoclimates of the past few tens of Myrs - the impact of Mars's changing orbit

- The climate of ancient Mars - the evidence and the theories

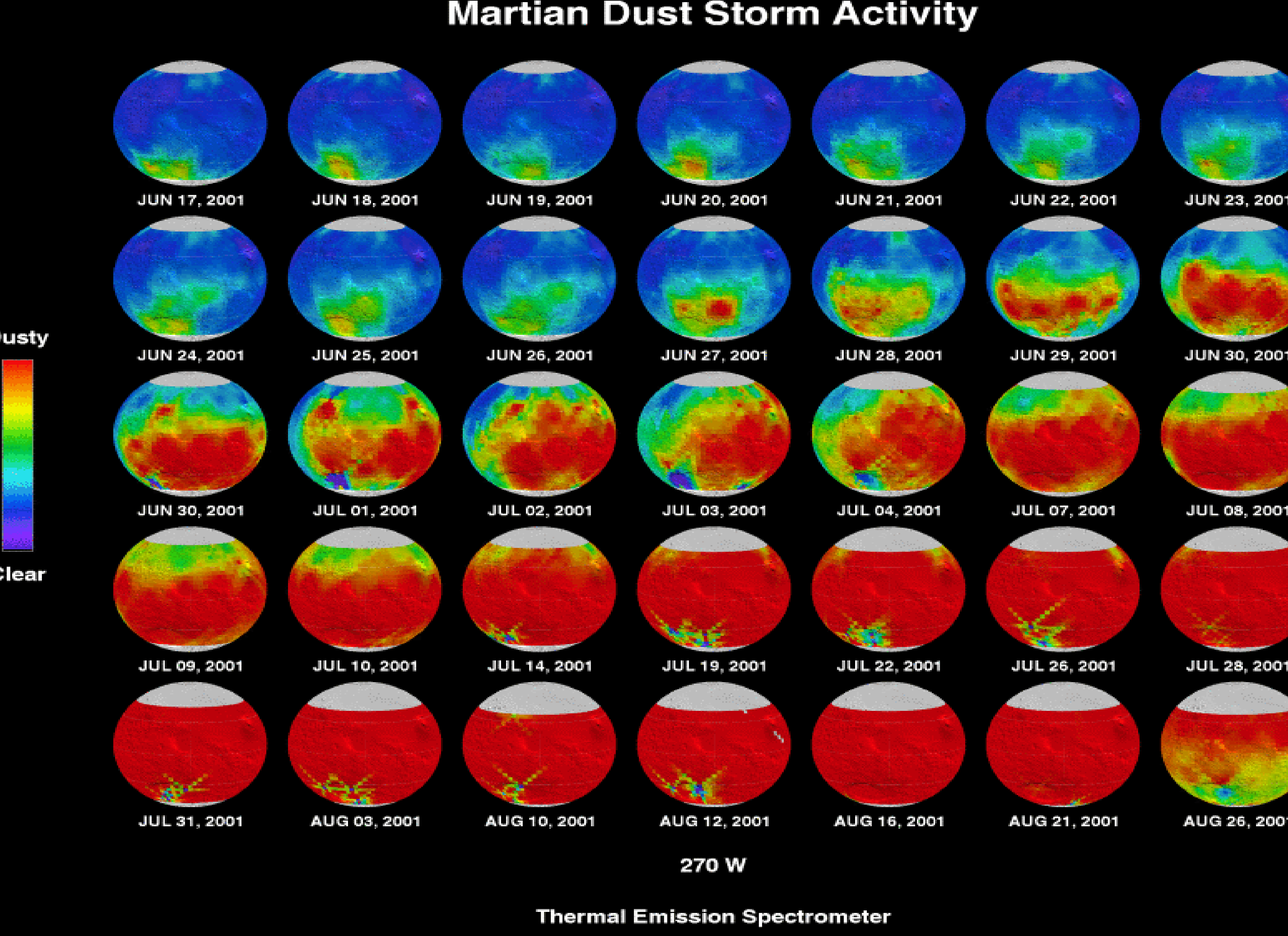
Interannual variability & dust storms

- Martian climate is very repeatable in northern spring/summer, but variable in northern fall/winter

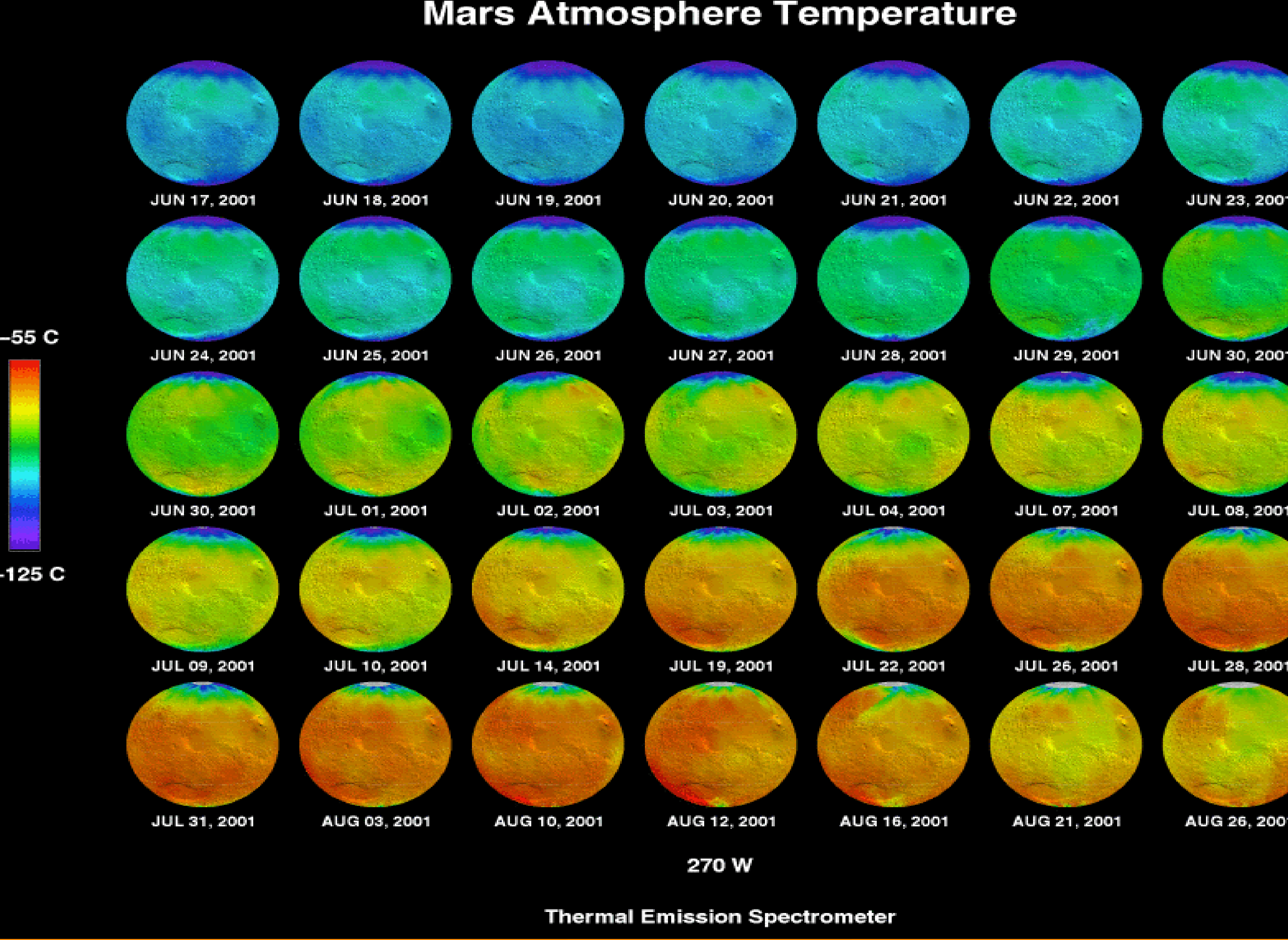
- This is strongly linked to variability in dust load during the so-called ‘dust storm season’

- On average ~1 global storm is observed every 3 years

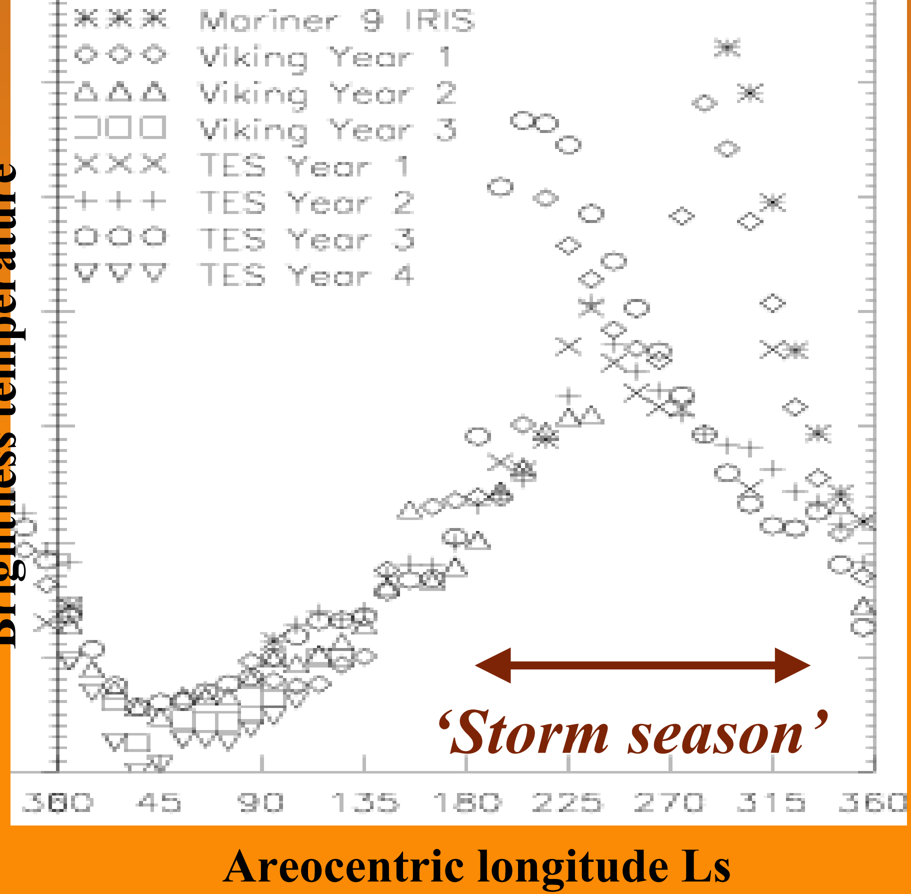
- A range of global and regional storm types is observed

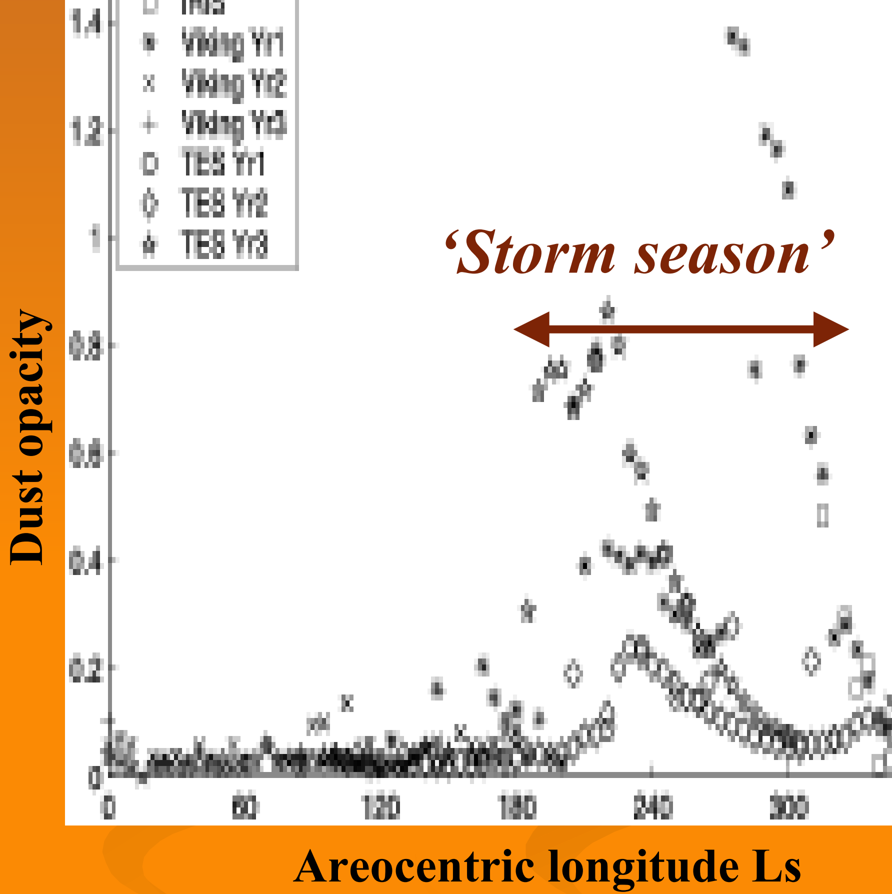


Dust opacities for 2001 global storm from MGS TES websi



~25km atmospheric temperatures for 2001 global storm from MGS TES websi



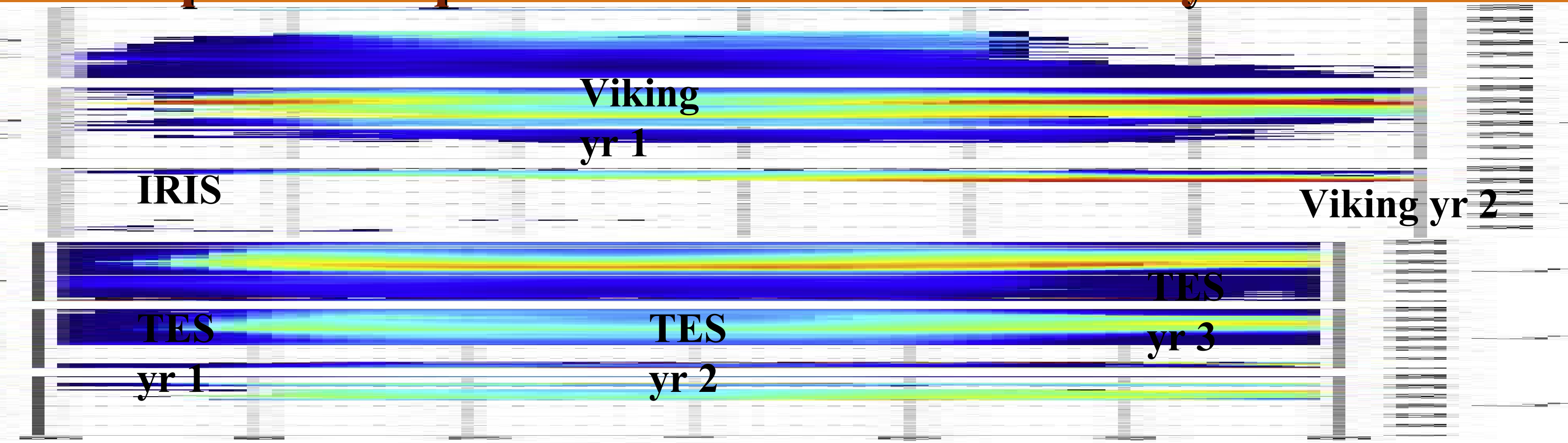


Demonstrates repeatability in Martian atmospheric temperatures (at ~25 m) in northern spring and summer, and the variability in fall and winter

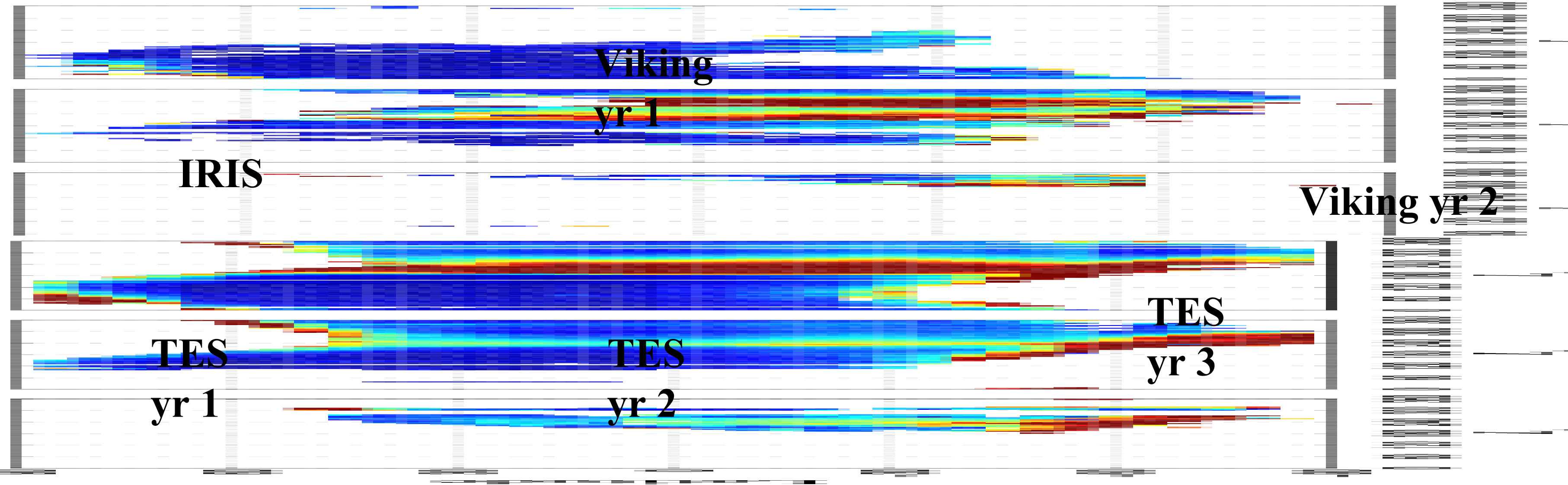
Also demonstrates the link between increased dust opacity in years with arge storms in the storm season, and raised atmospheric temperatures

From Liu et al. JGR 200

Atmospheric temperatures observed in different years on Mars



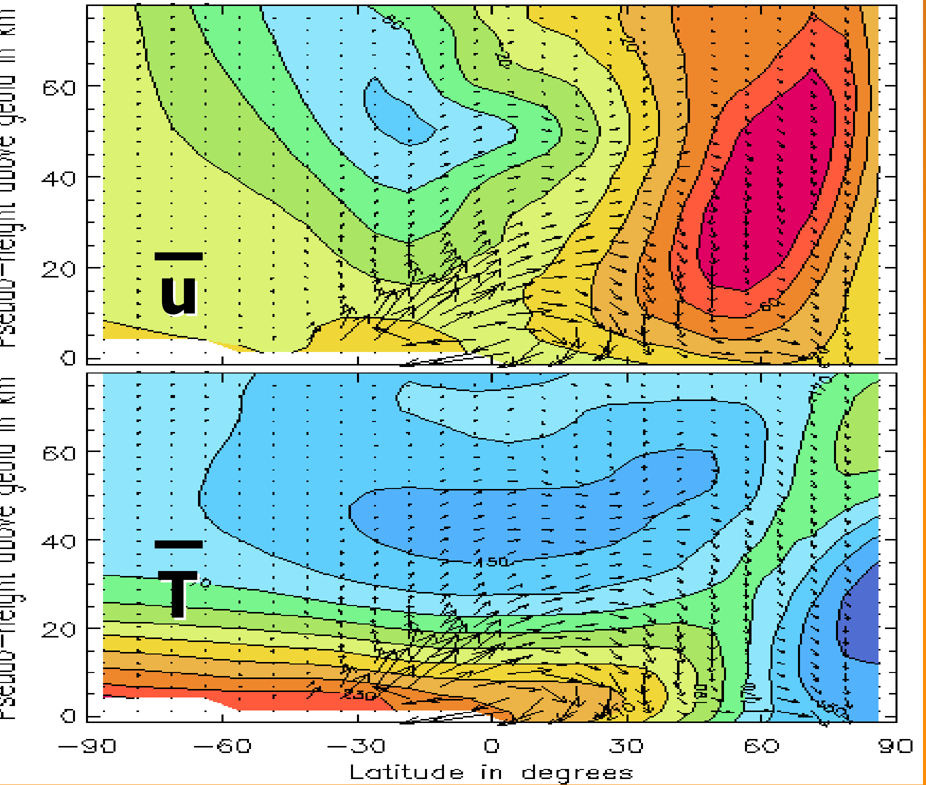
Dust opacity observed in different years on Mars



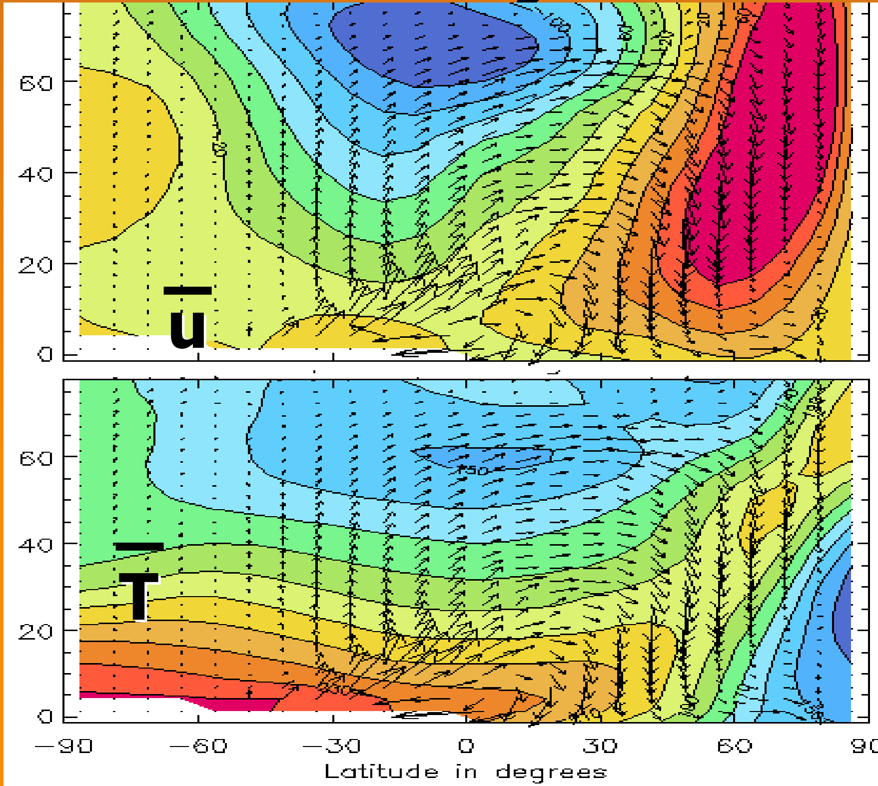
From Liu et al. JGR 2003

The effect of more dust on the circulation…

Southern summer: *low* dust levels



Southern summer: *higher* dust levels

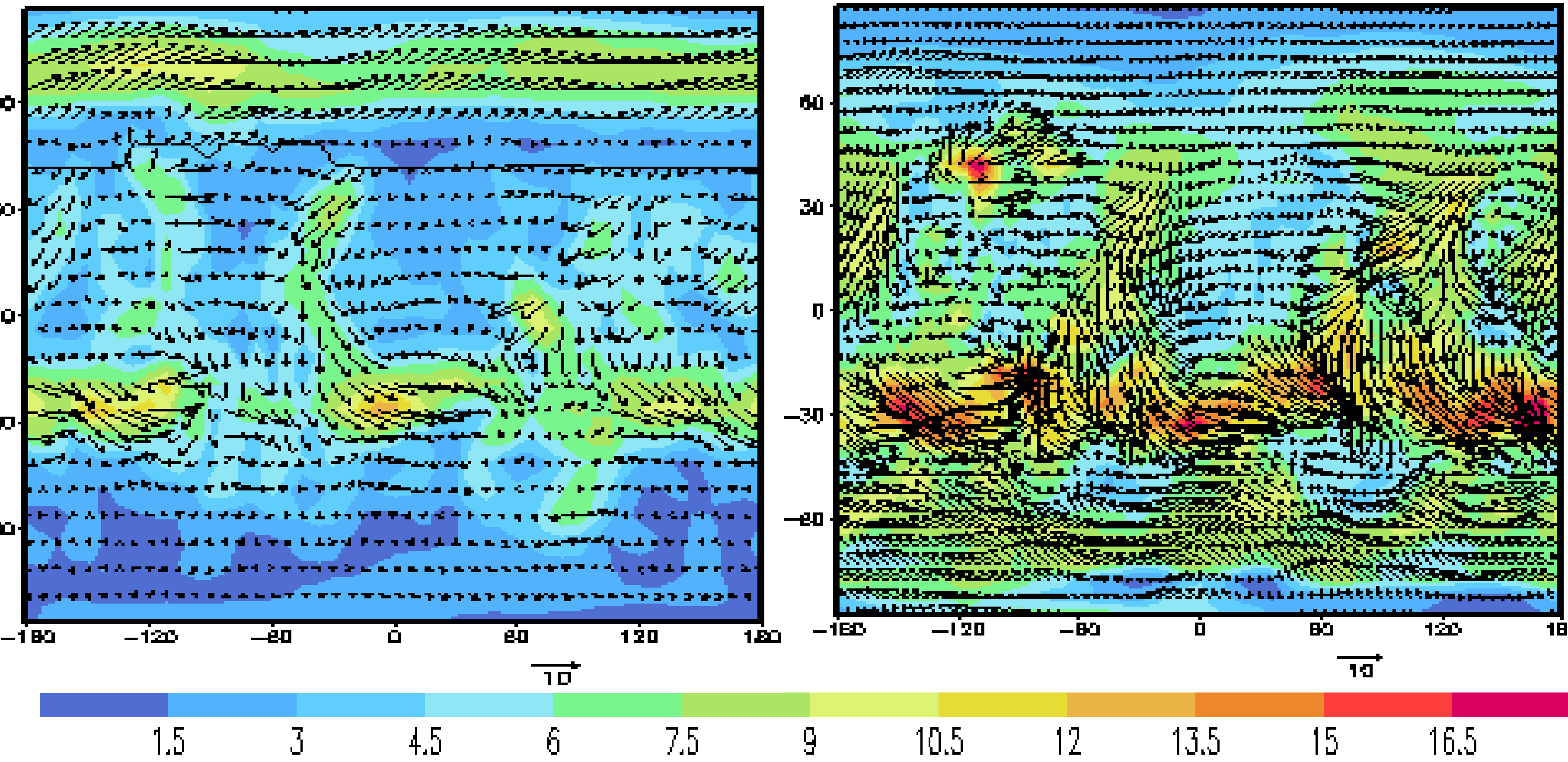


Increased dust levels => increased absorption of incoming solar radiation by atmosphere

Solsticial Hadley cell strengthens and (particularly at higher levels) broaden

Strong circulation => increased downwelling over the winter pole => stronger polar warming

...and on surface winds in southern summer


Low dust loading

High dust loading

As dust loading increases, so does the strength of flows linked to the main meridional circulation

Modeling the dust cycle

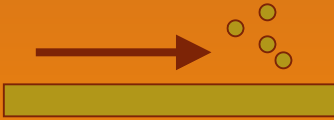
- Need to represent dust lifting, mixing, advection and sedimentation/deposition

- Currently parameterize lifting due to near-surface win stress and ‘dust devils’ (see previous talk for details)

- Realistic dust storms require feedbacks between atmospheric dust, the atmospheric state and further lifting to be enabled – we call this “radiatively active dust transport”

A *brief* description of lifting parameterizations

Wind stress lifting:



. Calculate near-surface wind stress ζ

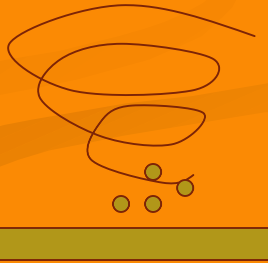
.* Lift dust if $\zeta > \zeta^t$, where ζ^t = *threshold* wind stress

.** Lifted dust flux varies roughly as $\sim \zeta^{3/2}$

Threshold may be constant or vary with e.g. atmospheric density

Lifted dust flux is generally set $\propto$ saltation flux (horizontal flux of more easily lifted sand-zed particles which 'kick up' smaller dust particles)

Dust devil lifting:



. Dust devils can be modeled as convective heat engines

. Can then calculate (A) energy available to drive engine* and (B) efficiency of engine**

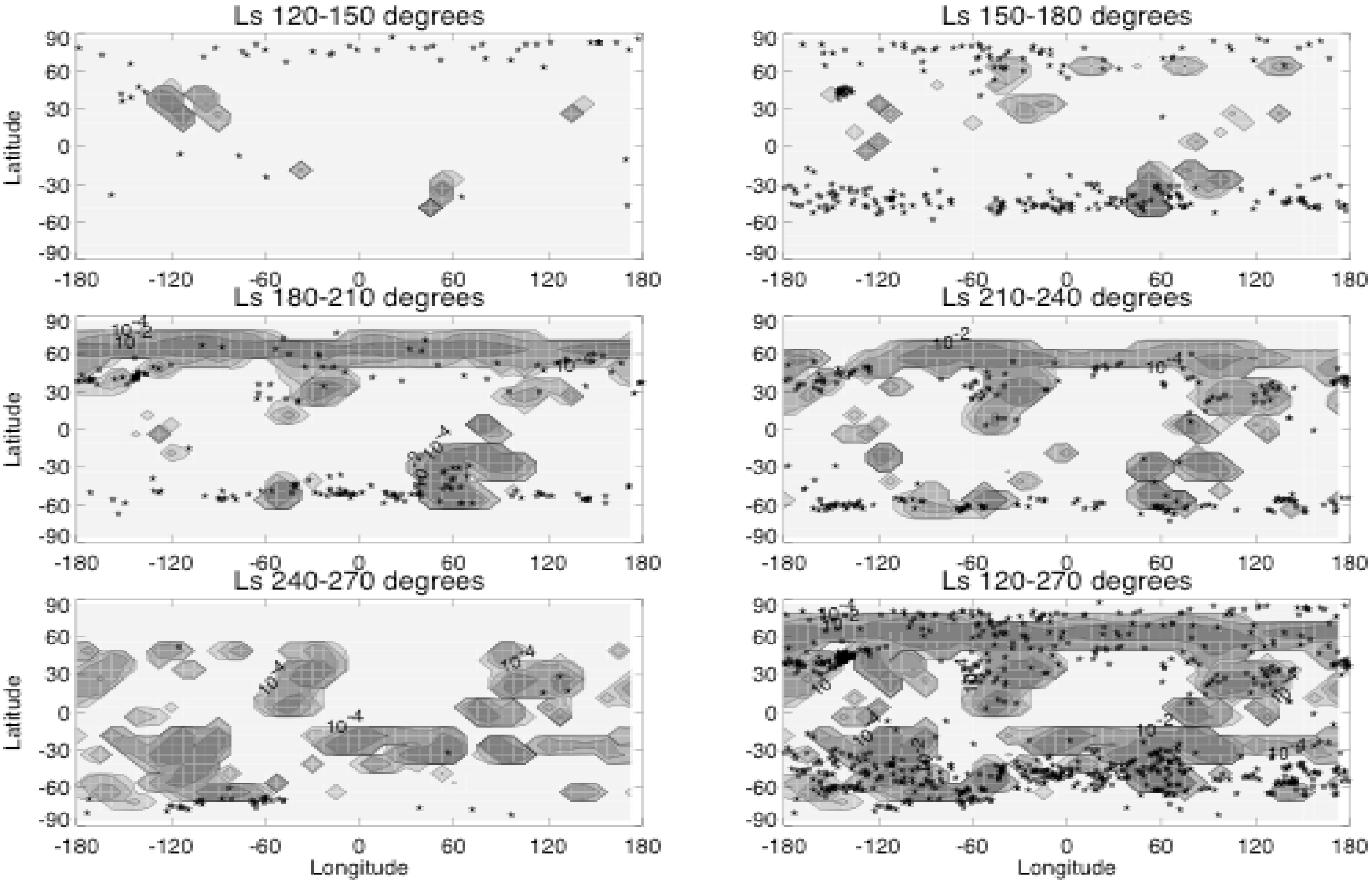
. Lifted dust flux varies as ~ A x B

A) is the sensible heat flux, which depends greatly on (T_{surface} - $T_{\text{near-surface atmosphere}}$)

=> no lifting if $T_{\text{near-surface atmosphere}} > T_{\text{surface}}$

(B) increases with convective boundary layer height

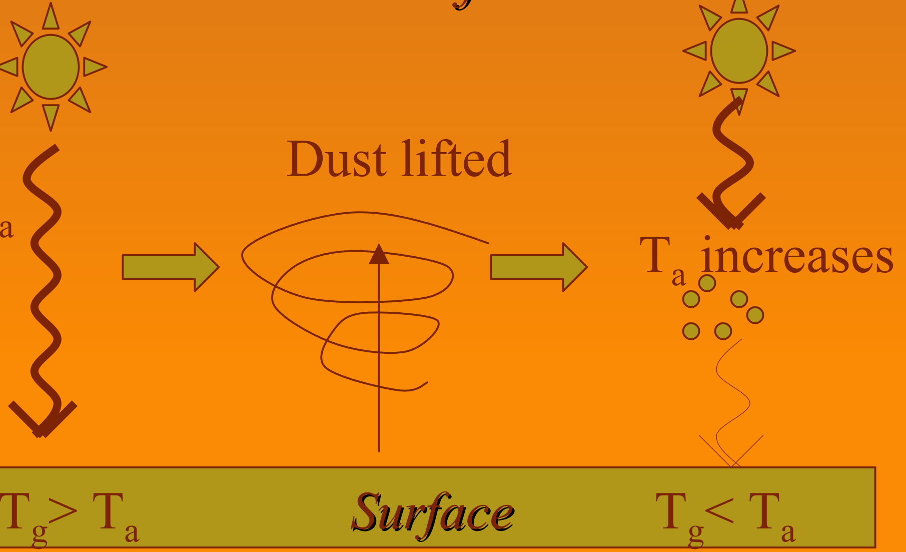
Comparison between predicted wind stress lifting contours) & initial storm clouds observed by MOC (



From Newman et al., submitted to Icarus

Feedbacks, dust lifting and dust storms

Dust devils: -ve feedbacks



a

Dust lifted

T_a increases

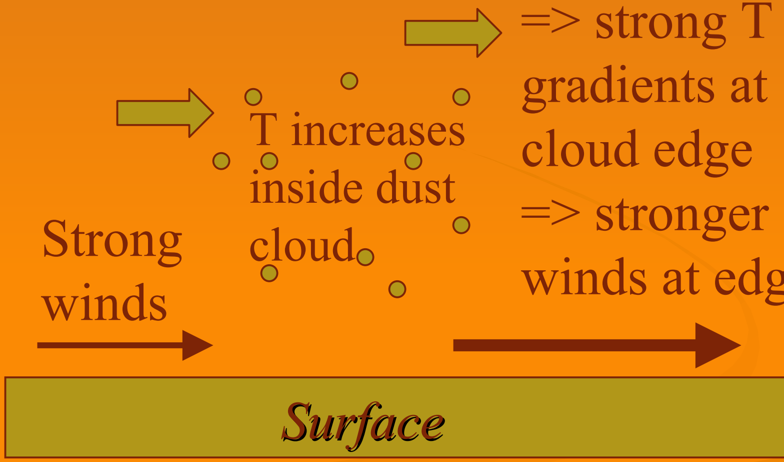
$T_g > T_a$

Surface

$T_g < T_a$

Dust devil lifting ceases

Wind stress lifting: +ve feedback
1 - local scale



=> strong T
gradients at
cloud edge
=> stronger
winds at edg

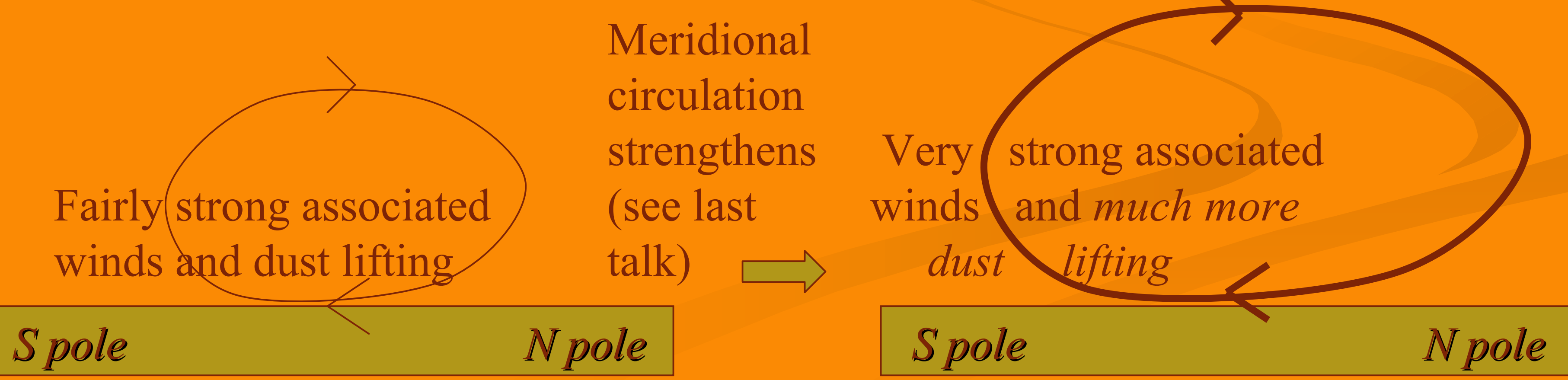
T increases
inside dust
cloud

Strong
winds

Surface

More wind stress liftin

Wind stress lifting: +ve feedbacks 2 - global scale



Fairly strong associated
winds and dust lifting

Meridional
circulation
strengthens
(see last
talk)

Very strong associated
winds and *much more*
dust lifting

S pole

N pole

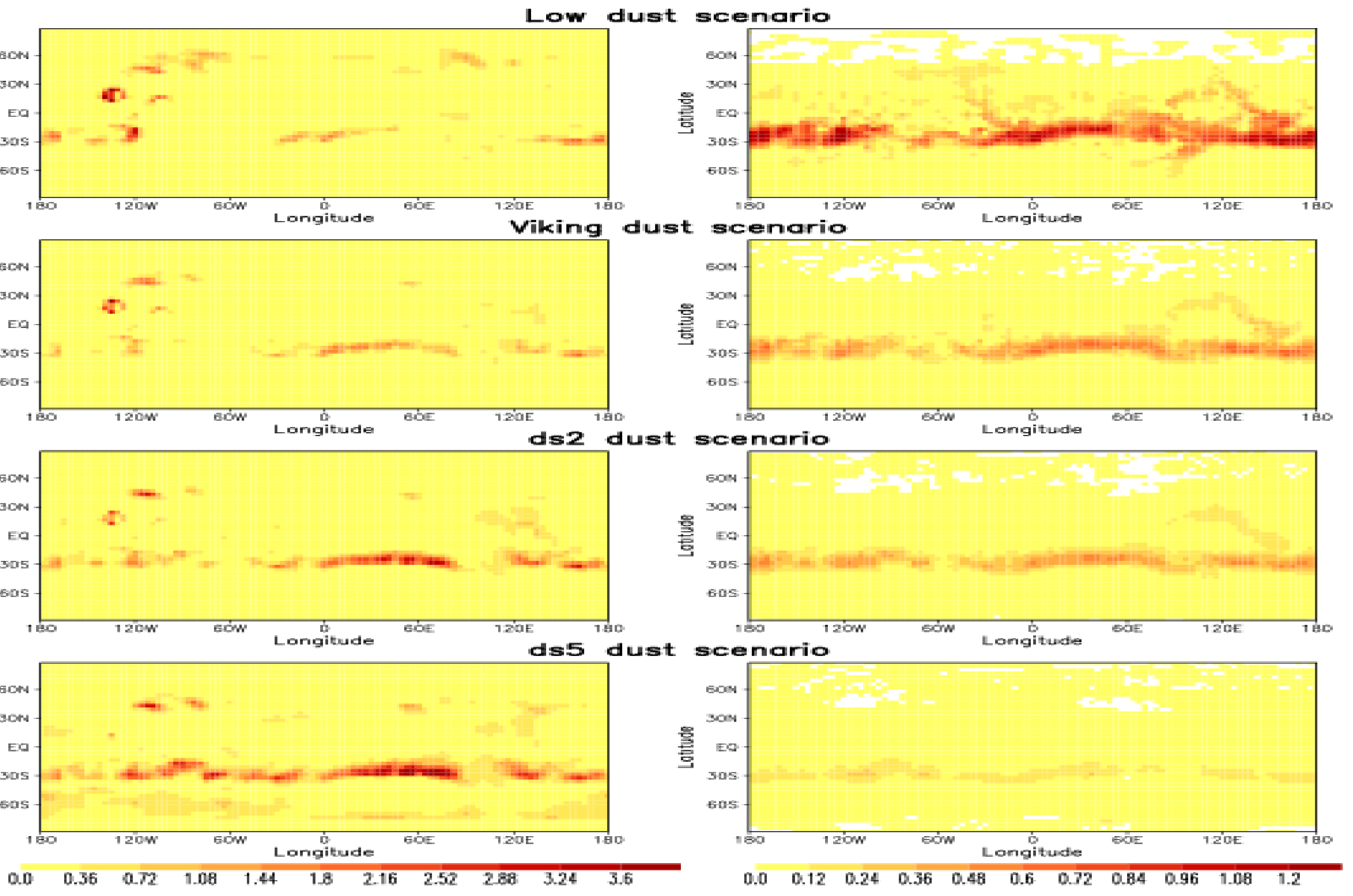
S pole

N pole

Global scale feedbacks on dust lifting

Wind stress lifting

Dust devil lifting



Least
back-
groun
dust

Most
back-
groun
dust

From Newman et al. JGR 2002

Onset, growth & decay of big dust storms

trong positive feedbacks on wind stress lifting help explain rapid onset nd growth, but create problems with storm decay

For big storms, models don’t predict decay until end of southern summe when solar forcing declines) - this is not consistent with observations

Possibilities are:

- models over-predict strength of positive feedbacks

r:

- global storms on Mars end when surface dust is depleted in source regions, stopping further lifting

r:

- dust particles are removed (‘scavenged’) during ice formation to act as condensation nuclei, thus are removed

Interannual variability & dust storms

Interannual variability may be due to:

Intrinsic atmospheric variability, causing slight changes in peak wind stresses which are reinforced by feedbacks if lifting occurs

Year-to-year changes in surface phenomena linked to atmospheric variability (e.g. position of seasonal polar cap edge)

Year-to-year differences linked to past dust activity, e.g., atmospheric dust opacity or surface dust availability

Our current understanding of the *main requirement* *for the observed interannual variability* in dustiness and climate, based on model results

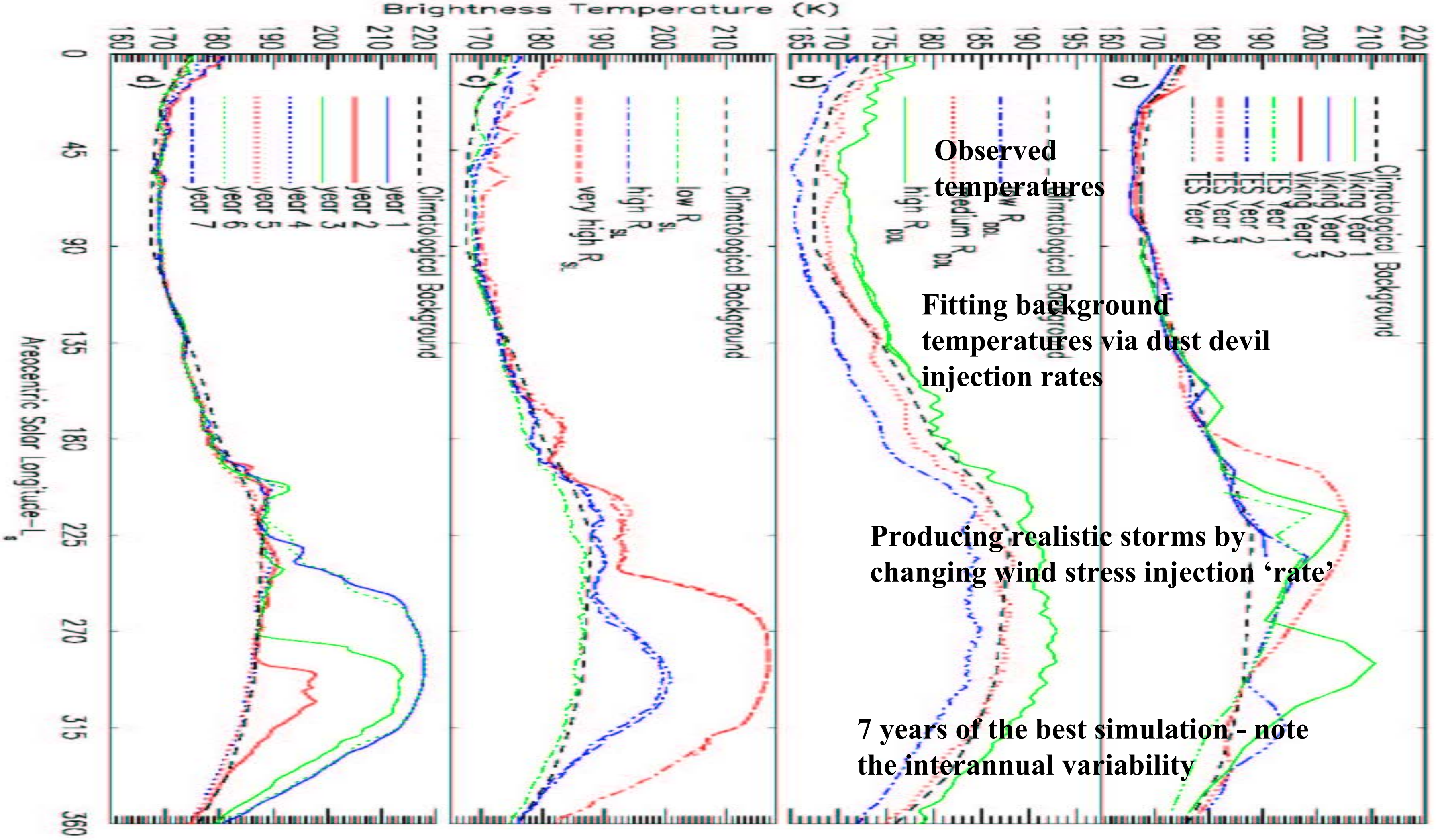
The most realistic annual dust cycles, storms and interannual variability are produced in Mars GCMs for which:

- **wind stress lifting is the dominant mechanism for storm productio**
- **high wind stress lifting thresholds are used**
- **dust devils provide the background dust loading**

Allowing surface dust source to be depleted increases interannual variability and improves storm realism

Interactions between dust and water cycles may also be key to getting realistic dust storms and variability

Atmospheric temperatures (indicating dust loading) from radiatively active dust simulations - the stages involved in producing *realistic dust cycles* with *interannual variability*



Observed temperatures

Fitting background temperatures via dust devil injection rates

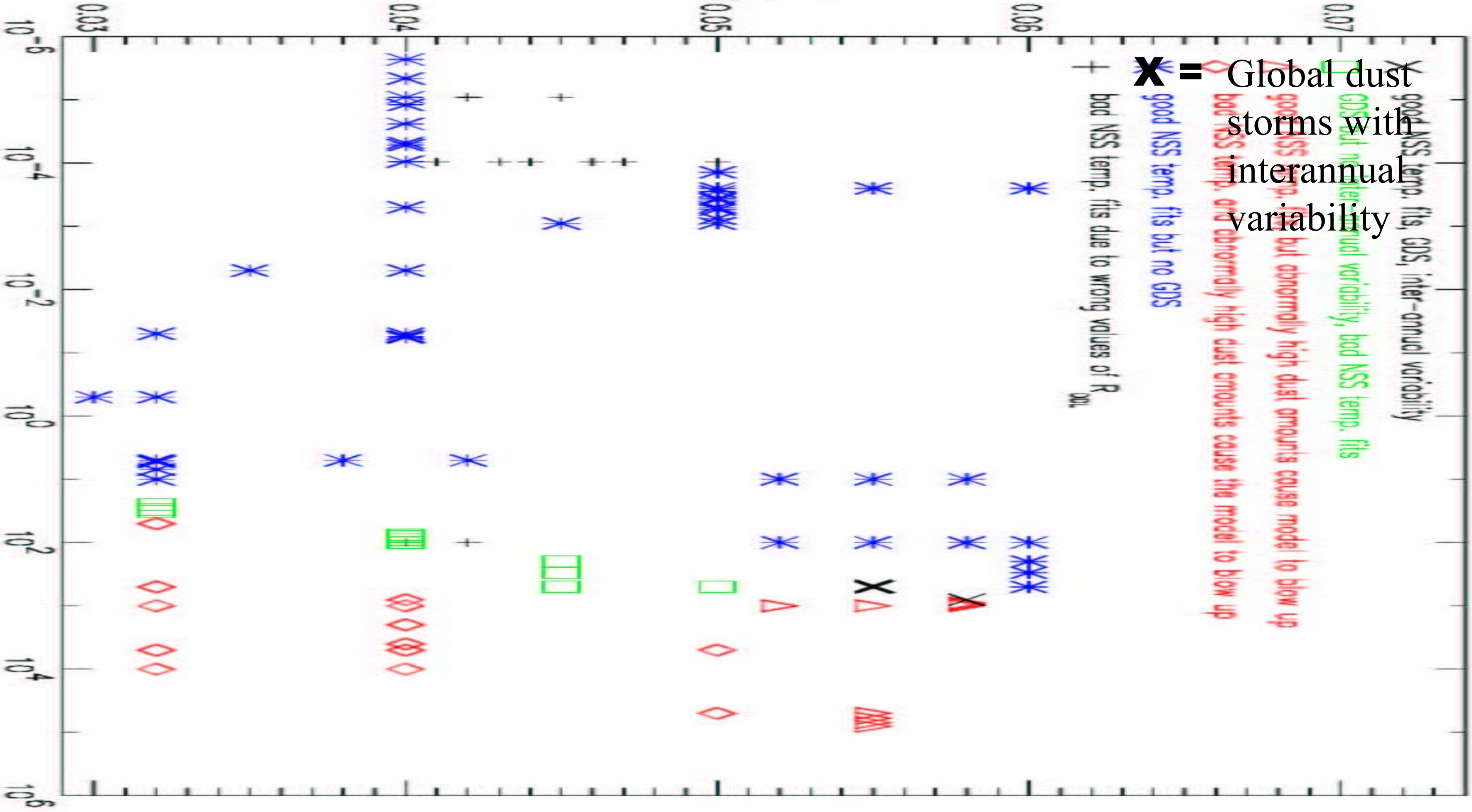
Producing realistic storms by changing wind stress injection 'rate'

7 years of the best simulation - note the interannual variability

Basu et al., submitted to JGR

Dust parameter regime diagram: varying threshold and efficiency for wind stress lifting

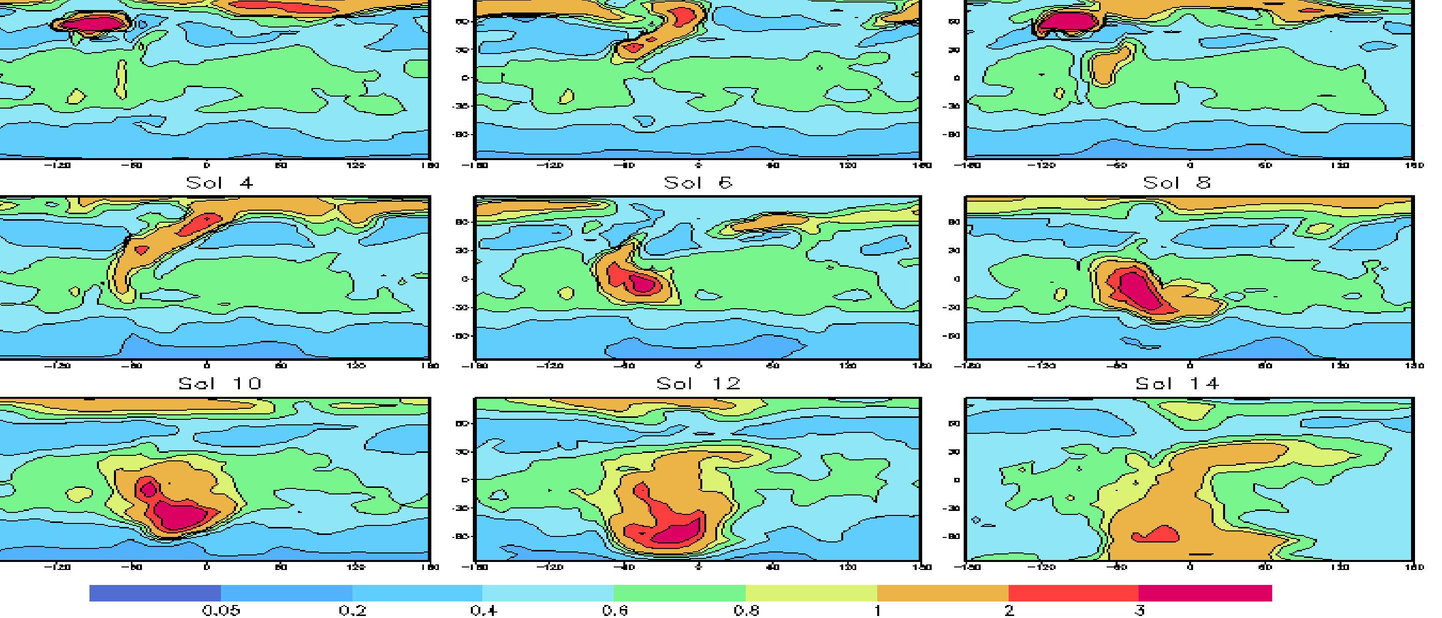
Threshold wind stress for dust lifting



X = Global dust storms with interannual variability

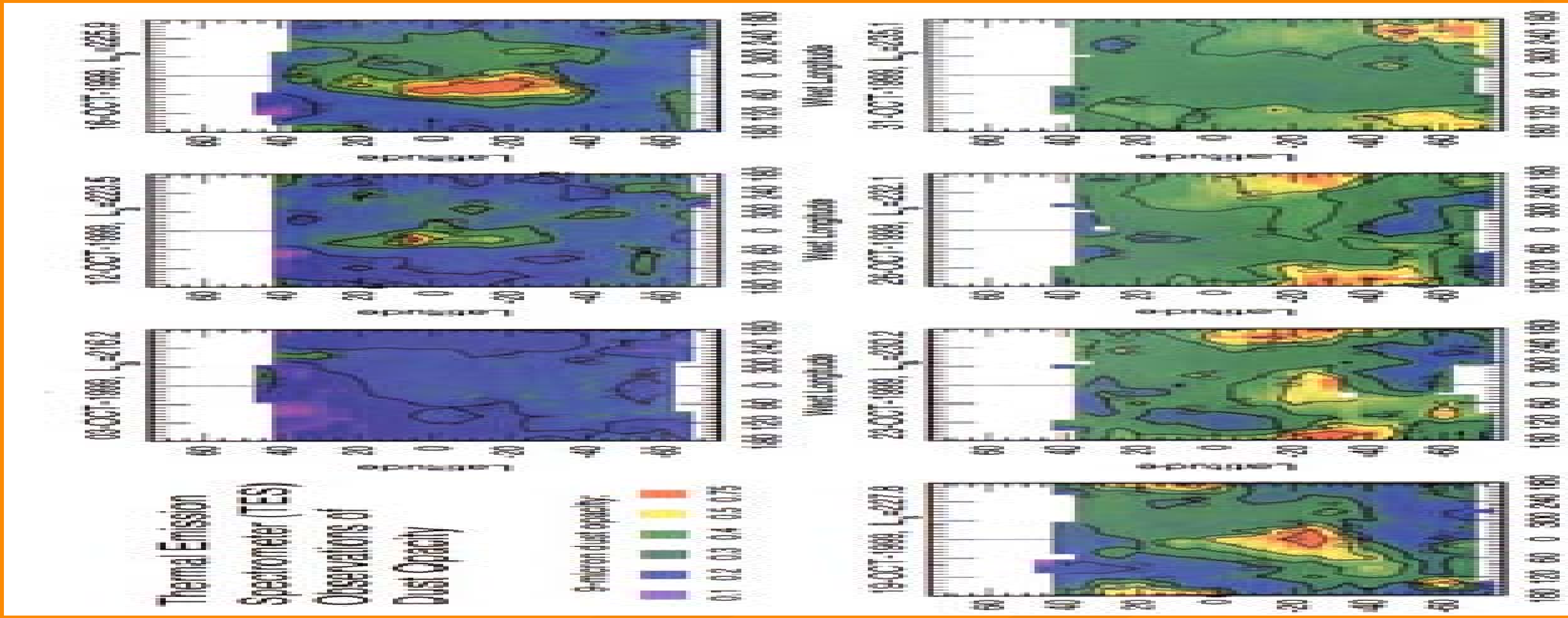
Constant of proportionality for amount of wind stress lifting

Basu et al., submitted to JG



Dust opacitie
for a
simulated
storm
beginning in
the Chryse
region and
moving sout
across the
equator

ust
pacities
or a
milar
torm
bserved
y TES



From Smith et al. JGR 200

Our current understanding of the *main requirements for the observed interannual variability* in dustiness and climate, based on model results

The most realistic annual dust cycles, storms and interannual variability are produced in Mars GCMs for which:

- **wind stress lifting is the dominant mechanism for storm productio**
- **high wind stress lifting thresholds are used**
- **dust devils provide the background dust loading**

Allowing surface dust source to be depleted increases interannual variability and improves storm realism

Interactions between dust and water cycles may also be key to getting realistic dust storms and variability

Why does interannual variability increase if surface dust can be completely depleted?

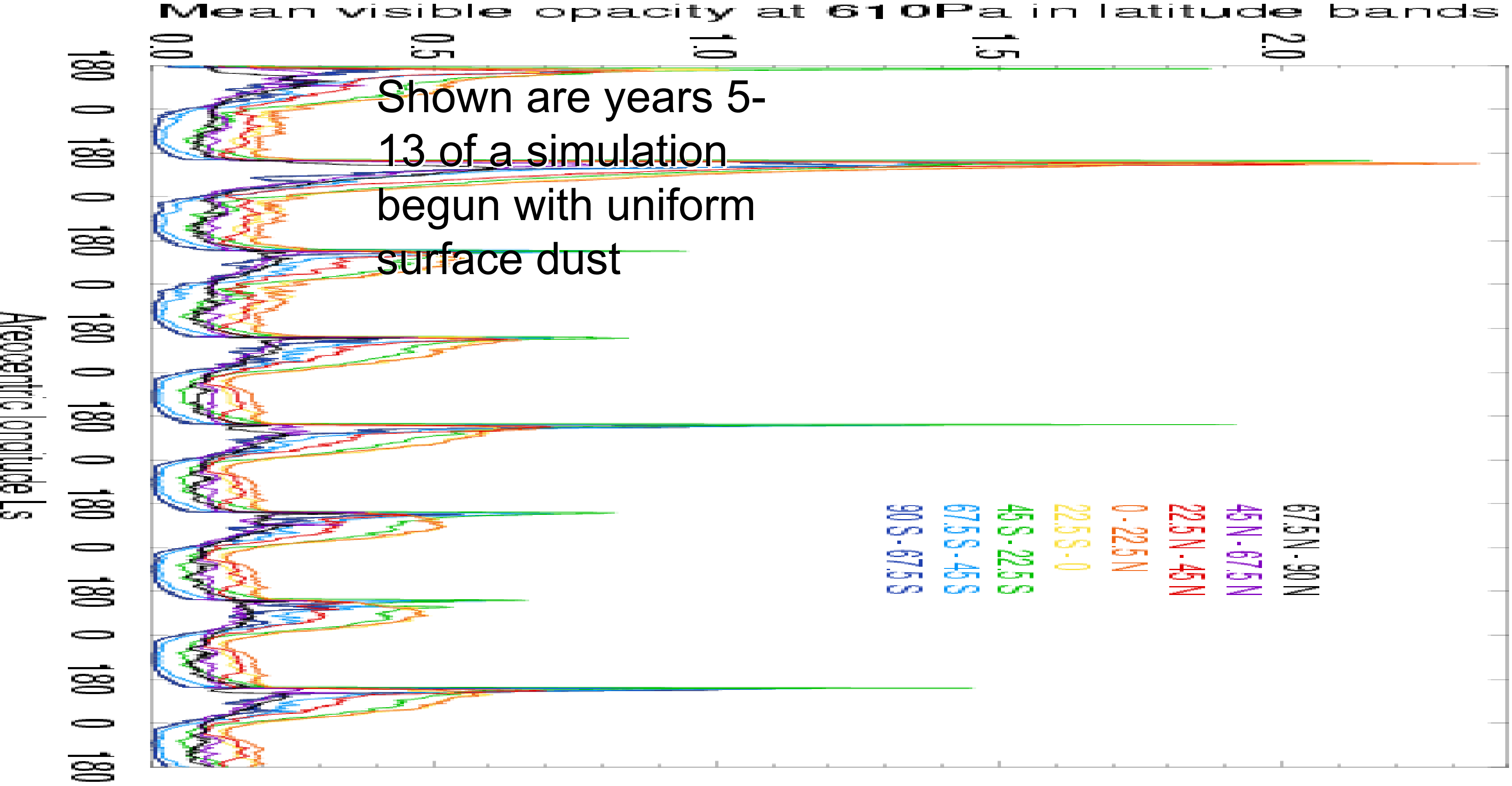
Possibility of source regions which are dust-free in some years but dusty in others, with replenishment in between

This changes the surface boundary condition for the system - e.g. a dust storm may no longer be able to develop as it did las year if the surface this year is dust free

However, regions with the strongest wind stresses (hence liftin rates) often have low re-deposition rates

=> many primary (and secondary) source regions are removed permanently, with main dust sources now regions which are replenished (but probably have lower lifting rates)

8 years of a simulation with surface dust allowed to deplete completely if insufficient re-deposition occurs



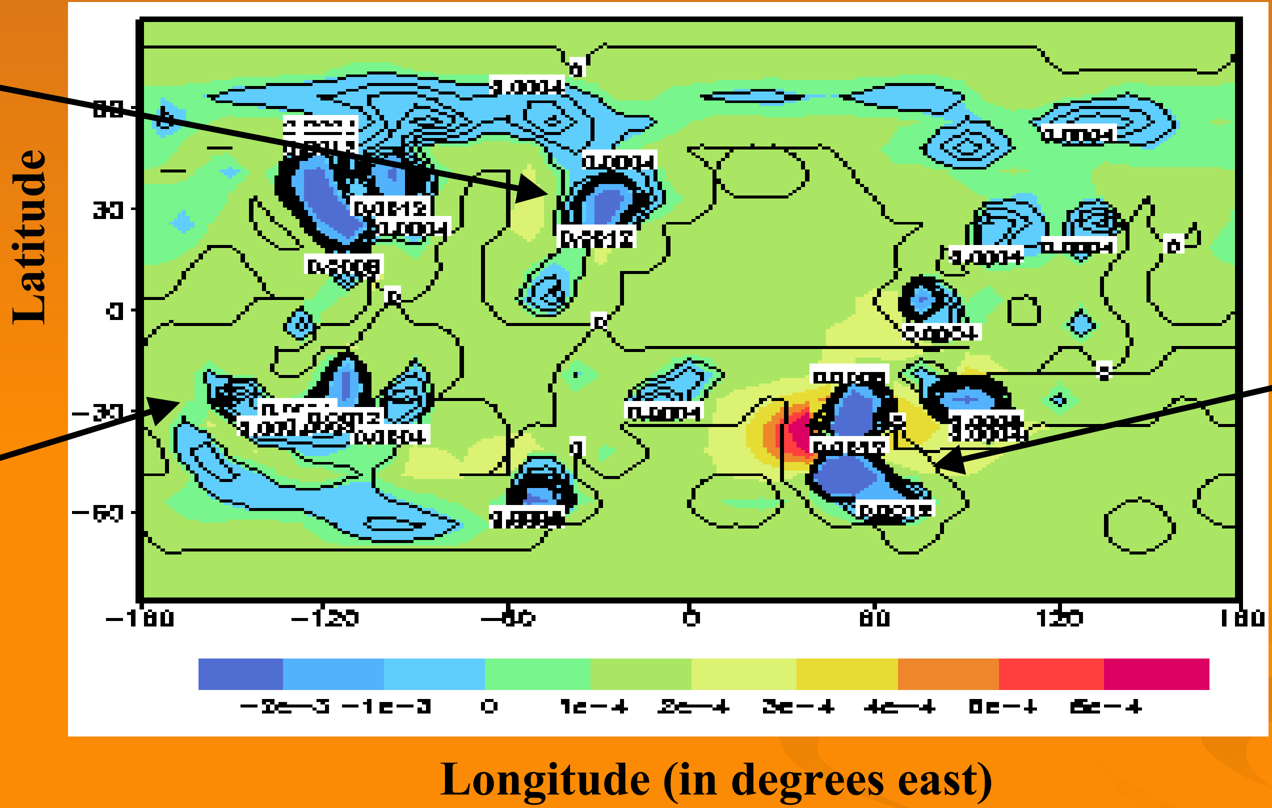
Shown are years 5-13 of a simulation begun with uniform surface dust

rimary lifting sites by year 5 were not (in general) primary lifting sites initially
efore many such regions were depleted)

Regions which may have more dust lifting than deposition (=> net loss

et loss in
estern
oundary
urrent
egions

et loss
rom much
f southern
idlatitude
and



Net loss
from
slopes o
Hellas

he typical *change* in the surface dust distribution after a year of lifting
nb - this simulation does not *yet* have any areas *completely* free of dust)

nits are annual mean increase / decrease in dust thicknesses in cm

Our current understanding of the main requirements for the observed interannual variability in dustiness and climate, based on model results

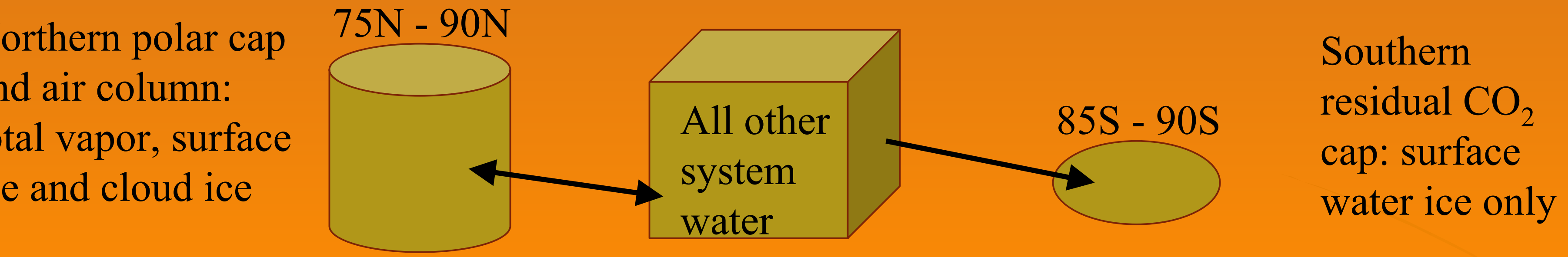
The most realistic annual dust cycles, storms and interannual variability are produced in Mars GCMs for which:

- **wind stress lifting is the dominant mechanism for storm production**
- **high wind stress lifting thresholds are used**
- **dust devils provide the background dust loading**

Allowing surface dust source to be depleted increases interannual variability and improves storm realism

Interactions between dust and water cycles may also be key to getting realistic dust storms and variability

The impact of climate variability on the present day water cycle



orthern polar cap
nd air column:
tal vapor, surface
e and cloud ice

75N - 90N

All other system water

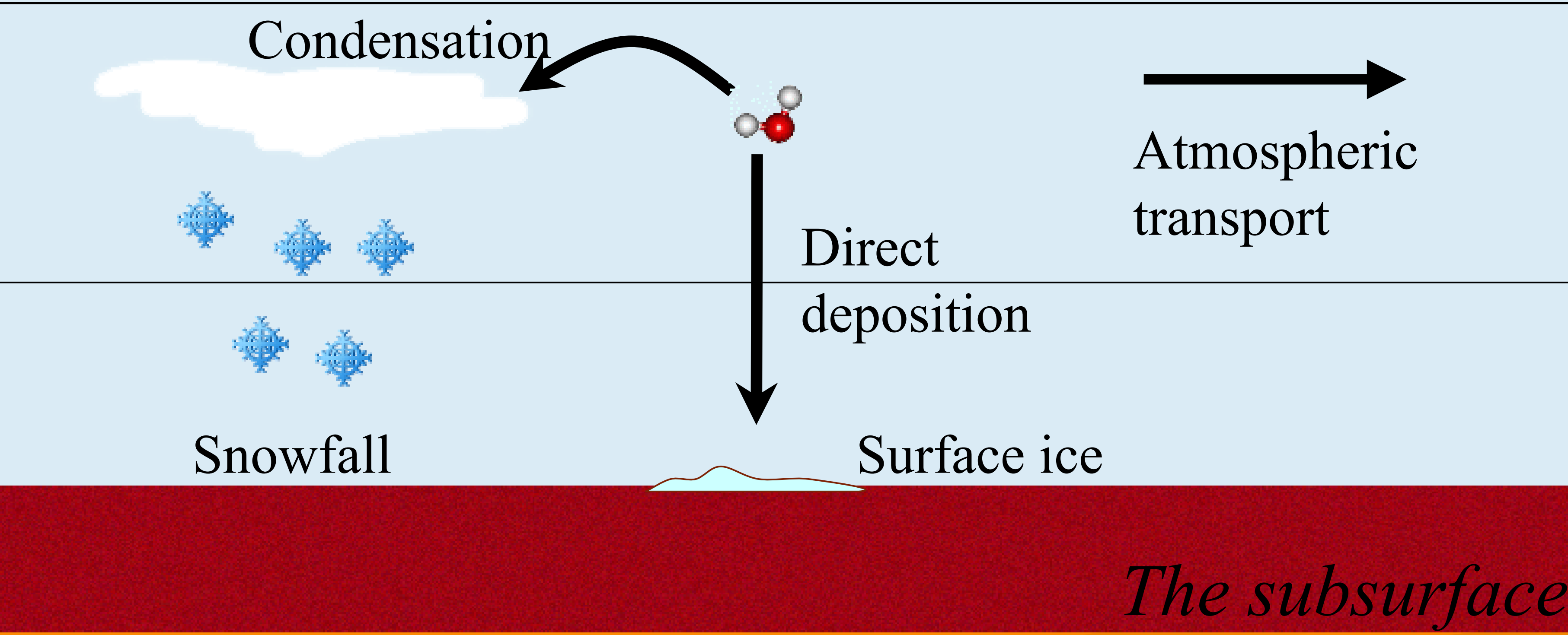
85S - 90S

Southern residual CO_2 cap: surface water ice only

The permanent north polar cap is mostly H_2O ice, and it is the balance betwee the amount of water held in this reservoir and in the atmosphere which largely controls the observed water cycle

The permanent south polar cap is mostly CO_2 ice, which acts as a cold trap for water vapor reaching south polar regions

Exchange of water between the atmosphere and regolith is not as important as once thought in producing the observed water cycle, which mainly consists of net transport (by the atmospheric circulation) of vapor released by the north polar cap in summer into the southern hemisphere



Condensation

Atmospheric transport

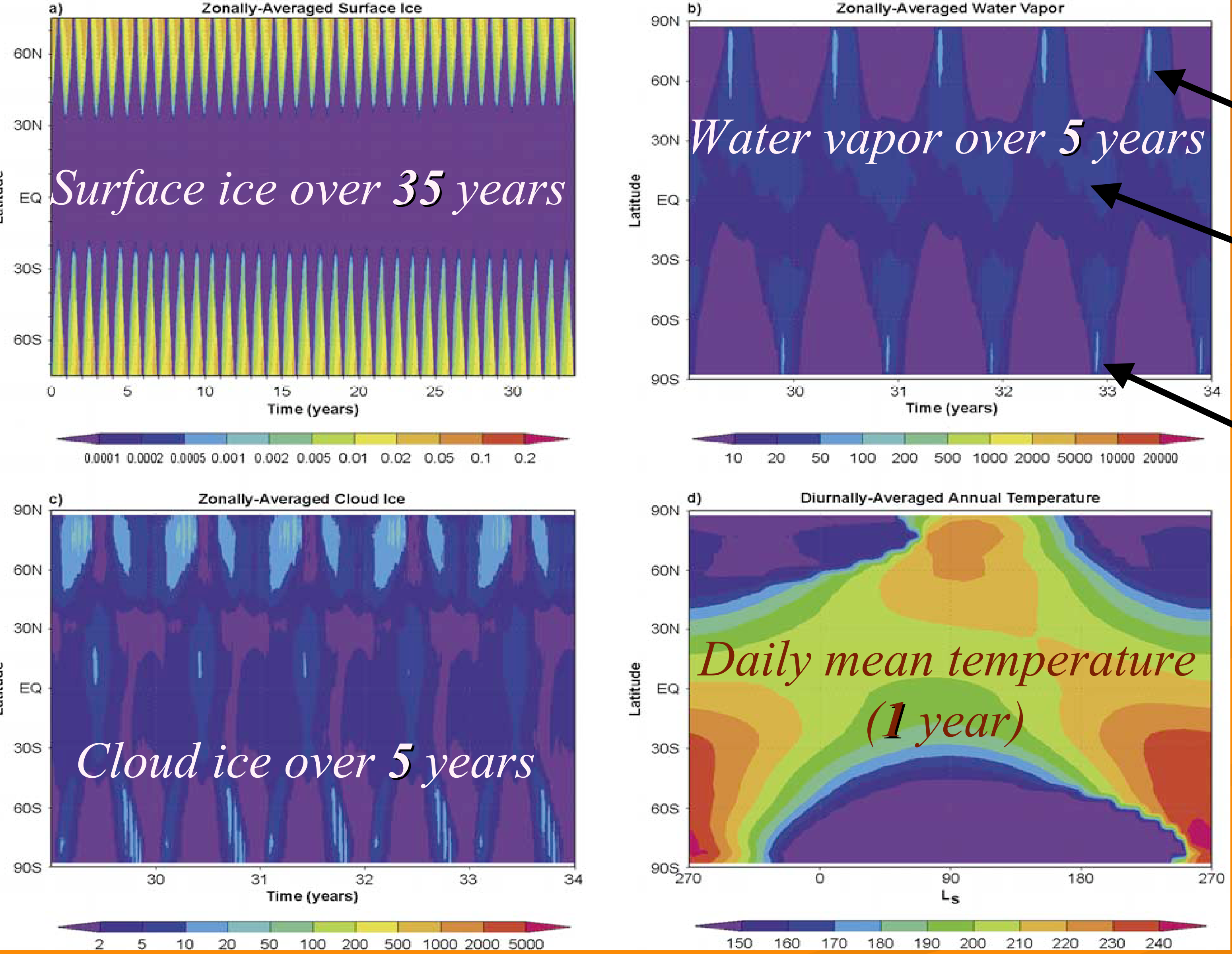
Direct deposition

Snowfall

Surface ice

The subsurface

- Basic water processes:
  - Condensation
  - Precipitation (as snow)
  - Direct deposition on surface (as ice)
  - Transport (by advection & mixing) within the atmosphere



*Surface ice over **35** years*

*Water vapor over **5** years*

*Cloud ice over **5** years*

*Daily mean temperature (**1** year)*

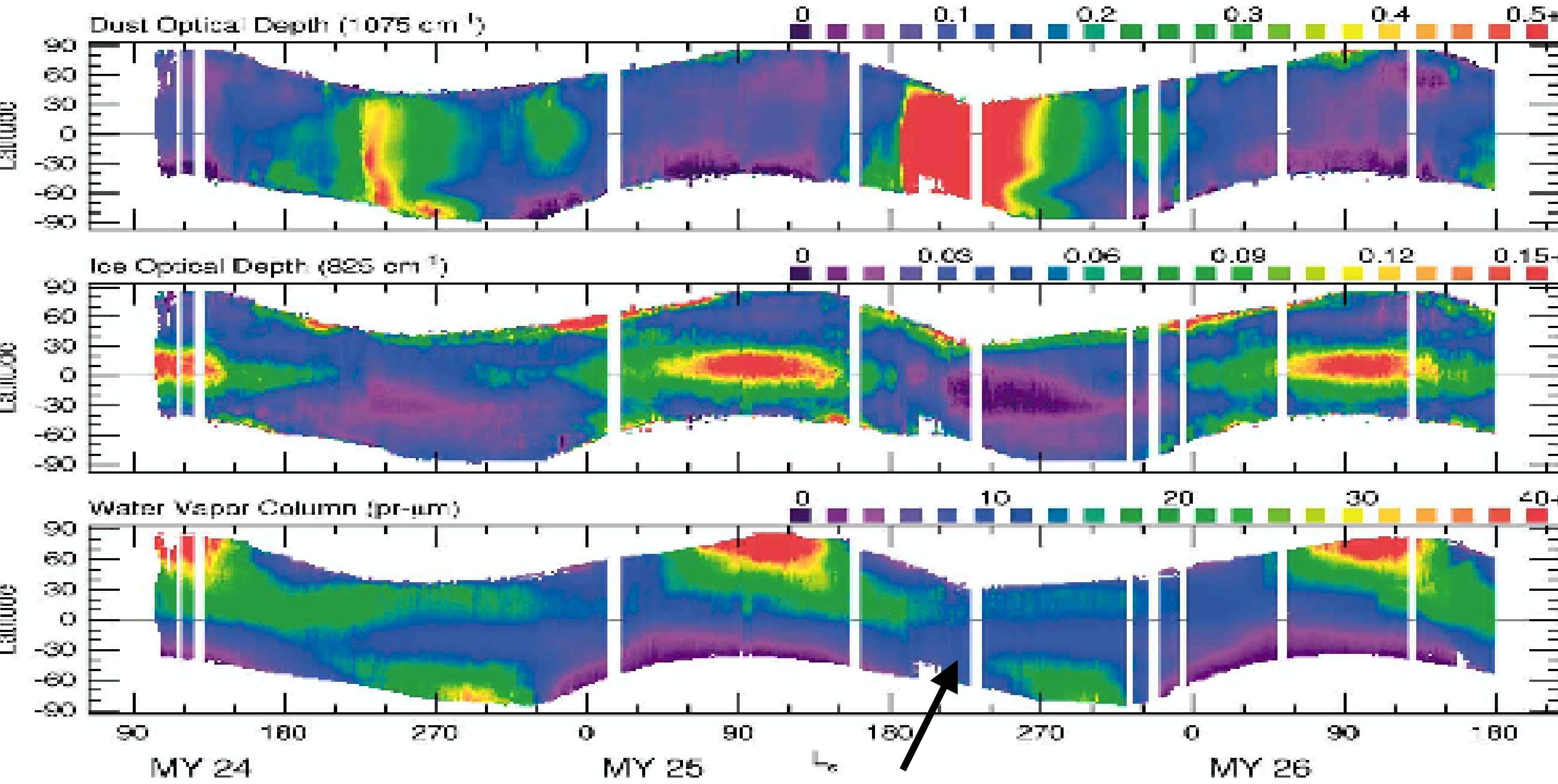
Water vapo released fro the north polar cap in summer is transported across the equator

Some water vapor is als released fro the south polar cap during its (warmer) summer

(Mars GCM results)

From Mischna et al. JGR 2003

The impact of climate Variability on the present day water cycle



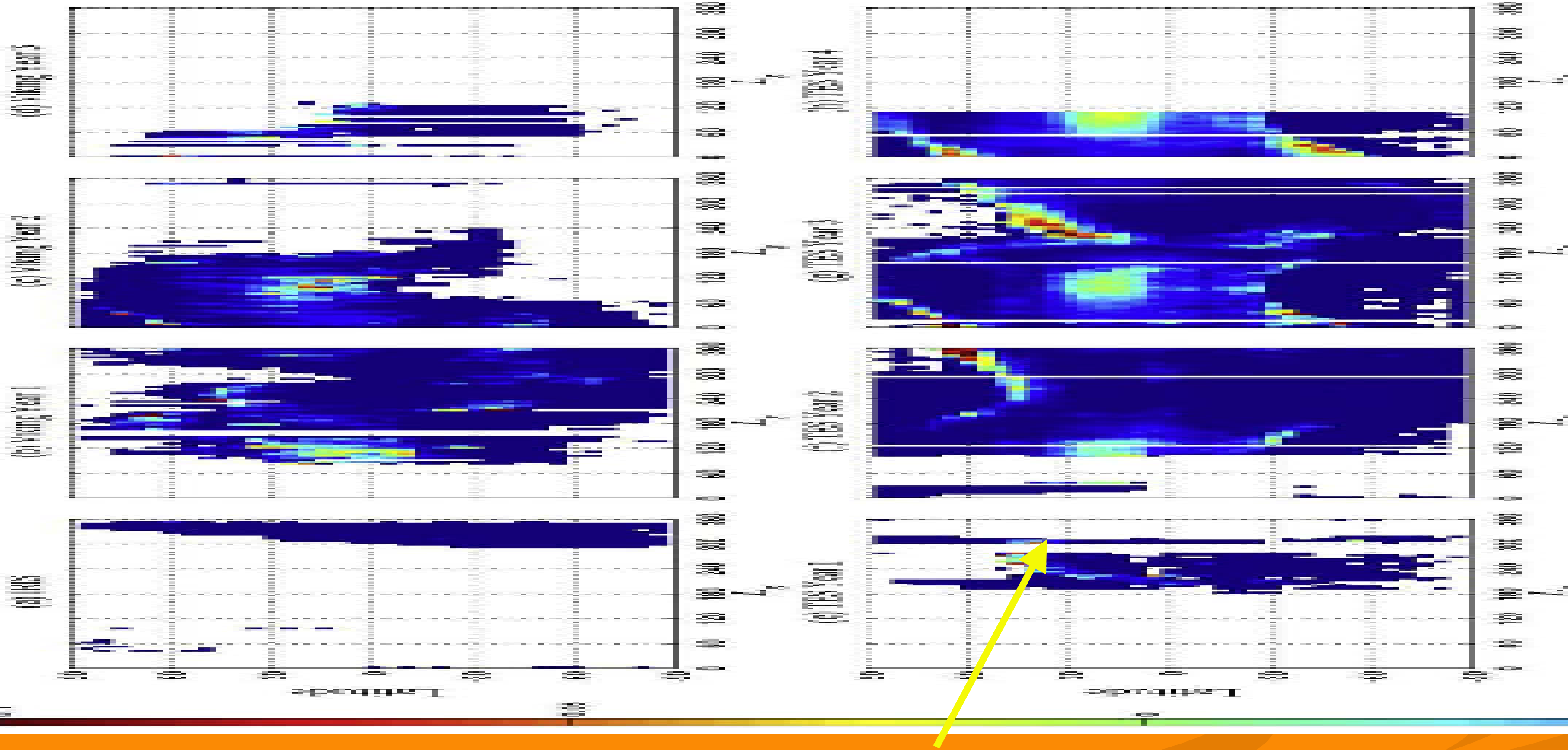
MGS TES
bservations)

Note the lower vapor abundance in southern summer during and after a global dust storm

From Smith et al. JG

The impact of climate variability on the present day water cycle

Water ice opacities for 8 different years



ote increased ice abundance during a global dust torm - dust particles provide extra condensation nuclei

(Mariner 9 IRIS, Viking IRTM and MGS TES observations)

From Liu et al., JGR 200

Possible decadal variability in southern residual cap extent

MOC image

"Swiss cheese" terrai
are areas of erosion o
the southern residual
CO_2 ice cap. Rates o
growth suggest the
cap may be gone in a
few decades - does th
southern cap undergo
decade to century
scale variability?

Present climate variability: conclusions

- Variability in southern spring/summer atmospheric dustiness is key to the observed climate variability

- The large dust storms observed on Mars are probably produced by sharp increases in wind stress lifting

- The observed interannual variability in these storms is probably due to how intrinsic atmospheric variability affects a near-threshold system with strong feedbacks

- Surface dust depletion &/or interaction with the water cycle probably affects storm evolution and variability

Present Climate Variability: Conclusions II

- The water cycle on Mars is largely controlled by transfer of water from the N polar cap during summer

- Atmospheric dust variability affects the H_2O cycle via
  - changes in atmospheric temperatures
  - the strength of the cross-equatorial circulation at solstice
  - the availability of dust particles as ice nuclei

- The south polar residual (CO_2) cap *may* disappear completely in some years, producing variability on ~decadal timescales, and affecting both water release in southern summer and possibly surface features near the south pole

Overview

- Investigative tools and techniques

- Review of the present climate
- Climate variability - mechanisms and simulations

- **Paleoclimates of the past few tens of Myrs - the impact of Mars's changing orbit**

- The climate of ancient Mars - the evidence and the theories

The changing orbit of Mars

Gravitational forces between all bodies in the solar system affect the orbits of the planets

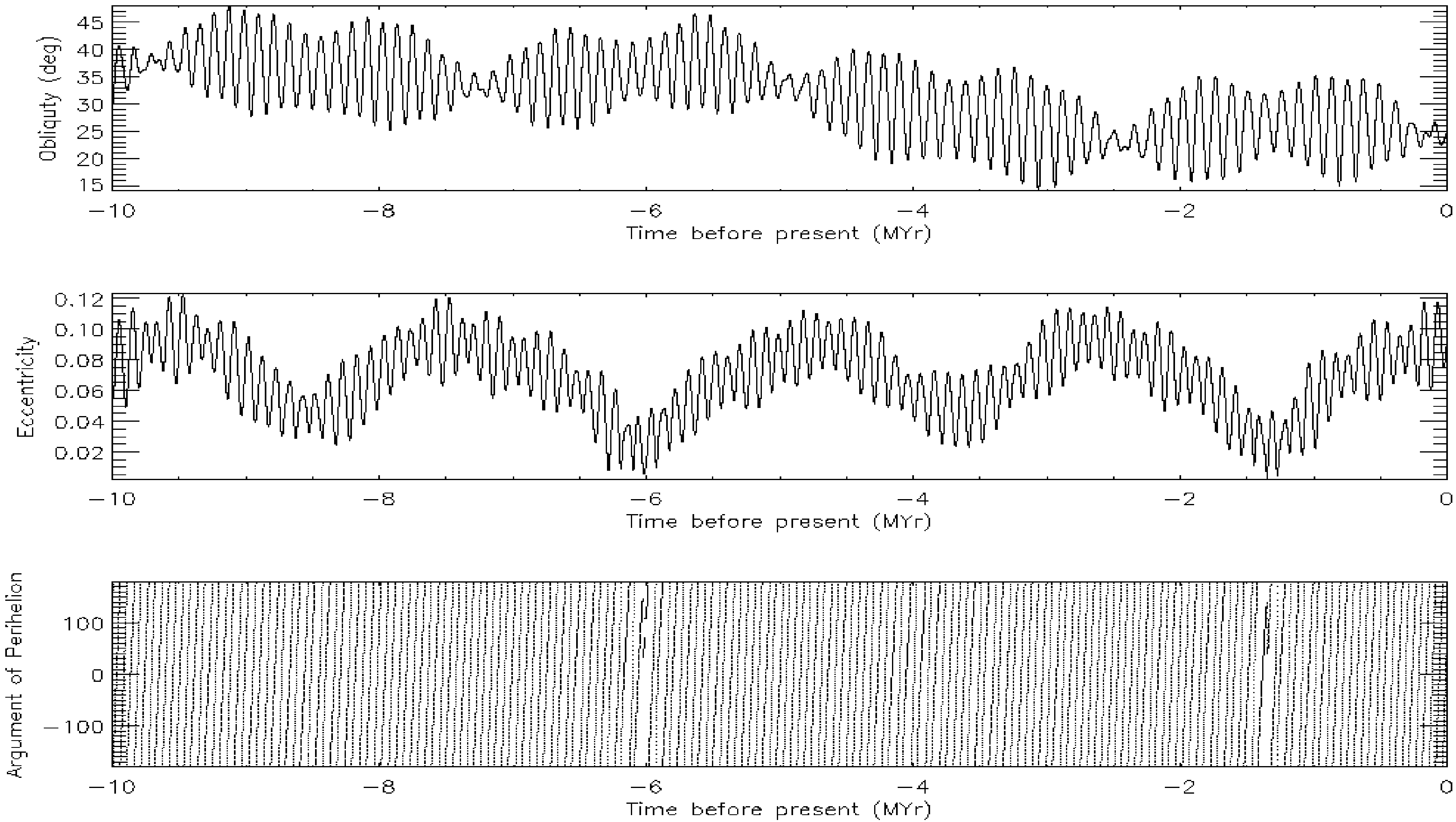
Milankovitch related these changes to the Earth's ice ages

The Earth's orbital parameters vary relatively little, and its obliquity is stabilized by the moon

The changes are far greater for Mars, however:

- over the past ~10 Myrs Mars's obliquity varied between 15° and 45° degrees (currently ~25°, similar to Earth)
- before this it may have been as high as 80° and as low as 0°
- but beyond ~10Myrs uncertainties in Mars's current orbit mean we cannot make 'predictions' ("chaotic obliquity")

Mars's obliquity, eccentricity and areocentric longitude of perihelion over the past 10Myrs



Data from Laskar et al., Nature 2002

Obliquity changes and the CO_2 cycle: *low* obliquity

- At lower obliquity a given pole is less tilted towards the sun in summer, and less tilted away from the sun in winter

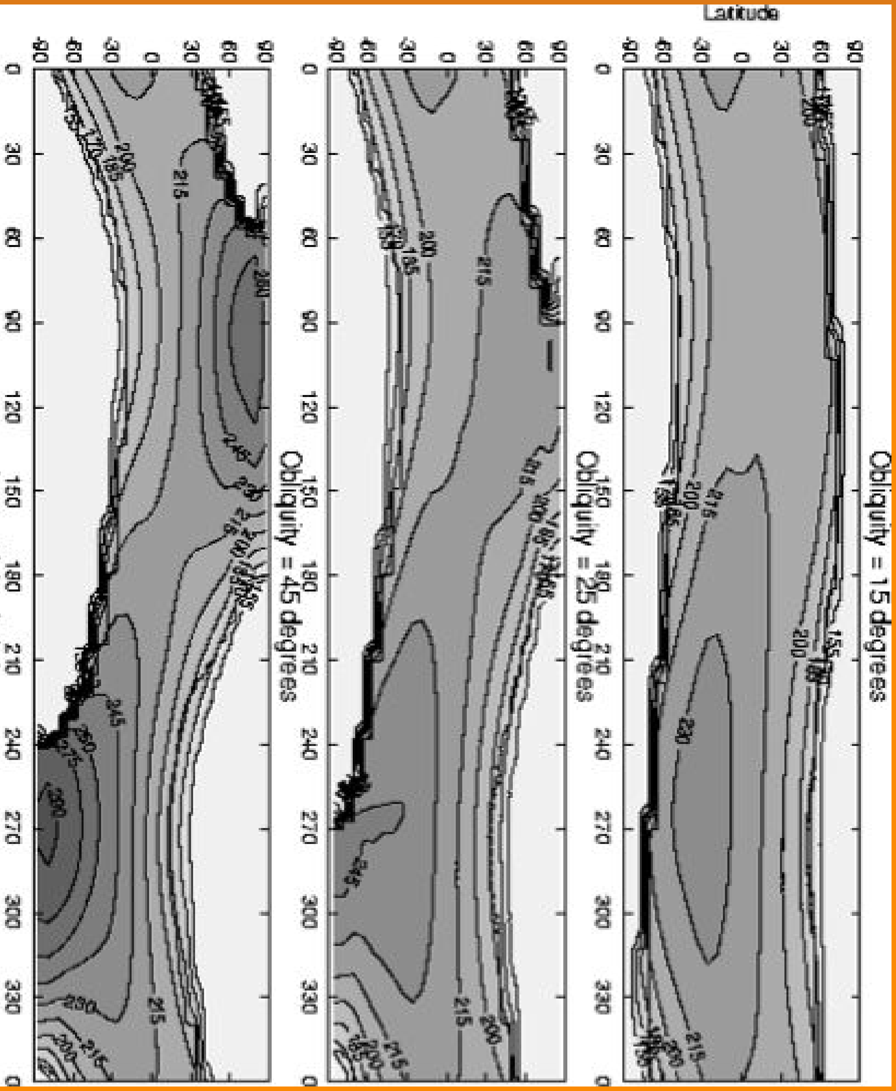
- => the temperature range at the poles over a year decreases

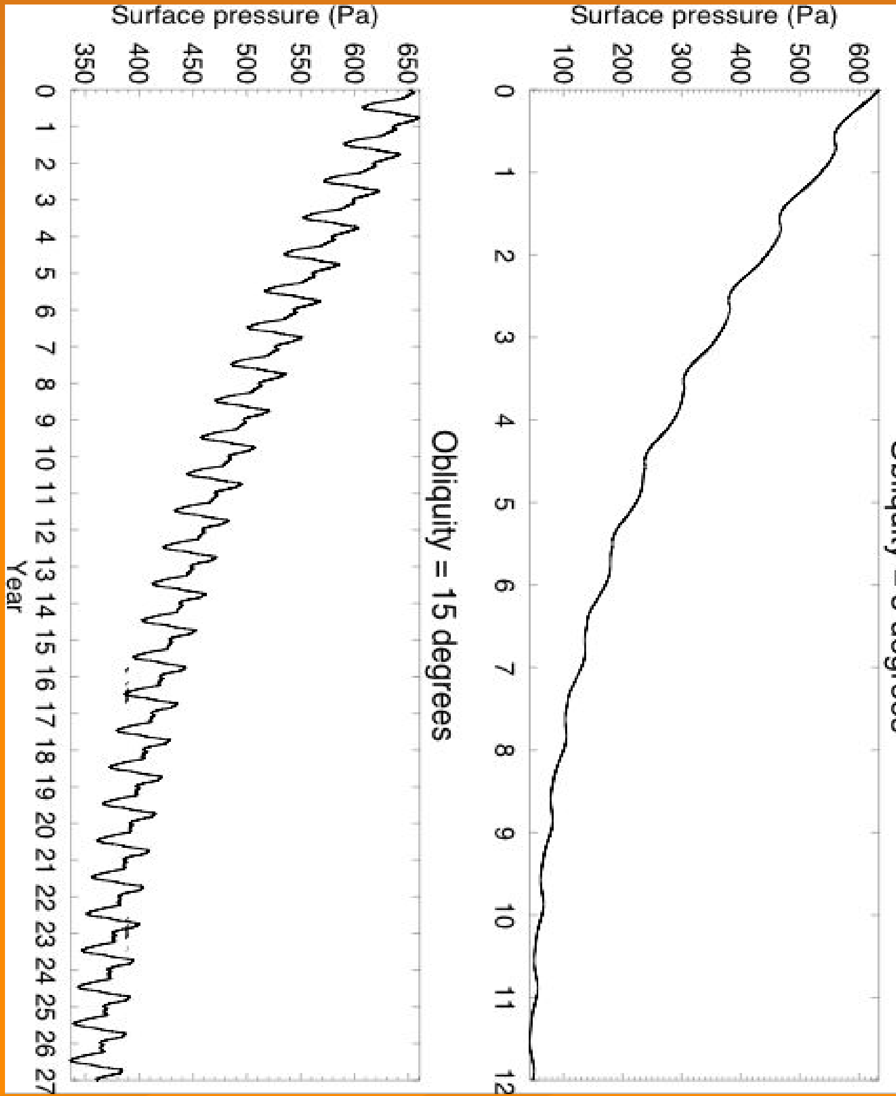
- The poles are also colder averaged through the year

- => CO_2 ice builds up and atmospheric pressure drops

Zonal mean surface temperatures & ice

Surface pressure trends at 5° and 15° obliquities





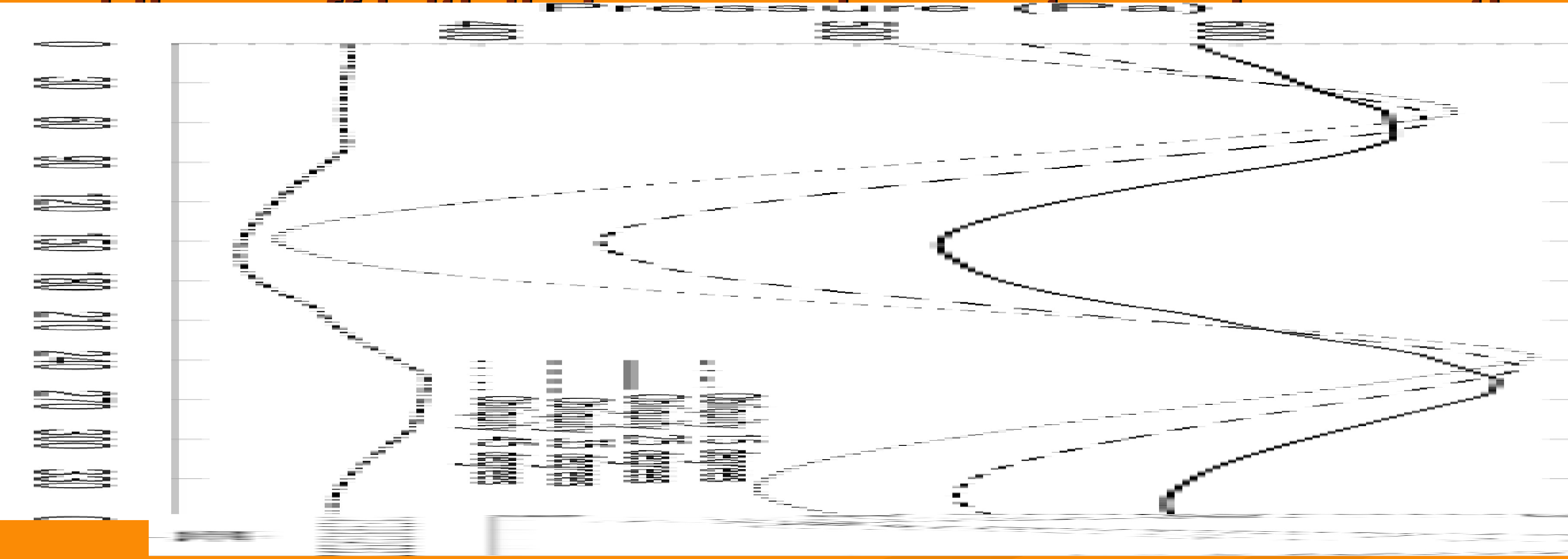
Newman et al., submitted to Icaru

Obliquity change & the CO_2 cycle: *high* obliquity

At higher obliquity, poles are warmer averaged through year

=> above some obliquity, no residual CO_2 remains at eithe pole, but the winter caps become very large

Annual pressure wave amplitudes increase as CO_2



Obliquity change & the CO2 cycle: *high* obliquity (continued)

At high obliquity, high latitude regolith becomes warmer averaged over a year

=> release of CO_2 previously adsorbed in regolith

However, it is unlikely that mean surface pressures will increase much at high obliquity, because:

- annual mean temperatures are now lower in the tropics, hence CO2 released will gradually become locked up here
- despite warmer temperatures, increased surface pressure will tend to suppress further desorption of CO

This becomes important because of the thicker atmosphere needed for liquid water to be stable at the surface (see later!)

Obliquity change & the atmospheric circulation

At *low obliquities*, peak forcing at solstice is at lower latitudes and atmosphere is thinner (less heating, lower TI)

=> a weaker, narrower meridional circulation at solstice

=> slower related surface winds at solstice

At *high obliquities*, peak forcing at solstice is at higher latitudes

=> stronger, broader cross-equatorial circulations at solstice

=> higher surface wind speeds at solstice

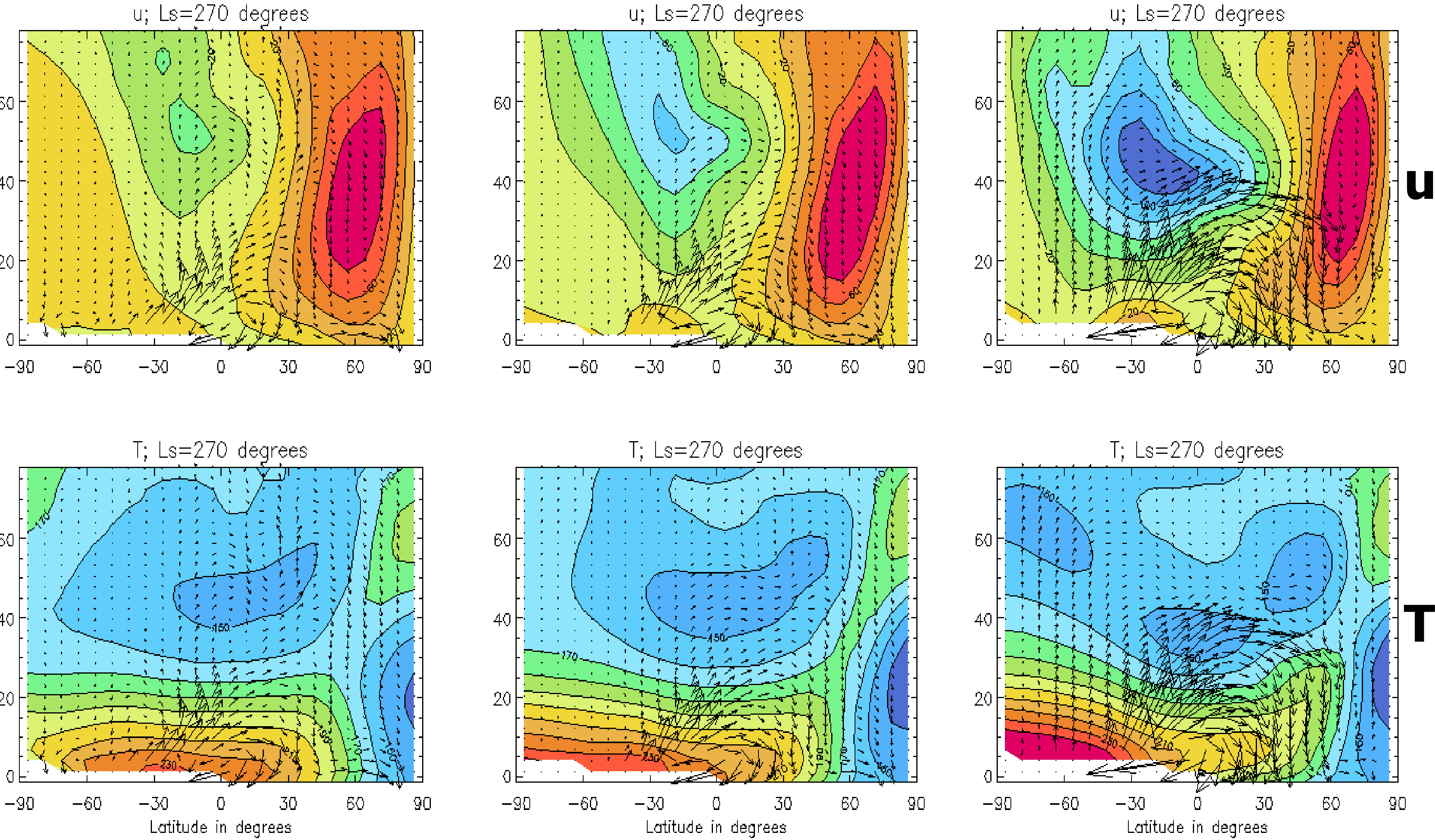
Little change to equinoctial circulations for varying obliquity

NB all simulations used same prescribed, moderate dust load

Obliquity 15 degrees

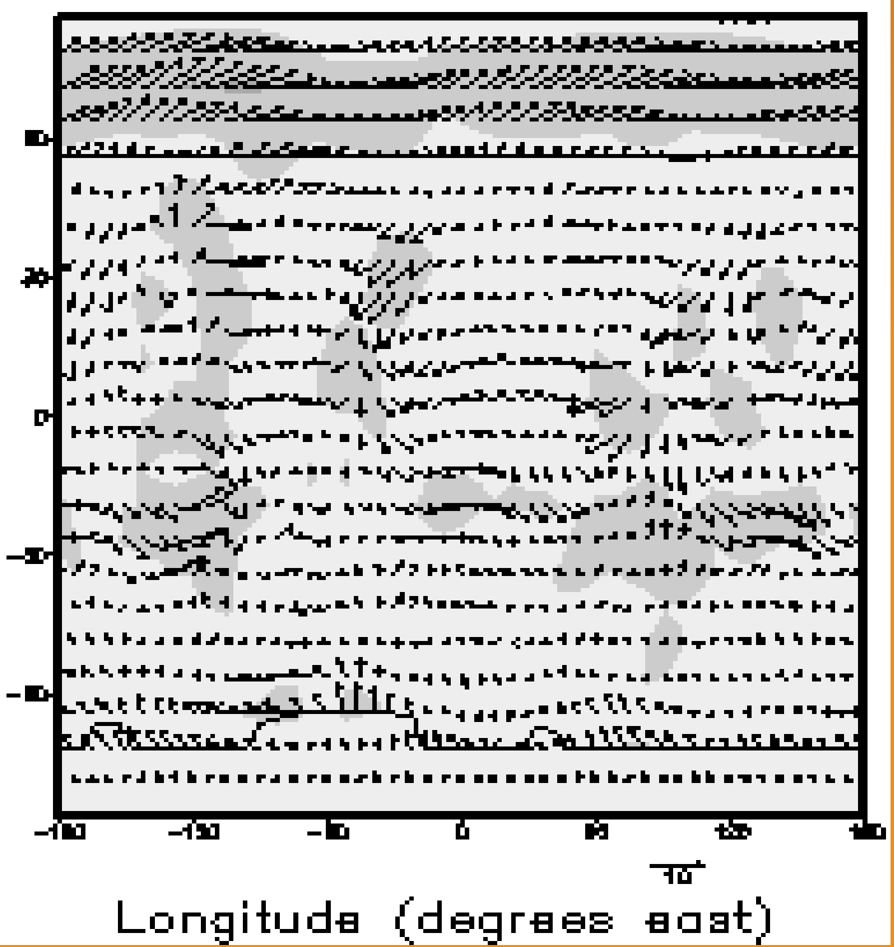
Obliquity 25 degrees

Obliquity 45 degrees

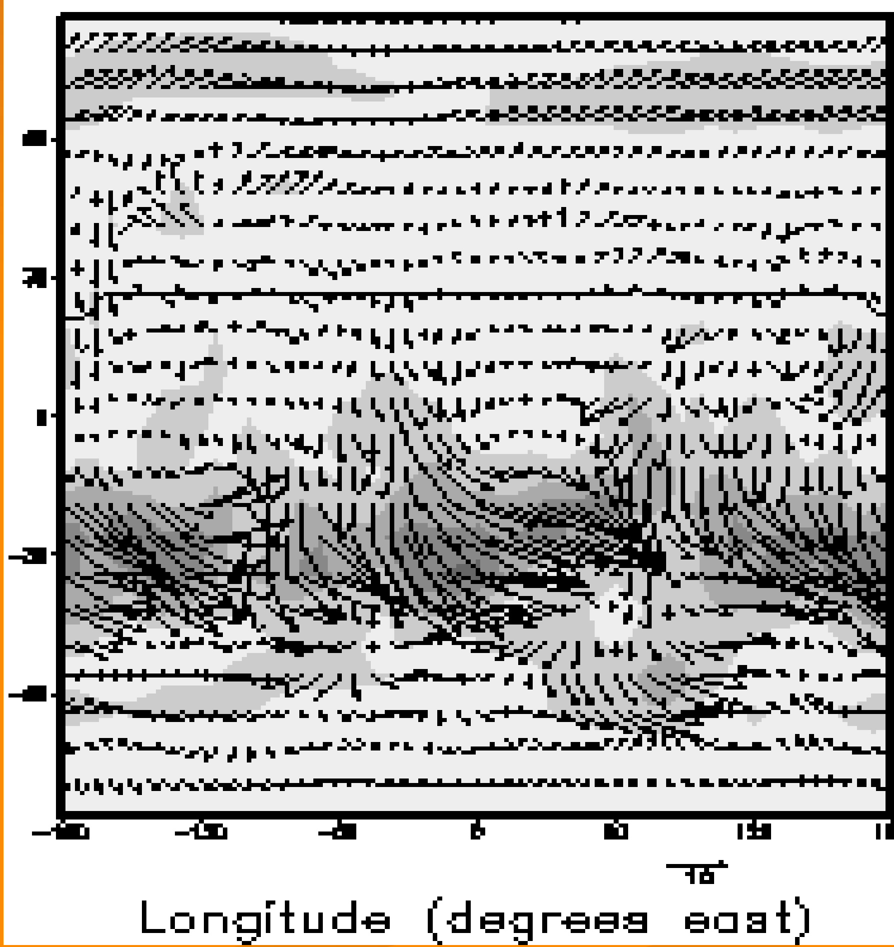


Surface winds in northern winter for low and high obliquities

Obliquity 15°



Obliquity 45°



Why are we interested in dust and water transport when looking at climate?

- Dust has a big effect on heating rates in the Martian atmosphere (see previous talk) and is very important to present day climate variability
- The surface of Mars contains a record of dust and water deposition in the past (see later!)
- We need to understand the present dust and water cycles, including deposition
- Then we can try to use the surface record to infer wha the past dust and water cycles - and the past climates - were like

Obliquity change & dust lifting by wind stress

At *low obliquity*, lower atmospheric pressures (for ~20 degrees and lower) => stress reduced for same wind spee

Surface winds are in general also weaker at solstice

Both => less dust lifting due to wind stress

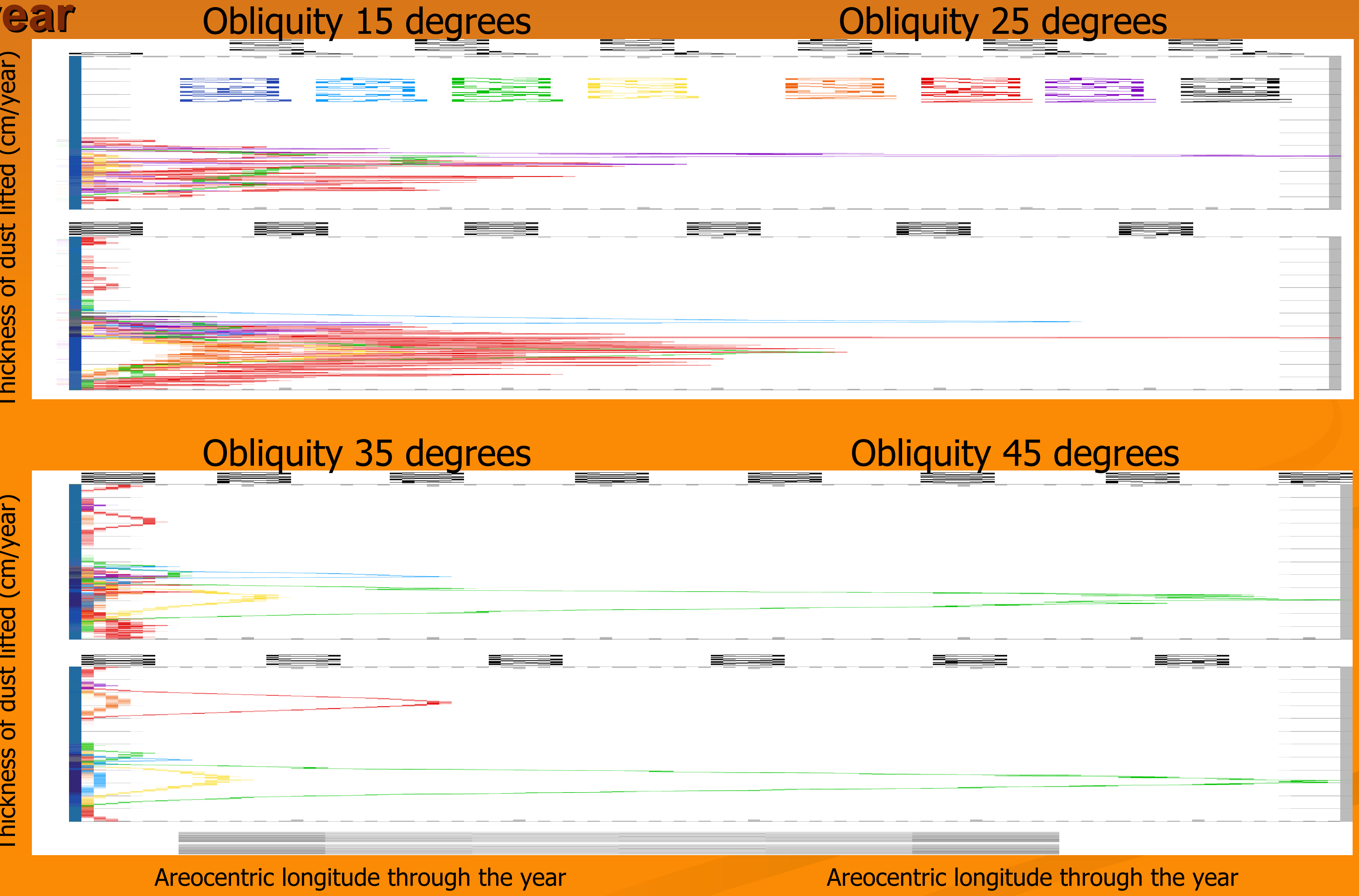
At *high obliquity*, surface winds generally stronger at solstice

=> more dust lifting due to wind stress

Lifting patterns change most near Hadley cell edge (tends to broaden at surface as well as aloft above a certain obliquity)

Also affected by change in position of polar cap edge (affects off-cap flows, baroclinic eddies, etc.)

Wind stress lifting averaged over 8 latitude bands for 1 ear



Obliquity 15 degrees

Obliquity 25 degrees

Obliquity 35 degrees

Obliquity 45 degrees

Newman et al., submitted to Icari

Can we relate simulated dust accumulation to observed surface features?

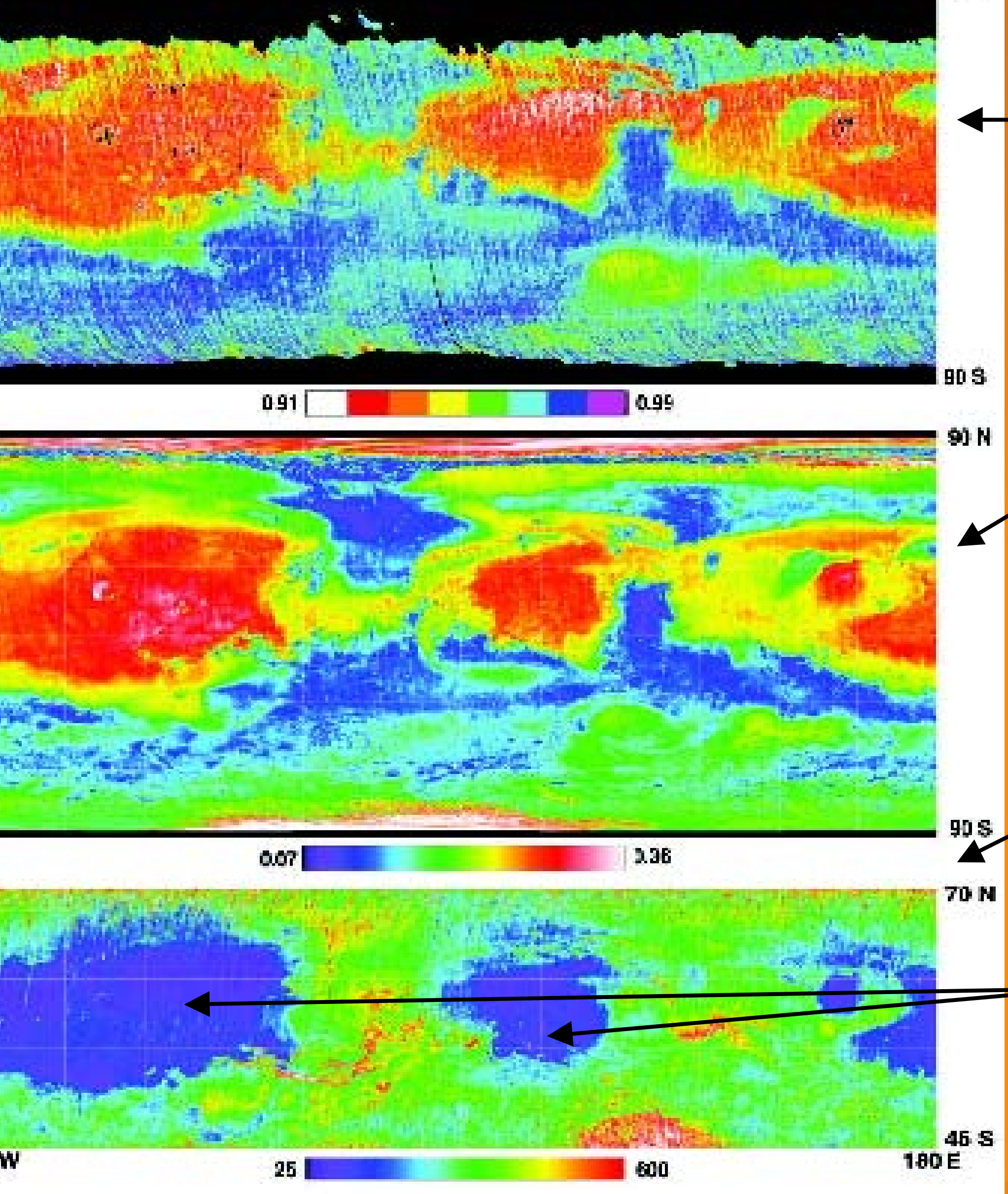
1. Formation of long term dust deposits which may have accumulated over several Myrs, possibly with no significant removal for any orbital configuration

2. The polar layered terrain - build-up of layers of dusty ice, probably due to changes in relative deposition rates under different orbital conditions

Can we relate simulated dust accumulation to observed surface features?

1. **Formation of long term dust deposits which may have accumulated over several Myrs, possibly with no significant removal for any orbital configuration**

2. The polar layered terrain - build-up of layers of dusty ice, probably due to changes in relative deposition rates under different orbital conditions



From Ruff and Christensen JGR 2003

[Ruff and Christensen's 'dust cover index', derived from both albedo an thermal inertia]

Albedo - high values generally indicates large fraction of surface covered by dust (thoug less sensitive to what lies just beneath surface layer)

Thermal inertia - low values generally indicate high dust content (more sensitive than albedo to near-surface material)

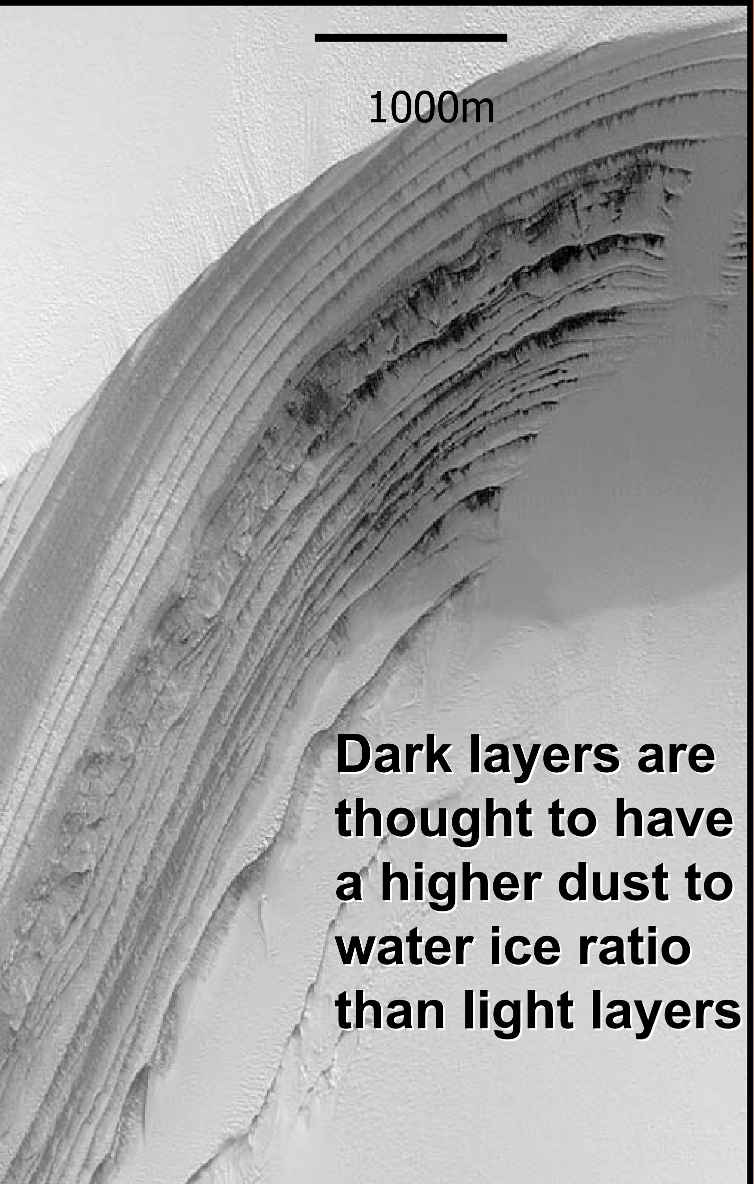
Idea that low thermal inertia regions could be lon term dust deposits which formed over several Myrs, with little erosion here for all orbital configurations

Can we relate simulated dust accumulation to observed surface features?

1. Formation of long term dust deposits which may have accumulated over several Myrs, possibly with no significant removal for any orbital configuration

2. **The polar layered terrain - build-up of layers of dusty ice, probably due to changes in relative deposition rates under different orbital conditions**

The polar layered terrain - description and possible formation mechanism



Dark layers are thought to have a higher dust to water ice ratio than light layers

Alternating light and dark layers at both poles, ranging from ~10-50m in thickness - ~4-5km thick in N, 1-2 in S (though S covers greater area)

Low obliquity: little atmospheric dust; H_2 ice builds up at poles, where permanent CO_2 caps act as water sinks => **largely dust-free, high albedo ice layer forms**

High obliquity: lots of atmospheric dust, and strong circulation reaching high latitudes; new H_2O ice deposits at poles are mostly transients which resublime in spring => **thick high dust content, lower albedo layer forms**

MOC image

Polar deposition in different epochs

Lower obliquity => less dusty atmosphere and narrower circulations. Both => *less* polar deposition

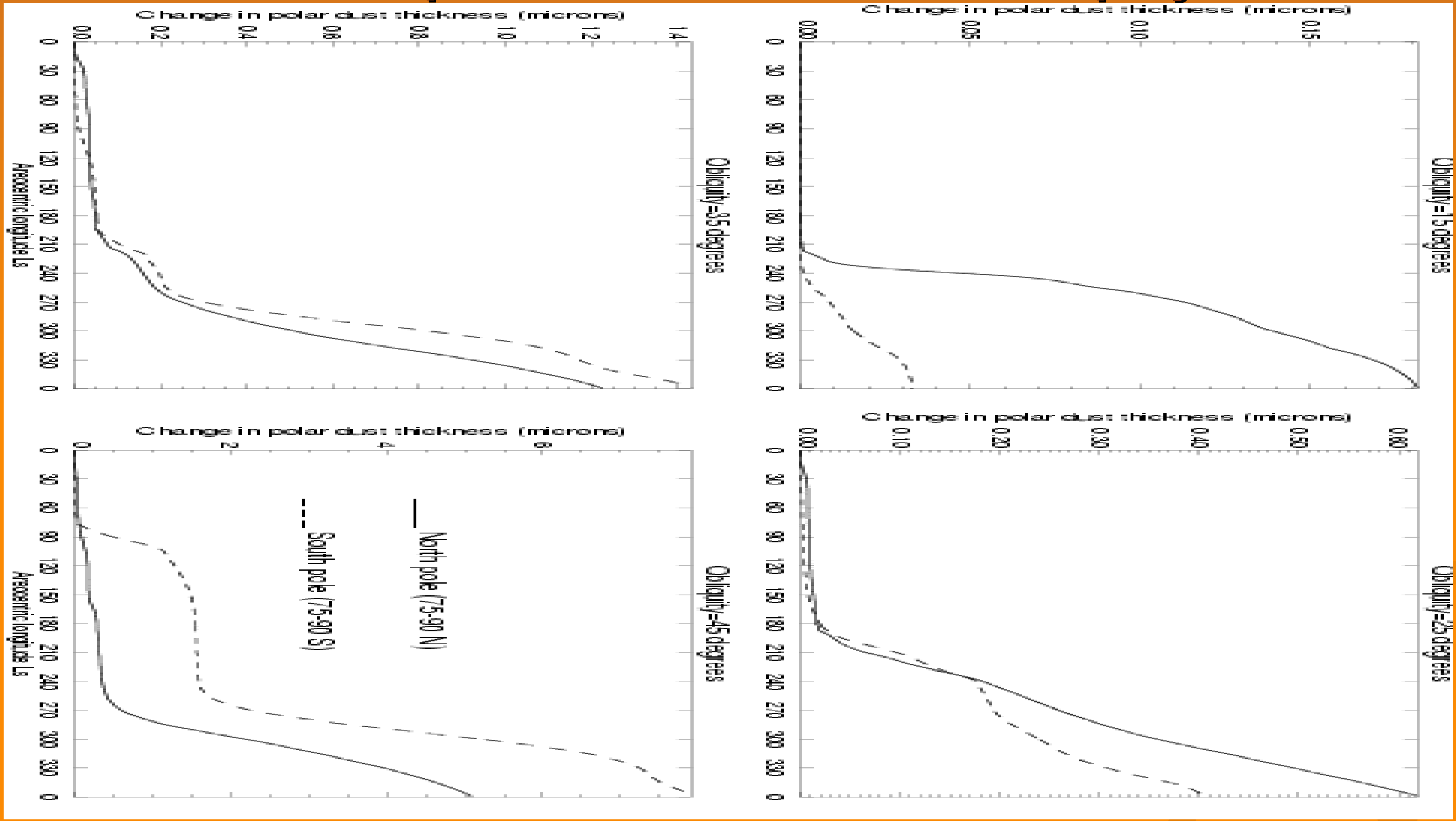
Higher obliquity => dustier atmosphere and broader circulation Both => *more* polar deposition

Relative deposition at either pole complicated:

- *moderate* circulations: dust lifted ~summer mid-latitudes is transported strongly across equator => may find more at *opposite* pole
- *stronger* circulations: dust is first transported polewards before being raised => may find more at *same* pole

Eccentricity and longitude of perihelion also vary – for latter, dynamical influence of hemispheric dichotomy => more lifting i south even when solar heating peaks in northern summer

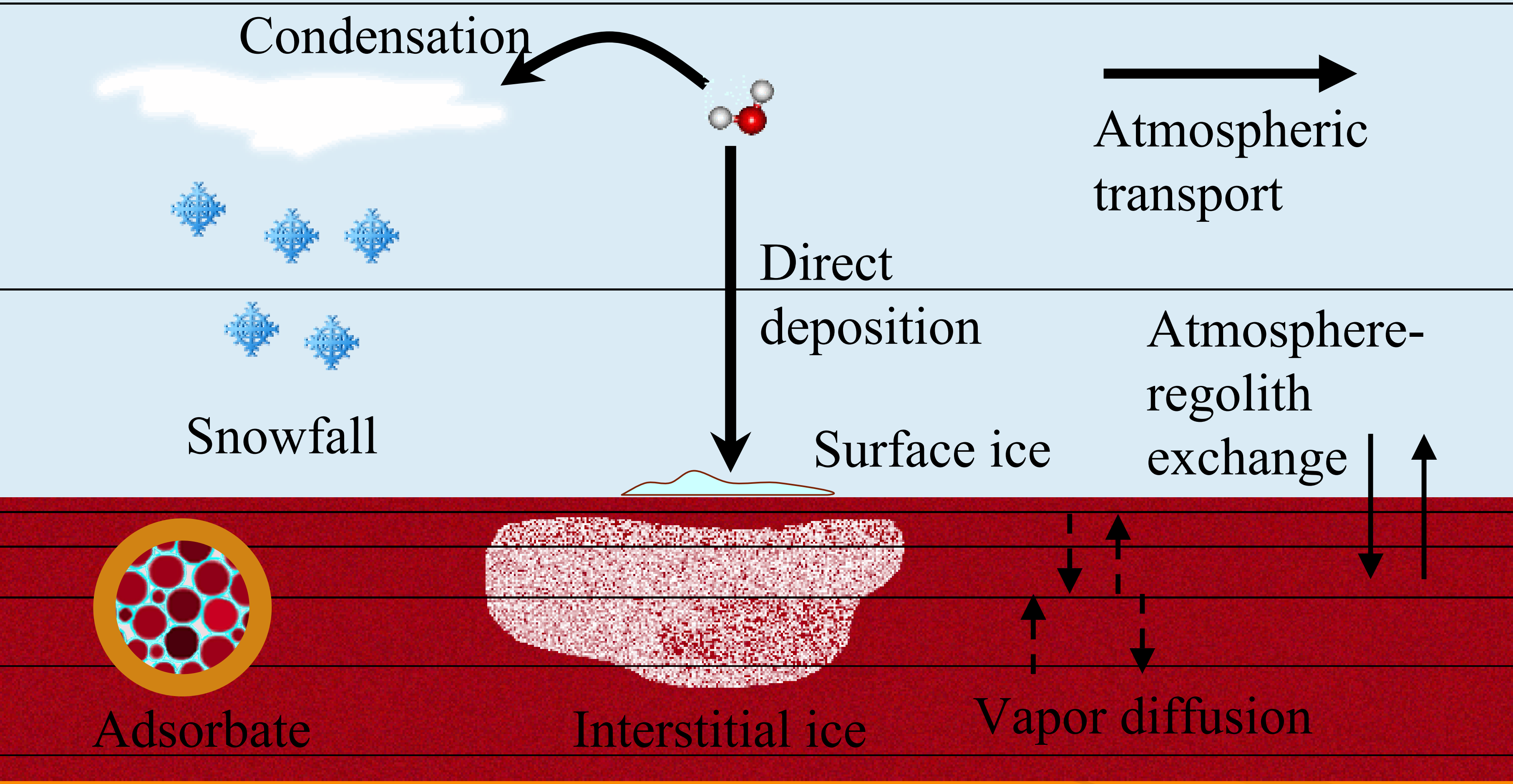
North and south polar accumulation as obliquity increases



Microns accumulated per year increases with obliquity

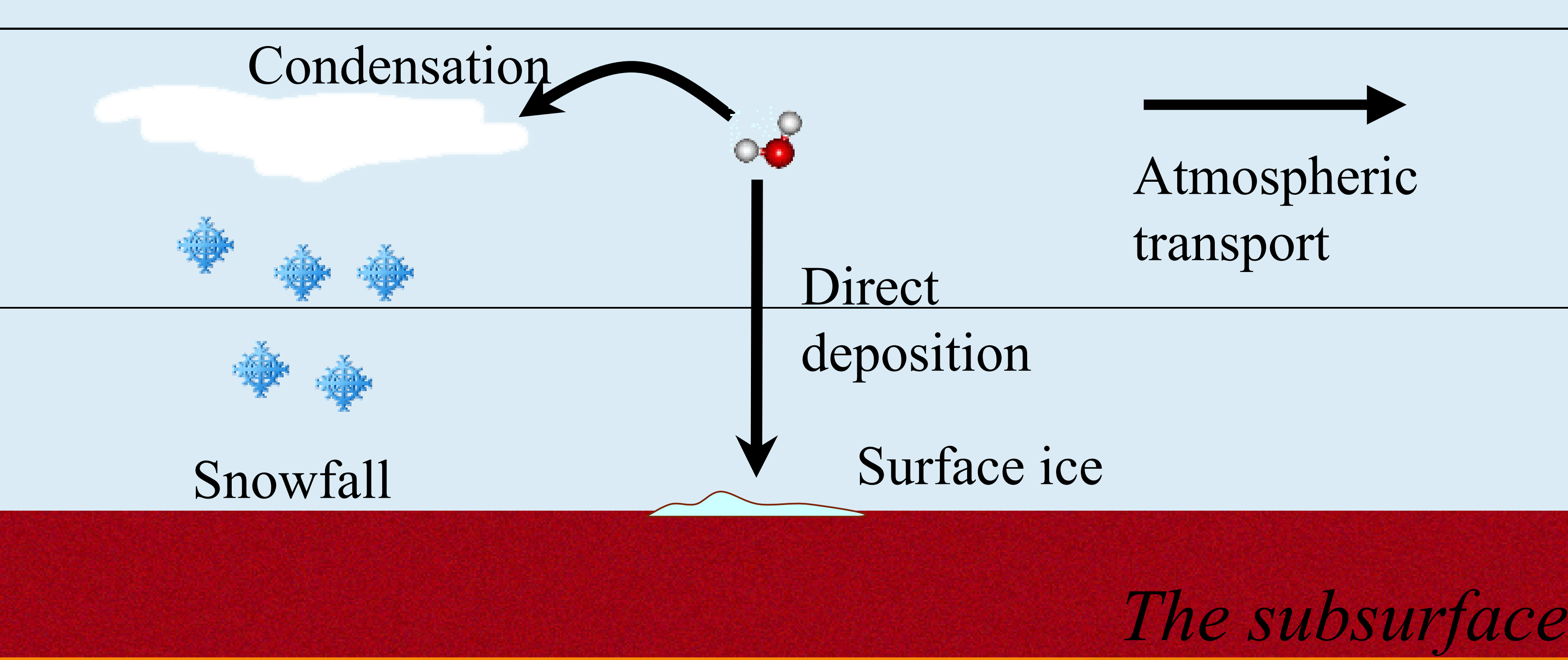
Pole with peak accumulation switches from N to S as obliquity is increased

Newman et al., submitted to Icaru



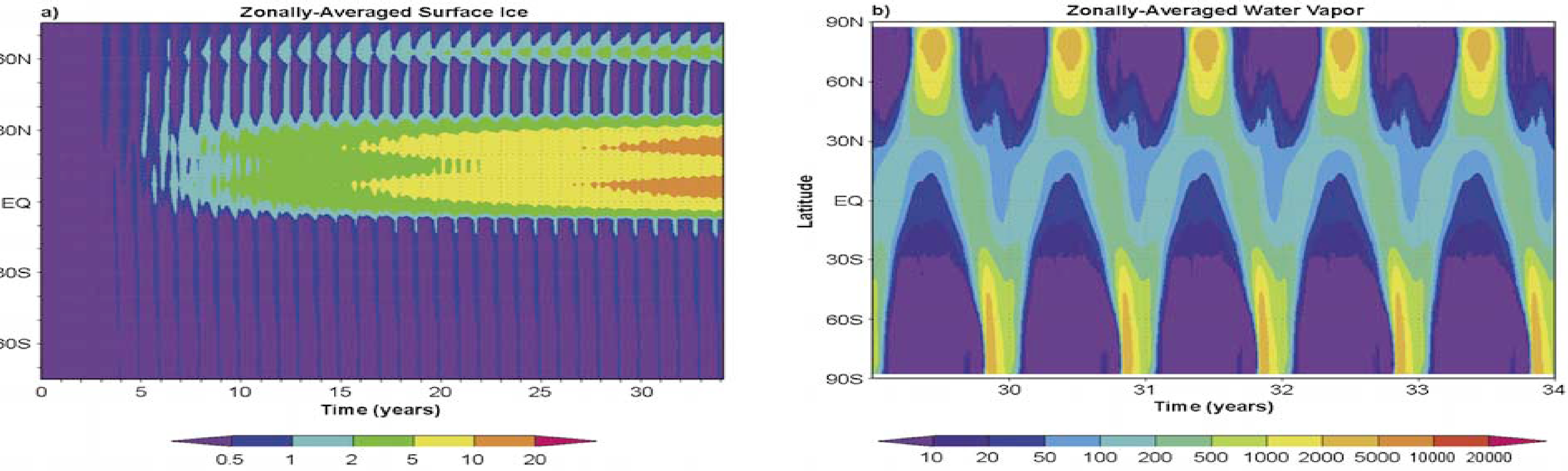
More complex set of water processes including:

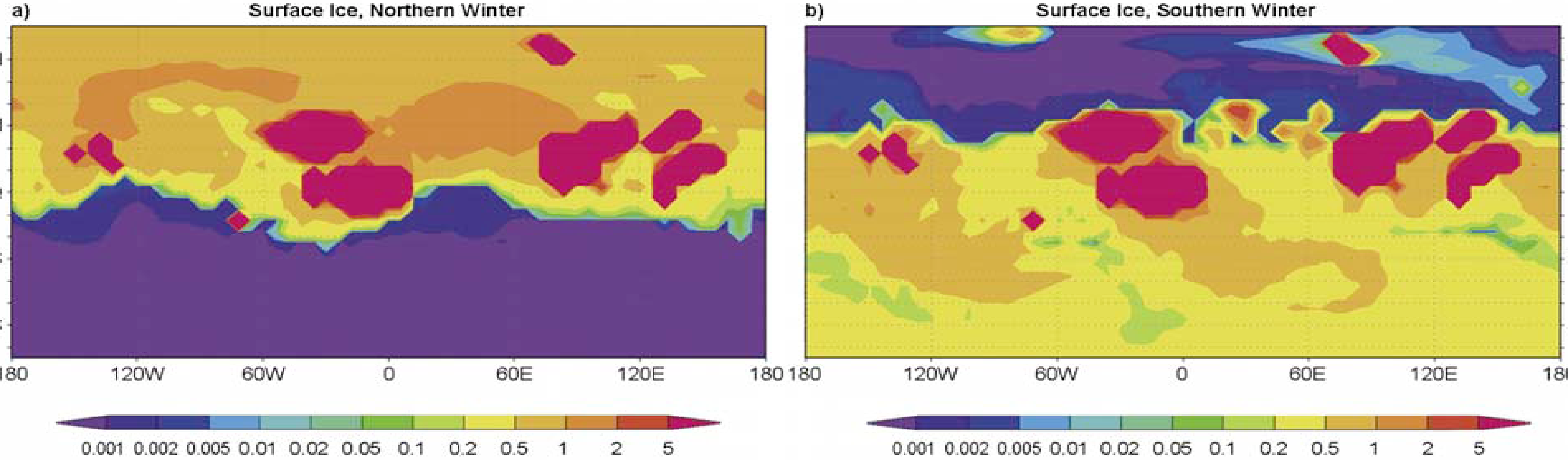
- Exchange between atmosphere and regolith
- Change of form (adsorbate, ice, vapor) within regolith
- Motion within regolith (diffusion)



- Basic water processes:
  - Condensation
  - Precipitation (as snow)
  - Direct deposition on surface (as ice)
  - Transport (by advection & mixing) within the atmosphere

Simulated water and *surface* ice at 45° obliquity



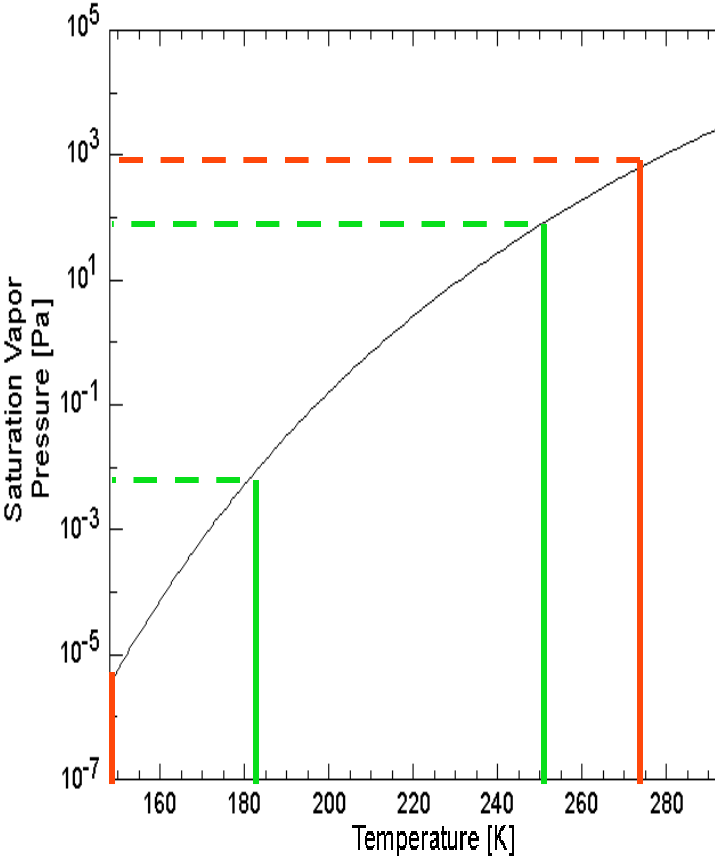


From Mischna et al. JGR 200

Question 1 - why is ice increasingly stable in tropics as obliquity increases?

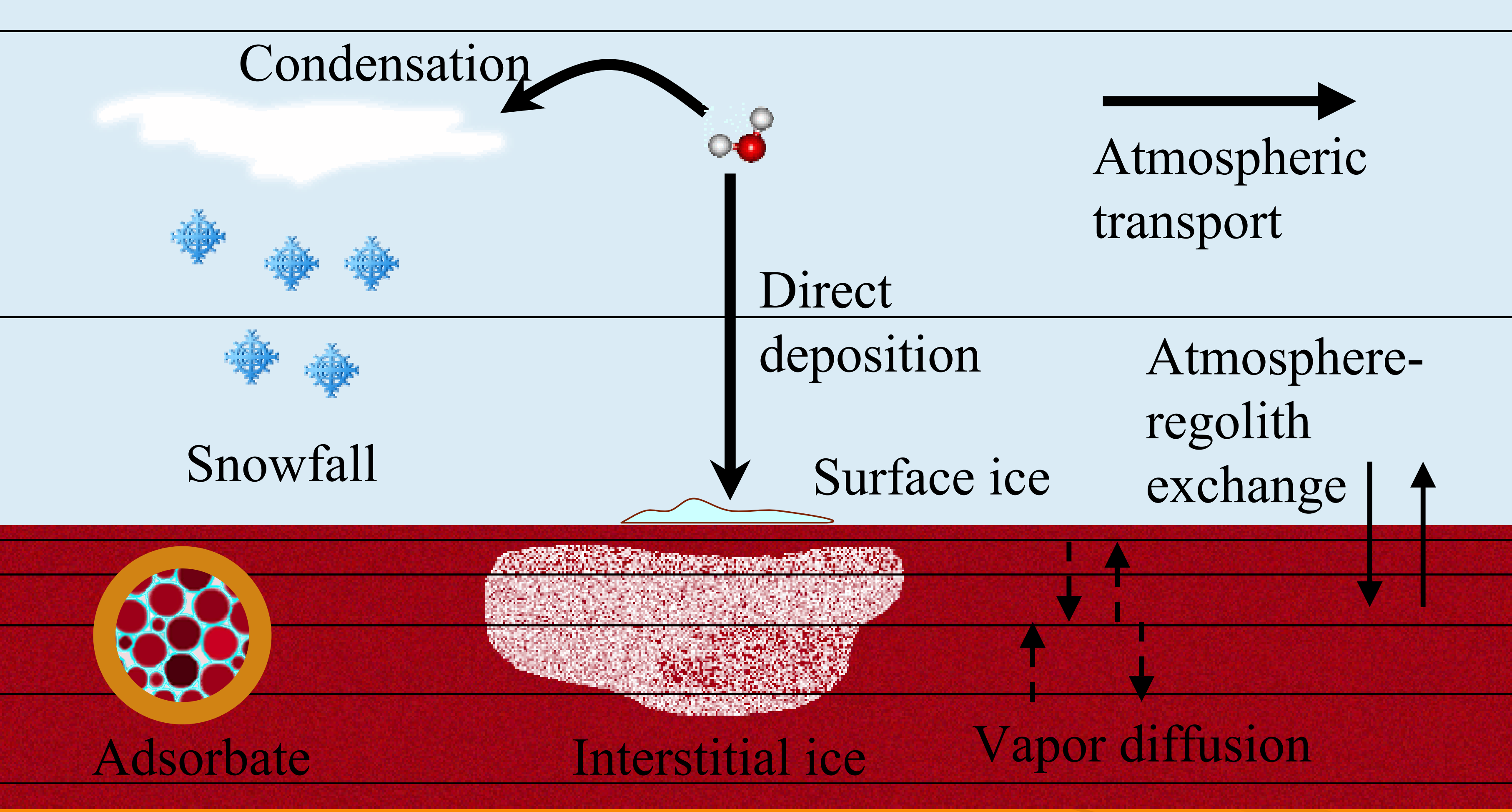
Ice is able to form when the partial pressure of water vapor in the atmosphere exceeds the saturation vapor pressure - this becomes lower (hence less water vapor is required and it is ‘easier’) as temperature decreases

At high obliquity, tropics have narrower range of temperatures than poles, hence water ice which forms at coldest times of year remains and deposits can accumulate; at poles, ice formed during winter sublimes during warm high obliquity summer



🟩 Max and min temperatures i
the tropics at high obliquity

🟥 Max and min temperatures
at the poles at high obliquity



Condensation

Atmospheric transport

Direct deposition

Atmosphere-regolith exchange

Snowfall

Surface ice

Adsorbate

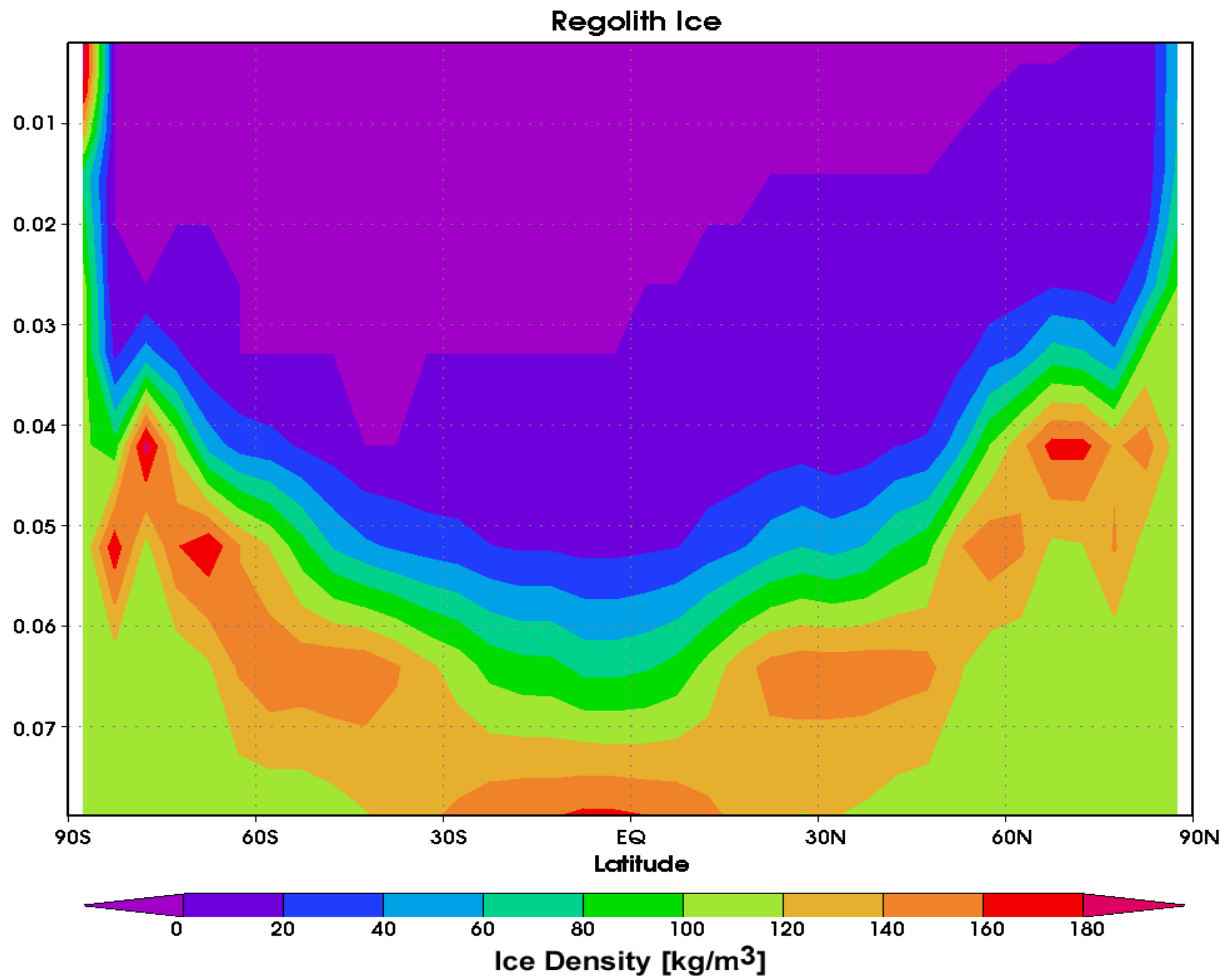
Interstitial ice

Vapor diffusion

More complex set of water processes including:

- Exchange between atmosphere and regolith
- Change of form (adsorbate, ice, vapor) within regolith
- Motion within regolith (diffusion)

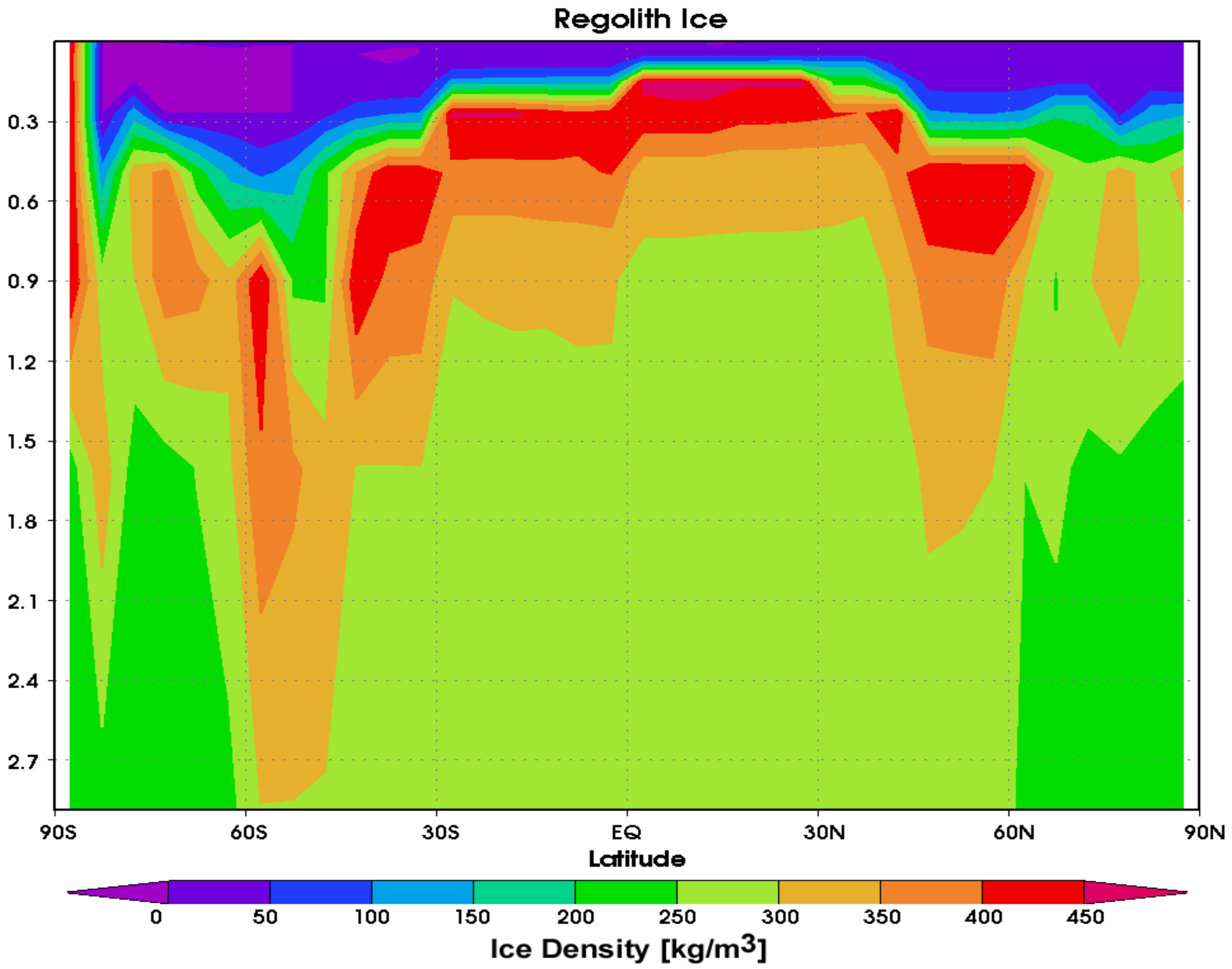
Simulated *subsurface* ice at the current obliquity



At the current obliquity, ice i best retained i polar regions

As ice sublimes, it either escapes or diffuses to deeper levels

Simulated subsurface ice at *high* obliquity

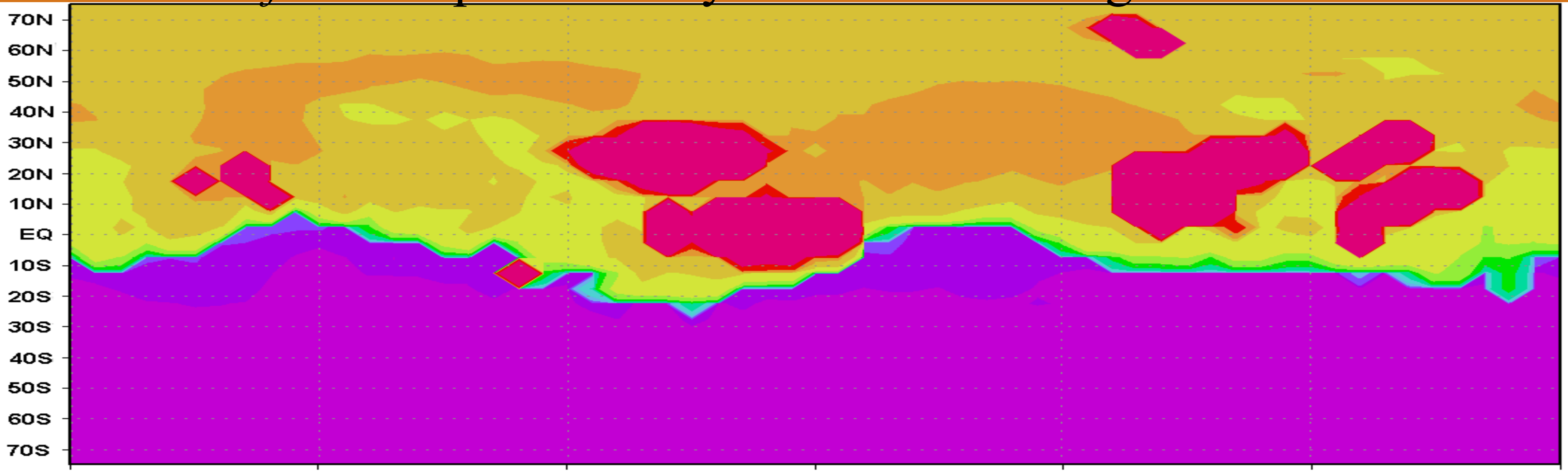


At high obliquity, ice is best retaine in the tropics

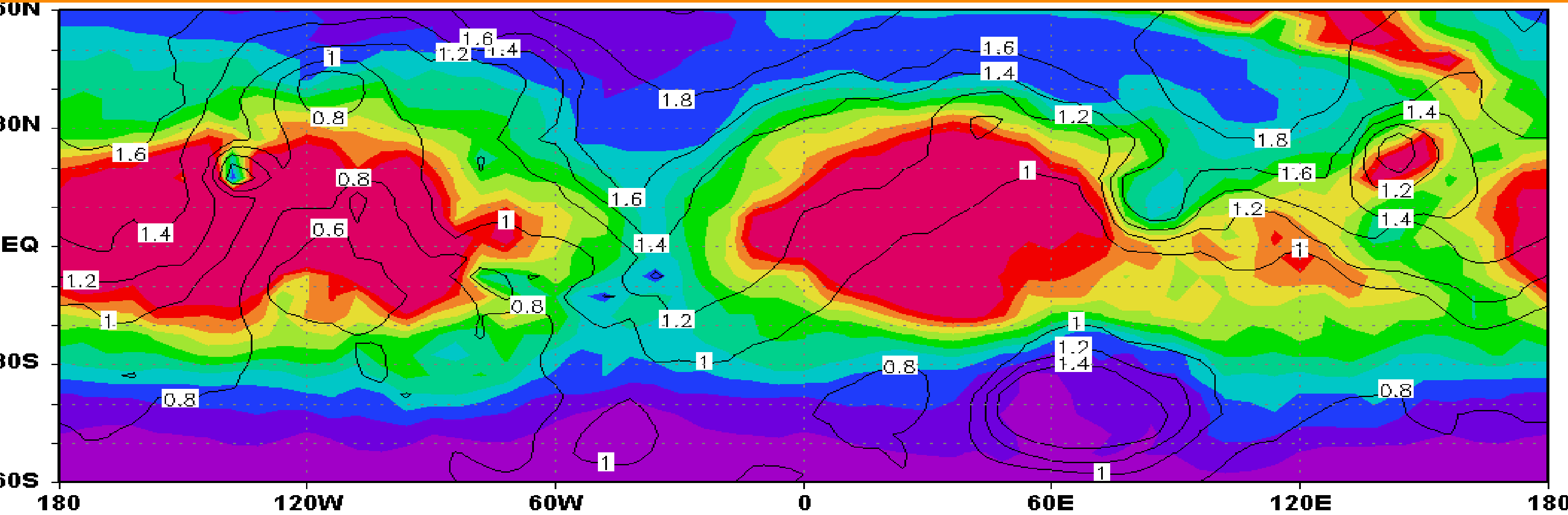
AND

Unlike the surfac ice predictions, the variation of *subsurface* ice with longitude is consistent with Mars Odyssey observations

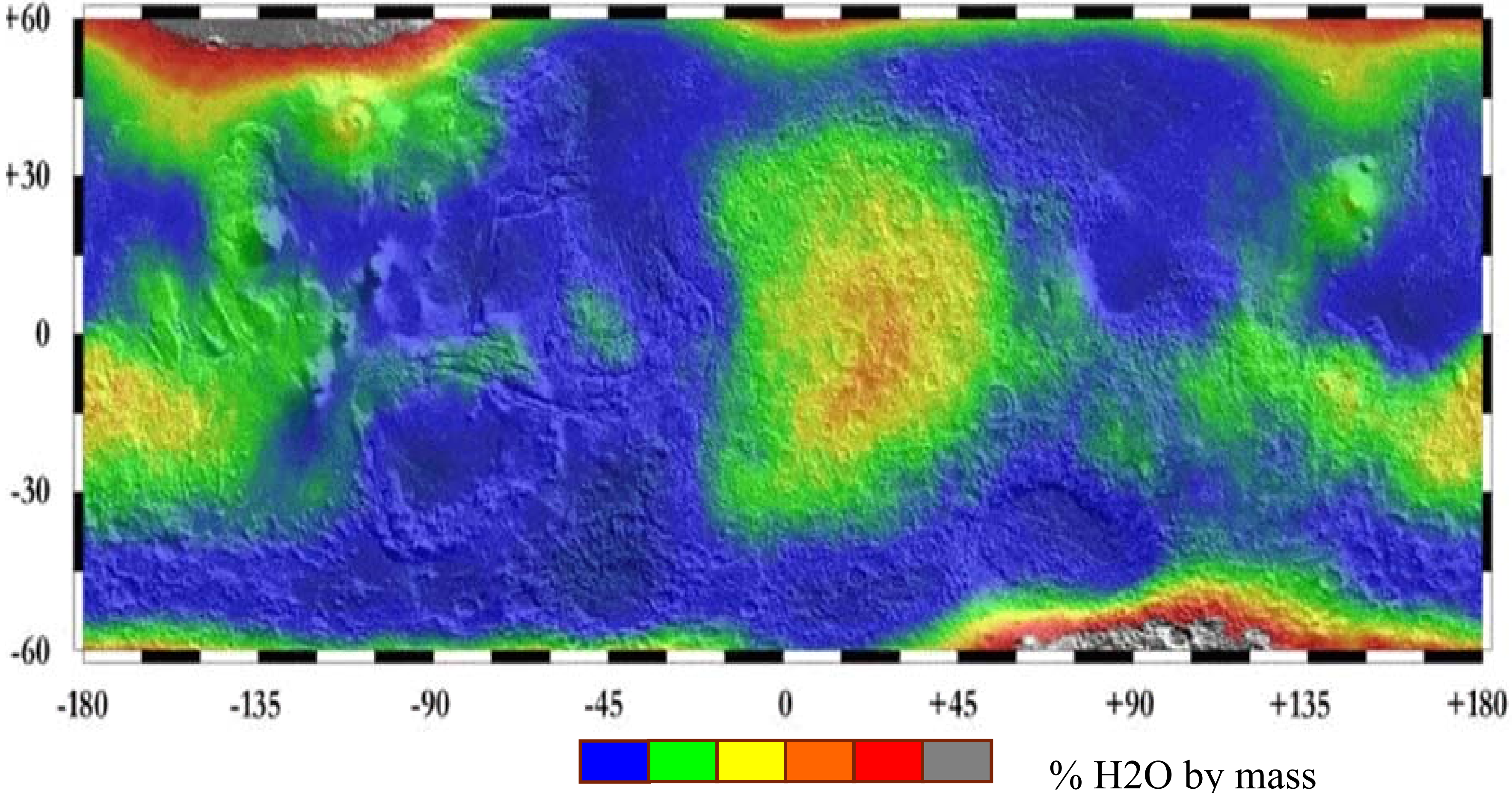
Surface ice predicted by GCM *without* regolith model



Subsurface ice predicted by GCM *with* regolith model



Odyssey Neutron Spectrometer Results



Question 2 - why does *surface* ice form preferentially in high thermal inertia (TI) regions but *subsurface* ice form preferentially in low TI regions?

Thermal inertia = $\sqrt{\rho c \kappa}$; ρ=density, c=specific heat capacity & κ=thermal conductivity; *most variations are due to variations in* κ

High κ => heat conducted efficiently into [out of] soil during the day [night] => soil temperatures stay close to daily average

=> if *surface* ice forms overnight in a high TI (hence κ) region, i is less likely to disappear during the day, since the peak surfac temperature reached is lower than in a low TI region

Subsurface ice forms preferentially where TI (hence κ) is low: less heat from the surface penetrates down to some depth

Overview

- Investigative tools and techniques

- Review of the present climate
- Climate variability - mechanisms and simulations

- Paleoclimates of the past few tens of Myrs - the impact of Mars's changing orbit

- **The climate of ancient Mars - the evidence and the theories**

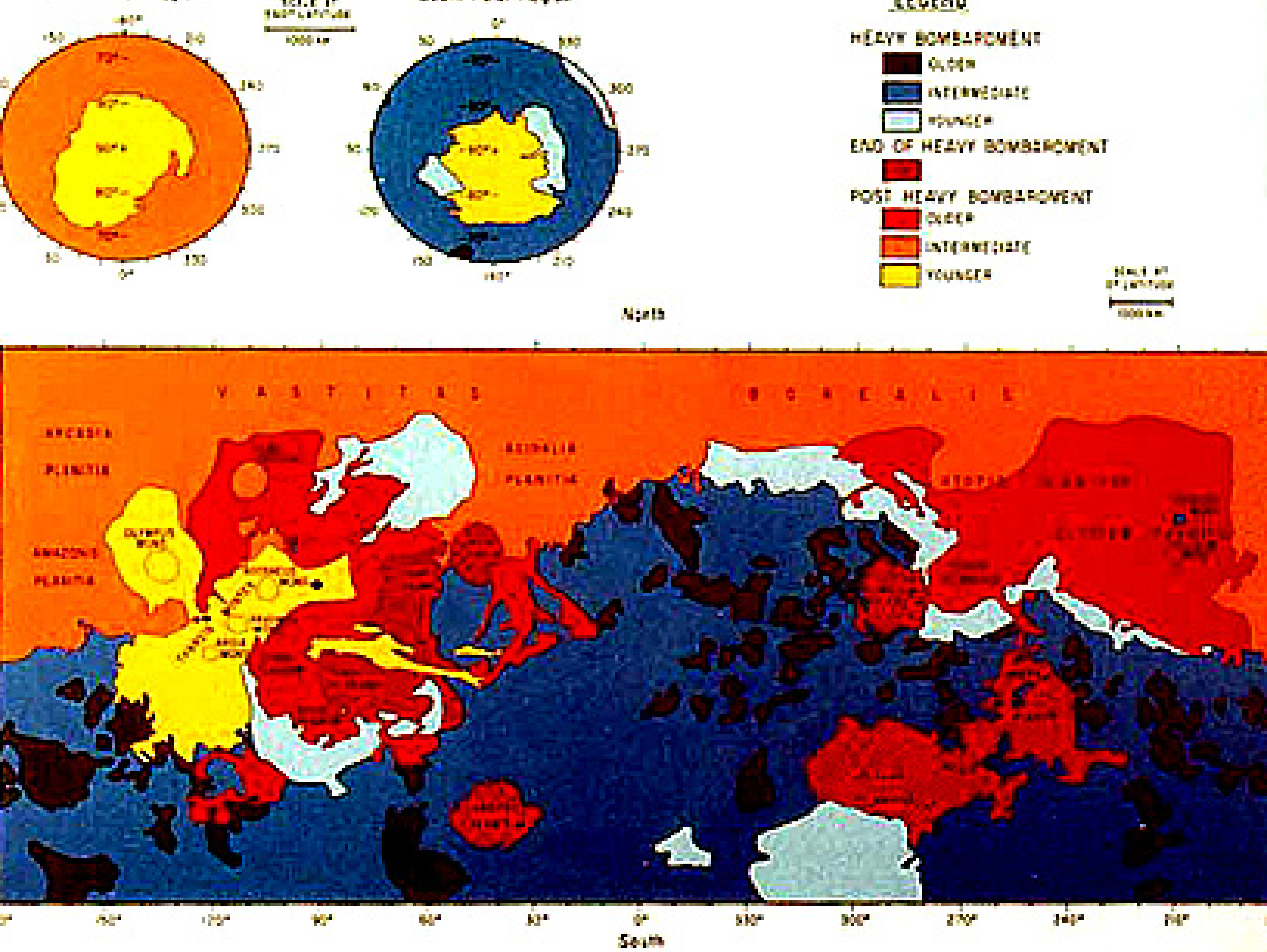
Geological timescales on Mars

Estimated using crater counts - idea that older surfaces have 'more craters' (though cratering rate depends on size too) and that absolute age can be calibrated by comparing to known ages of lunar surfaces

. Noachian: > ~3.6 Gyrs ago - the time of heavy bombardment - Mars thought to be warm and wet

. Hesperian: ~2.9-3.6 Gyrs ago - resurfacing of vast northern areas - Mars generally thought to be cold, with a thick permafrost

. Amazonian: < ~2.9 Gyrs ago - less geological activity - Mars generally thought to remain cold and dry throughout


HEAVY BOMBARDMENT
OLDER
INTERMEDIATE
YOUNGER
END OF HEAVY BOMBARDMENT
POST HEAVY BOMBARDMENT
OLDER
INTERMEDIATE
YOUNGER
SCALE AT 0° LATITUDE
1000 KM
North
VASTITAS BOREALIS
ARCADIA PLANITIA
ACIDALIA PLANITIA
AMAZONIS PLANITIA
OLYMPUS MONS
UTOPIA PLANITIA
South
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°

‘Fluvial’ surface features on Mars and other evidence of liquid water

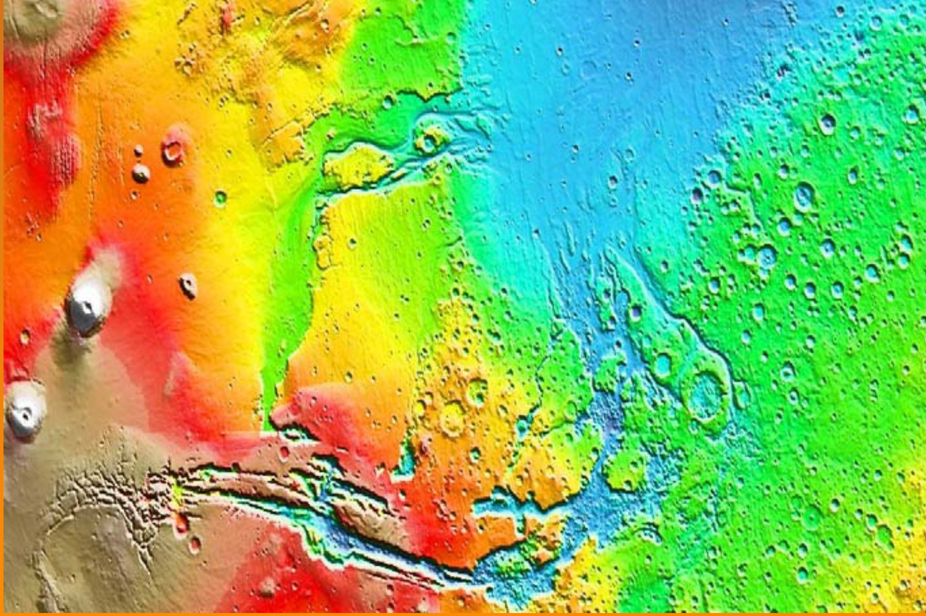
Some can be attributed to aeolian (wind-driven) erosion or volcanic flows

Some may have been produced by melting of subsurface ice o
quite short timescales

Some appear to require flowing water on the surface

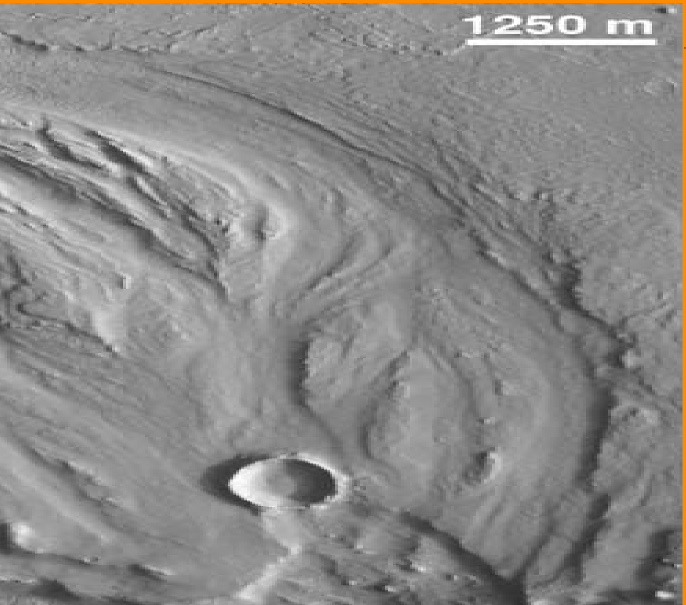
Some suggest the presence of large bodies of standing water -
‘lakes and oceans’ - particularly in the distant past (~4Gyrs ago

'Recent' gullies



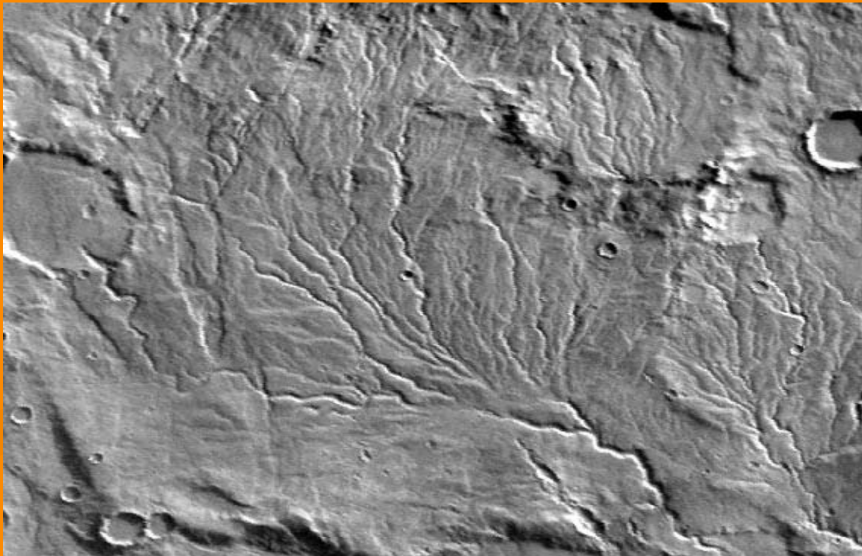
Huge outflows from Ares Vallis into the northern plains

Channel



MOC and MOLA data

Valley network



As mentioned above, some of these features may not have equired the presence of liquid water at the surface

For example, some gullies and valleys could have been produced by seepage of sub-surface water or ice due to hydrothermal activity

And some features which probably formed by liquid water on the surface may have formed under cold conditions

For example, due to their size and speed, the huge discharges of water which produced some of the outflow hannels may have occurred at T<273K *without freezing*

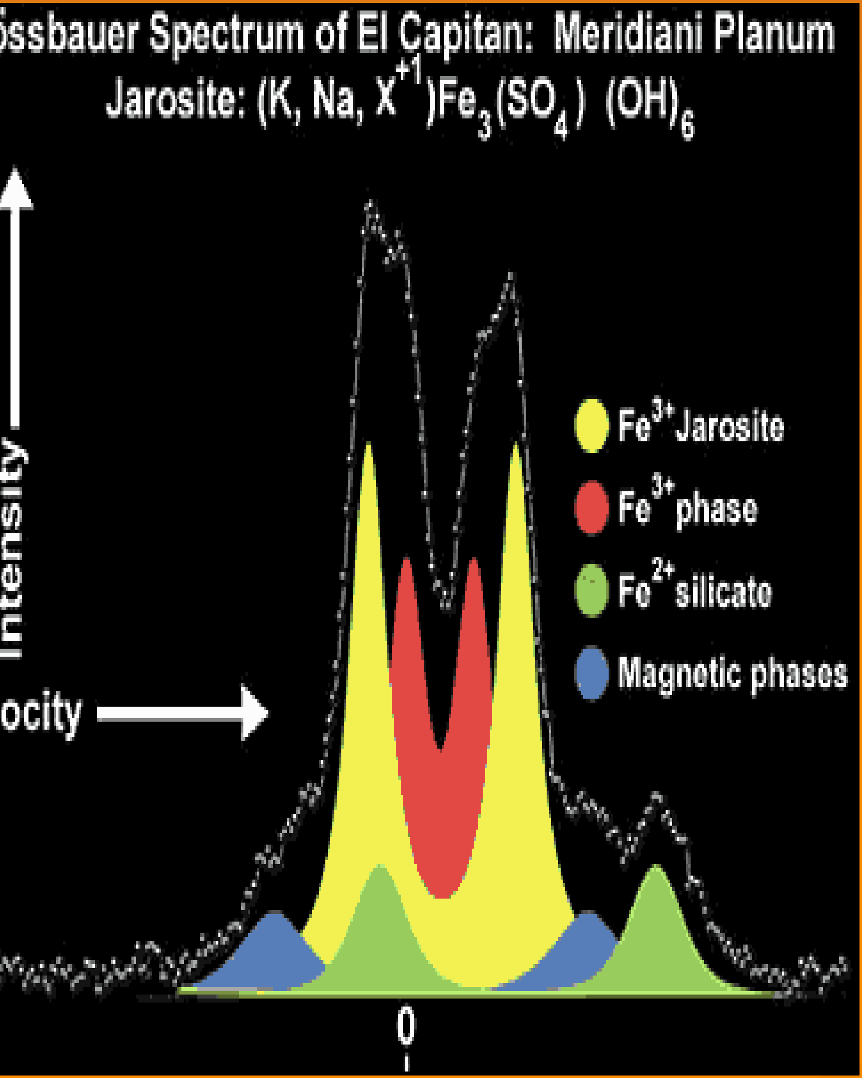
However, some 'fluvial' features seem to be explained only by a warm, wet climate, and other evidence adds to this:

Reduction in erosion rates as evidence for an early warm, wet Mars

Observations of crater erosion rates in the oldest terrain and in newer terrain => Mars had far higher erosion / weathering rates in the Noachian (> ~3.6 Gyrs ago), which decreased rapidly at the end of this period

The likeliest explanation by far is that the climate changed rapidly at this time, with the atmosphere becoming thinner and drier, thus greatly reducing erosion / weathering rates

Evidence of minerals probably formed in the presence of liquid water on Mars



From MER web pages

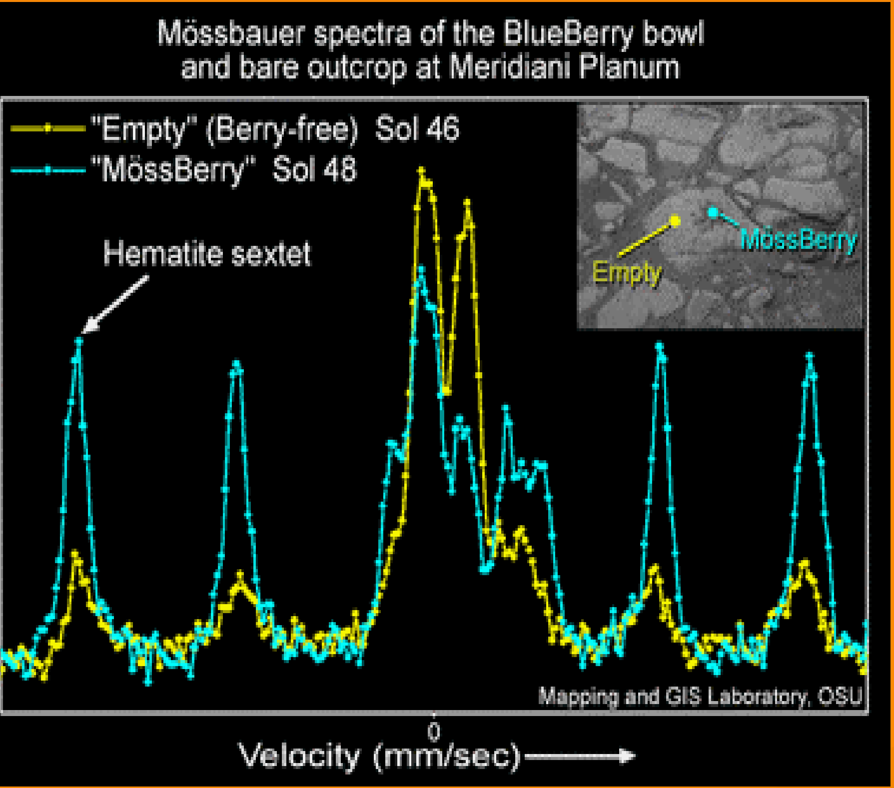
The Opportunity rover, which landed in Meridiani Planum on Jan 25, found evidence of hydrate iron sulphate mineral *jarosite*

On Earth, jarosite forms in dilute sulphuric acid in groundwater, suggesting the rocks were soaked in water

In the same rocks, high sulphur amounts in the form of *sulphate salts* also suggest formation in (or long exposure to) water

mbedded hematite-rich spherules ('blueberries') apear to be oncretions - i.e., to have been formed by the accumulation of inerals coming out of solution inside a porous, water-soaked rock

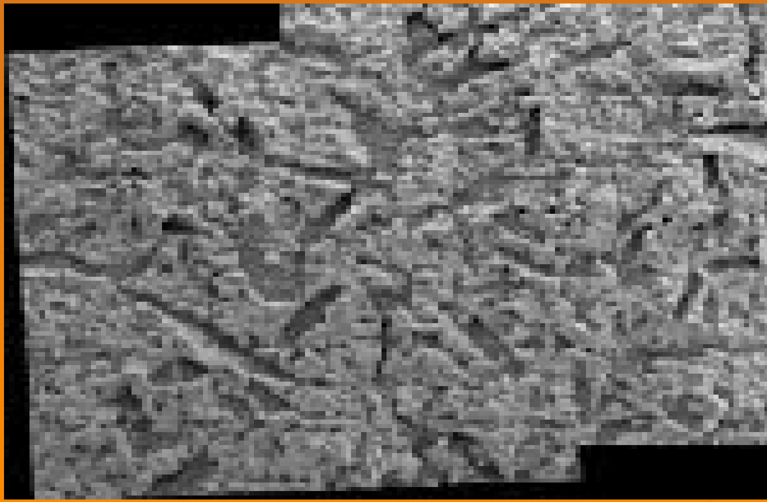
he hematite here was in fact first observed from orbit, and otivated sending a lander to this region, because this hematite was robably formed under warm, wet conditions

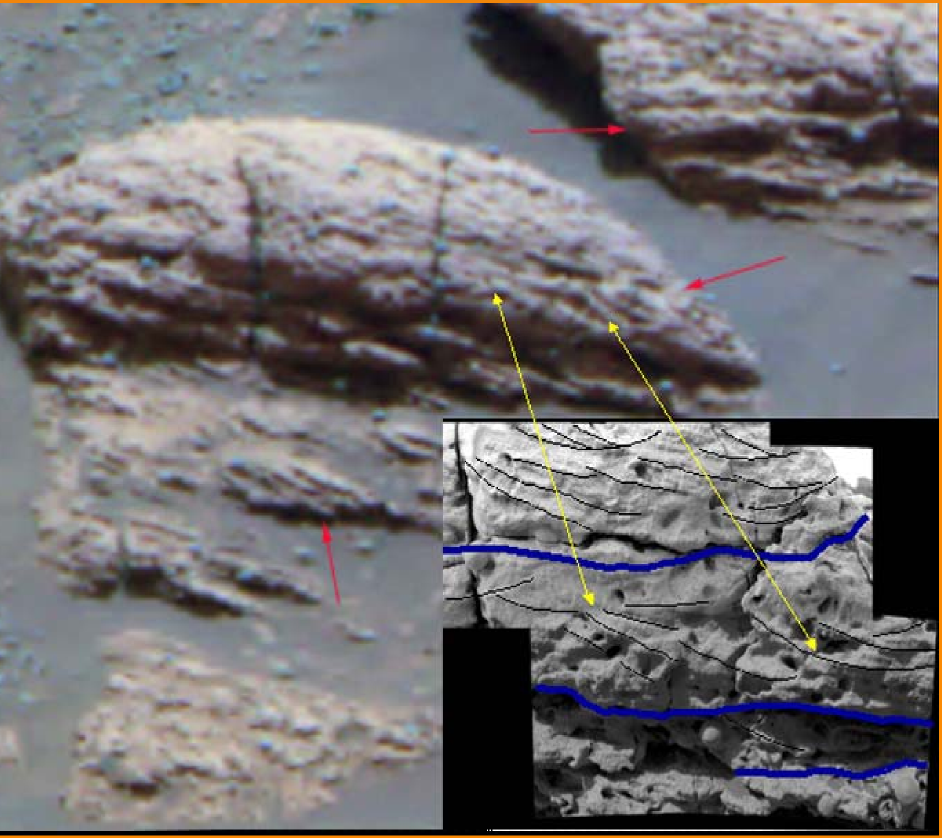


From MER web pages

ther evidence for liquid water found by the MER rovers includes:

Vugs’ - gaps left in rocks when
rystals of salt minerals, produced in
alty water, are removed via erosion
r by dissolving in less salty water





‘Crossbedding’ - layers in rocks which lie at an angle to the main layers, and can result from the action of wind or water - the scale and shape observed here suggest a watery origin

From MER web pages

‘Fluvial’ surface features on Mars and other evidence of liquid water

Some can be attributed to aeolian (wind-driven) erosion or volcanic flows

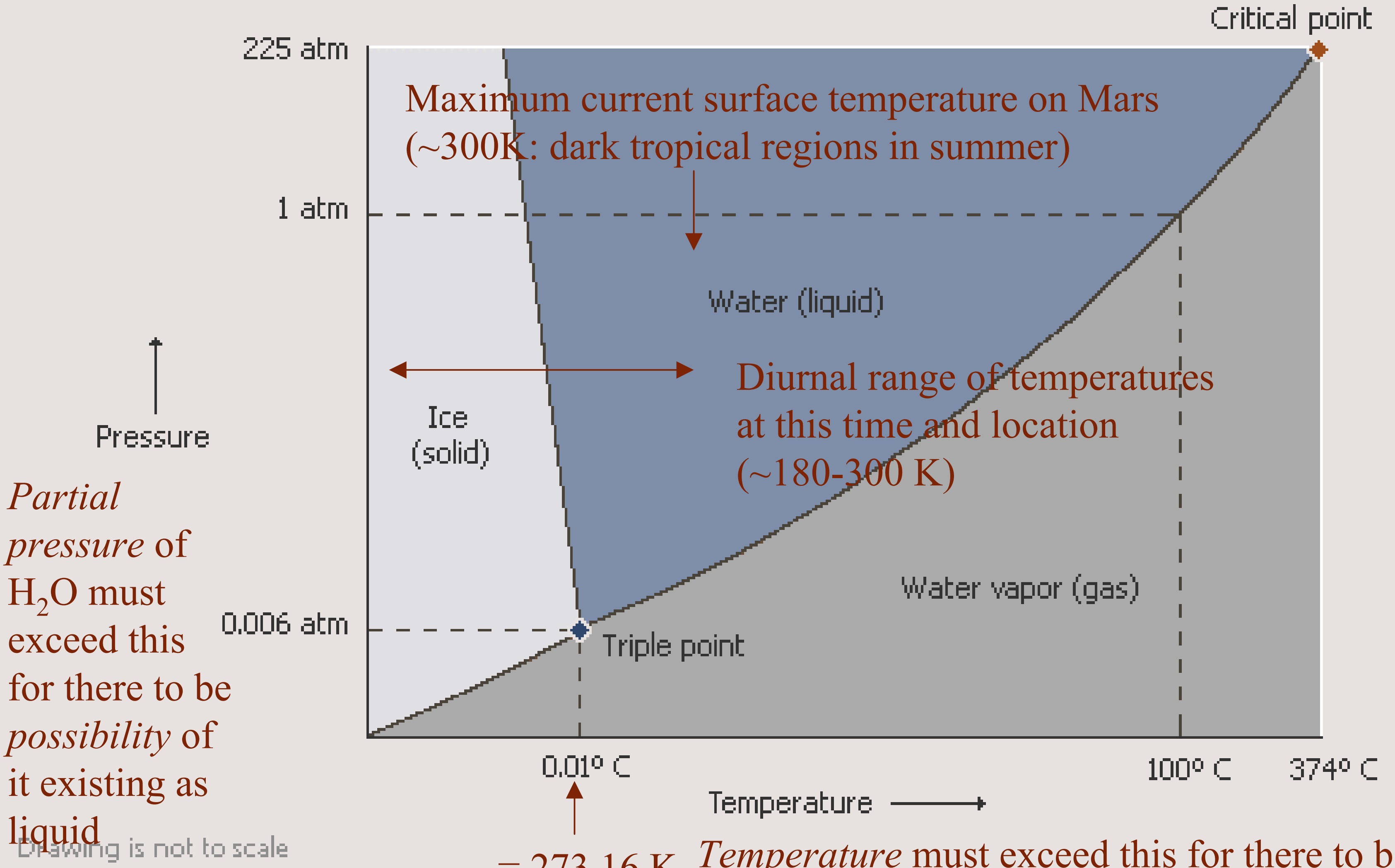
Some may have been produced by melting of subsurface ice o quite short timescales

Some appear to require flowing water on the surface

Some suggest the presence of large bodies of standing water - ‘lakes and oceans’ - particularly in the distant past (~4Gyrs ago

What is required to enable liquid water to be stable, for long periods of time, on the surface of Mars?

H_2O phase diagram



Maximum current surface temperature on Mars (~300K: dark tropical regions in summer)

Diurnal range of temperatures at this time and location (~180-300 K)

Partial pressure of H_2O must exceed this for there to be *possibility* of it existing as liquid

= 273.16 K

Temperature must exceed this for there to be *possibility* of H_2O existing as a liquid

mportant distinction between partial pressur of water vapor and atmospheric pressure

ey point: in the phase diagram, the pressure axis refers to the *artial pressure of water vapor*, <u>not</u> the atmospheric pressure!

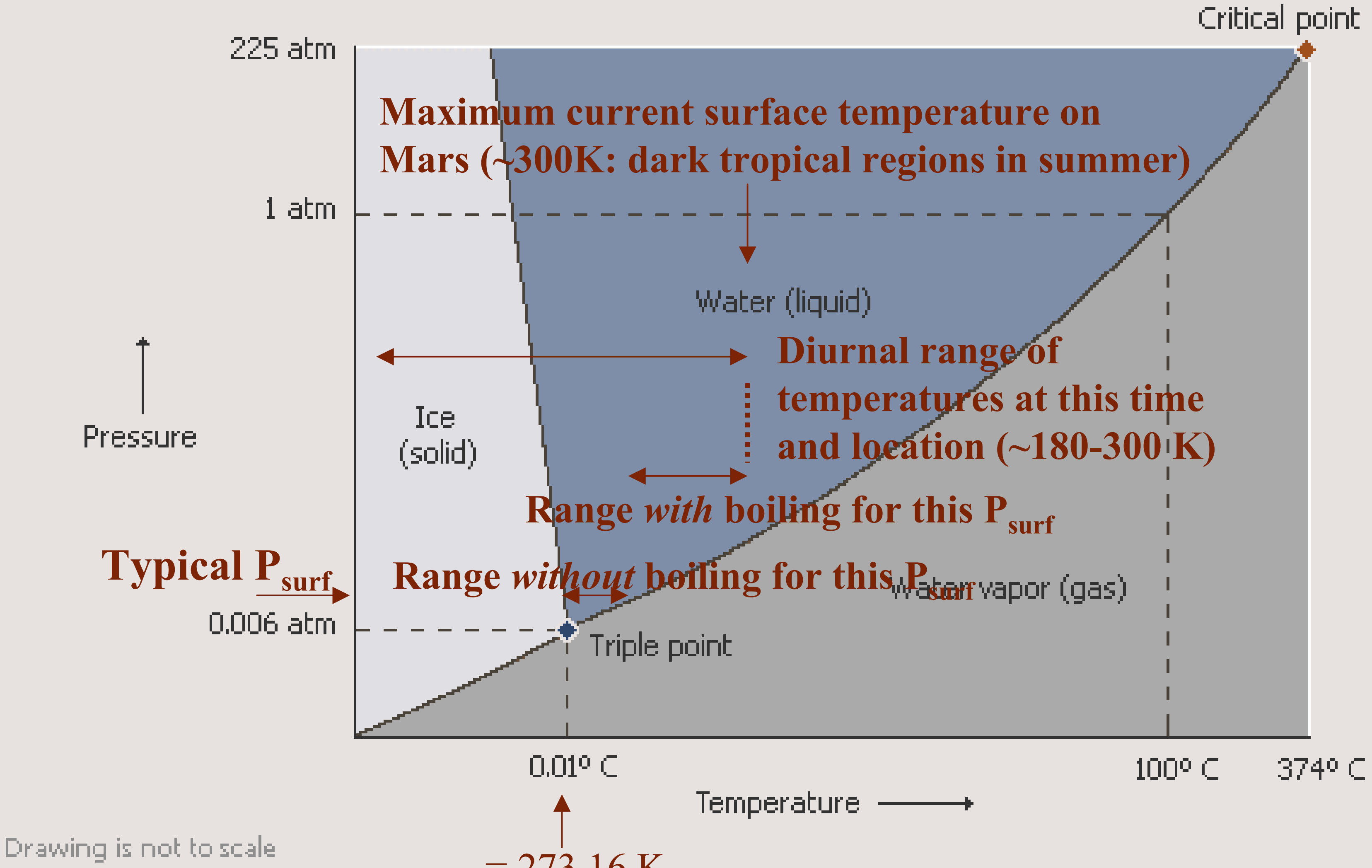
he *atmospheric pressure* is only relevant if you want to know whether quid water will *evaporate* or *boil* as temperature increases:

if saturation vapor pressure > atmospheric pressure, liquid *boils*
if atmospheric pressure > saturation vapor pressure, liquid *evaporates*

oiling produces *much* faster loss of liquid water because high saturatio apor pressures allow bubbles to form against atmospheric pressure

> transient liquid water stays longer for higher atmospheric pressures

H_2O phase diagram



Maximum current surface temperature on Mars (~300K: dark tropical regions in summer)

Diurnal range of temperatures at this time and location (~180-300 K)

Range *with* boiling for this P_{surf}

Typical P_{surf}

Range *without* boiling for this P_{surf}

= 273.16 K

Is there now liquid water on Mars's surface?

Liquid water *can never be stable* on Mars currently - the partial pressure of vapor is <1Pa - much lower than the triple point pressure of 610Pa

Transient liquid water can exist on the surface at present, e.g. as a film above ice, but only if the temperature is between the melting point of ice and boiling point of liquid

BUT transient liquid water can only exist if ice is present when temperatures are very high - exactly where you don't expect to find ice!

Further, because the total pressure on Mars is never very muc higher than 610Pa, the temperature range between melting an boiling (rather than just evaporating) is usually v. small (<10K)

What conditions would have been required for liquid water on the surface of Mars in the past?

Higher surface pressures allowing liquid water to evaporate, no boil over a wider range of temperatures

Higher surface temperatures and a lower range of temperature across Mars - currently most of Mars stays below the freezing point almost all the time

Need thicker atmosphere to:

- Increase the thermal mass of the atmosphere to limit day/night temperature differences
- Increase mean temperatures through the greenhouse effect
- Increase mean pressure to increase temperature range between melting and boiling (rather than just evaporating)

Possible ways to get higher surface temperatures

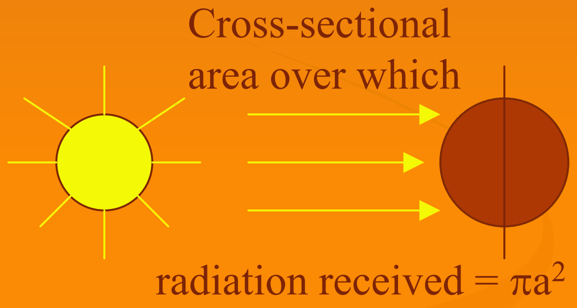
- Internal effects:
  - ‘Greenhouse effect’ - absorption of thermal radiation by atmosphere
  - Cloud effects - preventing thermal radiation leaving
- External effects:
  - Impact heating - sudden injection of heat from an object colliding with the planet - *this has been proposed, but is still quite controversial*

A simple model of an atmosphere

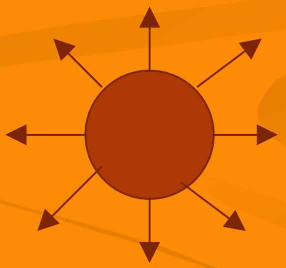
tep 1 - calculate ‘effective temperature’ of planet (T_{eff}) by equating ncoming and outgoing radiance (must be the same if no net heating)

otal radiation absorbed assuming a fraction *A*, here *A*=albedo, is reflected) $= (1-A) \times F_s \times \pi a^2$

Units are W/m^2


Cross-sectional area over which radiation received = πa^2

otal radiation emitted from lanet (surface area = $4\pi a^2$) $= F_0 \times 4\pi a^2$



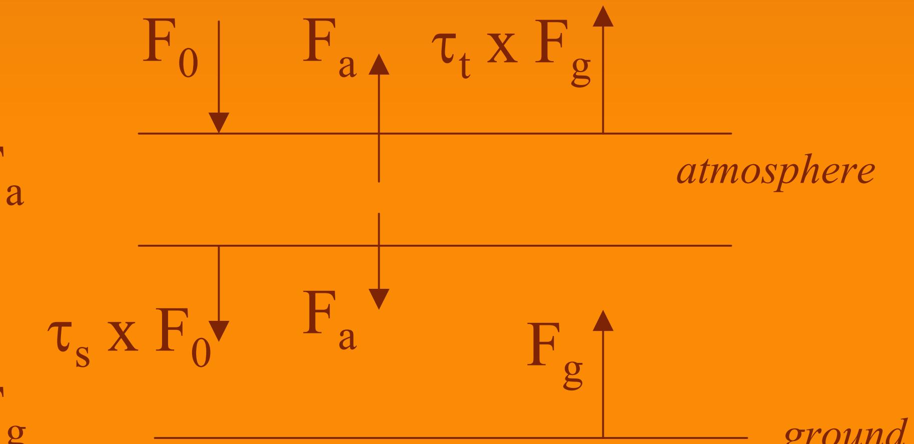
herefore $(1-A) \times F_s \times \pi a^2 = F_0 \times 4\pi a^2$, $\Rightarrow$ $F_0 = 1/4 \times (1-A) \times F_s$

reating planet as a black body ($\Rightarrow F_0 = \sigma T_{eff}^4$, where σ = Stefan oltzmann constant), $\Rightarrow$ $T_{eff} = [(1-A) \times F_s / (4\sigma)]^{1/4}$

tep 2 - calculate how the surface temperature differs from the 'effective emperature' (T_{eff}) in the presence of an atmosphere

$_0$ = radiation emitted by planet per unit surface area

= mean incoming radiation per unit surface area (in equilibrium)



τ_t = transmissivity of atmosphere for thermal wavelengths

τ_s = transmissivity for solar wavelengths

By Kirchoff's law, emissivity = absorptivity, which = 1 - transmissivity

Therefore atmosphere emits F_a = $(1- \tau_t)$ x σT^4 in all directions

et incoming radiation = $F_0 - F_a - \tau_t \times F_g = 0$ in equilibrium

et radiation at the surface = $\tau_s \times F_0 + F_a - F_g = 0$ in equilibrium

Solving gives **$F_g = [(\tau_s+1)/(\tau_t+1)]\, F_0$**

$$\mathbf{F_g = [(\tau_s+1)/(\tau_t+1)]\, F_0}$$

So if there were no atmosphere (=> $\tau_s = \tau_t = 1$) => $F_g = F_0$

=> $T_g = T_{eff}$

Now if we include an atmosphere which absorbs more at solar than at thermal wavelengths (=> $\tau_s < \tau_t$) => $F_g < F_0$

=> $T_g < T_{eff}$

Finally, if we include an atmosphere which absorbs more at thermal than at solar wavelengths (=> $\tau_s > \tau_t$) => $F_g > F_0$

=> $T_g > T_{eff}$

This is the so-called ‘greenhouse effect’

A more complex model

he simple model gives the main idea, but makes huge simplifications, .g. treats the atmosphere as a **single (thin) layer** at constant temperatur

he maximum greenhouse warming (for $\tau_s=1$, $\tau_t=0$) was only a $2^{1/4}$ time ncrease (<20%), which can't explain the increase of >300% for Venus!

---

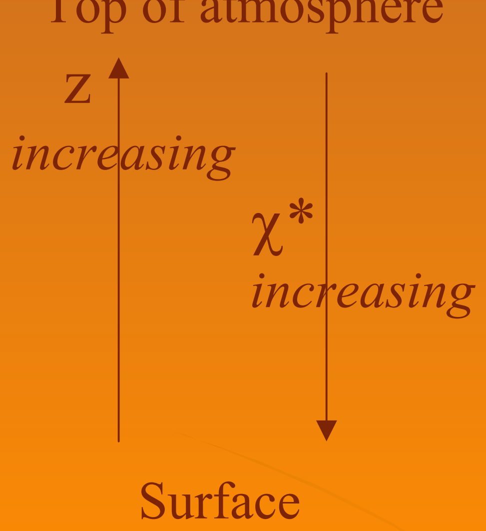
or a **deep** atmosphere things get harder, so for simplicity we'll assume:

the atmosphere is transparent to solar radiation ($\tau_s=1$)

we can use a *scaled optical depth* $\chi^* = 1.66\,\chi$ approximation => w an use vertical paths (and won't need to integrate over solid angles)

he *vertical optical depth* χ is defined as $\chi(z) = \int_z^\infty \kappa(z)\rho_a(z)\,dz$, here κ=extinction coefficient, ρ_a=gas density, hence is a measure of th bsorption expected by gas in the column above a height z

Some background concepts



chwarzchild's equation for the variation of adiation L along a path s:

$$\frac{dL}{ds} = -\kappa\rho L + \kappa\rho J$$

ate of hange long path

Absorption (proportional to amount of gas and radiation)

Emission (proportional to amount of gas and emission function, usually black body)

$$\chi^* = 1.66\,\chi(z) = 1.66 \int_z^{\infty} \kappa(z)\rho_a(z)dz$$

$$\pi B = \sigma T^4 \text{ (B=Planck fn)}$$

$$-\frac{dF^{\uparrow}}{d\chi^*} + F^{\uparrow} = \pi B \quad ①$$

$$\frac{dF^{\downarrow}}{d\chi^*} + F^{\downarrow} = \pi B \quad ②$$

These are equations for the ***upward*** F↑ *and* ***downward*** F↓ *longwave fluxes (in W/m²) - the sign change on the LHS is because we are using χ* not z*

Applying boundary conditions (e.g. incoming longwave flux = 0) and olving for the equilibrium case:

$$=> \quad F^{\uparrow} = 1/2\ F_0\ (2 + \chi^*), \qquad F^{\downarrow} = 1/2\ F_0\chi^*$$

o if we assume that the upward longwave flux from the ground is hat just above the ground ($F_g^{\uparrow}$), we can estimate the ground emperature T_g via:

$$\pi B(T_g) = \sigma T_g^4 = F_0\ (1 + 1/2\ \chi_{tot}^*)$$

$$=> \qquad \mathbf{T_g = \{F_0\ (1 + 1/2\ \chi_{tot}^*)\ /\ \sigma\}^{1/4}}$$

We can use this with *observed* ground temperatures to estimate the total tmospheric optical depth at longwave wavelengths (χ_{tot}^*) for Venus, arth and Mars:

$$=> \qquad \mathbf{\chi_{tot}^* = 2\ x\ \{4\ \sigma\ T_g^4\ /\ [(1\text{-}A)\ F_s]\ \ -\ \ 1\}}$$

Let's see how this applies to Venus, Earth and Mars

ome important parameters are:

	Venus	Earth	Mars
= distance from Sun (AU)	0.72	1	1.52
$_s$ = solar flux at planet (W/m^2) = E_s/d^2	2643	1370	593
= albedo	0.8	0.3	0.22
$_{eff} = [(1-A) x F_s / (4\sigma)]^{1/4}$	220	255	212
$_g = \{(1-A) F_s (1 + 1/2\ \chi_{tot}^*) / (4\sigma)\}^{1/4}$	730	288	218

$$\boldsymbol{\chi_{tot}^* = 2 x \{4 \sigma T_g^4 / [(1-A) F_s] - 1\}}$$

$$\sigma = 5.67e\text{-}8$$

Venus $\chi_{tot}^* = 62$, Earth $\chi_{tot}^* = 1.25$, Mars $\chi_{tot}^* = 0.2$

We therefore need to inject more ‘greenhouse gases’ into the atmosphere - options are:

- CO_2 - this is already present at the poles as ice, and there may be lots more adsorbed into the high latitude (colder) regolith

- H_2O - this is present in larger quantities in the polar ice caps (and there may be much more beneath the surface as ice or adsorbate) - will require far higher atmospheric temperatures than CO_2 to exist as a gas

- Other - e.g. CH_4, SO_2 - but these both have very short chemical lifespans in the atmosphere. To maintain CH_4 levels would probably require a biological component, and volcanic SO_2 would rapidly dissolve and rain out

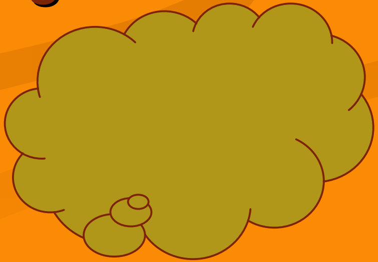
Is the greenhouse effect the only way to heat up Mars's surface?

Idea that a thick enough CO_2 atmosphere would become saturated at some levels and condense to form thick clouds, thus *limiting* the effectiveness of this mechanism for warming the surface long before high enough pressures were reached

However, such clouds might also be able to warm the surface – depending on cloud particle size, amount, location and other atmospheric components, scattering of thermal radiation back down by clouds may *also* warm surface

Would also warm *atmosphere*, tending to reduce condensation and destroy clouds, and thus be self-limiting

Overall effect not clear!



Unknowns

. Amount of liquid water on the surface, when it was present, and for how long

. How the thicker, warmer atmosphere required was produced (how sufficient greenhouse gases got into the atmosphere)

. Where all of the water is now

. What happened to the thicker atmosphere

Unknowns

. **Amount of liquid water which was released when it was released and for how long**

. How the thicker, warmer atmosphere required was produced (how sufficient greenhouse gases got into the atmosphere)

. Where all of the water is now

. What happened to the thicker atmosphere

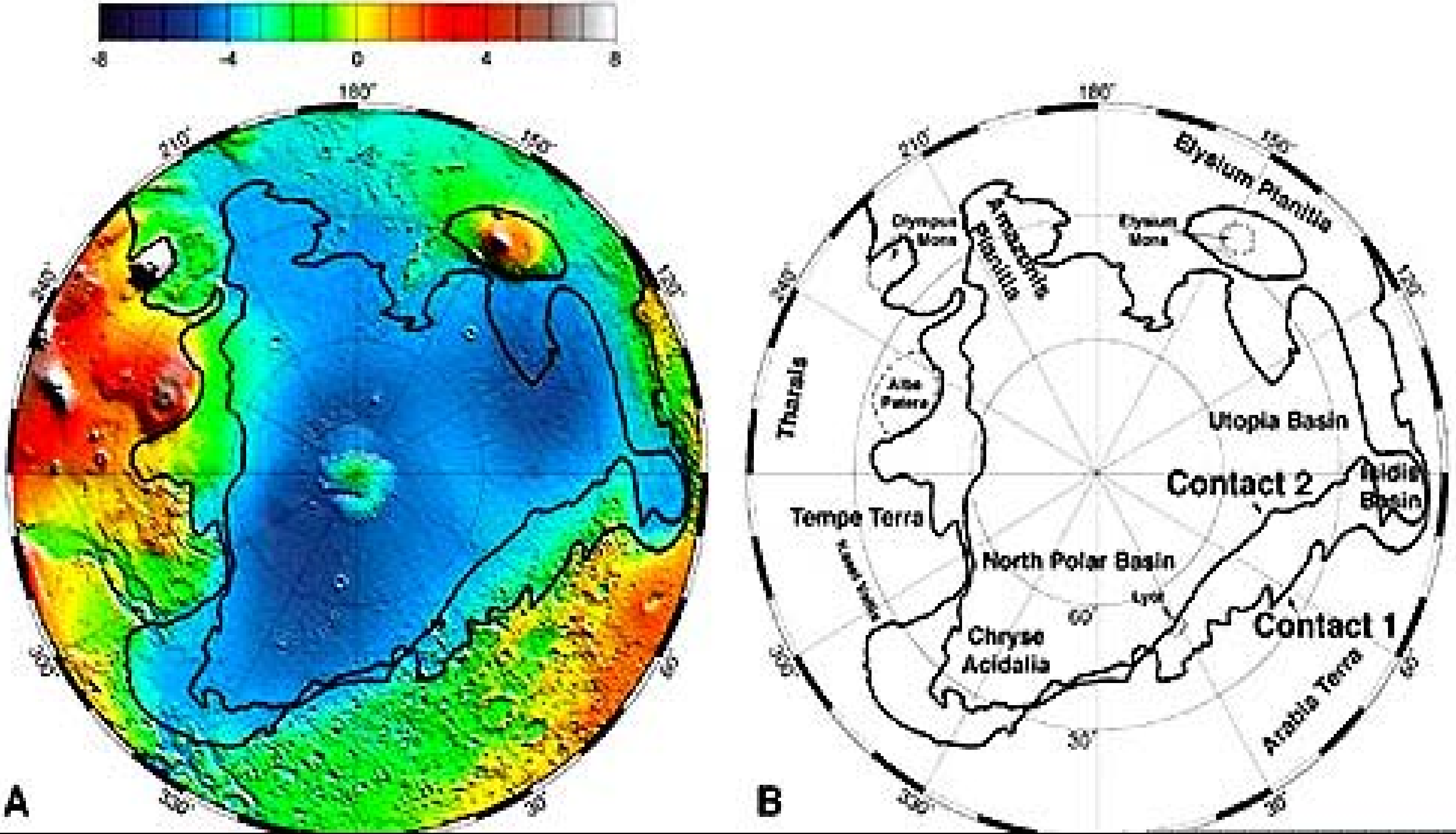
Estimates of the amount of water available to the surface of Mars in the past

- Based on geomorphological evidence - by e.g.:
  - estimating how much subsurface water was present to produce outflow channels, & assuming same across Mars
  - estimating the amount of water needed to form ‘oceans’

- Based on observed isotope ratios - by e.g.:
  - relating loss rates of noble gases to water loss rates using relationships for Earth
  - using the D/H ratio - *see later!*

- Based on models of planetary evolution - by e.g.:
  - estimating the water contained in (and later outgassed from) the rocks which formed Mars
  - estimating the water contributed from comets

The ‘shorelines’ hypothesis



From Head et al. Science 1999

Estimates are given as the depth of water depth if it were venly spread over the planet

For example, the water currently observed in the atmosphere, egolith and various polar reservoirs corresponds to only ~40r t the surface

Estimates of the water which was available at the surface in he past vary between a few 100m (from the current D/H ratio nd several km (from assuming that certain features in the orthern plains are shorelines of a massive ancient ocean)

When was liquid water present?

- Was there a big early greenhouse, with warm and wet conditions <~3.5Gyrs ago, followed by massive atmospheric loss and a rapid transition to today's cold, dry conditions?
- Was there a gradual transition to today's climate?
- Were there episodic warm, wet periods throughout Mars's history (perhaps becoming less intense/frequent with time), with cold, dry periods between?

ost evidence for stable liquid water requires that it was present efore ~3.6 Gyrs ago, in the Noachian:

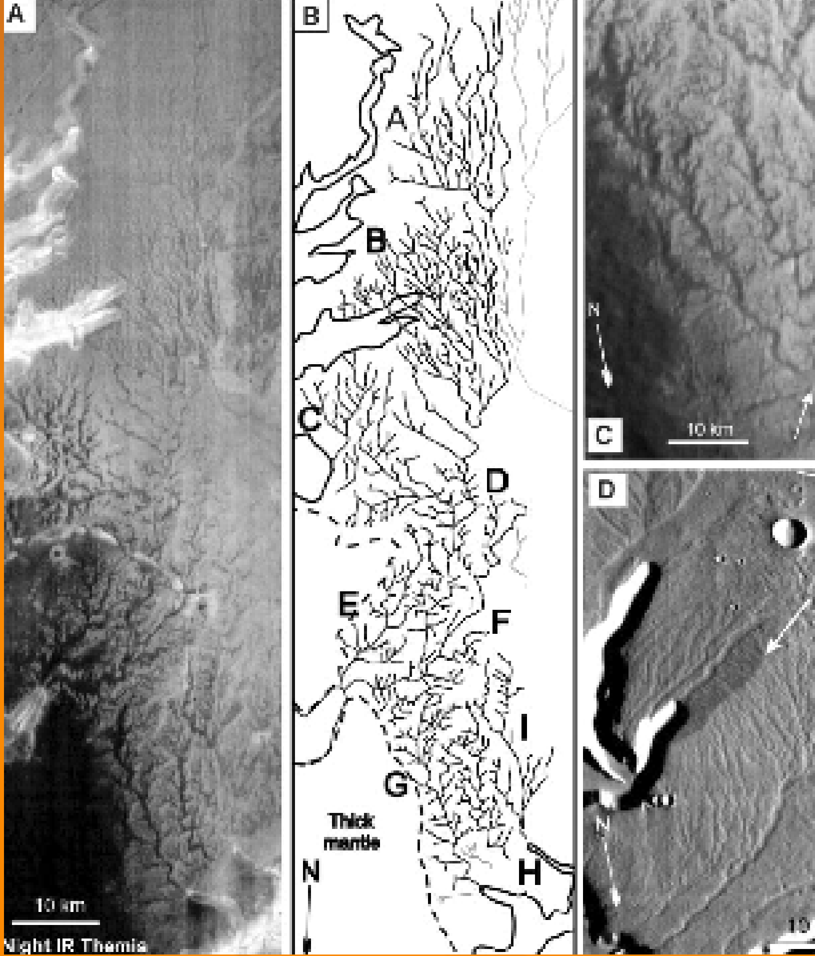
his is when most of the valley networks (possibly requiring recipitation and run-off) formed

he loss of a thick atmosphere at the end of the Noachian would also xplain a sudden decline in erosion rates at that point, which we see by:

- the far more eroded appearance of craters in Noachian surfaces tha in newer terrain, even accounting for age differences
- the lack of smaller craters in such regions (which have been eroded completely)

lowever, there is increasing evidence hat stable liquid water (including recipitation, run-off and gradual roduction of e.g. valley networks) vas present more recently than the Noachian (~3.6 Gyrs ago)

or example, the valley network to he right *(see yesterday's talk!)* is nconsistent with e.g. sub-surface eepage due to hydrothermal activity, ut lies on a surface dating from the ate Hesperian (~2.9-3.4 Gyrs ago)



Mangold et al. Science 200

o some way of making/keeping Mars warm later in its history vould explain this and other evidence

The episodic inundation hypothesis ***<u>proposes</u>*** that:

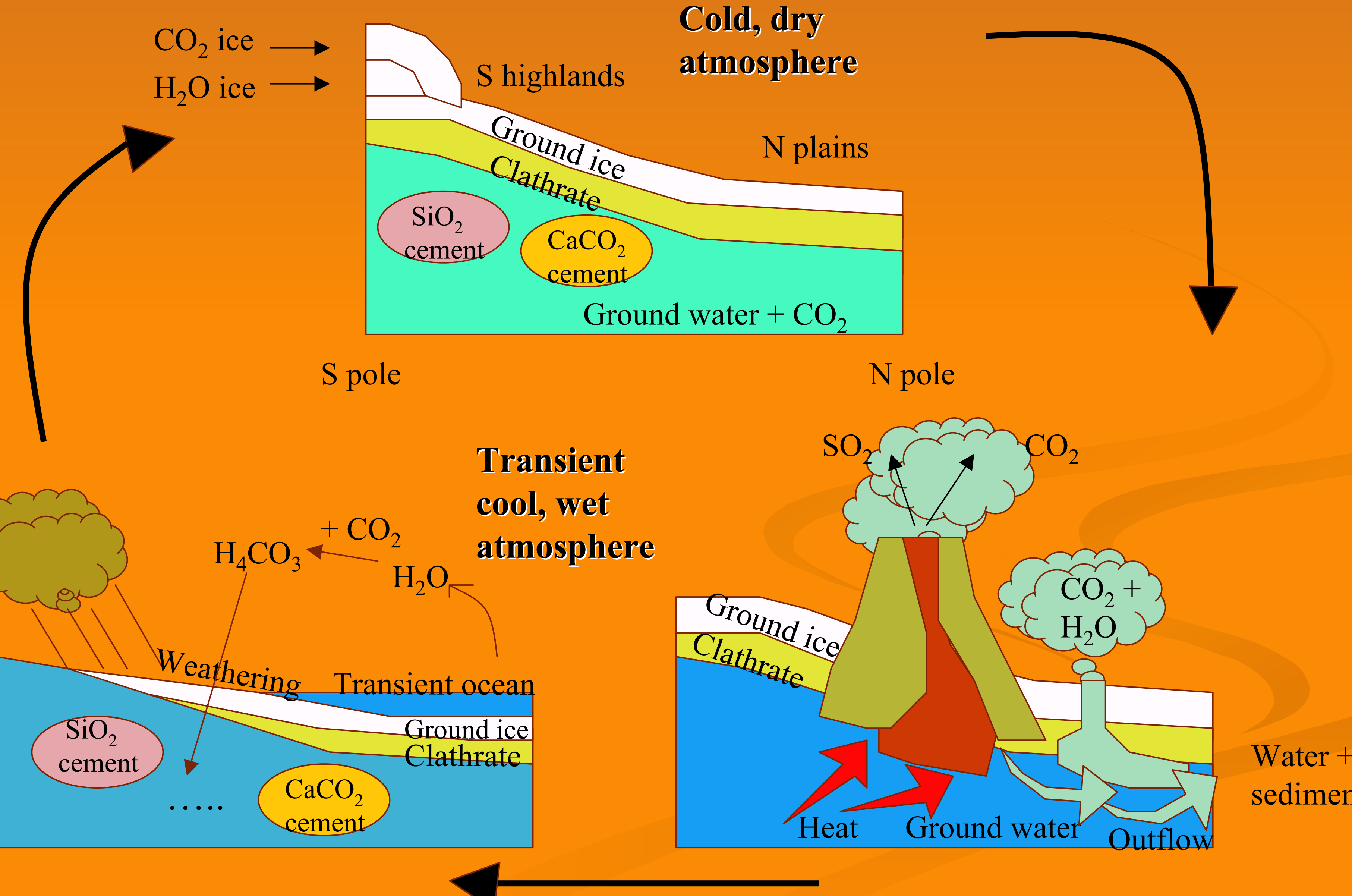
he outflow channels formed during episodes of massive heating and utgassing, which produced the necessary quantities of liquid water but lso enough CO_2 and other gases to produce a large greenhouse effect

his allowed oceans of stable liquid water to form within the northern lains, producing shorelines and other features associated with liquid ater

his means that several ‘warm, wet’ Mars episodes would have occurre ince the Noachian

ut the proposed ‘shorelines’ vary significantly in height, and much of he other evidence can be explained by the existence of frozen oceans in hese drainage regions, which don’t require a climate different to today’

Episodic inundation hypothesis



Cold, dry atmosphere

CO_2 ice

H_2O ice

S highlands

Ground ice

Clathrate

N plains

SiO_2 cement

$CaCO_2$ cement

Ground water + CO_2

S pole

N pole

Transient cool, wet atmosphere

SO_2

CO_2

Ground ice

Clathrate

CO_2 + H_2O

Heat

Ground water

Outflow

Water +
sedimen

H_4CO_3

+ CO_2

H_2O

Weathering

Transient ocean

Ground ice

Clathrate

SiO_2 cement

$CaCO_2$ cement

.....

Adapted from Baker Nature 200

Unknowns

- Amount of liquid water which was released, when it was released and for how long

- **How the thicker, warmer atmosphere required was produced (how sufficient greenhouse gases got into the atmosphere**

- Where all of the water is now

- What happened to the thicker atmosphere

How big a ‘greenhouse’ effect was needed?

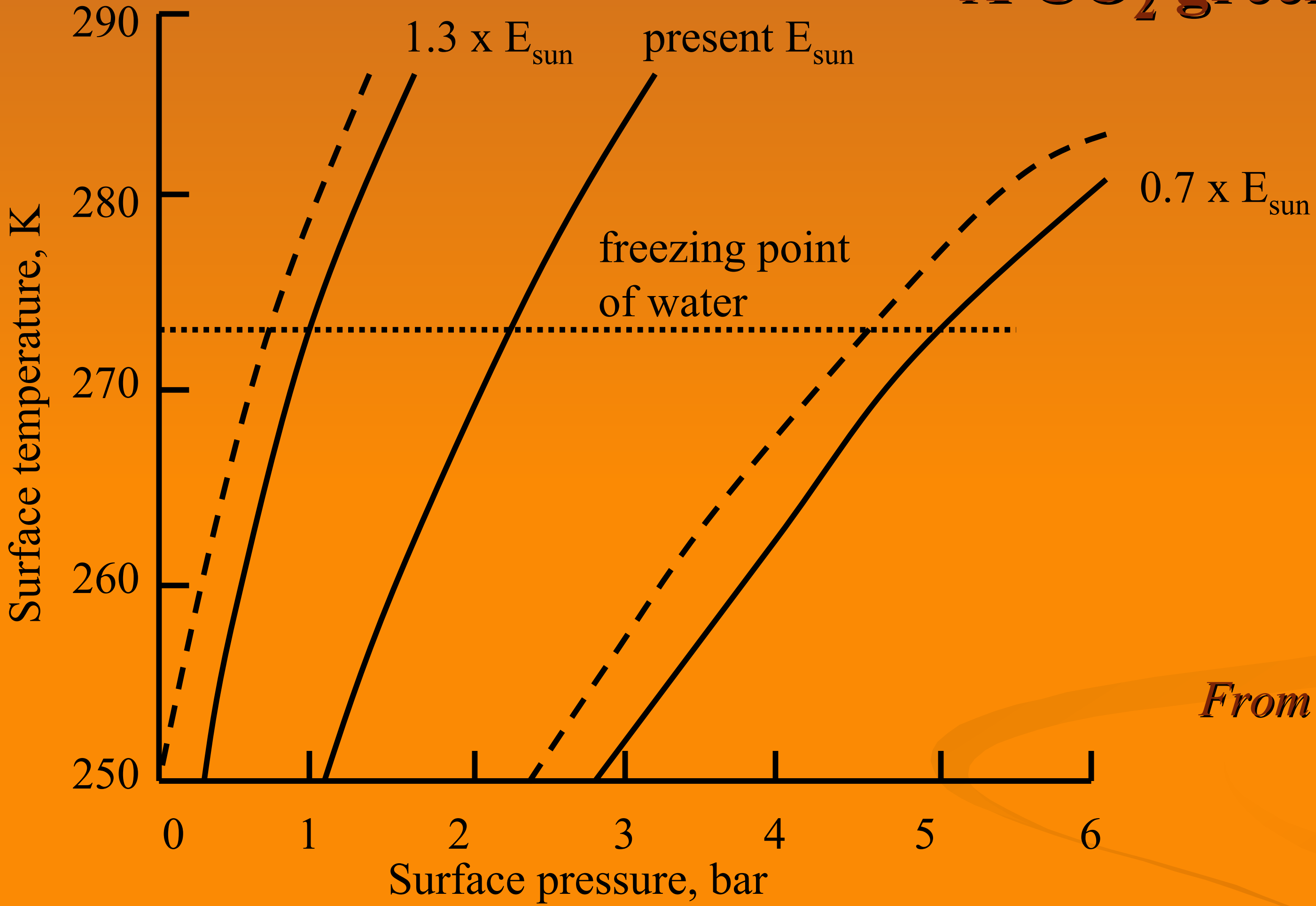
sing calculations like those shown earlier, and the known absorption oefficients of CO_2 and other greenhouse gases, we can estimate the mounts required to raise the surface temperature of Mars above 273K

further problem, however, is that the young Sun is estimated to have een ~25% dimmer ~3.8Gyrs ago - its output has increased over time

his is known as the ‘faint young Sun’ ***problem*** because an even ***bigger*** reenhouse effect is required to produce the ***same*** surface temperatures n early Mars (>~3.6 Gyrs ago), and this is ***just*** when a warm, wet limate is most needed to explain the observations

odels typically find a CO_2 atmosphere of ~2-5 bars was needed for urface temperatures > 273K, allowing stable liquid water at the surface

A CO_2 greenhouse



Dashed lines assume lower albedo (= 0.1), solid lines use current value

From Pollack et al. 198

raph shows results from a radiative-convective model which doesn't nclude CO_2 cloud formation; it has since been argued that clouds would

) Form in sufficient amounts to prevent enough solar radiation reaching the surface, => T=273 K could never have been reached

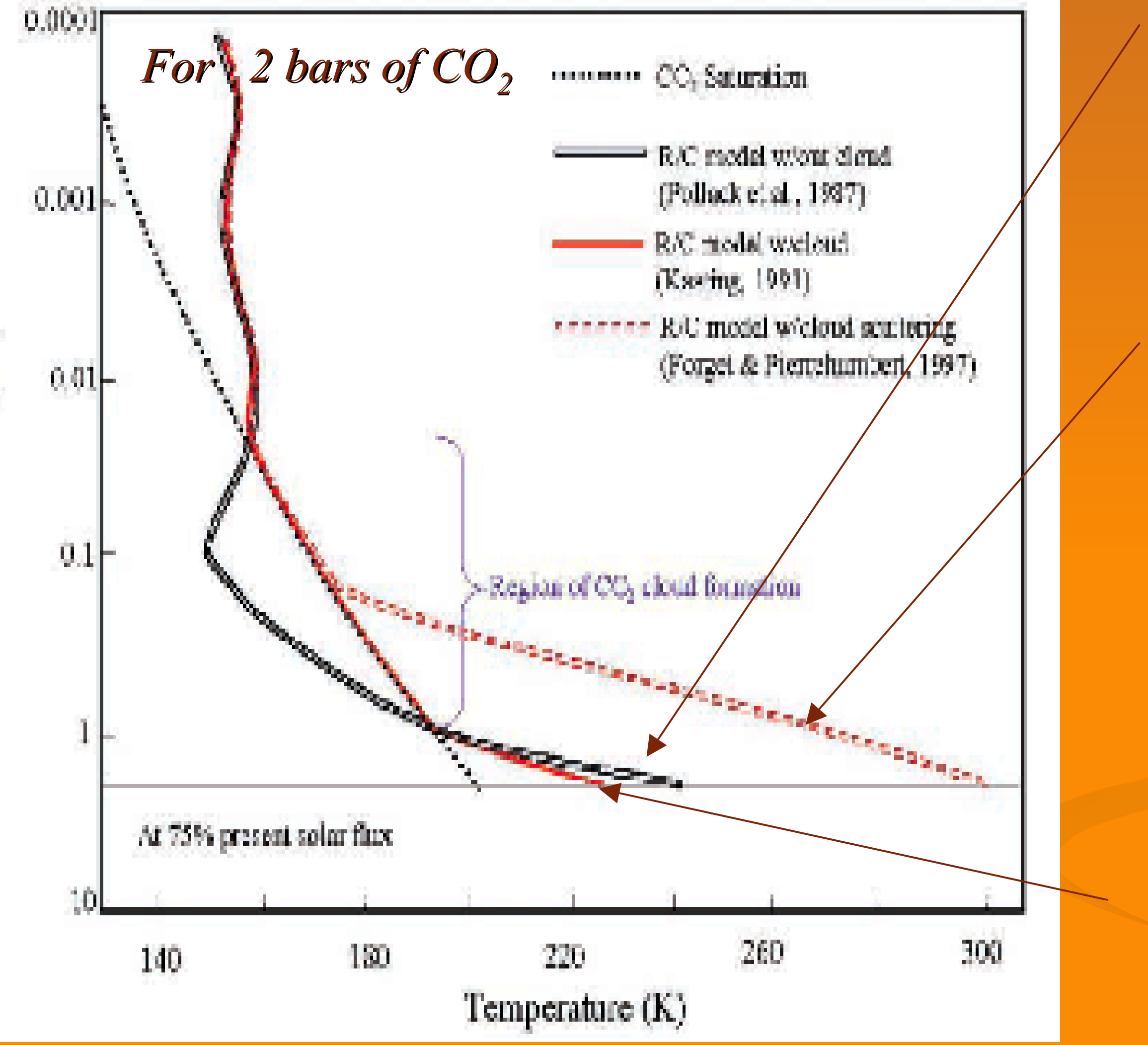
) Add to the surface heating via downward longwave scattering => would *increase* greenhouse effect

) Heat the atmosphere via latent heat release and radiatively, thus be self-limiting => ?

) Possibly have minimal effect if particle sizes etc. are modeled consistently => no impact

?!?

For 2 bars of CO_2



From Colaprete and Toon JGR 2003

a) No clouds

c) Clouds which now warm surface via longwave scattering - but only if high - same clouds lower found to cool surface (d)!

b) Follow moist CO_2 lapse rate => warmer atmosphere, cooler surface, and at ~1.5 bars reach point where more CO_2 added condenses ou

Unknowns

Amount of liquid water which was released, when it was released and for how long

How the thicker, warmer atmosphere required was produced (how sufficient greenhouse gases got into the atmosphere)

Where all of the water is now

What happened to the thicker atmosphere

Some important processes

pper atmosphere loss mechanisms - all referentially lose lighter isotopes

hermal Jeans) scape

Hydrodynamic escape - most important in early Noachian

Atmospheric sputtering - most important after loss of magnetic field

Dissociative recombination

Impact erosion / delivery - most important in the Noachian

Loss to the surface

nly light onstituents ost

Allow loss of heavy constituents, not just light

E.g. as subsurfac ice

Where the water went

I_2O exists on Mars today as surface ice (mostly at the poles) or as ubsurface ice / hydrated minerals (seen by Mars Odyssey)

Vater has also been lost to space via the processes just shown:

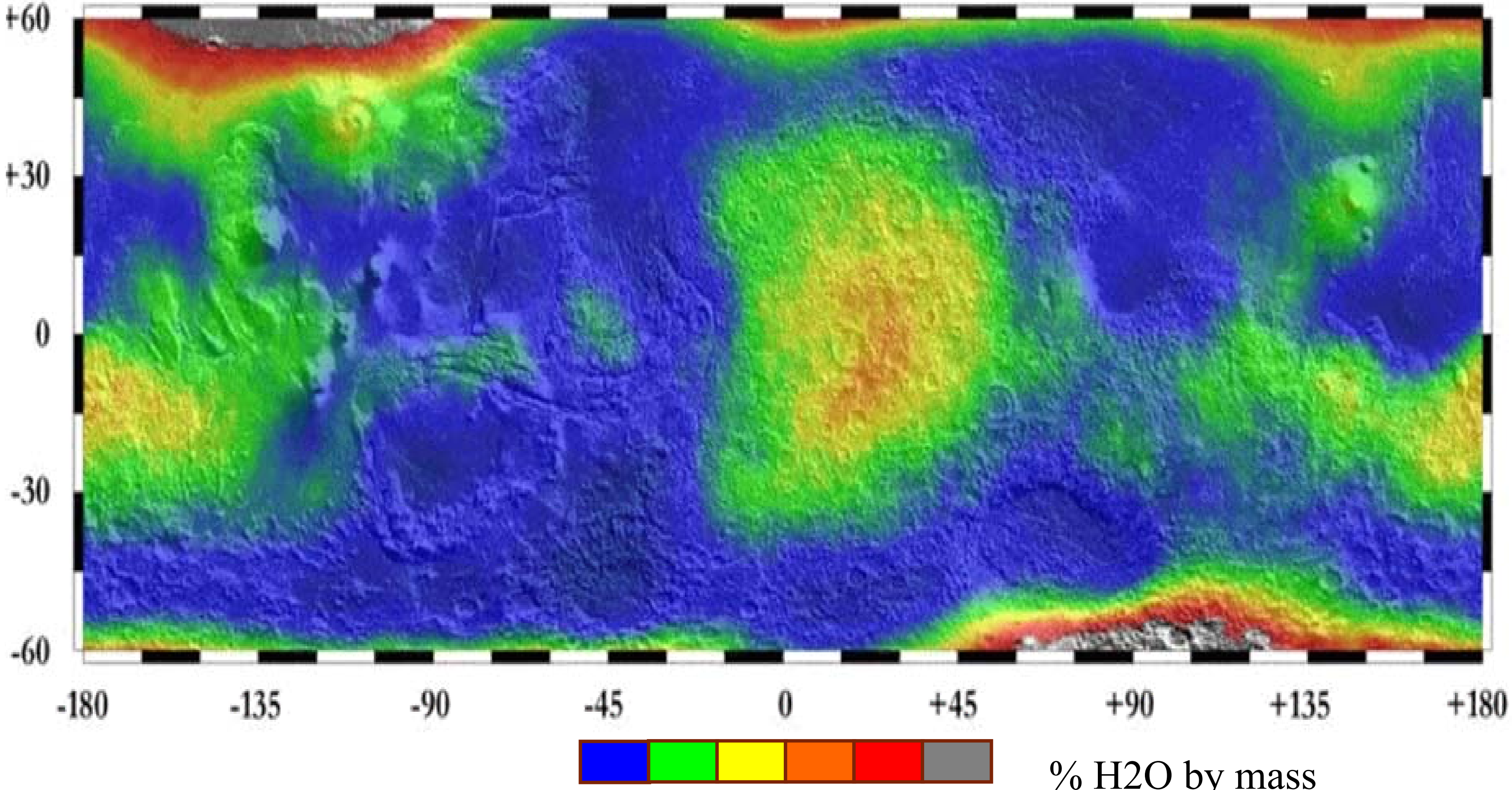
- impact erosion, which does not affect isotope ratios, would probably have dominated early on (in the Noachian)
- sputtering, which *does* affect isotope ratios (as do other upper atmosphere loss processes), would probably have been important after the magnetic field shut down (~ the end of the Noachian)

he D/H ratio on Mars today is ~5 x that on Earth, and depends on:

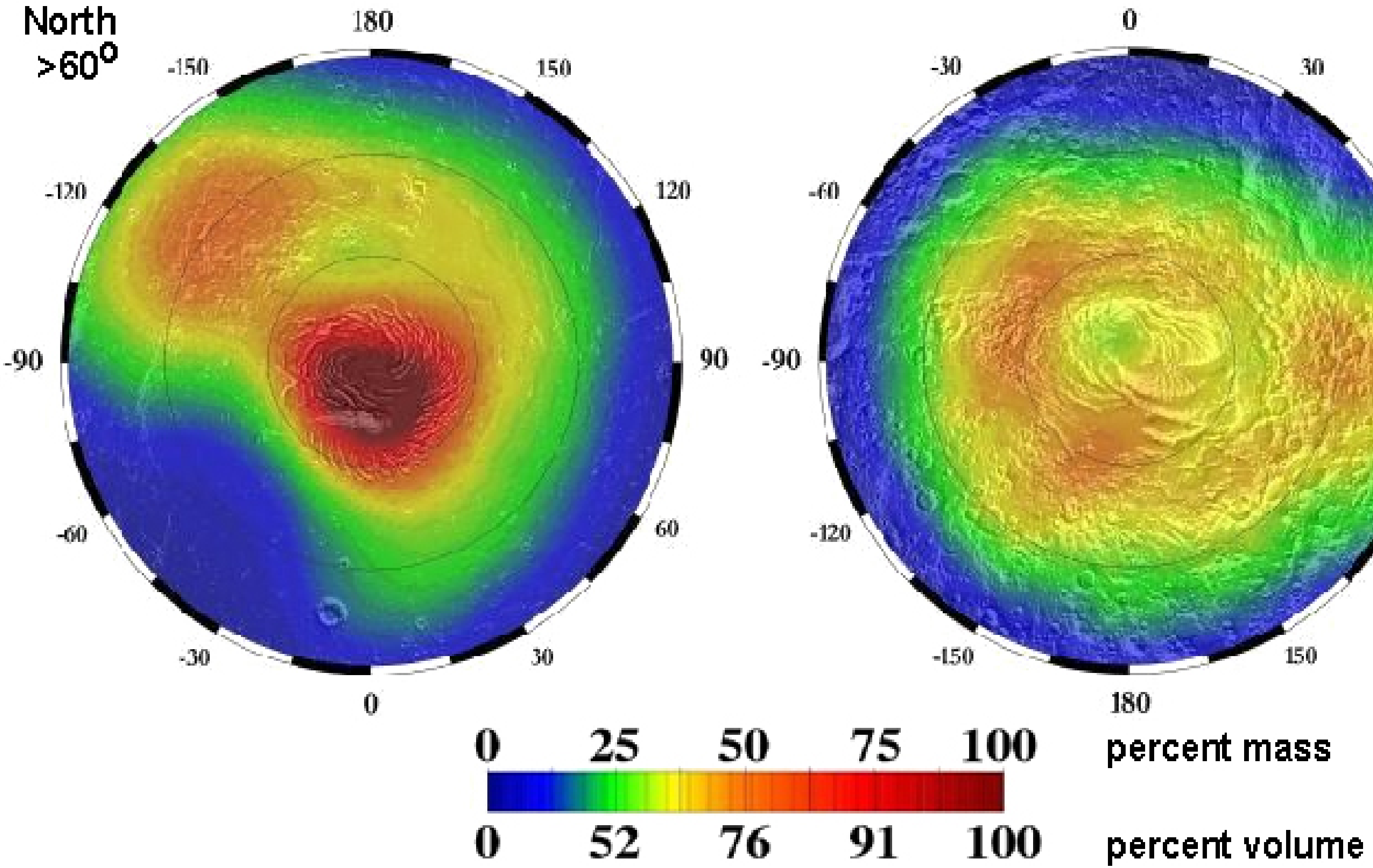
- the initial D/H ratio on Mars
- the relative amounts of each isotope reaching the upper atmosphere
- the relative loss rates of each isotope (depending on e.g. the efficiency of the escape process and time for diffusive separation)

ecent estimates based on this suggest that over two thirds of Mars' vater inventory have been lost to space

Odyssey Neutron Spectrometer Results



Odyssey Neutron Spectrometer Results



Unknowns

Amount of liquid water which was released, when it was released and for how long

How the thicker, warmer atmosphere required was produced (how sufficient greenhouse gases got into the atmosphere)

Where all of the water is now

What happened to the thicker atmosphere

Where the greenhouse gases went

- Harder than explaining where the water went is explaining where the hicker atmosphere required to raise Mars's surface temperature has gon
- CO_2 probably formed most of it, so substantial amounts should still be resent somewhere on Mars
- ome lost to space via impact erosion (more so earlier on), atmospheric puttering (since magnetic field turned off) or dissociative recombination
- The polar caps hold some, and perhaps 0.3 bar is held in the regolith as dsorbate, while CO_2 ice in the regolith is unlikely
- f liquid water existed on the surface below a CO_2 atmosphere, there hould have been significant aqueous production of carbonates - yet bservations *to date* only appear to account for a small fraction

Some important processes

pper atmosphere loss mechanisms - all referentially lose lighter isotopes

hermal Jeans) scape

Hydro-dynamic escape - most important in early Noachian

Atmospheric sputtering - most important after loss of magnetic field

Disso-ciative recom-bination

Impact erosion / delivery - most important in the Noachian

Loss to the surface

nly light onstituents ost

Allow loss of heavy constituents, not just light

E.g. by carbonate formation

Loss to the surface

n the presence of liquid water CO_2 will dissolve to form carbonic cid, which will then react with the surface (chemical weathering)

verall reactions are of the type:

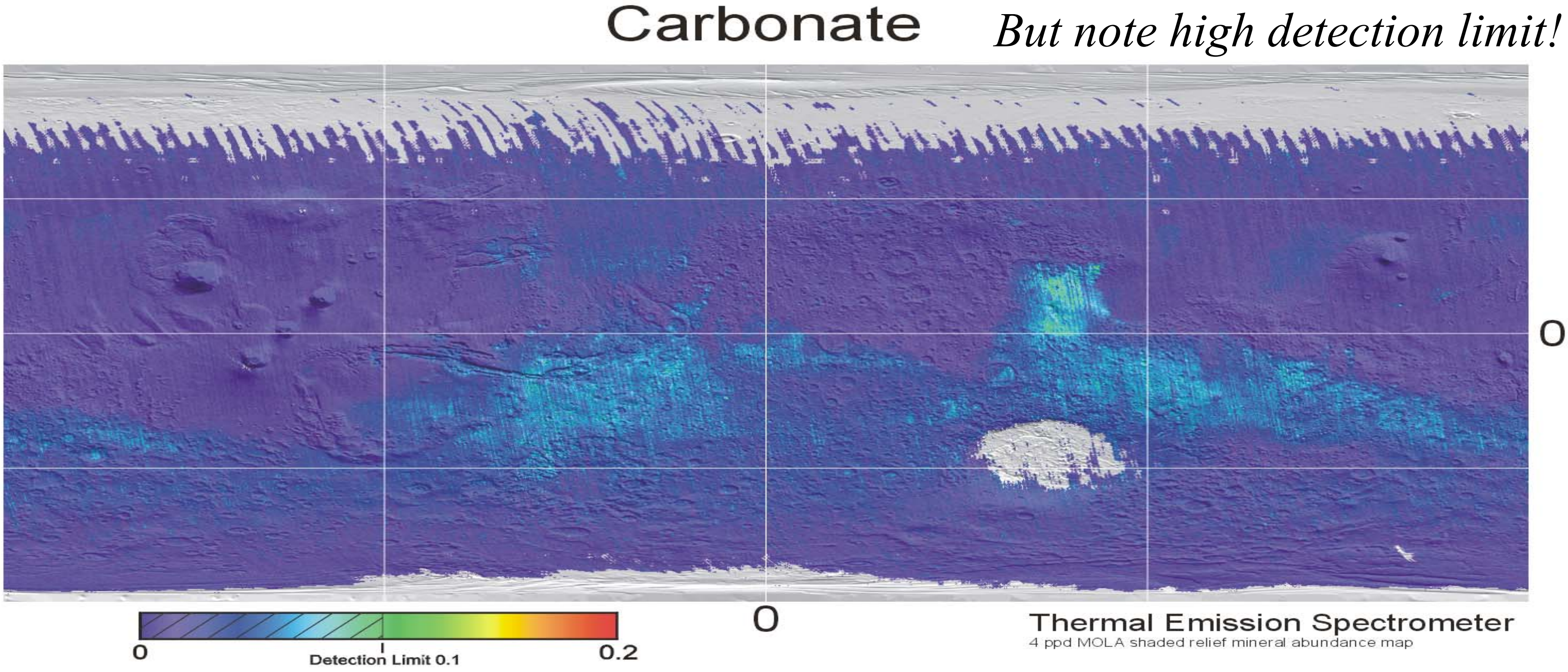
$CO_2 + CaSiO_3 = CaCO_3 + SiO_2$,

ith quantities of carbonates such as calcite ($CaCO_3$), siderite FeCO$_3$) and magnesite ($MgCO_3$) being produced in this way - ***if one are detected, this suggests more CO_2 is lost to space than to the urface***

B - the weathering lifetime of a massive CO_2 atmosphere is expected be so short that some recycling mechanism would be needed to ustain it, e.g. thermal decomposition by volcanism

Carbonate detection (just) on Mars

But note high detection limit!



•Expect to detect carbonates formed via aqueous weathering if formed in presence of large bodies of water

•CO_2 also lost via dissociation and loss to space
•CO_2 also stored as adsorbate in regolith and as ice

The timing is also important:

- lose the atmosphere too early (via impact erosion before the end of the Noachian) and there may not be enough for a warm, wet Mars to be maintained as long as necessary

- lose the atmosphere too late, and it’s hard to get rid of it all by the present day, certainly not without forming even *more* carbonates yet to be detected

Summary 1 - the present climate

The current Martian climate is most variable in southern spring/summer, when dust levels vary most

The source of dust storm variability is probably intrinsic atmospheric variability, which has a big impact for threshold-sensitive wind stress lifting with strong positive feedbacks, and rearrangement of surface dust deposits

Variability in the present water cycle is mostly due to changes in temperature, circulation and availability of condensation nuclei (for ice formation) due to changes in dust distribution

There may be also be variability in the water cycle if the permanent CO_2 south polar cap (which generally acts as a cold sink) disappears in some years

Summary 2a - climate change due to orbital variations - *low* obliquity

- As obliquity decreases, weaker circulations and wind stress lifting are produced, but dust devil lifting is less affected, and polar dust deposition rates may even increase slightly between 25 and 15 degrees

- CO_2 residual caps form at both poles (which have lower maximum annual temperatures), and for the lowest obliquities become rapidly thicker than at present, causing a decrease in atmospheric pressure

Summary 2b - climate change due to orbital variations - *high* obliquity

As obliquity increases, stronger circulations and dust storms are produced, and polar dust deposition rates are larger

No permanent CO_2 caps exist, but atmospheric pressure probably does not increase - huge seasonal caps form at the winter pole, and even if CO_2 desorbs from the warmer high latitude regolith, more is adsorbed at lower latitudes

Water ice becomes stable at low latitudes, where the maximum temperatures reached in summer are now lower than at the poles (so ice formed at the coldest times is lost less rapidly)

Surface [***sub-surface***] ice accumulates preferentially in high [***low***] thermal inertia regions

Summary 3 - the climate of early Mars

- Evidence suggests at least some period (most likely during the Noachian to early Hesperian, > ~3.7 Gyrs ago) when liquid water was *stable* on Mars's surface
- This requires a warmer mean surface temperature (> 273K) than today, which probably required a much thicker atmosphere to create a strong enough 'greenhouse effect' (particularly as the Sun is thought to have been ~25% fainter then)
- CO_2 outgassed during early strong volcanism is the main contender, with an estimated 2-5 bars being required

Summary 3 - the climate of early Mars (continued)

Later evidence of stable, liquid water conditions seems to suggest episodic warmer, wetter conditions more recently in Mars's past, with recycling of CO_2 between the surface and atmosphere to go from 'cold and dry' to 'cool and wet', though much of the evidence can also be explained in other ways

But even ignoring this, there is a major problem in explaining any 'warm, wet' period - while it seems possible to get rid of the water which was present, it is hard to get rid of the amount of CO_2 required - much of it could (and should) have been placed in the surface via chemical weathering, but we have not detected enough (as yet?)

A *short* list of suggested reading

Carr, M. H., “Water on Mars”, Oxford University Press, New York, 1996.

Pollack, J. B., J. F. Kasting, S. M. Richardson and K. Poliakoff, The case fo
a warm, wet climate on early Mars, Icarus, 71, 203-224, 1987.

Haberle, R. M., Early Mars climate models, JGR, 103, 28,467-28480, 1998.

Mars review articles in Nature vol. 412, no. 6843, July 2001.

Newman, C. E., S. R. Lewis, P. L. Read and F. Forget, Modeling the Martia
dust cycle, 2: Multi-annual radiatively active dust transport simulations, JGR
107, E12, 5124, doi:10.1029/2002JE001920, 2002.

Colaprete, A. and O. B. Toon, Carbon dioxide clouds in an early dense
Martian atmosphere, JGR, 108, E4, 5025, doi:10.1029/2002JE001967, 200

Mischna, M. A., M. I. Richardson, R. J. Wilson and D. J. McCleese, On the orbital forcing of Martian water and CO_2 cycles: A general circulation model study with simplified volatile schemes, JGR, 108, E6, 5062, doi:10.1029/2003JE002051, 2003.