GFDL Mars General Circulation Model

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Topics

Traveling waves climatology. These are associated with pre- and post-solstice dust activity that is evidently a prominent feature of the Mars dust cycle.

MGS Dust "Assimilation" Experiments
Force a Mars GCM with the evolving column opacity field derived from the TES observations and MOC imagery. This allows a comparison of simulated temperatures with TES retrievals to explore the influence of the dust particle size spectrum and the effects of radiatively active water ice clouds…. and identify model biases.

Interactive dust cycle simulations with a finite dust reservoir. A MGCM implementation of the idealized modeling described by *Pankine and Ingersoll* [2002, 2004]. The surface stress lifting threshold varies as a function of surface dust availability, introducing a negative feedback that allows the surface/atmosphere system to self-organize and support interannual variability in major dust storm activity.

Impact of radiatively active water ice clouds

Some thoughts on Data Assimilation

High Resolution Simulations: A Global Mesoscale Model

GFDL Flexible Modeling System (FMS)

- *Selection of dynamical cores*

  *Spectral, B-Grid, Finite Volume**

  **lat-lon and cubed-sphere geometries*

- *Support for a range of very large multi-processor systems*

  NOAA's Gaea at Oak Ridge (Cray) , Argonne (IBM)

- *Modular physics parameterizations*

- *Diagnostics Manager*

  Can distribute model output to multiple output files from the run script; specify instantaneous, time averaged, min/max, diurnal composite with (hourly, daily….) sampling.

- *Tracer Manager*

  Can add, remove, characterize and initialize tracer fields from the run script

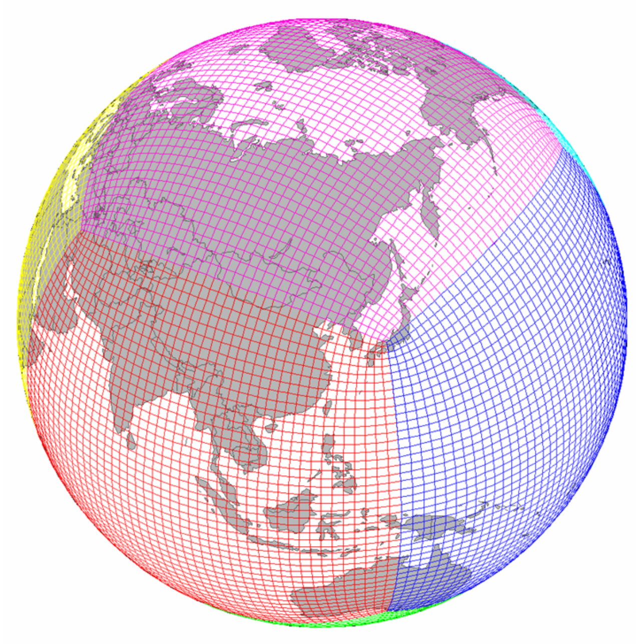
Finite Volume (FV) Model

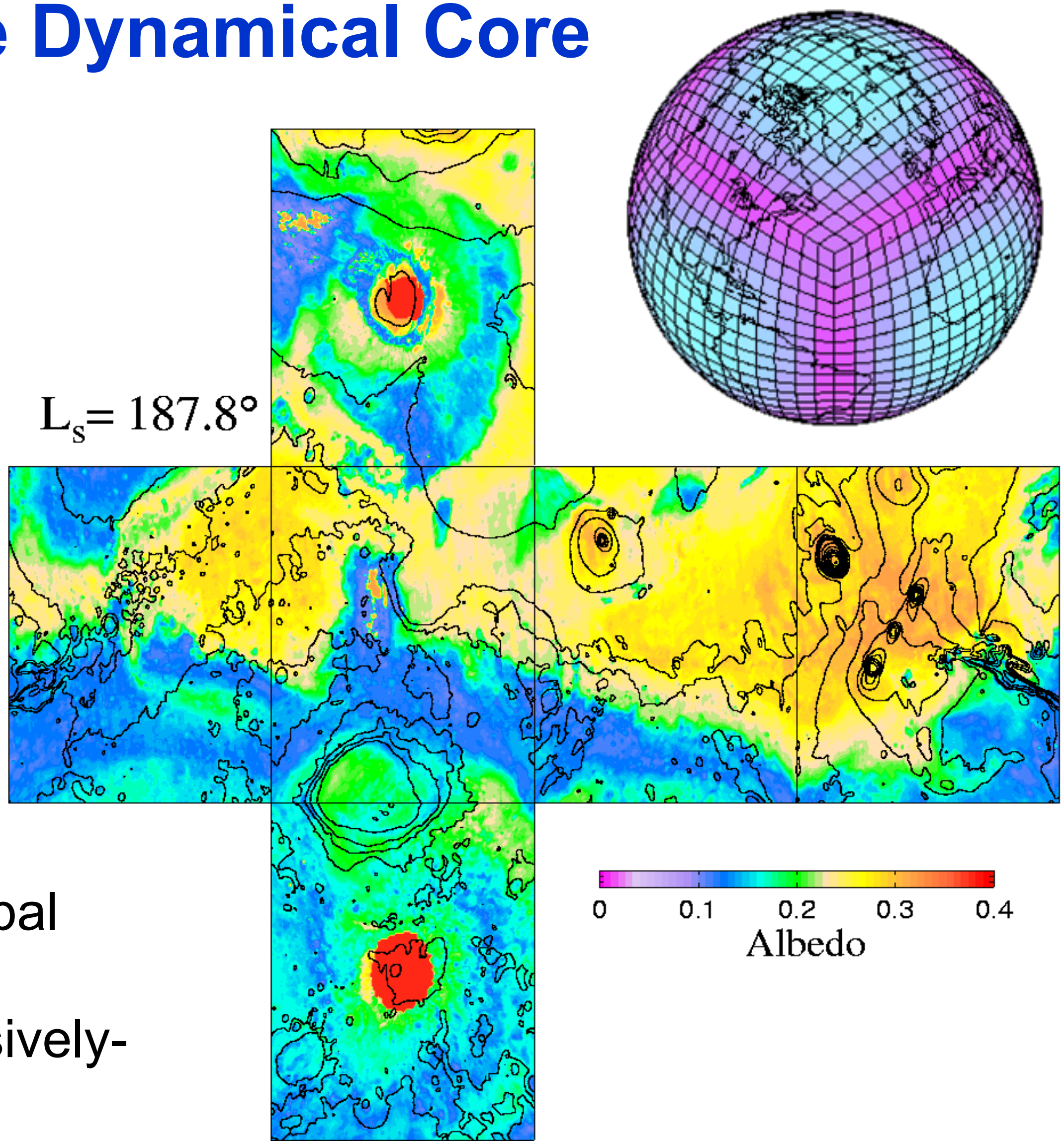
- Developed by Lin and Rood (1996), Lin and Rood (1997)
- 3D version available (Lin 2004), built upon the SW model:
- hydrostatic dynamical core used for climate and weather predictions
- Currently part of NCAR's, NASA's and GFDL's General Circulation Models

- **Numerics:** Finite volume approach
  - conservative and monotonic transport scheme
  - van Leer second order scheme for time-averaged numerical fluxes
  - PPM third order scheme (Piecewise Parabolic Method) for prognostic variables
  - Staggered grid (Arakawa D-grid), C-grid for mid-time levels
  - Orthogonal Latitude-Longitude computational grid

The importance of aerosols and tracers in climate evolution demands strictly conservative transport

Cubed-Sphere Dynamical Core



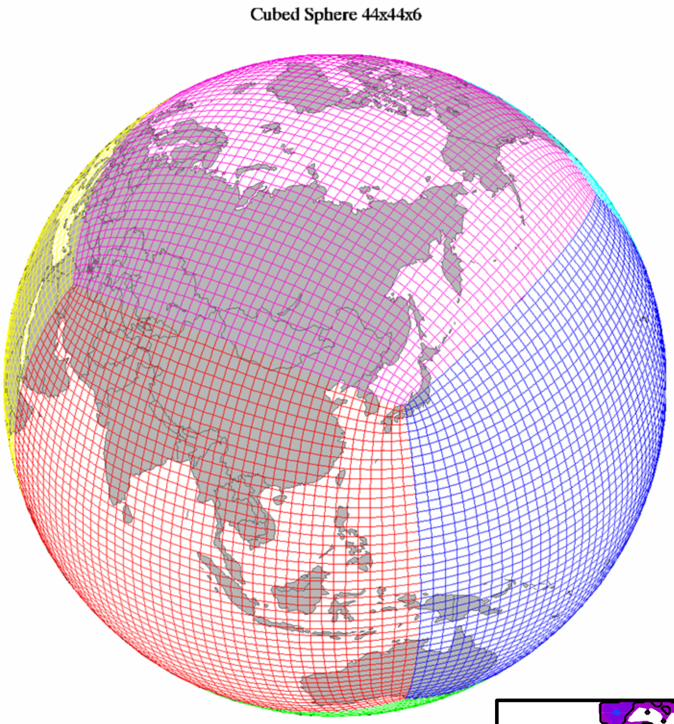


- Finite-Volume advection
- Provides relatively uniform global resolution
- Scales very efficiently on massively-parallel computer architectures

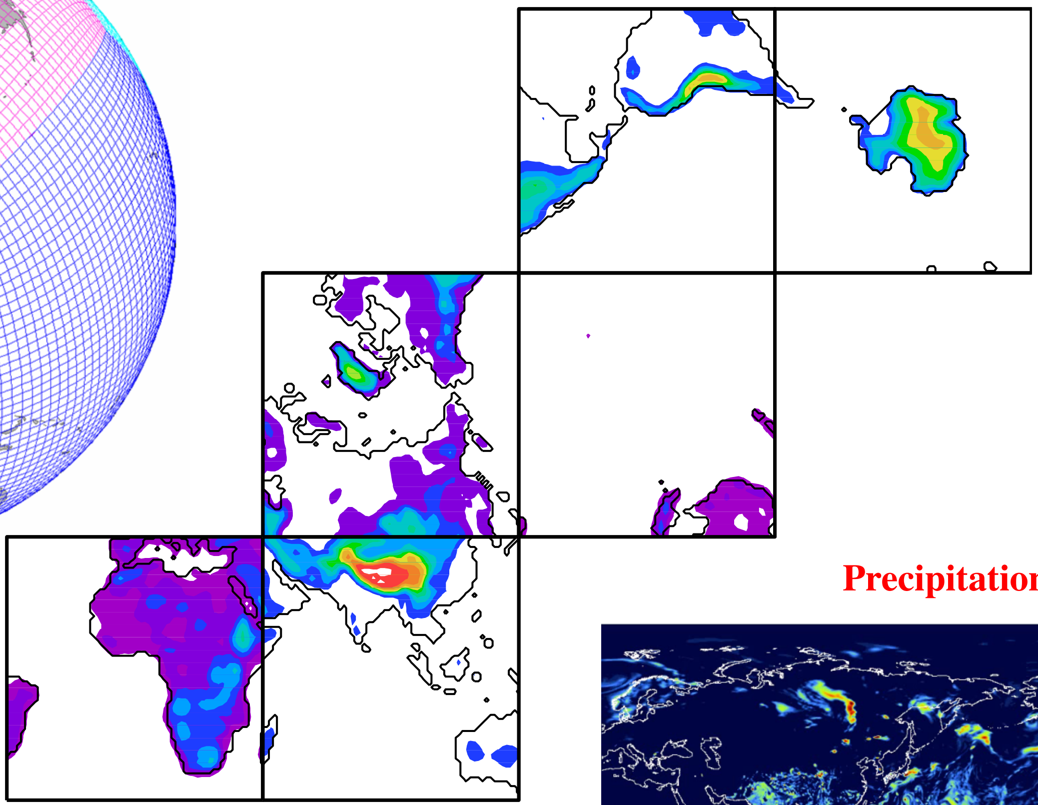
~ 15 km

C22: 4°×4°   C48: 2°×2°   C90: 1°×1°   C180: 0.5°×0.5°   C360: 0.25°×0.25°

3 ways to visualize the Cubed Sphere

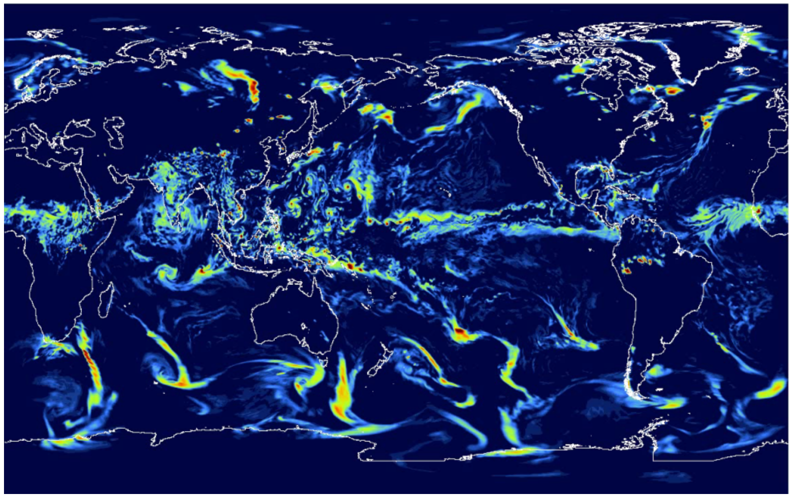


C48:
2°×2°



C360:
0.25°×0.25°

Precipitation: C360 HiRam-2



Cubed-Sphere Model Developments

2-way nested global/regional dynamical core

Transport of dust and volatiles on/off the polar caps

Dust lifting in selected regions

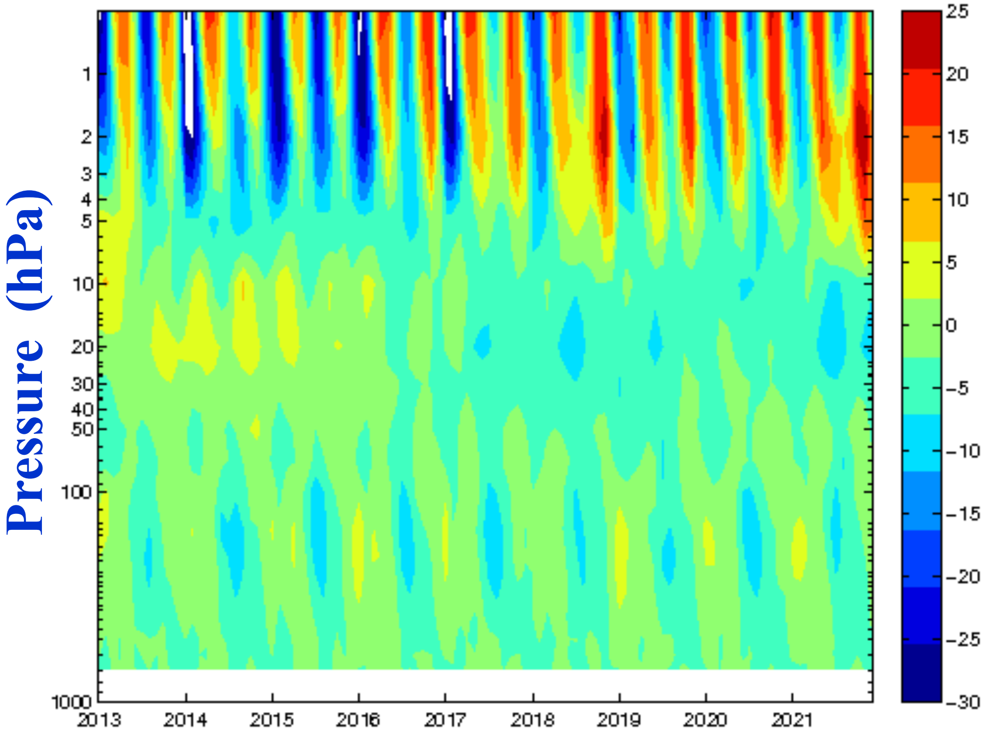
Non-hydrostatic dynamics

At what scales does this become significant?

Equatorial Zonal Wind Oscillations

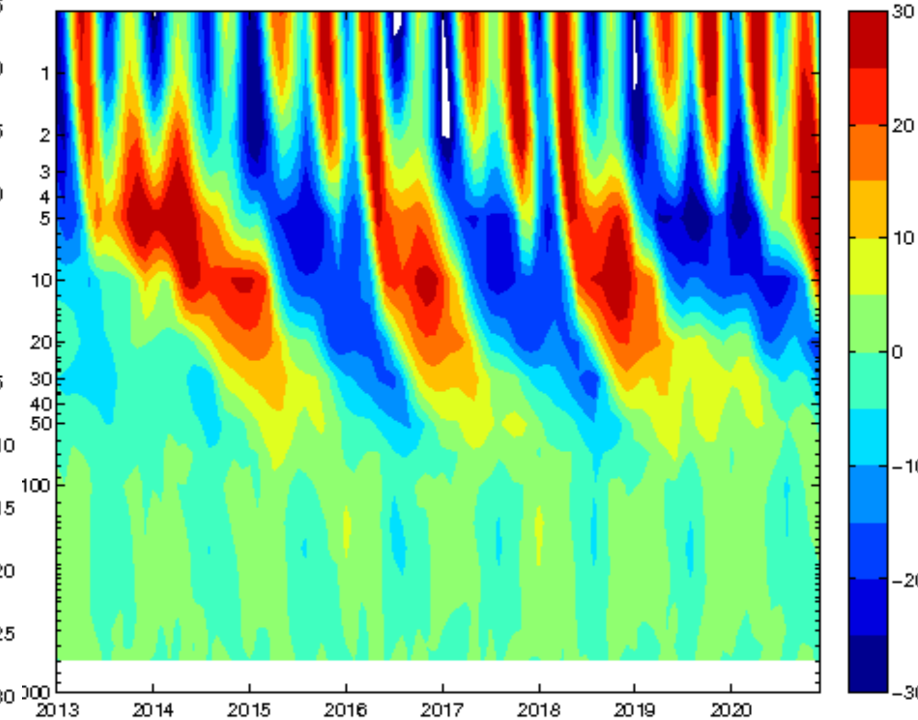
C360   0.25x0.25 resolution
Terrestrial Atmosphere; HiRAM physics

Hydrostatic Dynamics



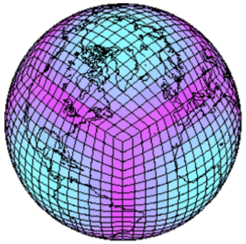
Years

Non-Hydrostatic Dynamics



Years

GFDL MGCM Description



- FV dynamical core with cubed-sphere geometry
- L28, L36, and L46 with a range of resolutions
- Radiation with interactive aerosol: 2 stream with correlated-k gaseous absorption (NASA/Ames)
- Full complement of physics: CO_2 & water cycles.
- A finite inventory of dust is maintained, partitioned between surface dust and aerosol.
- The stress threshold for dust lifting is allowed to vary with surface dust depth: The lifting threshold increases as dust is depleted from an initial depth that is spatially uniform
- Accumulated dust reflects seasonally integrated dust lifting and deposition; thus providing a memory of past lifting activity

Boundary Conditions

- Topography: MGS MOLA laser altimeter
- Surface Albedo: MGS TES broadband bolometer
- Surface IR emissivity: MGS TES
- Thermal inertia: Re-derived to allow the MGCM to closely match TES surface temperature (T_7, T_{20}) observations. 3-D field to allow for the effects of subsurface ice in the polar regions.
- Surface Roughness: (Hebrard et al. 2012, observed rock abundance)

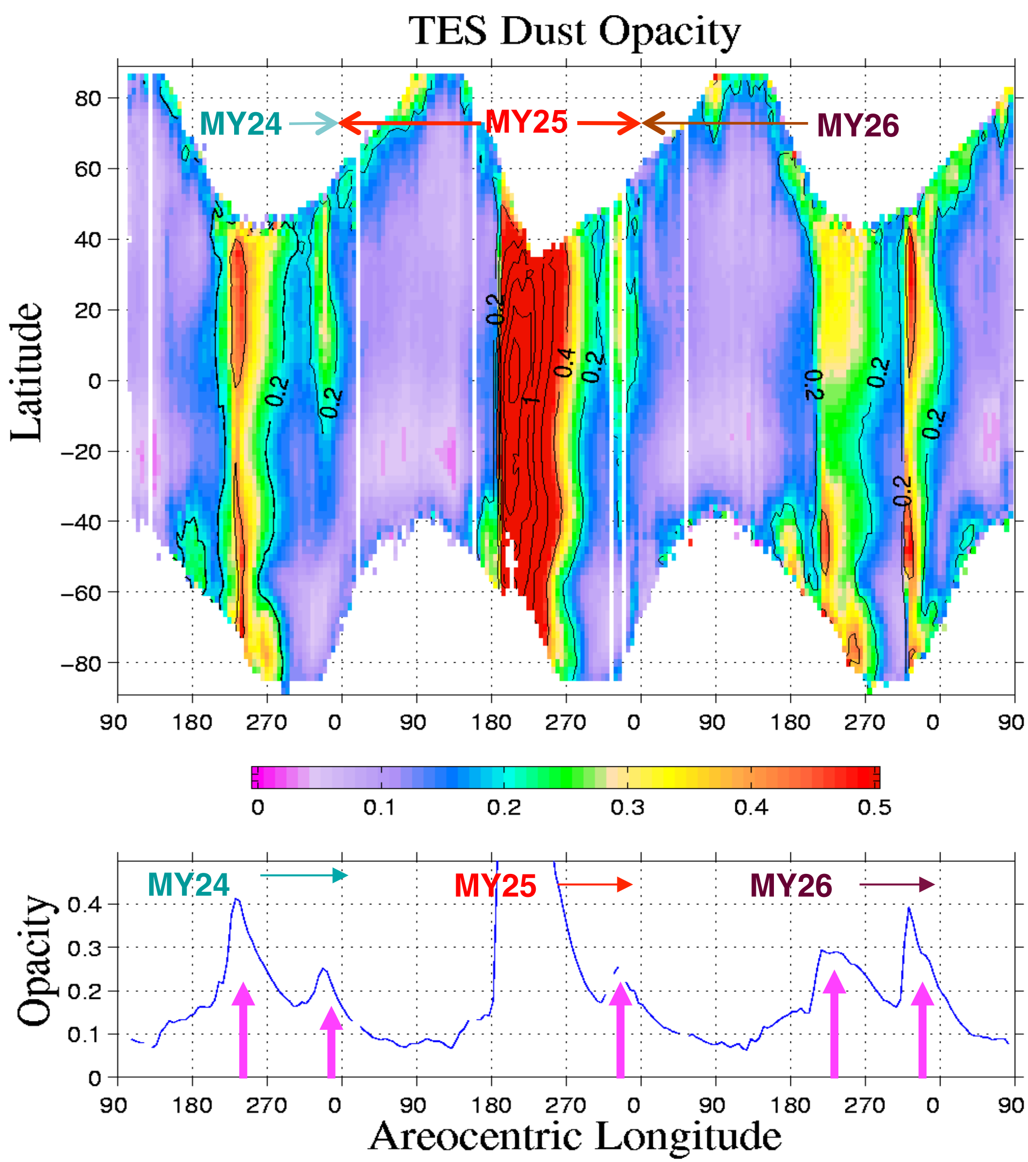
Optional Inputs

- Time-evolving column dust opacity: typically from TES
- Time-evolving maps for controlling dust injection:
  radiatively active or passive for tracing advection

MGCM Cubed-Sphere Configurations
Typical horizontal resolutions (L28)

$\Delta\varphi$ **x** $\Delta\lambda$	**Lat x Lon**		**Wall Clock**
C22: 4^{o} x 4^{o}	90x45		700 sols ~ 1.5 hours 24 CPUs
C36: 2.5^{o} x 2.5^{o}	144x72		700 sols ~ 1.5 hours 32 CPUs
C48: 2^{o} x 2^{o}	180x90		720 sols < 3.5 hours 54 CPUs
C90: 1^{o} x 1.0^{o}	288x180		160 sols < 6 hours 54 CPUs
C180: 0.5^{o} x 0.5^{o}	576x360		100 sols ~ 7.5 hours 96 CPUs
C360: 0.25^{o} x 0.25^{o}	1152x720		288 CPUs

Martian Dust Cycle



Mars Global Surveyor
3+ Years
- TES temperature and opacity retrievals
- Mars Orbiter Camera wide angle images

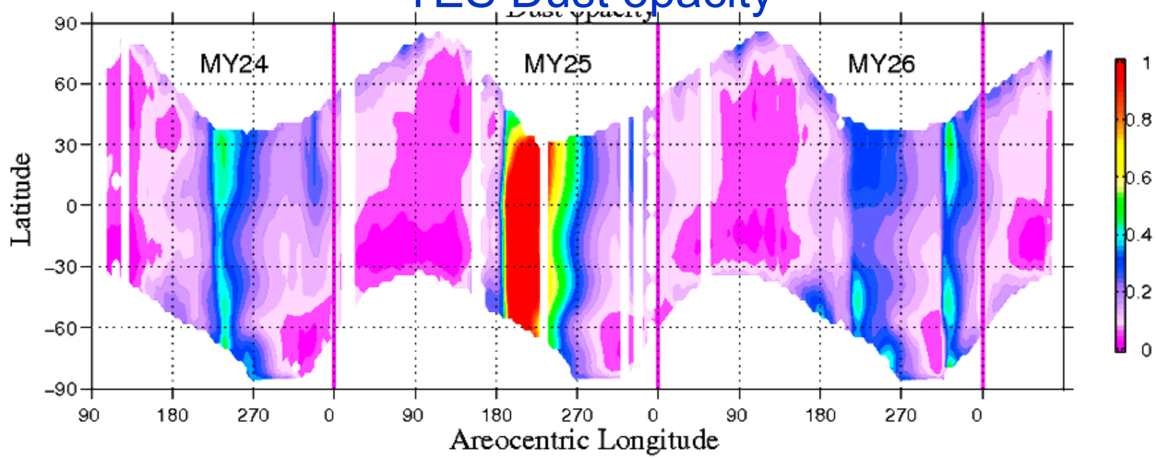
Flushing Storms

Pre solstice L_s= 210-240

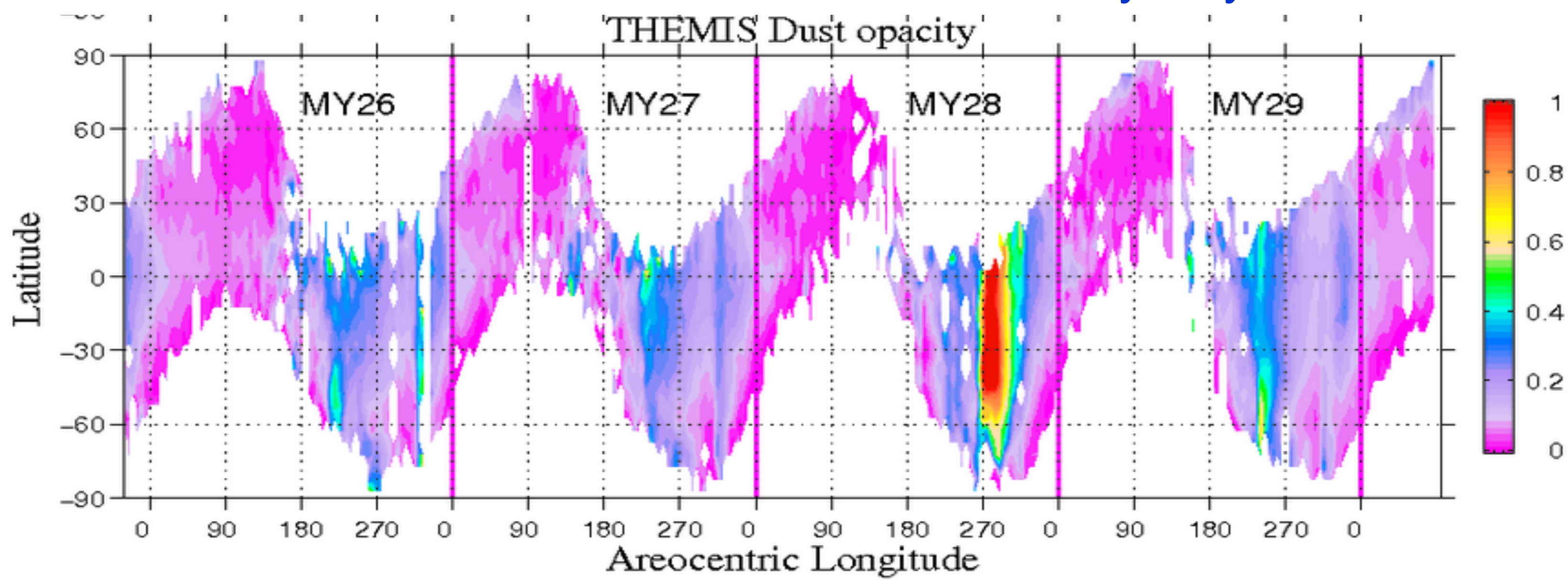
Post-solstice L_s= 310-350

a) The seasonal variation of zonally-averaged dust column opacity observed by TES for 3 Mars years (MY24 into MY27). (b) The variation of tropical opacity. The 2001 global dust storm occurs at L_s=187 in MY25. The 5 opacity peaks indicated by arrows are associated with “flushing” storm events. Data provided by M.D. Smith

TES Dust opacity



Mars Odyssey: THEMIS

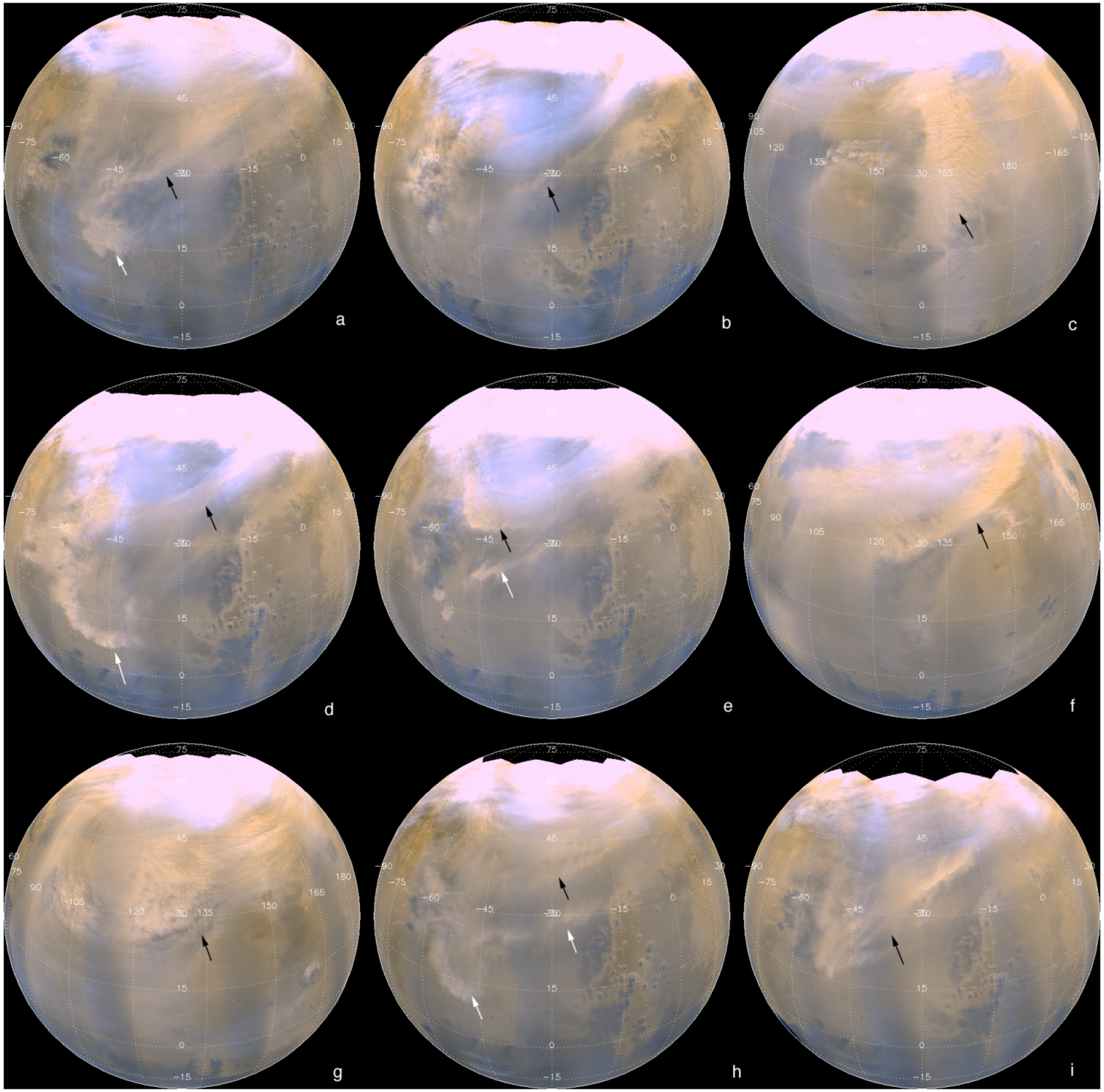


- Continued pattern of pre- and post-solstice storms in MY27 and MY29
- Solstice storm in MY28 in 2007 (first since MY21 Ls~250)

Data provided by Michael Smith

Flushing Storms

Mars Orbiter Camera (MOC)



AR: Arcadia
AC: Acidalia
UT: Utoptia

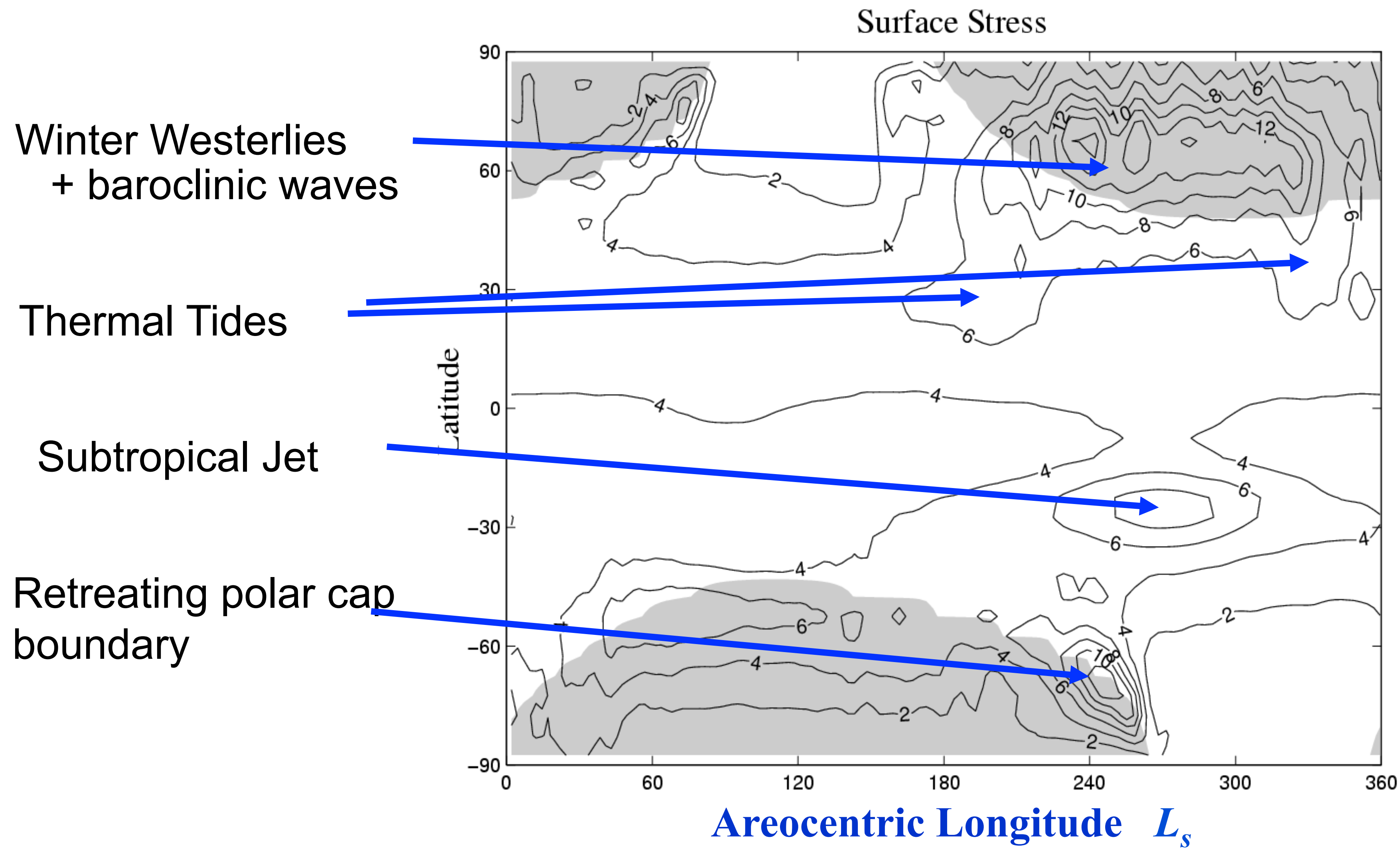
MY24: L_s 210 314 336
AC AC AR

MY25: L_s 316 324 324
AC AC UT

MY26: L_s 207 214 230
UT AC AC

Wang et al. 2005

MGCM Simulation of Zonal Mean Surface Stress

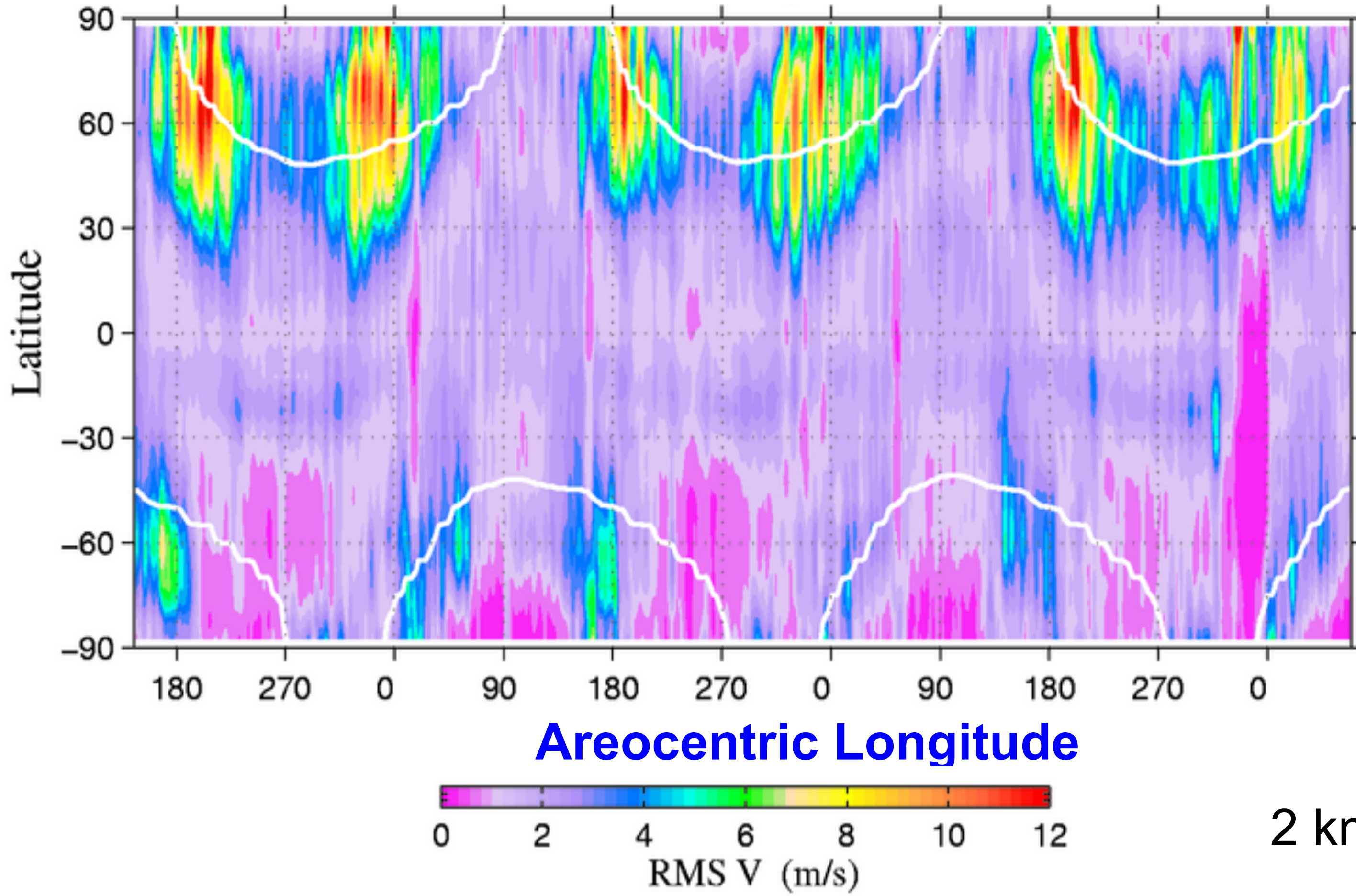


Polar CO_2 caps are shaded

Units: 10^{-3} Nm^{-2}

Zonally-averaged eddy rms V

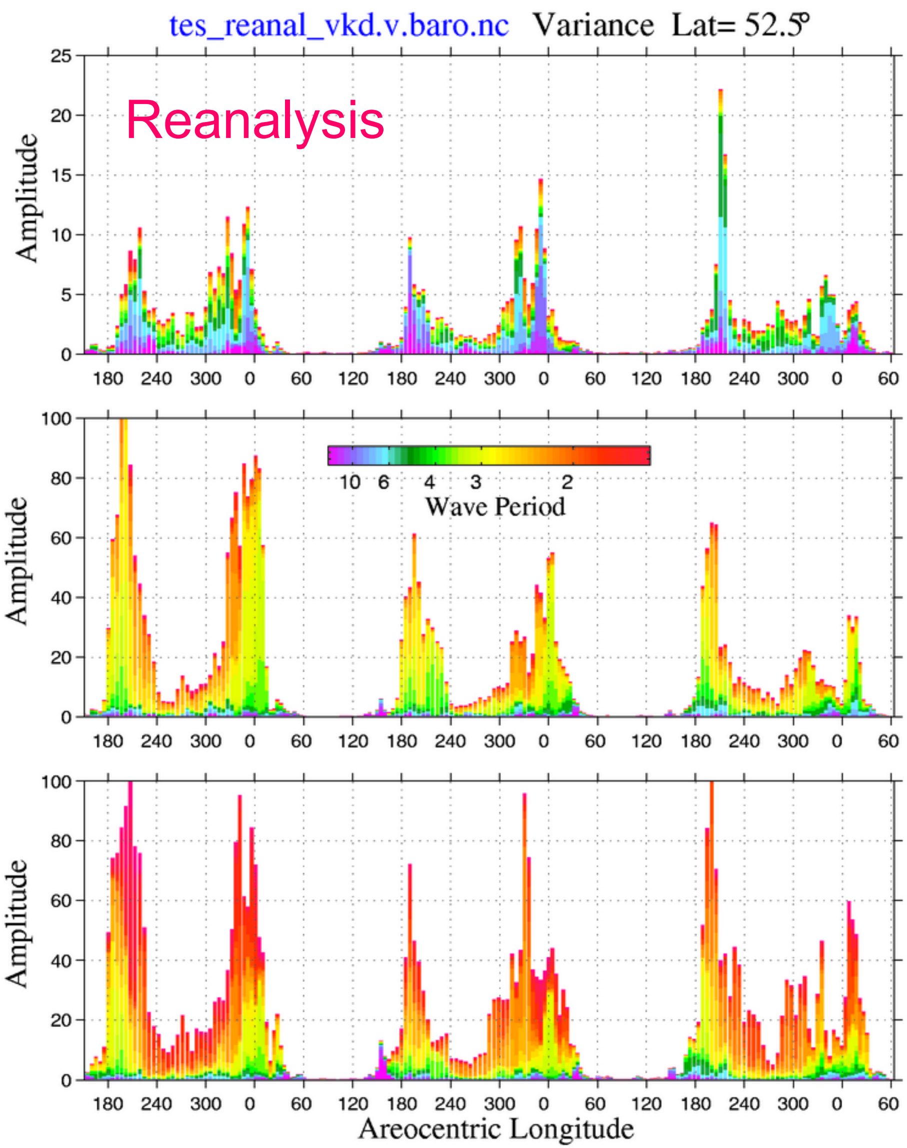
UK Assimilation of TES temperatures from the MGS mission

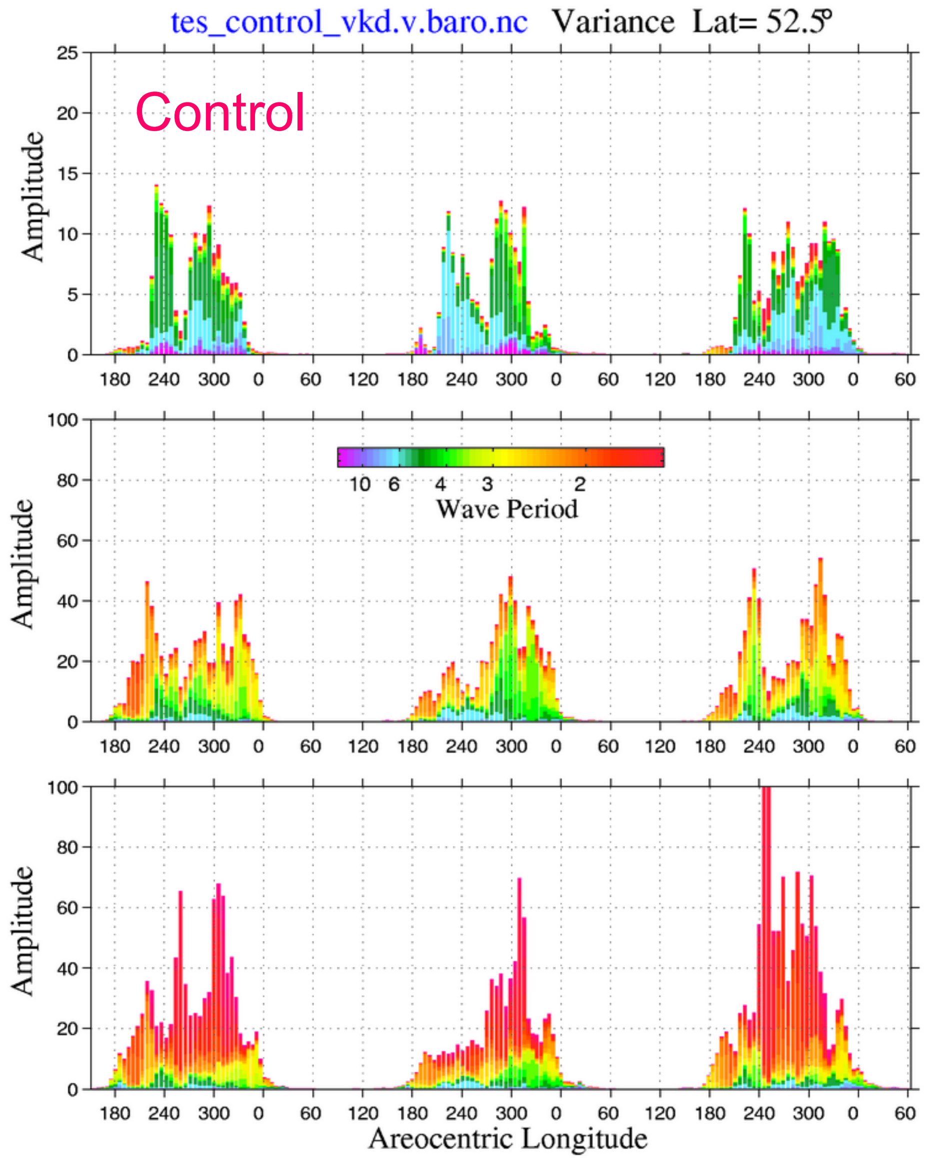


2 km agl

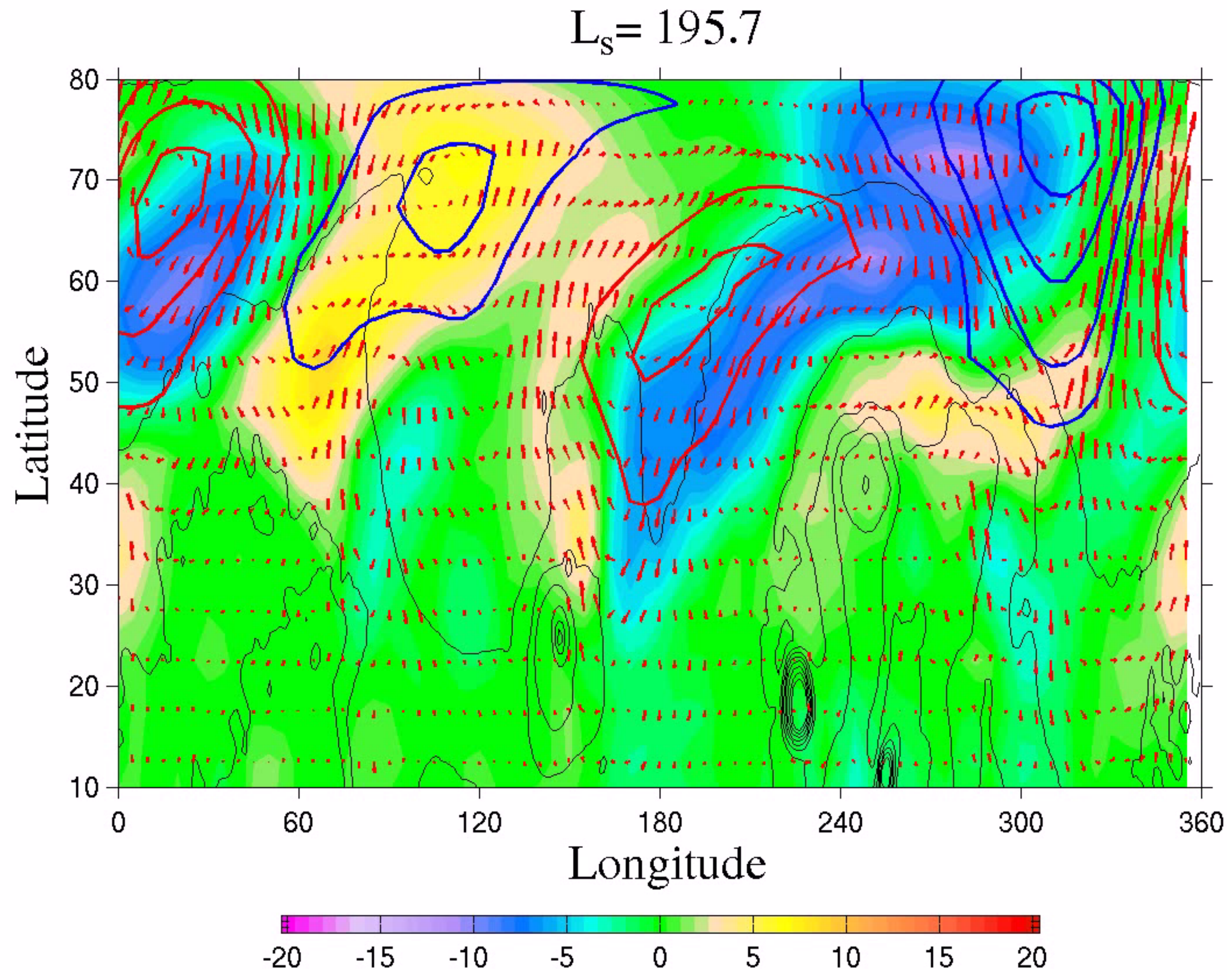
Seasonal evolution of the zonally-averaged eddy V variance (bandpass filtered 1.5-20 sols) at ~ 2 km above ground level. Units are ms^{-1}.

Eddy Meridional Velocity Variance   52.5 N



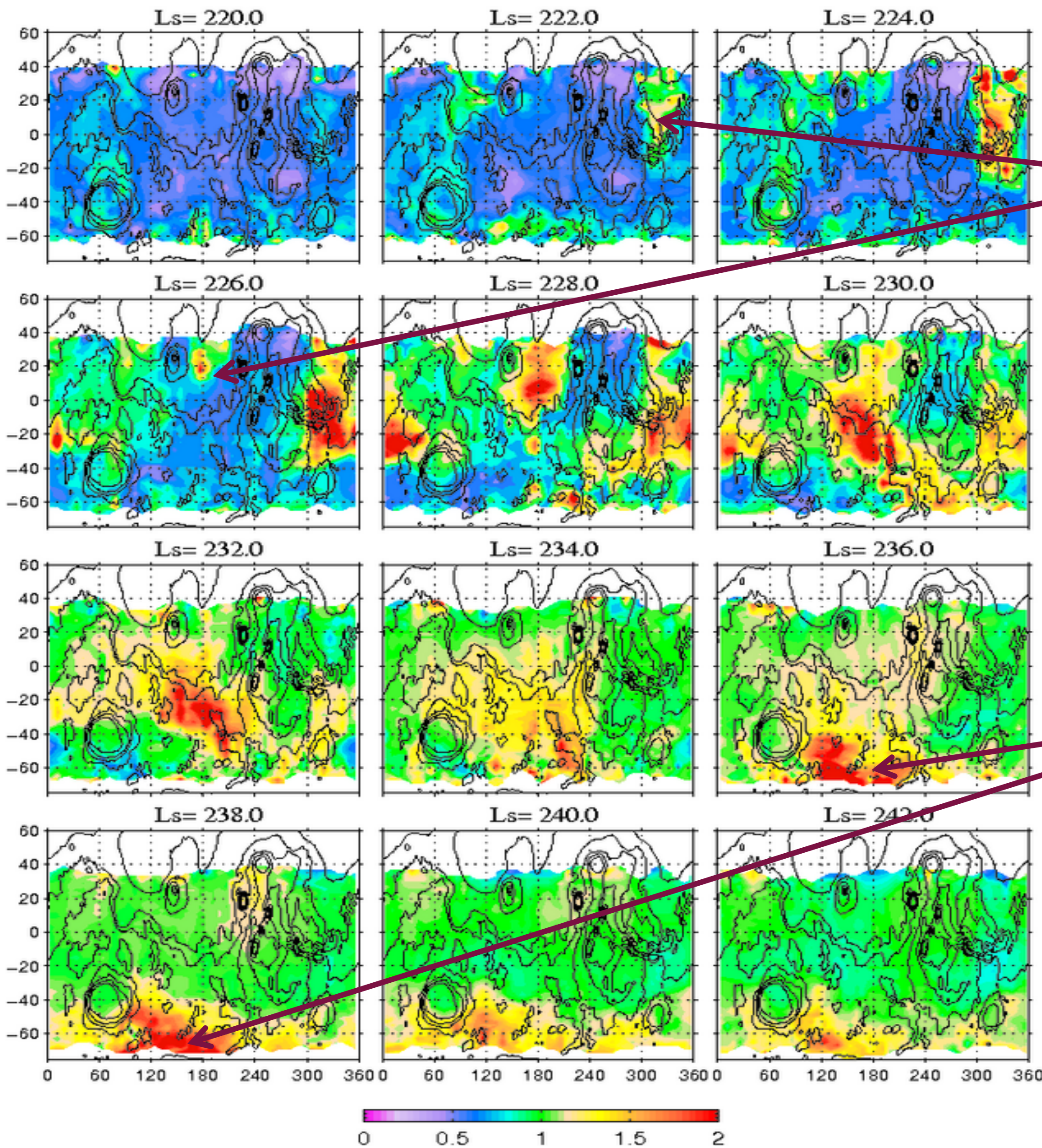


Traveling Waves in MY24 UK Reanalysis (MACDA)



MY24 Dust Column Opacity Evolution

L_s= 220 - 242°

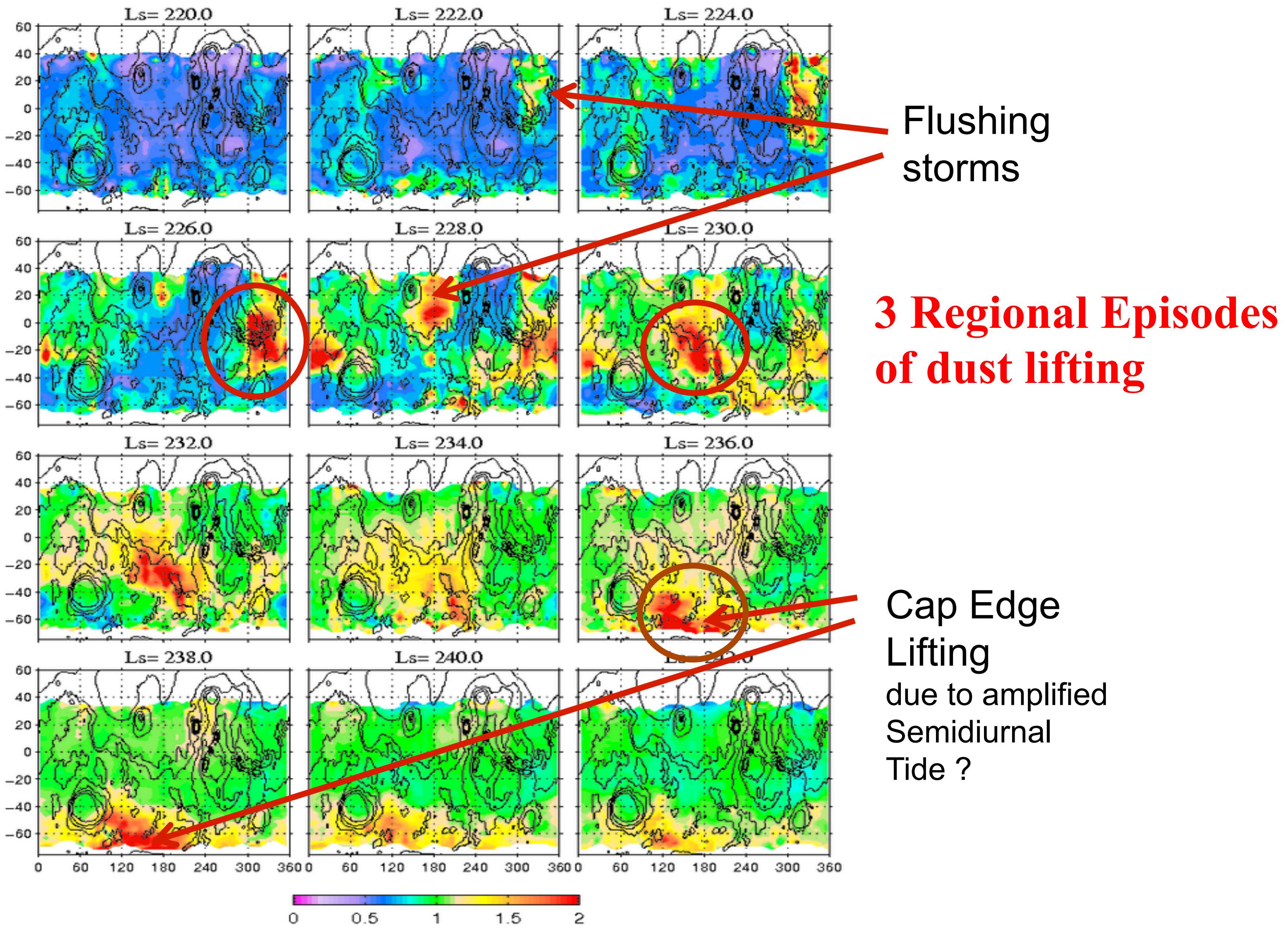


Flushing storms

Cap Edge Lifting
due to amplified Semidiurnal Tide ?

MY24 Dust Column Opacity Evolution

L_s= 220 - 242°



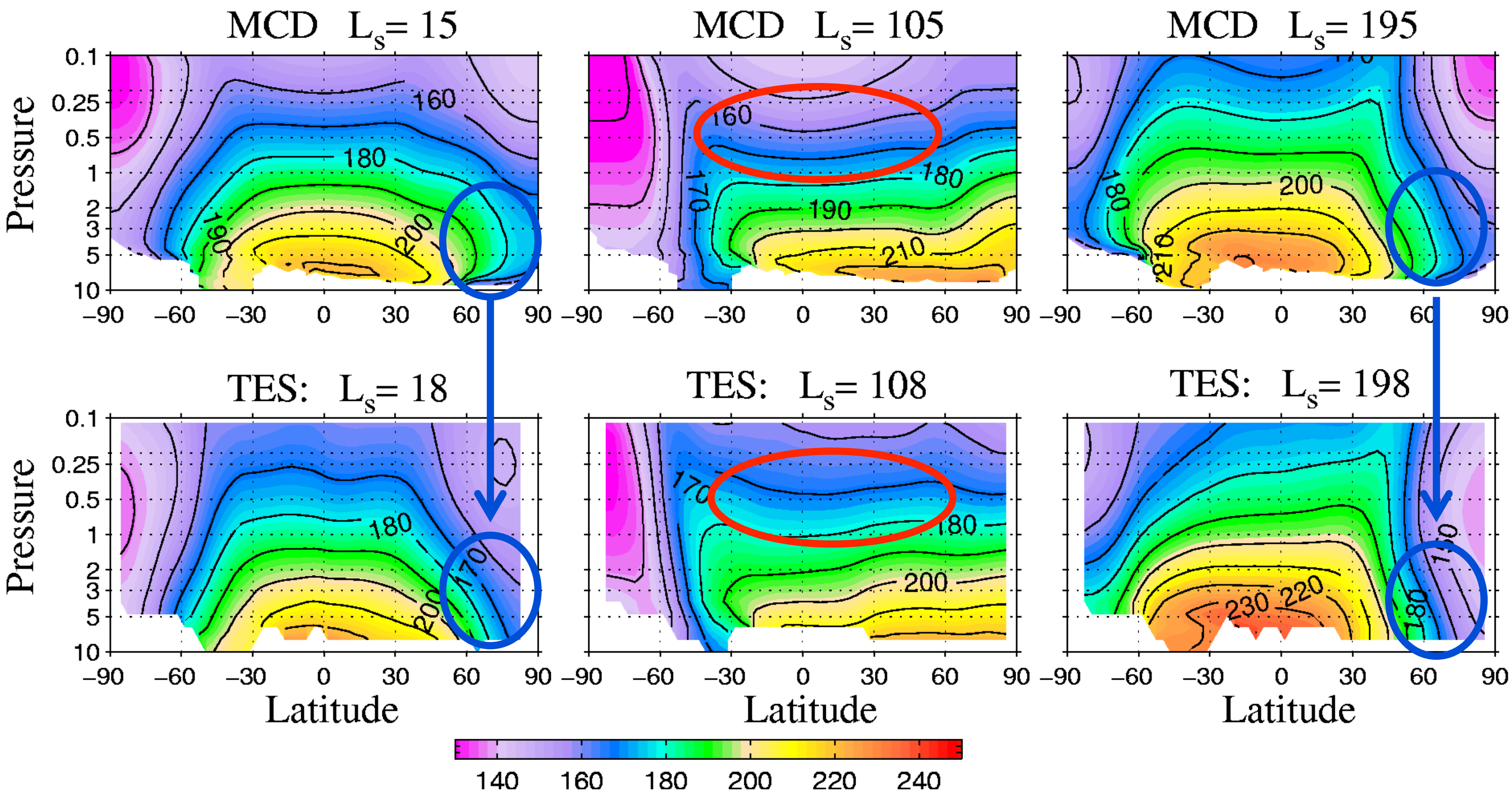
Mars Water Cycle and Water Ice Clouds

Important Radiative effects of water ice clouds:

Tropical Clouds: Net Heating due to absorption of upwelling IR radiation from the relatively hot surface
Intensified Hadley circulation in the upper atmosphere
Stronger forcing of thermal tides

Polar Hood Clouds: Net Cooling due to IR emission
Sharpening of Polar Vortex, modifying the character of baroclinic waves; significant for dust lifting

Temperature Bias in Mars GCMs



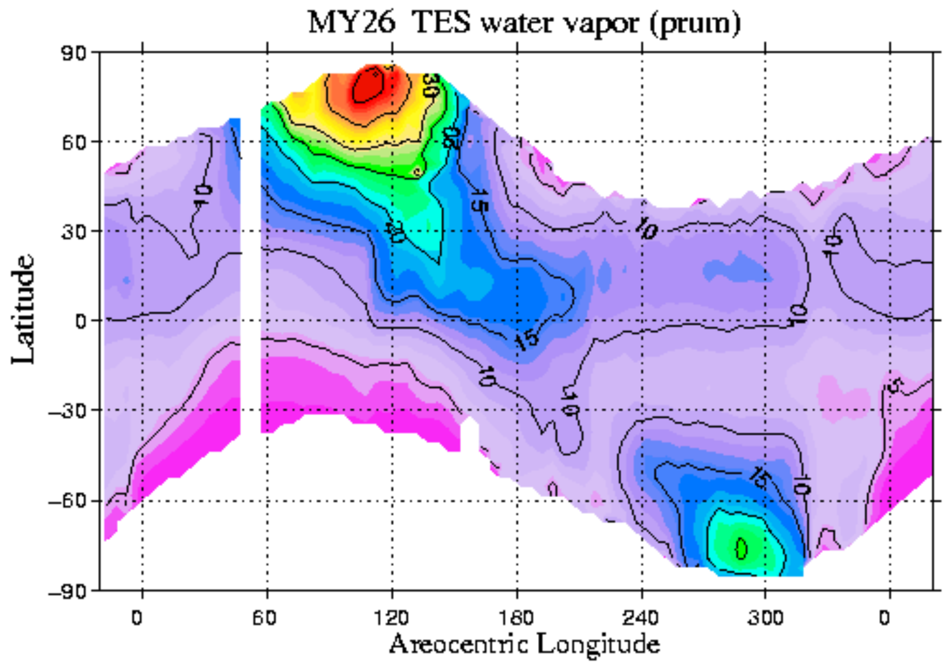
Bias due to the absence of radiatively active water ice clouds

Tropical water ice clouds provide midlevel heating during NH summer

Polar hood clouds yield low level cooling in the equinoctial seasons

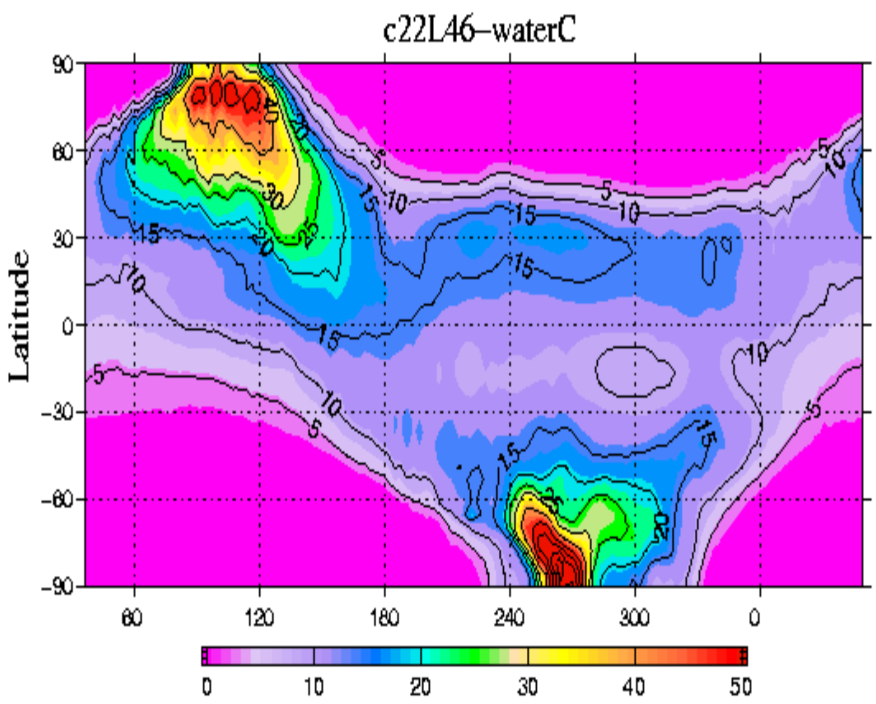
Mars Climate Database is shown, results are typical of other models as well.

Originally presented at the Mars Water Cycle Workshop, Paris, 2008



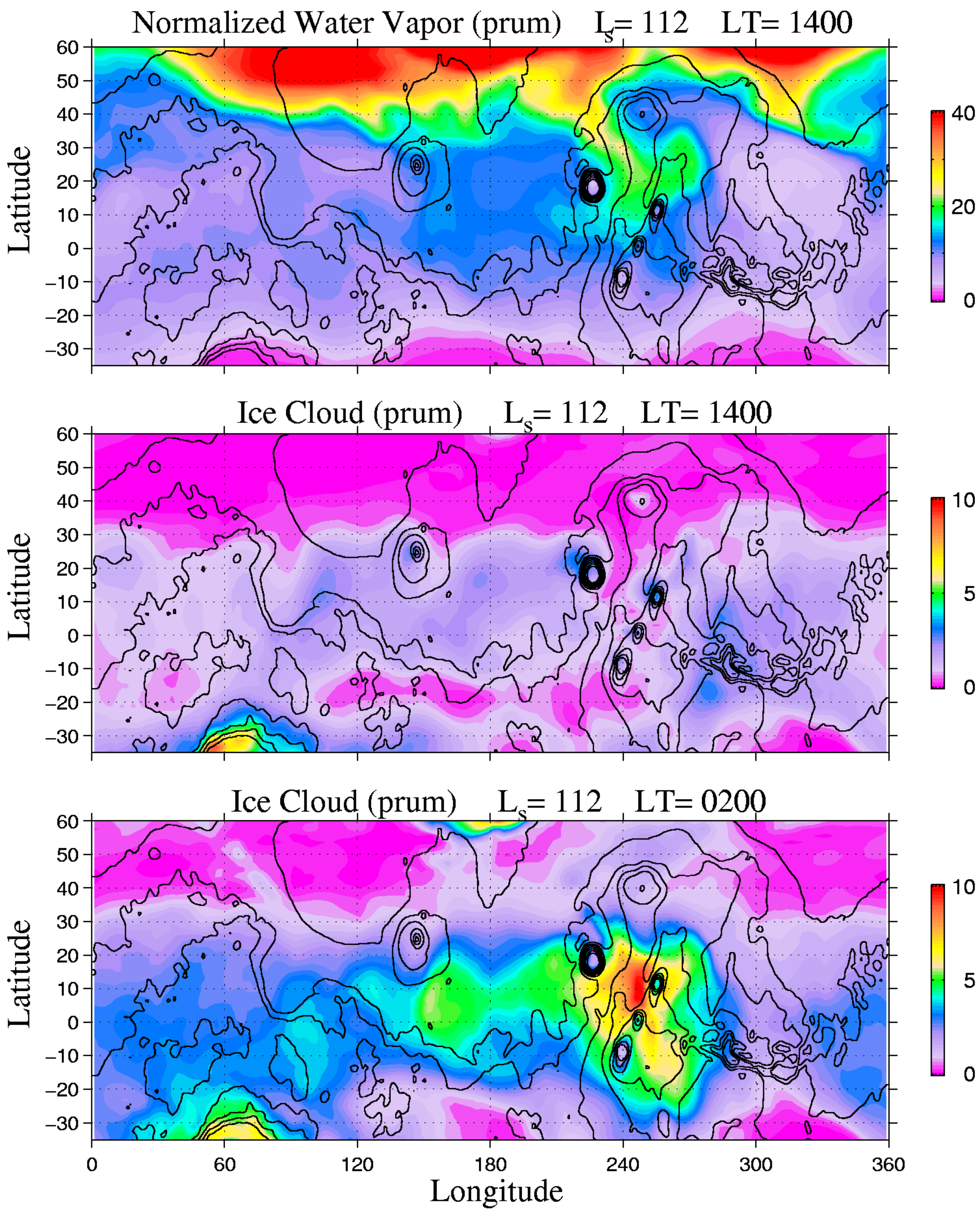
Water Cycle Simulation

Radiatively active water ice clouds

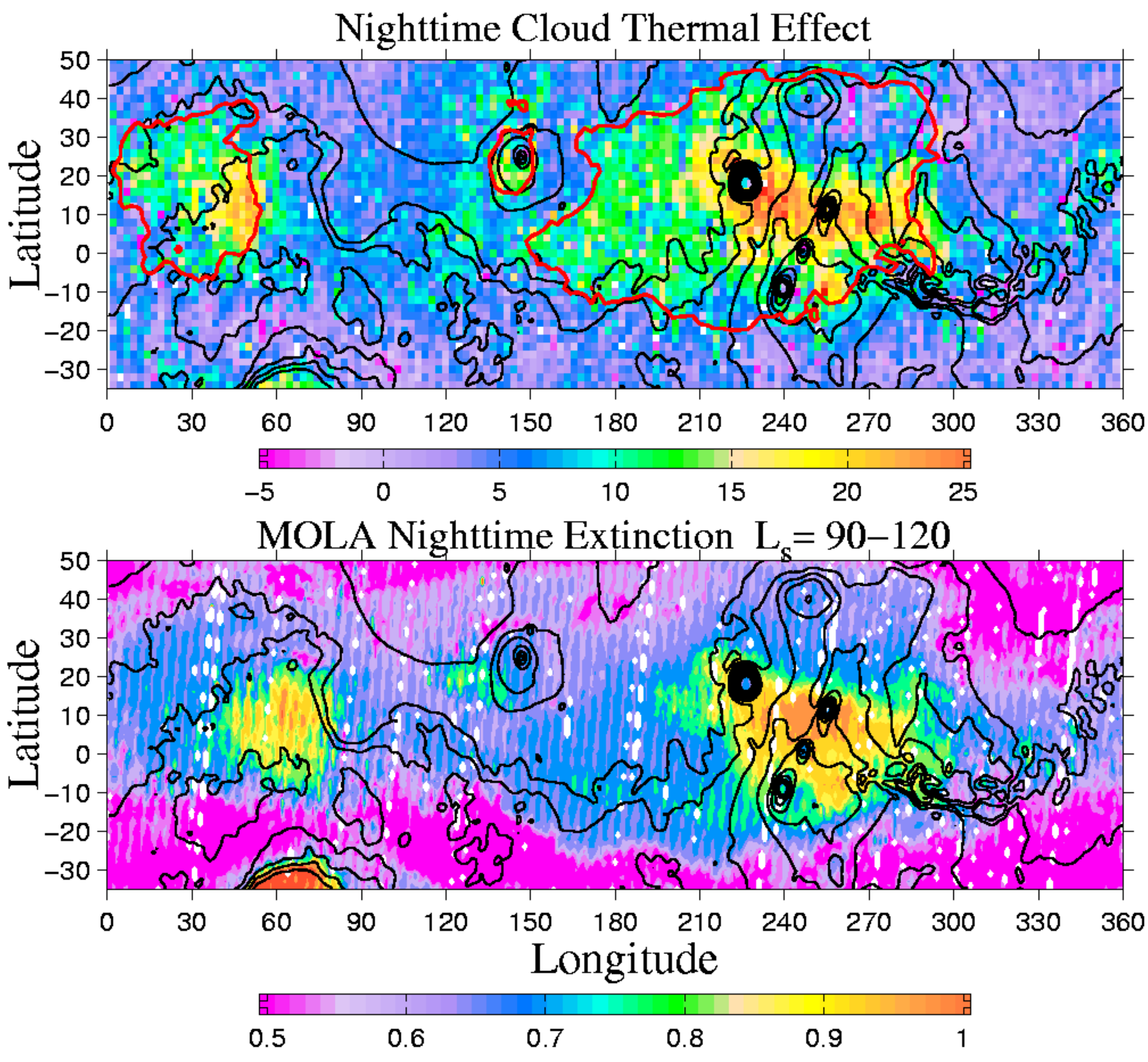


C22L46

Montmessin (2004) ice cloud scheme (using simulated dust distribution for dust cores)



Daytime (top) and Nighttime (bottom) clouds



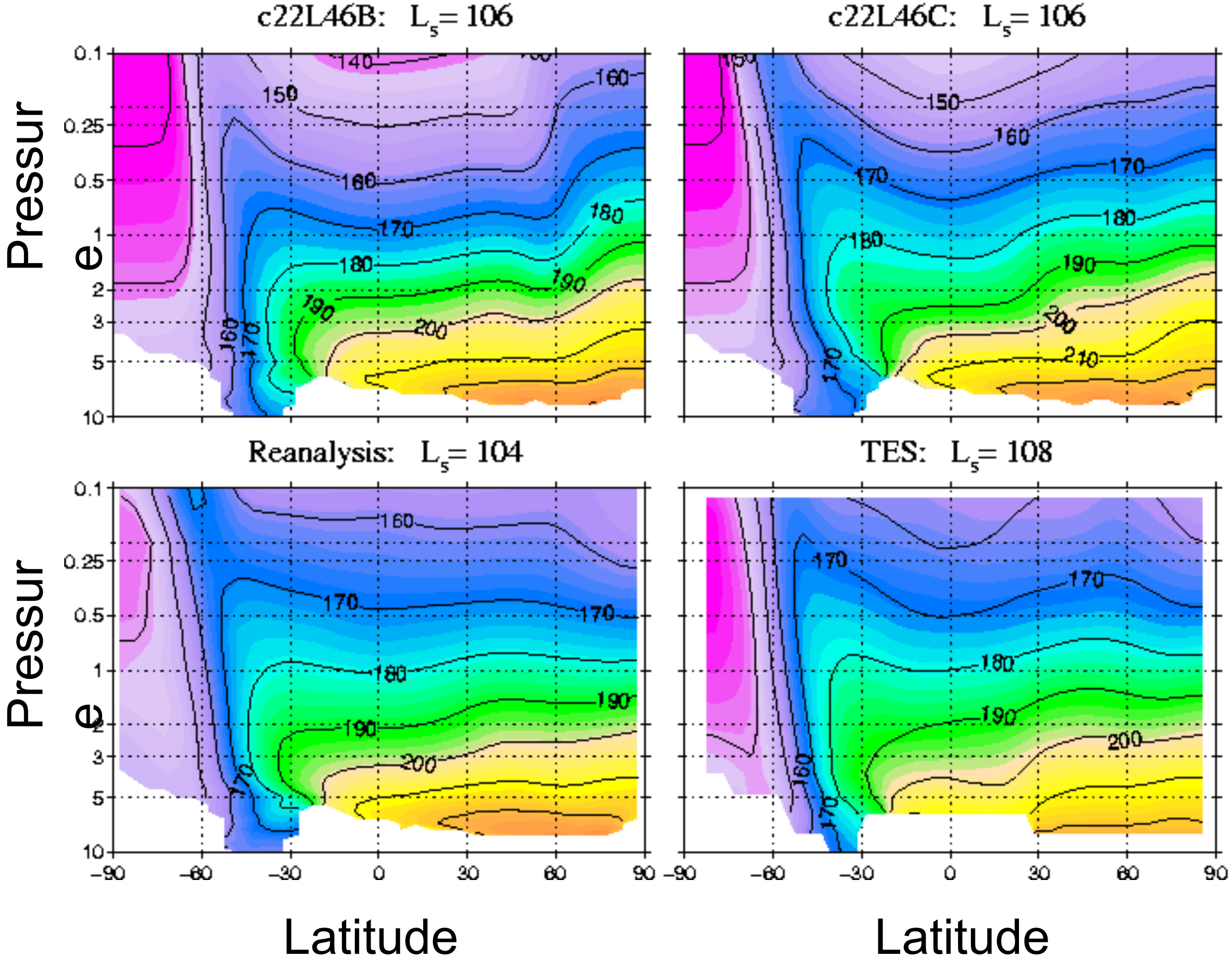
Nighttime Cloud Thermal Effect
Latitude
50
40
30
20
10
0
−10
−20
−30
0
30
60
90
120
150
180
210
240
270
300
330
360
−5
0
5
10
15
20
25
MOLA Nighttime Extinction L_s= 90−120
Latitude
Longitude
0.5
0.6
0.7
0.8
0.9
1

Radiative Influence of Water Ice Clouds

Improved agreement between simulation and observations with radiatively active water ice clouds

MGCM no cloud effect

MGCM with cloud effect

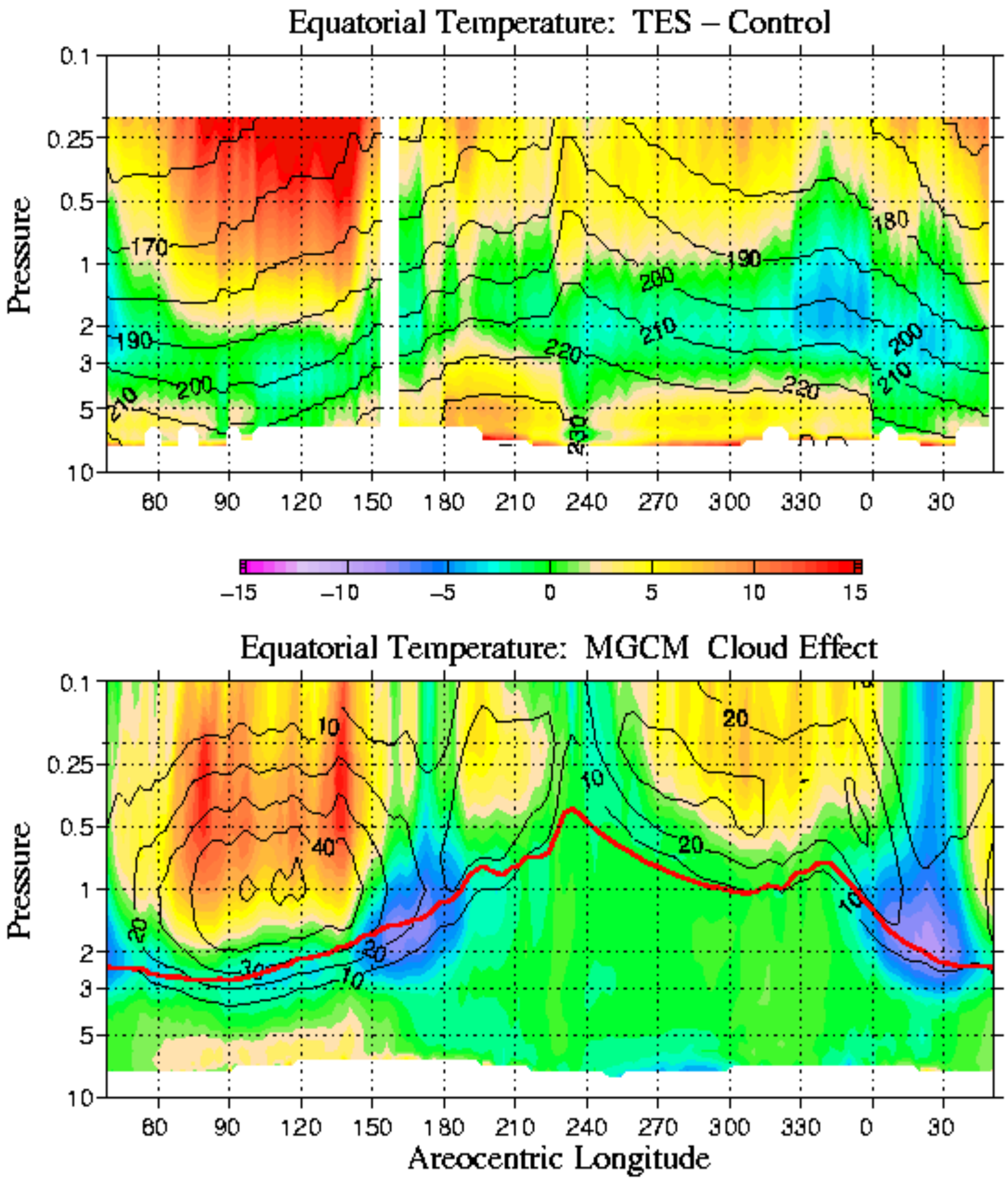


MGCM
Simulation

TES

Reanalysis and retrievals

Radiative Influence of Water Ice Clouds



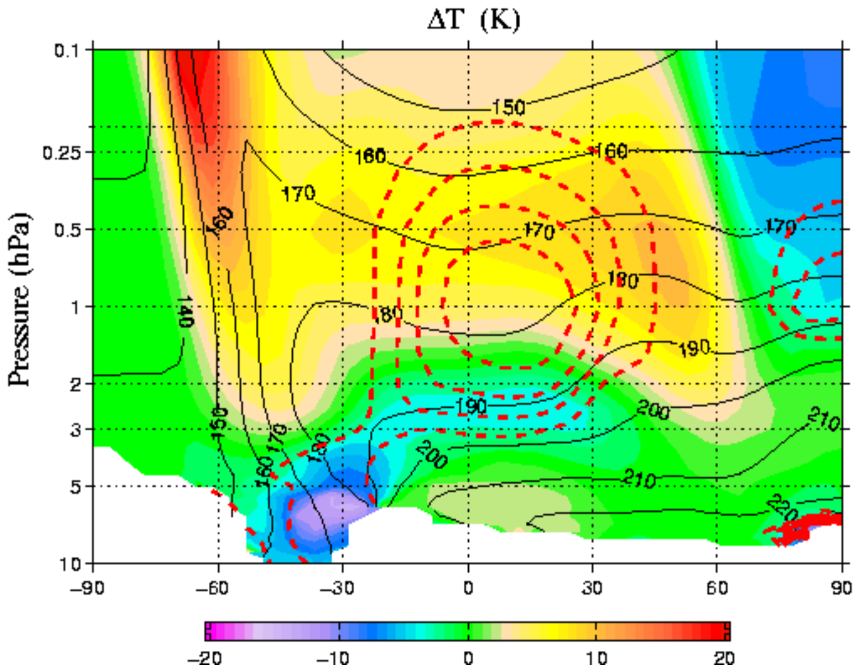
Equatorial Temperature

TES – Control

Model is cold in the tropical upper atmosphere

Addition of water ice clouds leads to atmospheric warming

Cloud Radiative Effects

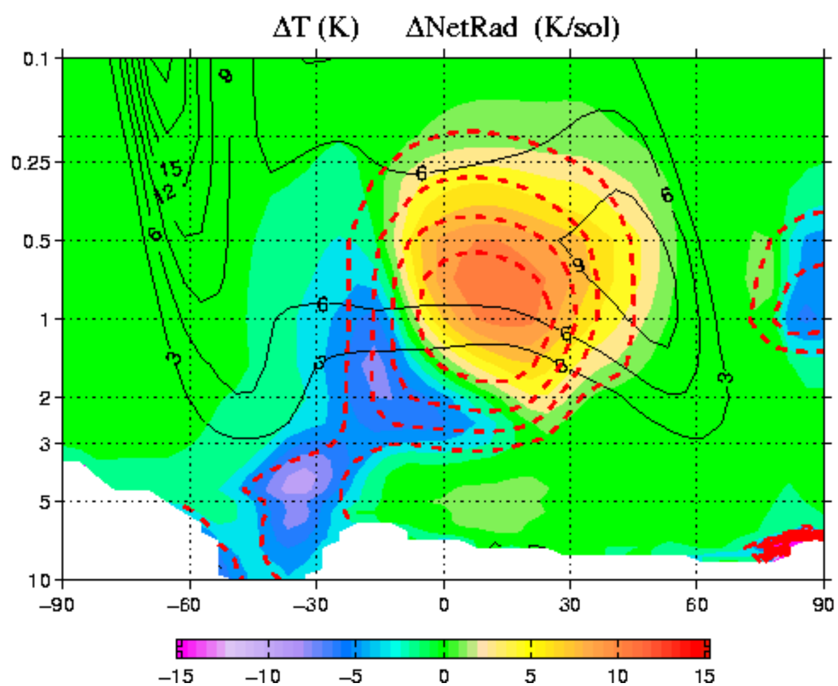


L_s ~ 100

--- Tropical Water Ice Clouds

--- Zonal Mean Temperature

ΔT (shading) Cloud Influence



--- Tropical Water Ice Cloud Belt

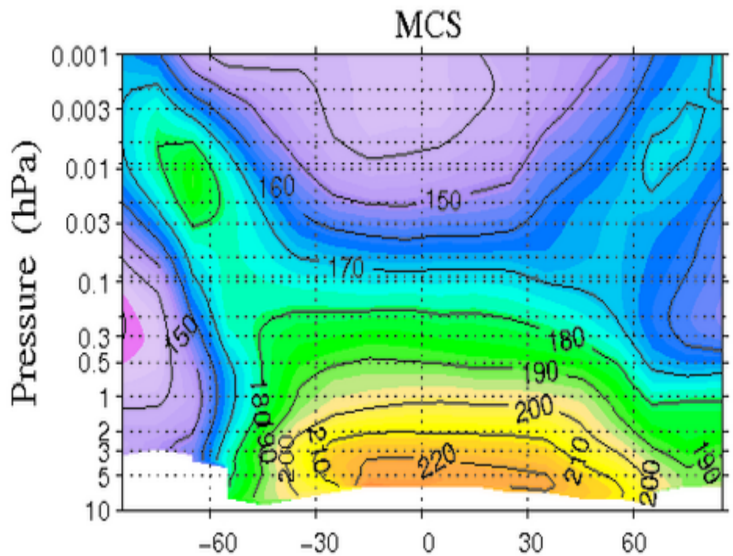
--- ΔT

Net Radiative Heating (shading)

- Dominated by absorption of upwelling LW radiation in the tropics

- LW cooling by low level clouds in the southern (winter) hemisphere.

Zonal Mean Temperature: MCS   Ls= 160



Latitude

Significantly deeper coverage than provided by TES:
~80 km vs 40 km

Prominent polar warming
McCleese et al. 2009

MGCM developments:

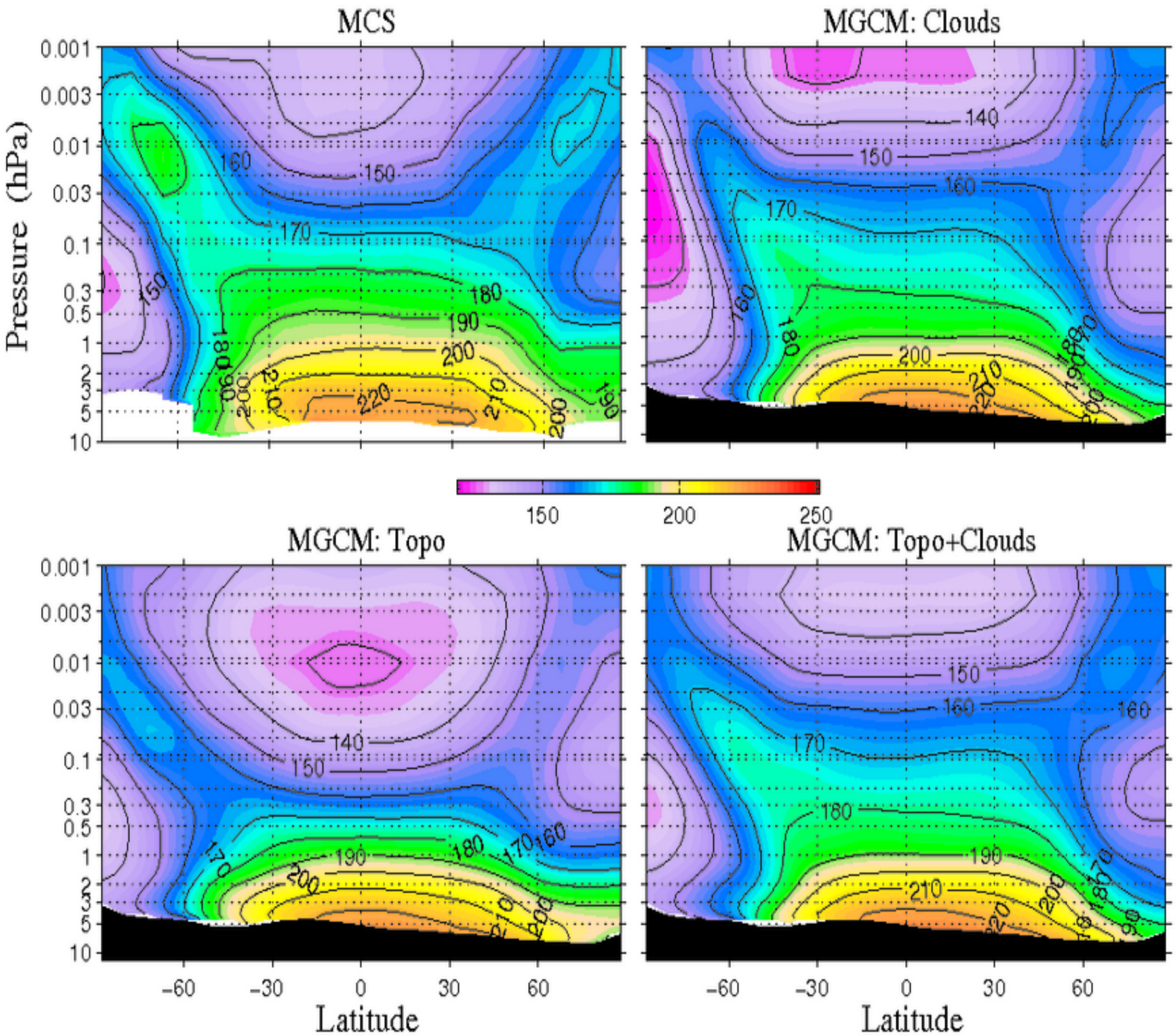
- Parameterized topographic wave drag

  Unresolved non-orographic waves may also contribute to drag

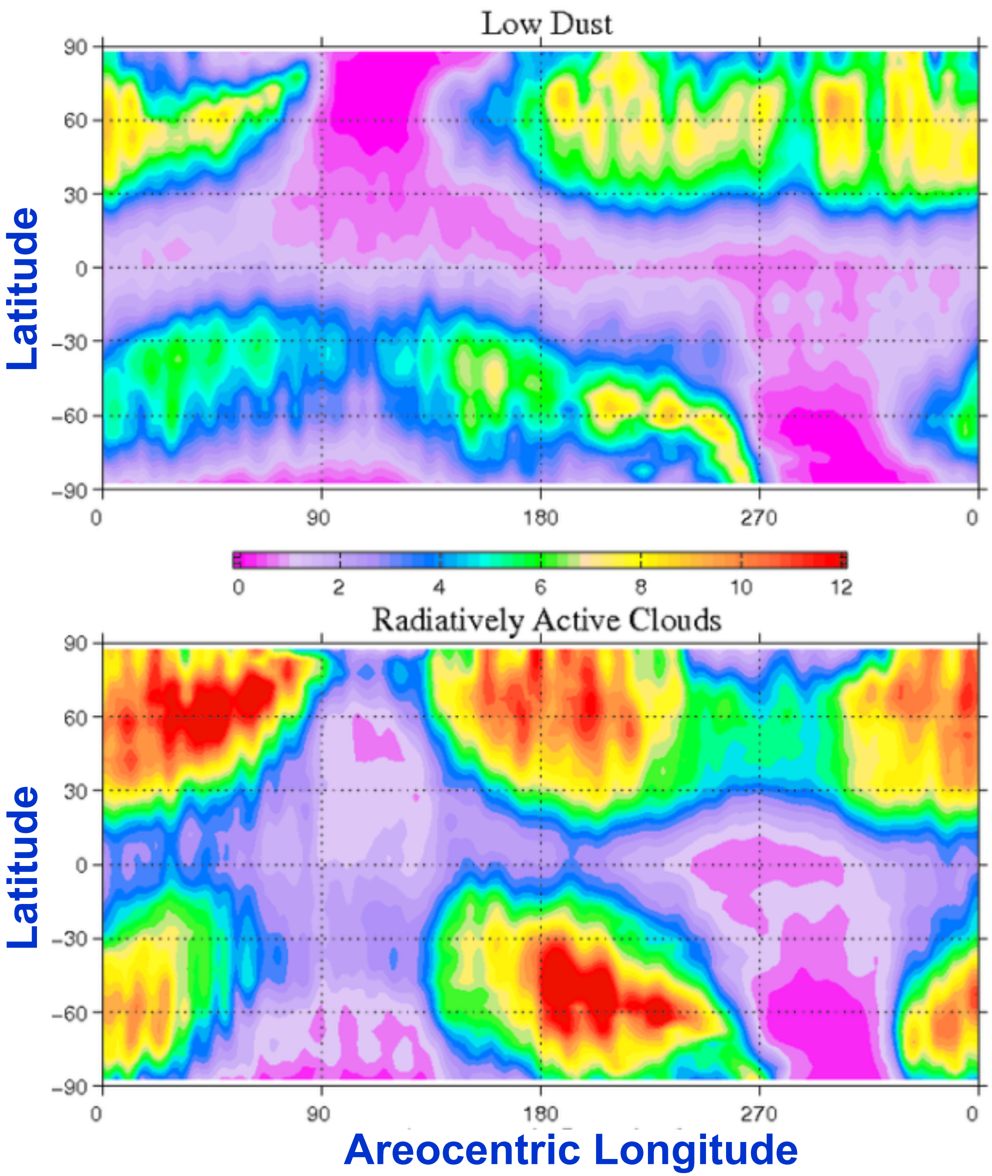
- Radiatively active water ice clouds

  Contribute to tropical heating and intensified Hadley circulation

Zonal Mean Temperature: MCS vs MGCM Ls= 160



Influence of Water Ice Clouds on Transient Eddy Activity



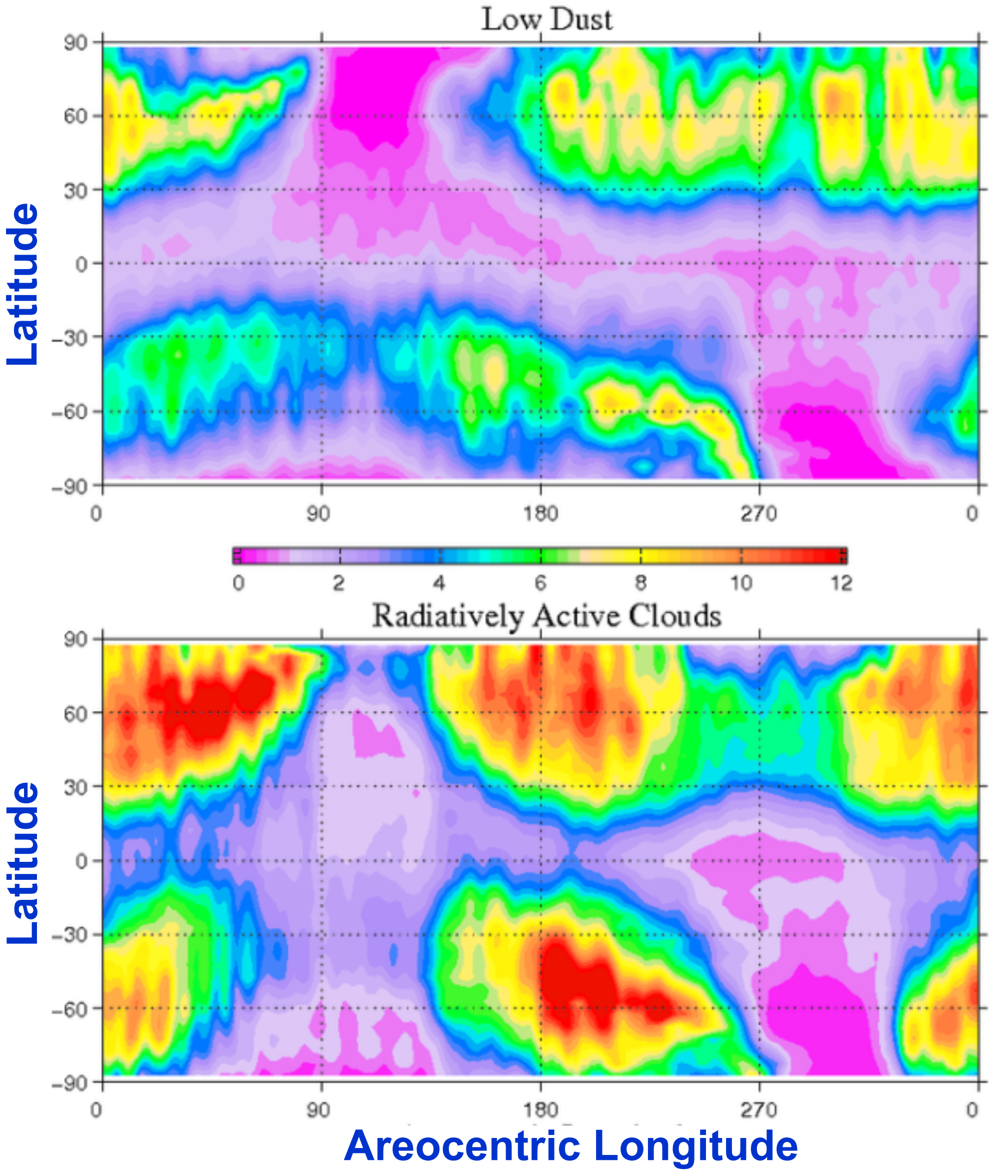
Eddy Meridional Wind at ~2km
1.5- 10 sol period

Fixed (low) Dust; Passive Clouds

Radiatively Active Clouds

Note: the simulated water ice clouds are probably too thick, particularly during NH spring.

Influence of Water Ice Clouds on Transient Eddy Activity



Fixed (low) Dust; Passive Clouds

Higher dust loading yields a more prominent solstitial break in eddy activity

Radiatively Active Clouds

As with increased dust, clouds contribute to a stronger Hadley circulation

Note: the simulated water ice clouds are probably too thick, particularly during NH spring.

Dust “Assimilation”

Goal: A realistic vertical and meridional variation of dust in simulations with prescribed dust opacity distribution(s)

The MGCM predicts the evolution of a 3D dust opacity field subject to the constraints of the available MGS TES dust column opacity observations.

Dust is added/removed from the boundary layer as needed to fit the observed column dust opacity

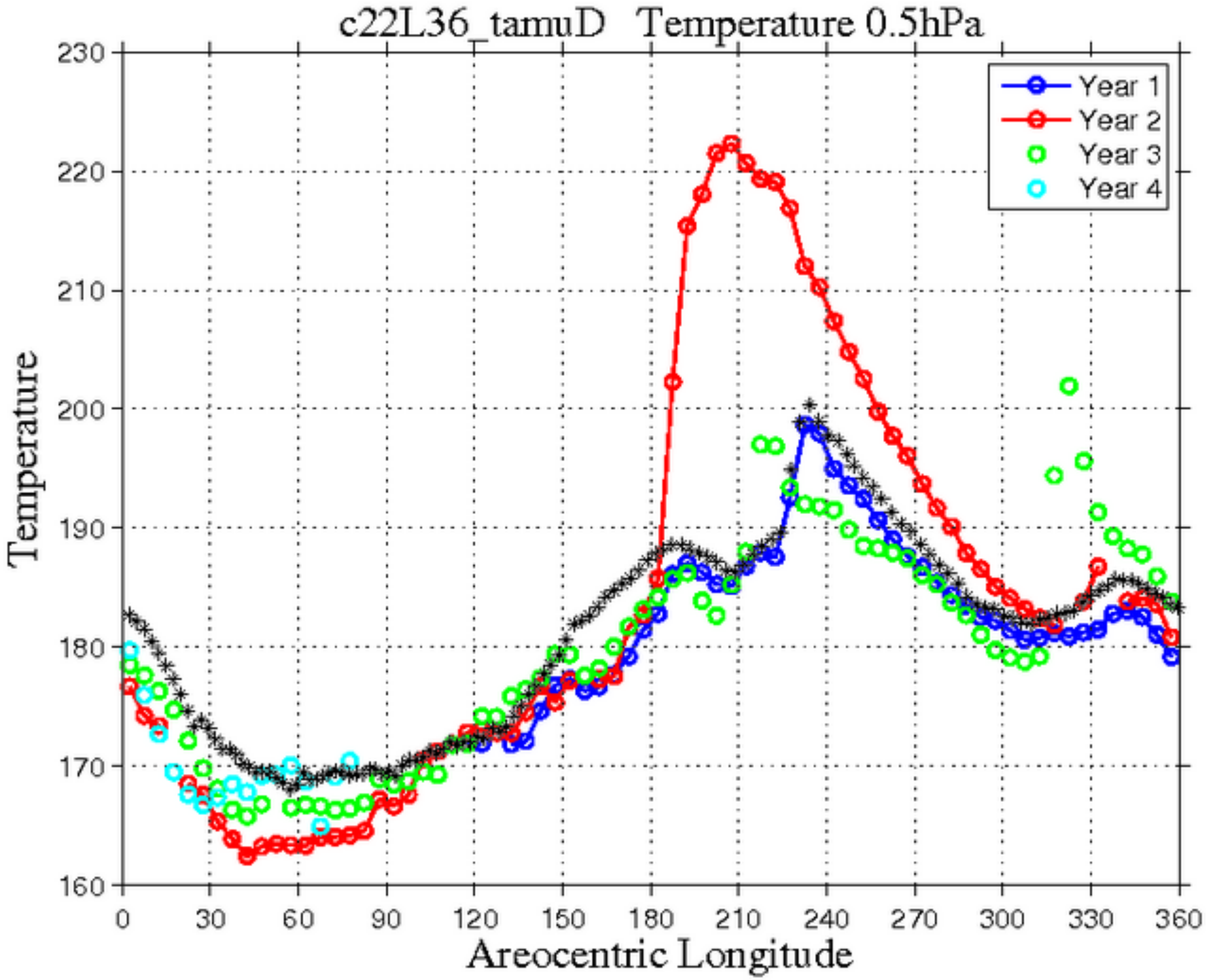
The dust particle size spectrum plays a significant role in the vertical and meridional extent of the resulting opacity field.

Currently using 5 dust tracer fields.

Dust removal is optional: Sedimentation should yield good agreement with TES temperatures

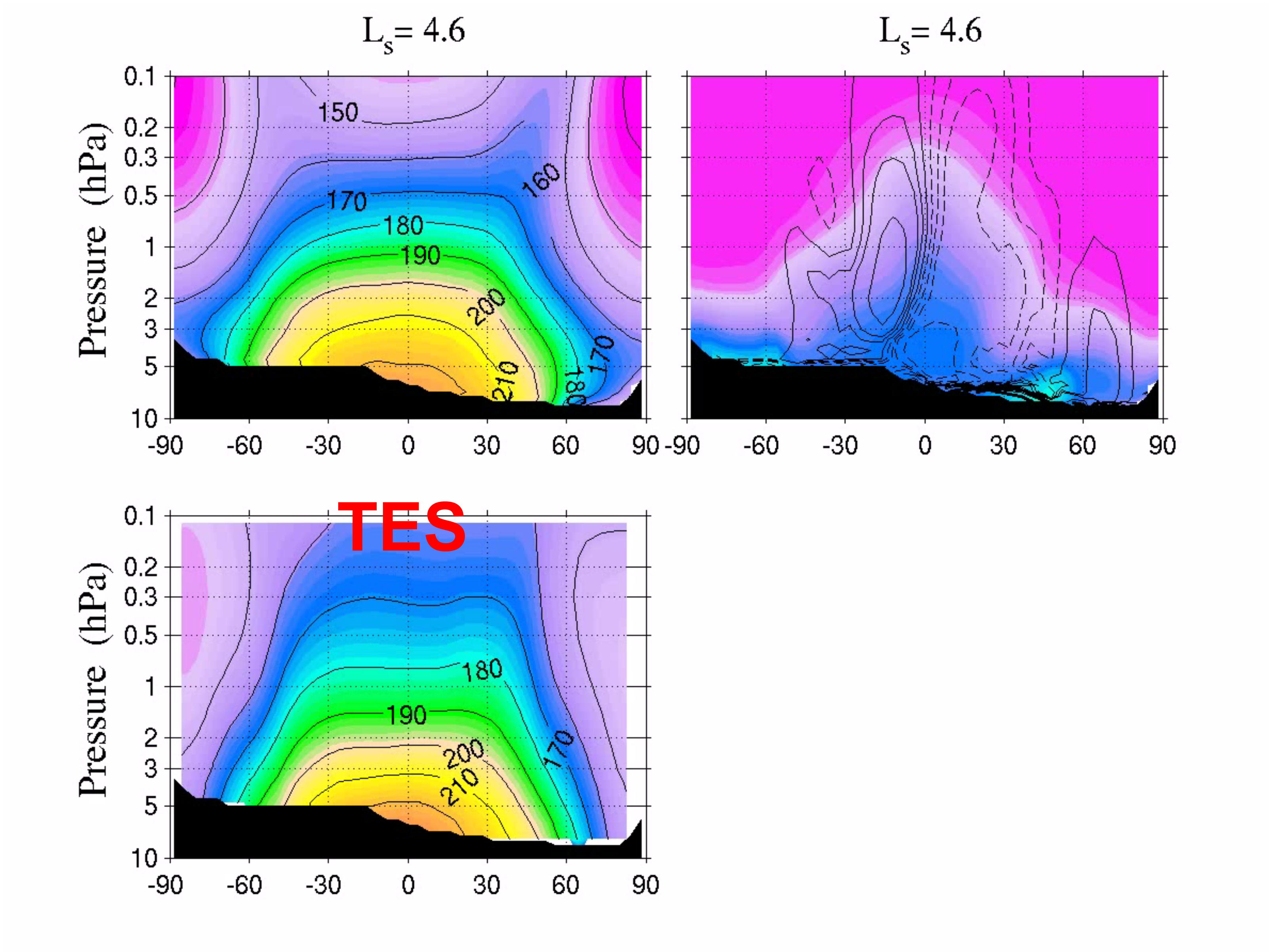
Assimilation is being used to “tune” the input dust size spectrum to improve agreement with temperature observations

Observed (TES) and Simulated Equatorial 50 Pa Temperatures



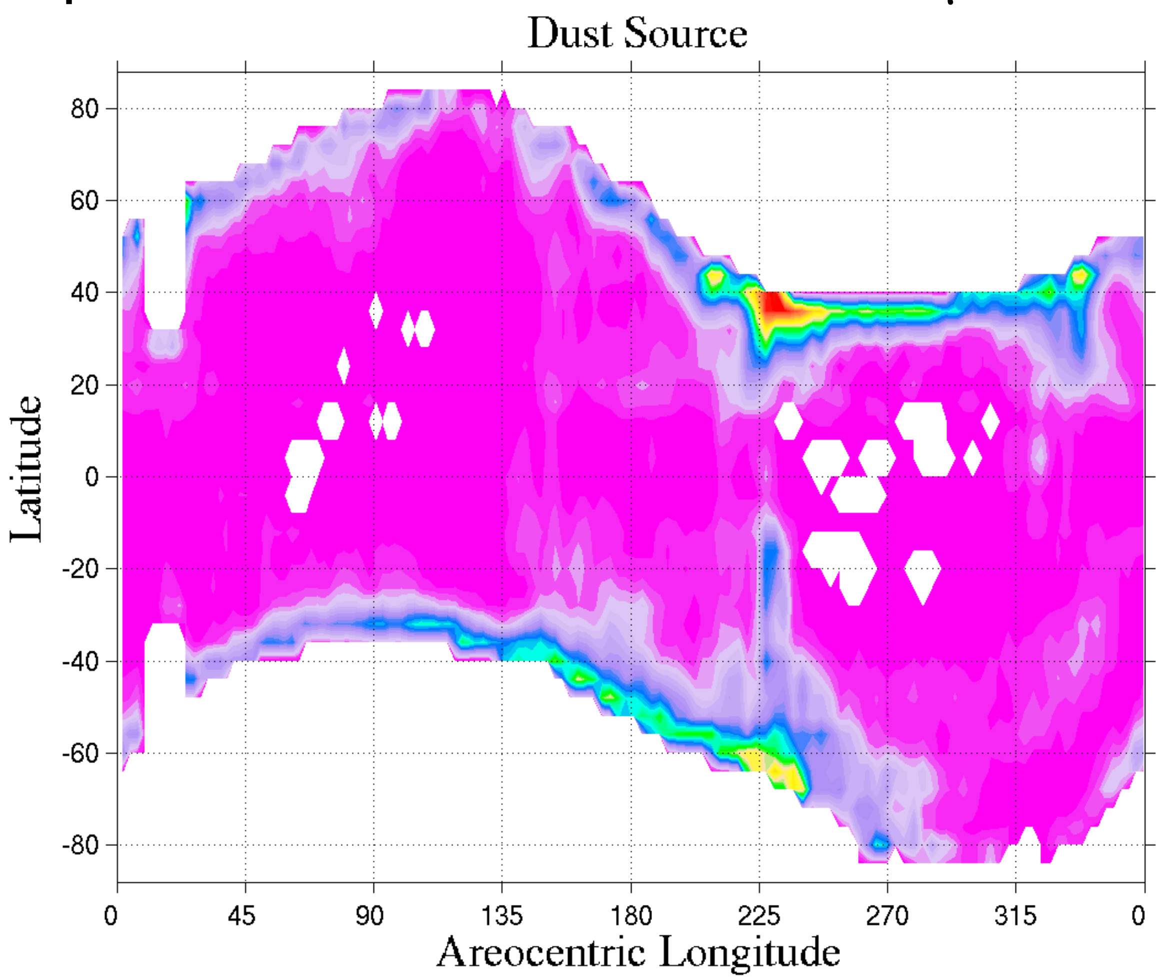
5 Dust Aerosol Fields + Radiatively Active Water Ice Clouds

Simulated Zonal Mean Temperature and Opacity



MY24/25 Dust Assimilation Experiment

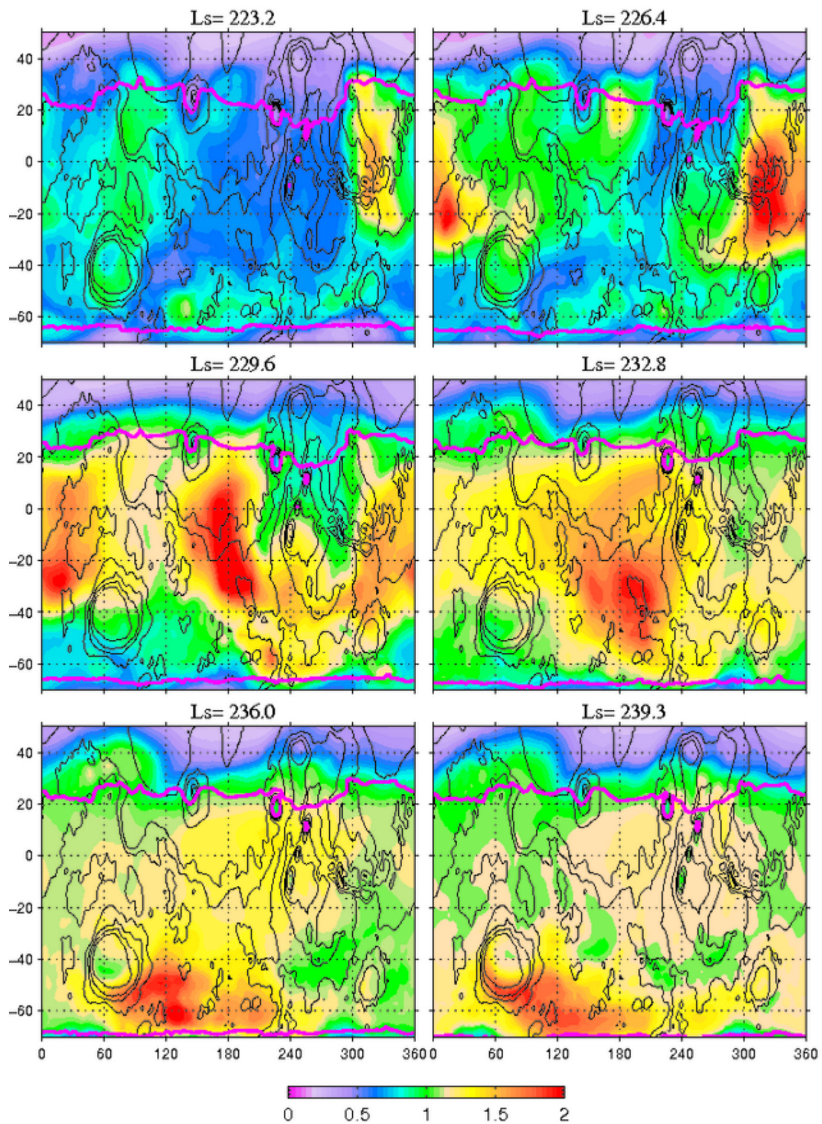
Implied Dust Source Term for 1.2 μm dust



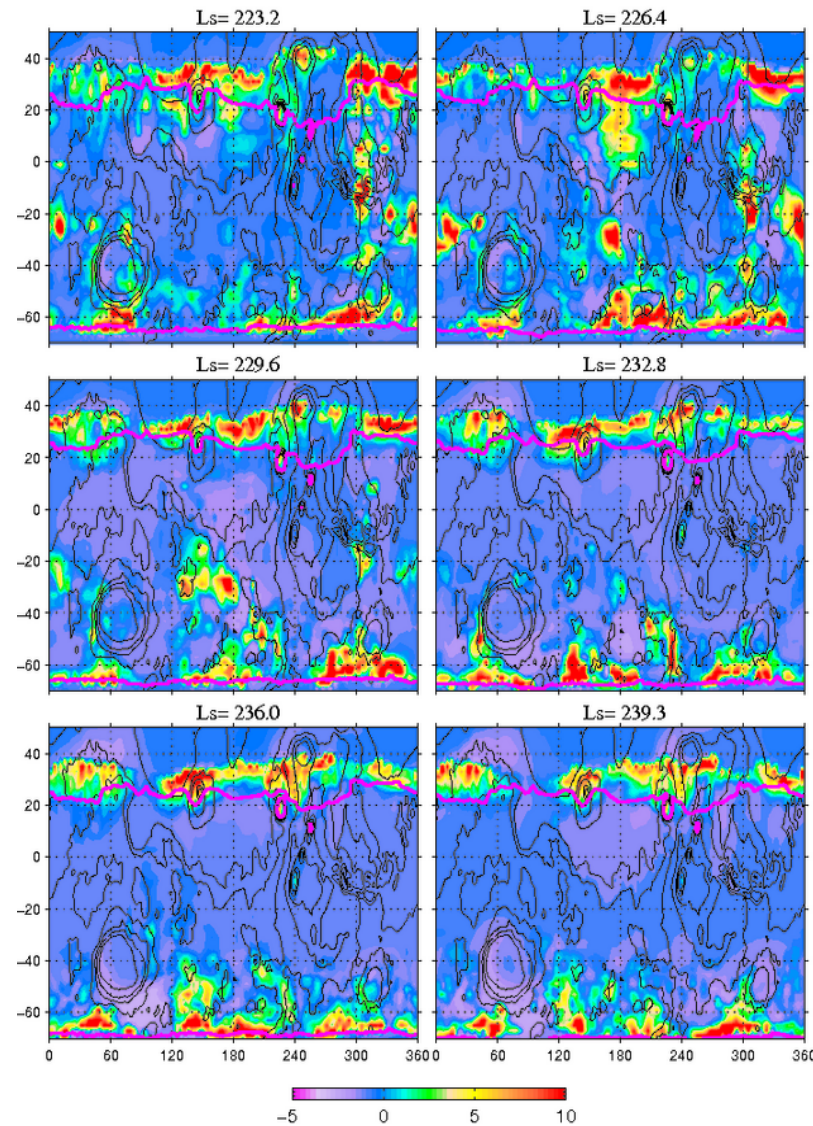
Kahre, Wilson, et al. 2009 Dust Cycle Workshop,

Simulated Dust Evolution for MY24 L_s= 223-239

Dust Opacity



dust injection/sedimentation

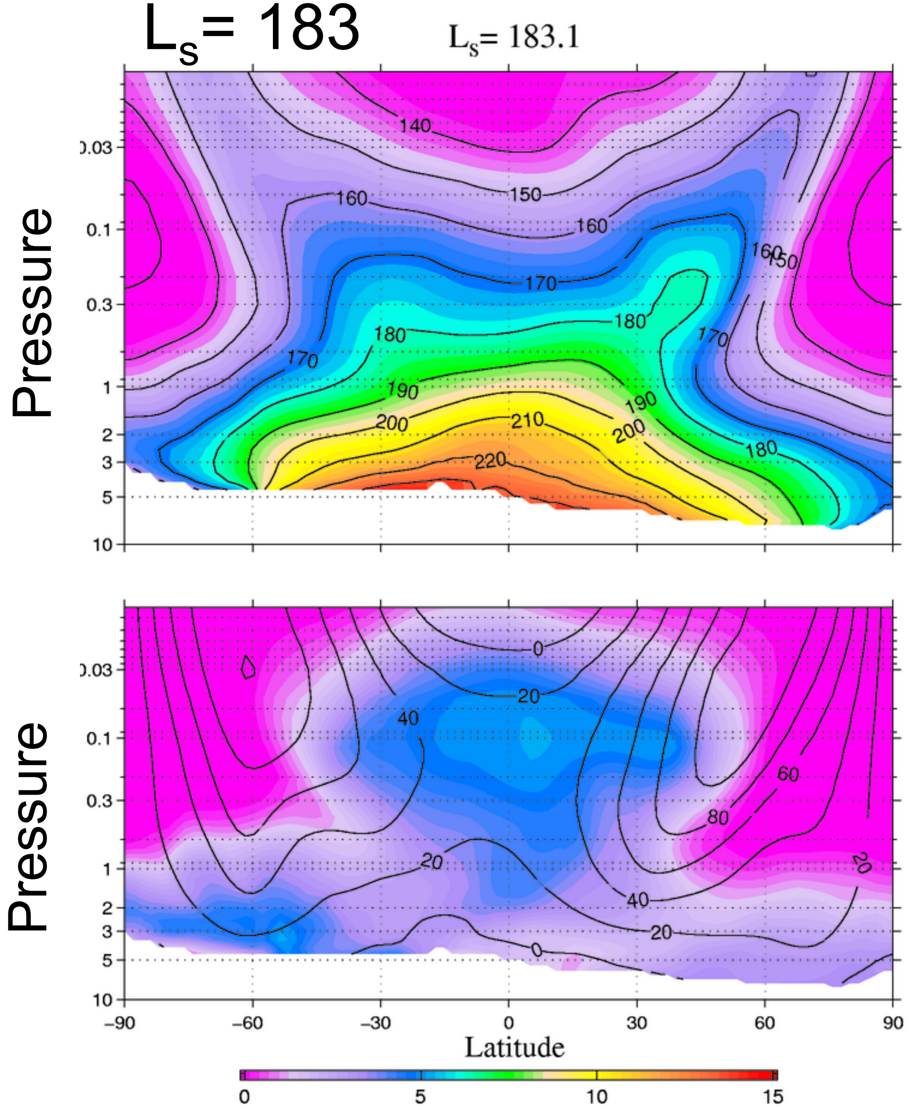


Source units in10^{-9} kgm^{-2}s^{-1}

MY25 Global Dust Storm

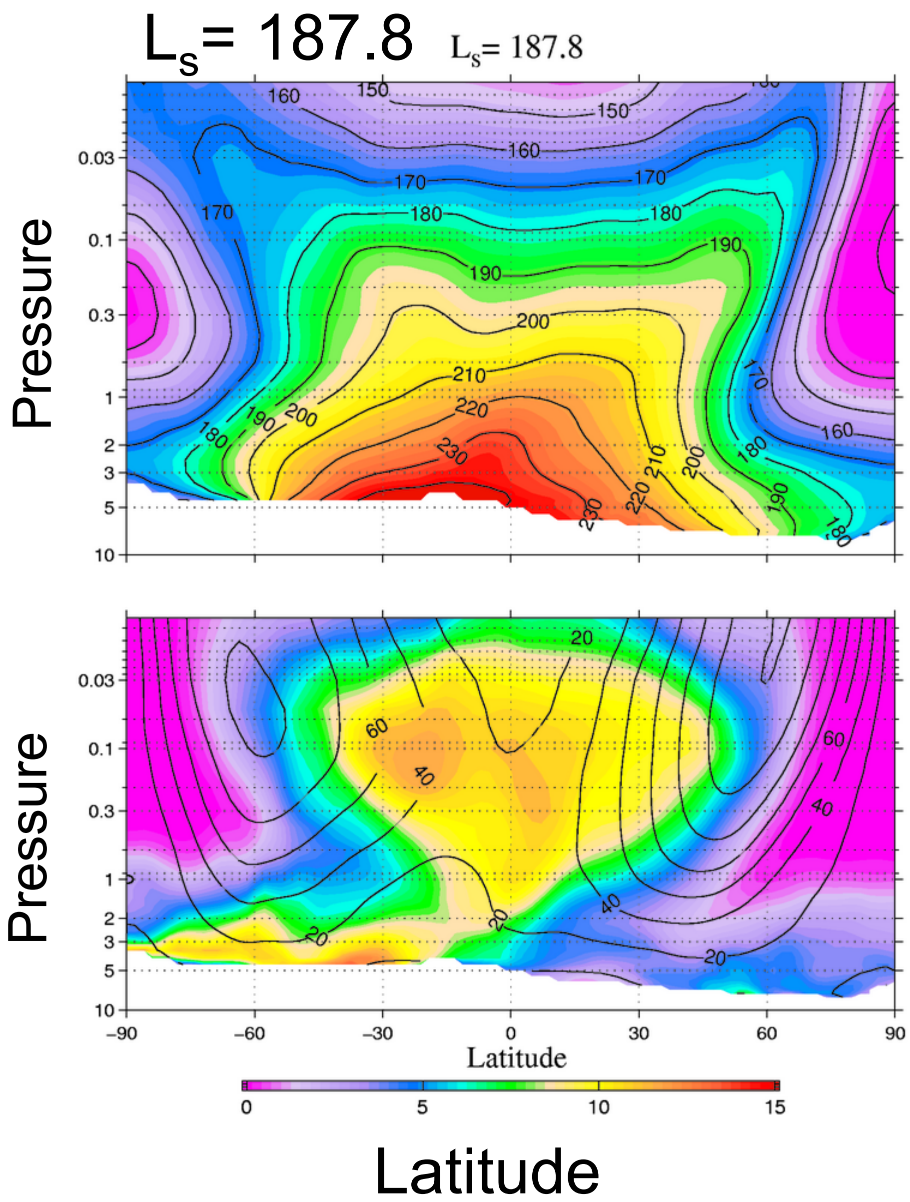
Simulated U, T, Opacity

L_s= 183

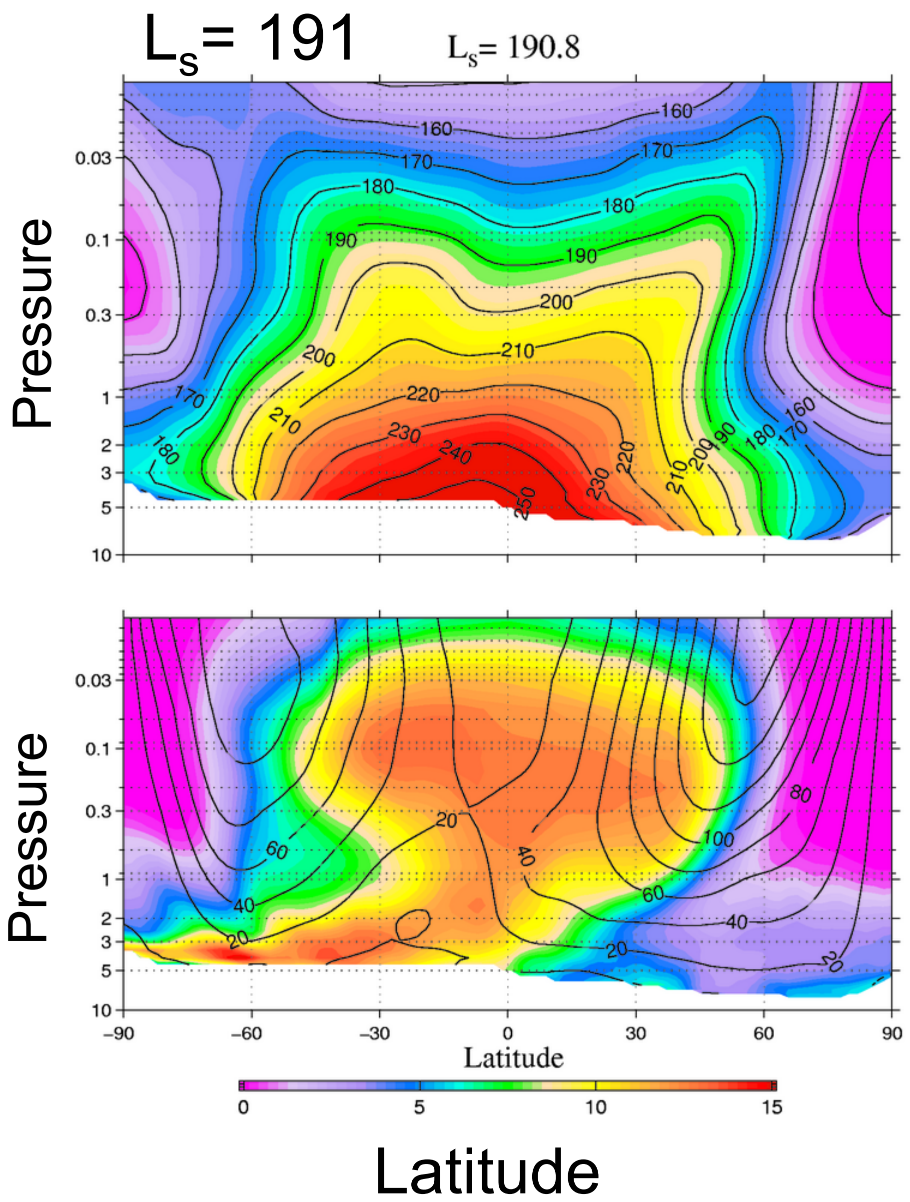


Latitude

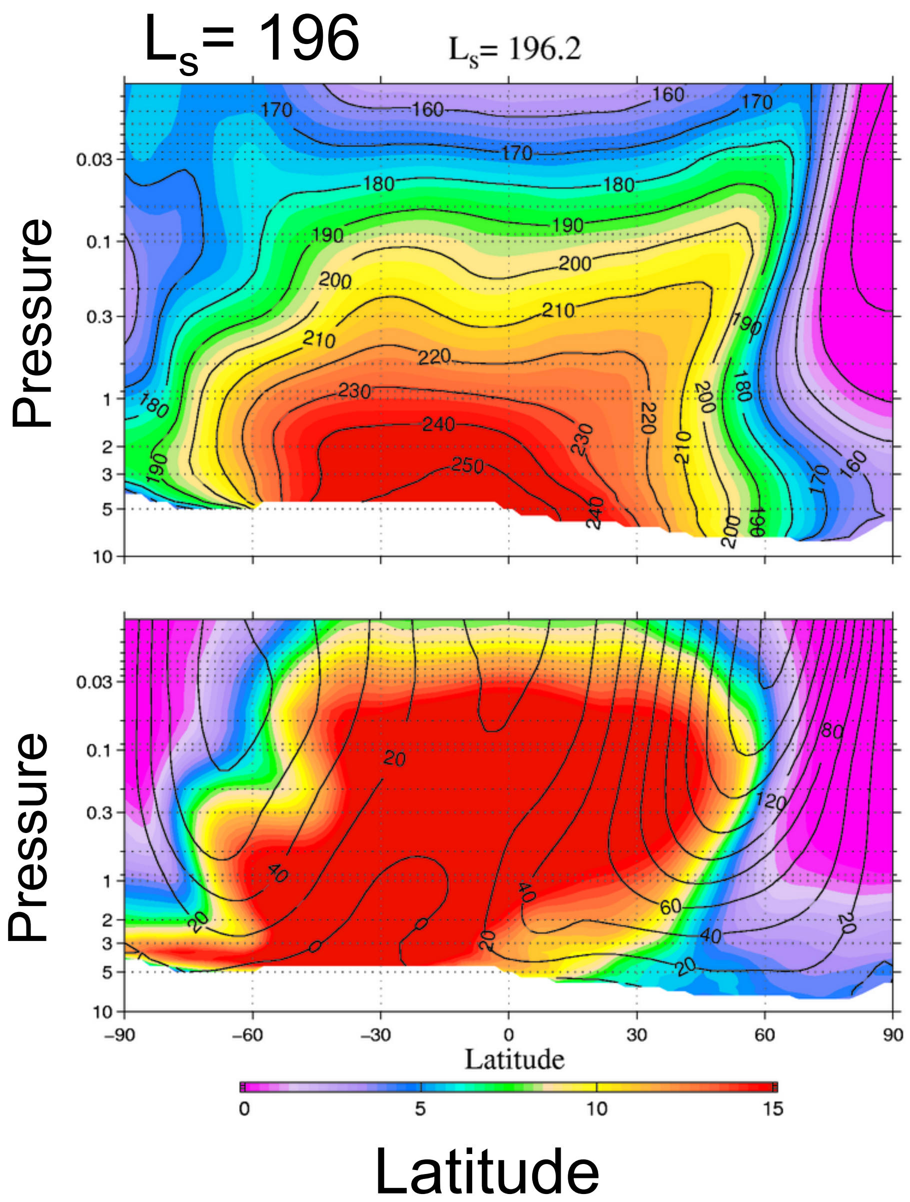
Simulated U, T, Opacity



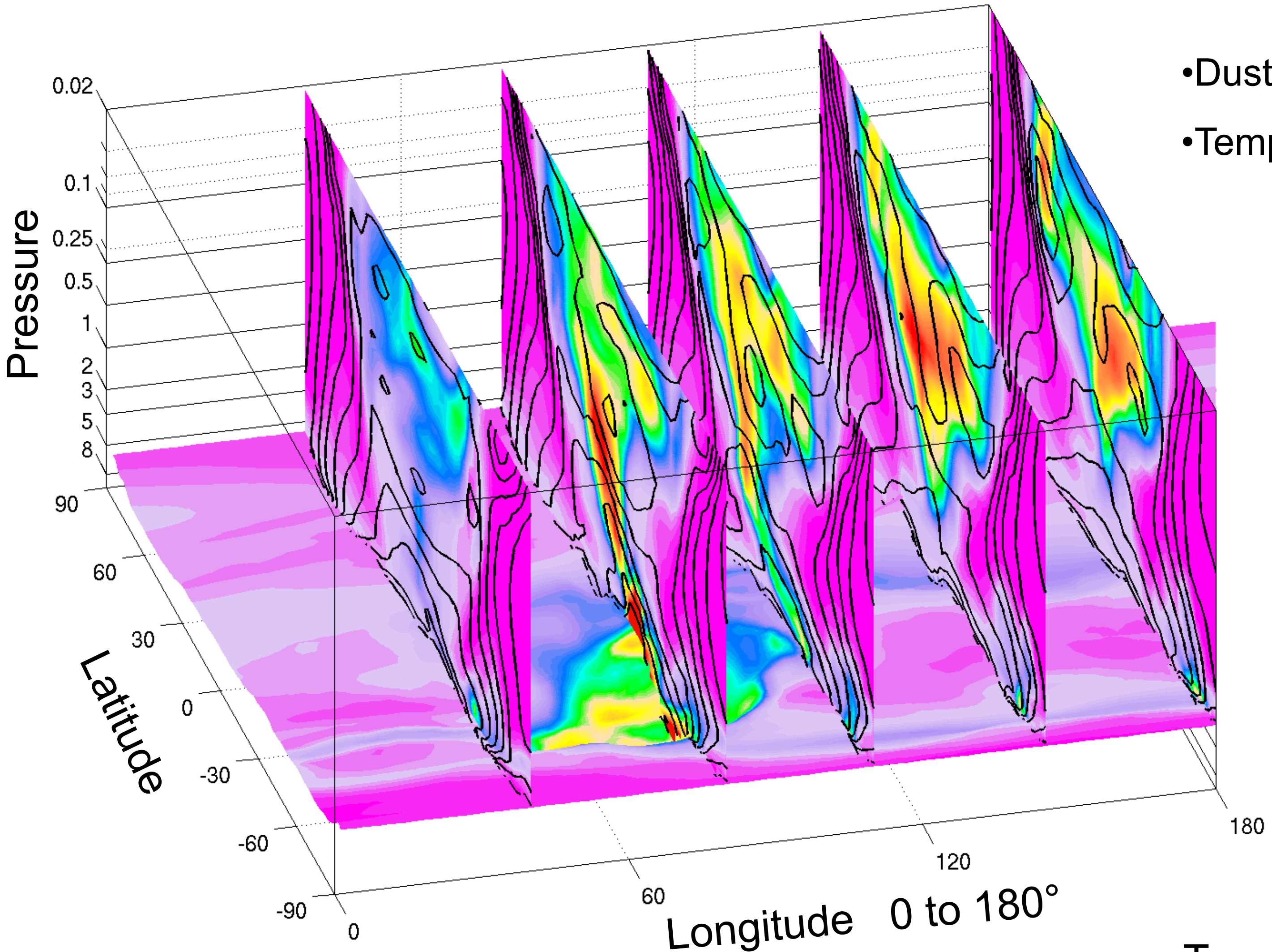
Simulated U, T, Opacity



Simulated U, T, Opacity



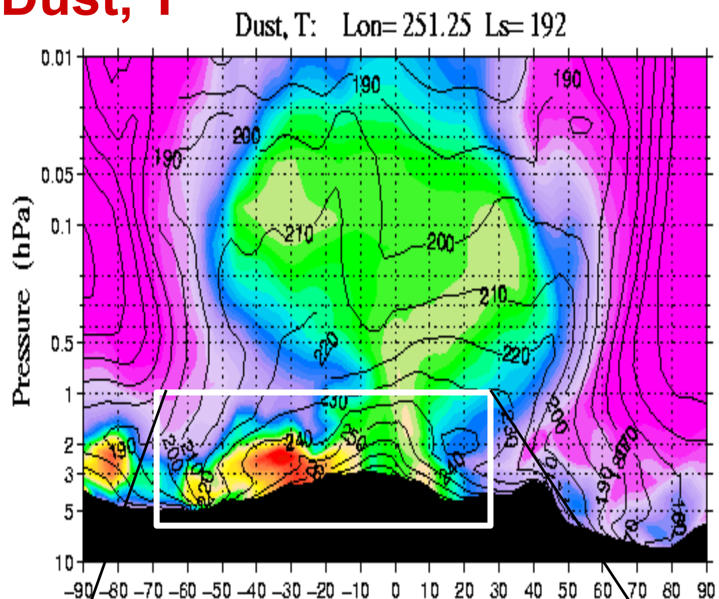
2001 Dust Storm Simulation: L_s= 187°



- Column dust opacity on bottom plane
- Dust mixing ratio (shaded)
- Temperature (contoured)

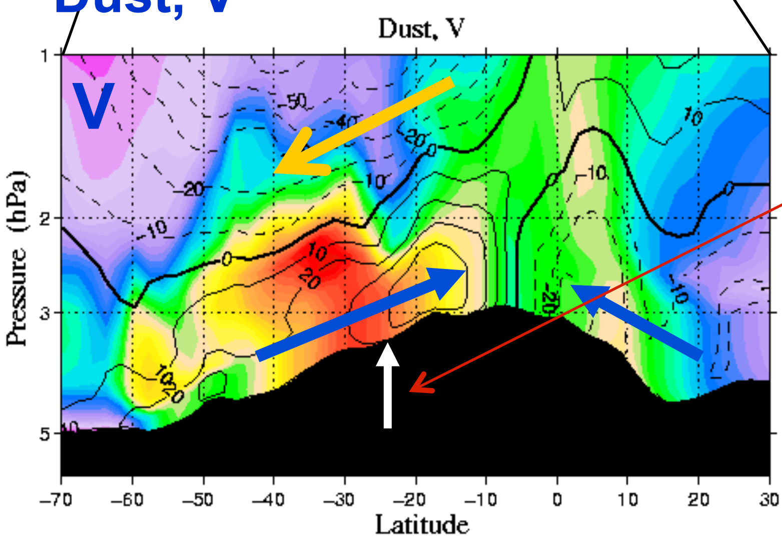
Temperature contoured at 10 K intervals

Dust, T

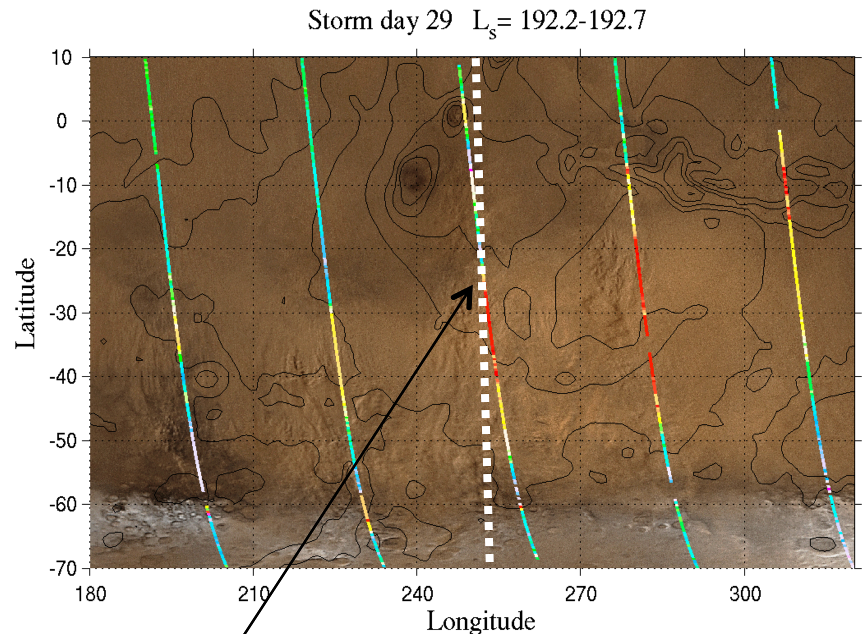


Latitude

Dust, V



V 10 ms^{-1} intervals



MOC Image

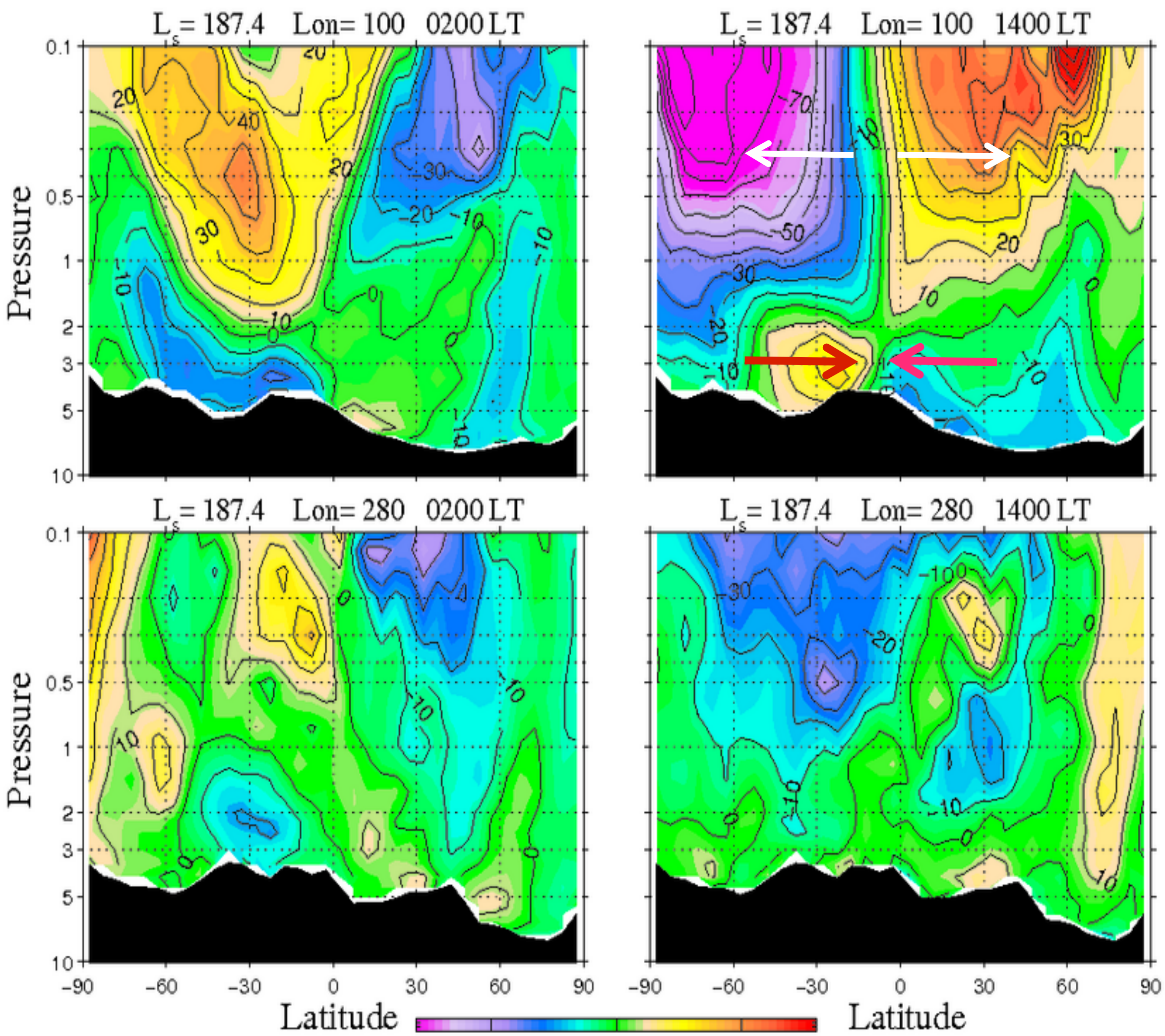
Dust front at 24° S and 250° E

MGCM Simulation: 1400 LT

Meridional Winds dominated by Tides

Meridional Wind in the Western (100°E) and Eastern (280°E) Hemisphere

L_s= 187.4



Lon= 100°E

Dominant Tide Circulation 2am (left) vs 2pm (right)

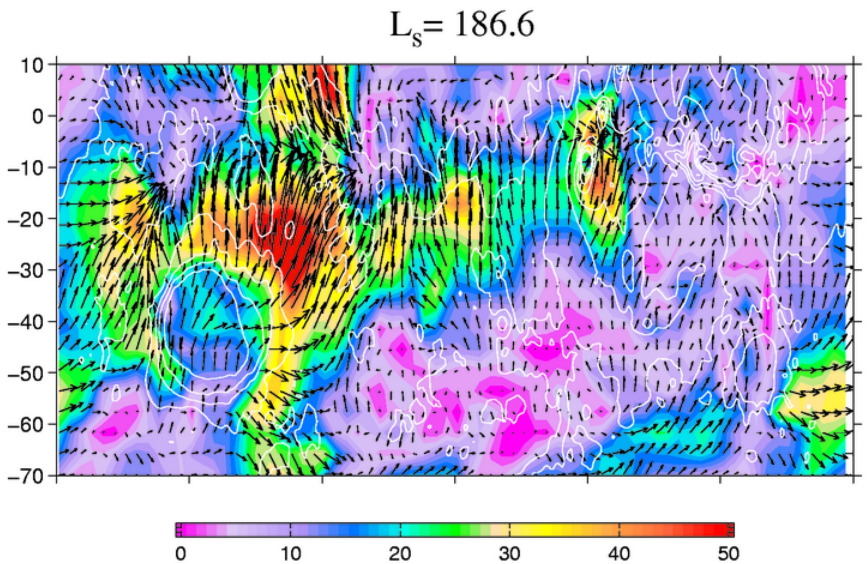
Localized to the western hemisphere at this time

Lon= 280°E

Low-level daytime convergence at equator during daytime

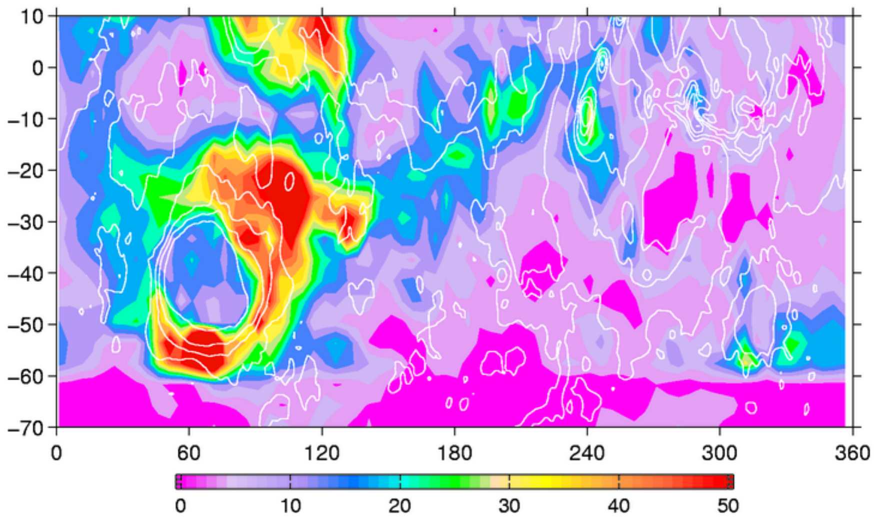
V @ 10 ms^{-1} intervals

2 pm Winds (top); Diurnal Maximum Surface Stress (bottom)



1400 Local Time Winds (1 km agl)

Wind magnitude (shaded)

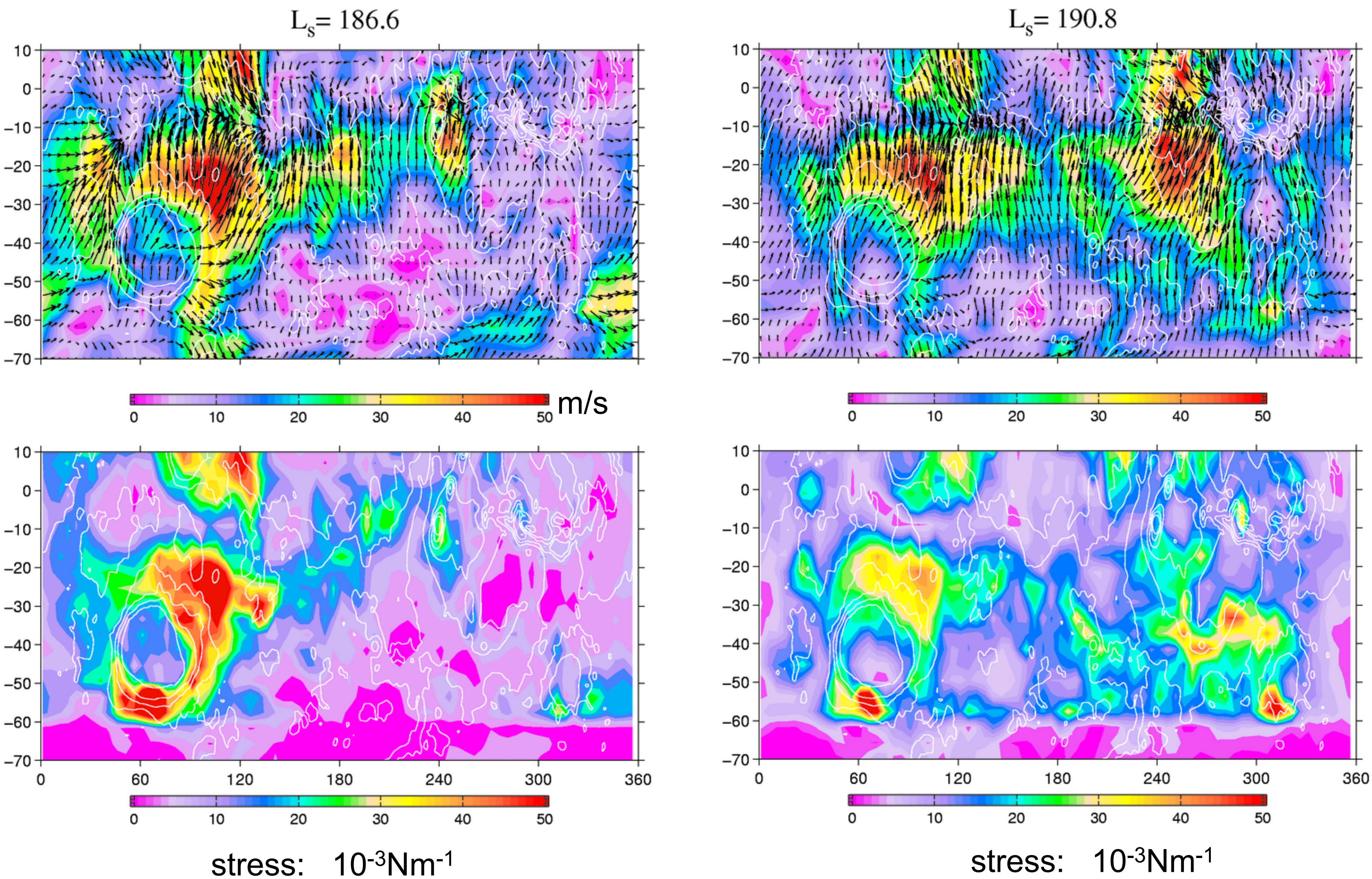


Daily maximum stress

$Nm^{-2} \times 10^3$

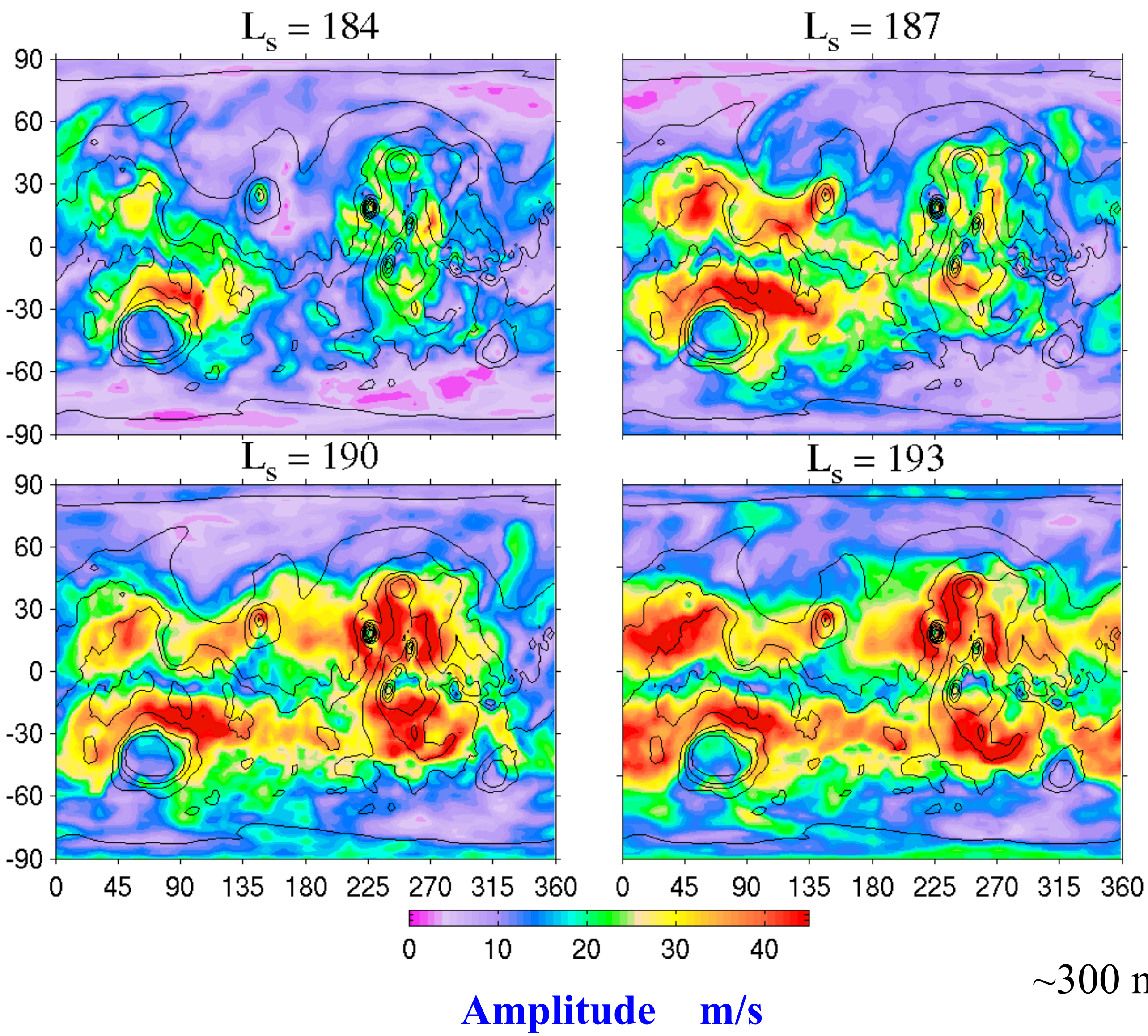
2 pm Winds (top); Diurnal Maximum Surface Stress (bottom)

wind vectors and amplitude



The evolution of tide wind amplitude

during the expansion phase of the 2001 dust storm

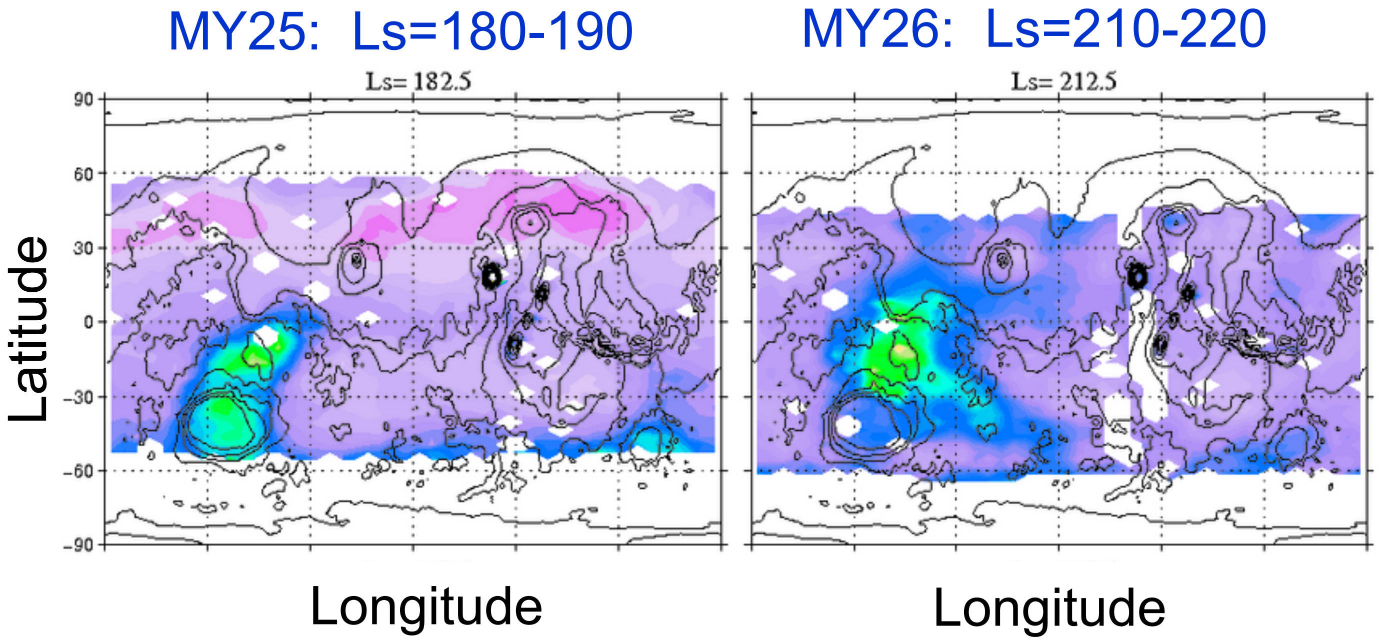


Amplification of tide winds with increasing dust loading:

In turn, the intensified tides lead to further dust lifting

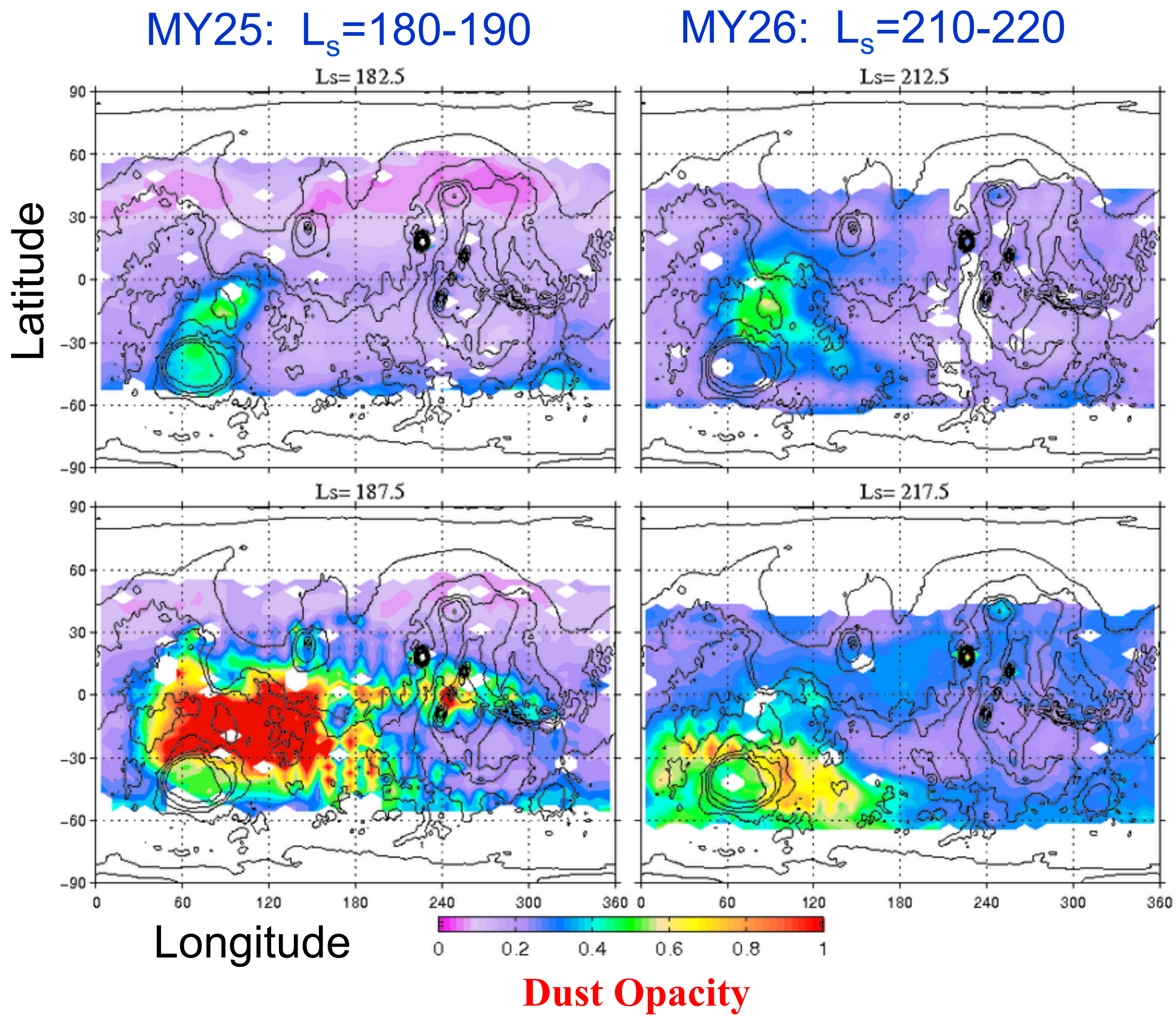
~300 m above ground level

Dust Opacity



Interesting differences starting from similar conditions

TES Dust Column Opacity



Dust Cycle Overview

Current Mars climate modeling is unable to represent the observed seasonal and interannual variability in the Mars dust cycle. This constitutes the major research issue in Mars atmospheric modeling.

To date, the representation of surface dust reservoirs has been very simplistic. Yet this seems to be the most plausible source of long term memory needed for interannual variability Pankine & Ingersoll [2002,2004]

I will show an example of how adding an element of potentially greater realism can yield interannual variability in the occurrence of global dust storms in a Mars general circulation model

MGCM Dust Cycle Modeling

Interactive Dust Lifting

- A finite inventory of dust is maintained, partitioned between surface dust and aerosol.
- The stress threshold for dust lifting is allowed to vary with surface dust depth: The lifting threshold increases as dust is depleted from an initial depth that is spatially uniform
- Accumulated dust reflects seasonally integrated dust lifting and deposition; thus providing a memory of past lifting activity

GCM Modeling of the Mars Dust Cycle

Interactive Dust Lifting Parameterizations

Newman et al. 2002; *Basu et al. 2004*, 2006; *Kahre et al.* 2005, 2006, 2008

Dust lifting by convective activity (parameterized "dust devils") and by resolved-scale wind stresses (dust injection via saltation process).

$$F = \beta \mathcal{D}(T_{sfc}, T_{air}) + \alpha U^3(1-R)(1+R^2); \quad \text{with } R = U_t/U; \; U > U_t$$

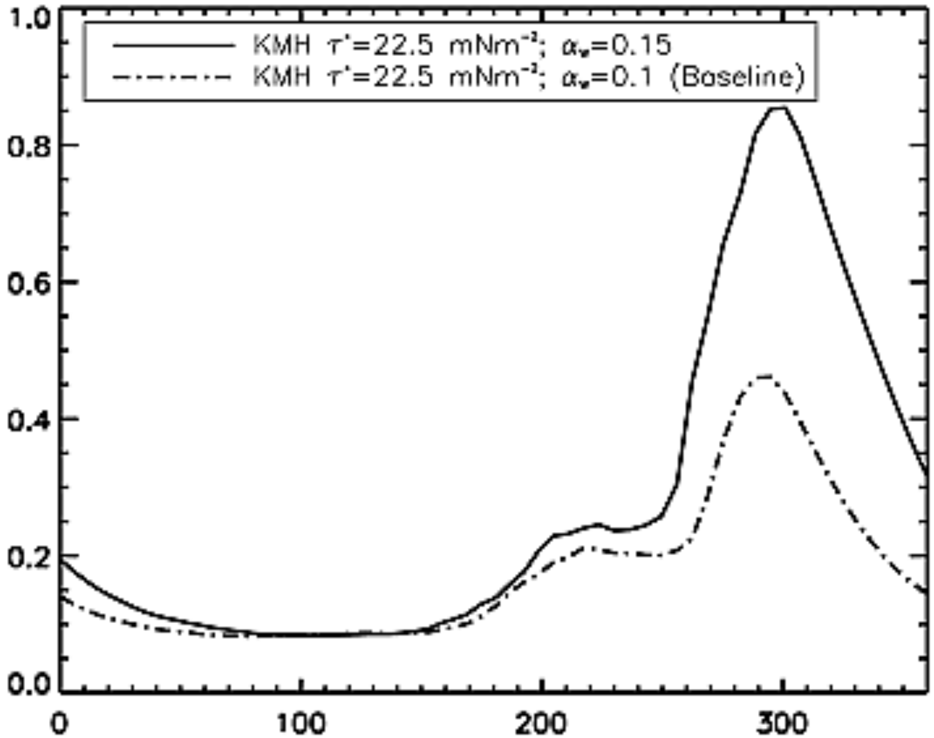
U_t is the threshold friction velocity (surface stress $\tau = \rho U^2$)

α, β are efficiency factors

Parameters β, α and U_t are adjusted to provide a reasonable correspondence between simulated global opacity to observations

Representative Dust Cycle Simulation

Global Mean Opacity



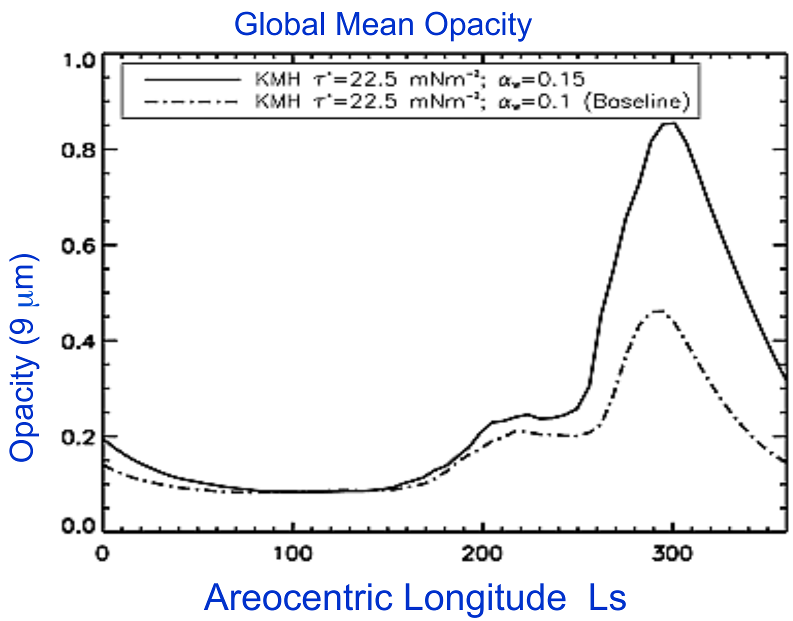
Opacity (9 μm)

Areocentric Longitude Ls

***Kahre et al.* 2006**

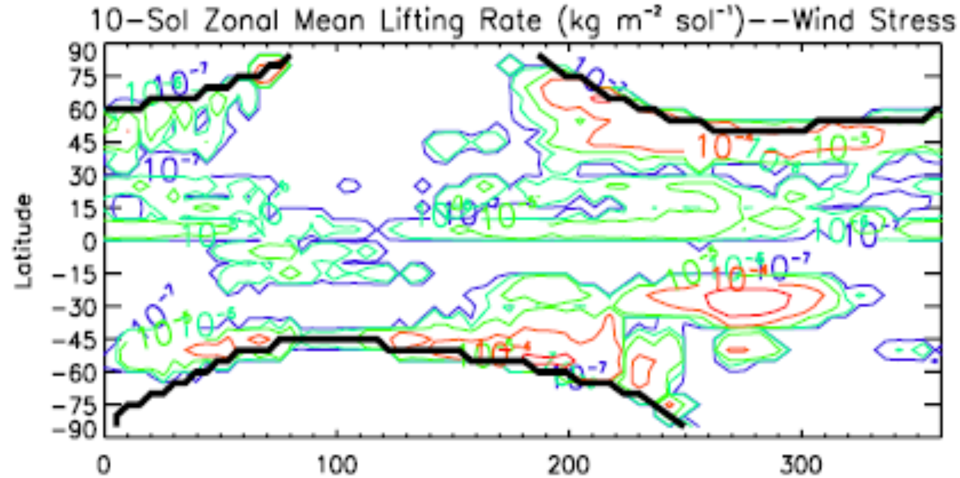
Two values of α:
More or less dust lifting during the storm season

Peak opacity at Ls= 290°; No Interannual Variability

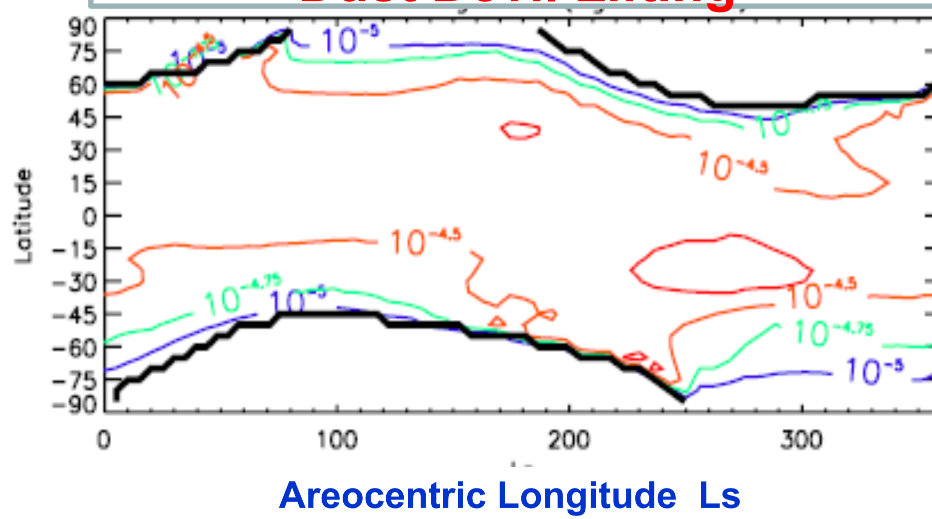


Wind Stress Lifting

(logarithmic scaling)



Dust Devil Lifting



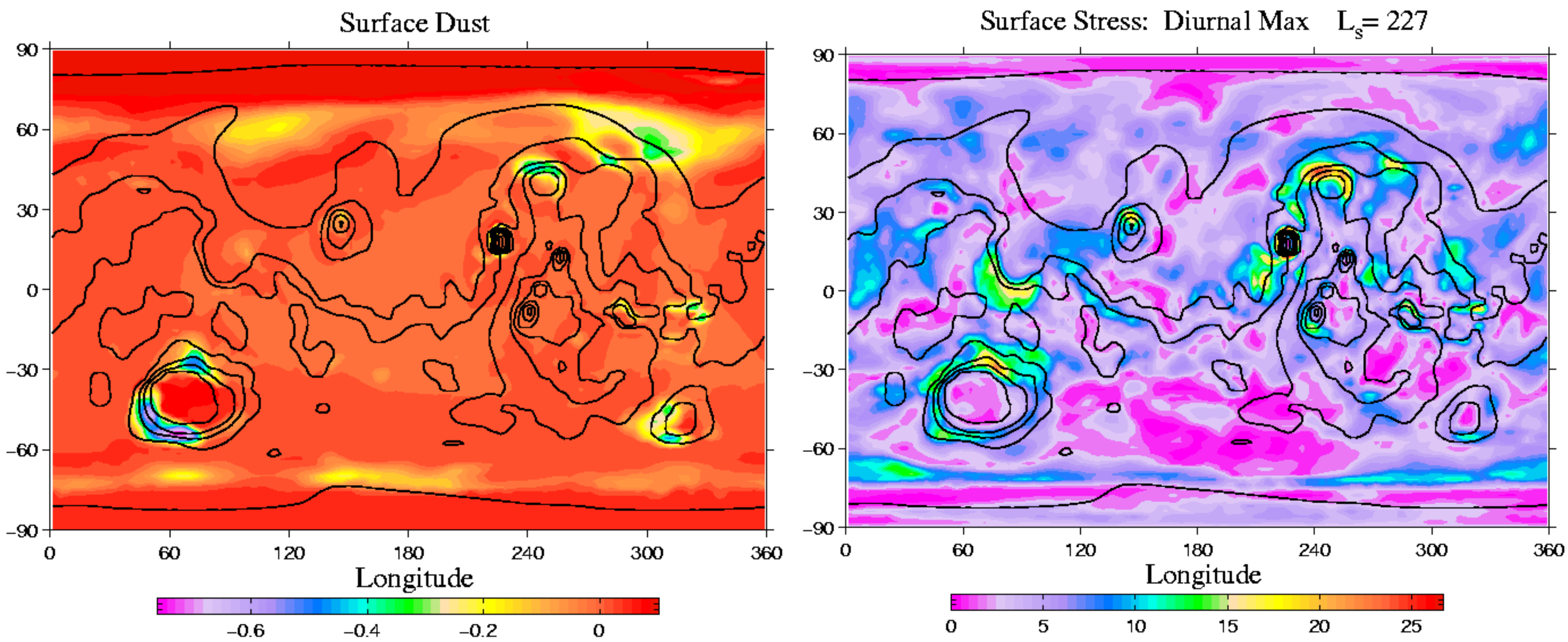
Lifting dominated by Cap Edge and Subtropical Jet stresses

***Kahre et al.* 2006**

***Convective lifting**: relatively weak seasonal variation; Source amplitude is constrained to allow model to match relatively low opacities during the NH spring/summer season*
***Negative feedback**: weakens with increased dust loading*

***Stress lifting** is then required to match the observed opacity/temperature during the dust storm season.*
***positive feedback:** stresses increase with increased radiative forcing*

Dust Cycle Modeling with Finite Surface Reservoirs



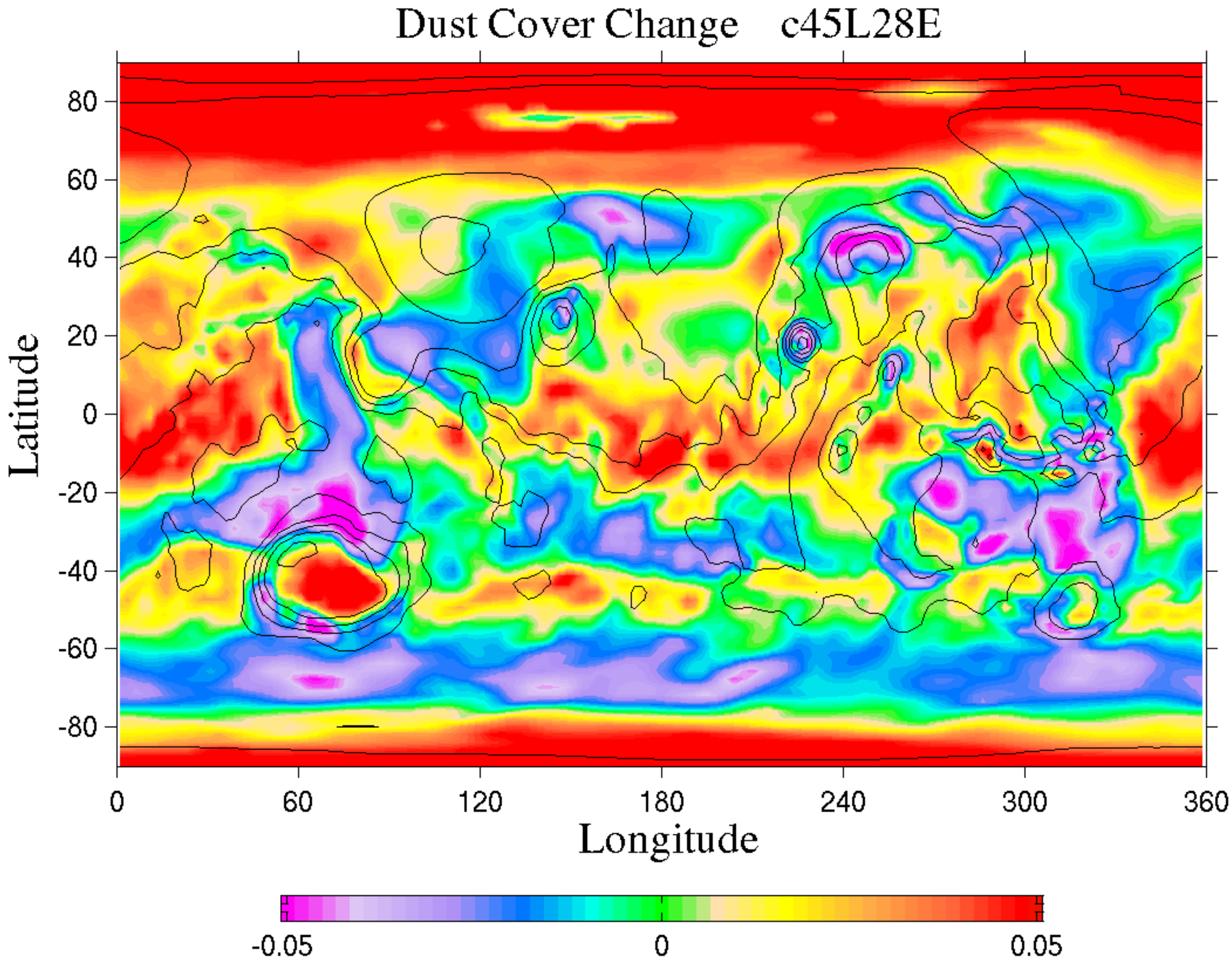
Goal: Improved spatial and temporal variability in dust lifting activity

Interactive dust lifting with finite surface dust reservoir

Stress thresholds for dust lifting are allowed to increase as surface dust is depleted

Regions of accumulated/depletion reflect seasonally-integrated dust lifting and deposition; provides a memory of past lifting activity

C48L28 (2°x2°)



Regions of accumulation/depletion reflect seasonally-integrated dust lifting and deposition; provides a memory of past lifting activity. Pattern is equilibrated.

Summary

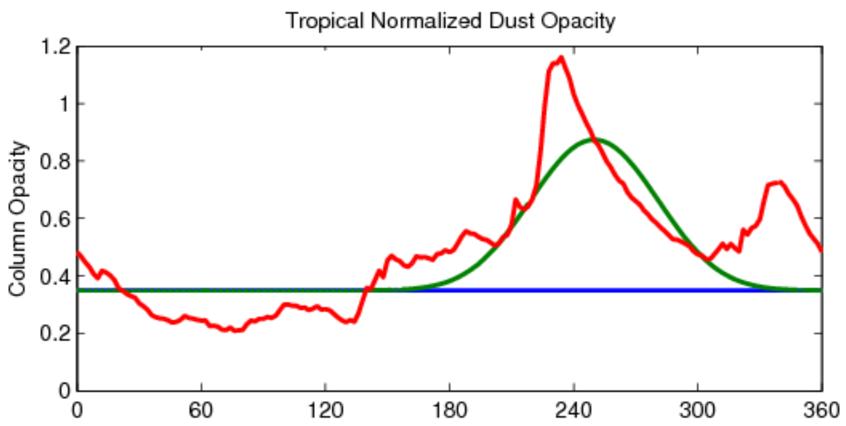
- **Allowance for finite dust deposits provides a negative feedback mechanism that can yield interannual variability**

- **More work remains in analyzing the observations and improving MGCM parameterizations:**
  - Need to reduce the extent of spatial connectivity, current simulation yielded only a quiescent/full-on-storm dichotomy
  - Models do not seem to adequately represent the response to flushing storm activity. Inclusion of radiatively active polar hood clouds improves the traveling wave climatology in model simulations. Preliminary results do not show a big impact on the character of the dust cycle.
  - Research and observations. Albedo is currently the best indicator of changes in surface dust, but is difficult to monitor during dust storm events.
  - New and/or improved physical descriptions of dust lifting.

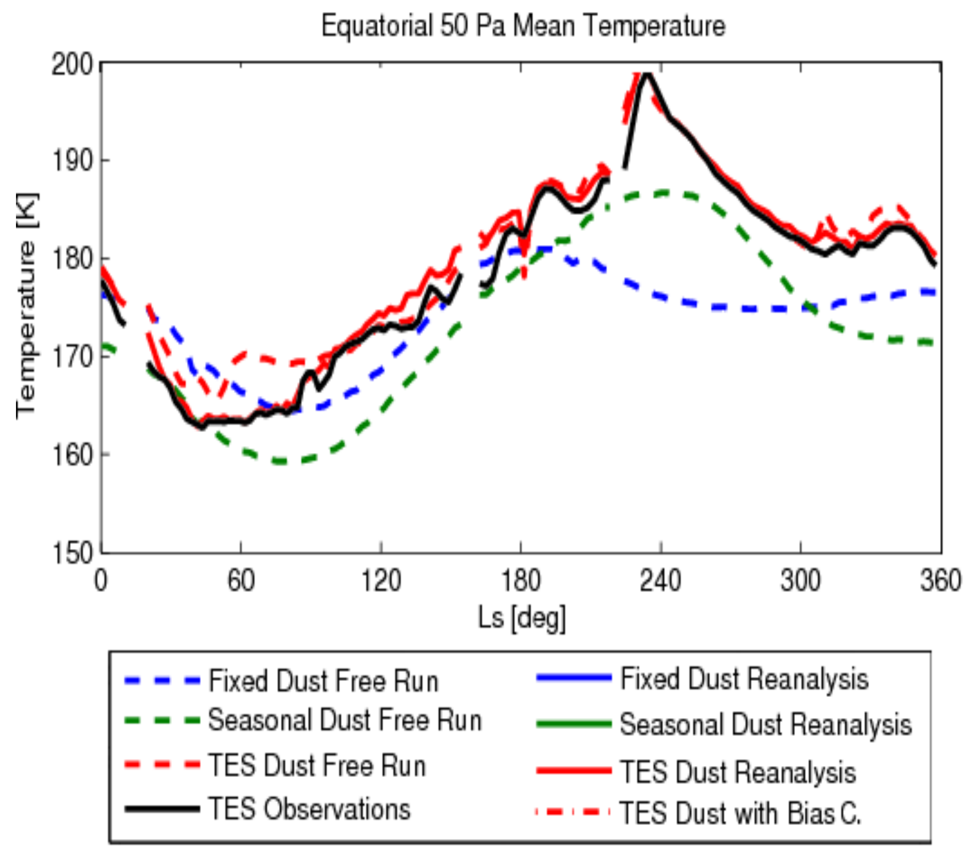
MGCM-LETKF Mars Reanalysis Goals

- Innovate ensemble data **assimilation** methodology for the unique characteristics of the Mars atmosphere and its observing systems.
- Improve **model** representation of dust and ice cloud aerosols.
- Provide community with 4-D **synoptic states** of atmospheric and aerosol fields to explore science questions: traveling waves, dust storm evolution, etc.
- **Evaluate** reanalysis through comparison with other reanalyses and observation products.
- Assess atmospheric **predictability** and analyzability.

How sensitive is the temperature reanalysis to the choice of dust aerosol distribution?



Areocentric Longitude

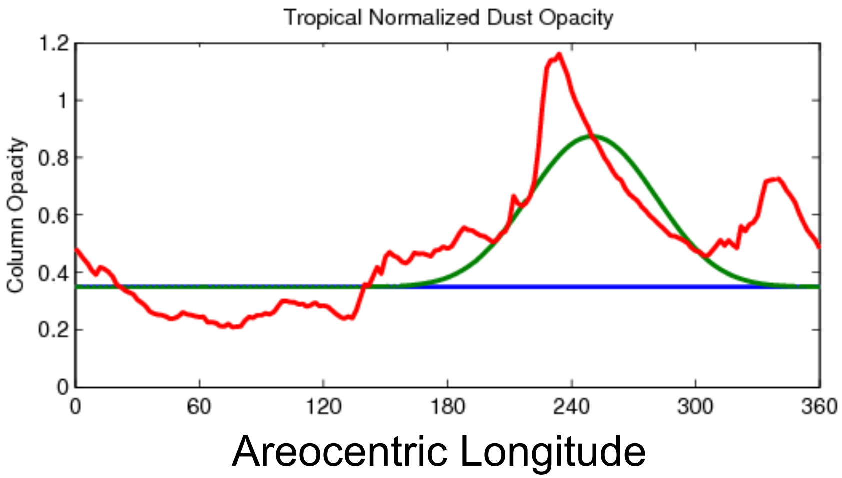


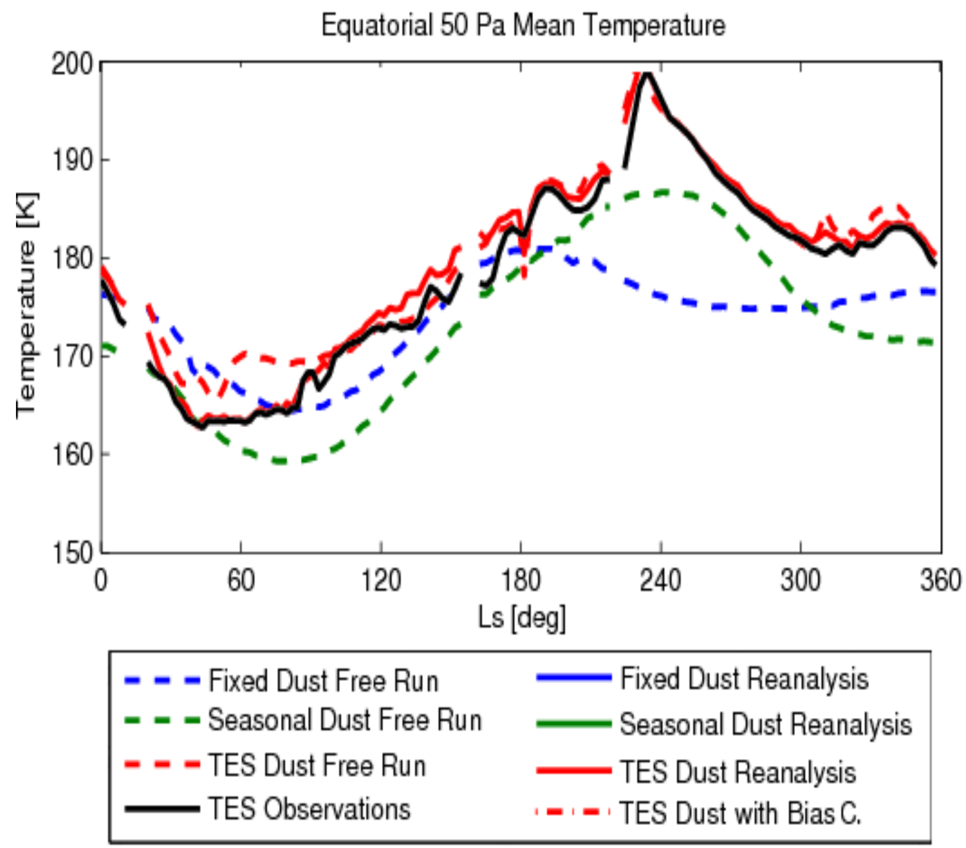
3 aerosol scenarios:

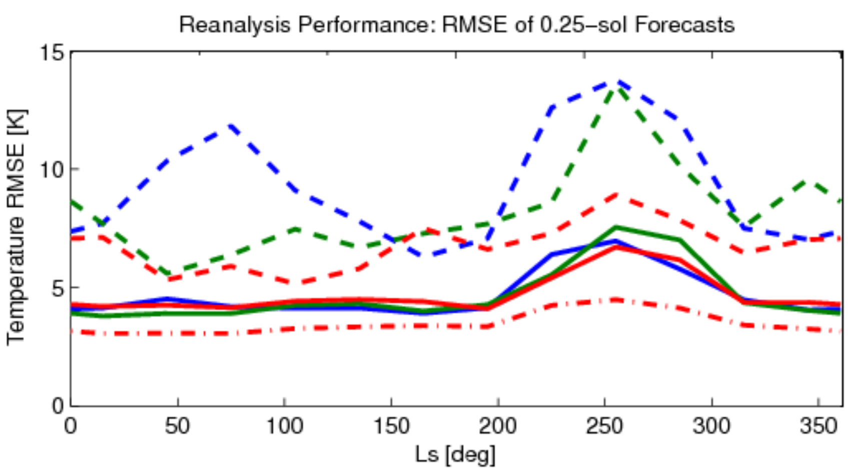
- fixed dust (t= 0.3)
- seasonal varying dust
- TES dust + ice cloud

Greybush et al. JGR. 2012

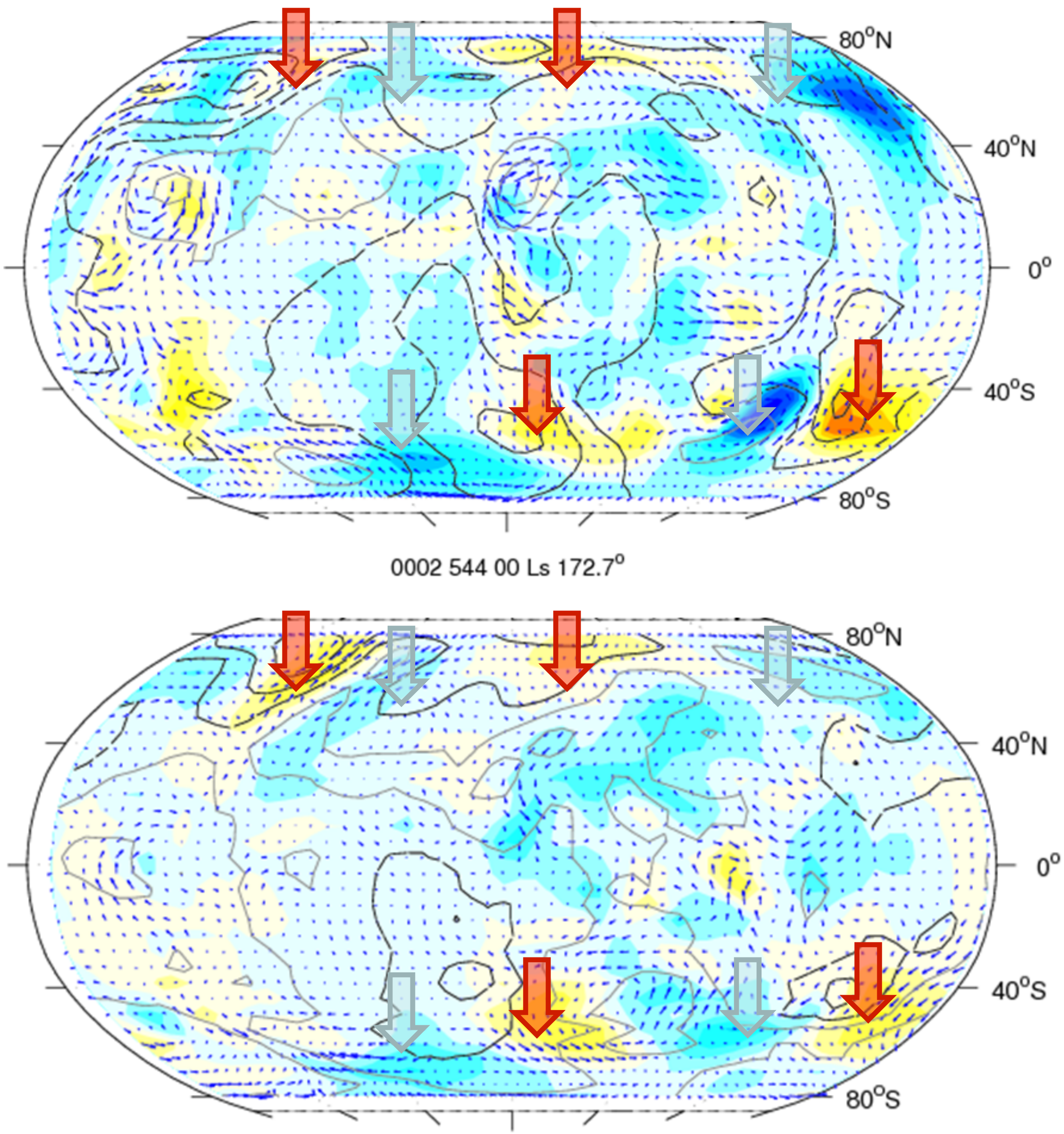
How sensitive are temperature reanalyses to the choice of dust aerosol distribution?







Synoptic Maps from Reanalysis



Simple Reanalysis:
Fixed Dust
No Bias Correction

Do reanalyses with different model configurations, initial conditions, and data assimilation techniques converge on the same synoptic state of traveling waves?

Advanced Reanalysis:
TES Dust and Water Ice Clouds
Empirical Bias Correction

Perturbed Assimilation Experiment: Doubled visible opacity: MY25

Reanal, Control and Reanal_B, Control_B

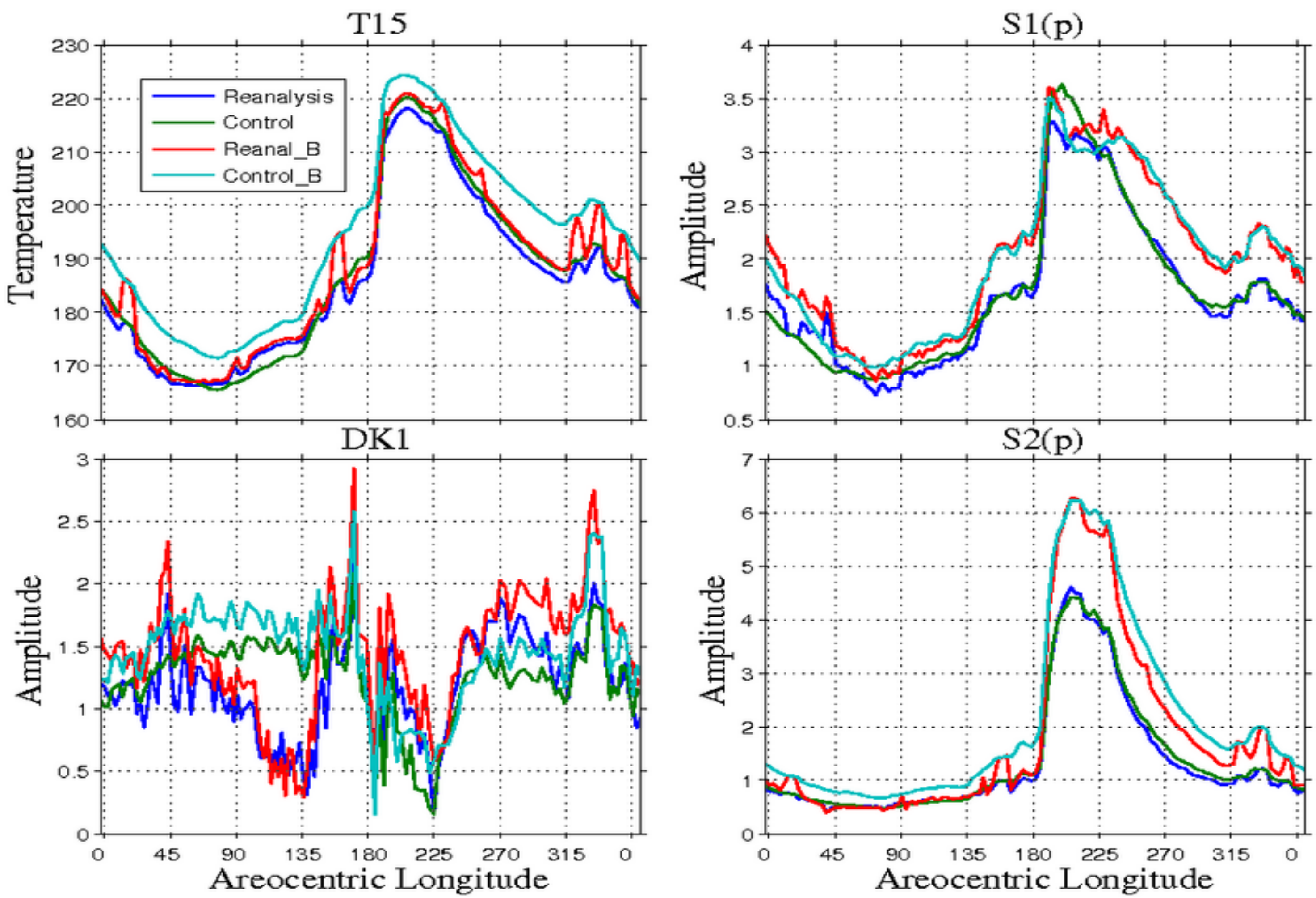


Figure 11. (a) Zonally-averaged equatorial T_{15} for 4 simulations for MY25. (b) The $S_1(p)$ (c) DK1 (d) $S_2(p)$. In all cases, the ReanalB and ControlB cases use the doubled visible dust opacity.

High Resolution Modeling

Global scale mesoscale model

Convective plumes driven by dust aerosol (Rocket dust storms)

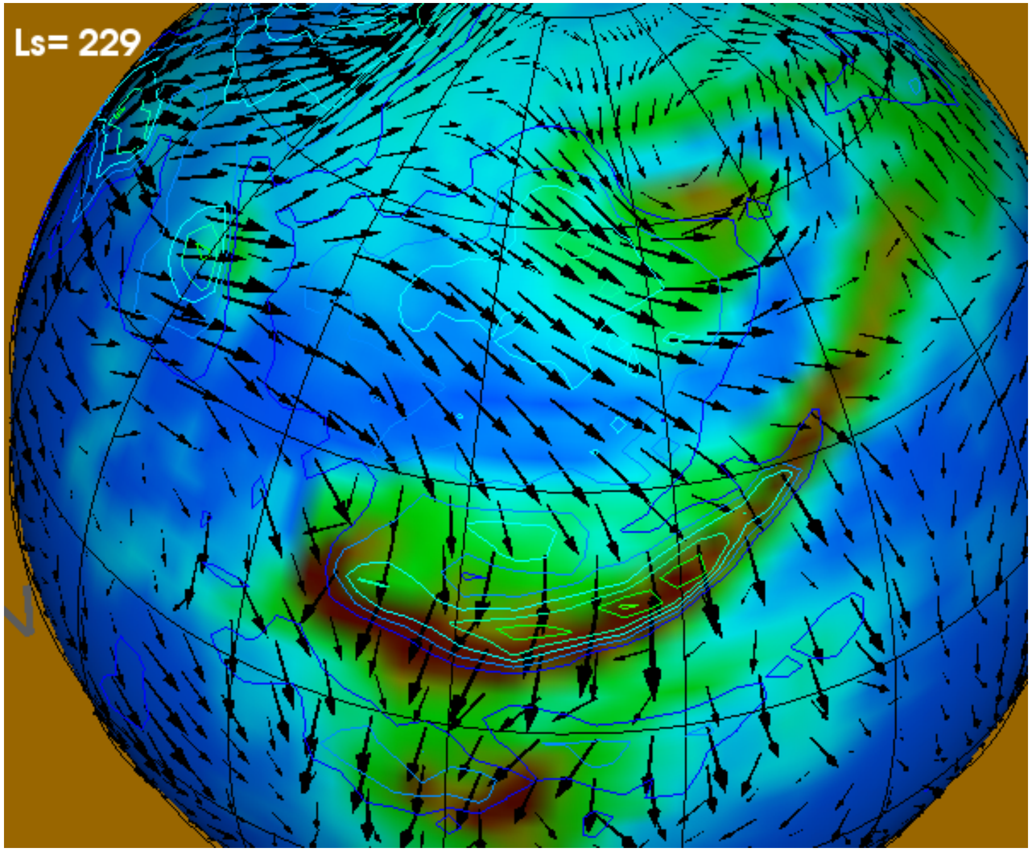
Surface/Atmosphere interactions---- slope winds

Frontal Circulations

Vertically propagating gravity waves: interactions with the large scale circulation

Collaborations with Aymeric Spiga and Takahashi-san

Frontal Storm Simulation



Chyrse Basin 330E, 40N

2°x 2.4° lat-lon

Interactive dust lifting

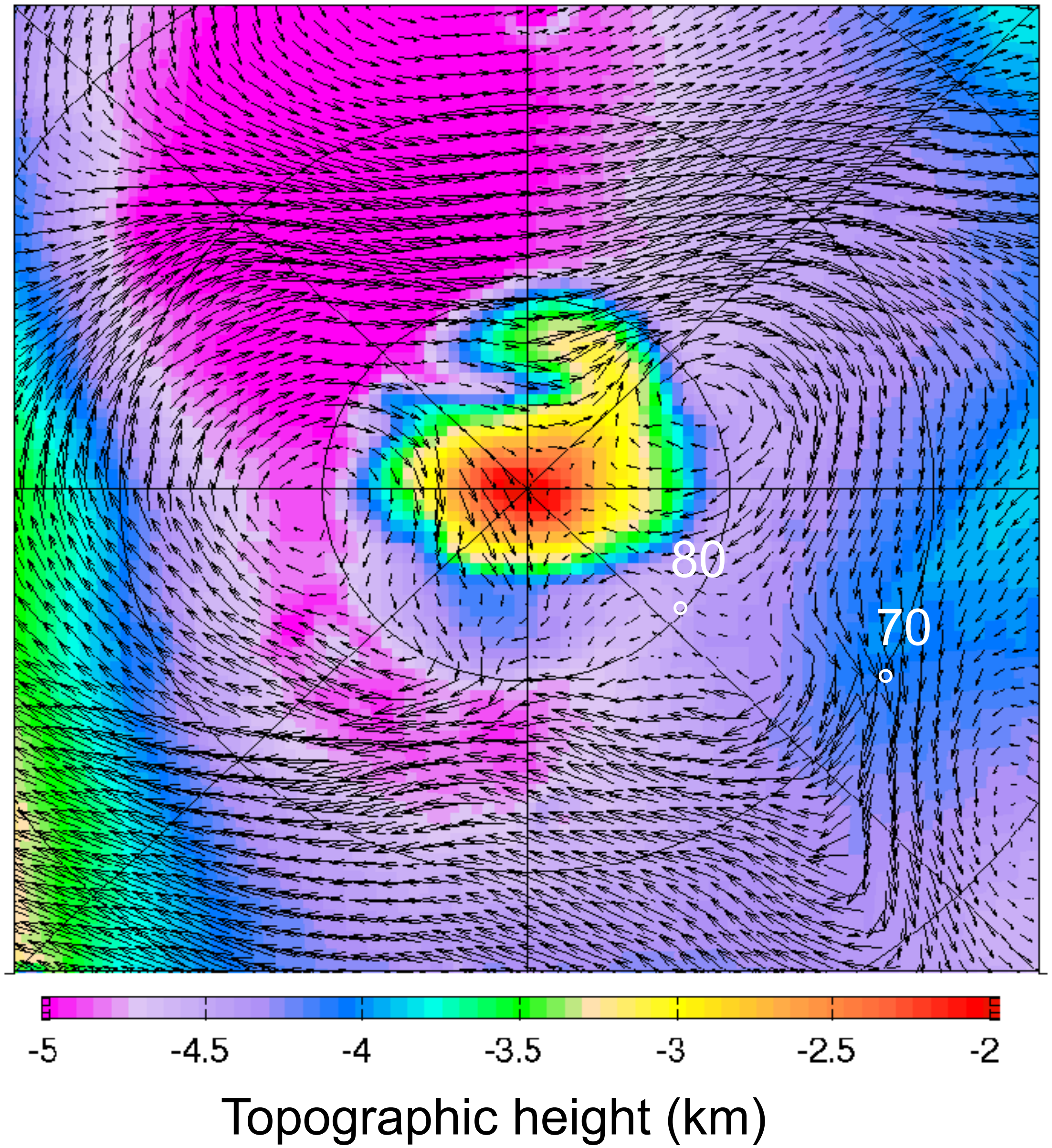
Dust column opacity (shaded)

Winds (1 km agl)

Surface Stress (contours)

Figure 8. High resolution simulation of a frontal system in the Chryse basin showing column dust opacity (shaded) and low-level (~1 km) winds. High values of surface stress are indicated by contour lines. The figure is centered on 330° E, 40° N.

Mars North Polar Cap   C180   0.5° x 0.5°

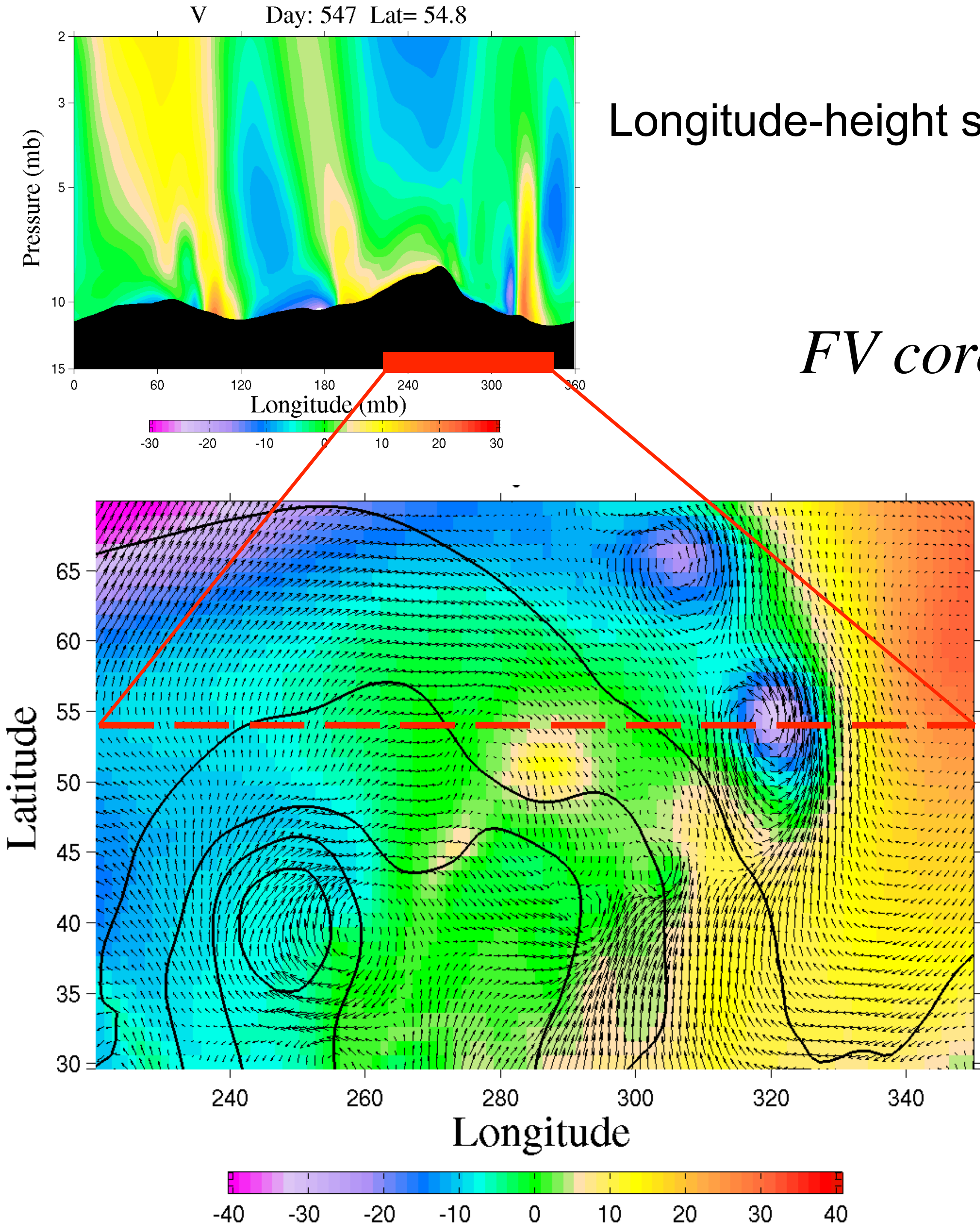


Winds @ 1 km agl

Subsampled at 1°x1°

Uniform resolution: no polar filtering

Longitude-height section of V field at 55° N



FV core: 1x1.2 resolution

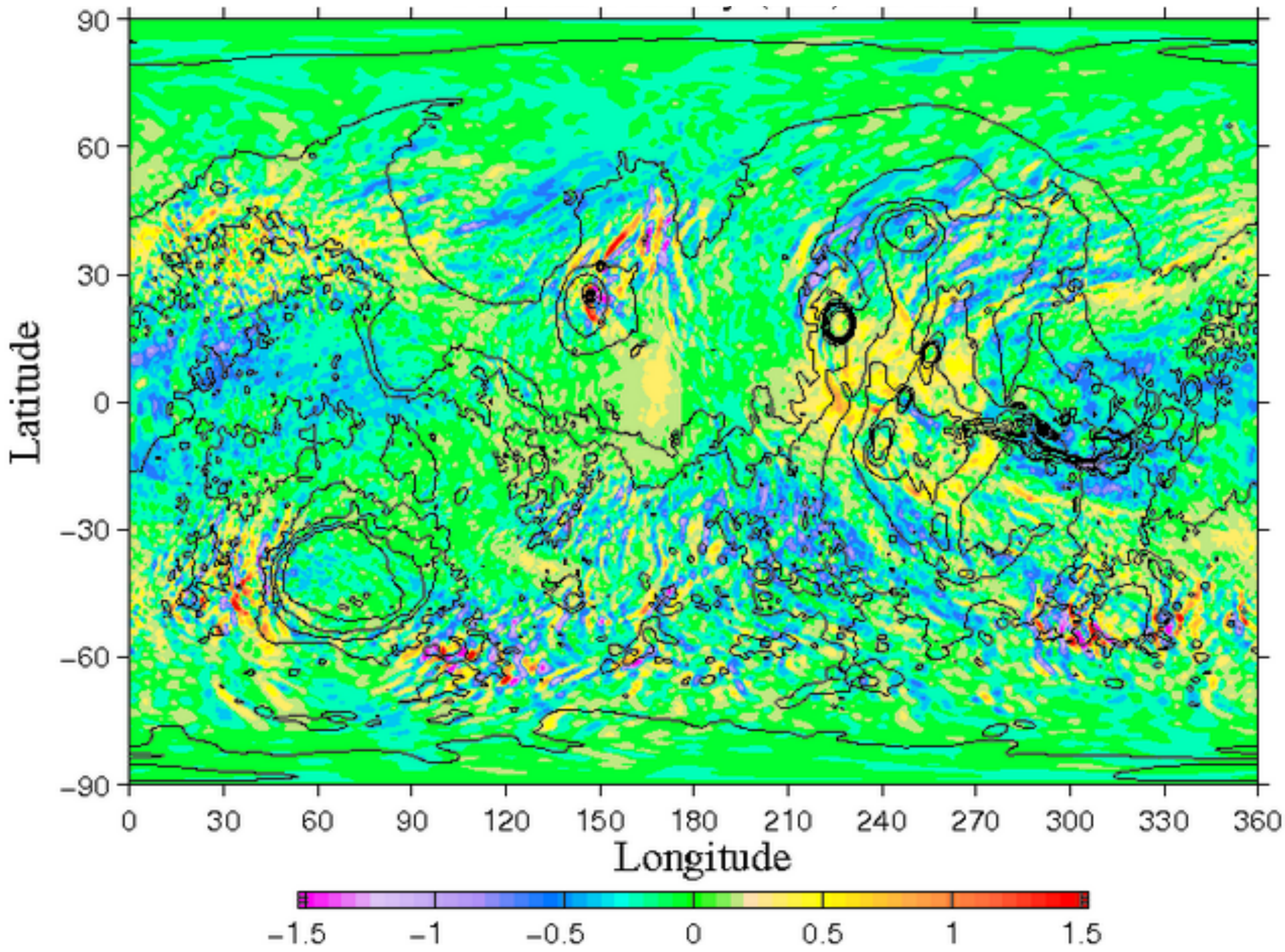
$L_s = 185$

Zoom view:

Near-surface winds (1 km)

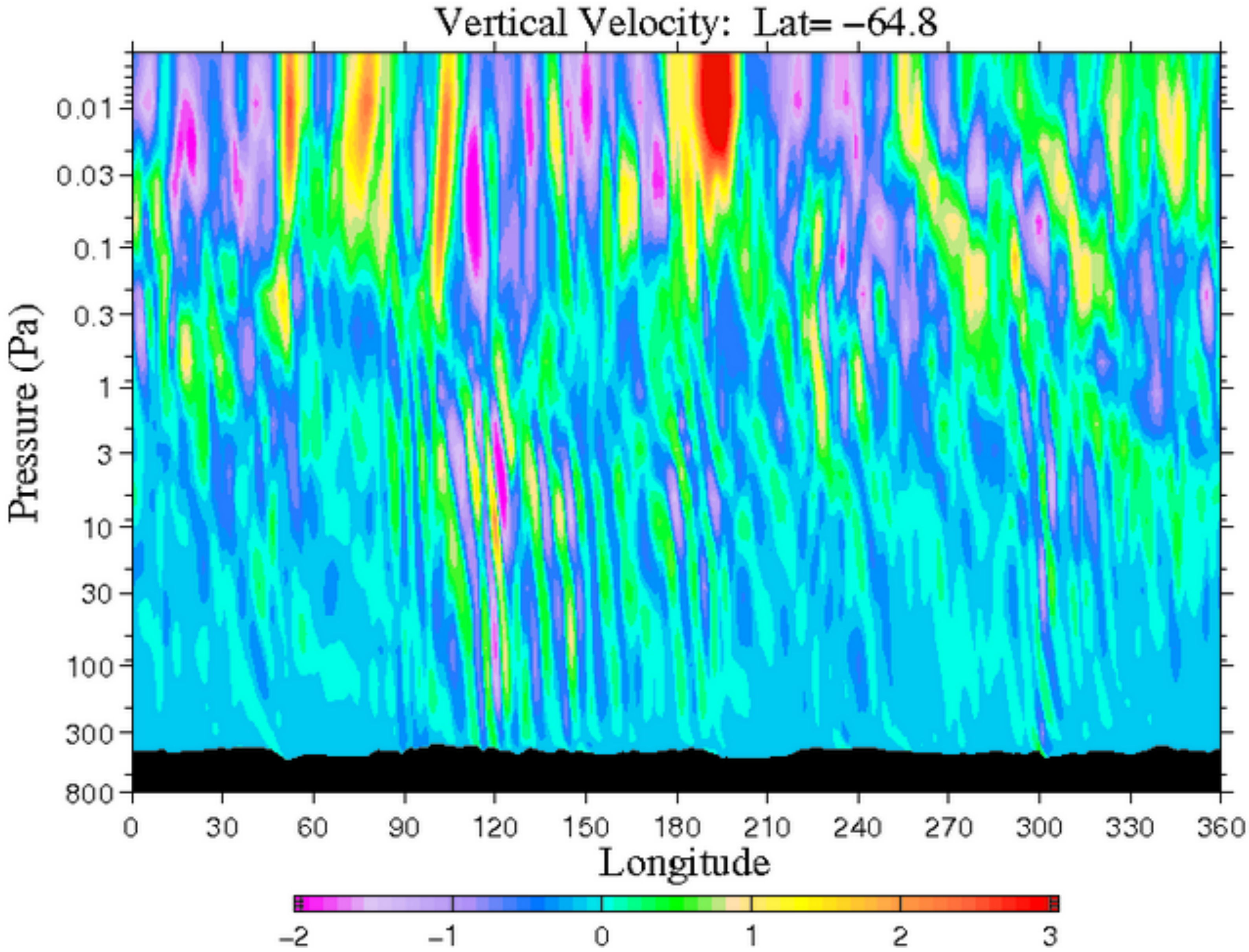
perturbation surface pressure *shaded* (Pa)

C180 0.5x0.5 Resolution Vertical Velocity 15 Pa

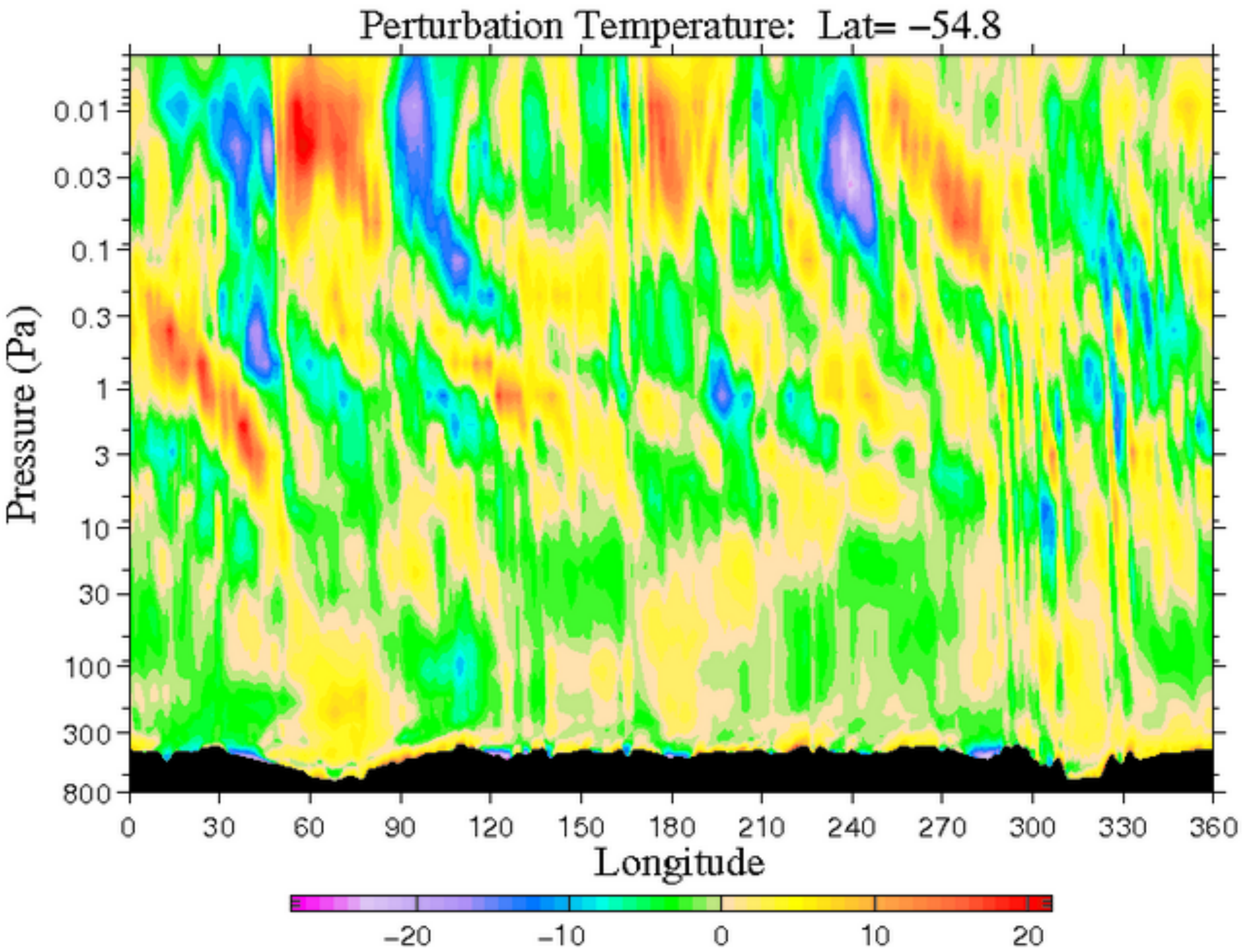


Vertical velocity (m/s) on the 15 Pa ($z \approx 35$ km) isobaric surface. L_s=178.

Gravity Waves



Thermal Tides and Gravity Waves



C360 0.25x0.25 Resolution Tprime (%)