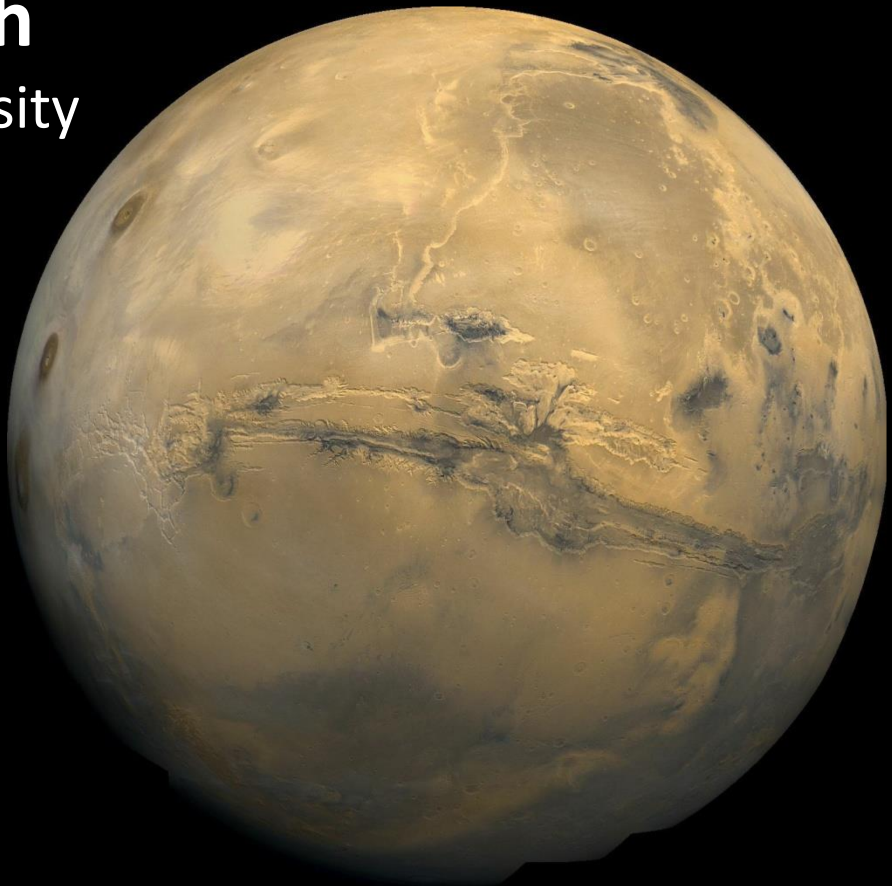
Ensemble Data Assimilation on Mars:
Insights into the ***Weather*** *and* ***Predictability*** *of the Red Planet*

Dr. Steven J. Greybush
The Pennsylvania State University



University of Reading
DARC Seminar
Wednesday 15 January 2014

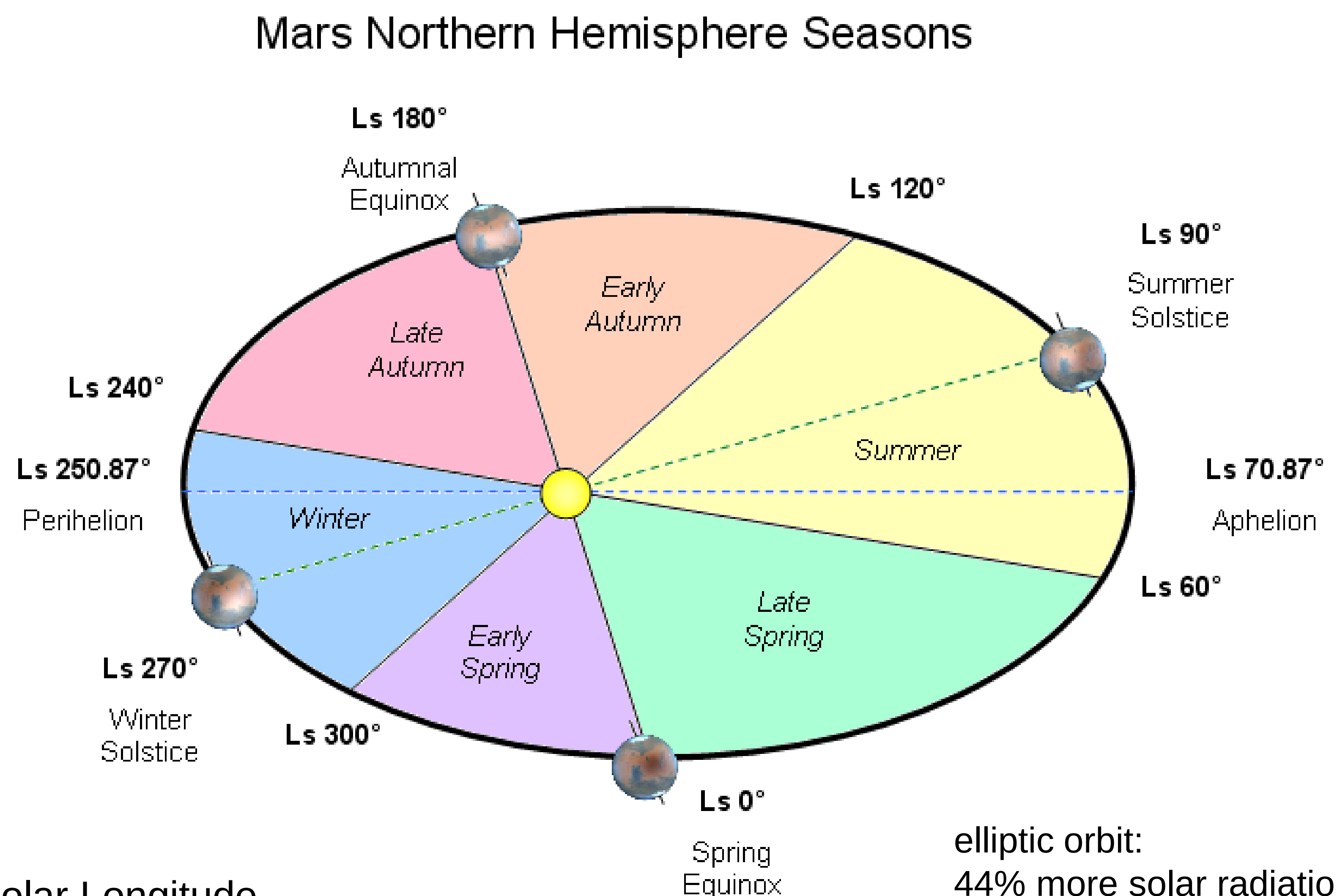
Outline

- Basics of the weather and climate of Mars
- Creating a Mars Reanalysis
  - Observations, Model, Assimilation System
  - Refinements and Evaluation.
- Exploring Science Questions
  - Instabilities and Predictability
  - Traveling Waves
  - Dust Storms and Water Ice Clouds

Comparing the Earth and Mars

Variable	Earth	Mars
Radius	6378 km	3396 km
Gravity	$9.81 \mathrm{m\ s^{-2}}$	$3.72 \mathrm{m\ s^{-2}}$
Solar Day	24 hours	24 hours 39 minutes
Year	365.24 earth days	686.98 earth days
Obliquity (Axial Tilt)	23.5 deg	25 deg
Primary Atmospheric Constituent	Nitrogen and Oxygen	Carbon Dioxide
Surface Pressure	101,300 Pa	600 Pa
Deformation Radius	1100 km	920 km
Surface Temperature	230-315 K	140-300 K

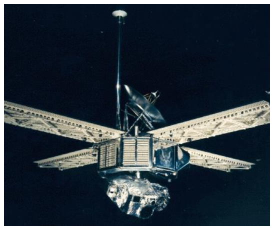
Orbit and Seasons of Mars



Ls = Solar Longitude

elliptic orbit:
44% more solar radiation at perihelion than aphelion

Spacecraft Exploration of Mars

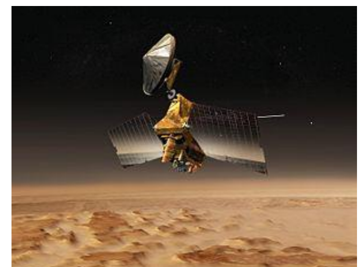


Mariner Program: Observed Dust Storms

Mars Global Surveyor: **TES**, MOC, MOLA…

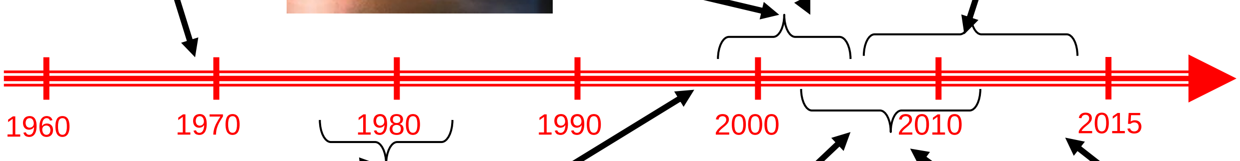
Mars Odyssey: Imaging and Spectrometry

Mars Reconnaissance Orbiter: **MCS**, MARCI…

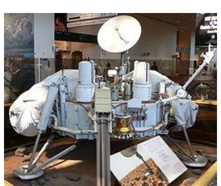


Mars Science Laboratory (MSL)

- Curiosity rover
- Launched Nov. 2011, Arrived on Mars Aug. 2012
- Rover Environmental Monitoring Station (REMS) – Air and Ground Temperature, Winds, Surface Pressure, Relative Humidity, UV Radiation

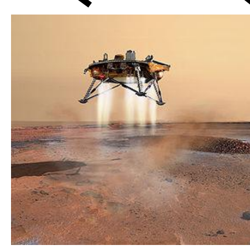


Viking Lander: Surface Pressure Time Series

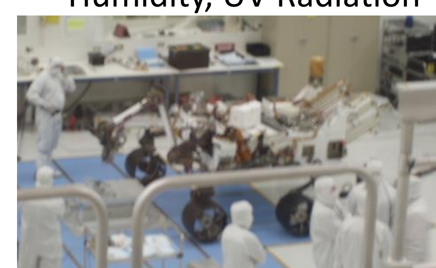


Mars Pathfinder: Surface Weather

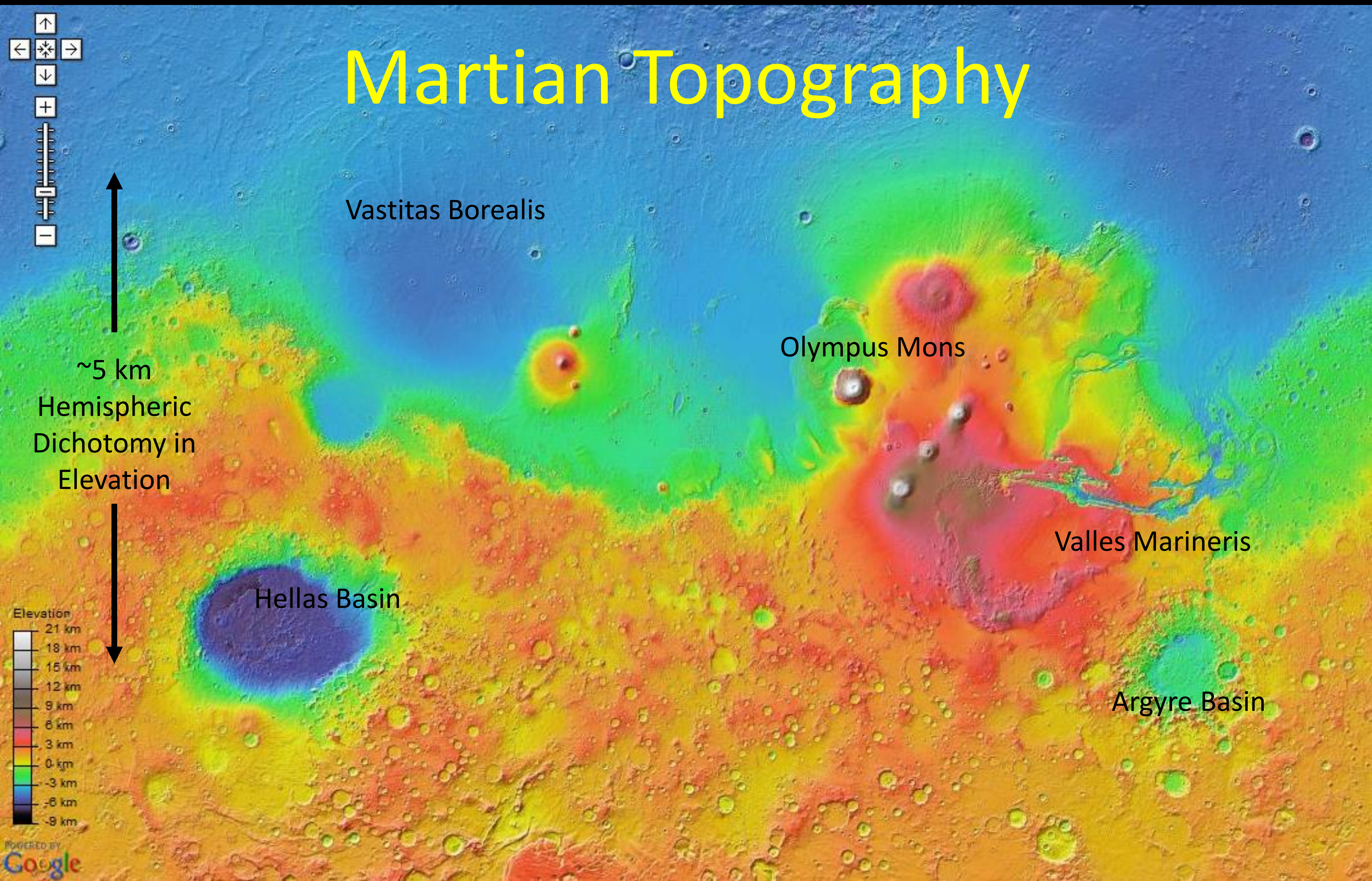
Mars Exploration Rovers: Dust Devils



Mars Phoenix Lander: Precipitation, Water Ice



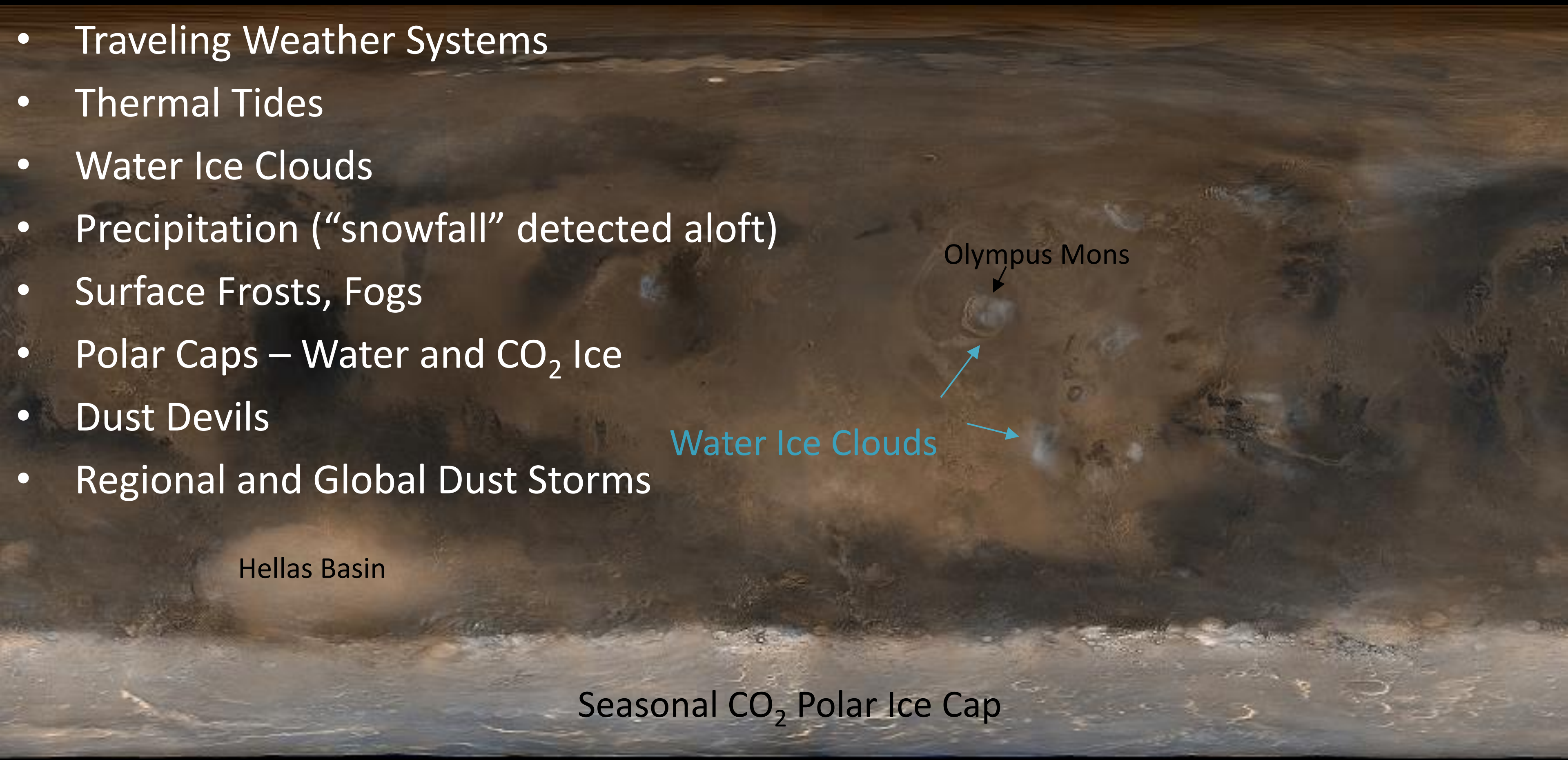
Martian Topography



Features of Martian Weather

Figure Courtesy of NASA/JPL and Malin Space Science

- Traveling Weather Systems
- Thermal Tides
- Water Ice Clouds
- Precipitation ("snowfall" detected aloft)
- Surface Frosts, Fogs
- Polar Caps – Water and CO_2 Ice
- Dust Devils
- Regional and Global Dust Storms

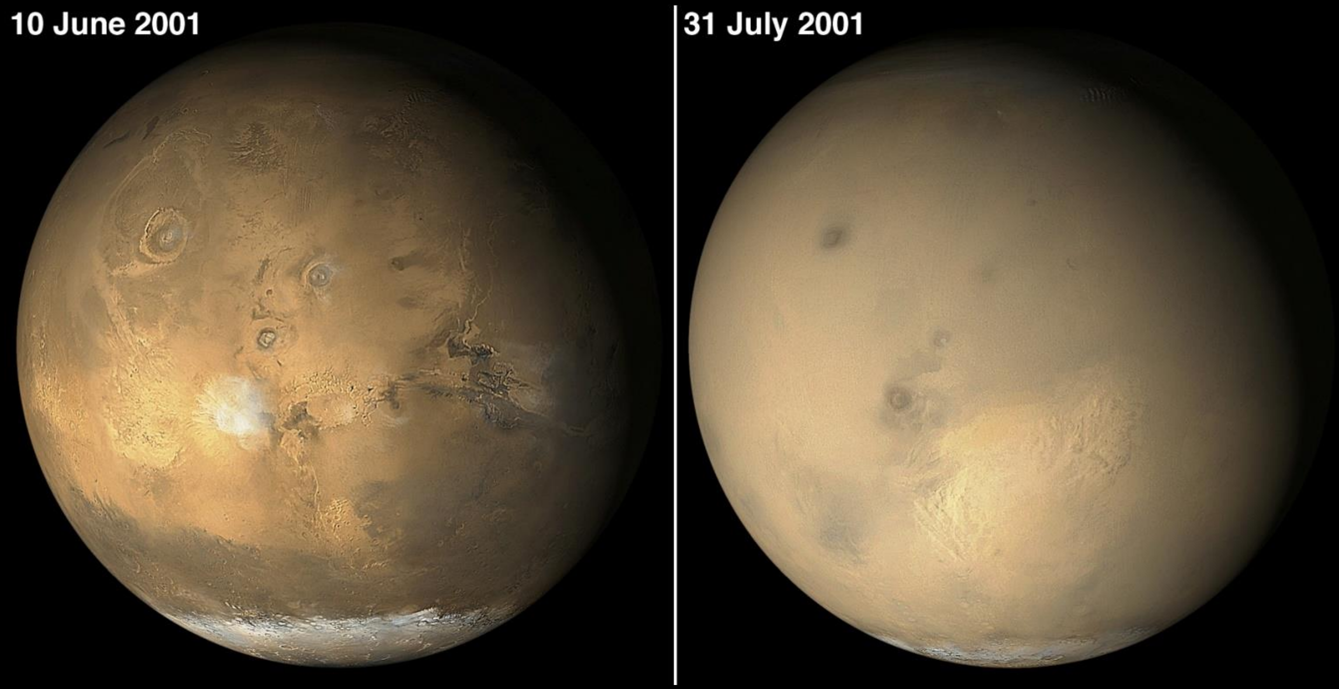


MGS Mars Orbital Camera (MOC) Visible Image

The Dust Storm Enigma

Whereas local dust storms occur every year, planet-encircling global dust storms occur irregularly every 2-3 Martian years.

The modeling of dust storms and their inter-annual variability remains a challenge for the Mars weather and climate community.



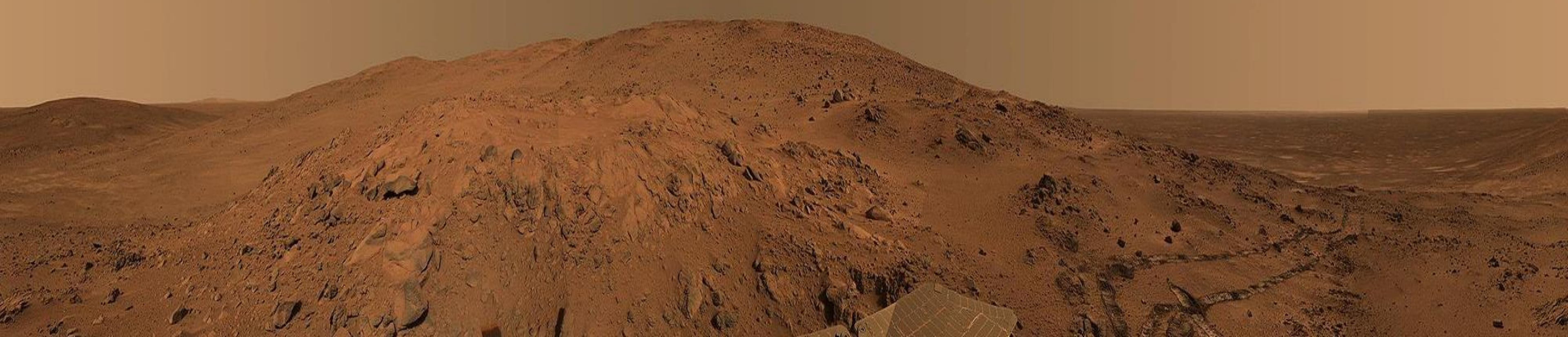
Prior to Global Dust Storm

During Global Dust Storm

Figure Courtesy of NASA/JPL

Creating a Mars Reanalysis

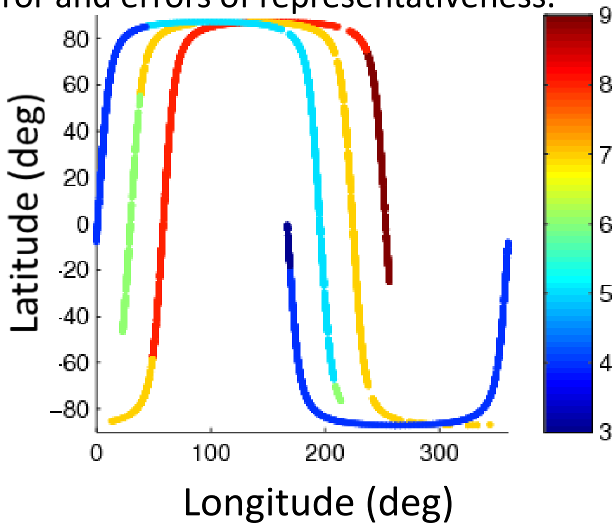
- Spacecraft Observations
- Mars Global Circulation Model
- Data Assimilation Techniques
- Performance Evaluation and Validation



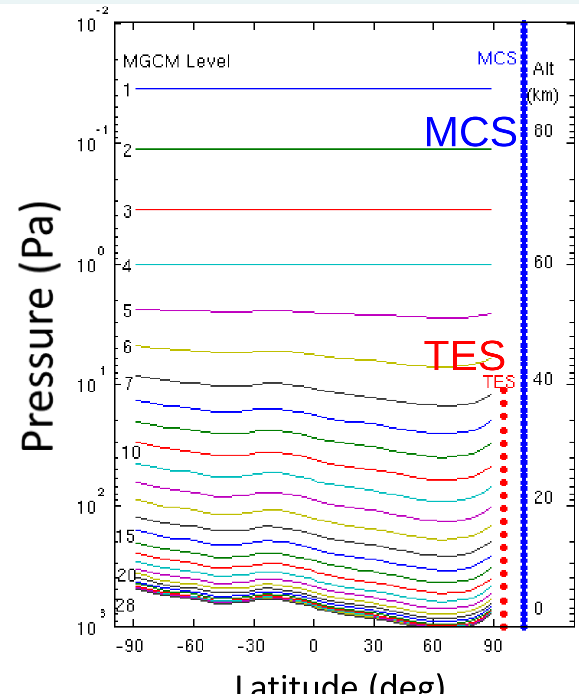
TES (Thermal Emission Spectrometer) MCS (Mars Climate Sounder)

Thermal Emission Spectrometer (TES)	Mars Climate Sounder (MCS)
Observations from 1997-2006.	Observations from 2006-present.
Nadir sounder.	Limb sounder.
Temperature retrievals at 19 vertical levels up to 40 km; column dust opacity.	Temperature, dust, and water ice retrievals at 105 vertical levels up to 80 km.
Observation error estimated at 3 K; characteristics not well known.	Random error < 1K at elevations below 50 km; estimated systematic error of 1-3 K.

Observation errors have both random and systematic components, and include instrument error and errors of representativeness.



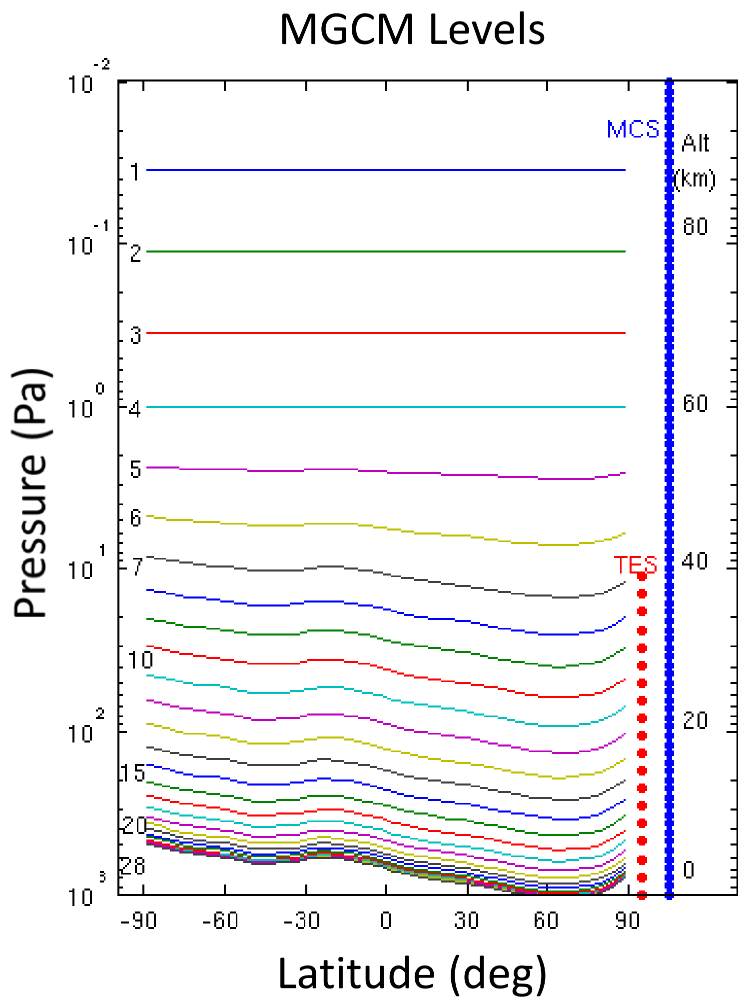
Sample locations of TES profiles during 6-hour interval



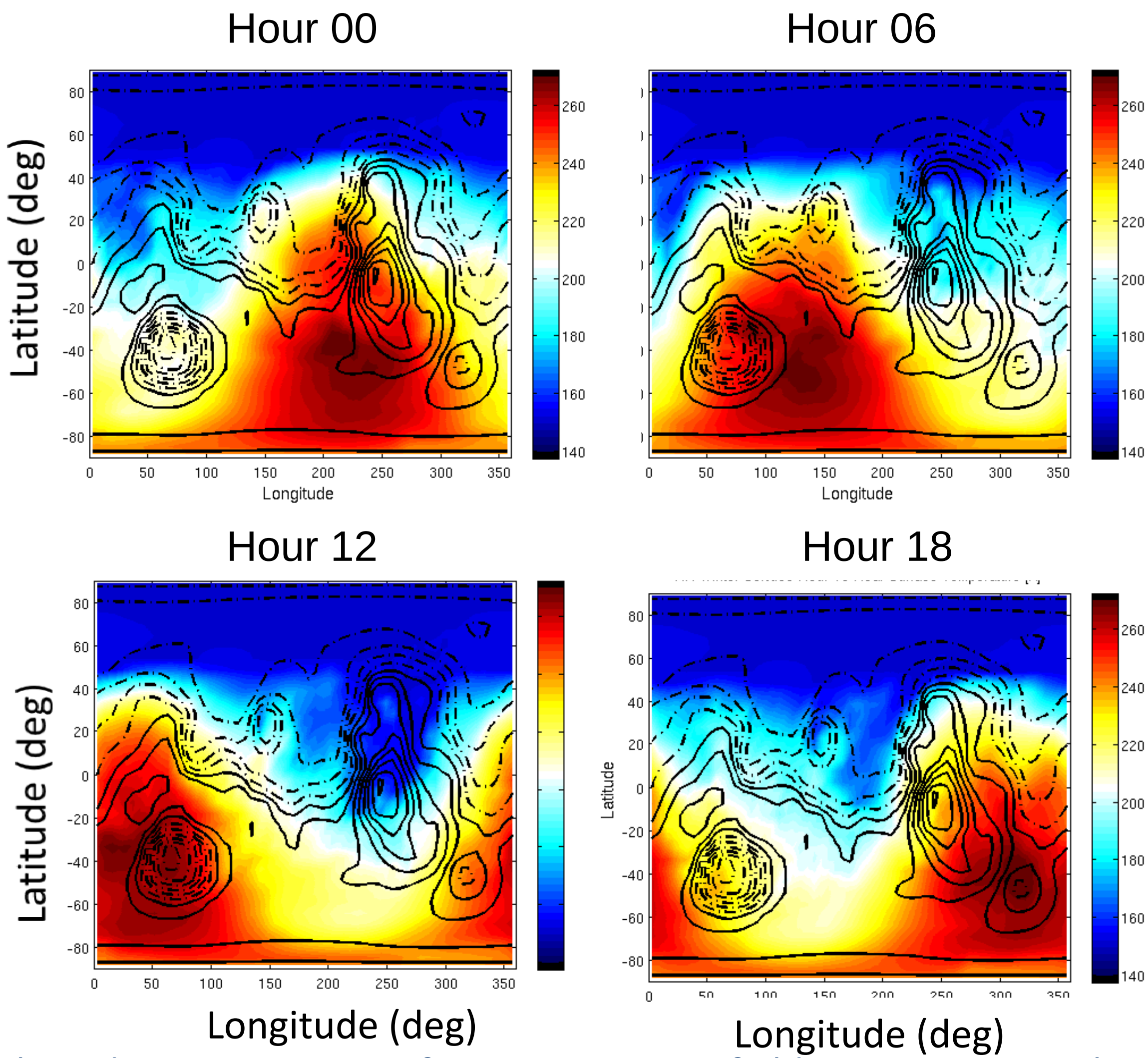
GFDL Mars Global Circulation Model (MGCM)

Developed by R. John Wilson, NOAA GFDL

- Finite volume dynamical core
- Latitude-longitude grid
- 60 x 36 grid points (6° x 5.29° resolution)
- 28 vertical levels
- Hybrid p / σ vertical coordinate
- Gaseous and condensed CO_2 cycle
- Shortwave and IR radiative transfer with the option for dust radiative feedback
- Soil model, boundary layer scheme, water budget, gravity wave drag, ice cloud microphysics
- Tracers for dust, water vapor, and water ice
- Dust lifting and sedimentation



Martian Diurnal Cycle

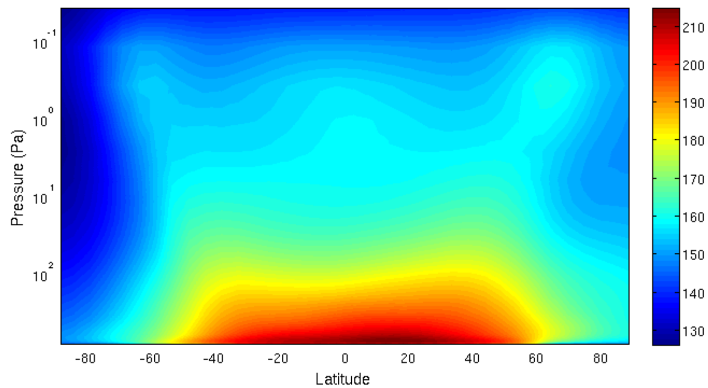


- The **thermal tide** can be tracked as the tongue of warm temperatures centered around the subsolar point as it moves across the planet over the course of a day.
- **Diurnal** temperature **changes** in the summer hemisphere can approach 100 K.

Plotted: MGCM near-surface temperature field at NH Winter Solstice in 0.25 sol intervals.

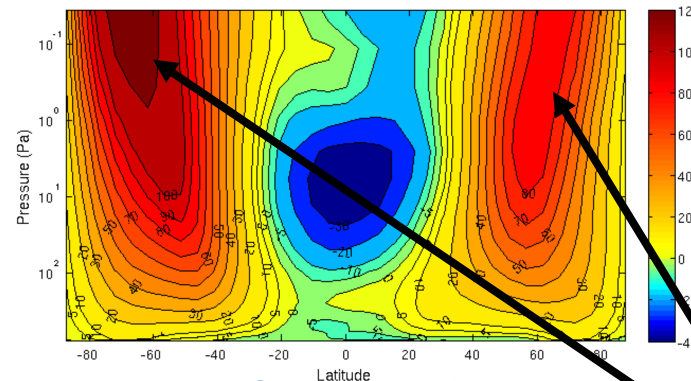
Contours are topography.

Martian Seasonal Cycle



NH Spring Equinox

Zonal Mean Temperature

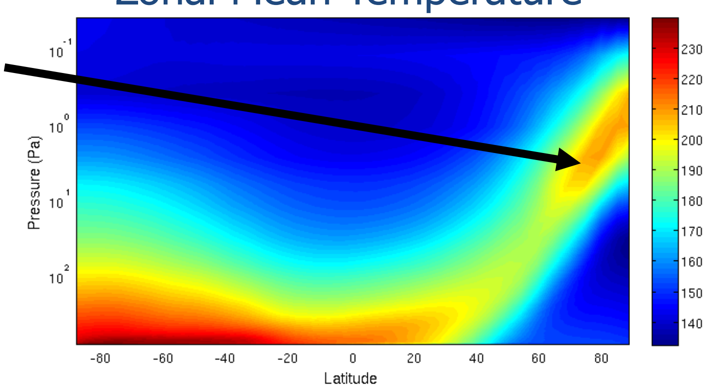


NH Spring Equinox

Zonal Mean U-Wind

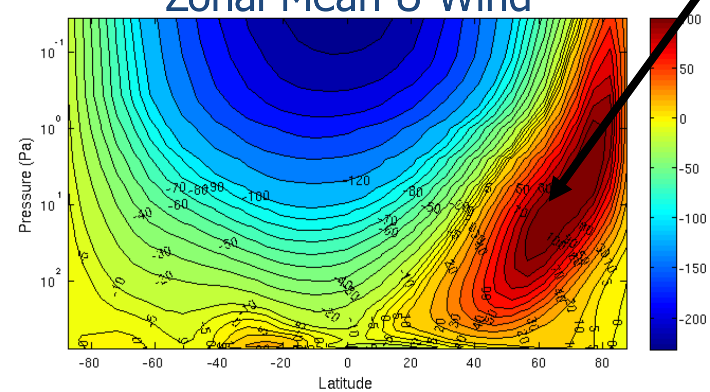
Westerly Jets

Adiabatic Warming from Global Hadley Cell Descent



NH Winter Solstice

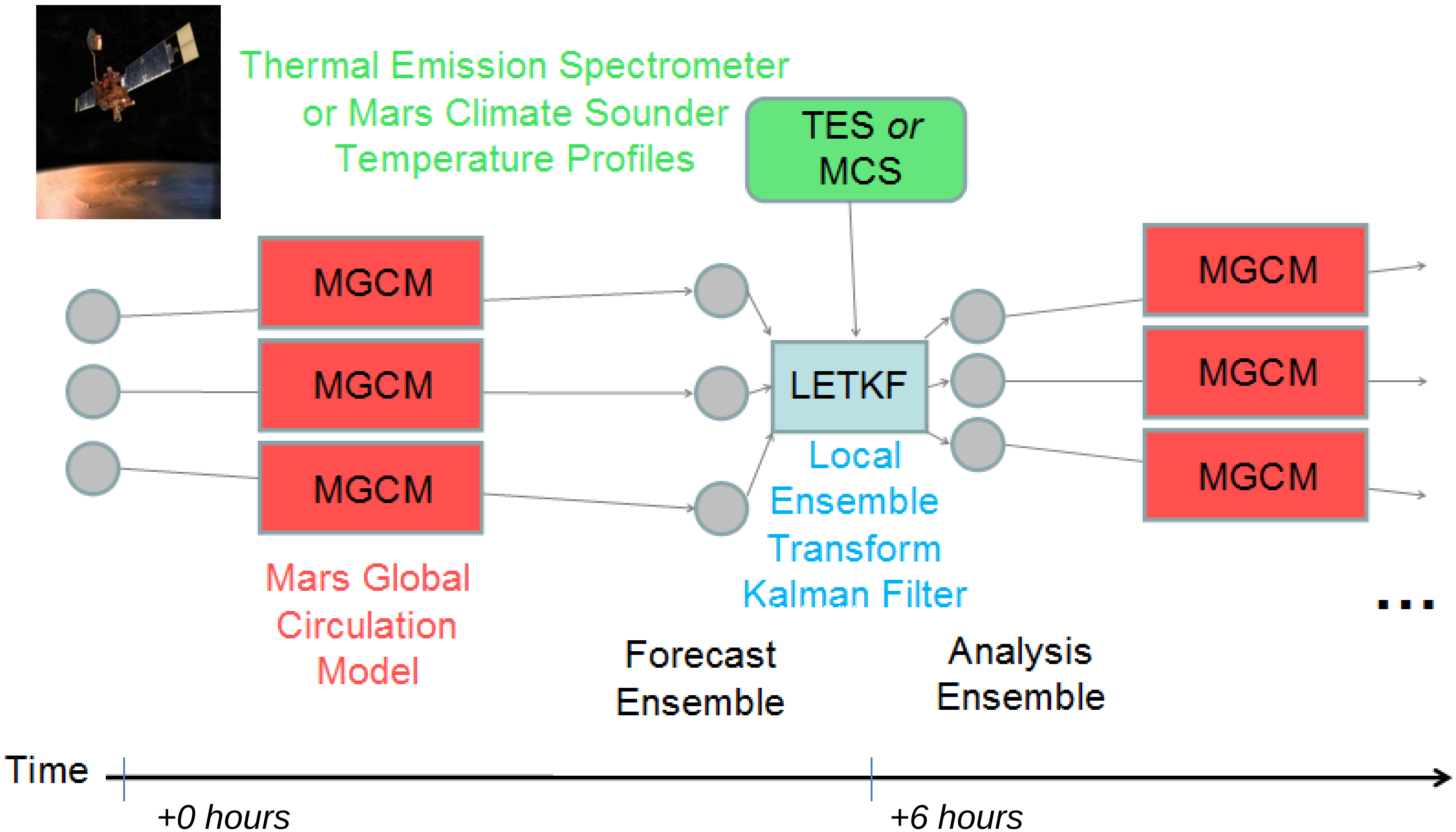
Zonal Mean Temperature



NH Winter Solstice

Zonal Mean U-Wind

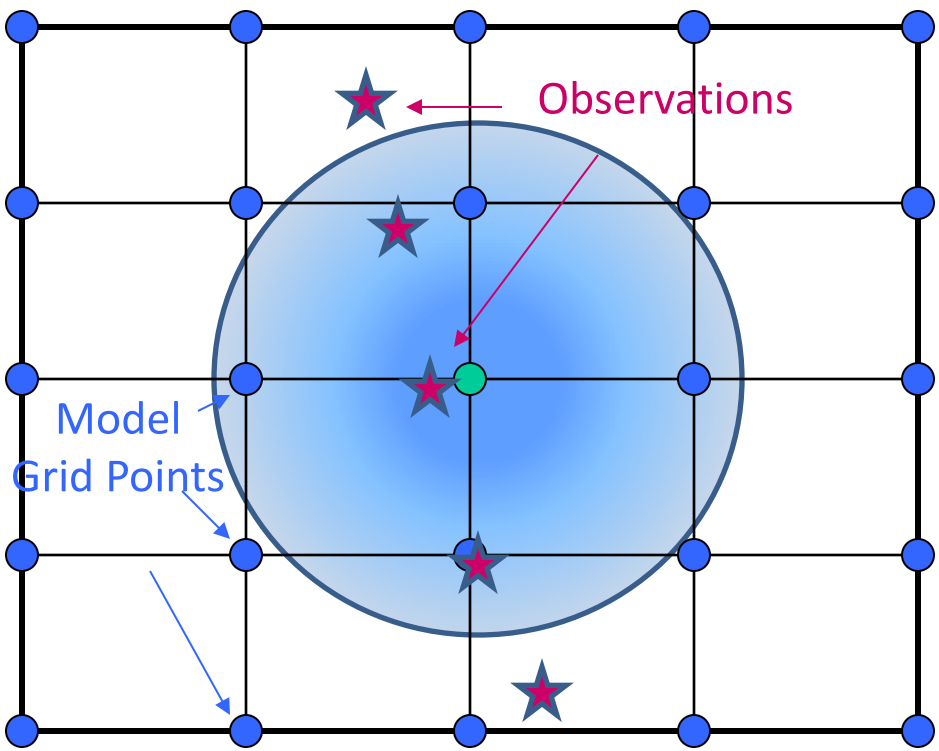
Assimilation: Optimally Combining Observations with a Model



Update: Temperature, U and V Wind, Surface Pressure

Local Ensemble Transform Kalman Filter (LETKF)

Goal: find analysis at each model grid point: $\mathbf{x}_a$



- Analysis at a given grid point is determined from the background at that point plus a weighted sum of observation increments within a **localization** radius. Observation influence gradually decreases with distance from the grid point.
- Analysis increment at a given grid point is a **local** linear combination of **ensemble perturbations**.
- Background, or forecast, errors are described by an ensemble of MGCM states , and evolve with the flow (an important **advantage** of **ensemble** data assimilation methods).

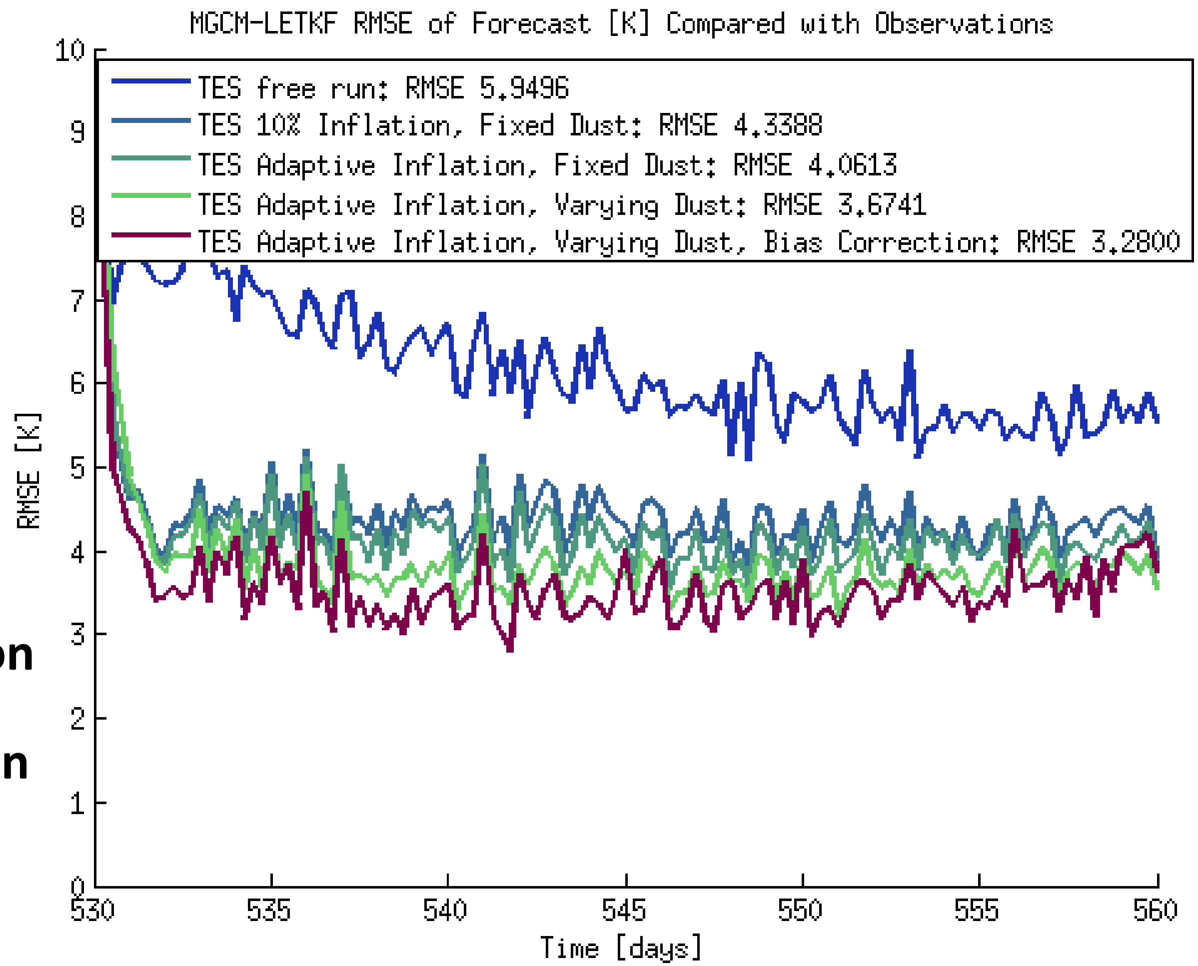
The **LETKF** *(Hunt et al., 2007)* is an efficient implementation of the Ensemble Kalman Filter (EnKF) suitable for Numerical Weather Prediction, and is competitive with the state-of-the art operational systems.

Improving LETKF Performance

- **Freely Running Model**
- **Initial Assimilation**
- **Adaptive Inflation**

  (Miyoshi 2011)
- **Varying Dust Distribution**
- **Empirical Bias Correction**

  (Danforth et al., 2007)



Evaluated by comparing 0.25 sol forecasts with observations.

Improving LETKF Performance

- Freely Running Model
- Initial Assimilation
- Adaptive Inflation
- Varying Dust Distribution
- Empirical Bias Correction
- Localization Tuning
- CO2 Mass Conservation

Ongoing Development:

Assimilation Window Length and the Diurnal Cycle
(Grad Student Yongjing Zhao)

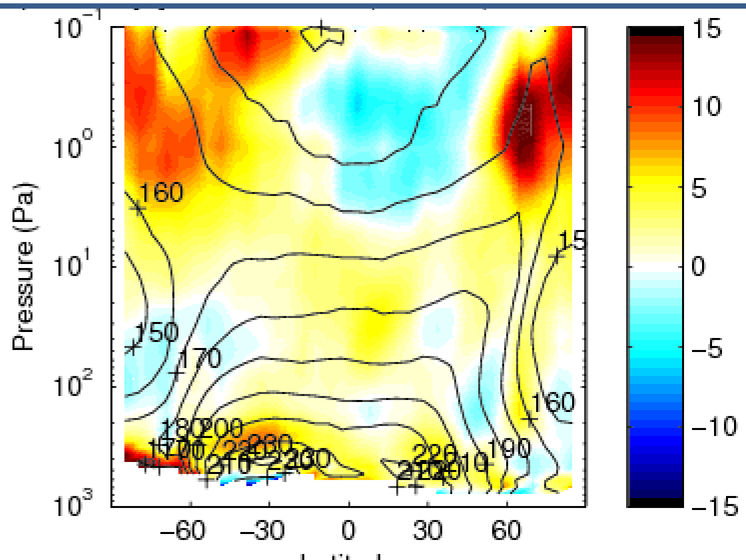
New methods for assimilating retrievals: transforming observations to remove the prior and vertical error correlations, enabling interactive retrievals
(Collaborator Ross Hoffman, AER)

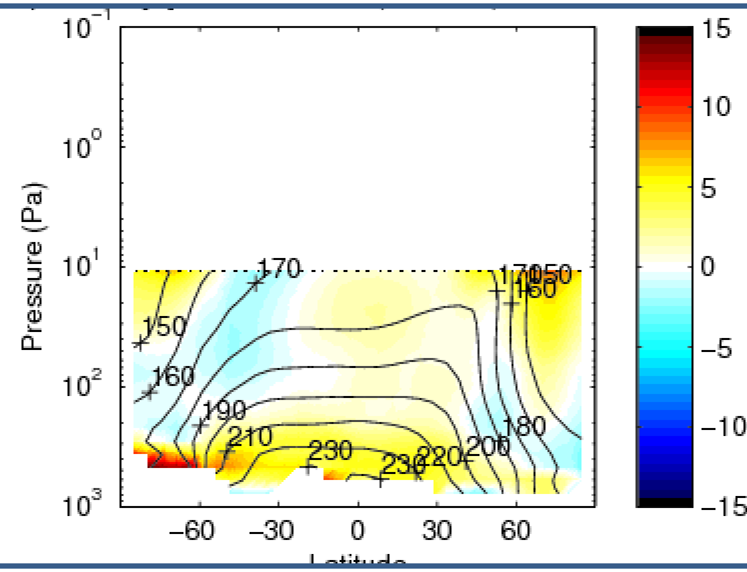
Evaluated by comparing 0.25 sol forecasts with observations.

NH Autumn Ls 185-203

MCS | **TES**

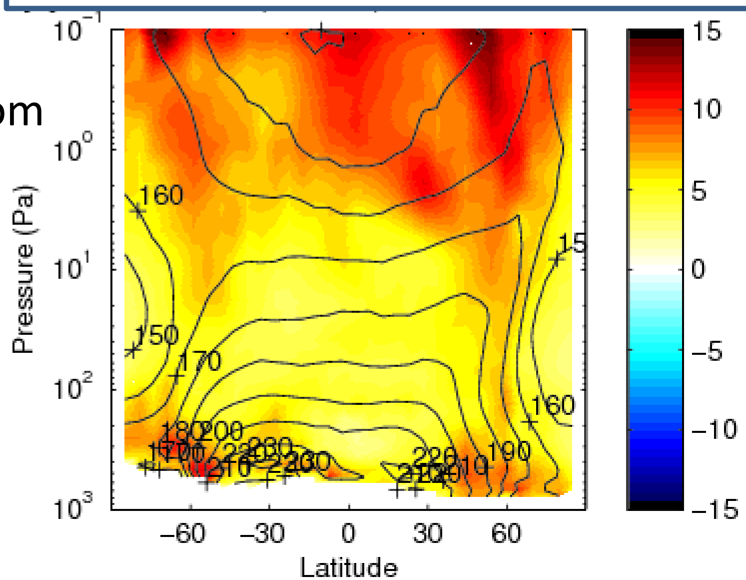
Bias

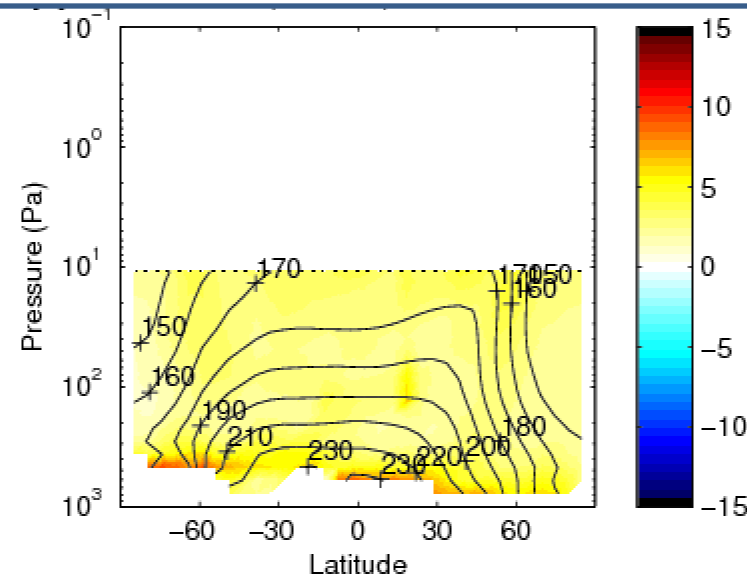




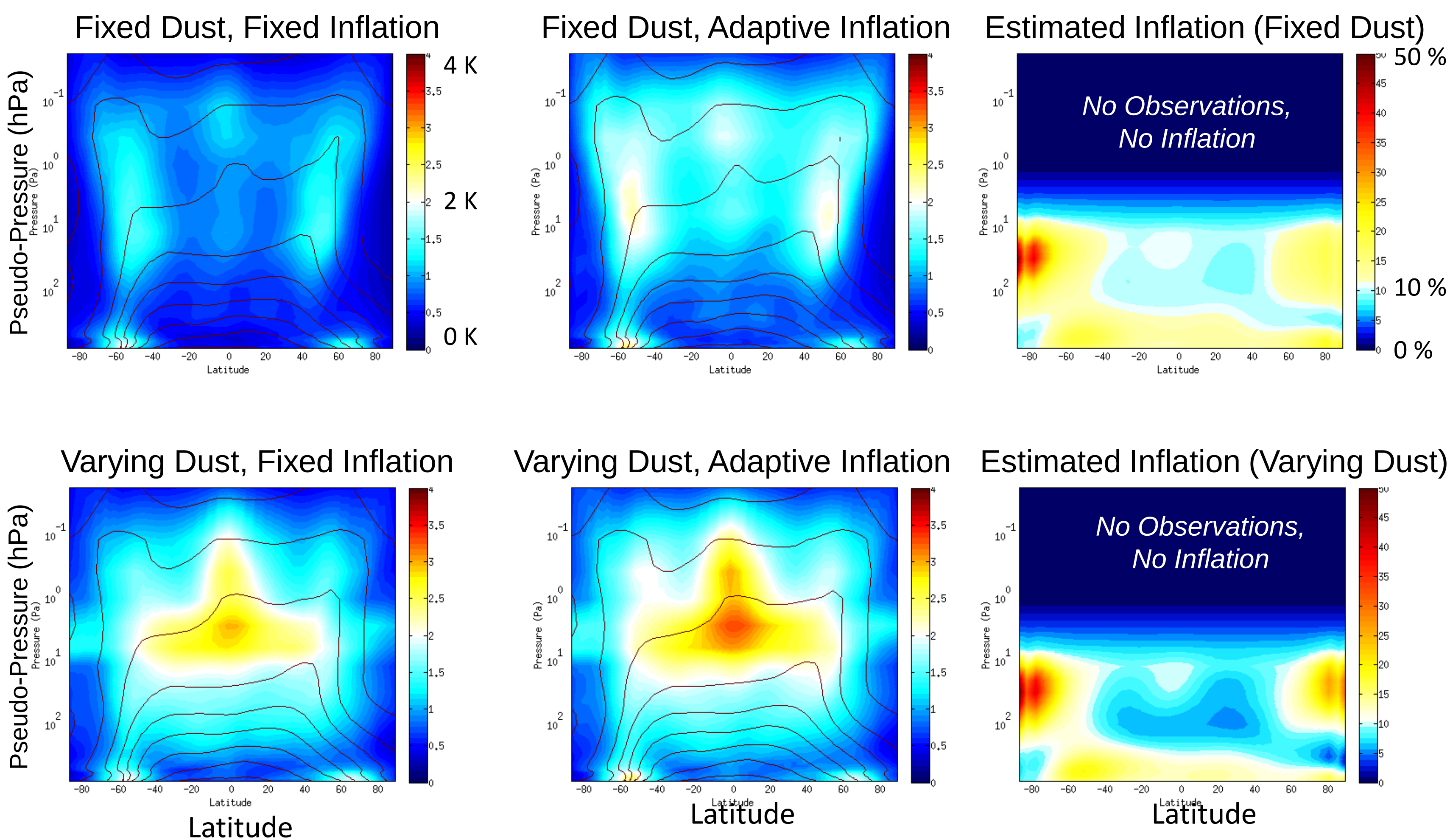
MCS | **TES**

Random Error





Characterizing Uncertainty: Ensemble Spread



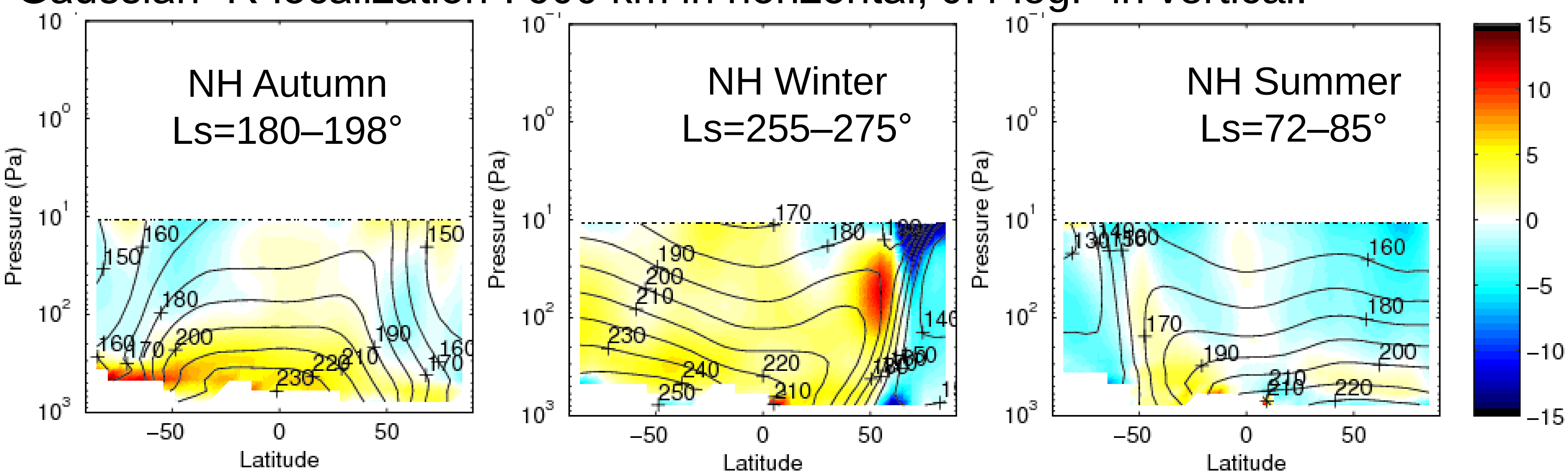
Contours: Temperature Ensemble Mean; Shaded: Temperature Ensemble Spread

Baseline Reanalysis:

Assimilating TES Temperatures with Fixed Dust Distribution, No Water Ice Clouds

Adaptive Inflation (Miyoshi, 2011) and varying dust among ensemble members.

Gaussian “R-localization”: 600 km in horizontal, 0.4 logP in vertical.



Contours: Ensemble Mean Forecast

Shaded: Observation minus Forecast Bias

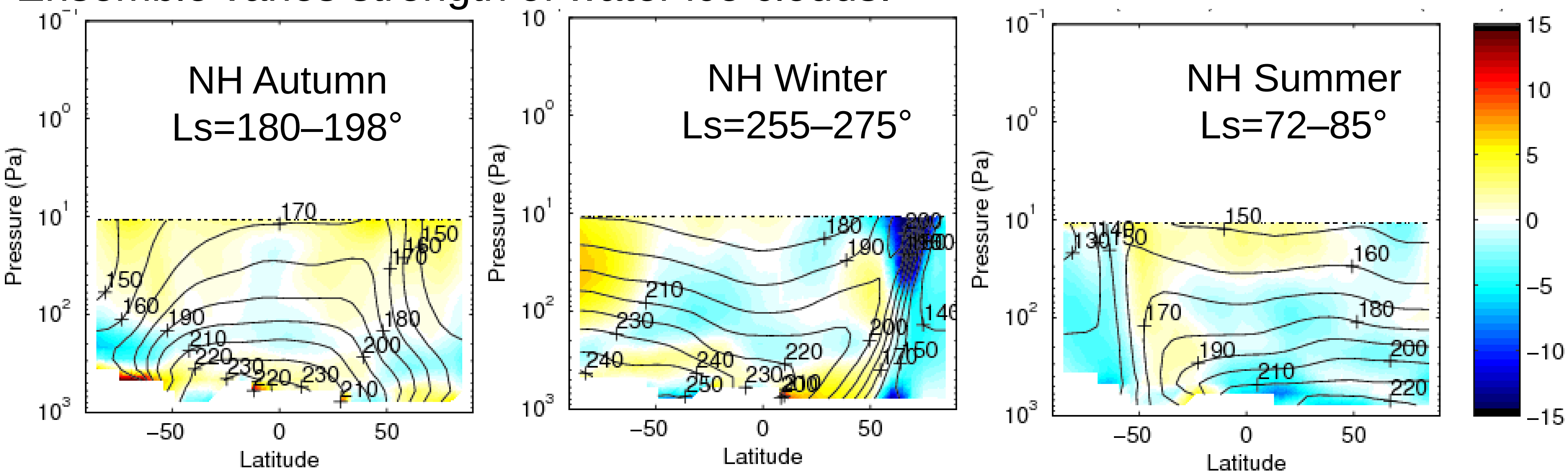
RMSE dominated by biases, including those due to dust and water ice cloud forcing errors.

Reanalysis forced by **TES Dust Opacities**

Horizontal and vertical dust distribution determined by MGCM advection of tracer

Dust injected/removed from boundary layer to match observations.

Ensemble varies strength of water ice clouds.

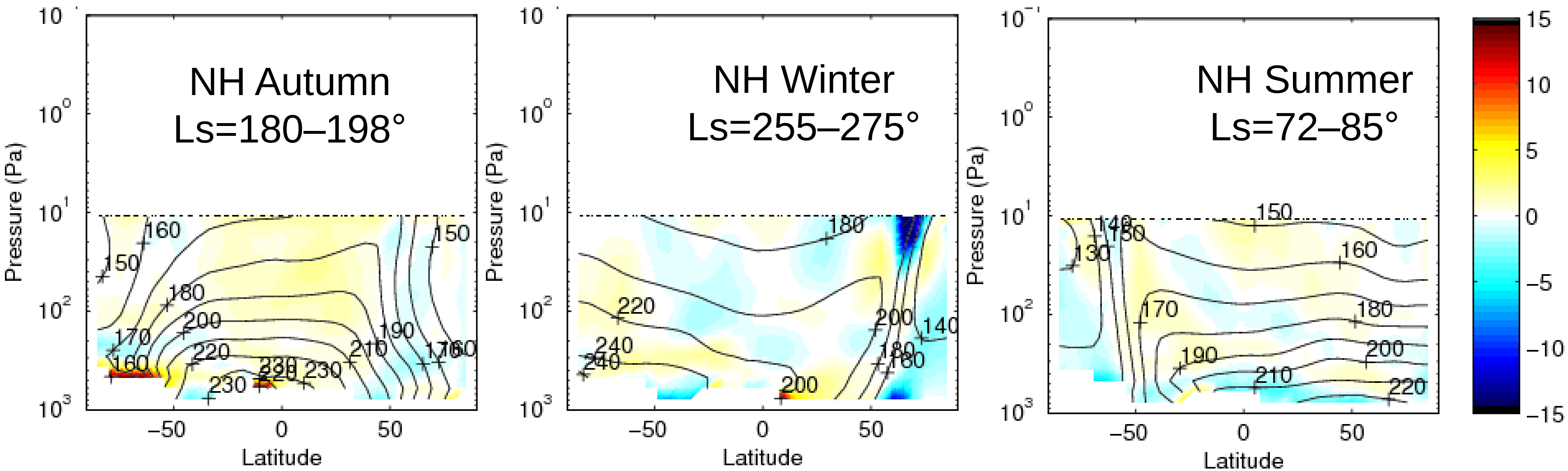


With model improvements and use of observed dust information, biases are generally reduced.

Reanalysis with diurnal **Empirical Bias Correction** using 10-sol window.

Time mean analysis increment from past 10 sols is applied every 0.25 sol

Empirical bias correction accounts for model error, including imperfect knowledge of dust and water ice aerosol distributions and properties.



Reduction in bias will occur with improved MGCM parameterizations, as well as by improving the dust and water ice distributions through formal assimilation of observation information and parameter estimation.

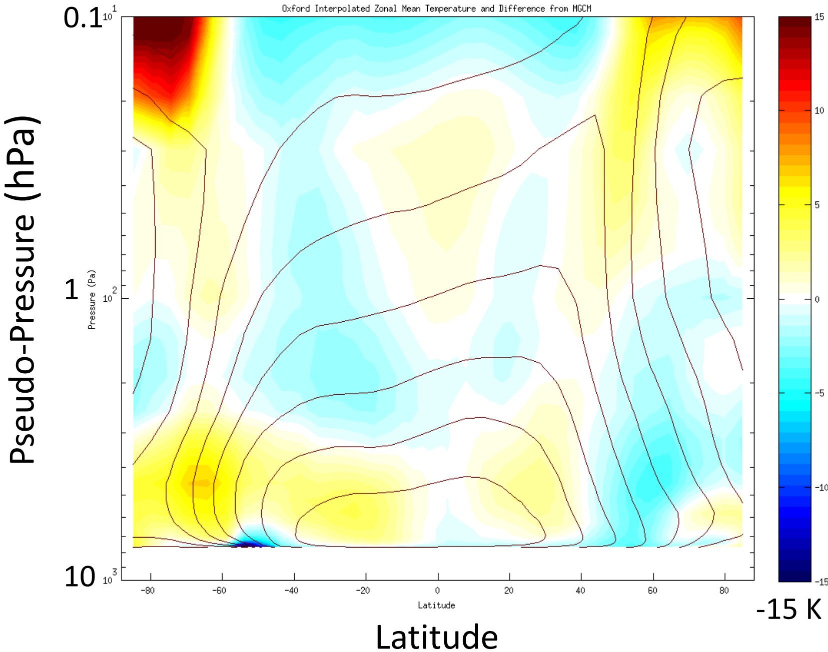
Evaluating the Reanalysis

- Short term (0.25 sol) forecasts compared to observations (independent in time).
- Longer (1–10 sol) forecasts compared to analyses.
- Comparisons to UK Reanalysis.
- Comparisons to independent Radio Science temperature profiles.
- Comparisons to satellite-derived wind vectors.
- Analysis of travelling waves compared to Fourier analysis of TES observations.

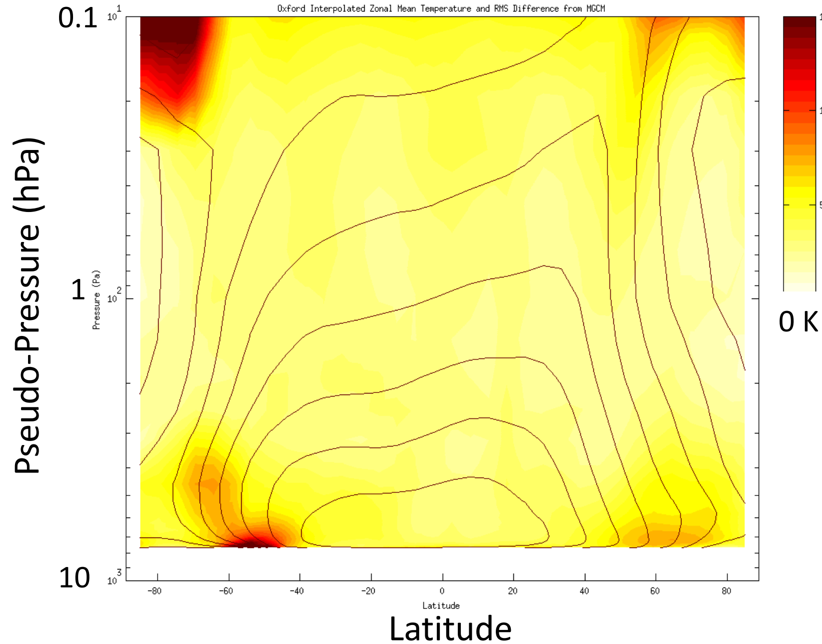
Comparing with the U.K. Reanalysis: Zonal Mean Statistics

Preliminary
Limited Duration Comparison

Temperature Bias
(UK – LETKF)



Temperature RMS Difference
(UK vs. LETKF)

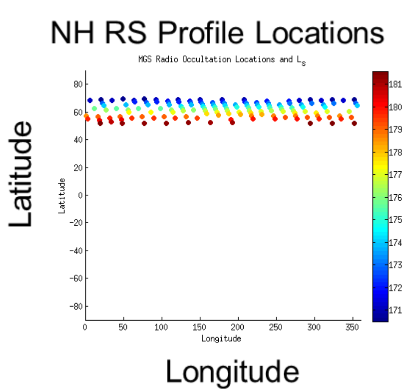


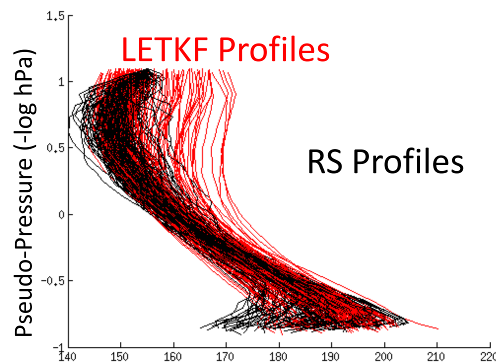
- Zonal mean statistics of temperature differences between the analyses reveal a general agreement of the analyses, within 5 K in most of the domain.
- Larger disagreements exist at cap edge baroclinic zones, as well as in upper levels above TES coverage, which is due to bias from model differences.

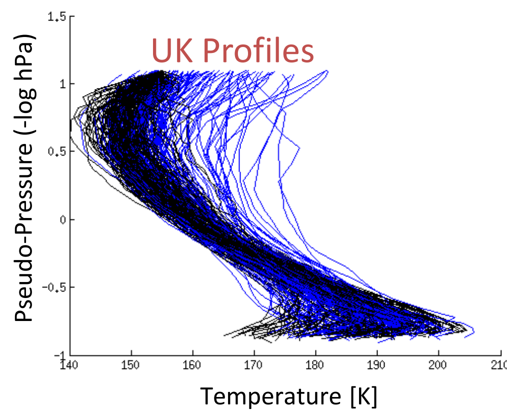
Comparison with Radio Science Profiles

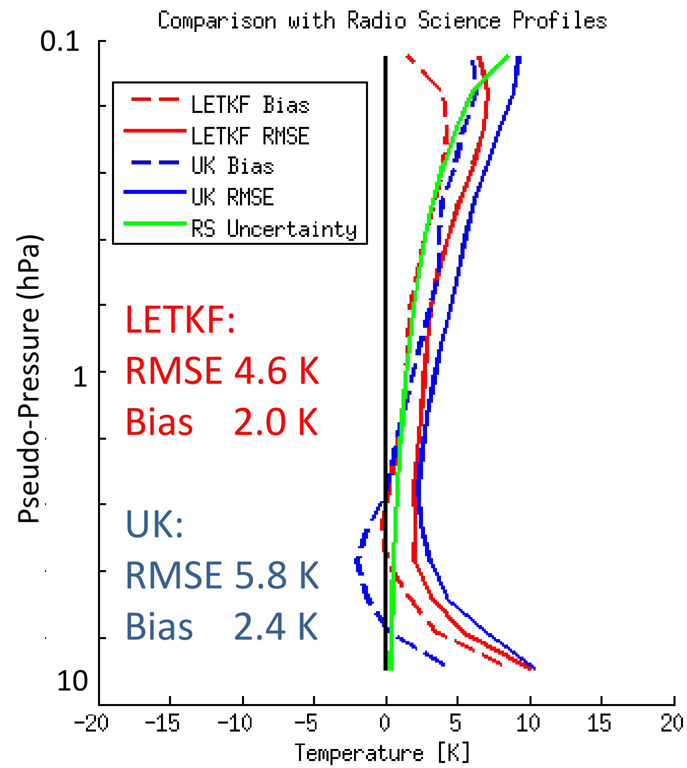
Preliminary
Limited Duration Comparison

- Radio Science (RS) occultation measurements *(Hinson et al., 1999)* can be used to derive independent temperature profiles.
- Here, profiles from the NH sub-arctic (50-70°N) are used.
- RMSE is 3-6 K, except near the surface and at higher altitudes.
- Both analyses have a warm bias compared to RS observations.







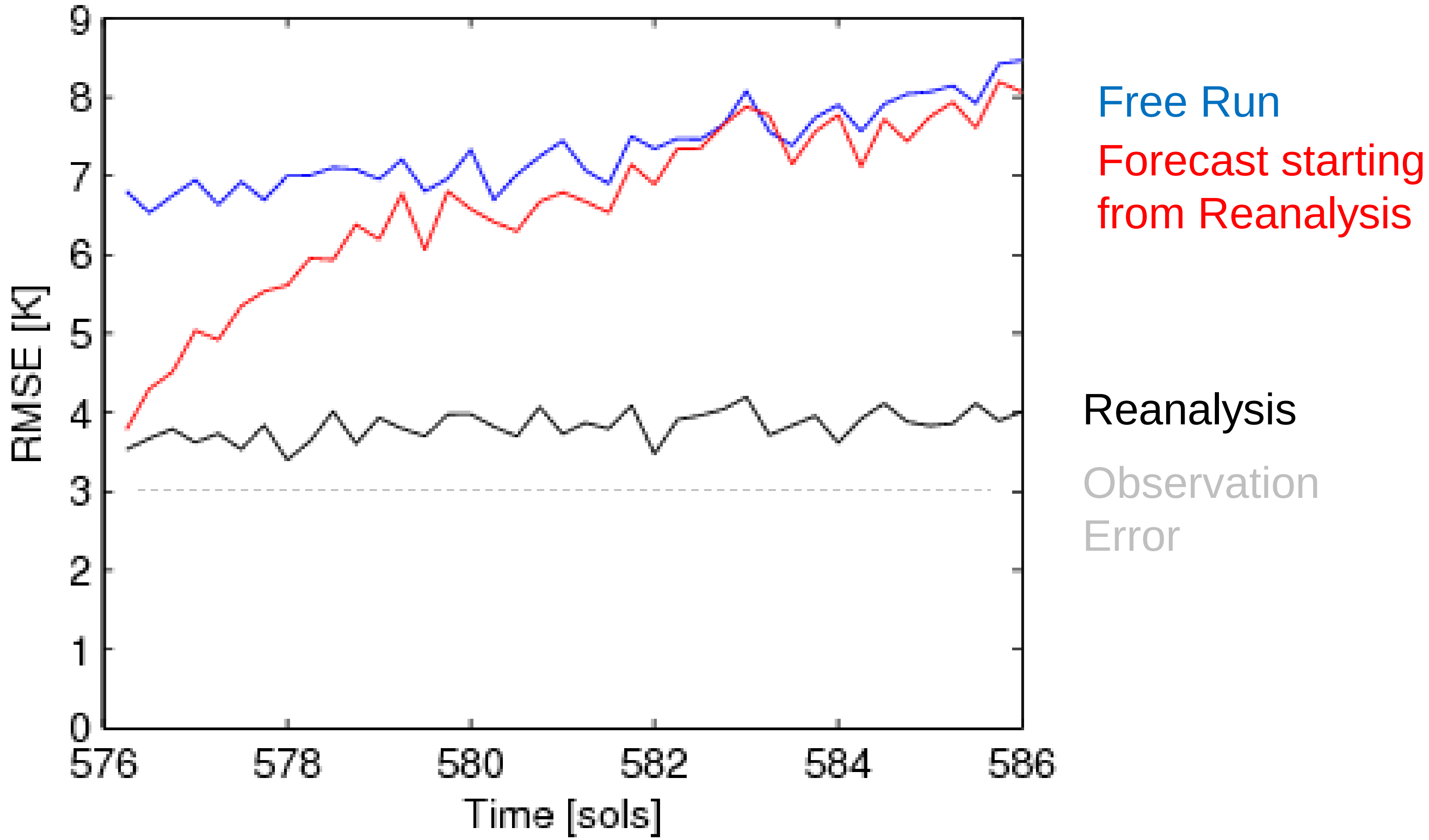


Mars Atmosphere Science Questions

Curiosity Rover
Courtesy of NAS

Assessing Predictability through Numerical Weather Prediction

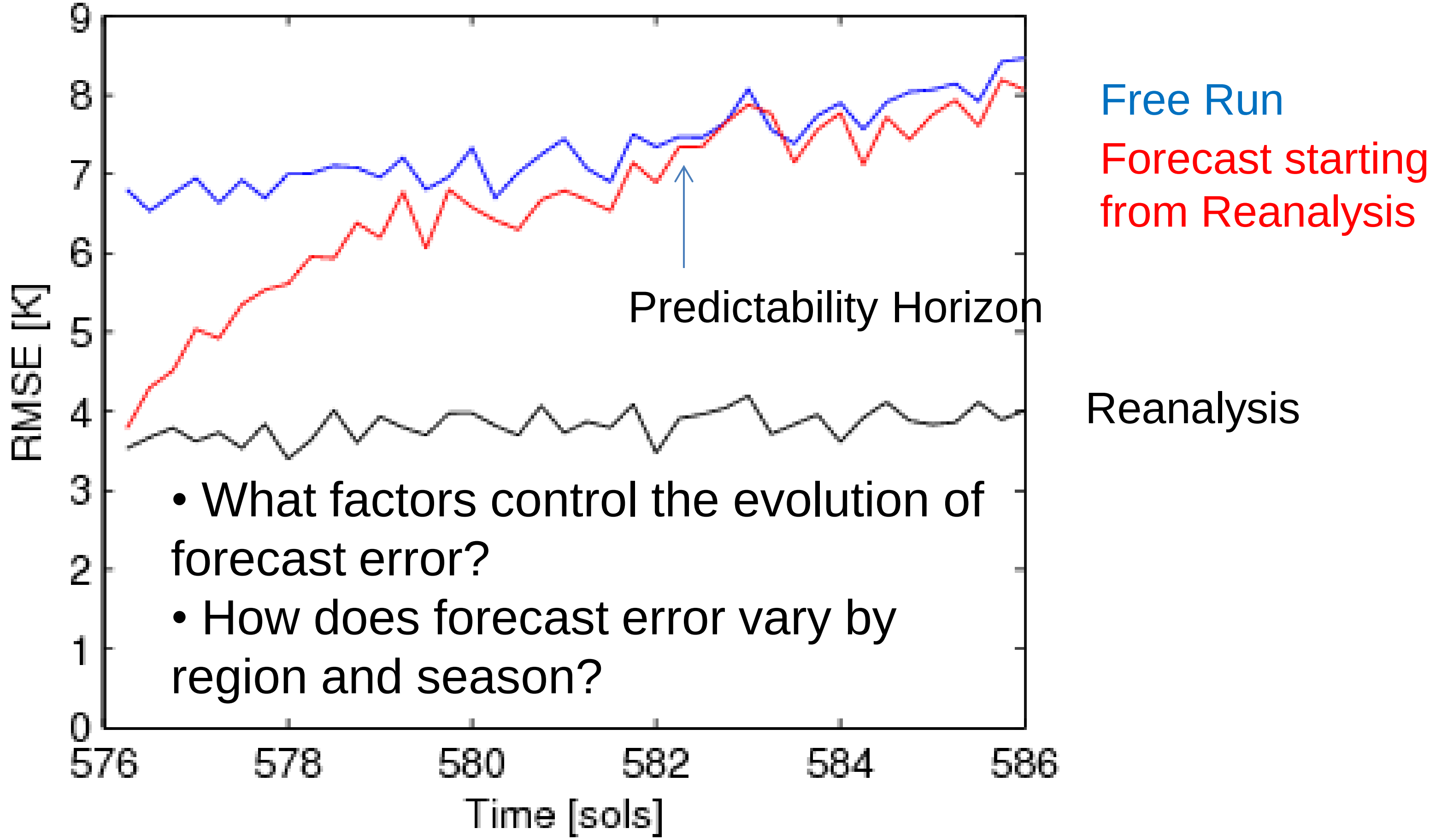
Example from NH Autumn, MY 24
Forecast Initiated from Ls=192°



Assessing Predictability through Numerical Weather Prediction

Example from NH Autumn, MY 24

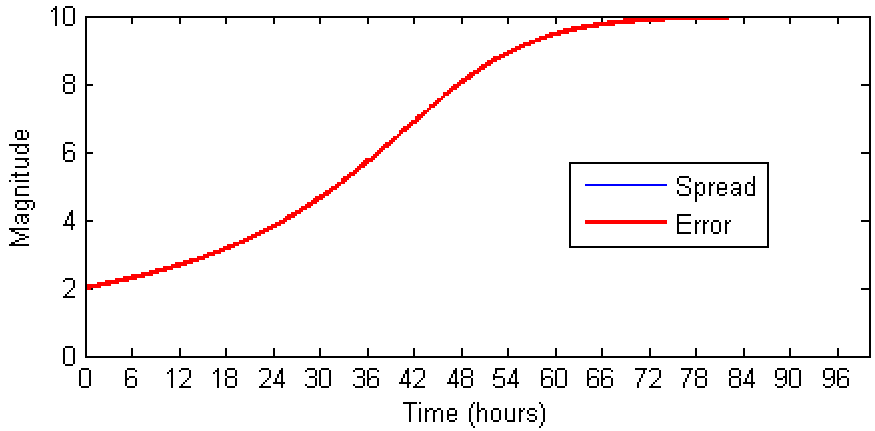
Forecast Initiated from Ls=192°



- What factors control the evolution of forecast error?
- How does forecast error vary by region and season?

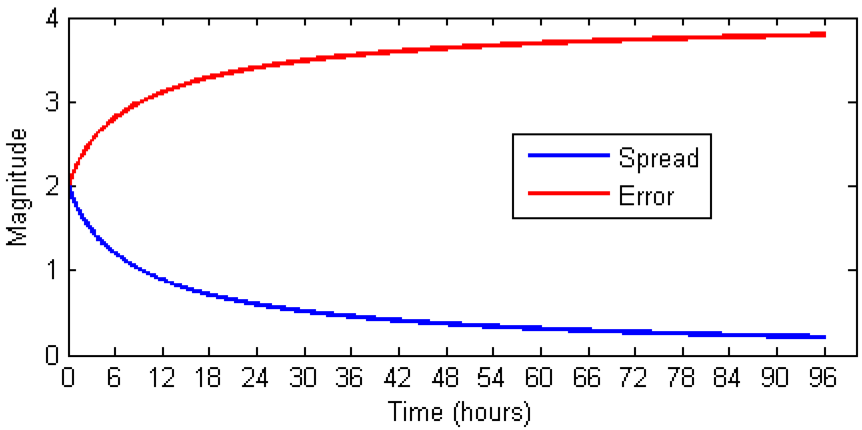
Sources of Forecasting Error

- Dynamical Instabilities / Chaos



Small differences in initial conditions between two similar states grow until the error saturates and they are no different than two random states from climatology.

- Model Error / Forcing



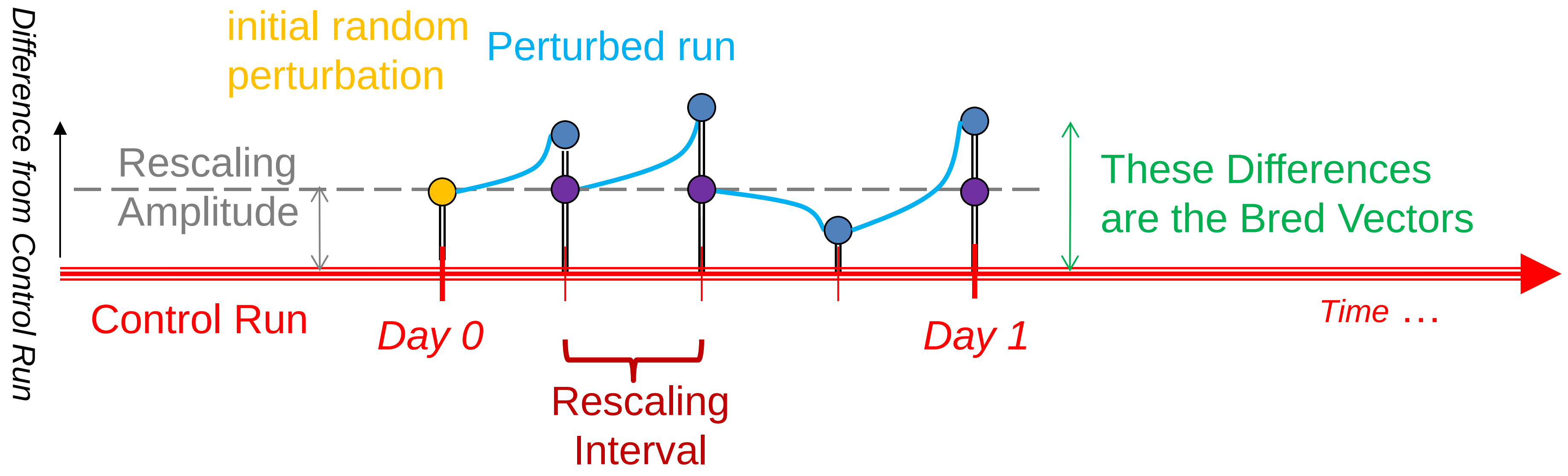
Model errors have both random and systematic components.

In a forced system, spread decreases over time as states are forced to converge.

If the model attractor differs from the real attractor, error will instead grow until it saturates at the difference in forcing.

Elucidating Instabilities with Bred Vectors

- In chaotic systems, two states that are initially similar grow far apart.
- There is at least one unstable direction, or pattern, that grows in time.
- Breeding is a simple method for finding the shapes of these instabilities (errors).
- In forecasting context, represent the errors due to uncertain initial conditions

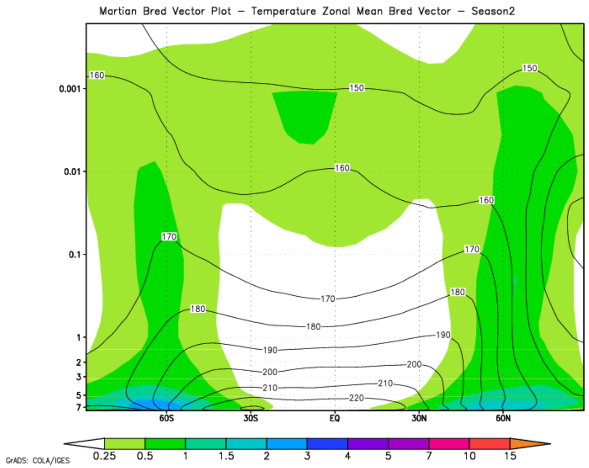


Zonal Mean BV by NH Season (Fixed Dust)

Contours: Zonal Mean Temperature; Shading: Bred Vector Temperature

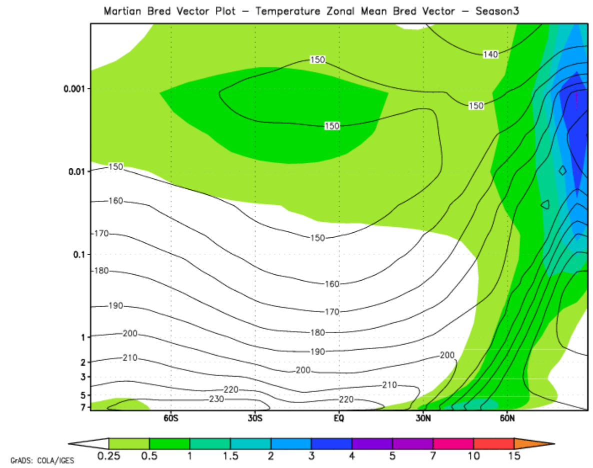
Late Autumn

Ls=180–240°



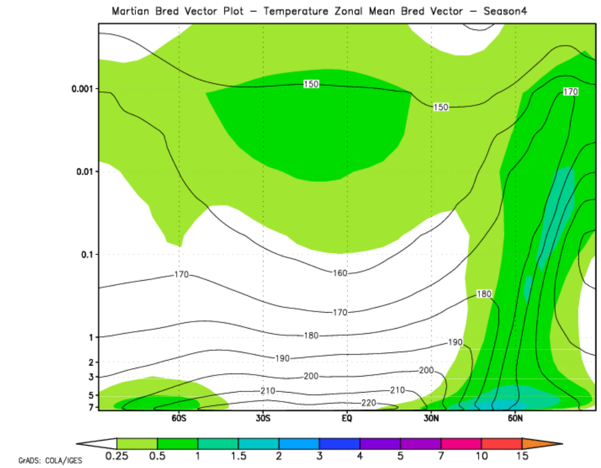
Winter Solstice

Ls=240–300°



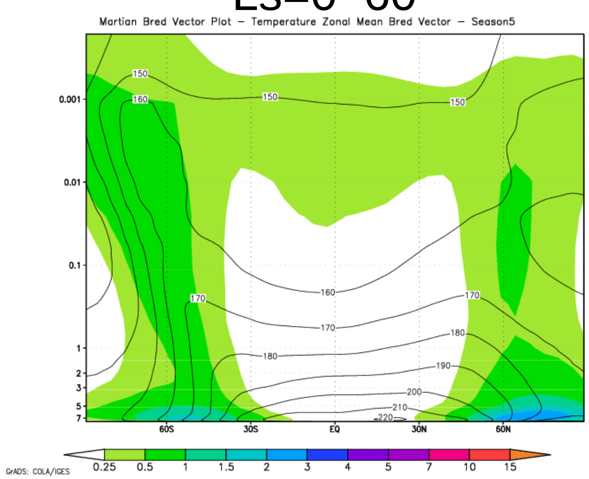
Early Spring

Ls=300–360°



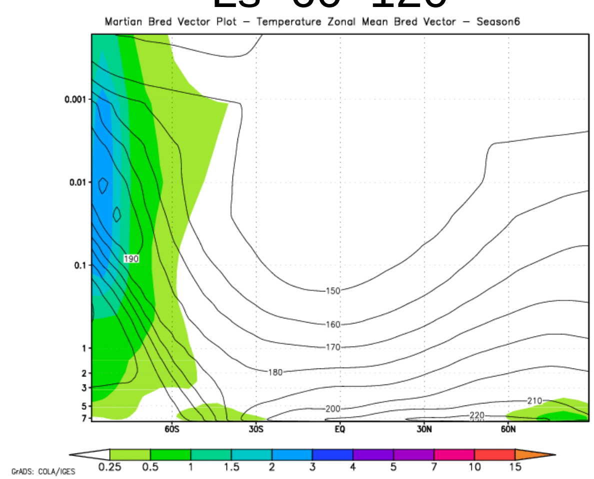
Late Spring

Ls=0–60°



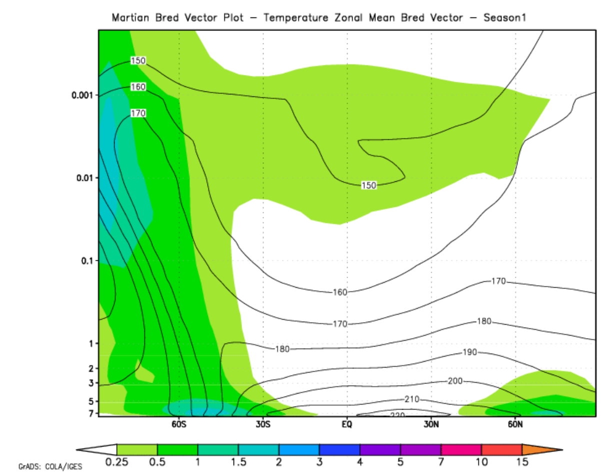
Summer Solstice

Ls=60–120°



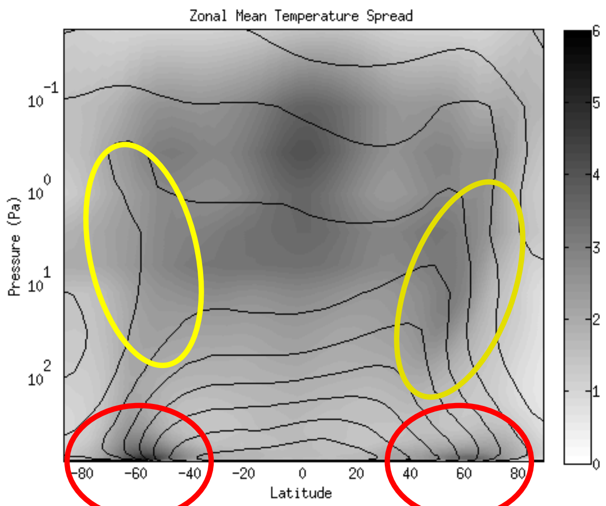
Early Autumn

Ls=120–180°

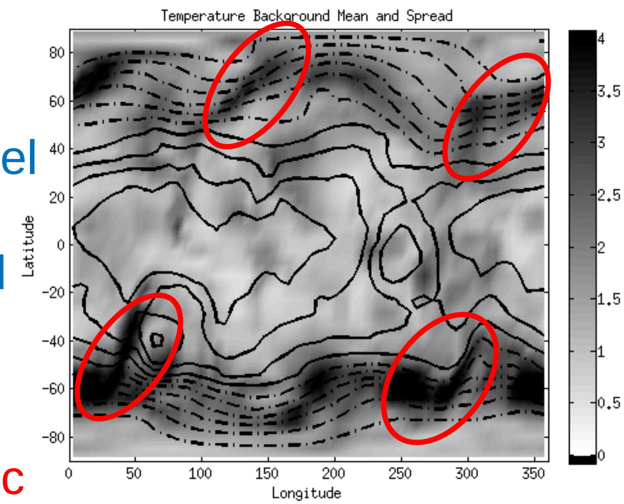


Bred Vectors indicate instabilities that clearly drive the Ensemble Spread

Zonal Mean Temp. Spread

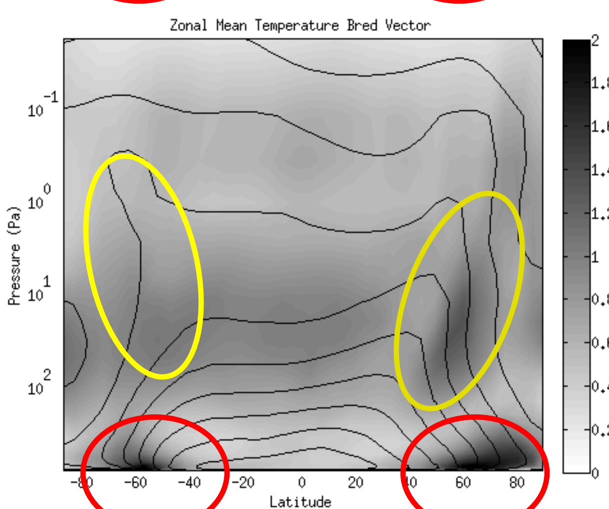


Low Level Temp. Spread

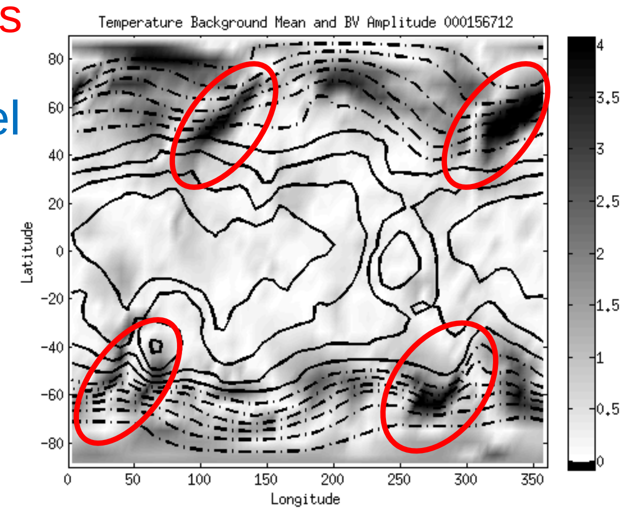


Baroclinic Instabilities

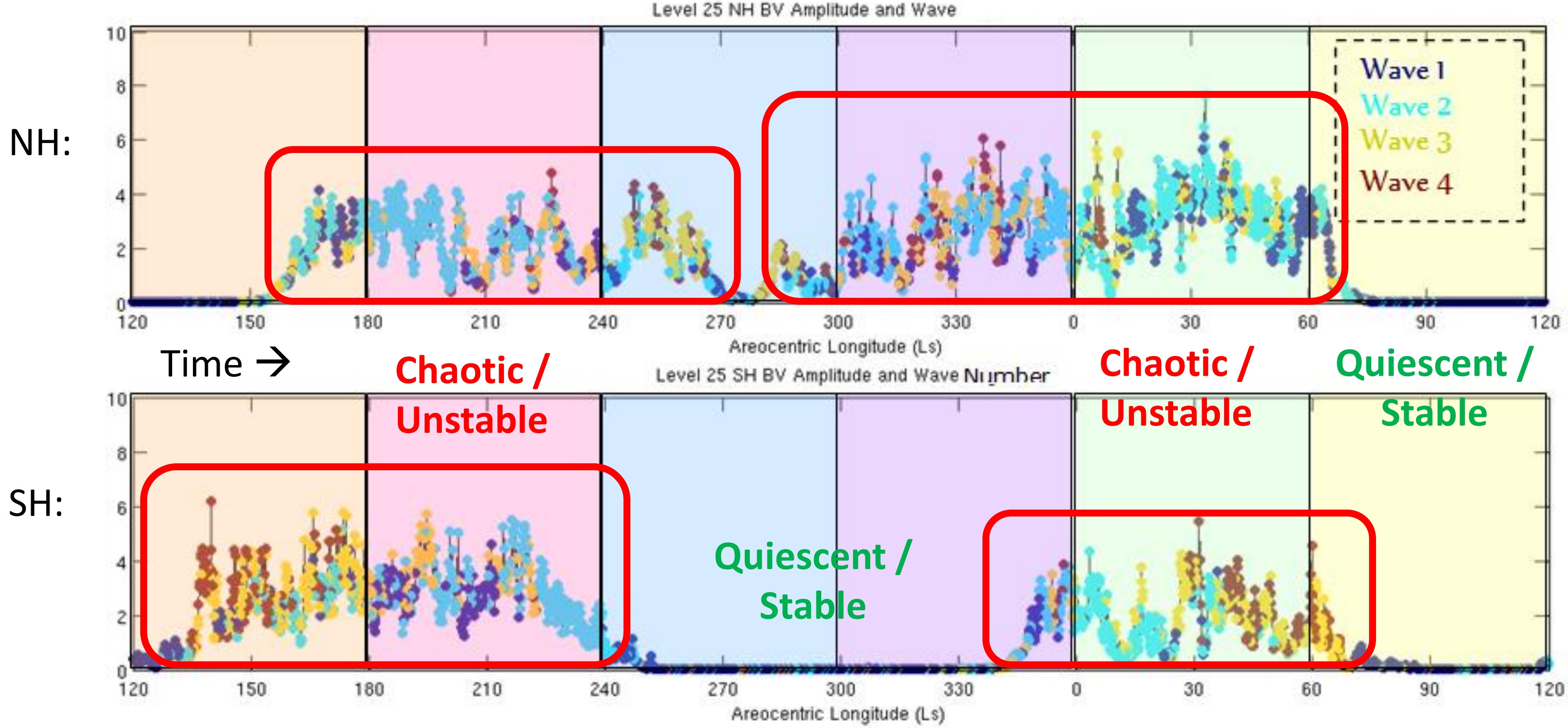
Zonal Mean Temp. Bred Vector



Low Level Temp. Bred Vector



Level 25 (Near Surface) BV Size and Wave Number

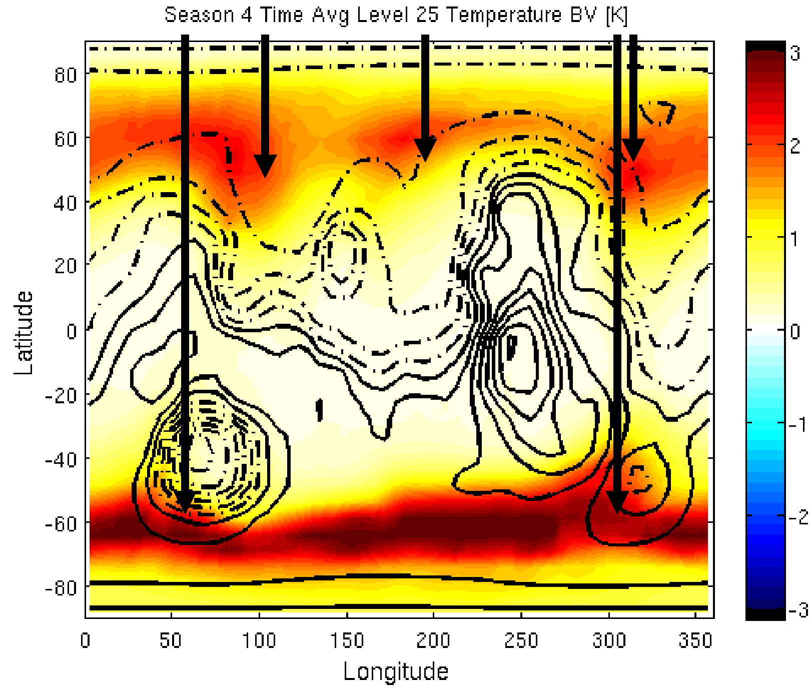


- Near surface activity peaks in the transition seasons.
- Wave 1 instabilities are dominate in upper levels (not shown), whereas waves 1-4 occur near the surface.
- The atmosphere can rapidly grow from quiescent to active within a few days.

Season	Ls	BV Simulation Day	Season
1	0-60	475-601	Boreal Post-Equinox
2	60-120	602-733	Austral Solstice
3	120-180	65-178	Austral Pre-Equinox
4	180-240	179-274	Austral Post-Equinox
5	240-300	275-368	Boreal Solstice
6	300-360	369-474	Boreal Pre-Equinox

Martian Atmosphere Near-Surface Instabilities in relation to **Topography**

Wave 3 longitudinal peaks in seasonal mean BV activity correspond to regions downstream of elevated terrain, indicating **lee cyclogenesis** may be an important source of instability.



Shading: Bred Vector

Contours: Temperature

Origins of Instabilities:
BV Kinetic Energy Equation

$$\frac{\partial K_b}{\partial t} = -\left[\boldsymbol{v}\bullet\nabla K_b + \dot{\sigma}\frac{\partial K_b}{\partial \sigma}\right] - \left[\nabla\bullet(\boldsymbol{v}_b\Phi_b) + \frac{\partial \dot{\sigma}_b\Phi_b}{\partial \sigma}\right] - \left[\dot{\sigma}_b\alpha_b p_{sb}\right] - \left[\boldsymbol{v}_b\bullet\left((\boldsymbol{v}_b\bullet\nabla)\boldsymbol{v}_c + \dot{\sigma}_b\frac{\partial \boldsymbol{v}_c}{\partial \sigma}\right)\right]$$
$$-\frac{\Phi_b}{p_{sb}}\left(\frac{\partial p_{sb}}{\partial t} + \boldsymbol{v}_b\bullet\nabla p_{sb}\right) + \boldsymbol{v}_b\bullet\left(-\sigma\alpha\nabla p_s + \sigma_c\alpha_c\nabla p_{sc}\right)$$

Baroclinic **Barotropic**

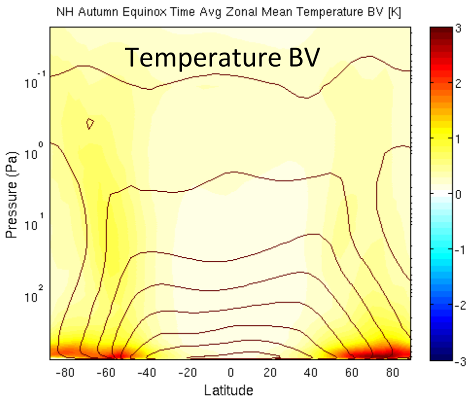
•Begin from the equations of motion for the MGCM (momentum equation in sigma coordinates).

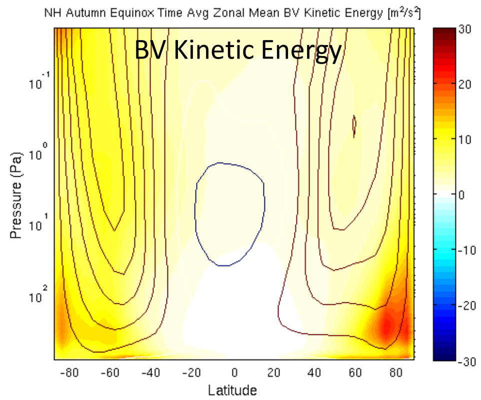
•Control run and perturbed run both satisfy these equations exactly.

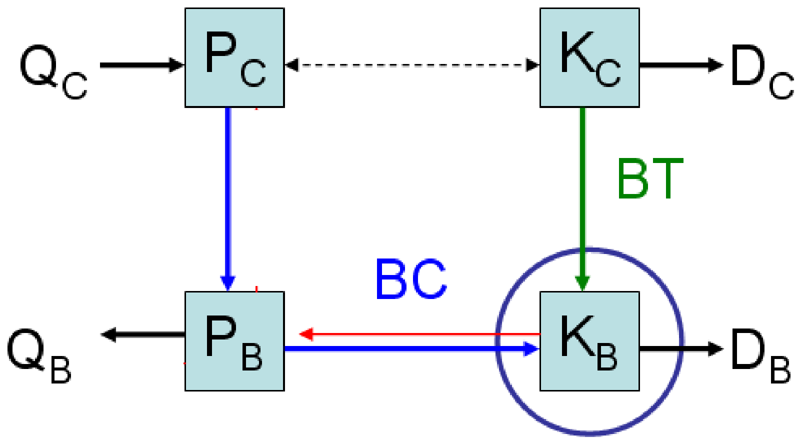
•Derive kinetic energy equation for bred vectors (difference between control and perturbed runs).

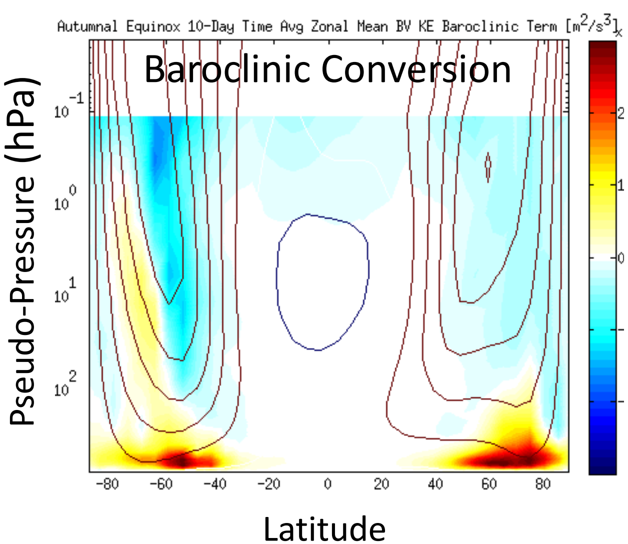
Term 1: Transport of BV KE by the total flow
Term 2: Pressure Work
Term 3: Baroclinic Conversion Term
Term 4: Barotropic Conversion Term
Term 5: Coordinate Transform Term

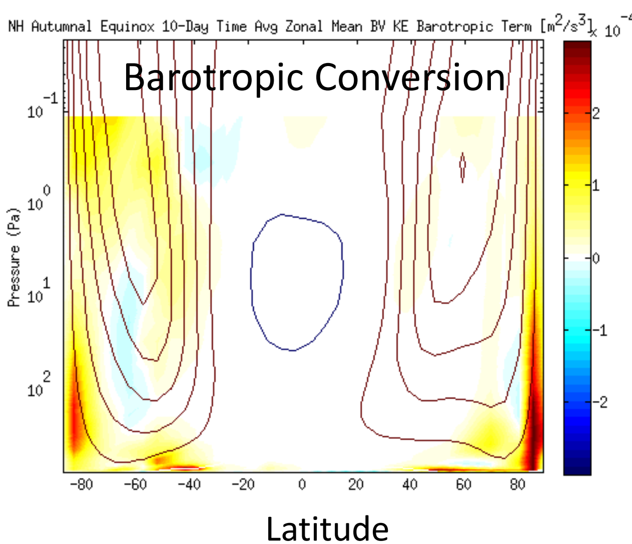
Barotropic and Baroclinic Processes











Near surface: baroclinic conversion:

BV Pot. En.=> BV Kin. En.

In jets aloft: regions of barotropic conversion:

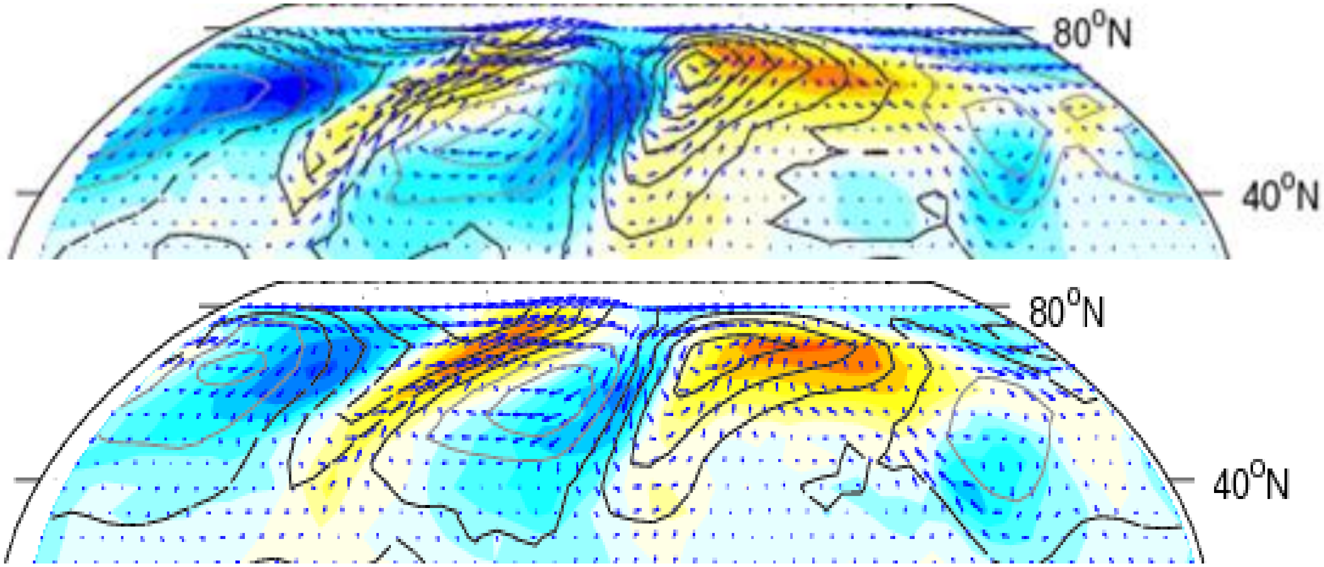
Control Kin. En.=> BV Kin. En.

Near jet maxima:

BV Kin. En. => BV Pot. En.

What is the sensitivity of analyses to aerosol distribution?

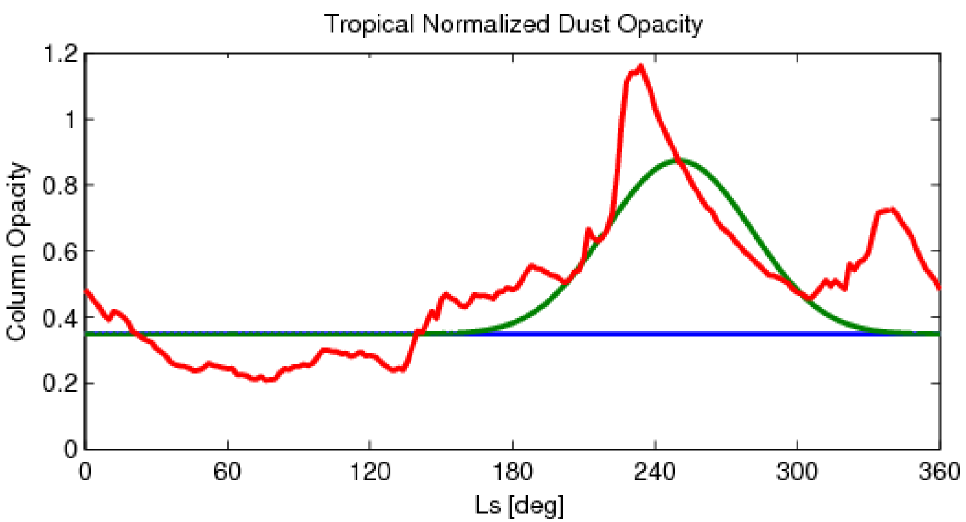
Can we converge upon a synoptic state?



Thermal Emission Spectrometer (TES) Full Year Reanalysis

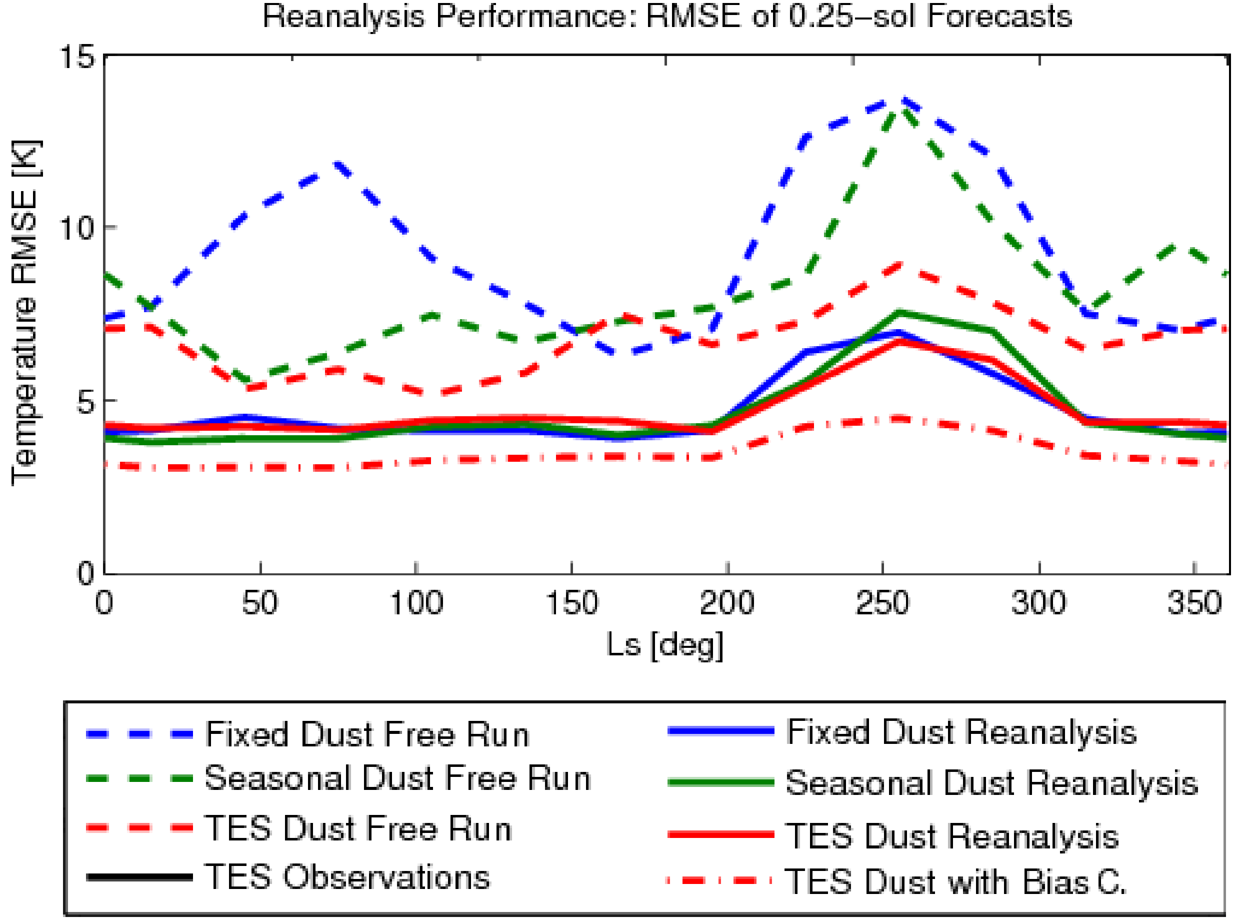
- Mars Year 24 Ls 180 – MY 25 Ls 180.
- Fixed Dust: Dust opacity constant in time.
- Seasonal Dust: Dust opacity and height evolve with season and latitude according to analytic formula.
- TES Dust: Dust opacities from TES observations dataset, adjustment occurs in boundary layer. Vertical distribution determined from tracer fields. Water ice clouds included.

We investigate whether analyses created with differing aerosol scenarios converge upon the same synoptic state.



Mars TES/LETKF Performance

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



Next step: formal aerosol assimilation with the LETKF.

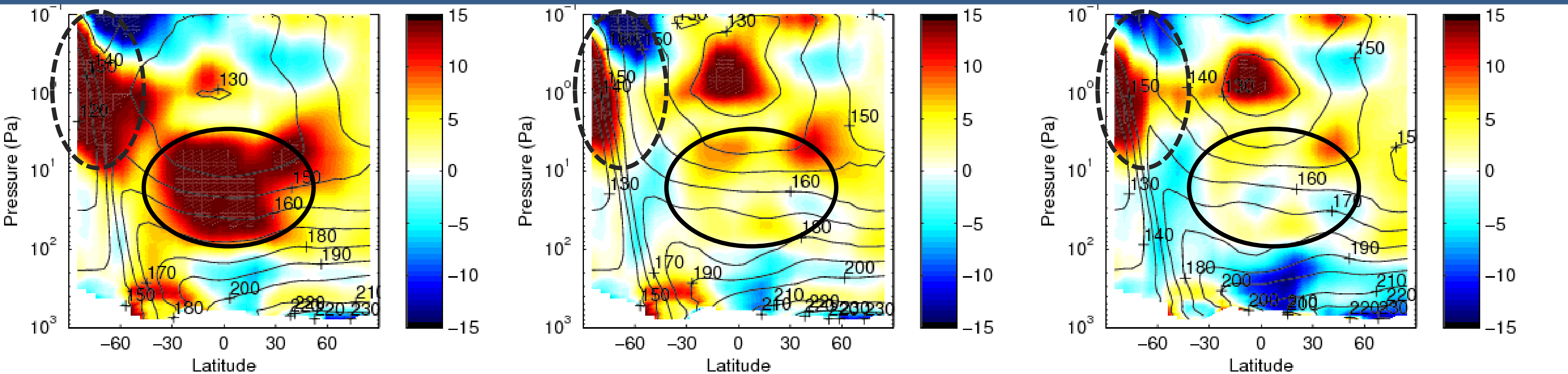
MGCM-LETKF- TES MCS

Ensemble Mars Atmosphere Reanalysis System (EMARS)

Improving Aerosol Representation

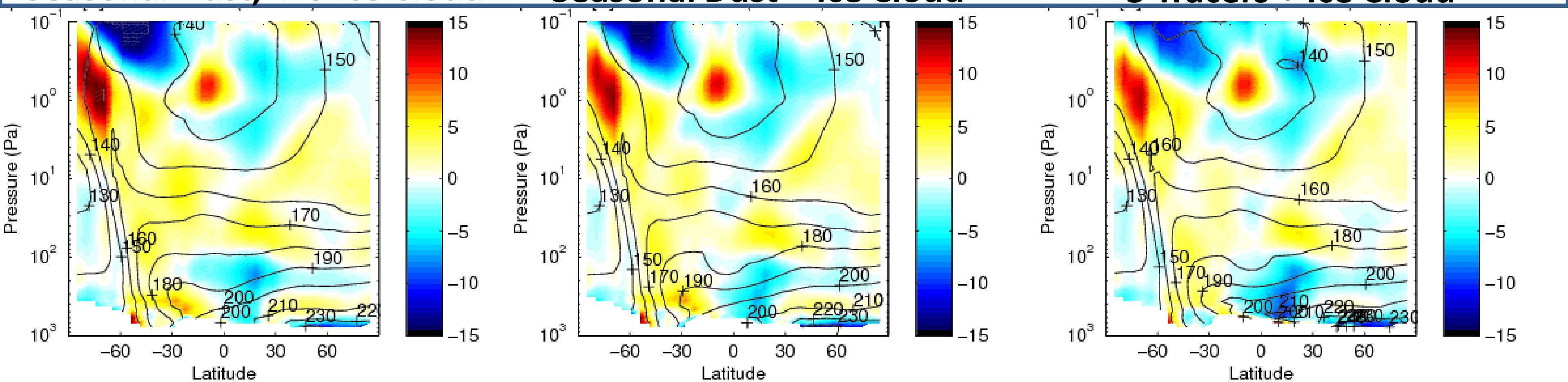
MCS Free Runs: Observation minus Model Bias

Seasonal Dust, No Ice Cloud | **Seasonal Dust + Ice Cloud** | **3 Tracers + Ice Cloud**

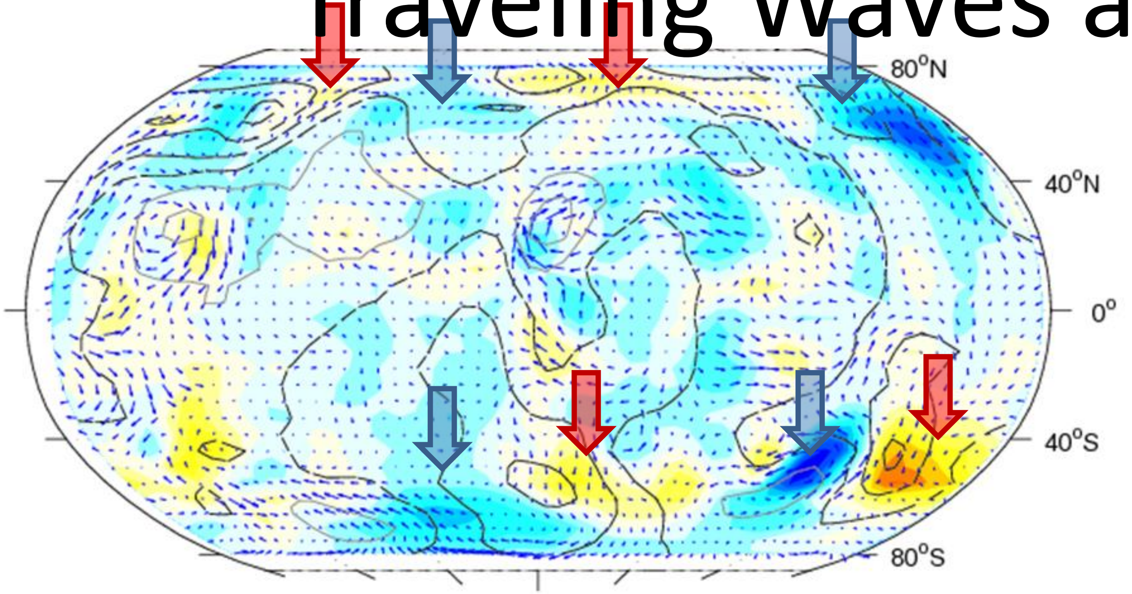


MCS Assimilation: Observation minus Model Bias

Seasonal Dust, No Ice Cloud | **Seasonal Dust + Ice Cloud** | **3 Tracers + Ice Cloud**

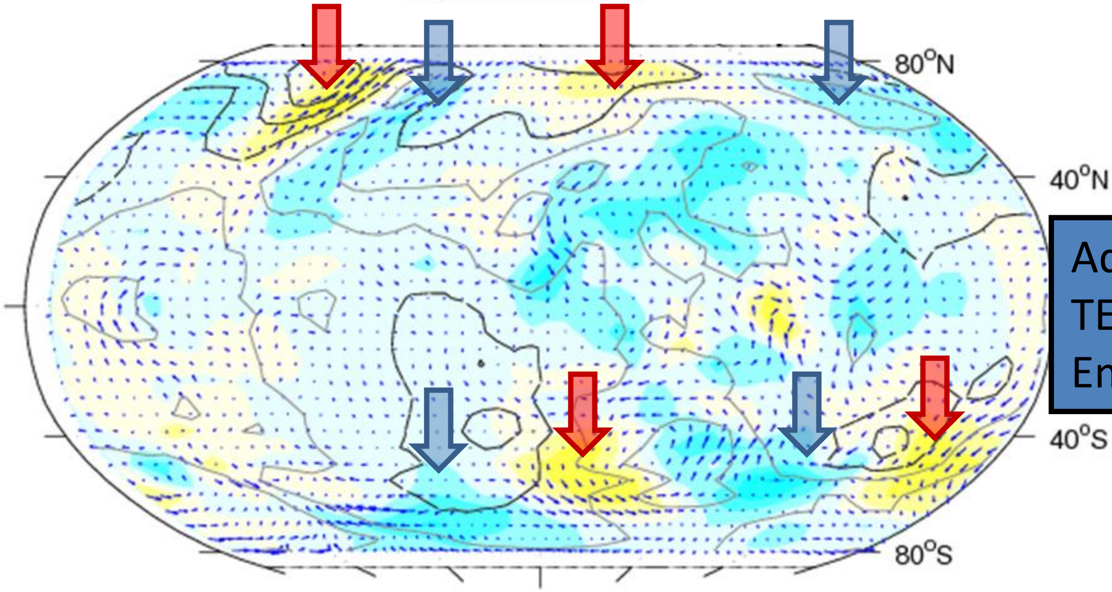


Traveling Waves and Dust



Simple Reanalysis:
Fixed Dust
No Bias Correction

0002 544 00 Ls 172.7°



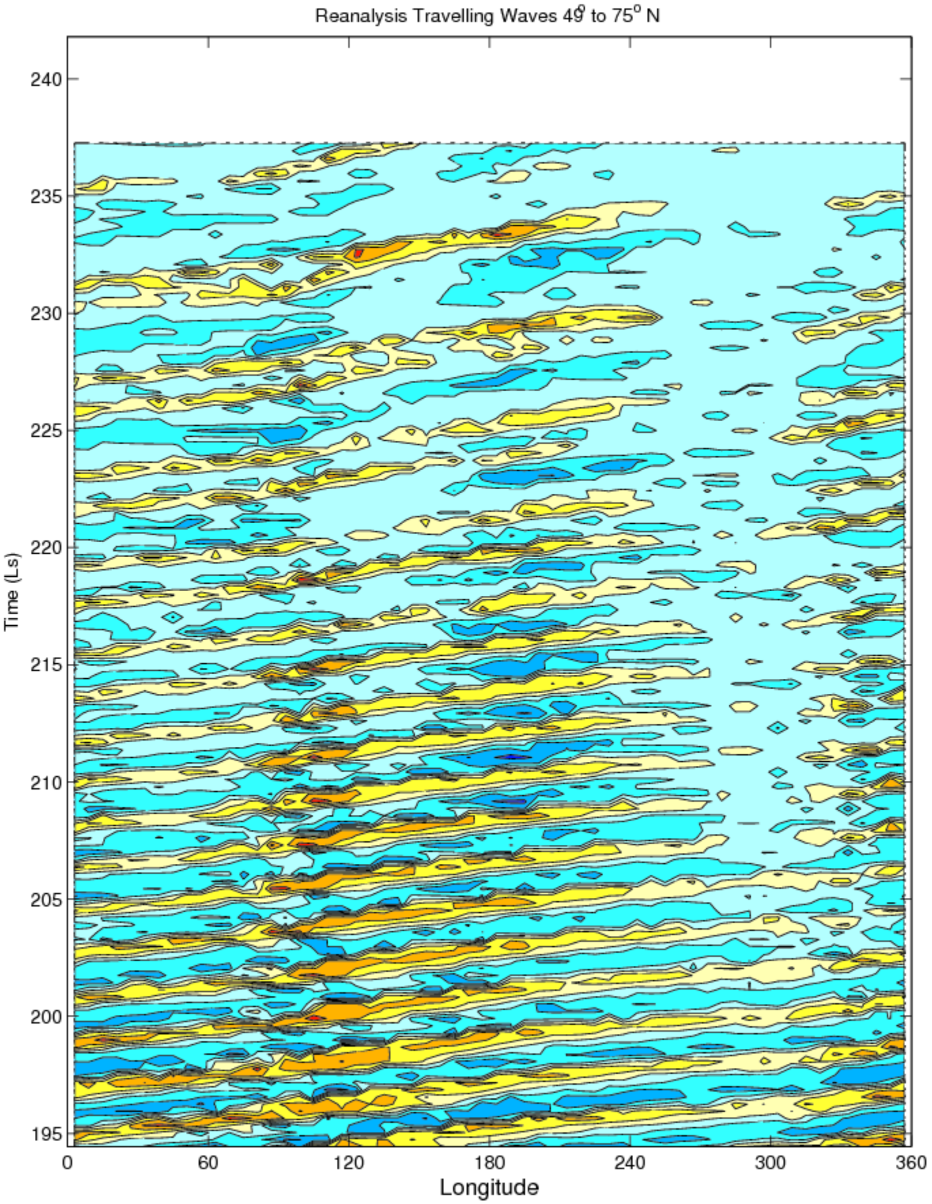
Do reanalyses with different model configurations, dust specification, initial conditions, and data assimilation techniques converge on the same synoptic state of traveling waves?

It appears they may, although the details differ.

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

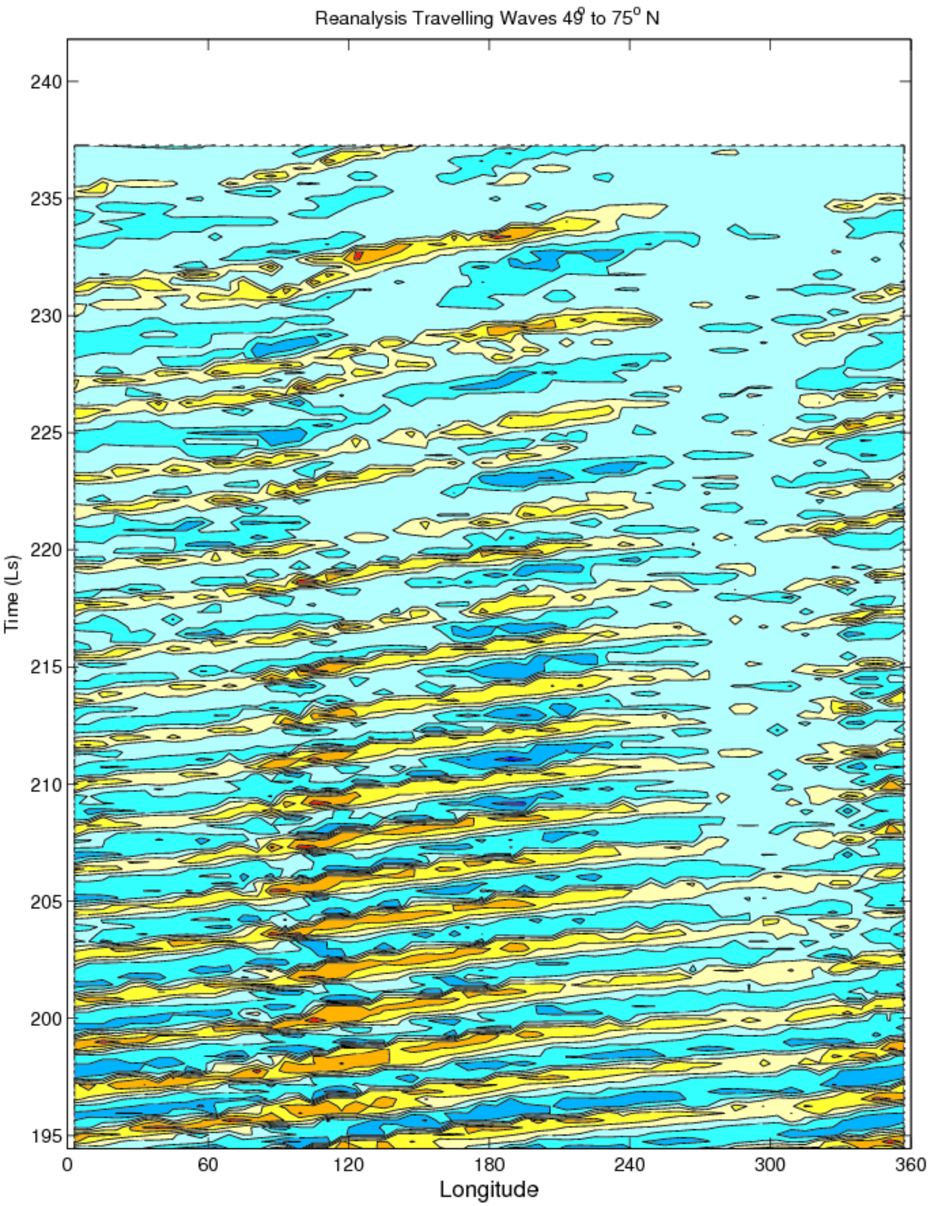
3.5 km eddy T [shading], (u, v) [arrows], p_s [contours]

TES Seasdust Nature

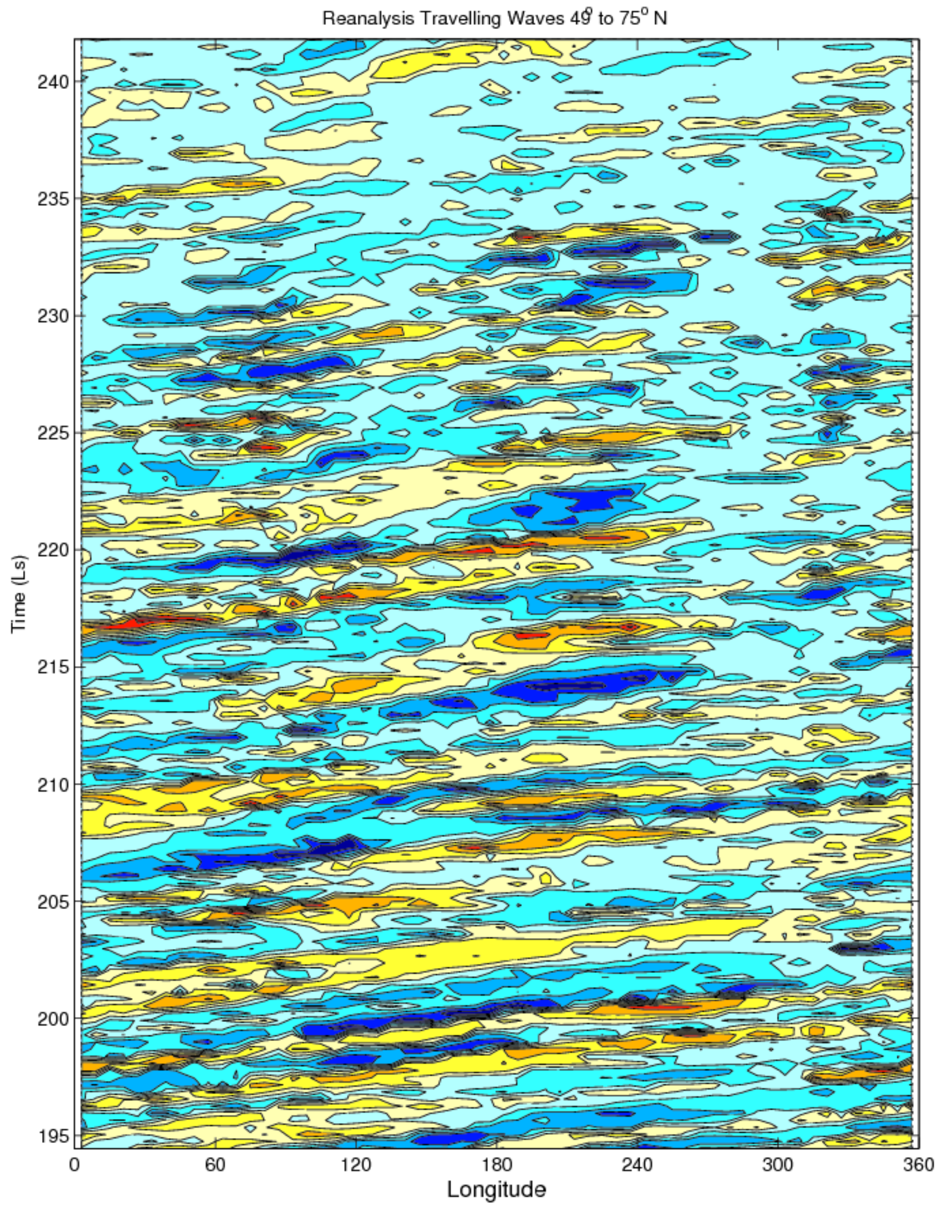


- Time Period: Late Autumn, MY 24 Ls 180°– 240°
- Create eddy state by subtracting 21-sol moving climatology at same time of day.
- Plot eddy temperatures at Level 20 (~3.5 km).
- Use maximum eddy magnitude within extratropical band, as waves shift latitude through the season.

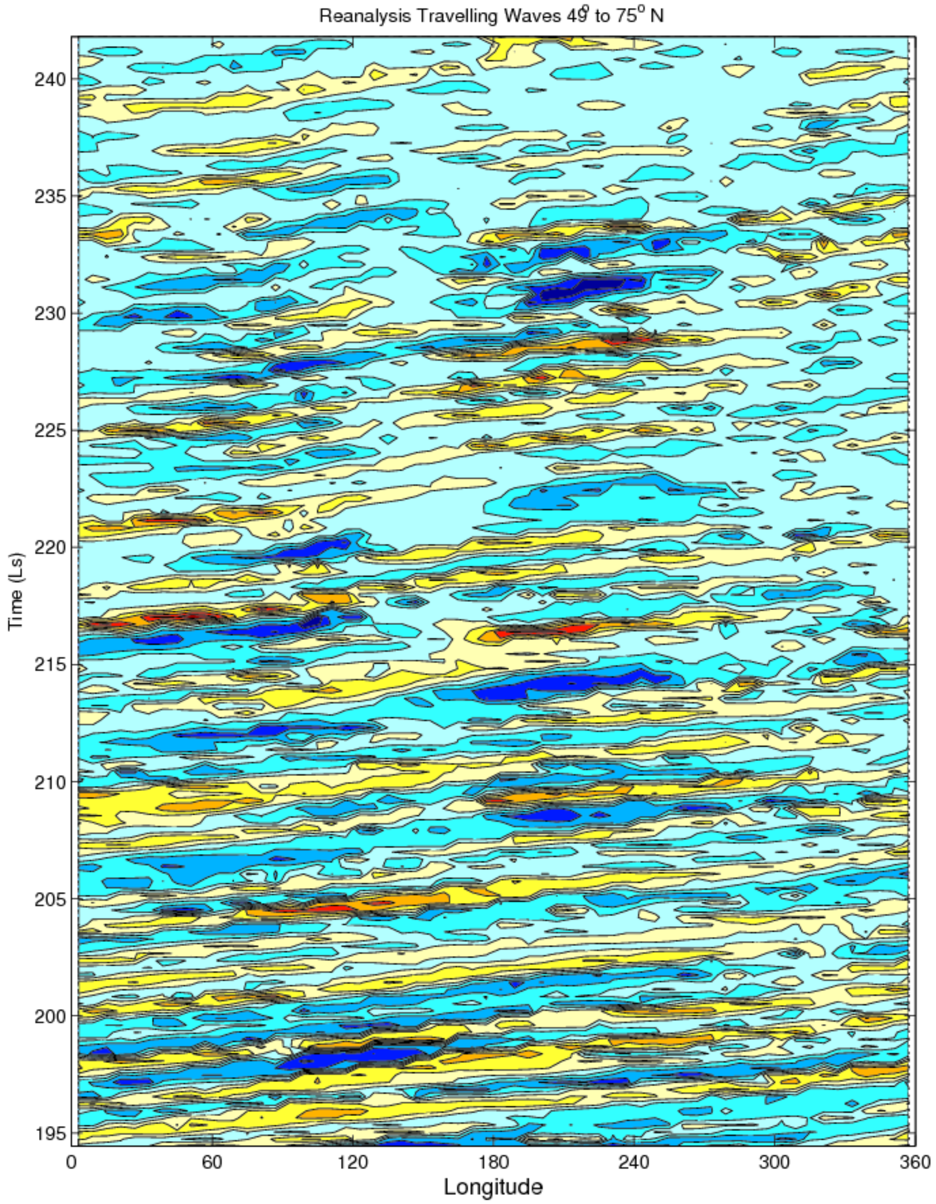
TES Seasdust Nature



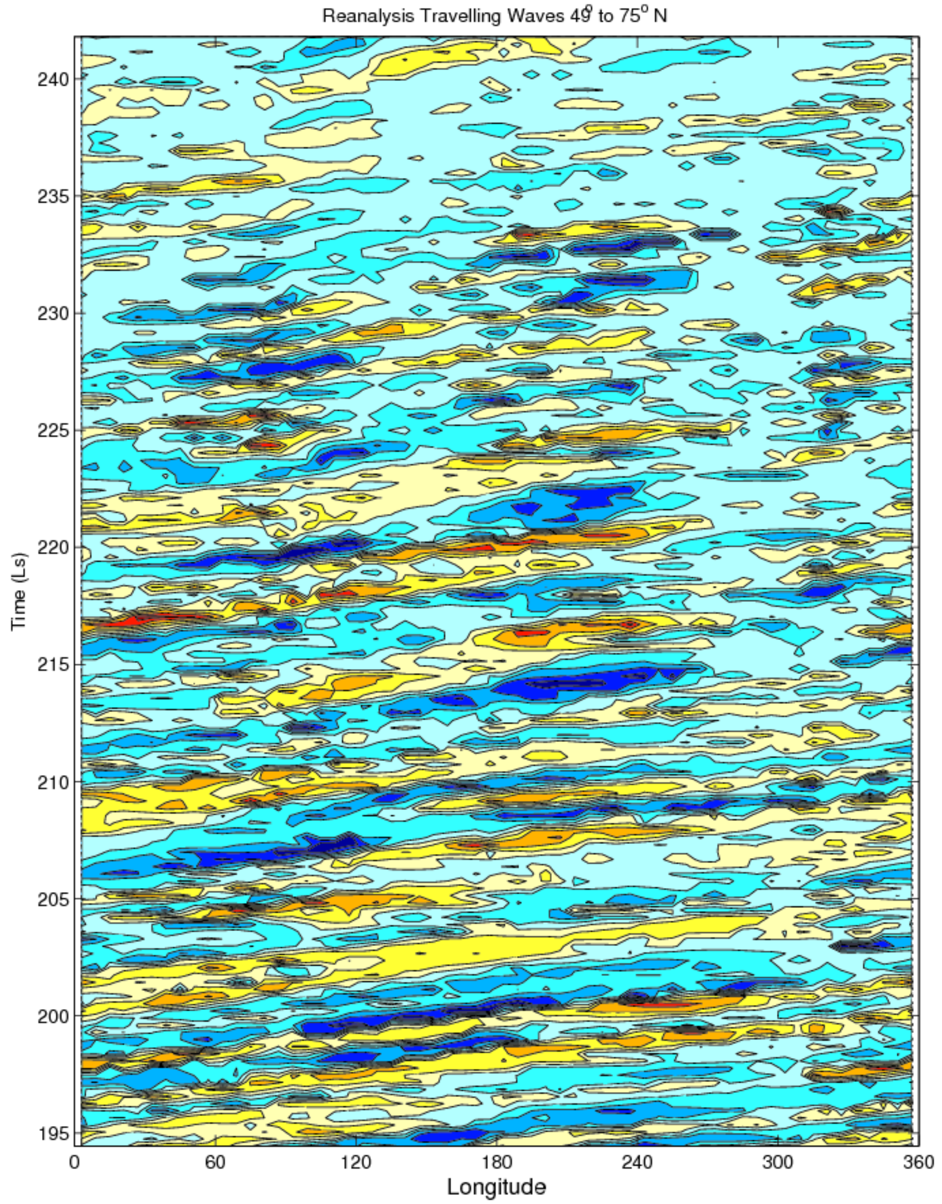
TES Seasdust Reanalysis



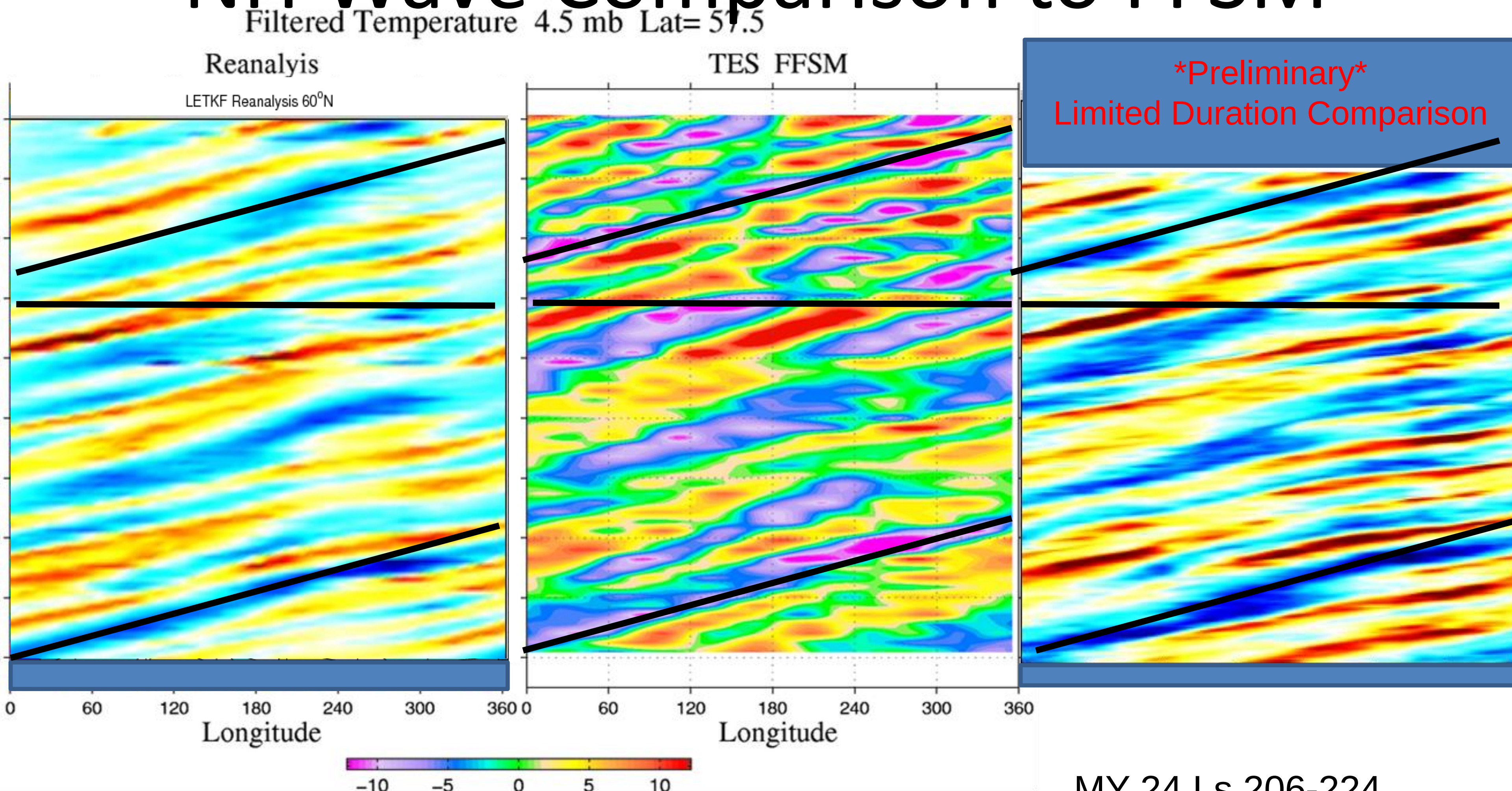
TES Dust Tracer Reanalysis



TES Seasdust Reanalysis



NH Wave Comparison to FFSM



MY 24 Ls 206-224

0.25 sol granularity
EMARS Reanalysis (Plotted SJG)

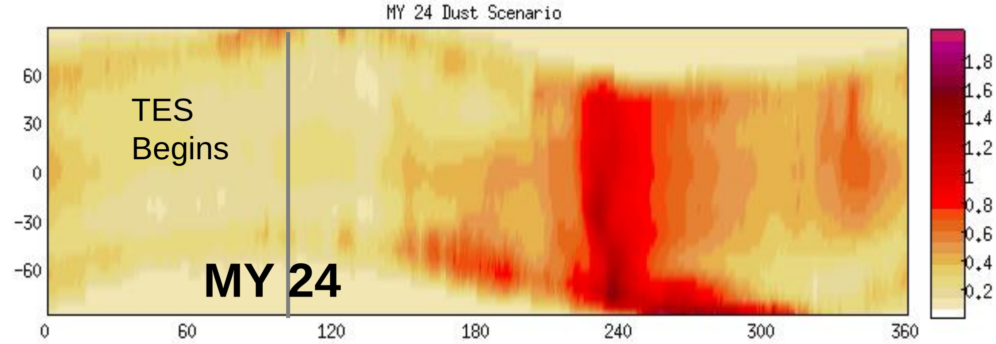
TES FFSM (Plotted RJW)
Courtesy of Jeff Barnes

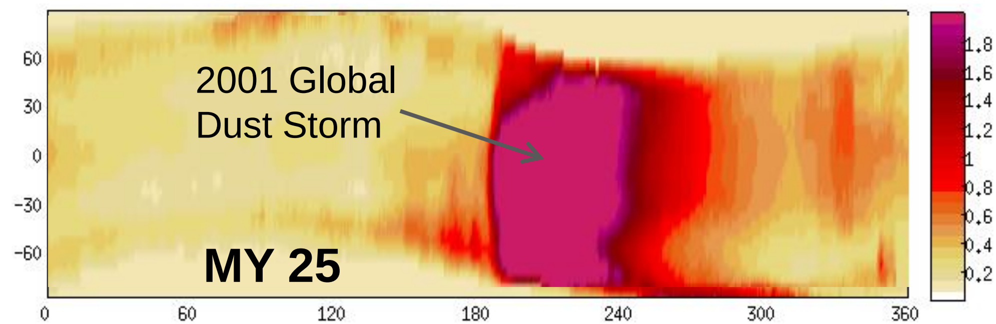
MACDA Reanalysis (Plotted SJG)
At 60 S, MGCM Level 20, MCD Dust

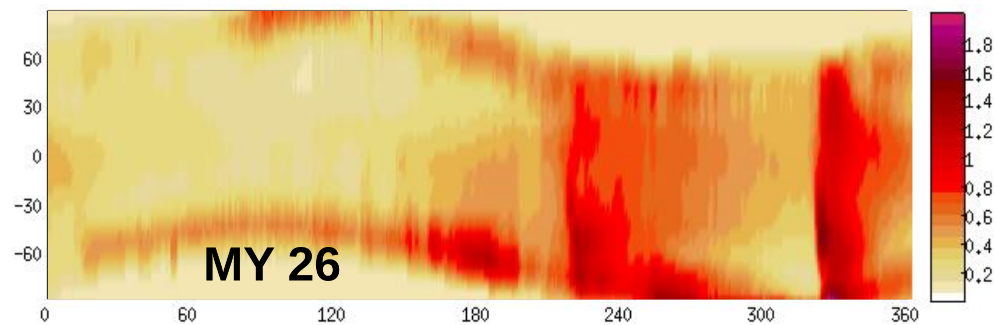
Dust Visible **Column Opacity**

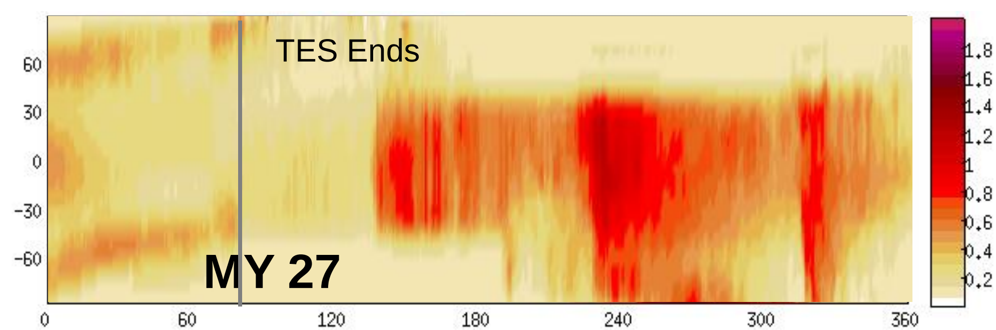
(From Observations Only)

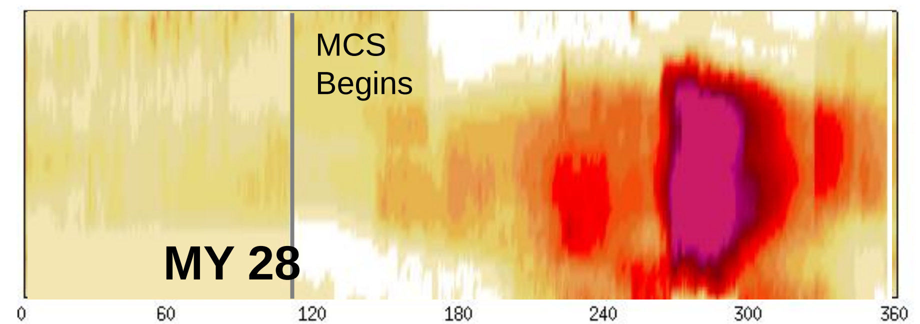
MCD Product Courtesy of Luca Montabone

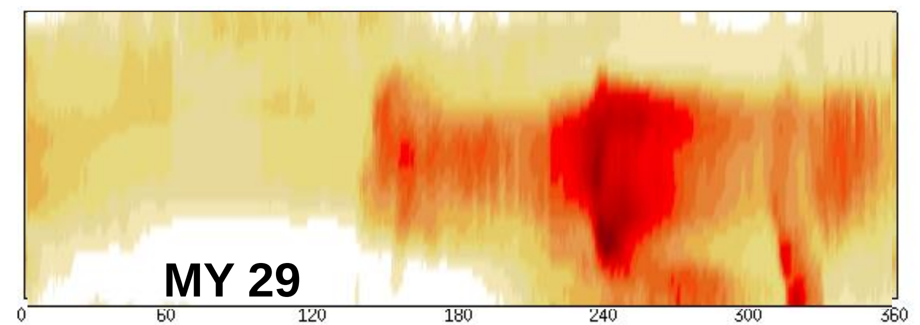


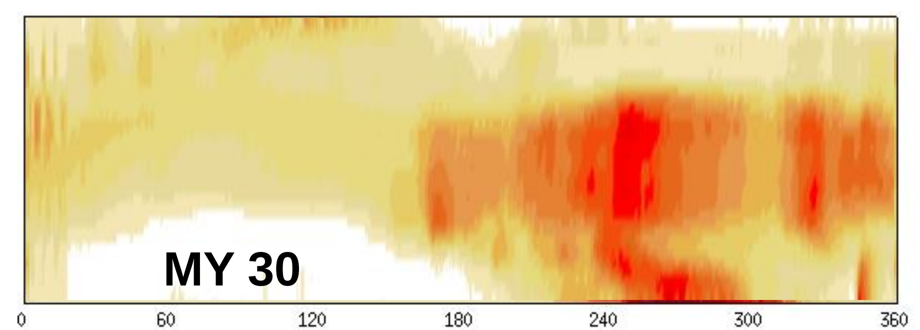








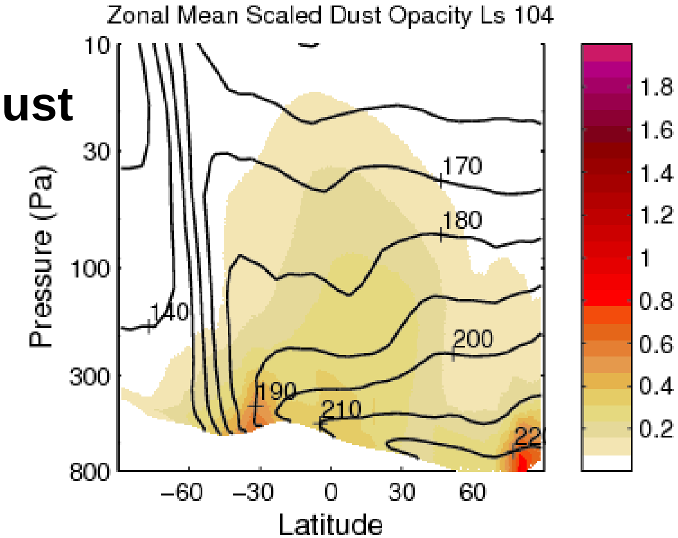


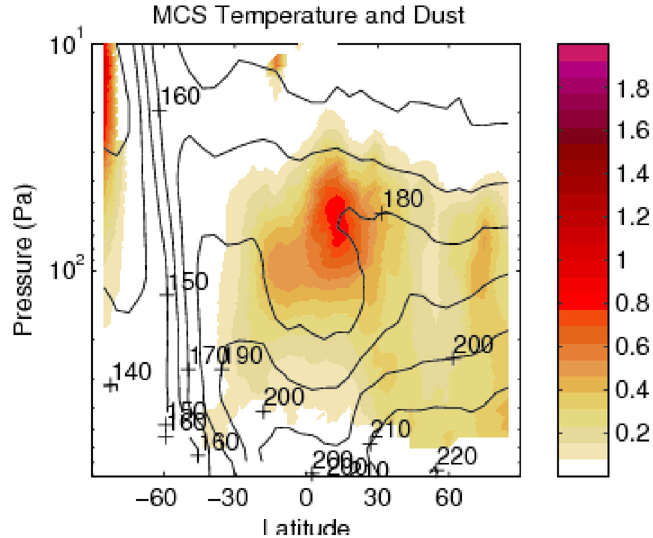


MGCM vs. MCS Aerosol

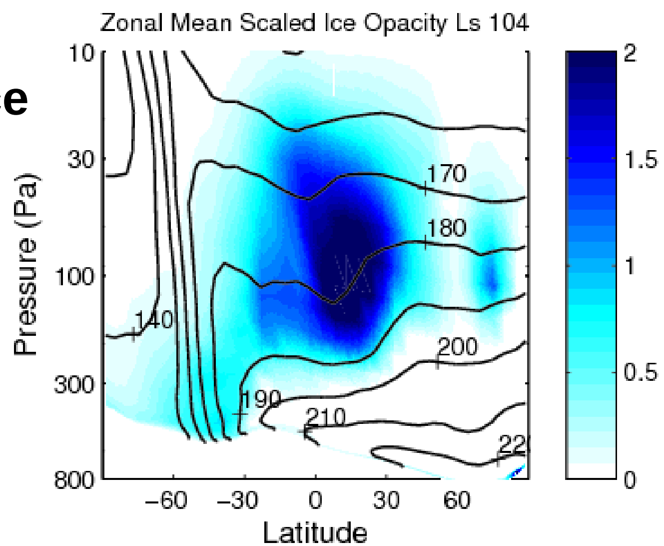
MGCM Forecast Aerosol | **MCS Retrieved Aerosol** | **Opacities Normalized to 610 Pa**

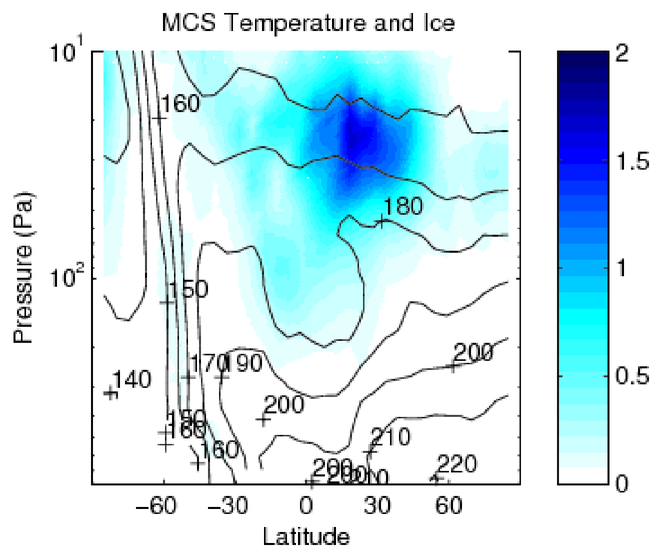
Dust





Ice





Challenges for GCMs:

Mars GCMs do not yet handle detached dust layer very well.

Two hypotheses:

Rafkin: topographic convection

Spiga: “rocket dust storms”

Mars Atmospheric Observations

	TES Nadir	TES Limb	MCS Limb
Temporal Coverage	2x per sol	Sporadic	2x per sol
Aerosol	Column Opacity	Profile	Profile
Aerosol Weakness	Daytime Only, Missing in High Opacity	Missing Boundary Layer	Missing Boundary Layer
Orientation	Nadir	Limb	Limb, along or cross track
Weakness	Overly Smooth	Sparse Coverage	Tropics Missing Sometimes
Vertical Resolution	Coarse	Moderate	Fine

Additional Observations:
Radio Science (High Resolution Temperature Profiles, but sporadic)
Surface Pressure (Viking Lander and Curiosity Rover)
Visible Imagery (from MGS and MRO)

Aerosol Representation in the MGCM

- Dust (3 tracer sizes: 0.3, 1.2, 2.5 micron)
- Water (Ice and Vapor phase)
- Advection
- Sedimentation
- Lifting
  - To Match Observations (in PBL)
  - Convective (Dust Devils)
  - Wind Stress (Dust Storms)

Strategies for Analyzing Aerosol

Constrain vertical distribution:

- From aerosol vertical profiles.
- From temperature fields.

Constrain column opacity:

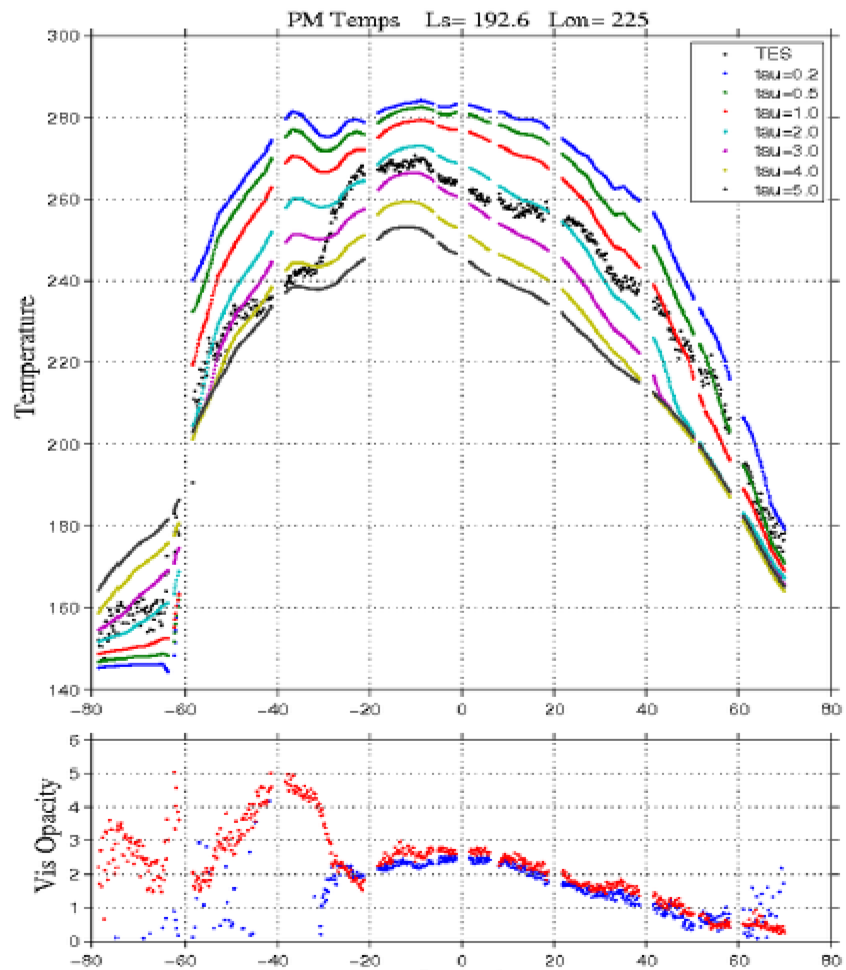
- From brightness temperature fields.
- From column opacity products.

Estimate model / assimilation parameters:

- Distribution of increment among tracer sizes.
- Ice cloud radiative scaling factor.
- Surface dust fluxes.

Inferring Dust Opacity from Brightness Temperatures

- Wilson et al. (2011) demonstrated that brightness temperature is sensitive to column dust opacity.
- This allows opacity to be inferred when retrievals are unreliable (during dust storms).



Findings: Mars Atmosphere Reanalysis

- We have **successfully assimilated** both nadir (TES) and limb (MCS) Mars **temperature profiles**, creating 4 years of **reanalysis**.
- We have demonstrated that data assimilation analyses converge about a **unique synoptic state**, and compare favorably with other products.
- We have used the reanalysis to examine **predictability**, **traveling waves**, **thermal tides**, and the impact of **dust** and **water ice clouds**.
- The Mars atmosphere has regions of chaotic **error growth**, as well as relatively quiescent regions dominated by aerosol forcing, which has implications for ensemble spread.
- Comparisons of free runs and assimilations with observations identify **vertical aerosol distribution** as a leading cause of bias (and RMSE) in analyses and forecasts. This encourages the development of an aerosol reanalysis.

Ensemble Data Assimilation on Mars: *Insights into the **Weather** and **Predictability** of the Red Planet*

Acknowledgements:

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