# The atmosphere of Mars:

## *Insights on weather and predictability from ensemble data assimilation of spacecraft observations*


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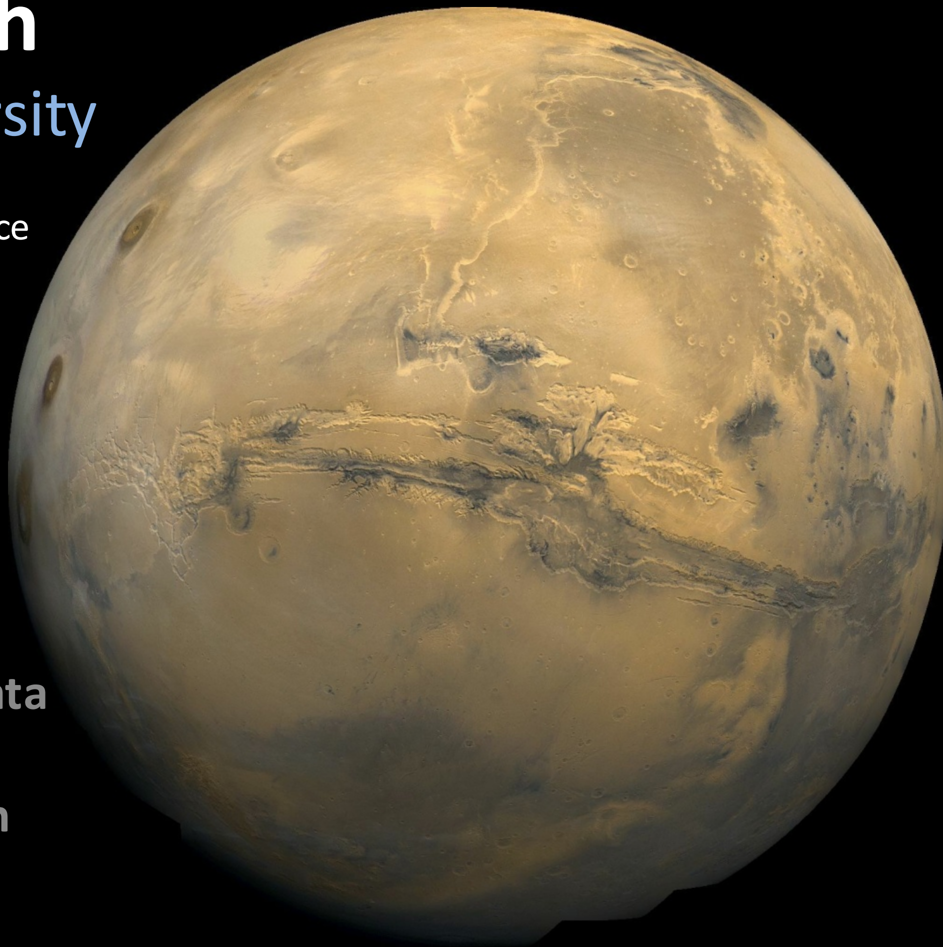

## 7th EnKF Workshop

**Symposium on Advanced Assimilation and Uncertainty Quantification in BigData Research for Weather, Climate and Earth System Monitoring and Prediction**

Tuesday 24 May 2016

# 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

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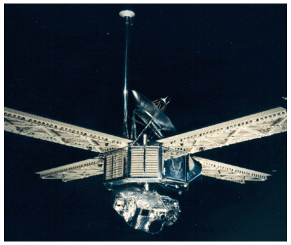
# Comparing the Earth and Mars

| Variable | Earth | Mars |
|---|---|---|
| Radius | 6378 km | 3396 km |
| Gravity | 9.81m $s^{-2}$ | 3.72m $s^{-2}$ |
| 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 |

# Spacecraft Exploration of Mars

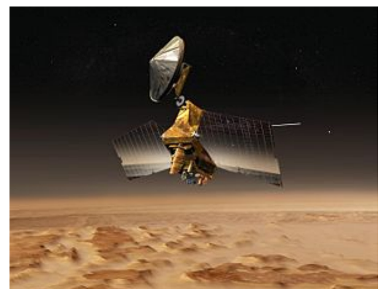


Mariner Program: Observed Dust Storms

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

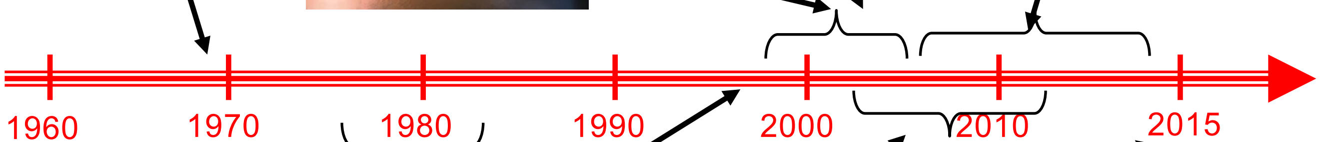
Mars Odyssey: Imaging and Spectrometry

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

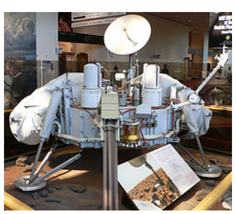


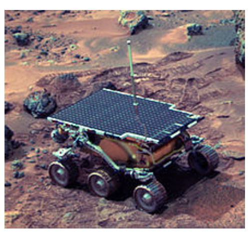
Mars Science Laboratory (MSL)

- 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



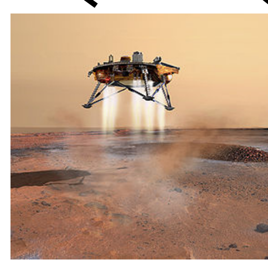

Viking Lander: Surface Pressure Time Series





Mars Pathfinder: Surface Weather

Mars Exploration Rovers: Dust Devils



Mars Phoenix Lander: Precipitation, Water Ice

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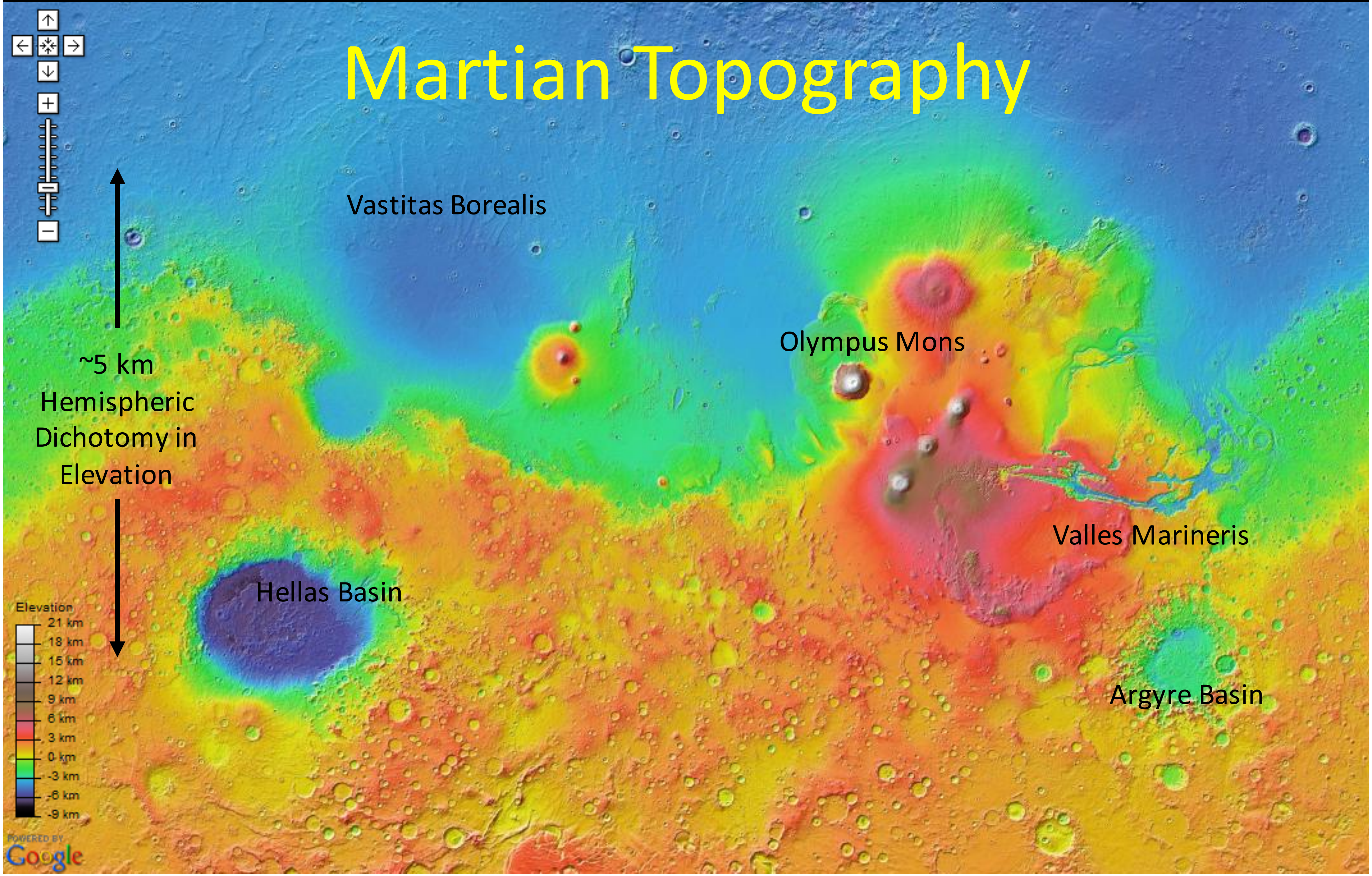
# Martian Topography



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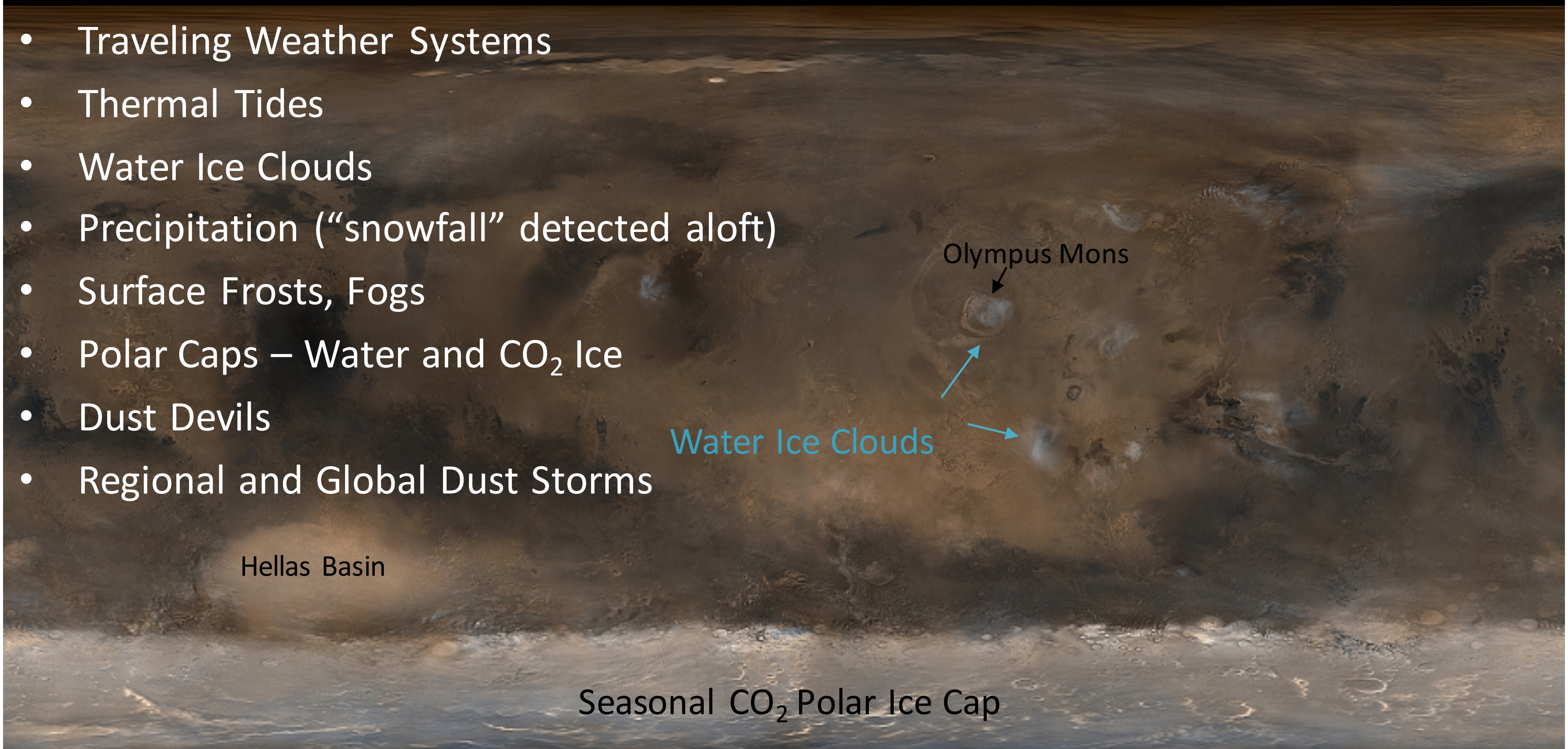
# Features of Martian Weather

*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

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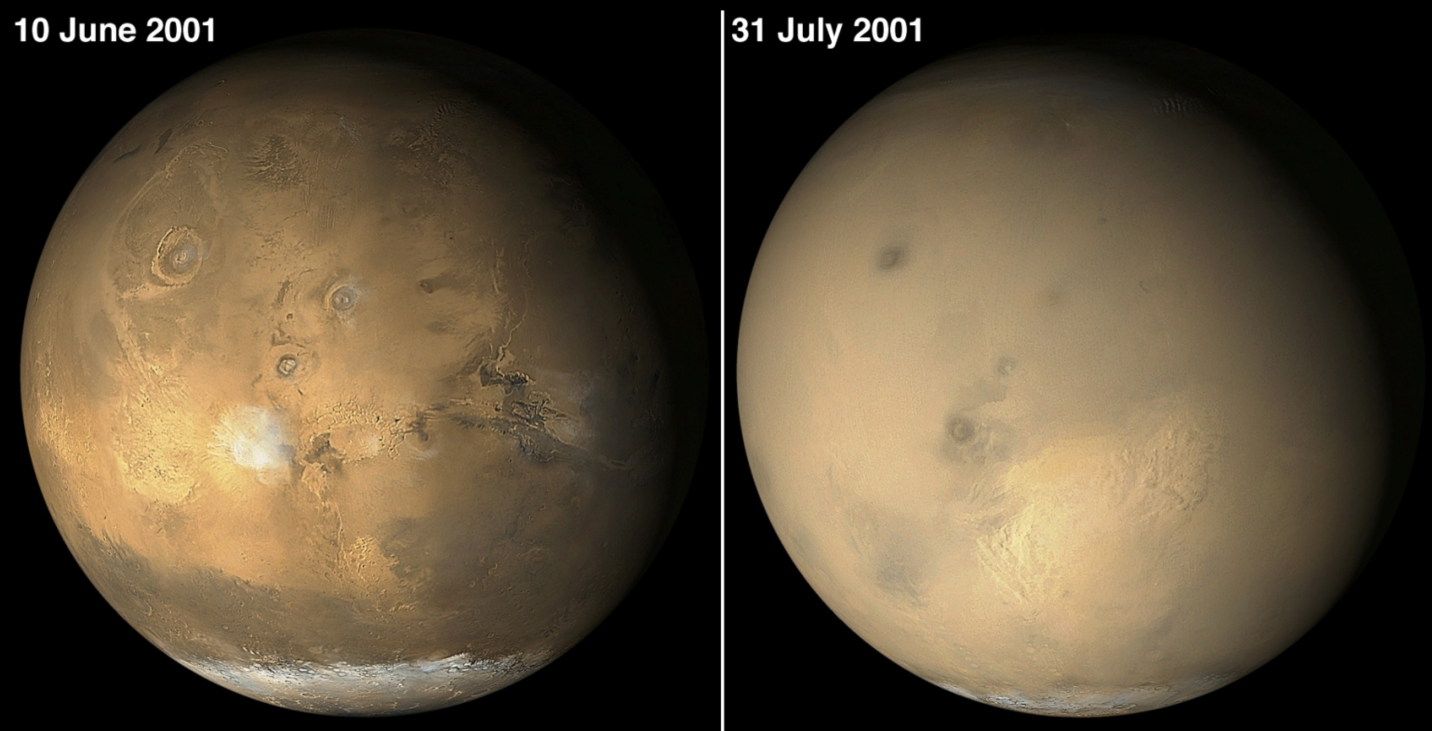
# The Dust Storm Enigma

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.



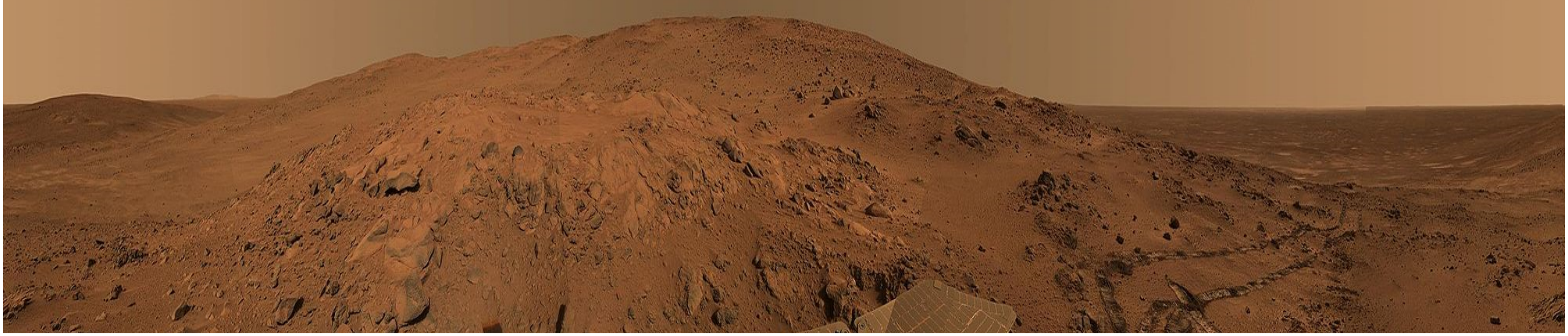

Prior to Global Dust Storm

During Global Dust Storm

*Figure Courtesy of NASA/JPL*

# Creating a Mars Reanalysis

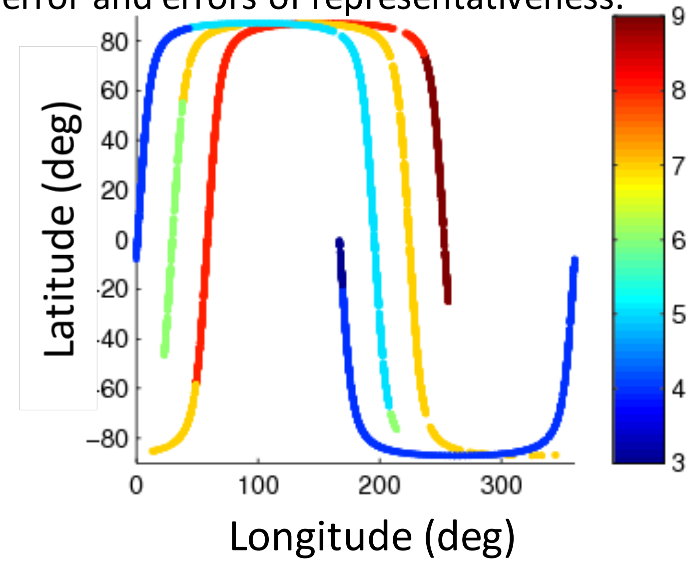
- Spacecraft Observations
- Mars Global Circulation Model
- Data Assimilation Techniques
- Performance Evaluation and Validation



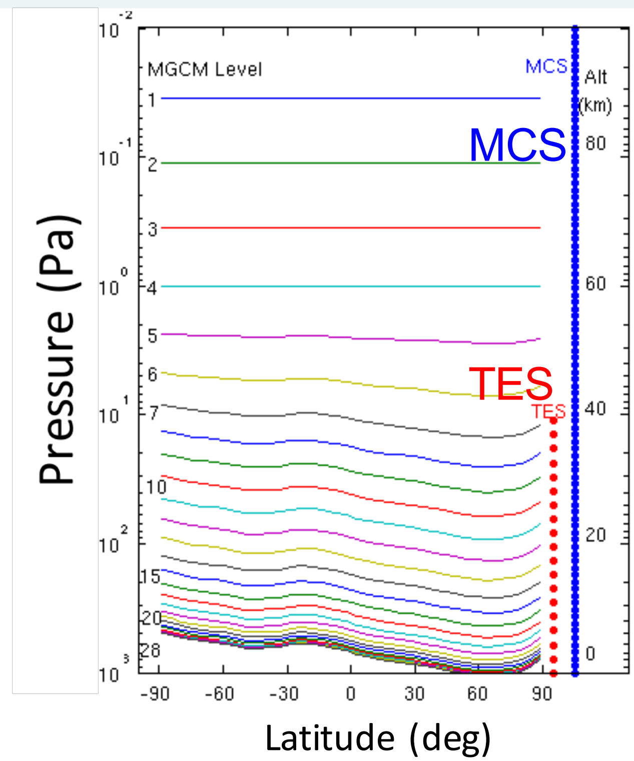
## TES (Thermal Emission Spectrometer) MCS (Mars Climate Sounder)

| 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.



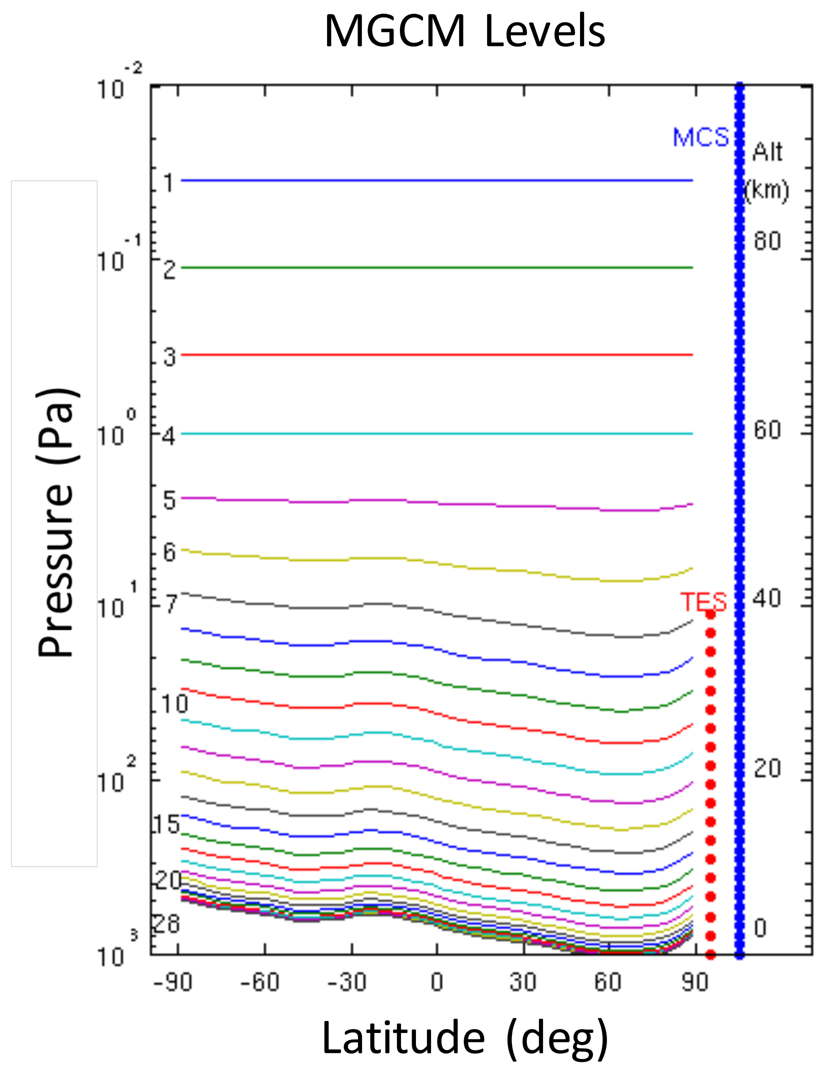

Sample locations of TES profiles during 6-hour interval



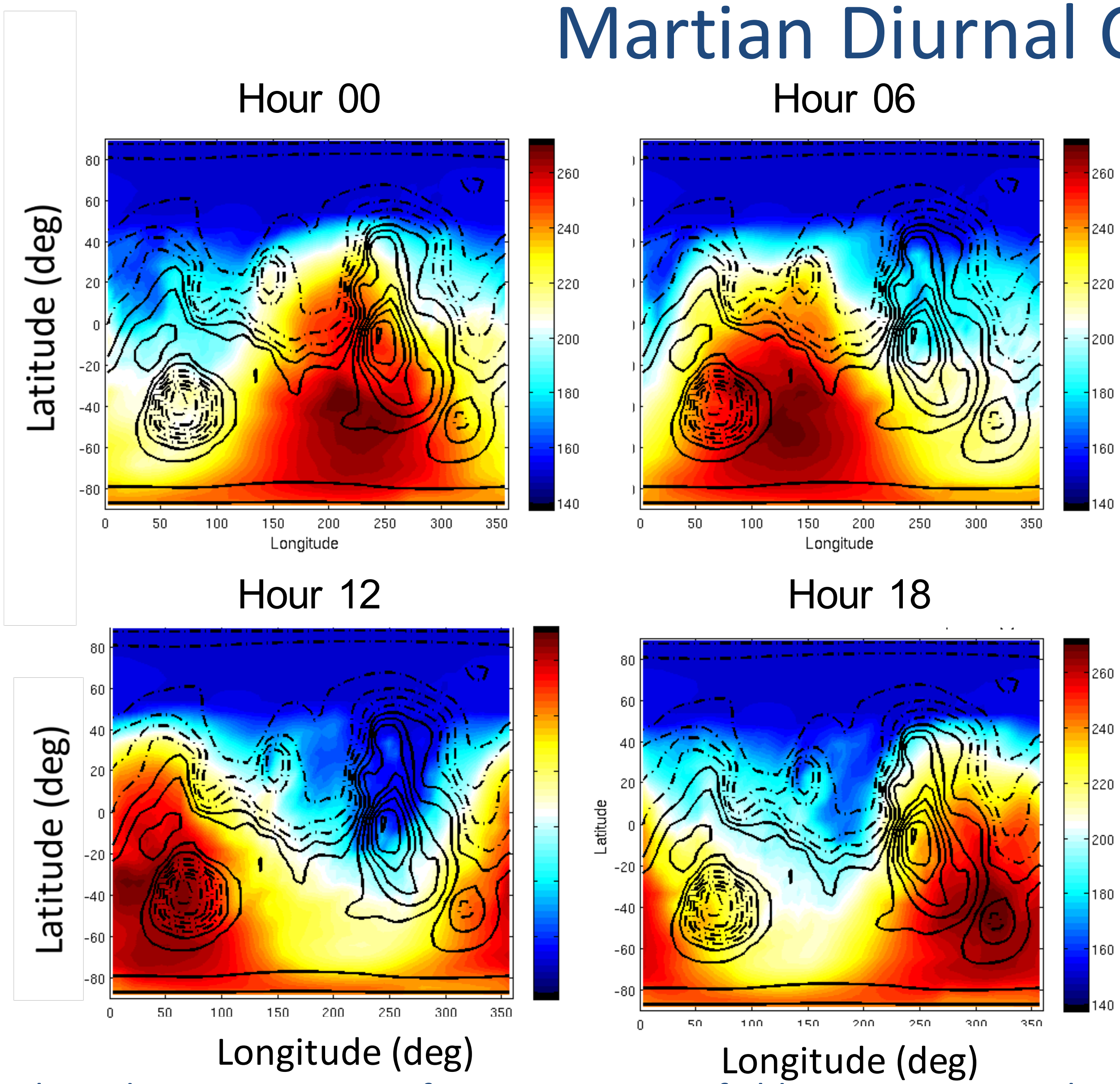
# GFDL Mars Global Circulation Model (MGCM)

*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

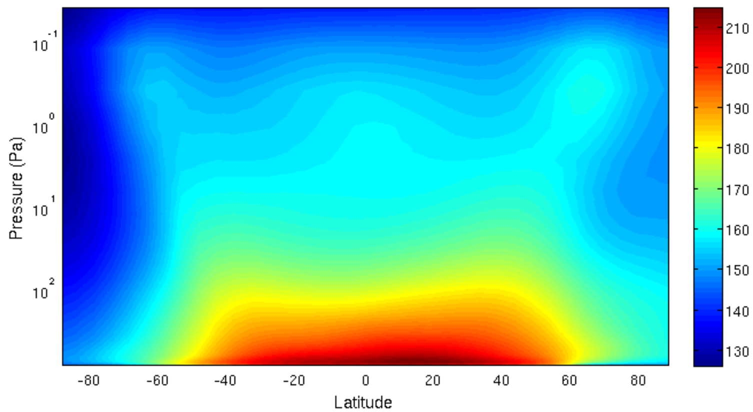



- The **thermal tide** can be tracked as the tongue of warm temperatures centered around the subsolar point as it moves across the planet over the course of a day.
- **Diurnal** temperature **changes** in the summer hemisphere can approach 100 K.

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

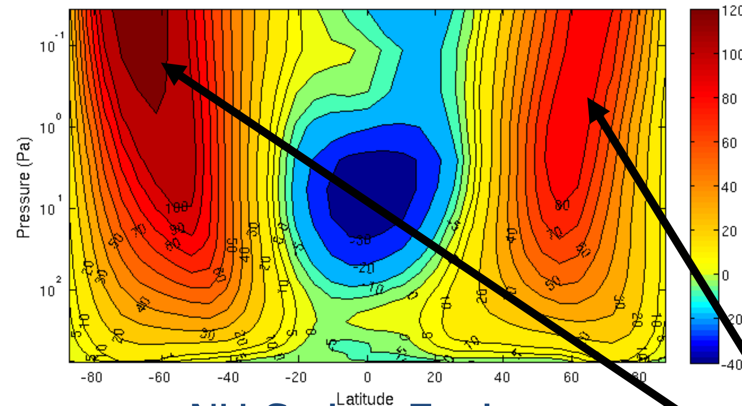
Contours are topography.

# Martian Seasonal Cycle




NH Spring Equinox

Zonal Mean Temperature

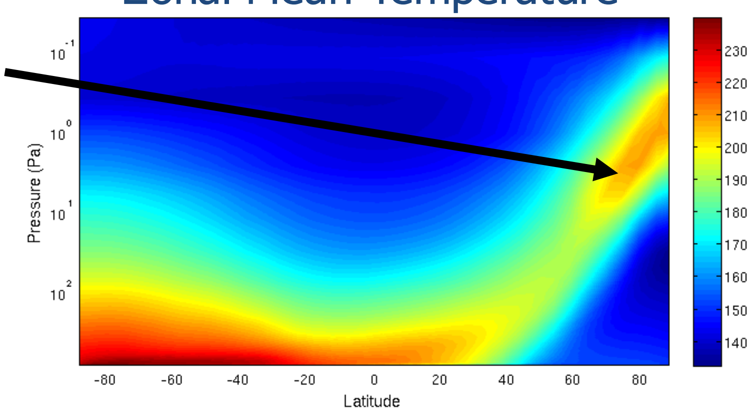



NH Spring Equinox

Zonal Mean U-Wind

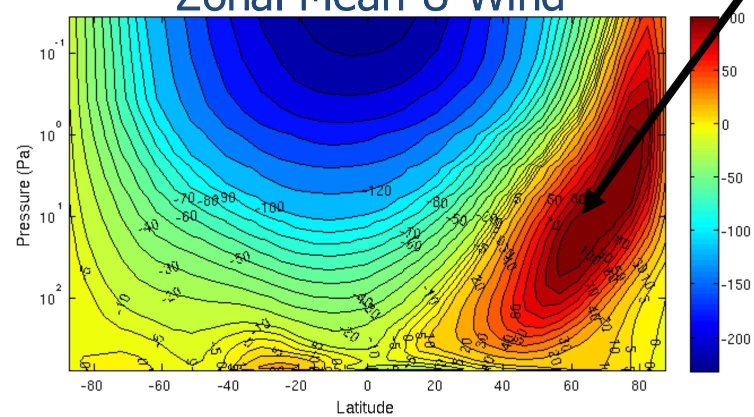
Westerly Jets

Adiabatic Warming from Global Hadley Cell Descent




NH Winter Solstice

Zonal Mean Temperature




NH Winter Solstice

Zonal Mean U-Wind

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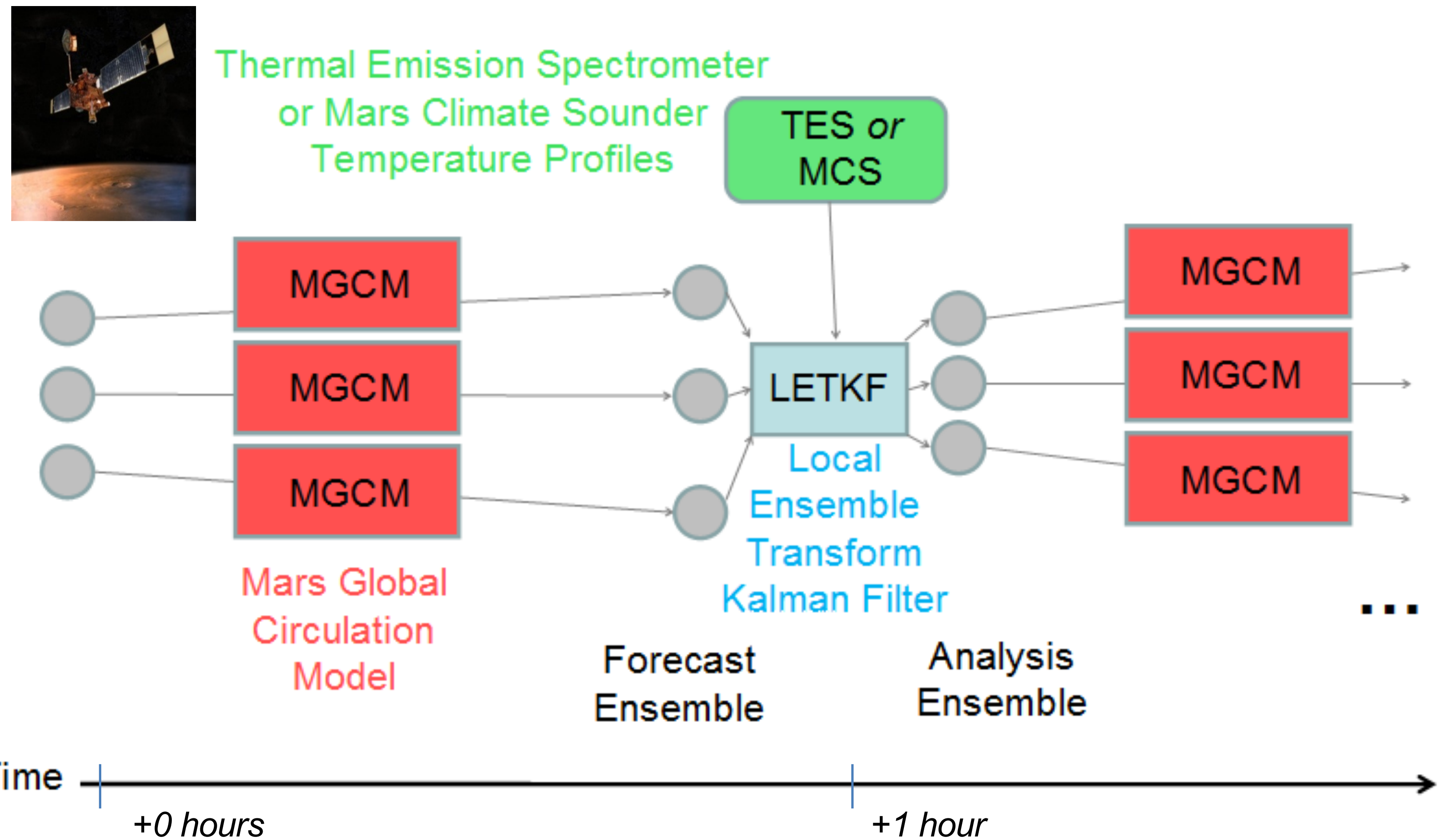
# Assimilation: Optimally Combining Observations with a Model



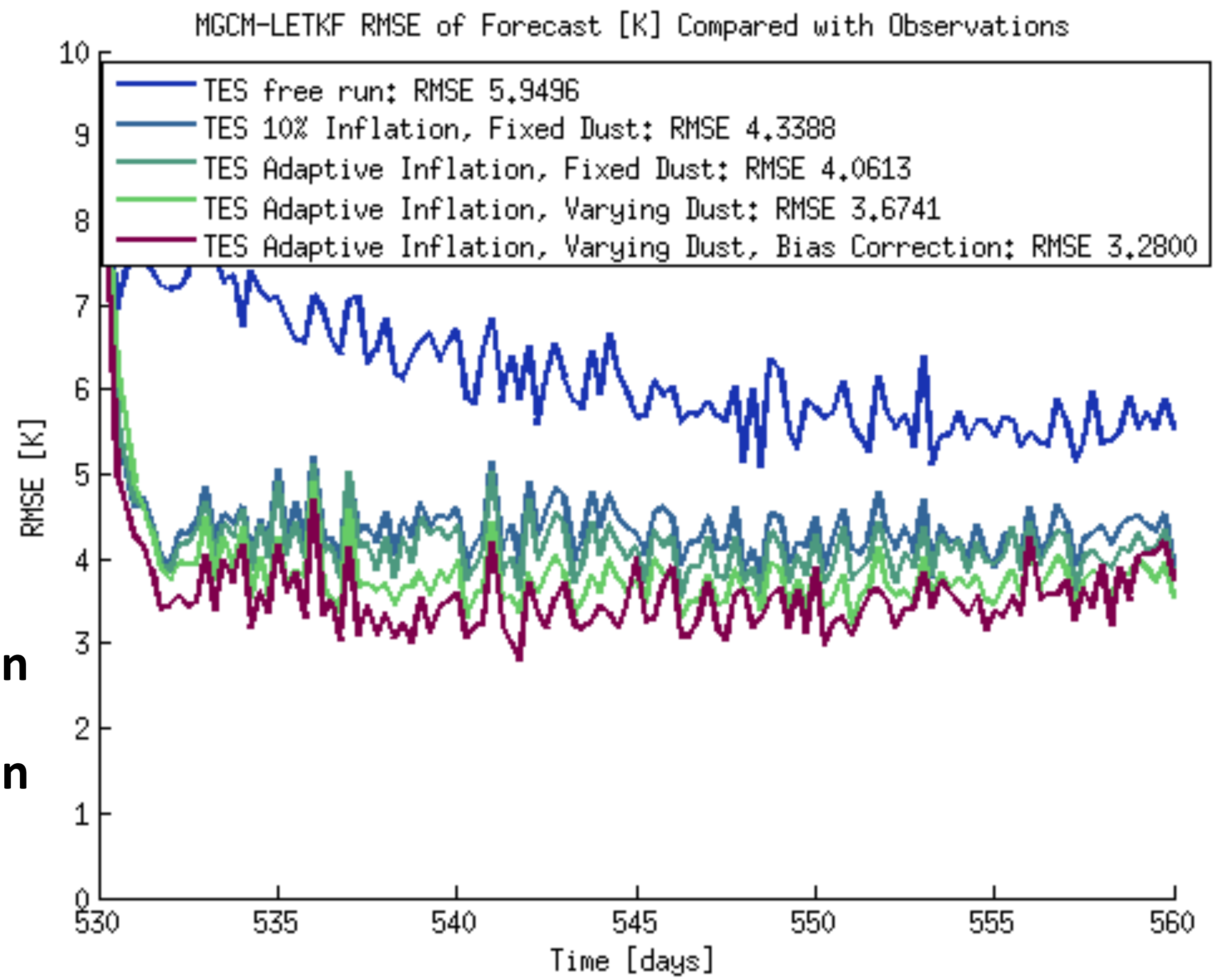

Update: Temperature, U and V Wind, Surface Pressure

# Improving Assimilation 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 Assimilation Performance

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

*Ongoing Development:*

Hybrid EnKF/Var Data Assimilation
(Grad Student Matthew Wespetal)

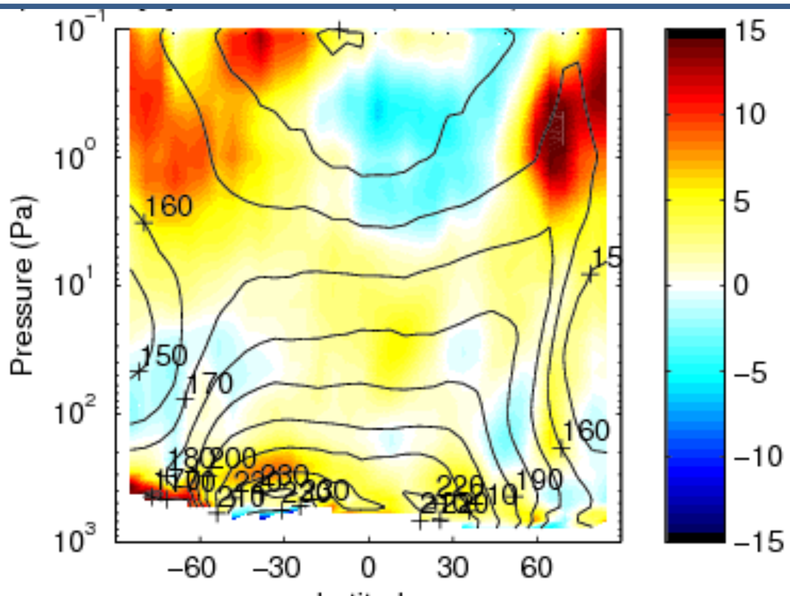
New methods for assimilating retrievals: transforming observations to remove the prior and vertical error correlations, enabling interactive retrievals
(Collaborator Ross Hoffman, AER)

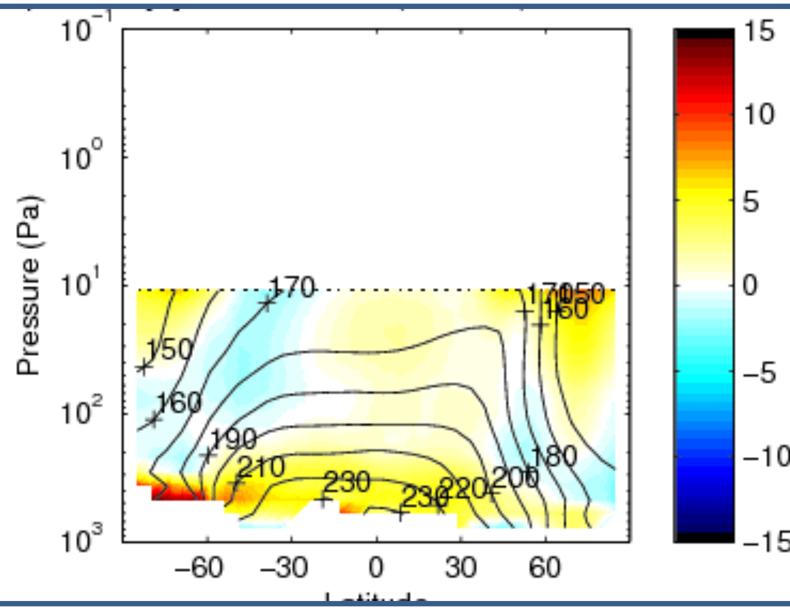
Evaluated by comparing 0.25 sol forecasts with observations.

# NH Autumn Ls 185-203

**MCS** **TES**

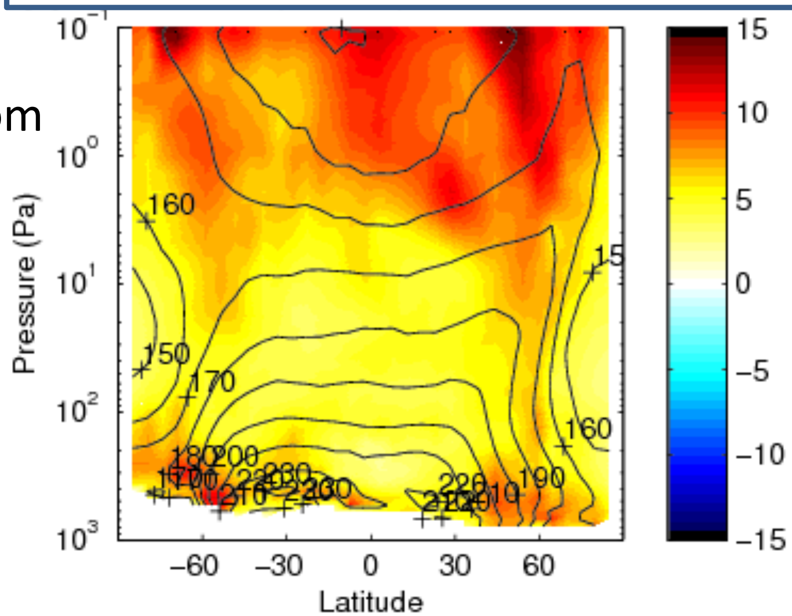
Bias

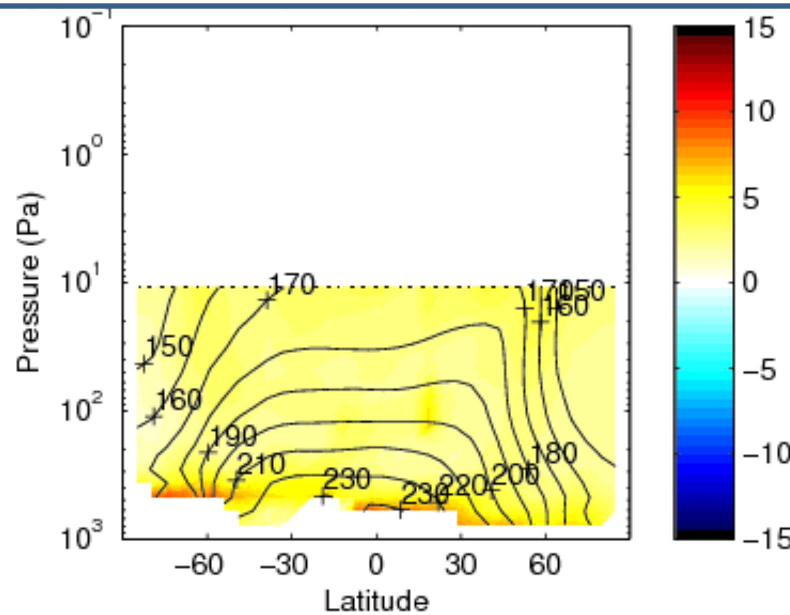



**MCS** **TES**

Random Error



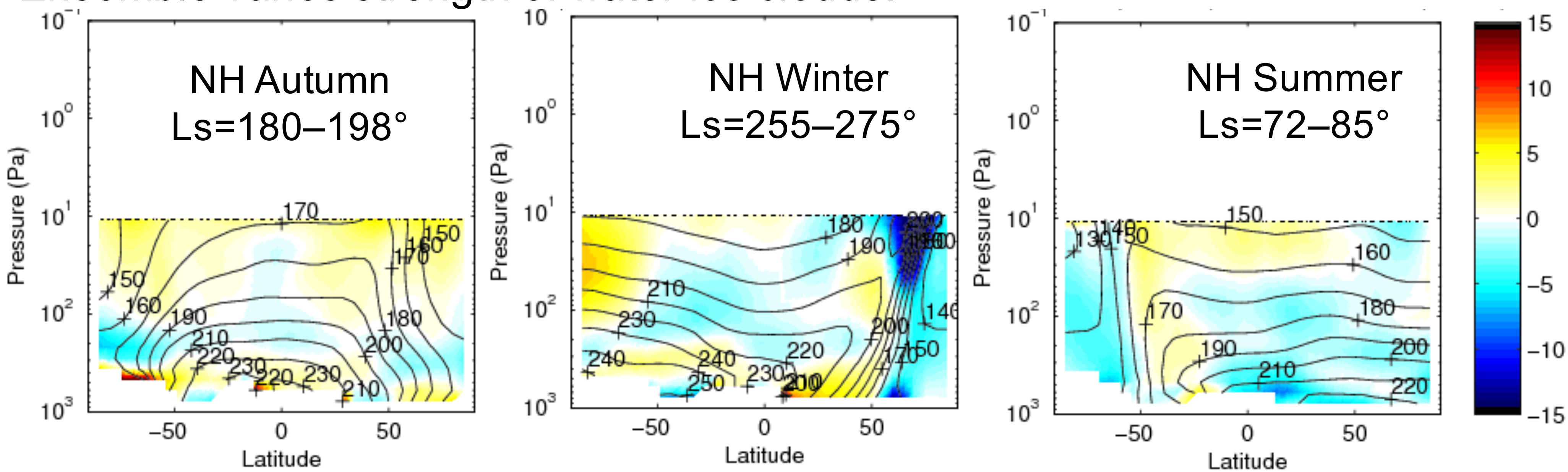



**Reanalysis** forced by **TES Dust Opacities**

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.

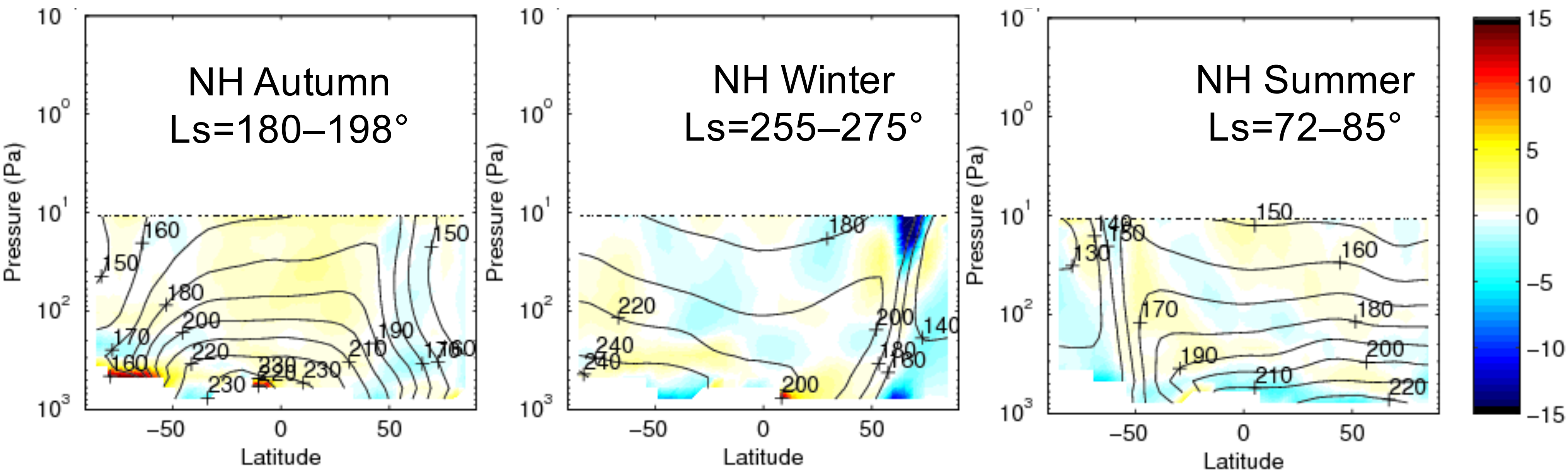



With model improvements and use of observed dust information, biases are generally reduced.

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

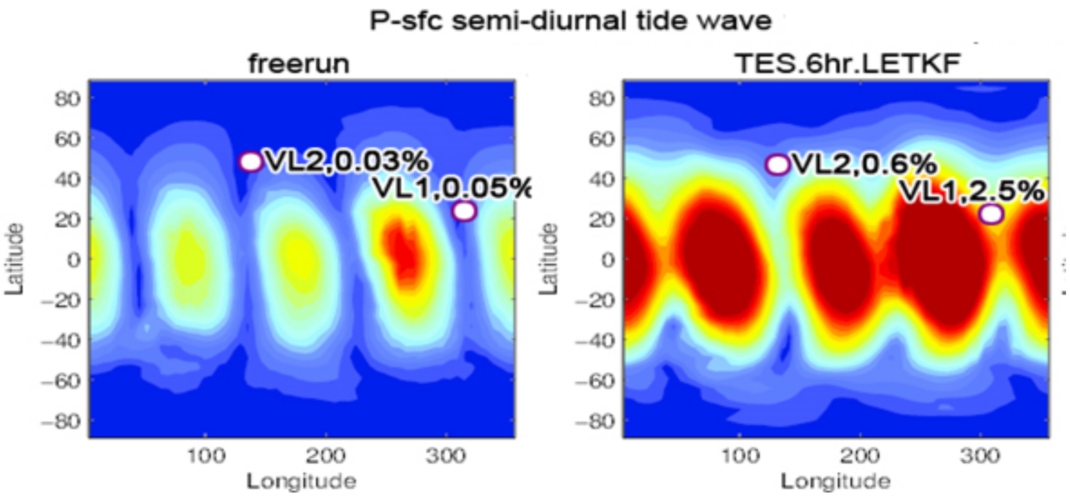
Time mean analysis increment from past 10 sols is applied every 0.25 sol

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



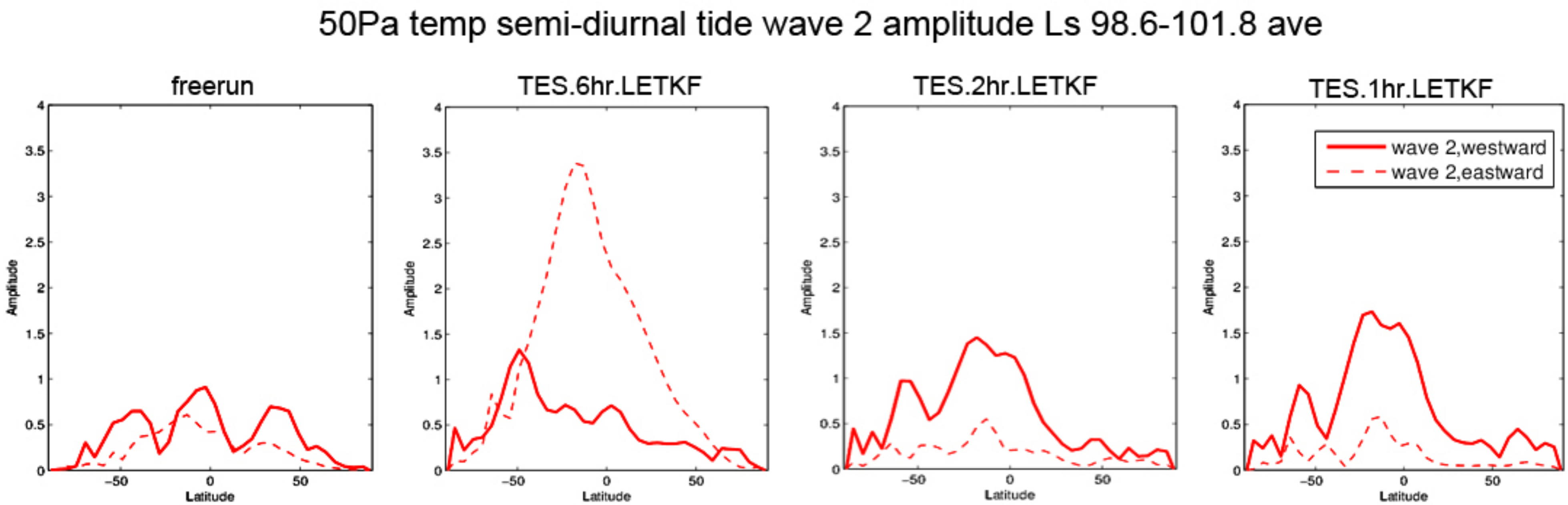

Reduction in bias will occur with improved MGCM parameterizations, as well as by improving the dust and water ice distributions through formal assimilation of observation information and parameter estimation.

# Resonance induced to Semi-Diurnal Tide by 6-hr Data Assimilation Windows




Wave 4 spatial pattern of observation increments modulates semi-diurnal tidal modes through constructive interference.
(On Mars, topography also modulates the tides.)

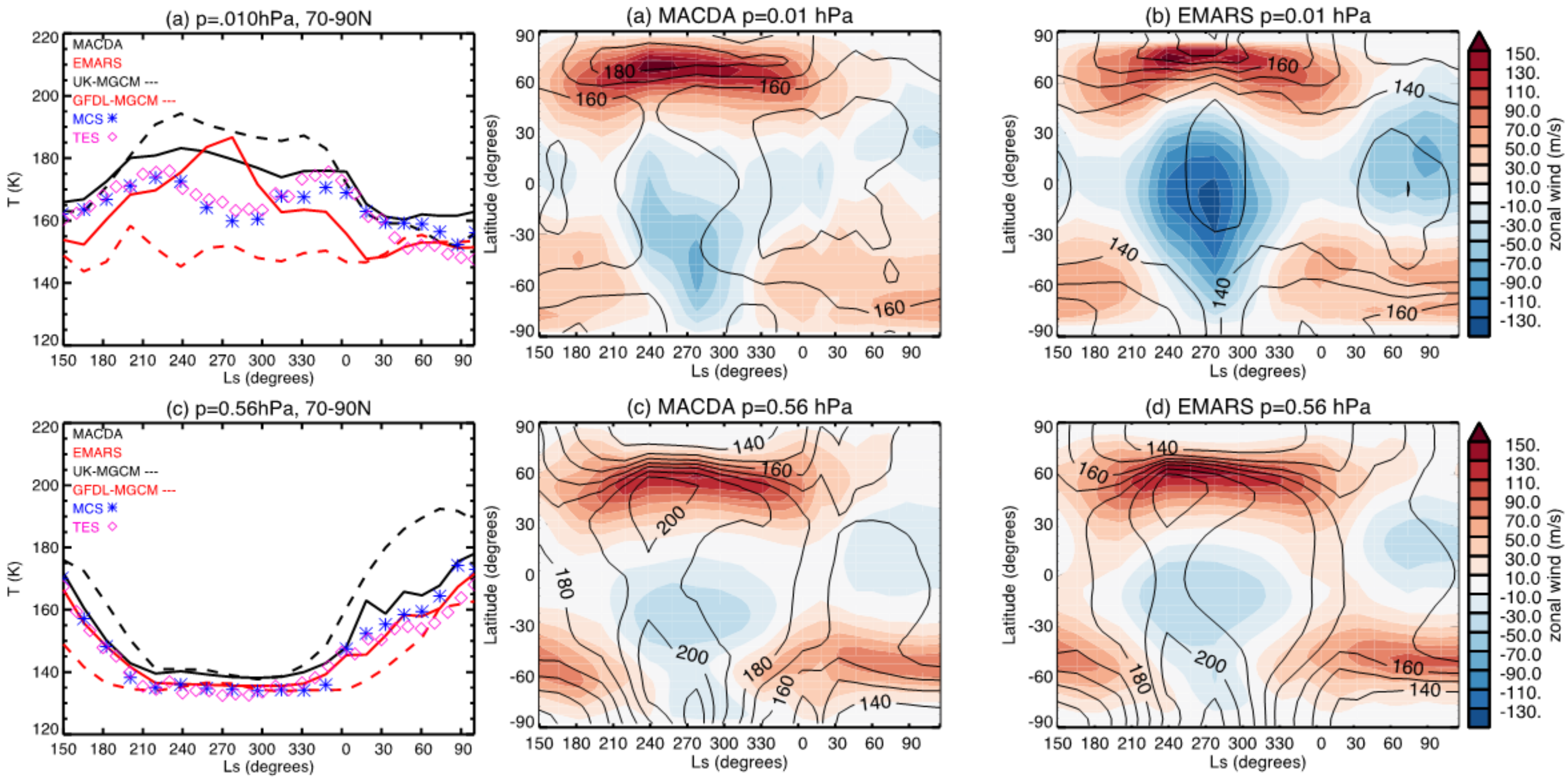
*Solution:*
Use shorter assimilation window (1 or 2 hours)



# Evaluating the Reanalysis

- Comparisons with freely running forecasts.
- RMSE and bias of short term forecasts initiated from ensemble analyses.
- Comparisons to other reanalyses.
- Comparisons to independent Radio Science temperature profiles and rover data.
- Feature-based evaluation: traveling waves, tides, aerosols.

# Reanalysis Intercomparison



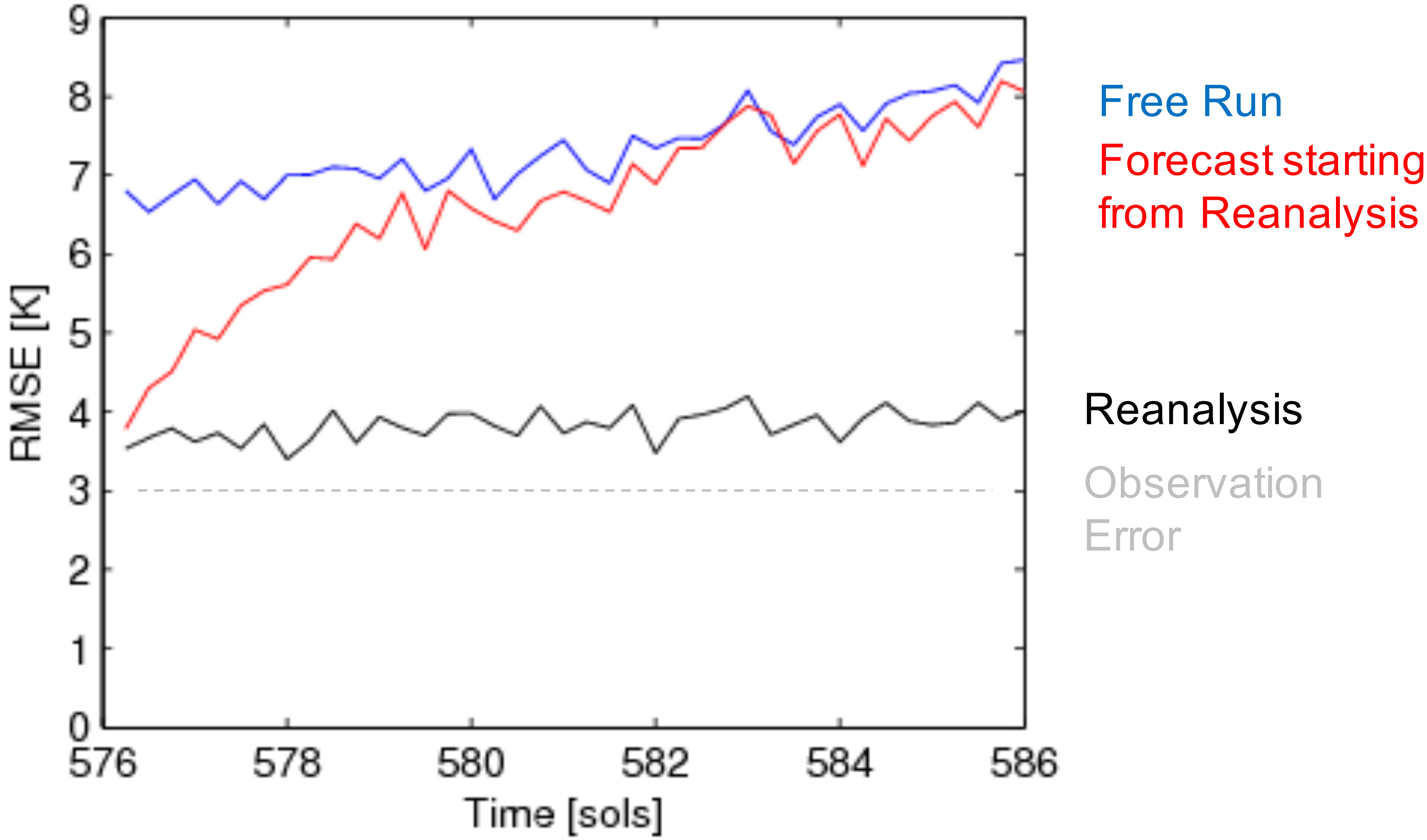

- Zonal mean statistics of temperature differences between the analyses reveal a general agreement of the analyses.
- Larger disagreements exist at cap edge baroclinic zones, as well as in upper levels above TES coverage, which is due to bias from model differences.
- Reanalysis also compare favorably to independent Radio Science profiles.

# 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
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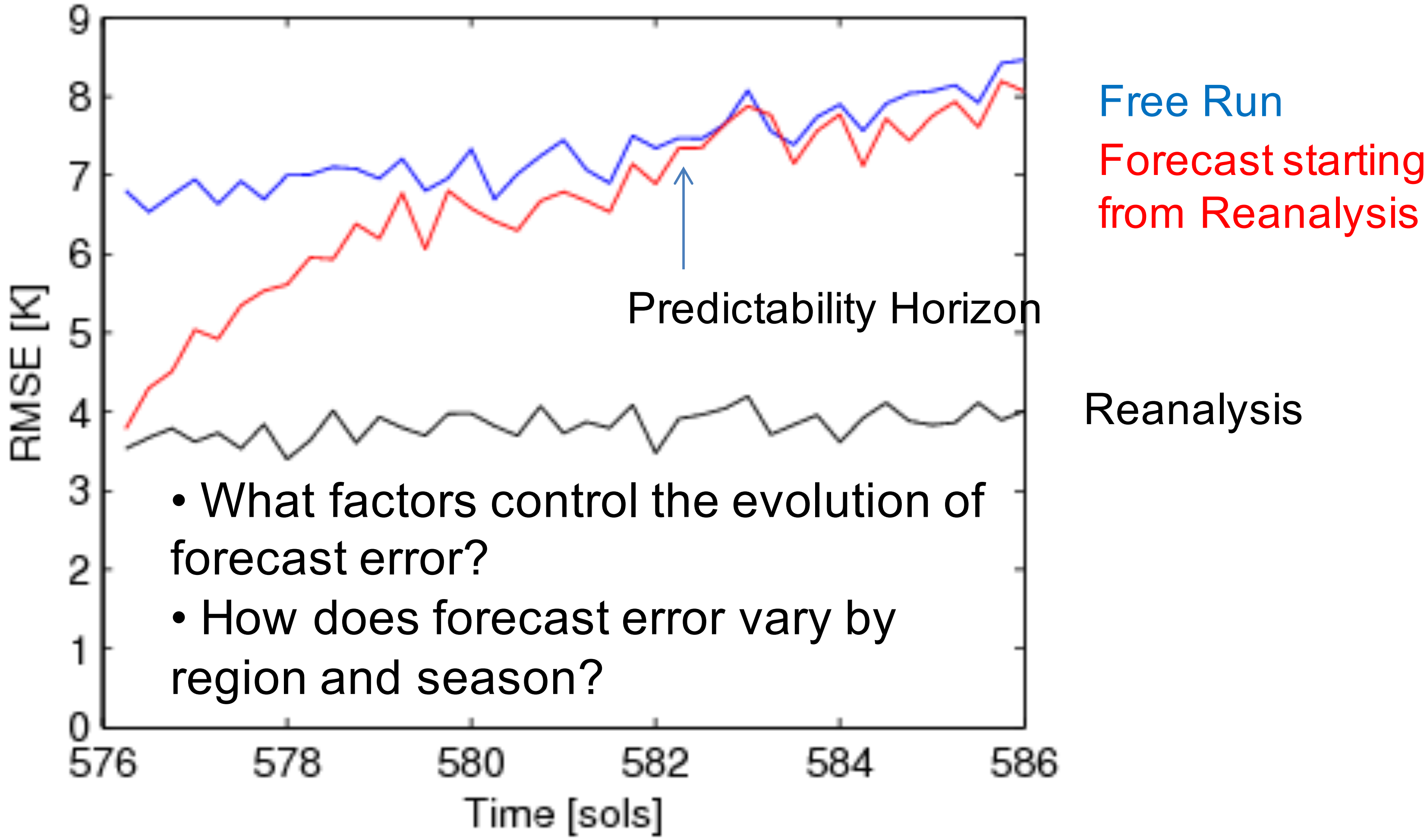



- What factors control the evolution of forecast error?
- How does forecast error vary by region and season?

# Forecast Skill on Mars

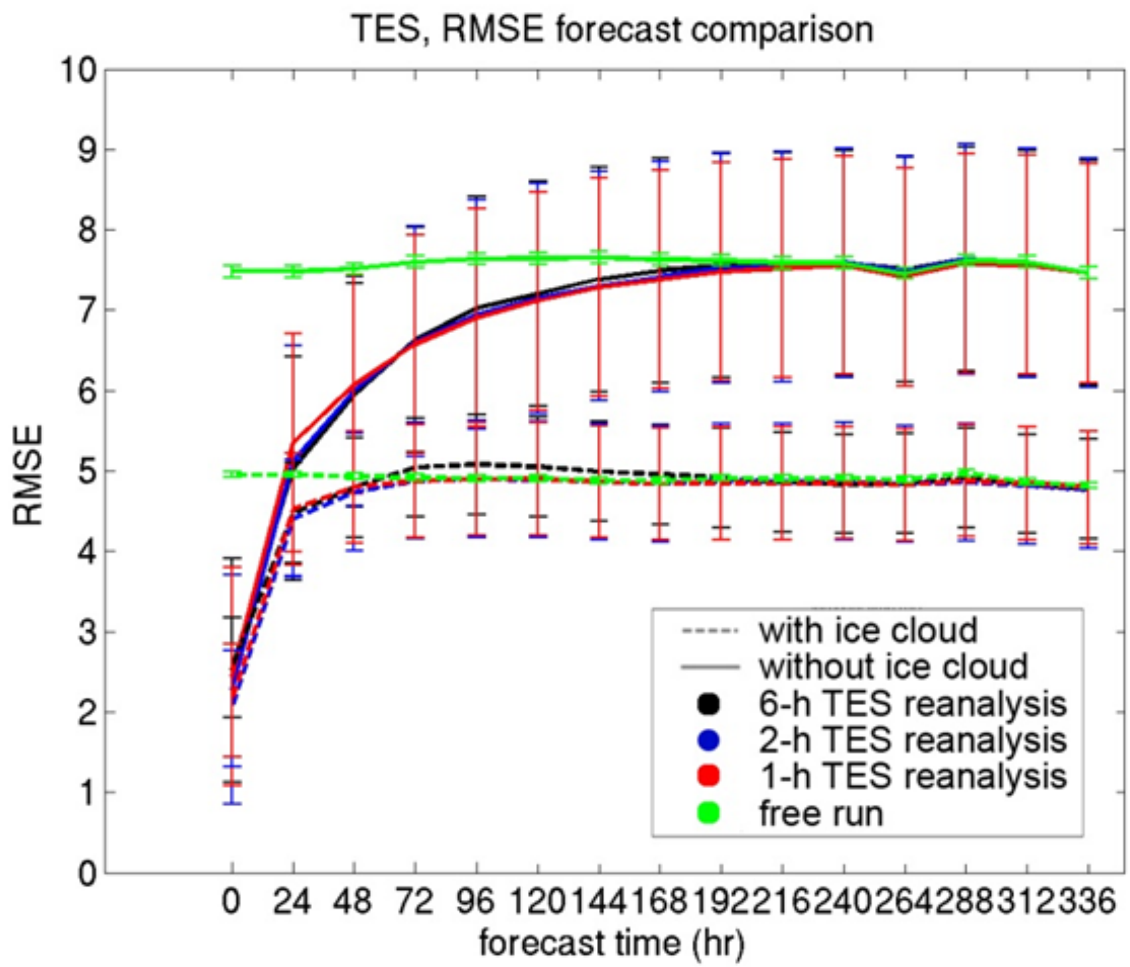
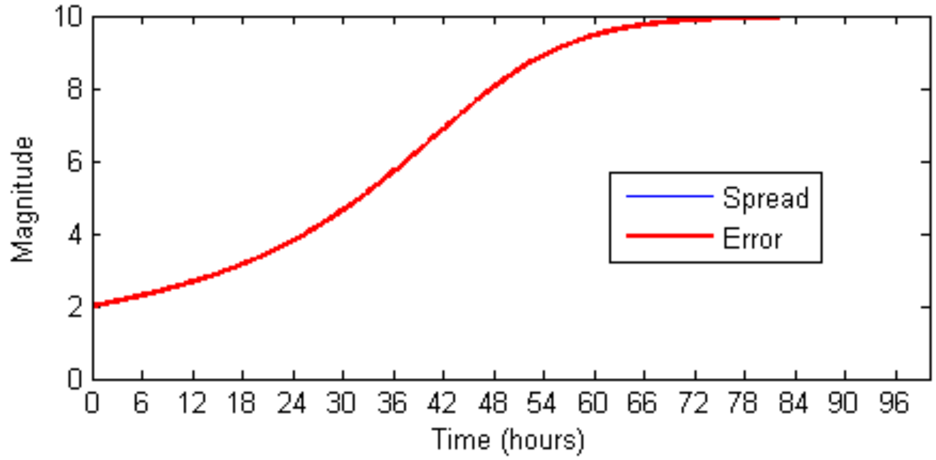



Fig. 1. Performance of the MGCM-LETKF during NH summer (~Ls 100), evaluated by comparing RMS differences of forecasts with TES observations, without and with ice cloud parameterization, and with various assimilation window lengths. Error bar with one standard deviation for each experimental run is also included. (From Zhao et al., 2015)

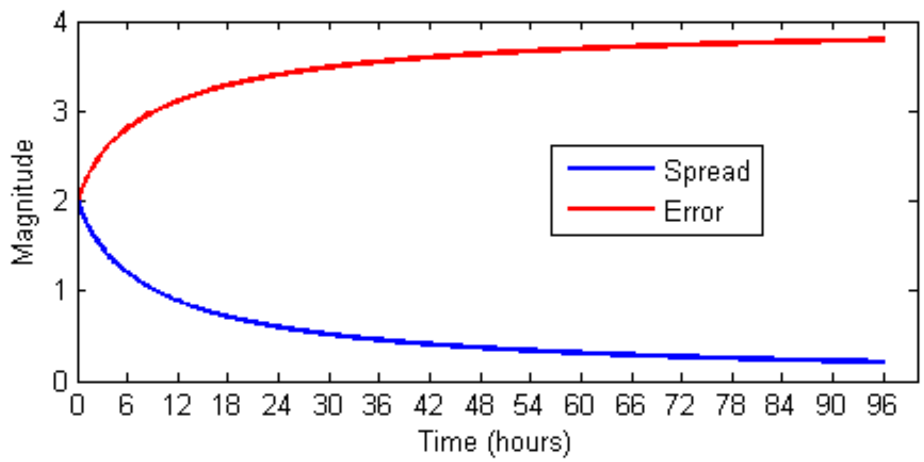
# Sources of Forecasting Error

- 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.

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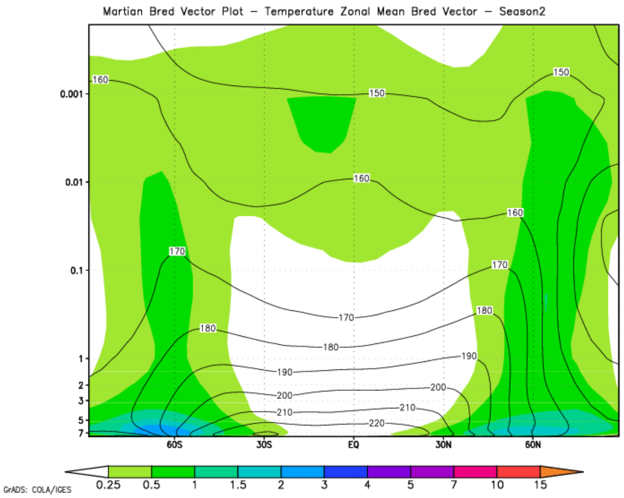
# Elucidating Instabilities with Bred Vectors

*Contours: Zonal Mean Temperature; Shading: Bred Vector Temperature*

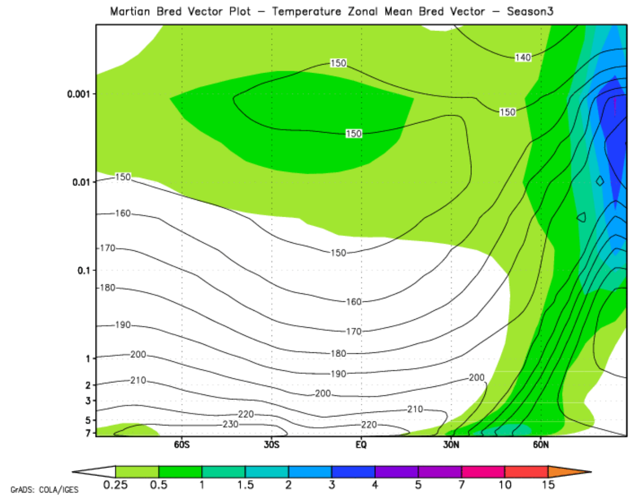
Late Autumn

Ls=180–240°



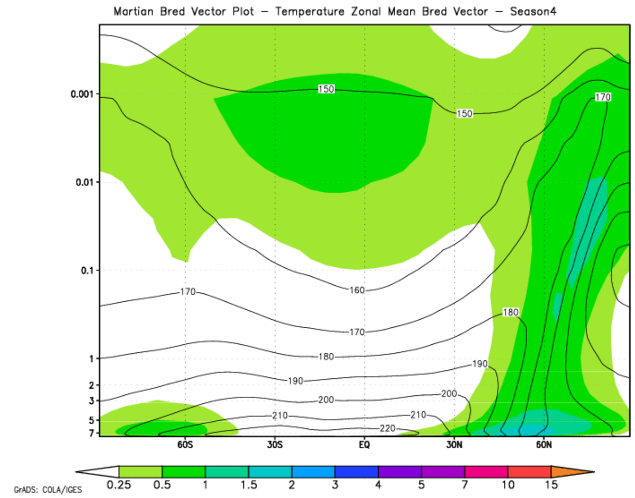

Winter Solstice

Ls=240–300°



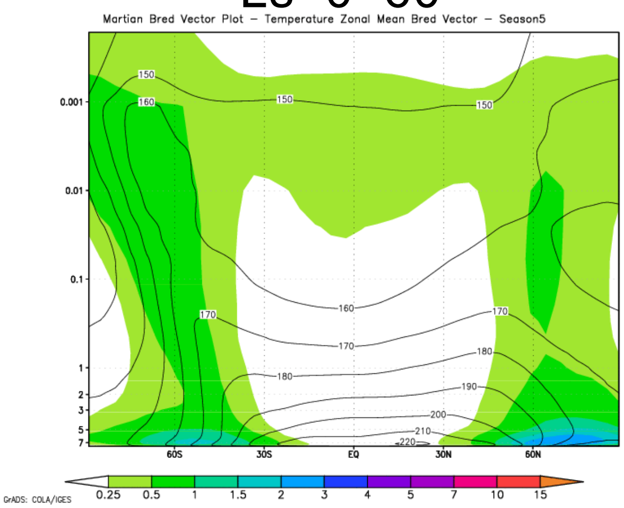

Early Spring

Ls=300–360°



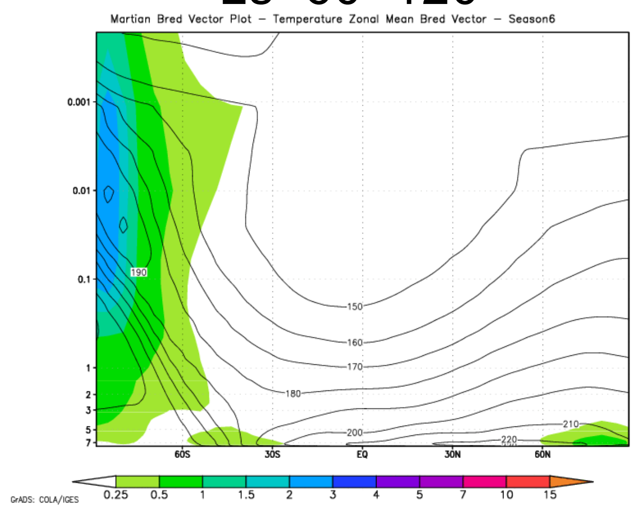

Late Spring

Ls=0–60°



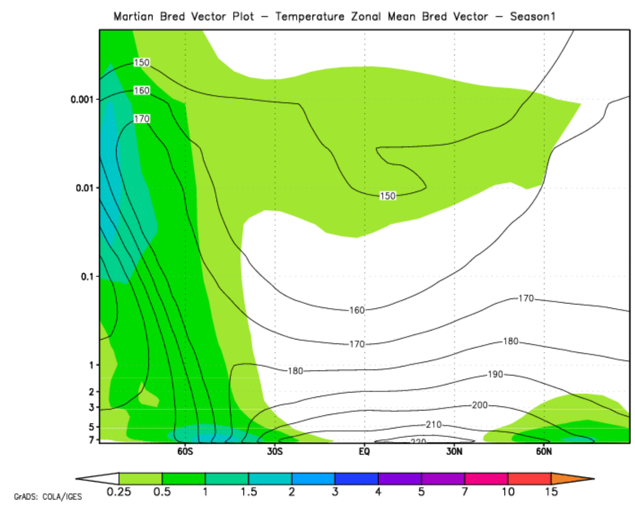

Summer Solstice

Ls=60–120°




Early Autumn

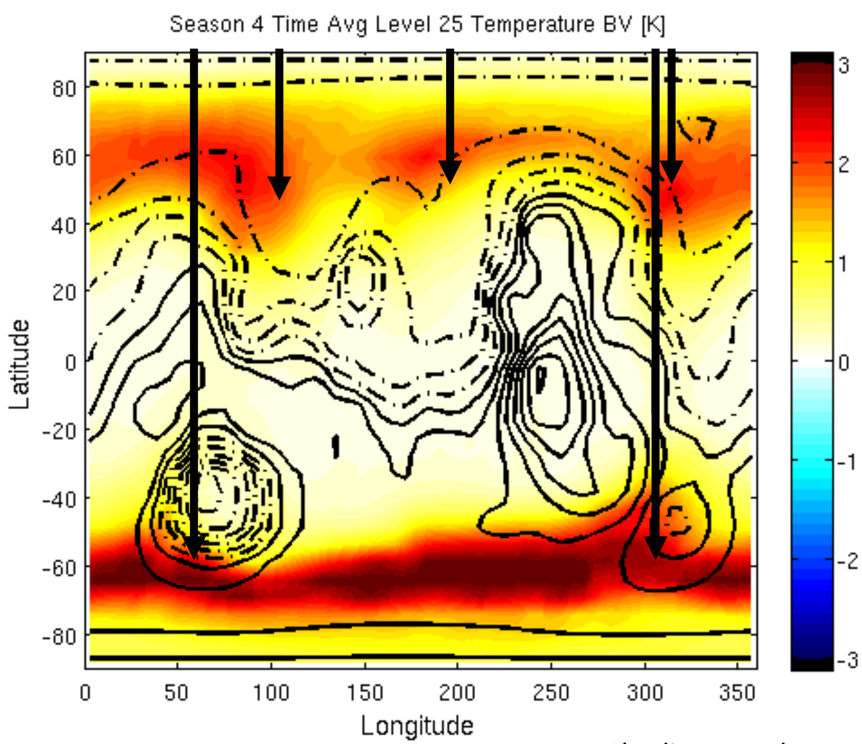
Ls=120–180°



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

Bred Vectors indicate instabilities that clearly drive the ensemble spread.

The seasonal evolution of bred vectors reveal quiescent periods, as well as those marked by chaotic error growth.

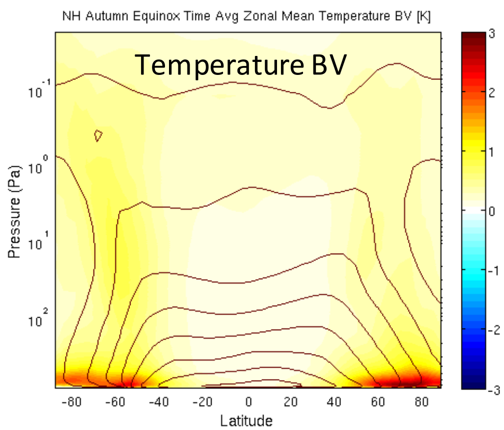


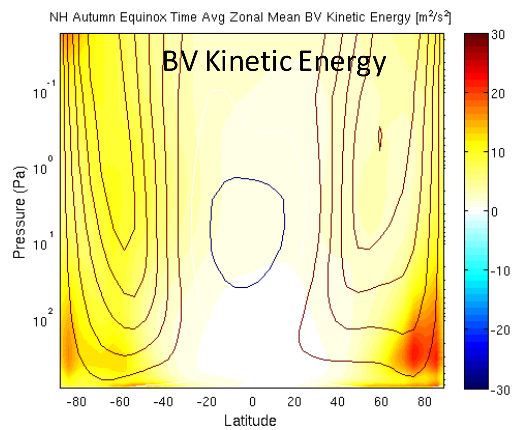

*Shading: Bred Vector*

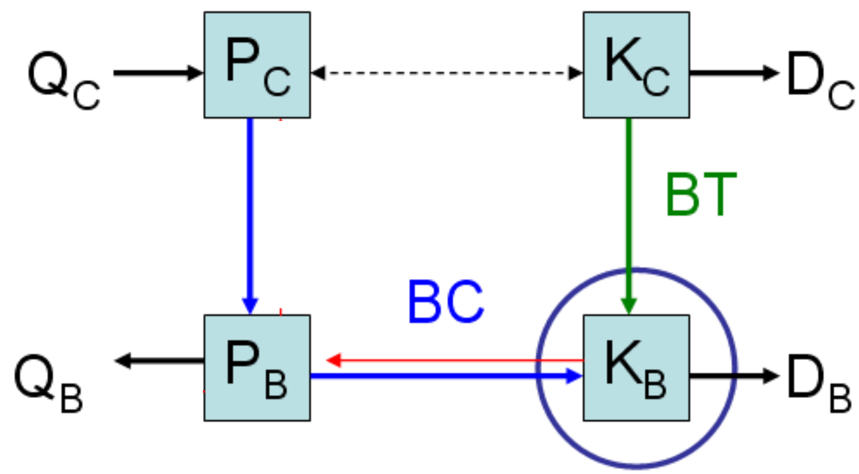
*Contours: Temperature*

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.

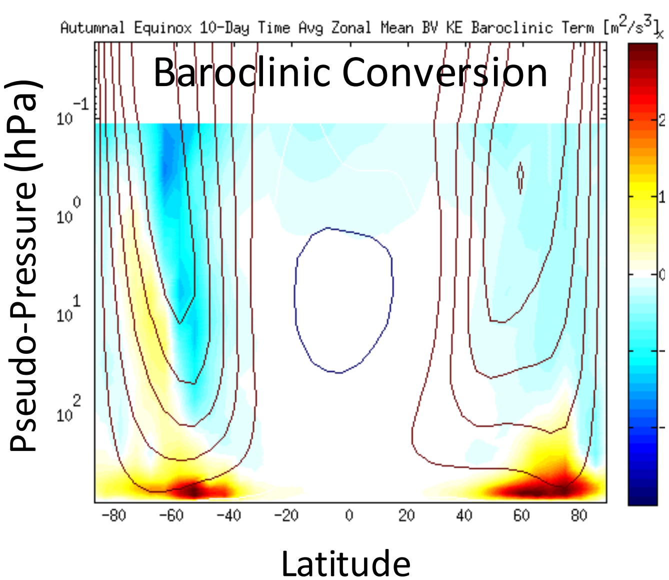
# Barotropic and Baroclinic Processes

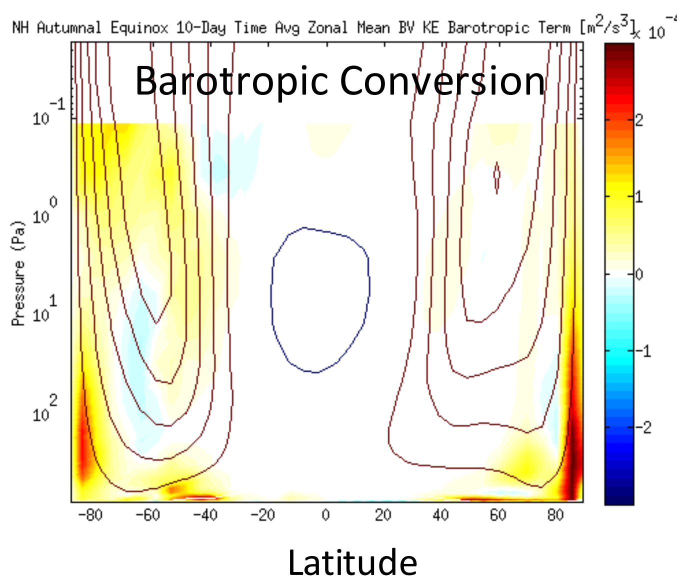



## Origins of Instabilities:
## BV Kinetic Energy Equation




Near surface: baroclinic conversion:

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

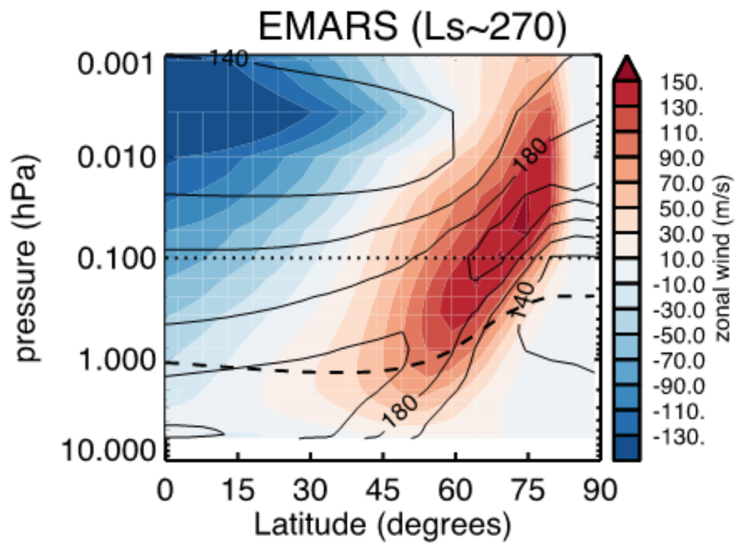
In jets aloft: regions of barotropic conversion:

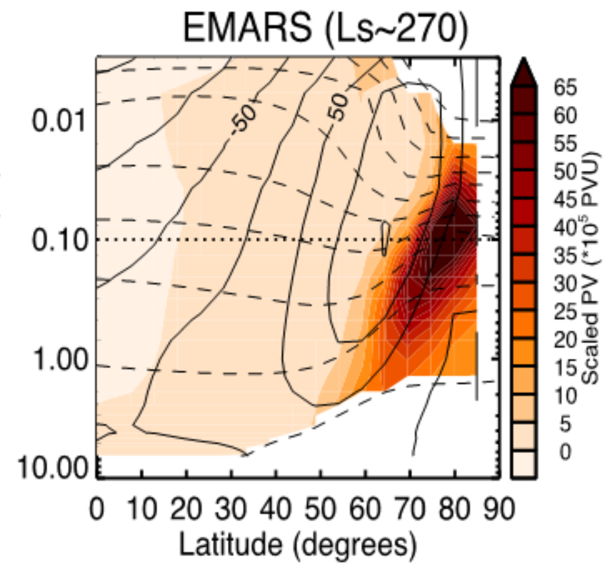
Control Kin. En.=> BV Kin. En.

Near jet maxima:

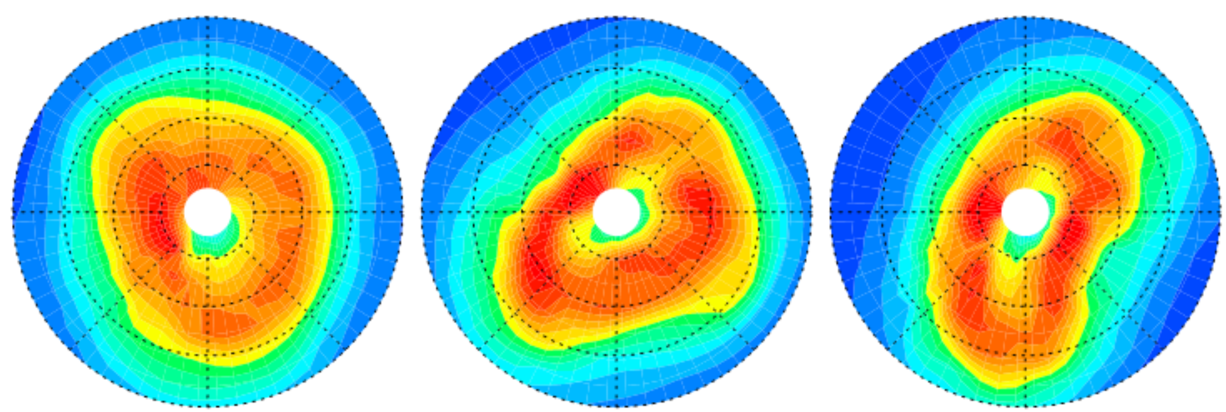
BV Kin. En. => BV Pot. En.

# The Martian Polar Vortex



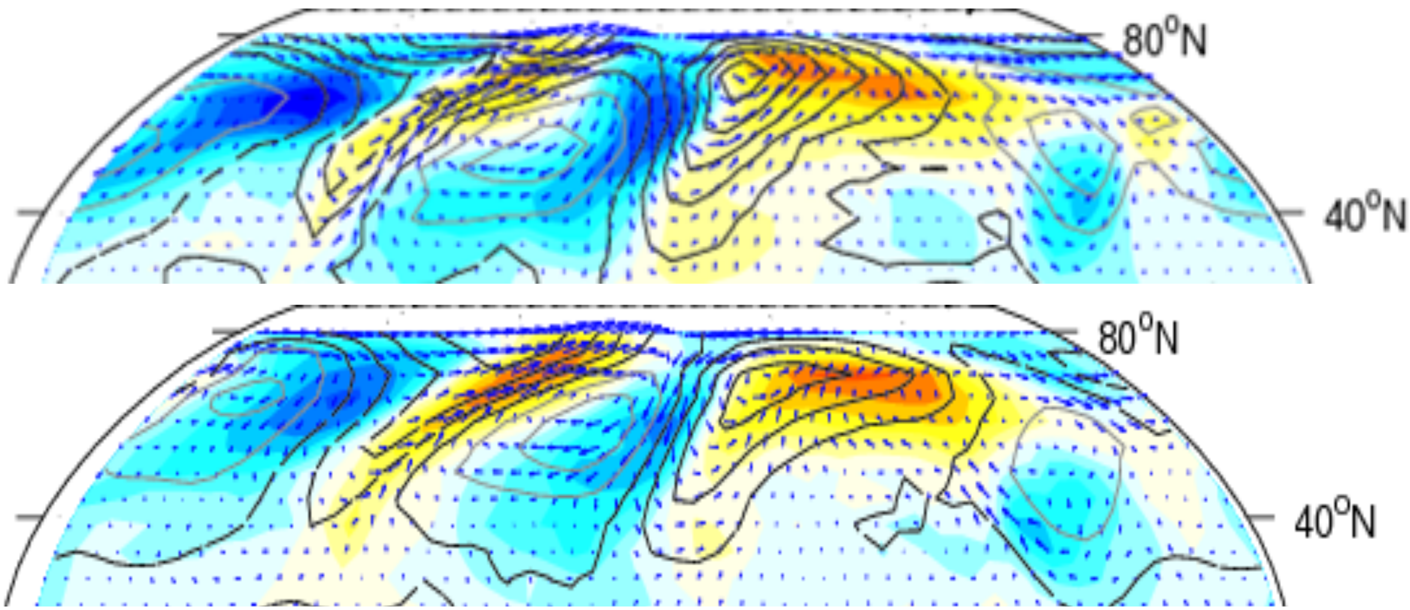




"Blobs" of potential vorticity rotate around the pole; the time mean PV field reveals an annular structure.

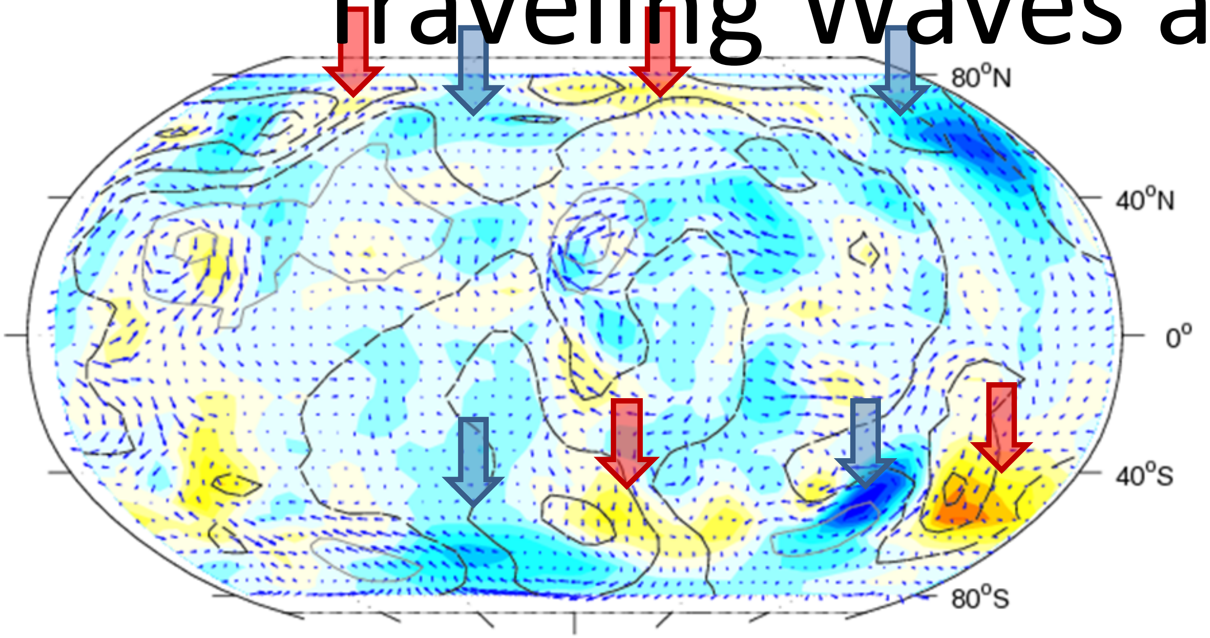



# What is the sensitivity of analyses to aerosol distribution?

# Can we converge upon a synoptic state?



# Traveling Waves and Dust

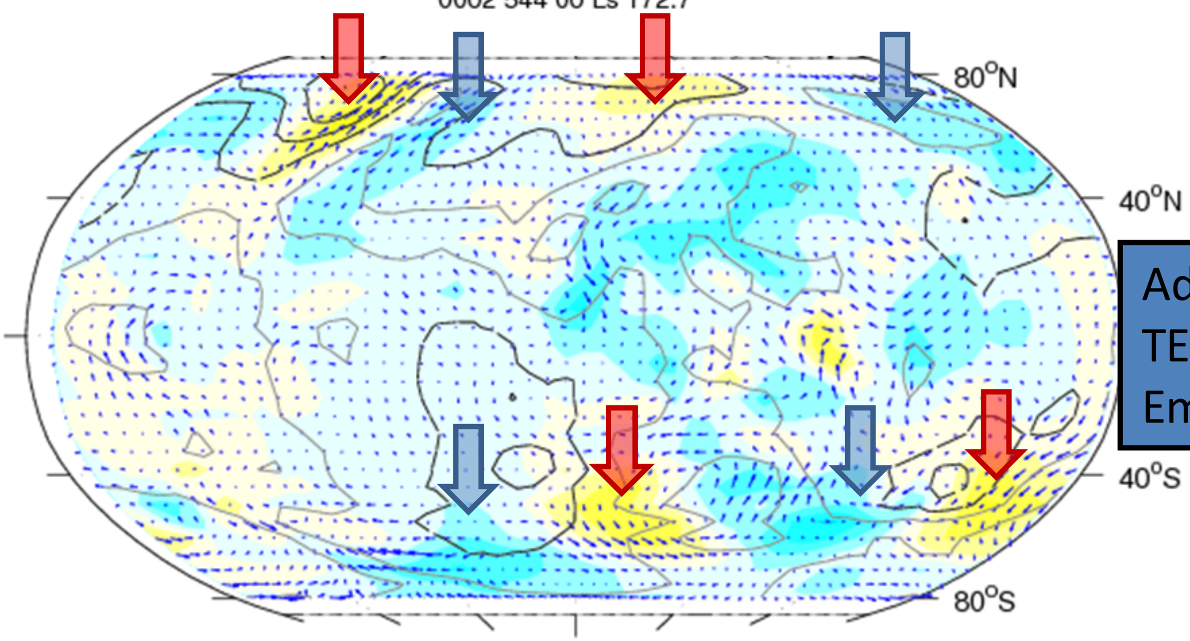



Simple Reanalysis:
Fixed Dust
No Bias Correction

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

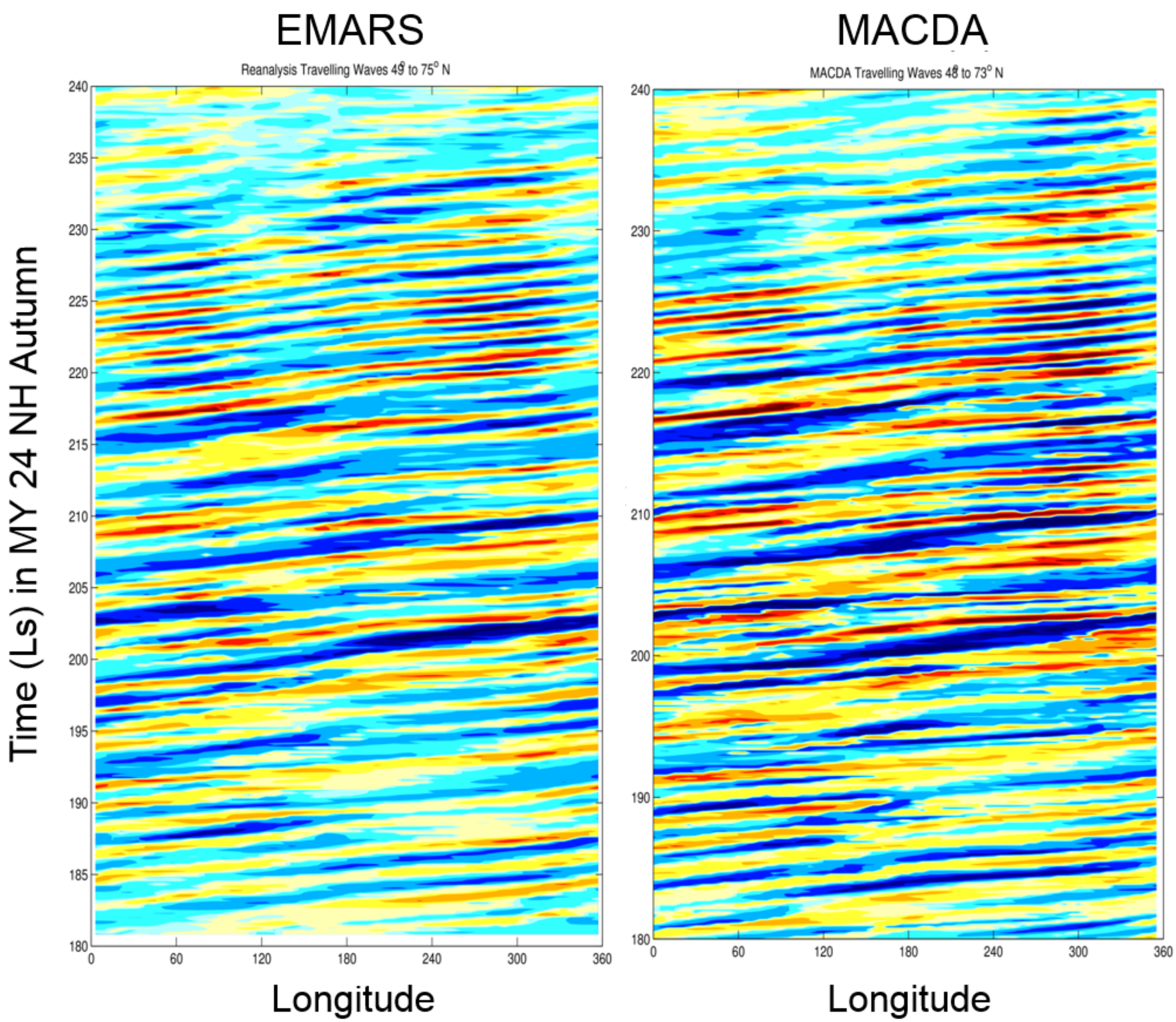
It appears they may, although the details differ.

0002 544 00 Ls 172.7°



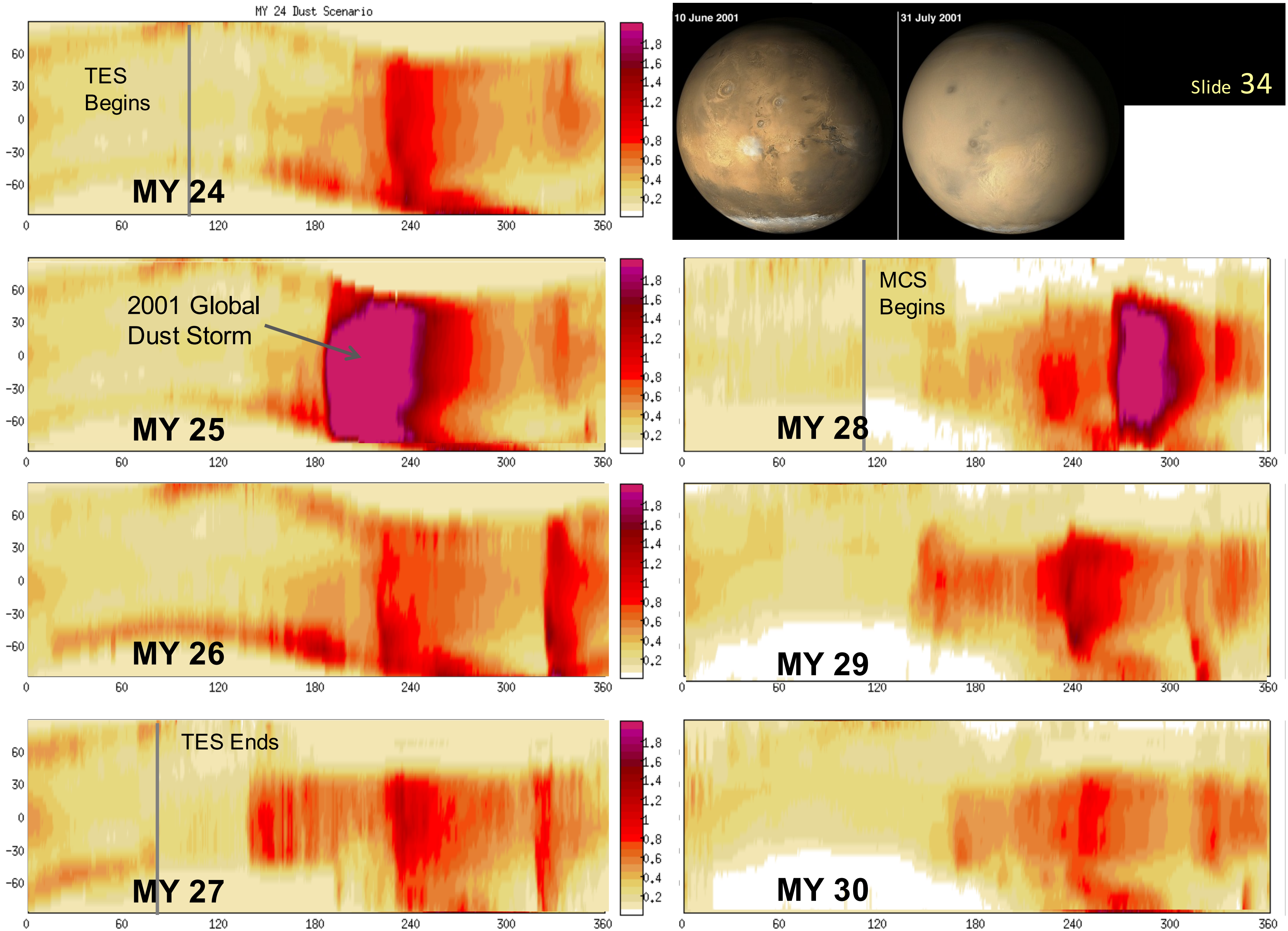

Advanced Reanalysis:
TES Dust and Water Ice Clouds
Empirical Bias Correction

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




Wave Comparison:

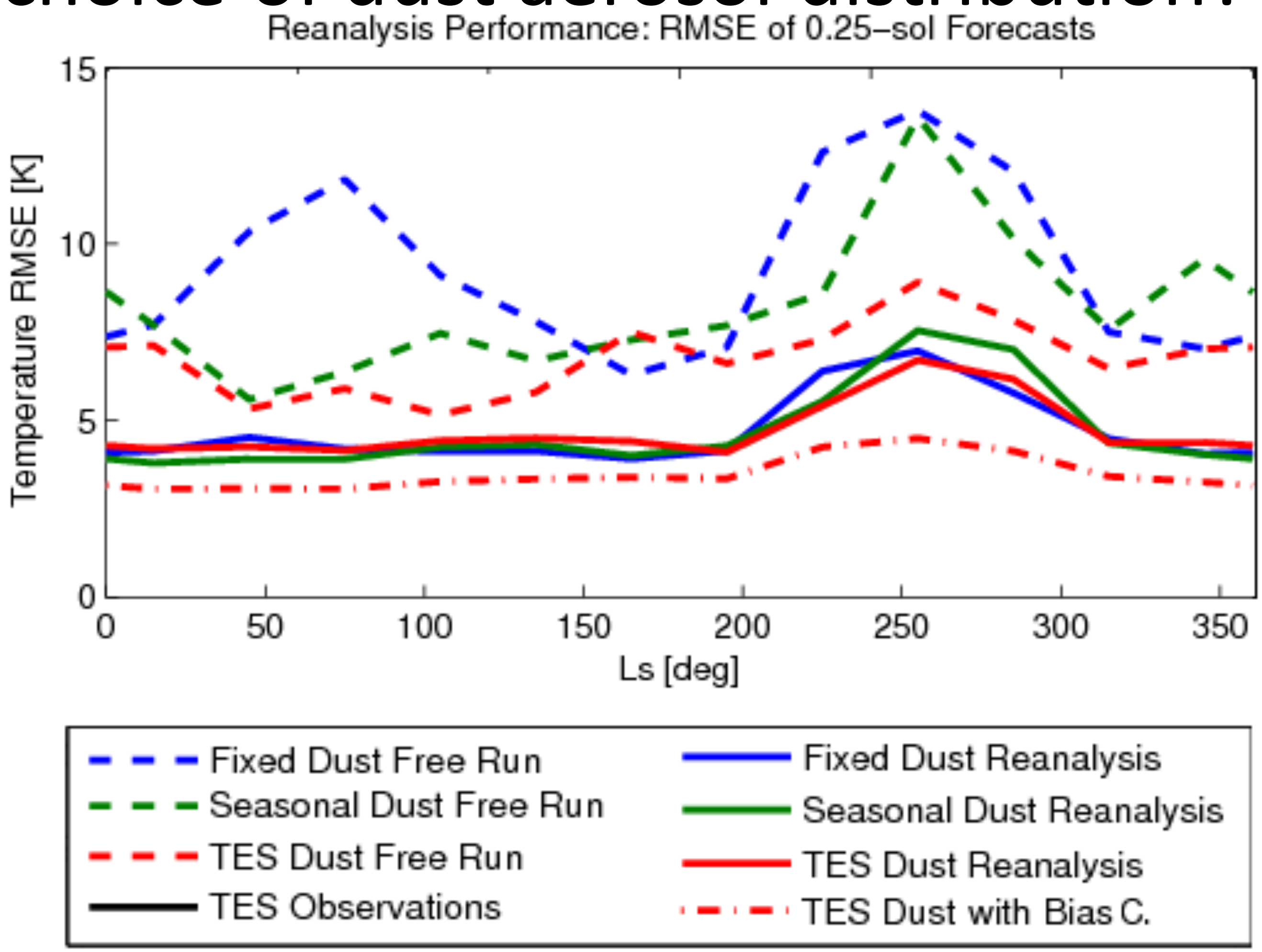
NH wave amplitudes compare favorably among reanalyses, and with TES FFSM product.




Mars Climate Database 5 **Dust** Visible **Column Opacity** *Courtesy of Luca Montabone*

# Mars TES/LETKF Performance

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



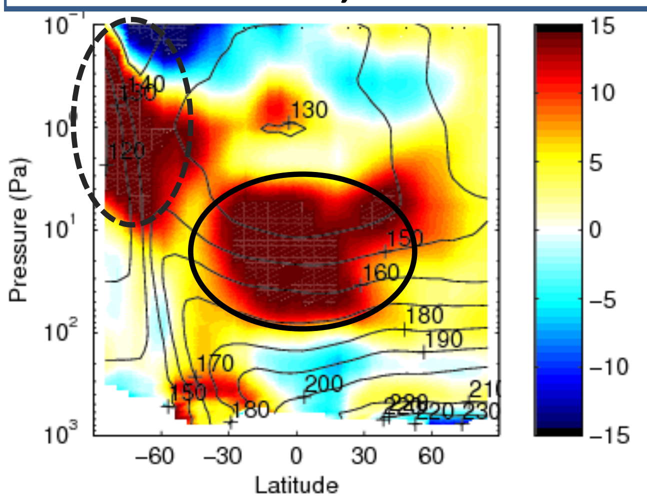

Next step: formal aerosol assimilation with the LETKF.

MGCM-LETKF- TES MCS Ensemble Mars Atmosphere Reanalysis System (EMARS)

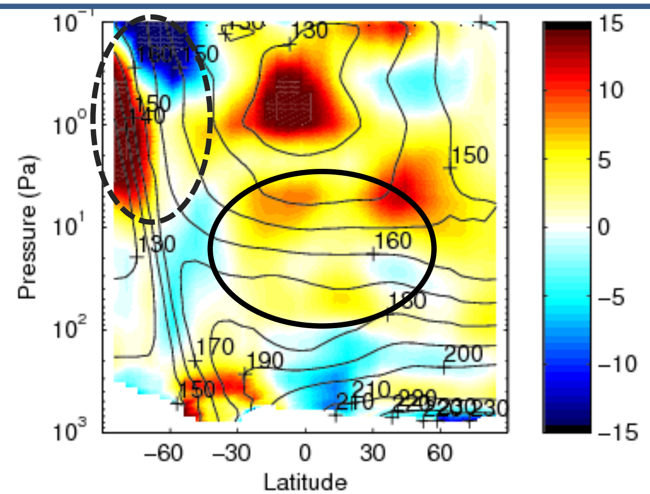
# Improving Aerosol Representation

***MCS Free Runs: Observation minus Model Bias***

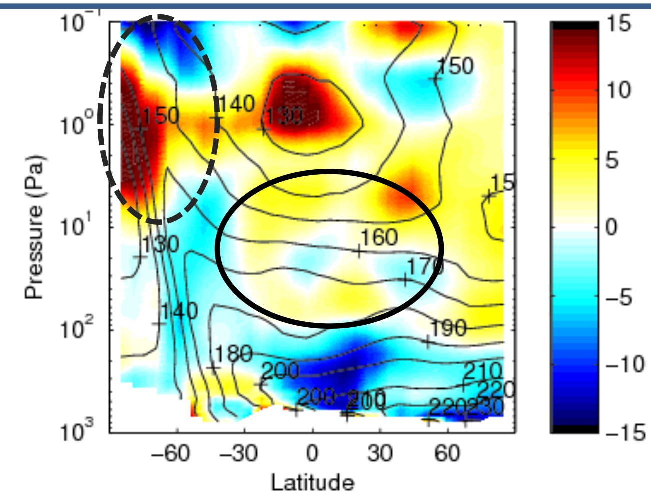
**Seasonal Dust, No Ice Cloud**




**Seasonal Dust + Ice Cloud**

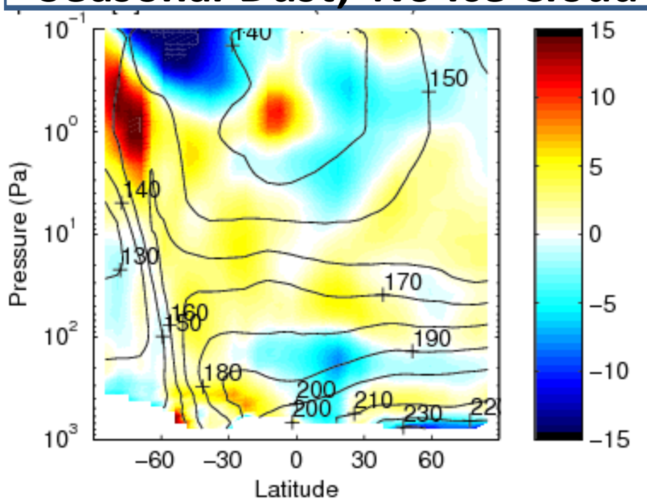



**3 Tracers + Ice Cloud**

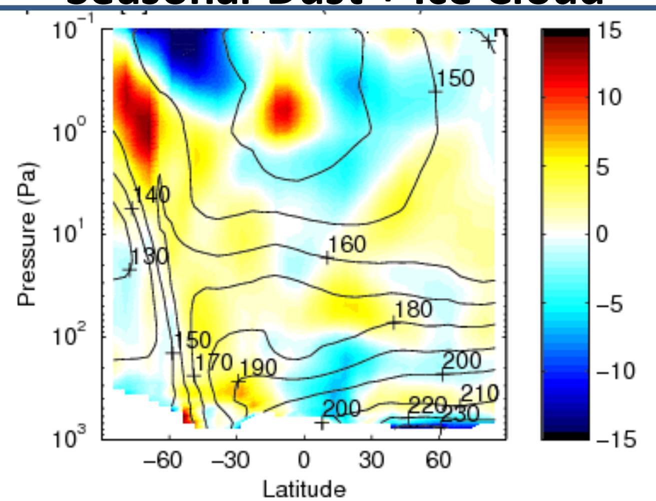



***MCS Assimilation: Observation minus Model Bias***

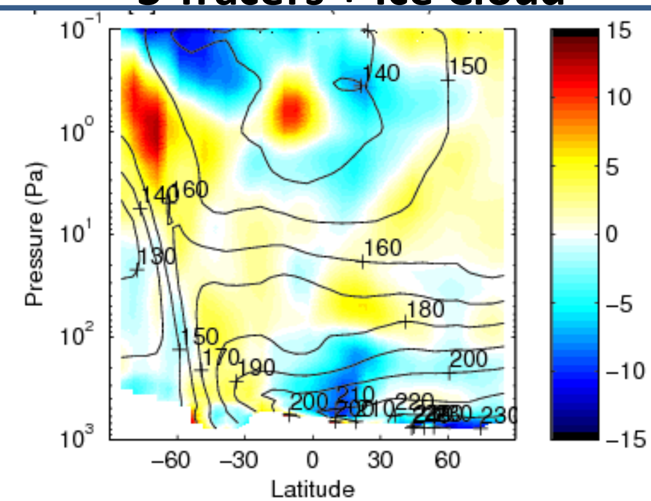
**Seasonal Dust, No Ice Cloud**




**Seasonal Dust + Ice Cloud**




**3 Tracers + Ice Cloud**

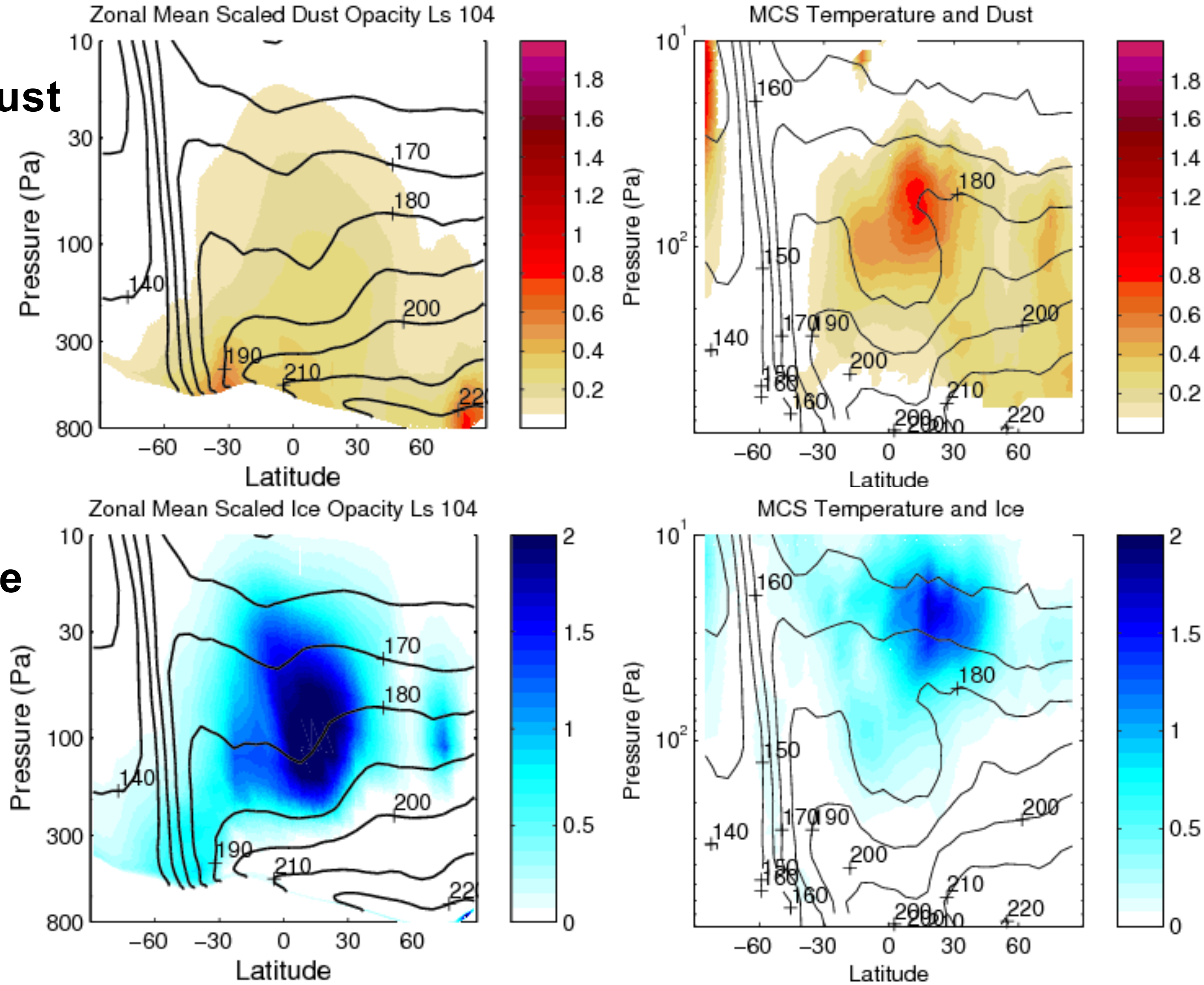


# MGCM vs. MCS Aerosol

**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.

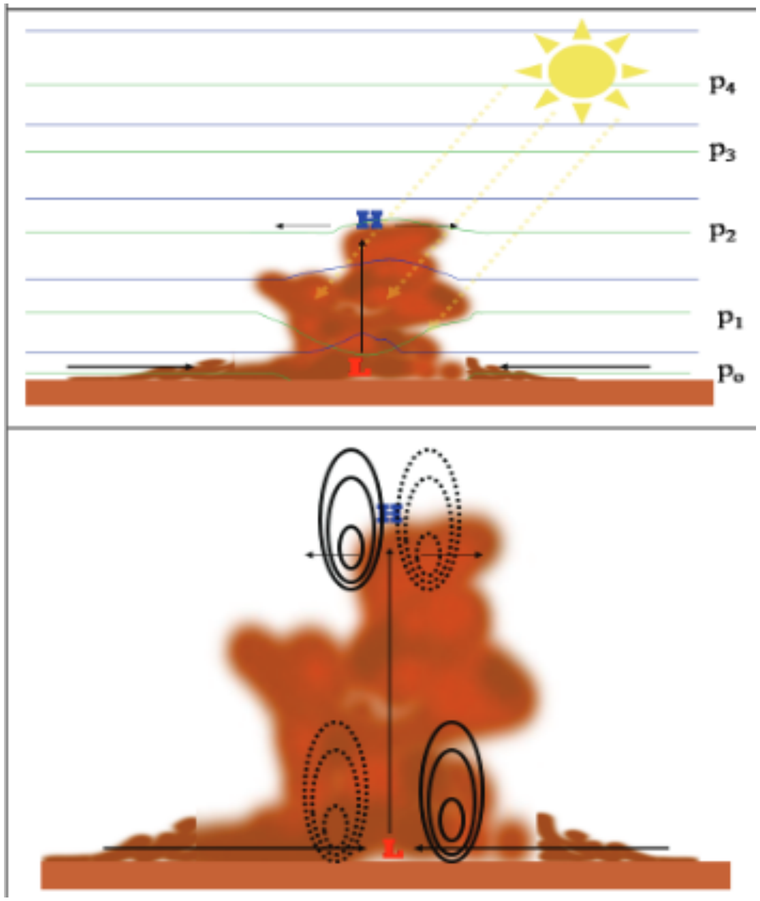
Two hypotheses:

Rafkin: topographic convection

Spiga: “rocket dust storms”

# New Hypotheses for Dust Lifting

Rafkin: radiative-dynamic feedbacks




Spiga: “rocket” dust storms

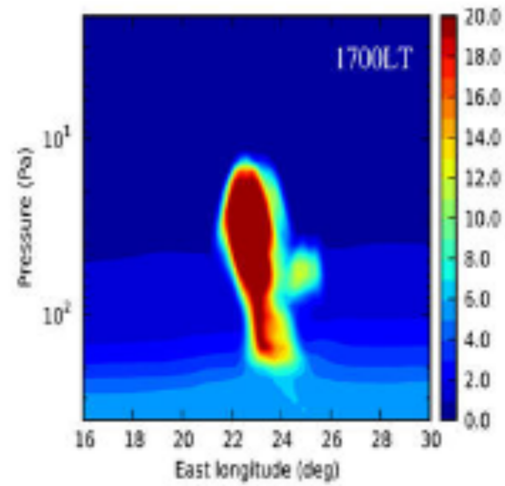



Figure 5: *Rocket dust storm (shown in the dust density-scaled opacity field) or conio-cumulonimbus (Spiga et al., 2013) (left) vs. terrestrial cumulonimbus (right, source: NOAA website).*

*http://www-mars.lmd.jussieu.fr/oxford2014/abstracts/spiga_oxford2014.pdf*

*http://www-mars.lmd.jussieu.fr/paris2011/abstracts/rafkin1_paris2011.pdf*

# 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.

# Synoptic Weather Map on Mars during a Dust Storm

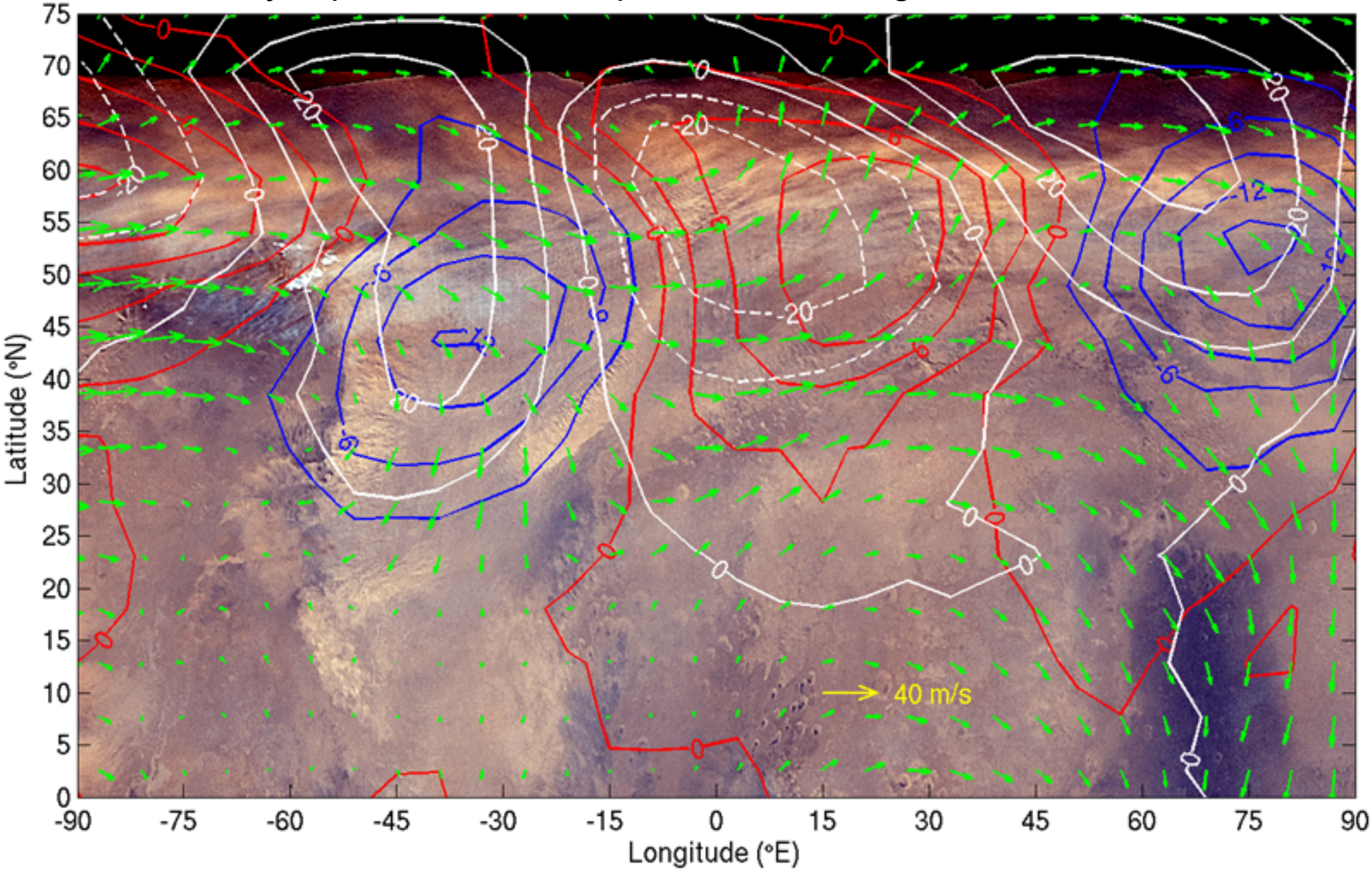



Fig. 2. Demonstration of EMARS reanalysis fields overlaid on Mars Orbital Camera (MOC) imagery during the MY 24 Ls 224 flushing storm. Reanalysis winds can be used to study the transport of dust equatorward, as well as frontal structures associated with the storm.

MGCM-LETKF- TES MCS Ensemble Mars Atmosphere Reanalysis System (EMARS)

Steven Greybush
Penn State University



# Features of Martian Weather
# Inform Assimilation System Design
# And Motivate Science Questions

*Figure Courtesy of NASA/JPL and Malin Space Science*

- Diurnal Cycle, Thermal Tides, Topography
- Traveling Weather Systems
- Water Ice Clouds
- Seasonal $CO_2$ Polar Ice Caps
- Dust Devils, Regional and Global Storms

- Optimal Window Length and Inflation
- Localization Scales, Verification Metrics
- Tuning Model Physics
- Enforcing $CO_2$ Conservation
- Representing Aerosols in Ensemble

- What is the predictability horizon for Mars weather forecasting?
- What instabilities give rise to forecast errors and changes in wave regimes?
- How well are tides and traveling weather systems depicted in reanalyses, and can they be linked to dust lifting?
- What is the spatial distribution and time evolution of ice and dust aerosol?
- What mechanisms are responsible for global dust storm formation?

# 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. The development of an aerosol reanalysis is underway.

# The atmosphere of Mars:

## *Insights on weather and predictability from ensemble data assimilation of spacecraft observations*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