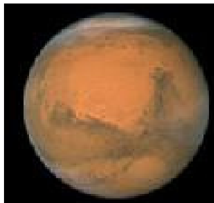

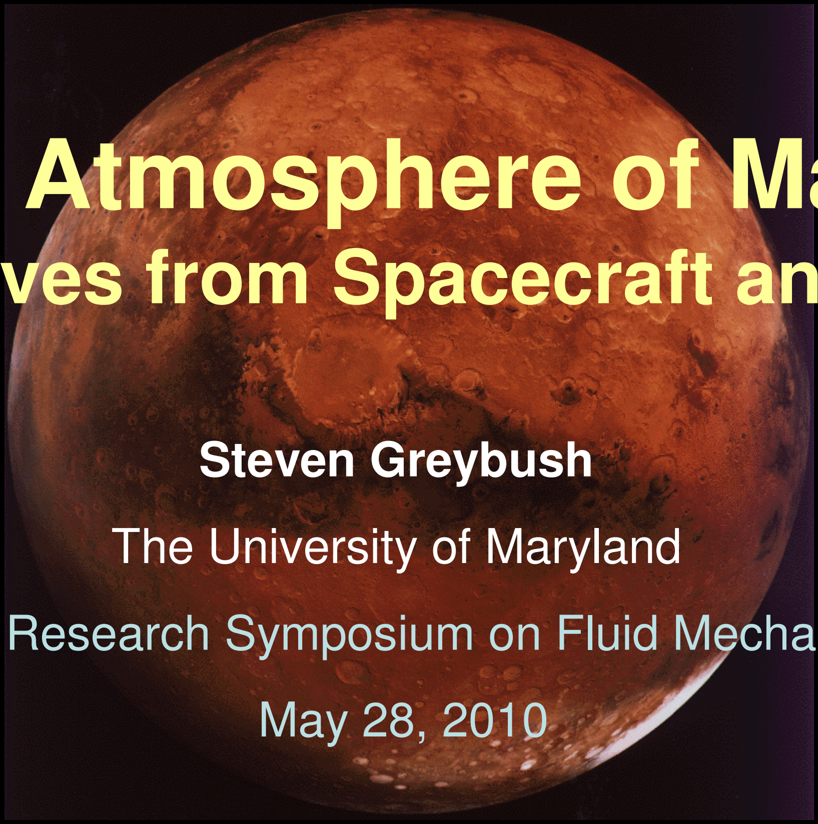

The Atmosphere of Mars:
Perspectives from Spacecraft and Models

Steven Greybush

The University of Maryland

Joint Research Symposium on Fluid Mechanics

May 28, 2010

With Acknowledgements to:
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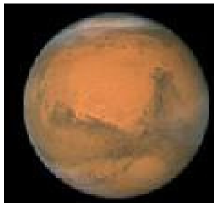


Outline

- Basics of Martian Weather and Climate
- Mars Atmosphere Breeding: Elucidating Atmospheric Instabilities
- Mars Atmosphere Reanalysis: Assimilation of Temperatures, and eventually Dust

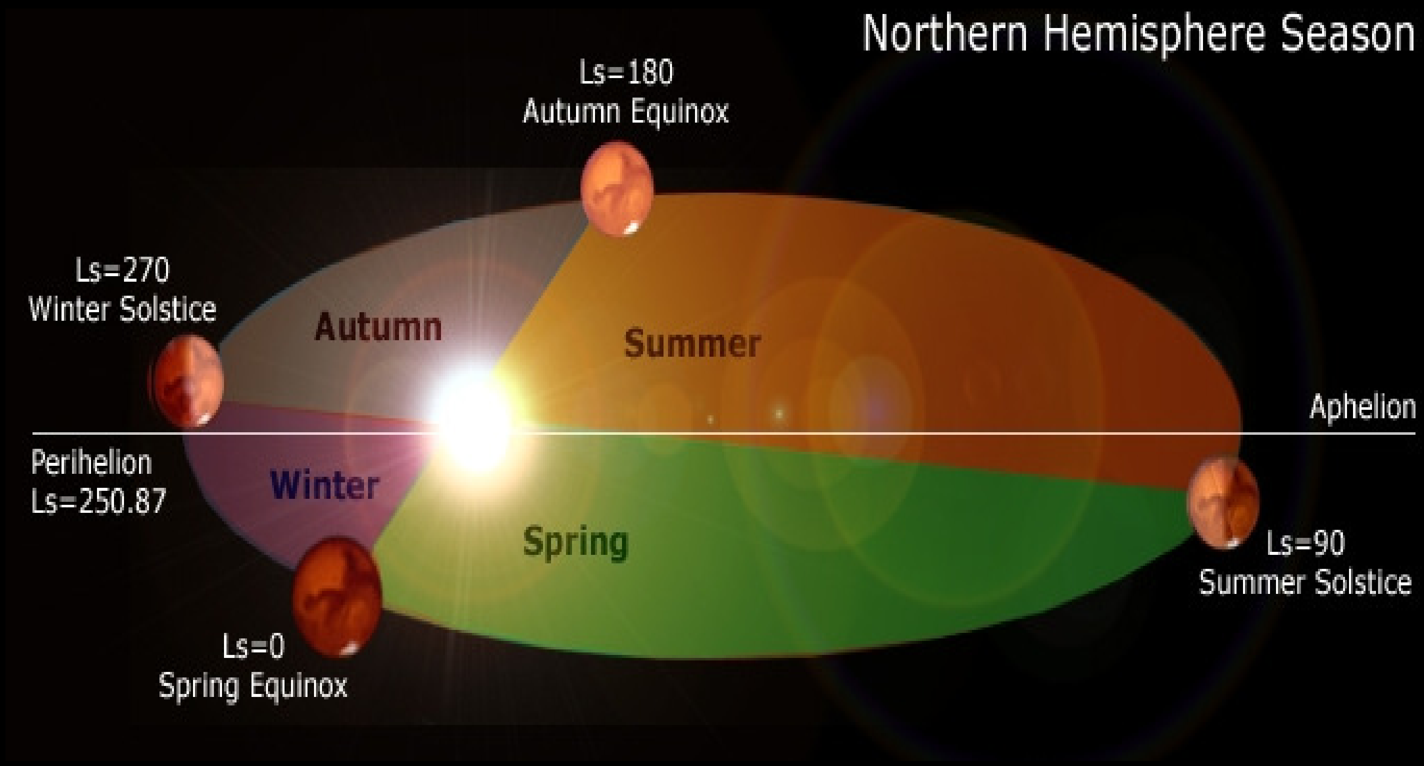
Comparing Mars and Earth

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

Table Courtesy of Matthew Hoffman and John Wilson

Seasons on Mars

Ls = Areocentric Longitude

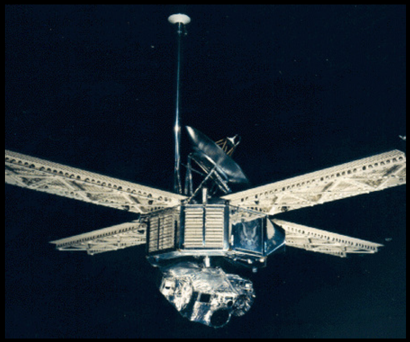


Elliptic orbit: 44% variation in solar radiation between aphelion & perihelion

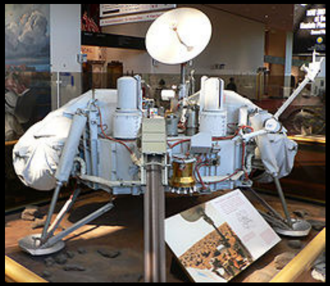
Slide Courtesy of John Wilson

Exploration of Mars

and Relevance for Weather and Climate

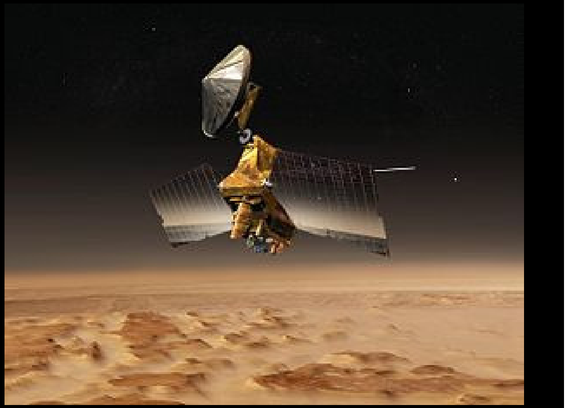


Mariner Program: Observed Dust Storms



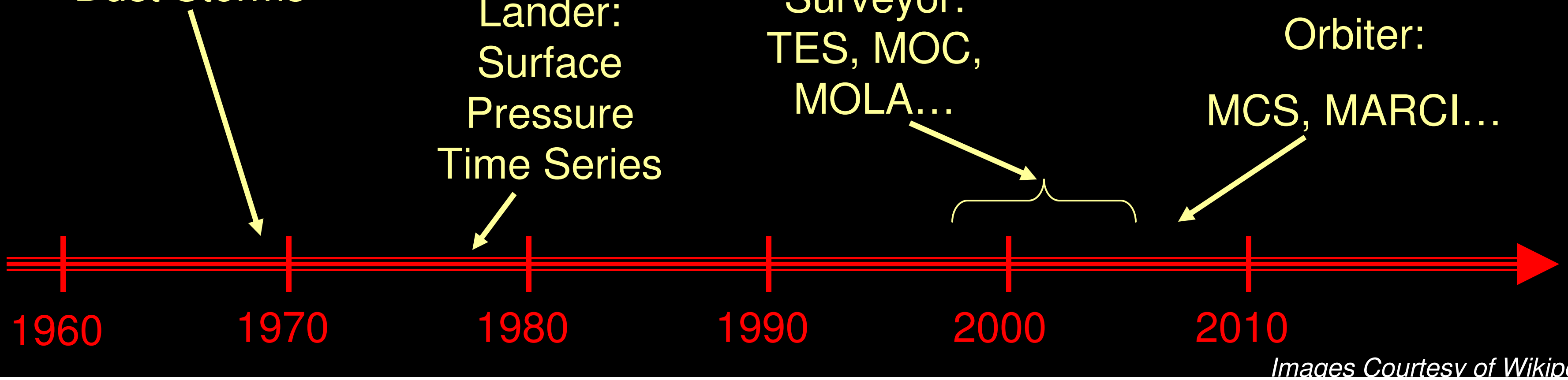
Viking Lander: Surface Pressure Time Series

Mars Global Surveyor: TES, MOC, MOLA…



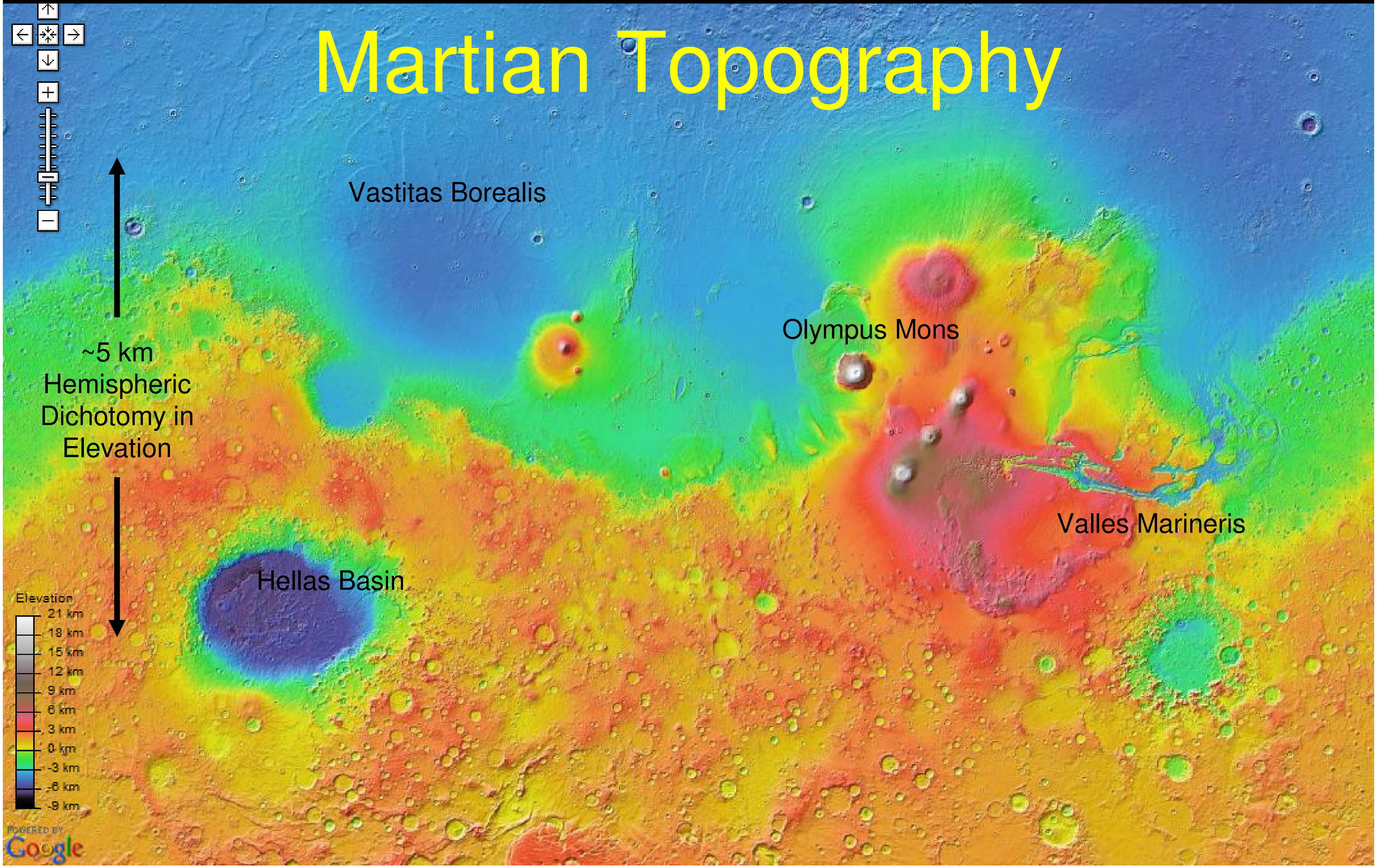
Mars Reconnaissance Orbiter:

MCS, MARCI…



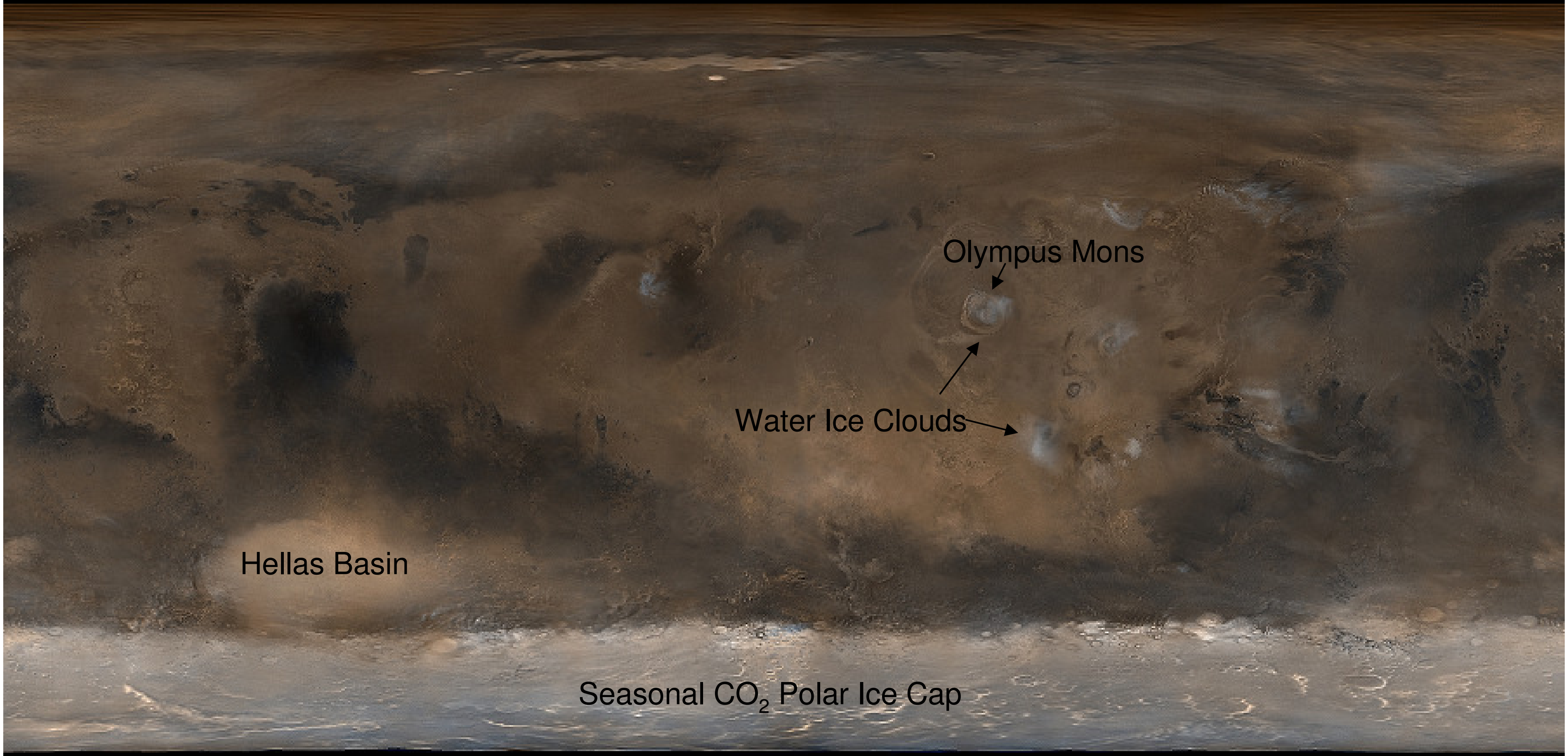
Images Courtesy of Wikipedia

Martian Topography



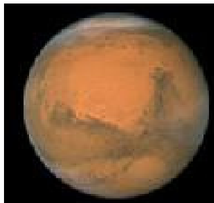
~5 km Hemispheric Dichotomy in Elevation

Mars Orbital Camera (MOC) Image



View from the Martian Surface

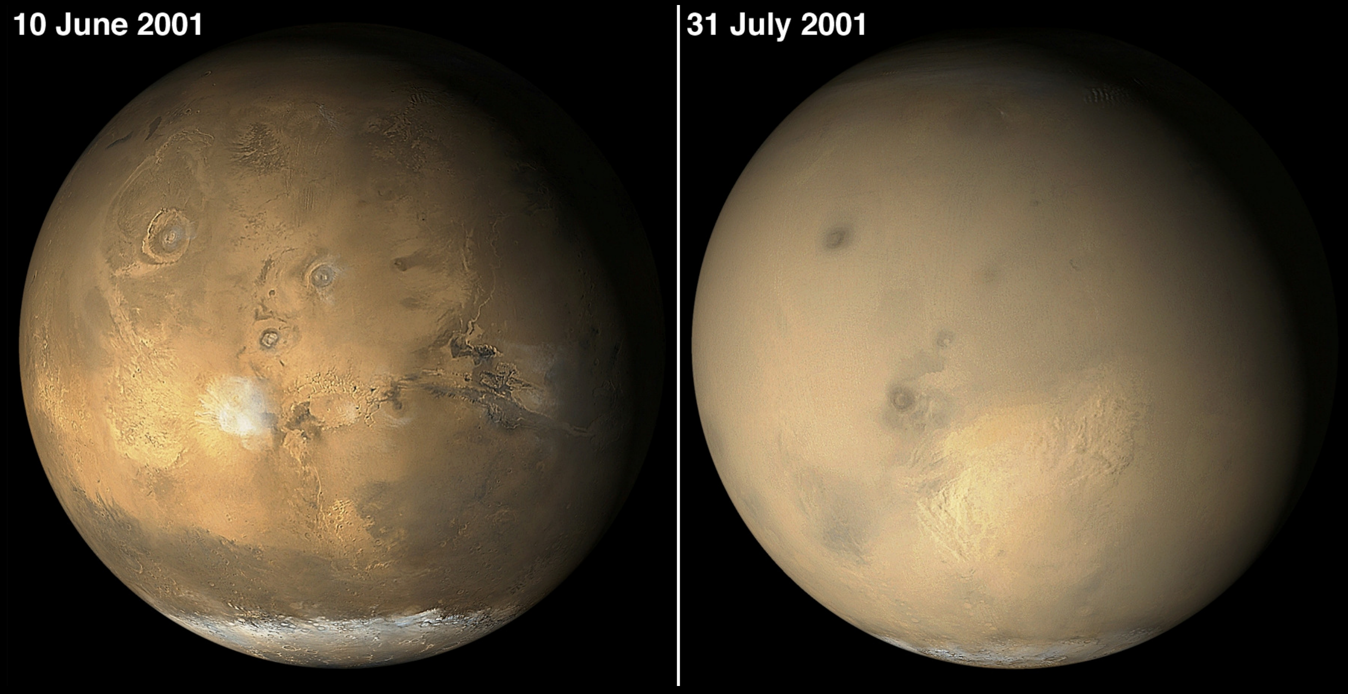
Radiative effects of dust aerosol suspended in the atmosphere can strongly influence temperature profiles.



MGCM-LETKF-TES Martian Atmosphere Reanalysis Project

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

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



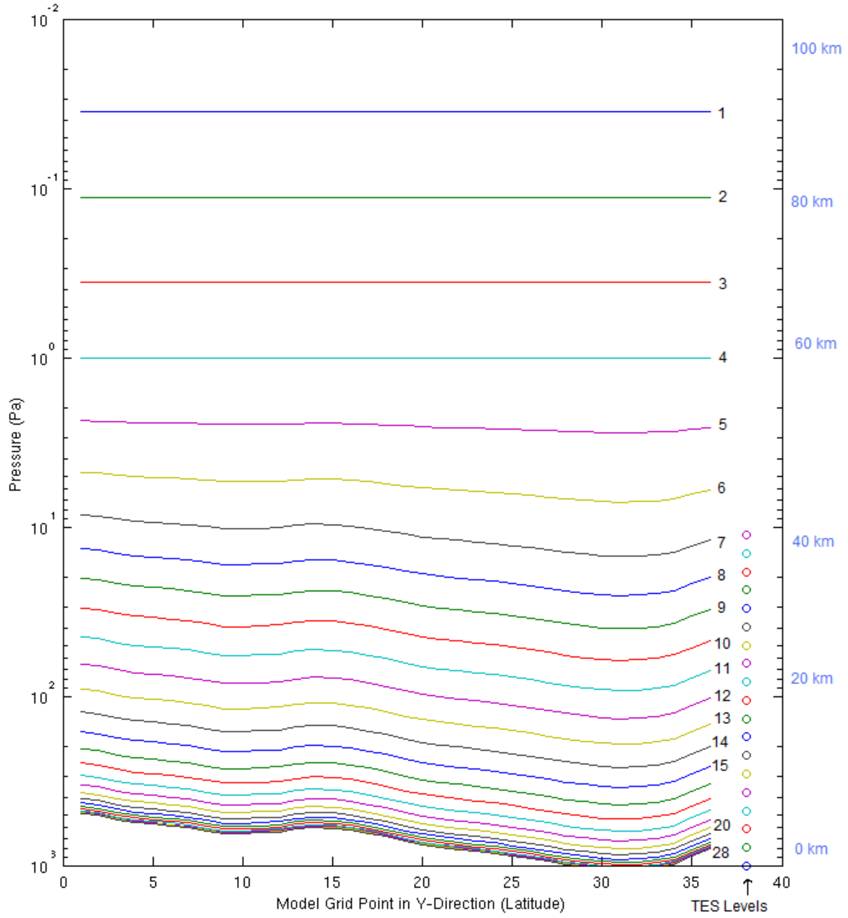
Prior to Global Dust Storm

During Global Dust Storm

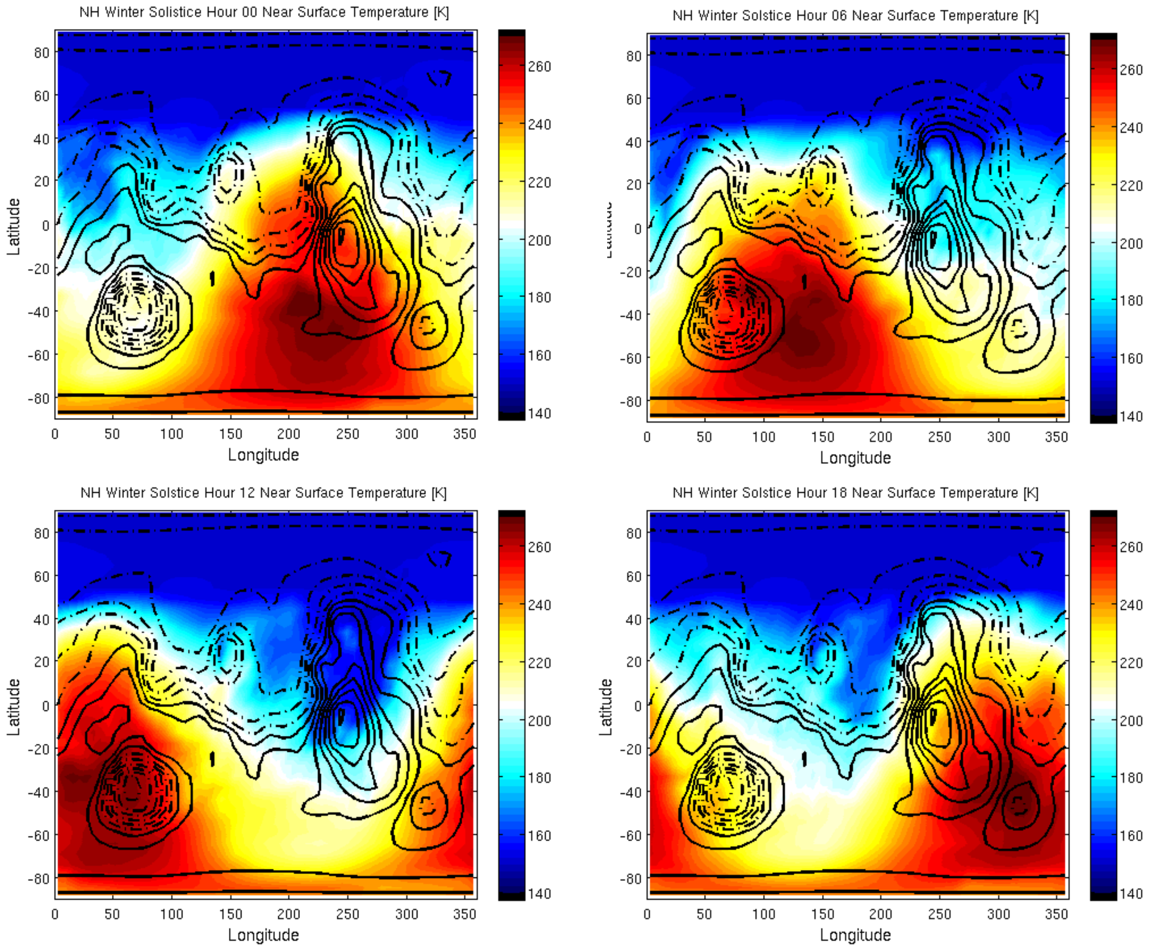
Figure Courtesy of John Wilson

GFDL Mars GCM

- Uses finite volume dynamical core
- Latitude-longitude grid
- 60x36 grid points (6°x5.29° resolution)
- 28 vertical levels
- Hybrid p / σ vertical coordinate
- Gaseous and condensed CO_2 cycle
- Tracers for dust and water vapor, with the option for dust radiative feedback



Martian Thermal Tide


NH Winter Solstice Hour 00 Near Surface Temperature [K]

NH Winter Solstice Hour 06 Near Surface Temperature [K]

NH Winter Solstice Hour 12 Near Surface Temperature [K]

NH Winter Solstice Hour 18 Near Surface Temperature [K]

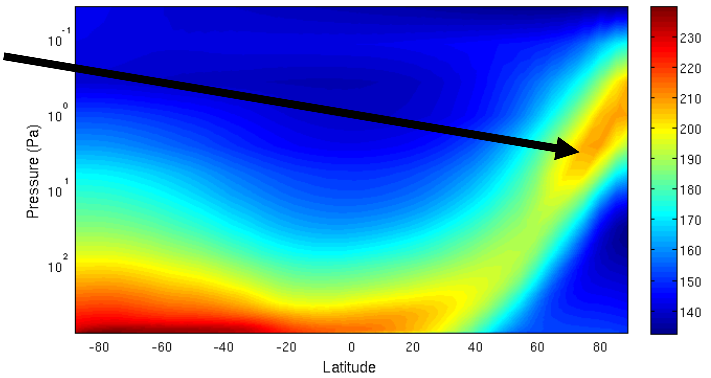
- The thermal tide can be tracked as the tongue of warm temperatures centered around the subsolar point as it moves across the planet over the course of a day.
- Diurnal temperature changes in the summer hemisphere can approach 100 K.

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

Contours are topography.

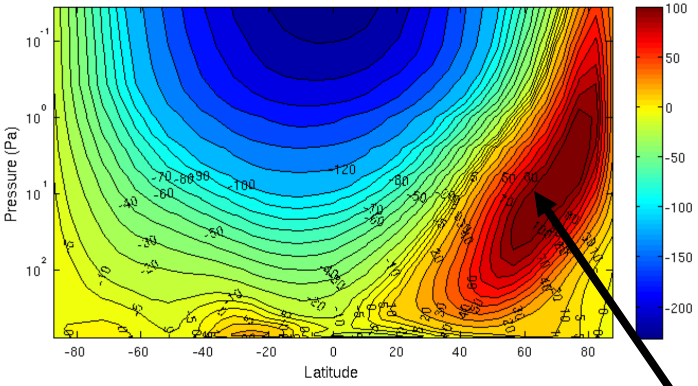
Martian Seasonal Cycle

Adiabatic Warming from Global Hadley Cell Descent



NH Winter Solstice

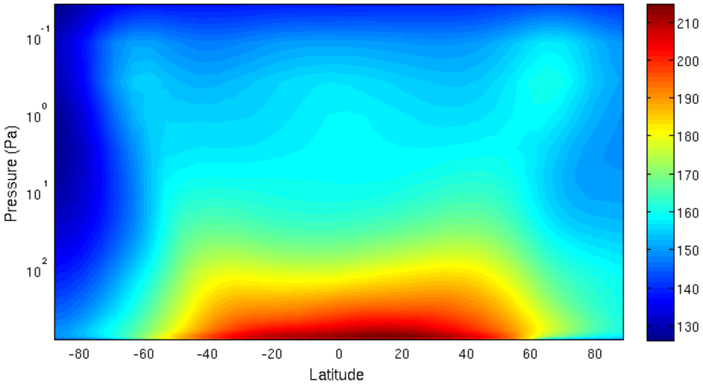
Zonal Mean Temperature



NH Winter Solstice

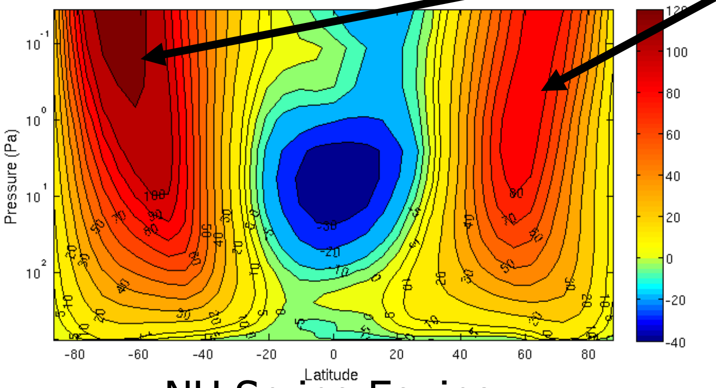
Zonal Mean U-Wind

Westerly Jets



NH Spring Equinox

Zonal Mean Temperature



NH Spring Equinox

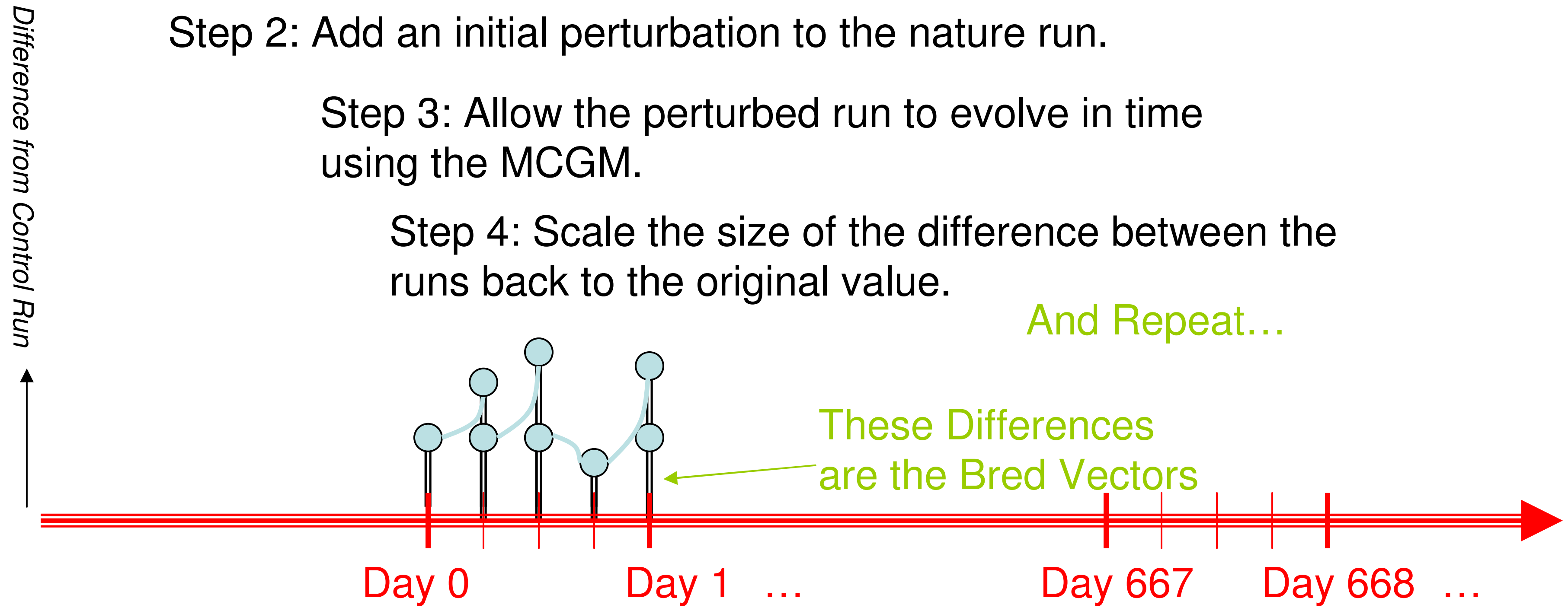
Zonal Mean U-Wind

Bred Vector Motivation

- 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).

The Bred Vector technique was invented by Toth and Kalnay (1993) as a nonlinear, finite time generalization of Lyapunov vectors.

Bred Vector Procedure



Step 2: Add an initial perturbation to the nature run.

Step 3: Allow the perturbed run to evolve in time using the MCGM.

Step 4: Scale the size of the difference between the runs back to the original value.

And Repeat…

These Differences are the Bred Vectors

Step 1: Create a long nature run (control run) of the MGCM.

MGCM Breeding Experiment Parameters:

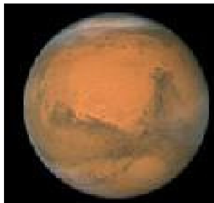
Rescaling Time Interval: **6 hours**
Rescaling Amplitude: **1 K**

Rescaling Norm: Temperature-Squared Norm, Scaled by Cosine Latitude
Experiment Length: 1 Martian Year (668 Martian Days)

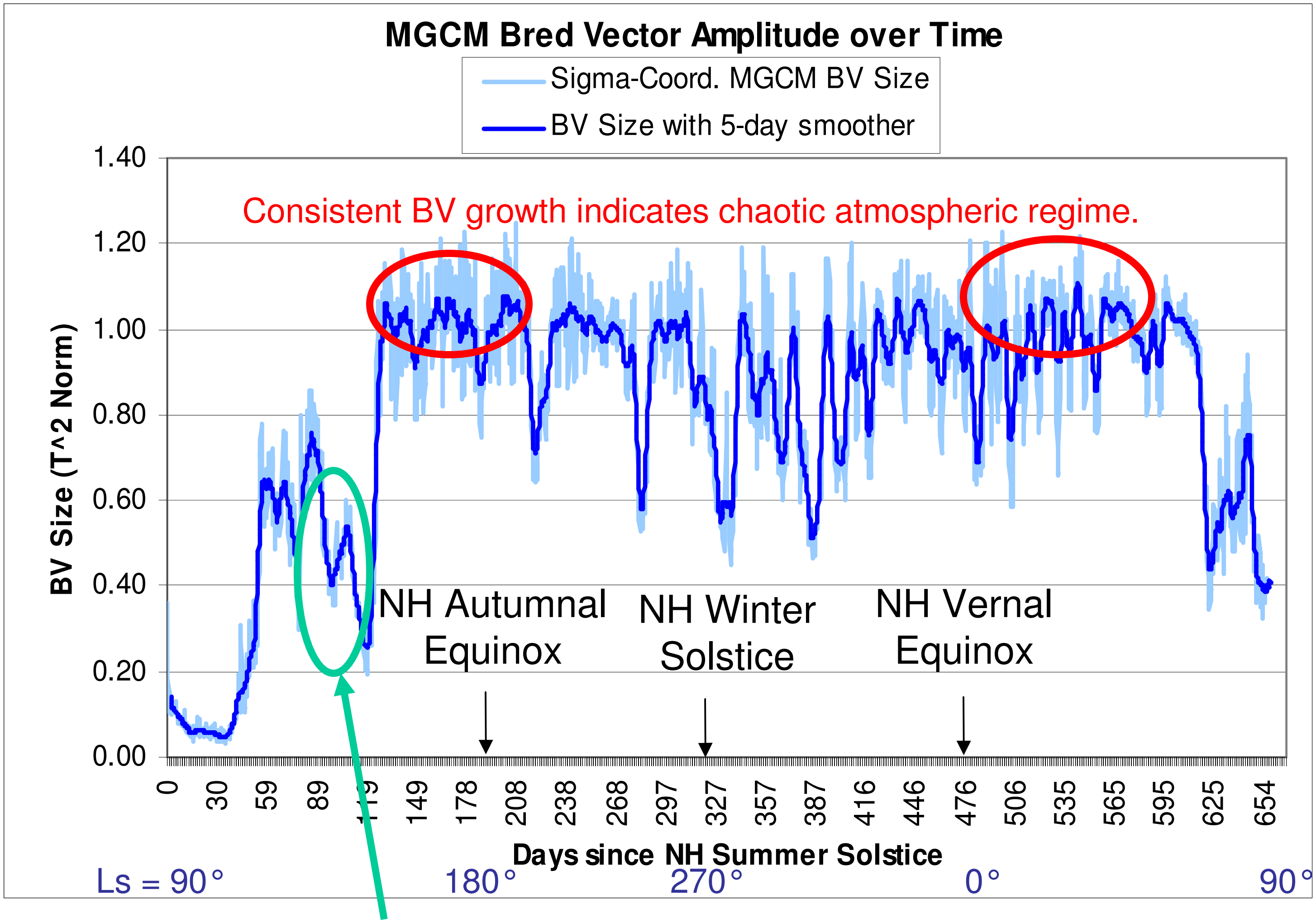
Rescaling only occurs during periods of Bred Vector growth beyond original amplitude.

Bred vectors are kept young by adding random perturbation each rescaling interval whose magnitude is 1% of the original perturbation.

Fixed dust scenario (opacity = 0.3)



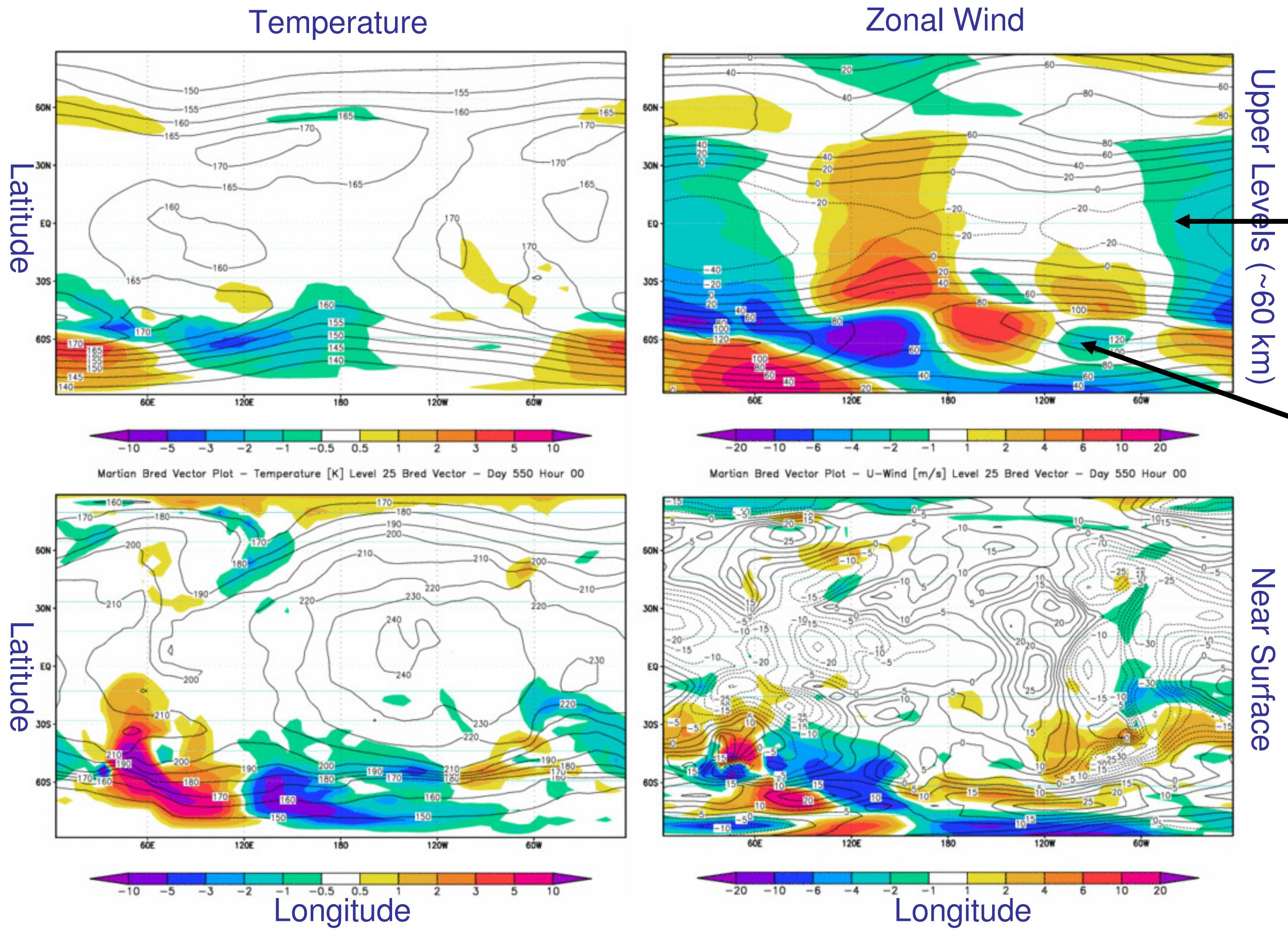
MGCM-LETKF-TES Martian Atmosphere Reanalysis Project



Consistent BV growth indicates chaotic atmospheric regime.

Some seasons are more chaotic than others; NH summer appears most stable.

Sample Bred Vector snapshot during NH autumn.



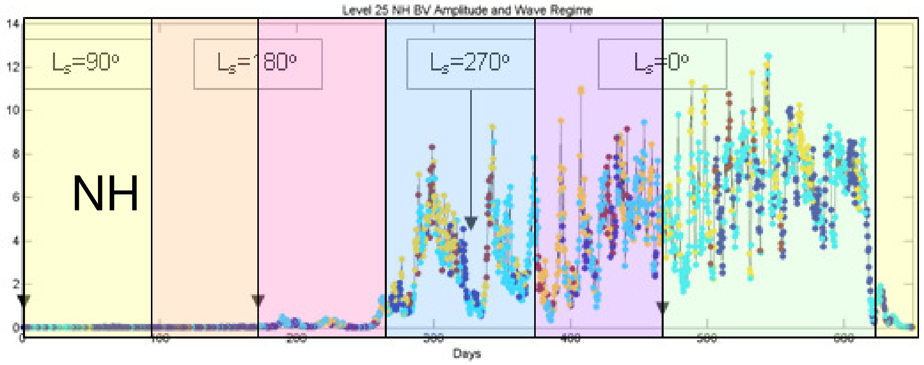
Wave 1 instability in tropics.

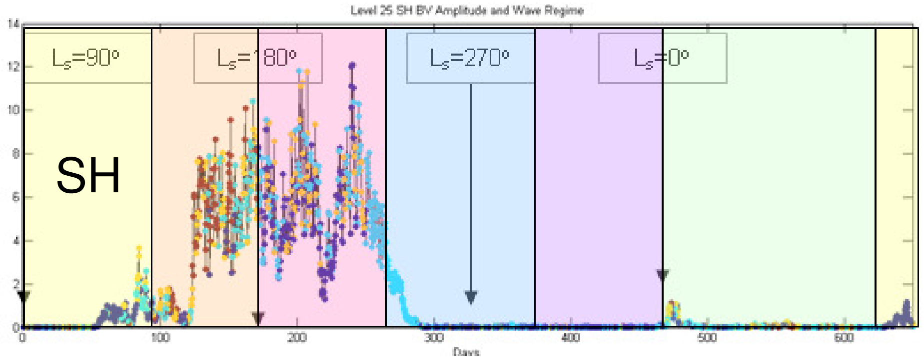
Wave 2 instability along polar jet.

Bred Vectors tend to move in time along with travelling waves in the atmosphere.

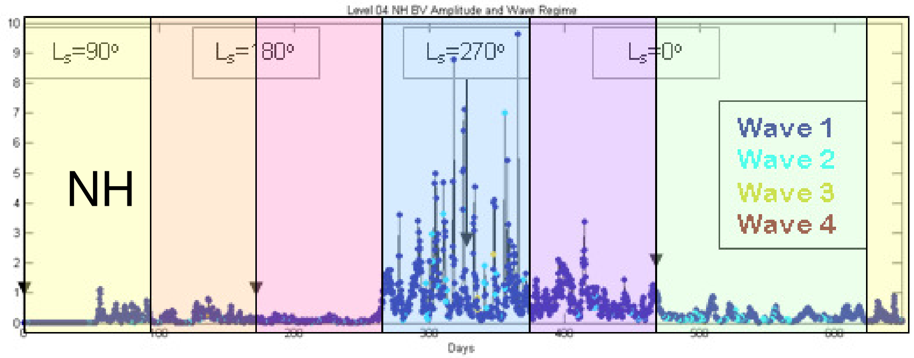
MGCM-LETKF-TES Martian Atmosphere Reanalysis Project

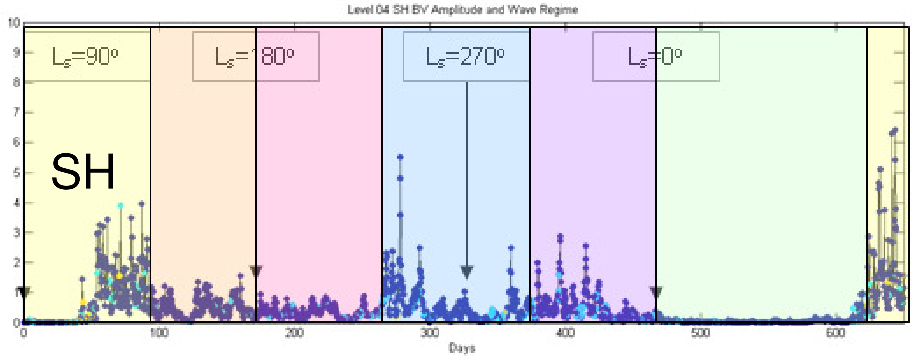
Level 25 (Near Surface)


Level 25 NH BV Amplitude and Wave Regime


Level 25 SH BV Amplitude and Wave Regime

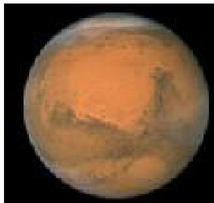
Level 04 (~60 km; ~1 Pa)


Level 04 NH BV Amplitude and Wave Regime


Level 04 SH BV Amplitude and Wave Regime

- Bred vector activity is divided here into 6 “seasons”.
- Upper levels are most active around the solstice, while near surface activity peaks in the transition seasons.
- Wave 1 instabilities are most common in upper levels, whereas waves 2-4 occur near the surface.

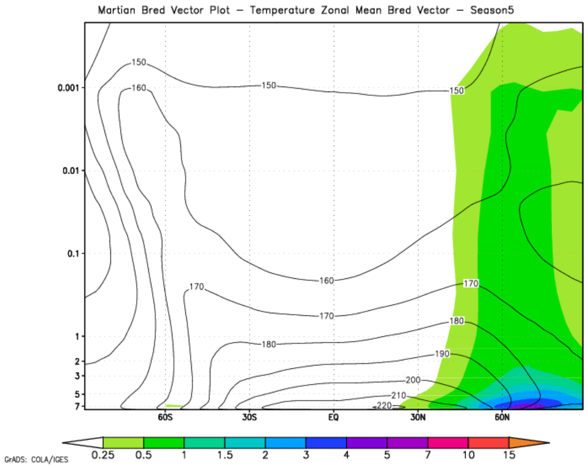
Season	Ls	BV Day	Season Description
1	0-60	475-601	Boreal Post-Equinox
2	60-120	602-733	Austral Solstice
3	120-180	65-178	Austral Pre-Equinox
4	180-240	179-274	Austral Post-Equinox
5	240-300	275-368	Boreal Solstice
6	300-360	369-474	Boreal Pre-Equinox



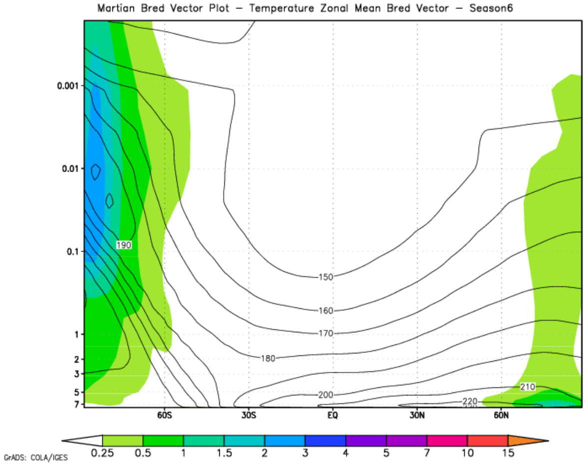
MGCM-LETKF-TES Martian Atmosphere Reanalysis Project

Zonal Mean Bred Vector Activity by Season

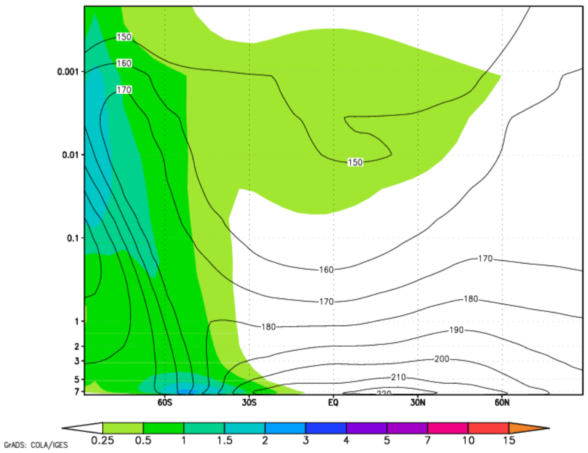
Boreal Post-Equinox



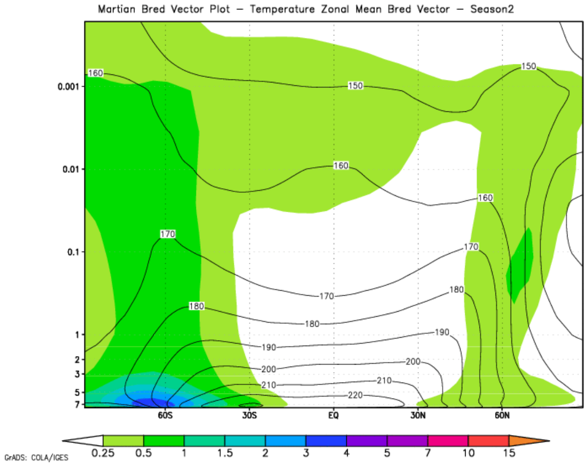
Austral Solstice



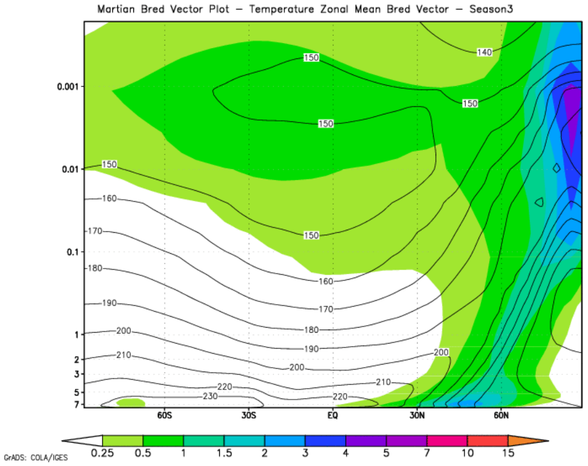
Austral Pre-Equinox



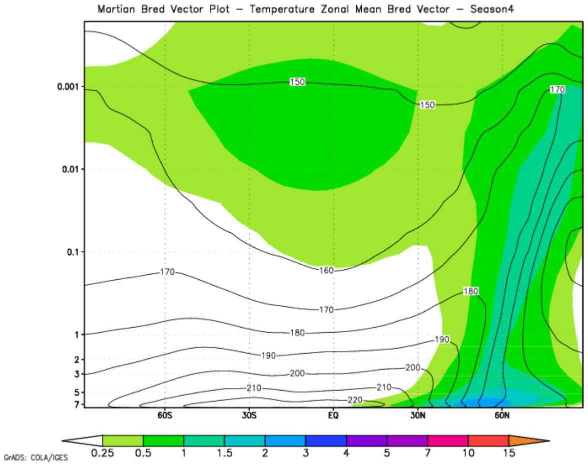
Austral Post-Equinox



Boreal Solstice

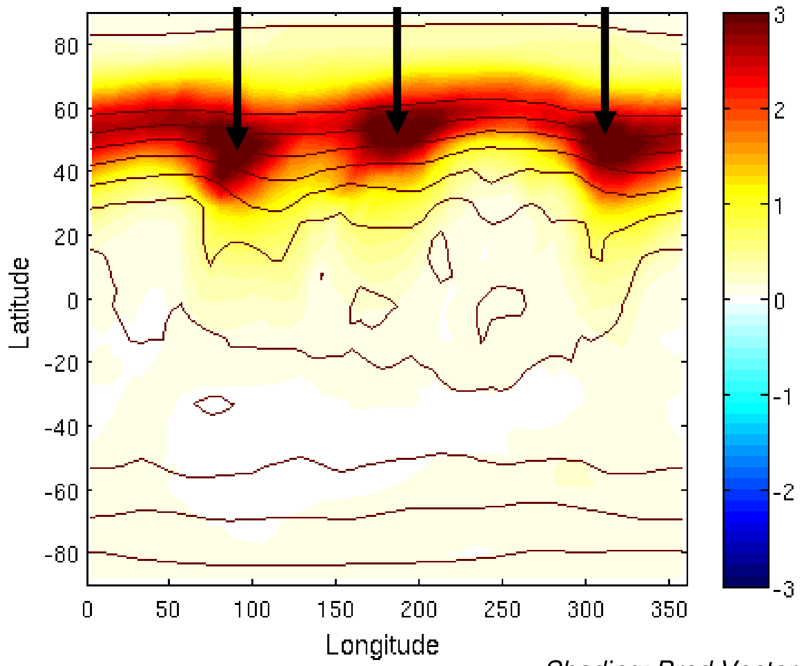


Boreal Pre-Equinox



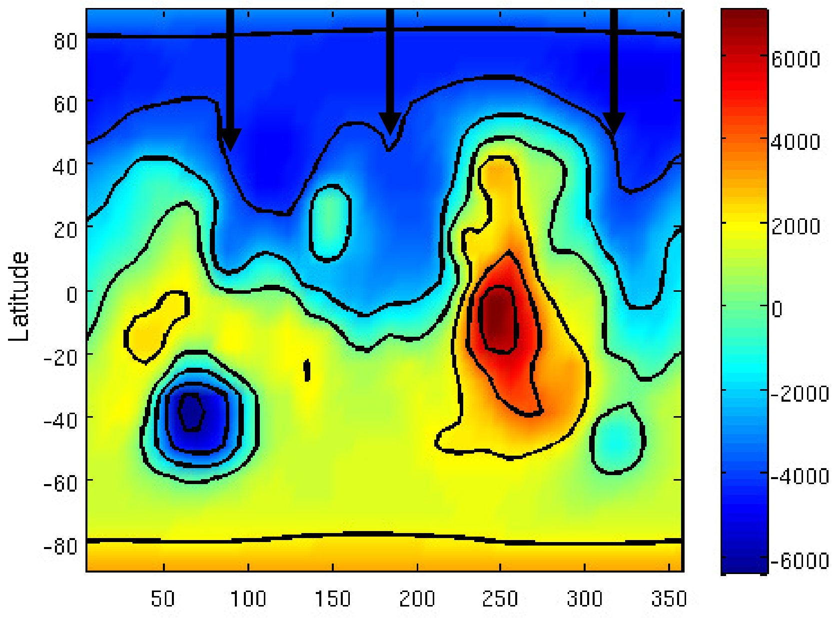
Martian Atmosphere Near-Surface Instabilities in relation to Topography

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.


NH Pre-Equinox Time Avg Level 25 Temperature BV [K]

Shading: Bred Vector

Contours: Temperature


Martian Surface Topography [m]

BV Kinetic Energy Equation

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

$$-\frac{\Phi_b}{p_{sb}}\left(\frac{\partial p_{sb}}{\partial t} + \boldsymbol{v}_b\bullet\nabla p_{sb}\right) + \boldsymbol{v}_b\bullet(-\sigma\alpha\nabla p_s + \sigma_c\alpha_c\nabla p_{sc})$$

- 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

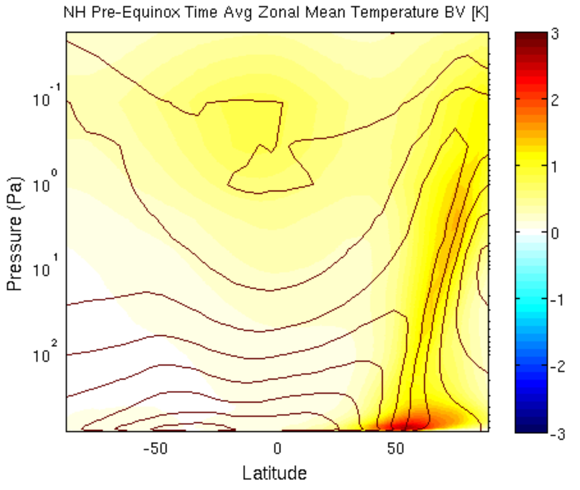
Term 3: Baroclinic Conversion Term

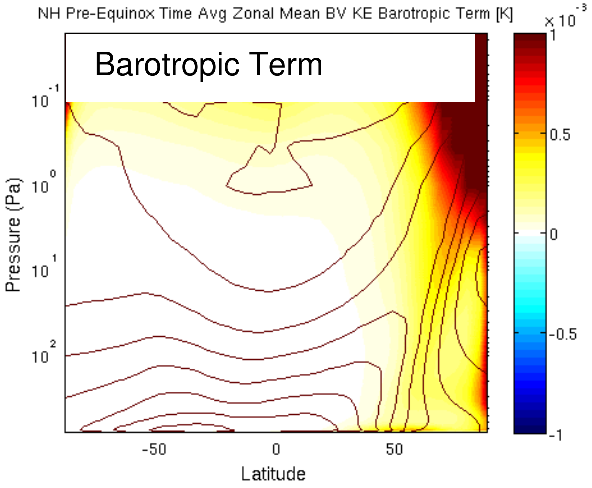
Term 4: Barotropic Conversion Term

Term 5: Coordinate Transform Term

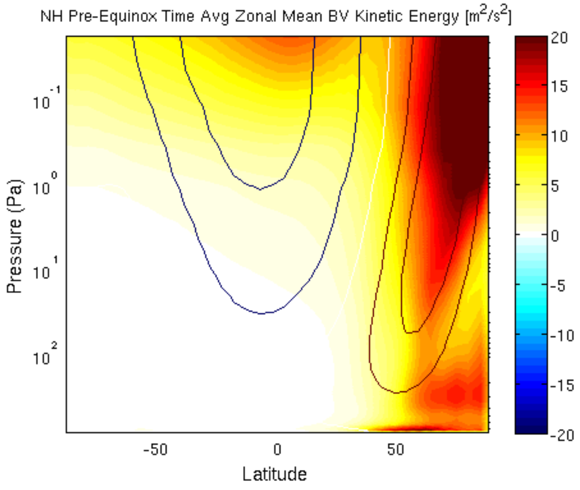
* PRELIMINARY *

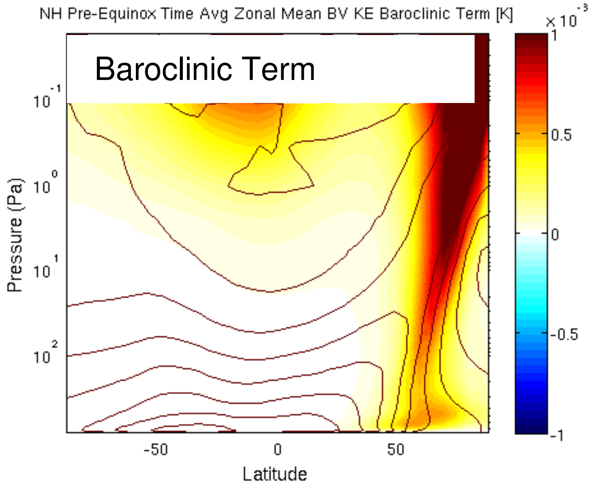
Energy Equation Application: NH Pre-Equinox Season


NH Pre-Equinox Time Avg Zonal Mean Temperature BV [K]


NH Pre-Equinox Time Avg Zonal Mean BV KE Barotropic Term [K]

Baroclinic instability appears to dominate along the polar temperature front, particularly in the lower atmosphere.


NH Pre-Equinox Time Avg Zonal Mean BV Kinetic Energy [m^2/s^2]


NH Pre-Equinox Time Avg Zonal Mean BV KE Baroclinic Term [K]

Upper atmosphere instability may be of mixed origin.

Martian Breeding Conclusions

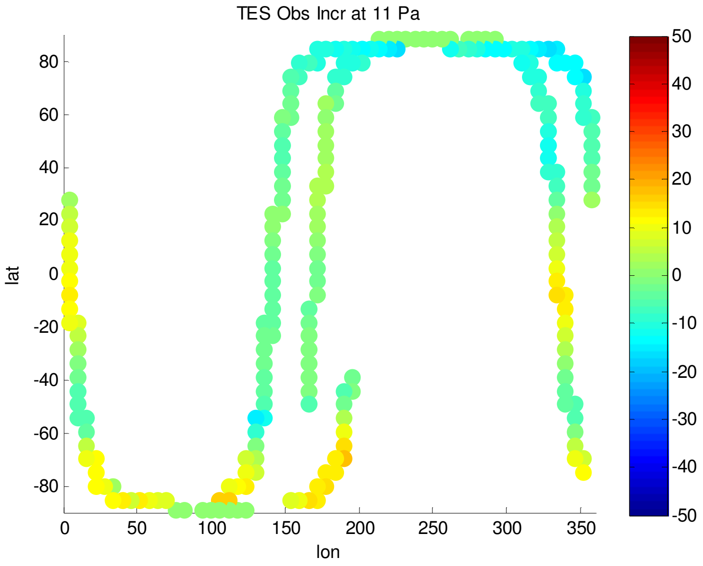
- Atmospheric instabilities most active in winter and spring hemispheres, particularly along temperature front. System rapidly grows from quiescent to active within a few days.
- Wavenumber 1 (upper levels) and 1-4 (near surface) most dominant, with occasional higher frequency signal.

Future Work:

- Continue interpretation of energy equations to diagnose the origin of the instabilities.
- Breed with an interactive dust scheme in order to estimate the characteristics of instabilities and the role of heating during dust storms.

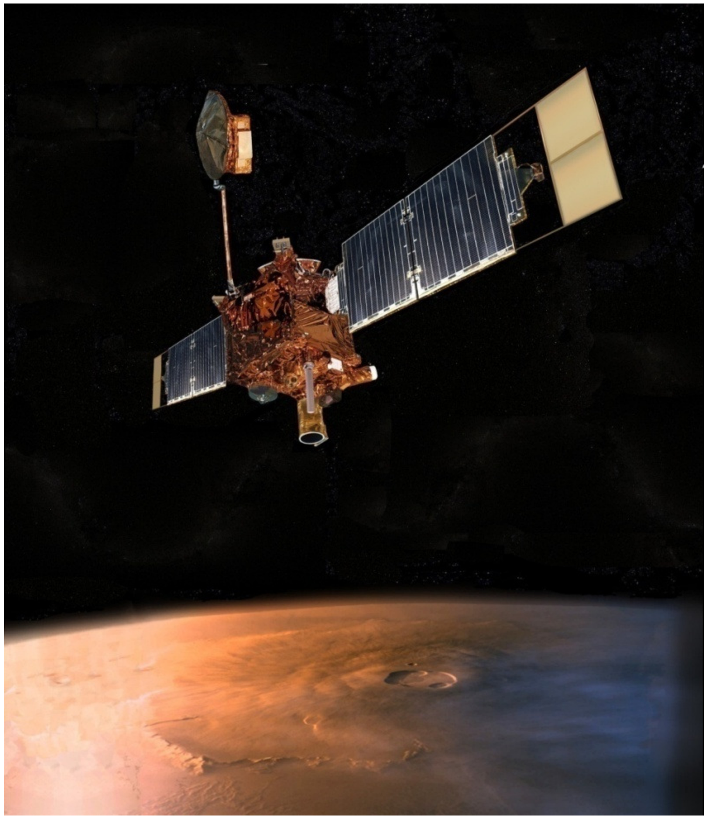
Assimilation of TES Data

- Observations from 1999-2005
- Temperature Retrievals at 19 Vertical Levels
- Observation Error ~ 3 K
- Use of Superobservations

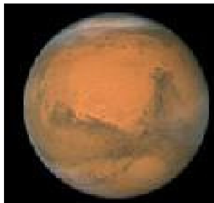


Sample locations of TES profiles during 6-hour interval

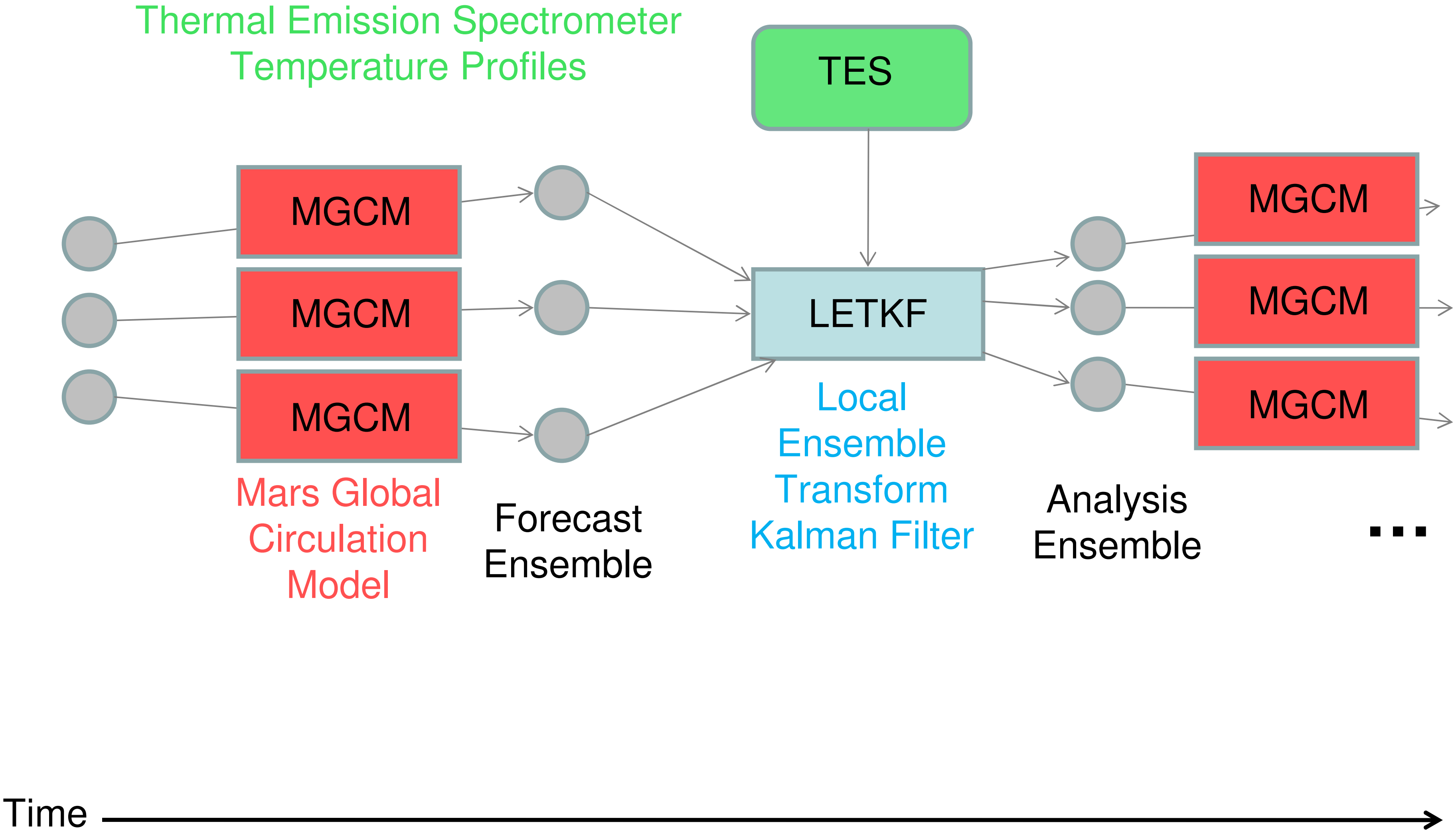
Mars Global Surveyor



Courtesy NASA/JPL-Caltech



MGCM-LETKF-TES Martian Atmosphere Reanalysis Project



Thermal Emission Spectrometer Temperature Profiles

TES

MGCM

MGCM

MGCM

LETKF

MGCM

MGCM

MGCM

Mars Global Circulation Model

Forecast Ensemble

Local Ensemble Transform Kalman Filter

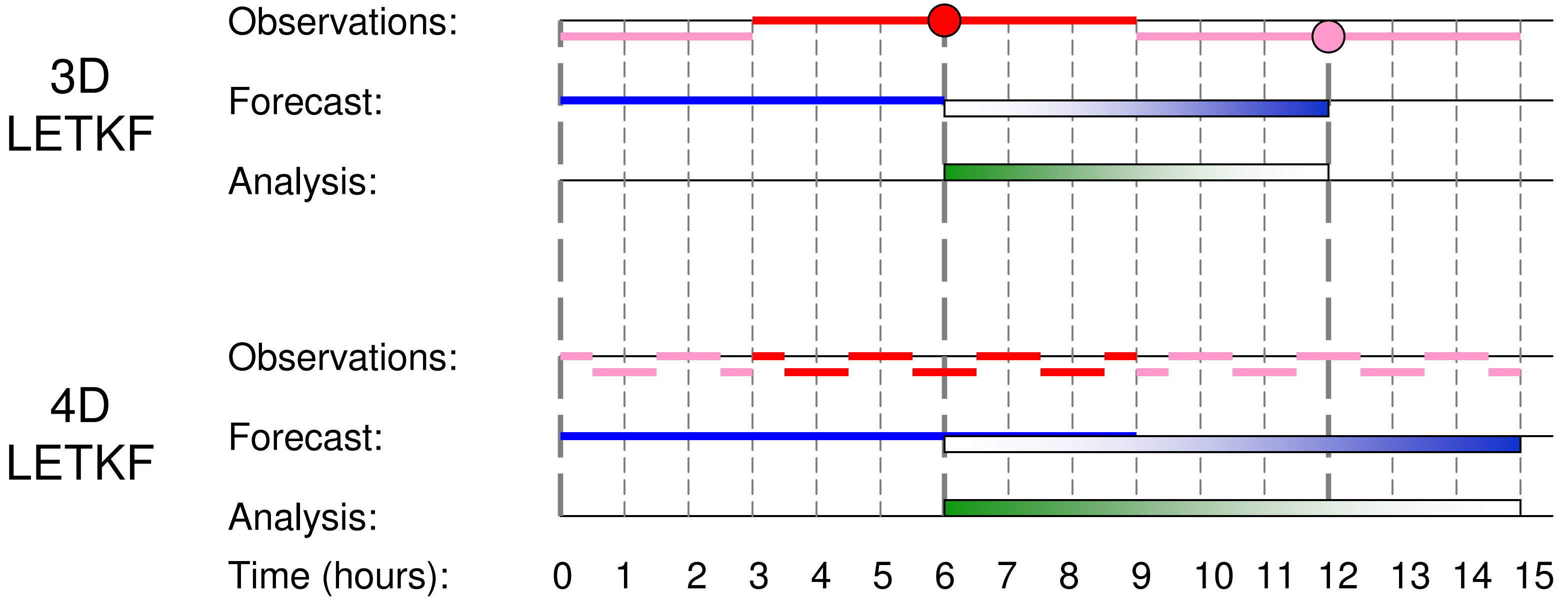
Analysis Ensemble

...

Time

4D LETKF

- Considers observations at correct hourly timeslot rather than assume that they were taken at 6-hourly intervals.
- Important for the strong diurnal changes on Mars.



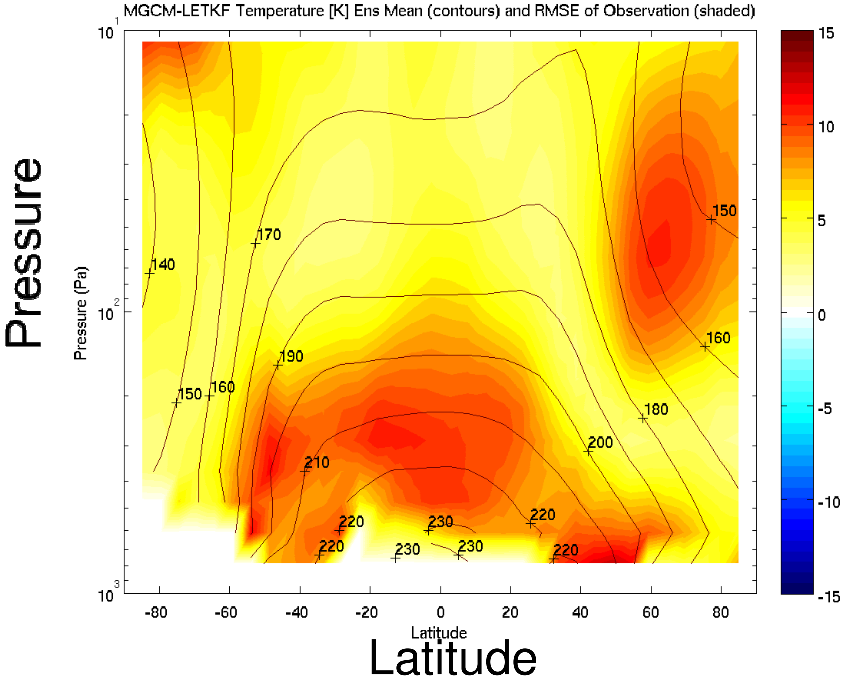
LETKF Parameters

- **30 day assimilation**: Day 530 – Day 560 (Northern Hemisphere Autumn)
- TES Profiles prior to 2001 Dust Storm
- Temperatures at 19 Vertical Levels
- **3 K Observation Error**
- Quality Control Threshold (5 * obs error)
- Superobservations: 1 per grid point
- Polar Filtering
- **16 Member Ensemble**; Initially from 16 previous model states (at 6-hour intervals)
- Gaussian Localization: 400 km in horizontal; 0.4 log P in vertical; 3 hours in time
- **4D-LETKF**: 7 time slots (1 per hour) for each 6-hour cycle
- **10 % Multiplicative Inflation**
- **10 % Additive Inflation** (based on differences between randomly selected nearby dates from different years of nature run)
- Inflation tapers to zero in upper model levels where there is no observation impact
- Fixed dust distribution, $\tau=0.3$

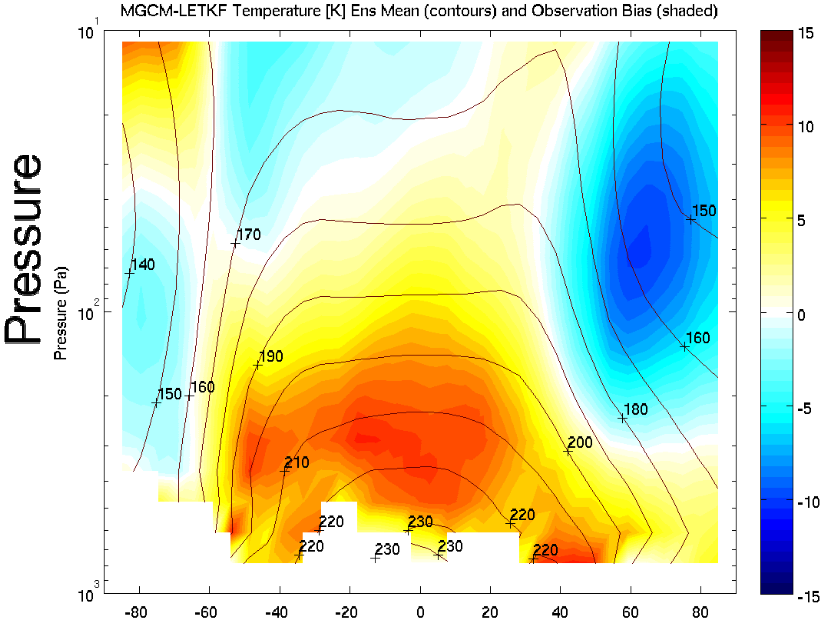
Free Run (No Assimilation)

(How would the model without assimilation compare to observations?)

RMSE (Obs vs. Fcst)

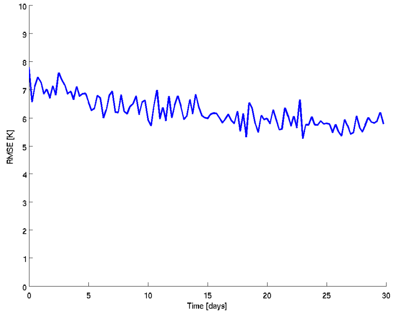


Bias (Obs vs. Fcst)



Latitude

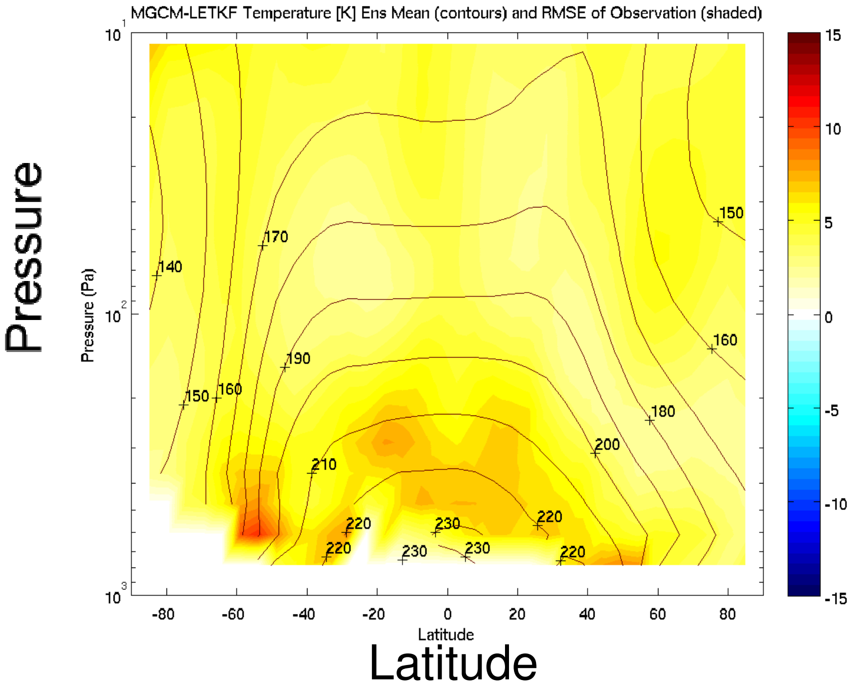
Contours: Ensemble Mean Temperature



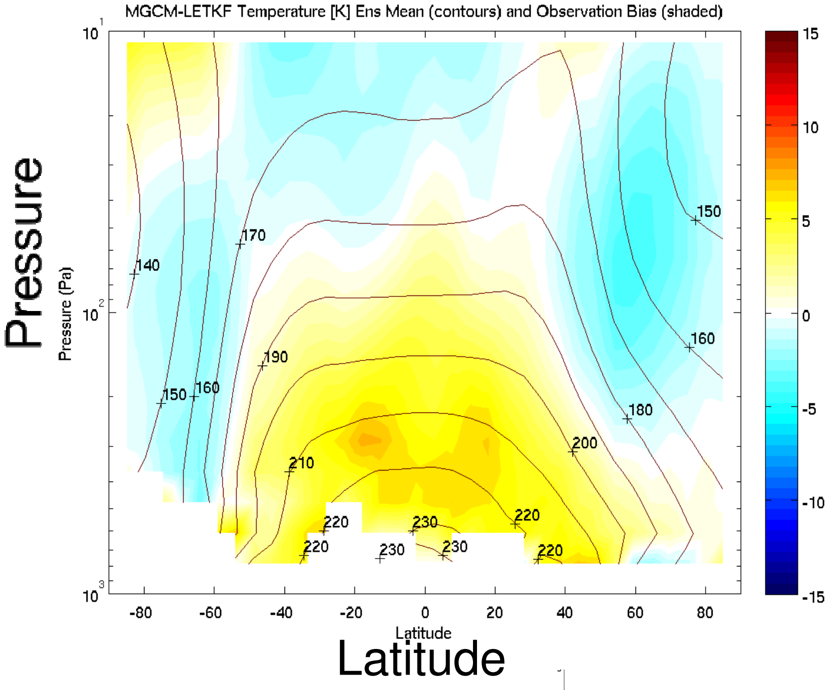
Differences between the MGCM and TES observations are 3-12 K, with large biases in lower atmosphere tropics and along NH polar vortex.

LETKF Initial Run

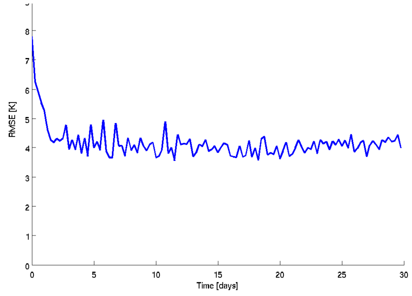
RMSE (Obs vs. Fcst)



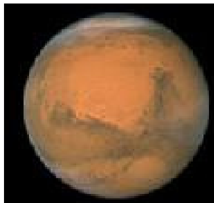
Bias (Obs vs. Fcst)



Contours: Ensemble Mean Temperature

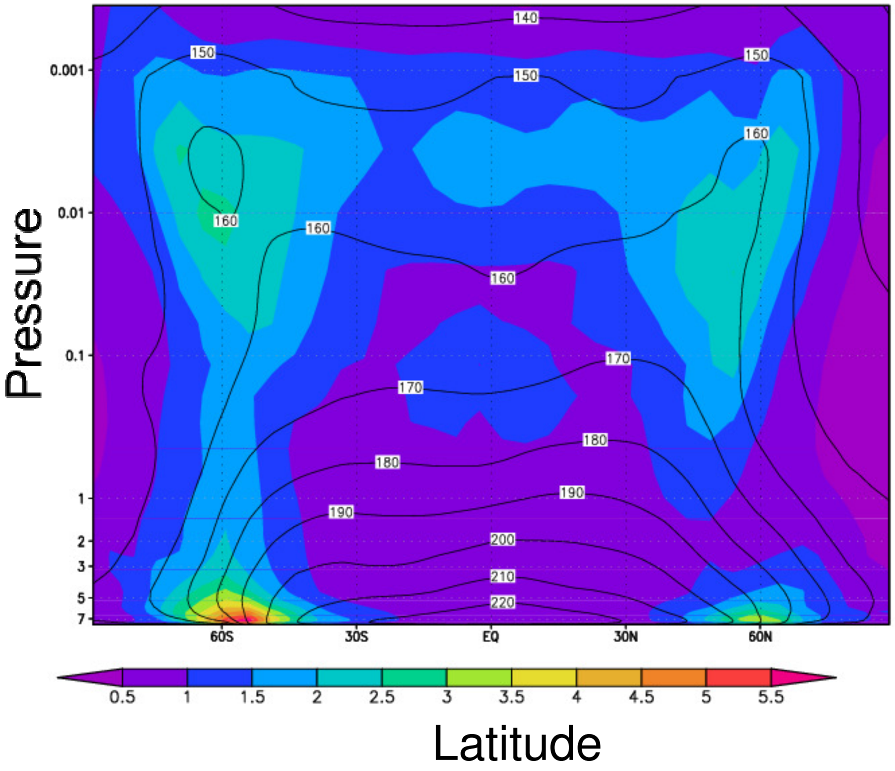


- 6 hour forecast errors compared to TES observations are mainly < 5 K, with a bias remaining in lower atmosphere tropics.
- Data assimilation spin-up time is order of 2-3 days.
- There is a significant improvement over the free run.

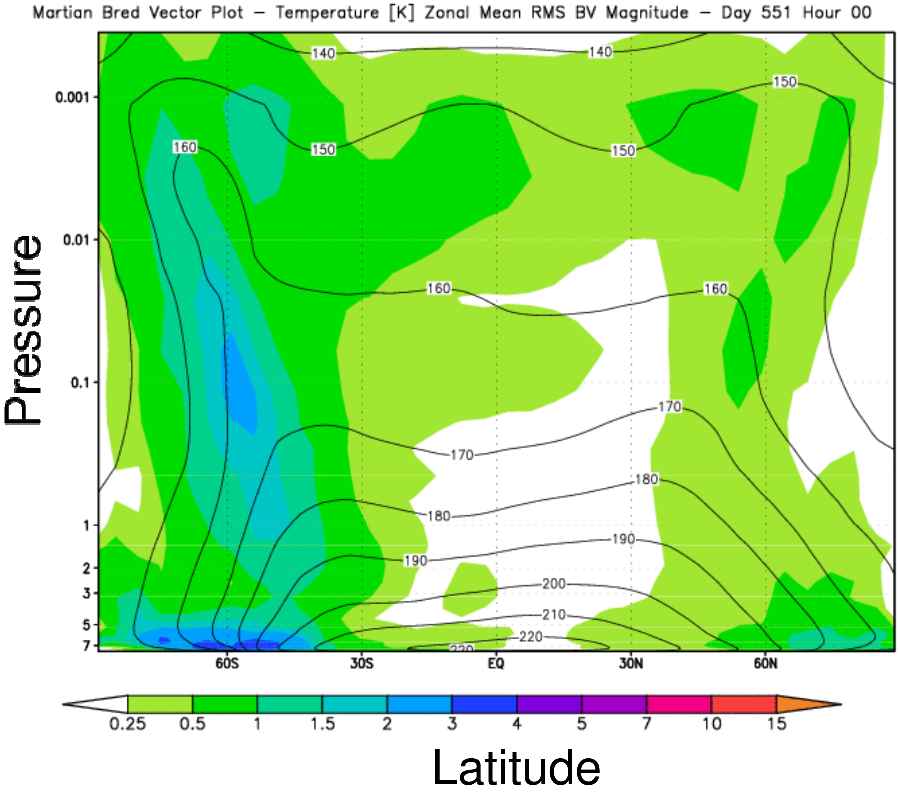


MGCM-LETKF-TES Martian Atmosphere Reanalysis Project

Analysis Ensemble Spread
Using 10% Multiplicative Inflation

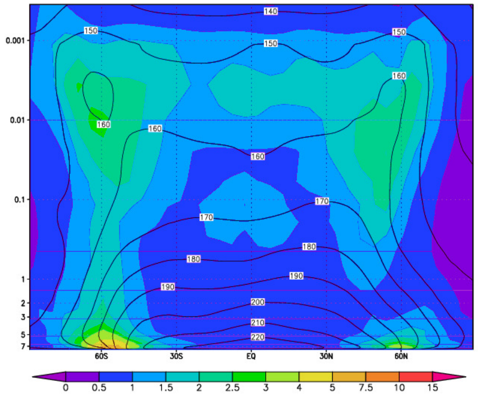


Bred Vector Amplitude

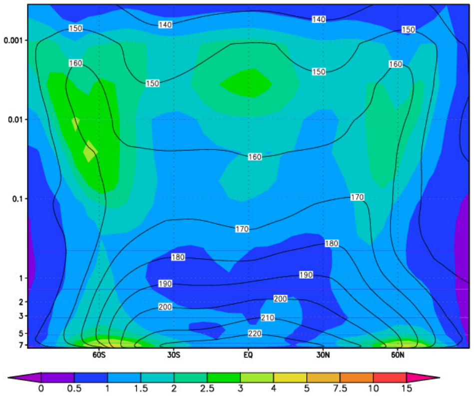


- Ensemble spread (which characterizes the uncertainty in the model state) matches visually with the instabilities inferred from the bred vectors.
- Lack of spread in the tropical low levels (where forcing is strong, and hence the atmosphere is stable with respect to perturbations) means the assimilation system is overconfident in the model background, preventing the errors in this region from being corrected by observations.

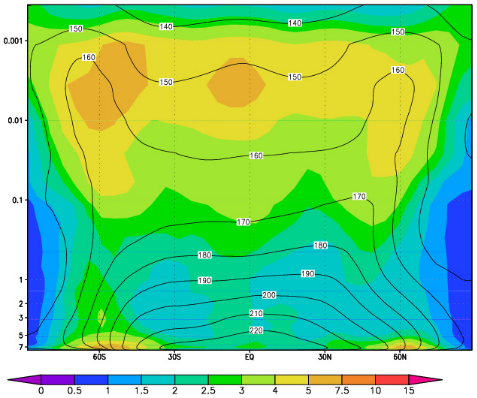
Tuning the LETKF:
Analysis Ensemble Spread



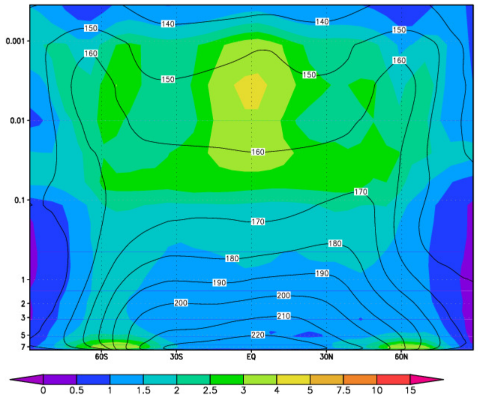
10% Multiplicative Inflation



10% Multiplicative Inflation
10% Additive Inflation

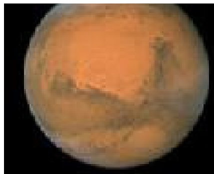


Online Adaptive Inflation
(53.2% Global Multiplicative)
Online Error Estimation (**2.7 K**)



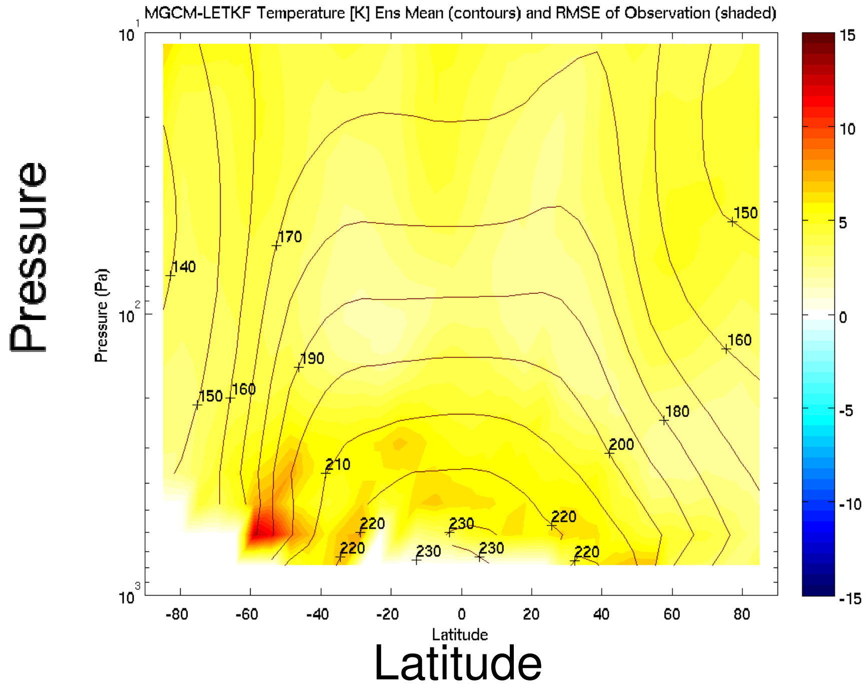
10% Multiplicative Inflation
10% Additive Inflation
Dust Varies τ=0.2-0.5
Among Ensemble Members

- There are various methods for improving the spread in an Ensemble Kalman filter.
- Tuning the inflation parameter provided some improvement in the ensemble spread.
- Varying the dust opacity among ensemble members resulted in the greatest success.

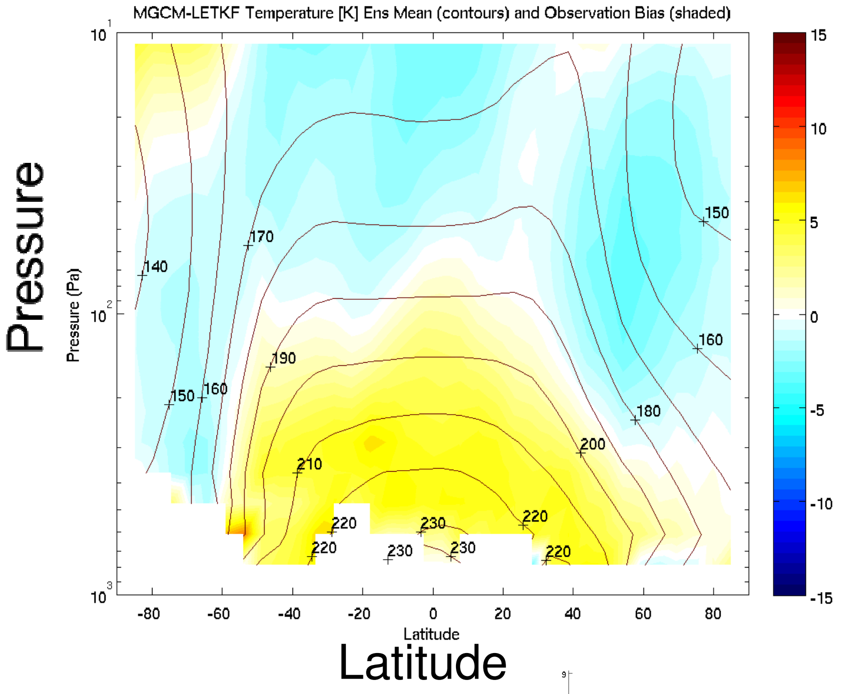


Ensembles with different dust (τ=0.2-0.5)

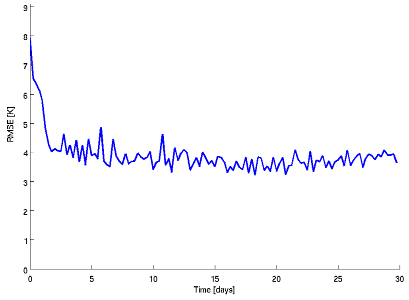
RMSE (Obs vs. Fcst)



Bias (Obs vs. Fcst)

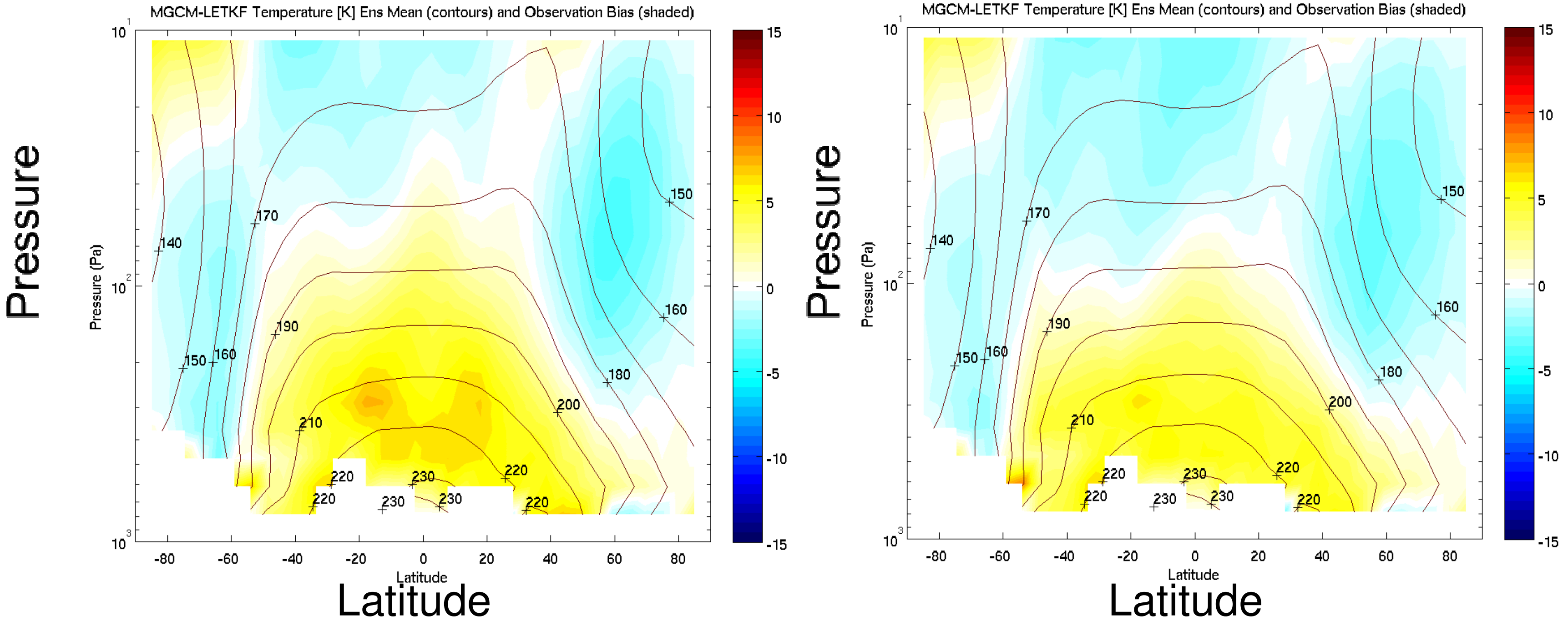


Contours: Ensemble Mean Temperature



- Varying the dust opacity among ensemble members significantly reduced the temperature bias in the lower level tropics.
- The largest errors are now along the SH polar ice cap edge.

Comparison of Bias



Fixed Dust (τ=0.3)

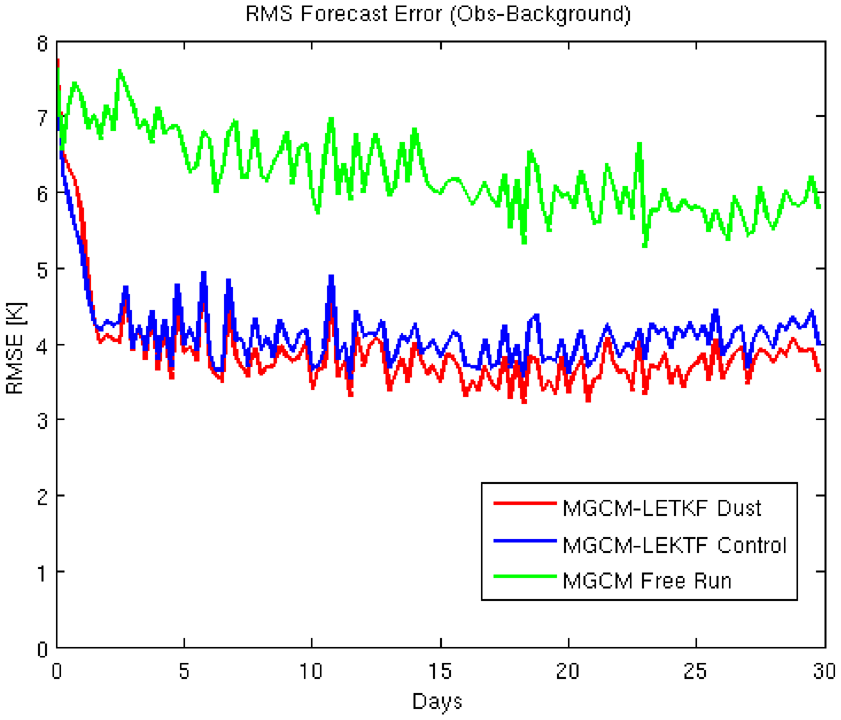
Variable Dust (τ=0.2-0.5)

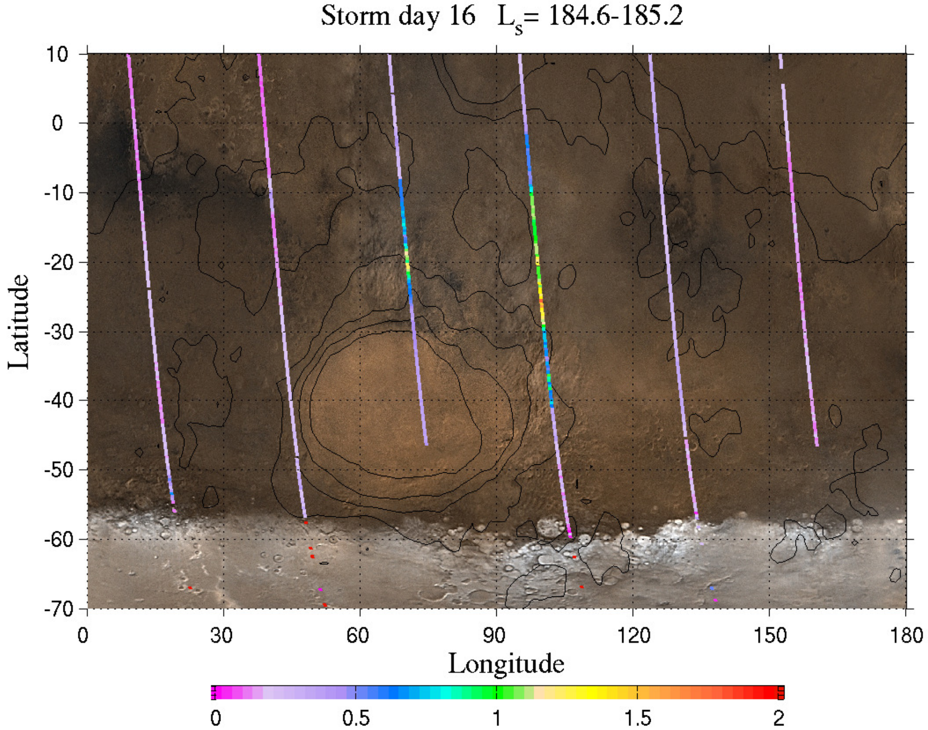
Contours: Ensemble Mean Temperature

- Varying the dust opacity among ensemble members significantly reduced the temperature bias in the lower level tropics.
- The largest errors are now along the SH polar ice cap edge.

Assimilation Conclusions

- Assimilation system successful at improving temperature errors along polar front and in areas of high instability.
- Some biases remain in tropical low levels.



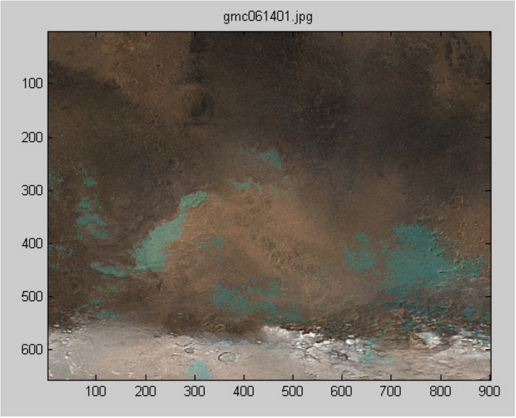


Storm day 16 L_s= 184.6-185.2

Top Image Courtesy of John Wilson

Future Work:

- Dust Variability and Assimilation
- TES Radiance Assimilation
- Bias Correction and System Tuning
- Comparison to the Oxford Reanalysis



Dust Assimilation from TES Dust Opacities and MOC Imagery

← Dust Lifting Mask

Ice Cap Mask →