MGCM-LETKF-TES Martian Atmosphere Reanalysis Project
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EnKF Data Assimilation and Breeding for the Martian Atmosphere

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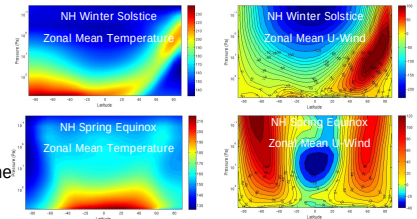
Research Goals

- Characterize the spatial distribution, temporal evolution, and physical mechanisms of instabilities in the Martian atmosphere.
- Create a Mars weather and climate reanalysis by assimilating spacecraft observations into a Mars GCM.

GFDL Mars Global Circulation Model (MGCM)

- 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



Breeding in the Martian Atmosphere

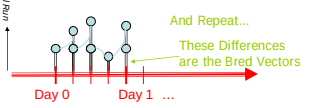
- In chaotic systems, two states that are initially similar grow far apart.
- There is at least one unstable direction, or pattern, that grows in time.
- Breeding is a simple method for finding the shapes of these instabilities (errors).

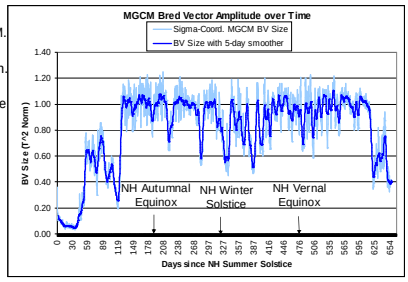
Step 1: Create a nature run (control run) of the MGCM.

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.





MGCM Breeding Experiment Parameters:

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

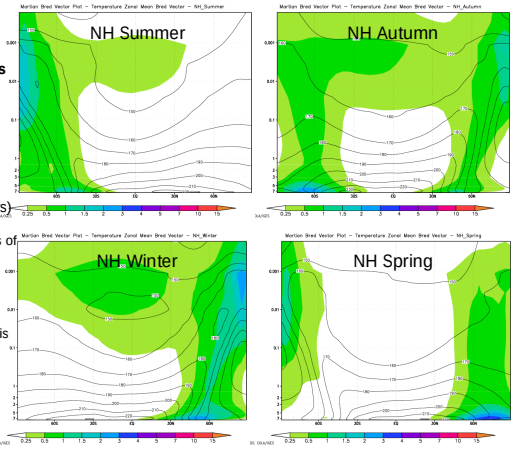
Rescaling Norm:
Temperature-Squared Norm, Scaled by Cosine Latitude

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)

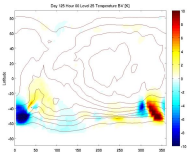


Describing Instabilities: Bred Vector Energy Equations

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

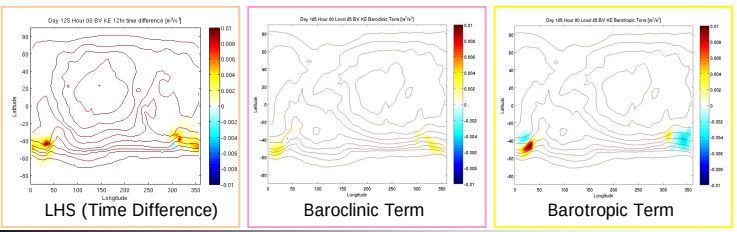
LHS: Local Time Rate of Change of BV KE
Term 1: Transport of BV KE by the total flow
Term 2: Pressure Work
Term 3: Baroclinic Conversion Term
Term 4: Barotropic Conversion Term
Term 5: Coordinate Transform Term

- Begin from the equations of motion (momentum equation in sigma coordinates).
- The control run and perturbed run both satisfy these equations exactly.
- Derive a kinetic energy (KE) tendency equation for bred vectors (difference between control run and perturbed run).



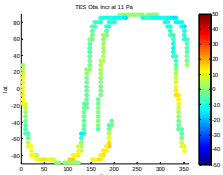
Contoured: $T_{control}$
Shaded: T_{BV}

Application: Day 125 (NH Autumn during time of rapid growth), Level 25 (near surface)

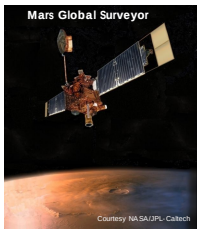


Thermal Emission Spectrometer (TES) Observations

- Observations exist for 1999-2005
- Temperature Retrievals at 19 Vertical Levels
- Observation Error ~ 3 K
- Superobservations: 1 per grid point
- QC threshold: 5 * observation error
- Here, 30 day assimilation near NH autumnal equinox prior to 2001 planetary dust storm

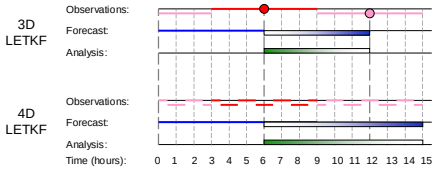


spatial coverage of TES observations (along MGS orbit) in 6 hour time period



Local Ensemble Transform Kalman Filter (LETKF)

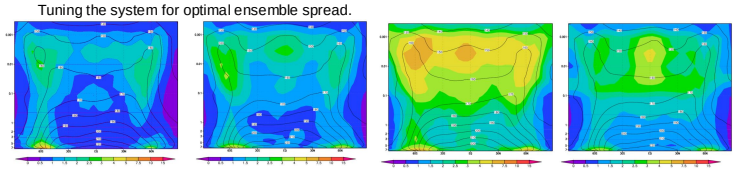
- 4D-LETKF considers observations at correct hourly timeslot rather than assume that they were taken at 6-hourly intervals.
- Important for the strong diurnal changes on Mars.



30 day assimilation: Day 530 – Day 560
16 Member Ensemble; Initially from 16 previous model states (at 6-hour intervals)
4D-LETKF: 7 time slots (1 per hour) for each 6-hour cycle
Gaussian **Localization**: 400 km in horizontal; 0.4 log P in vertical; 3 hours in time
Polar Filtering of T, U, V
Multiplicative Inflation
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

MGCM-LETKF Data Assimilation System Performance

Tuning the system for optimal ensemble spread.



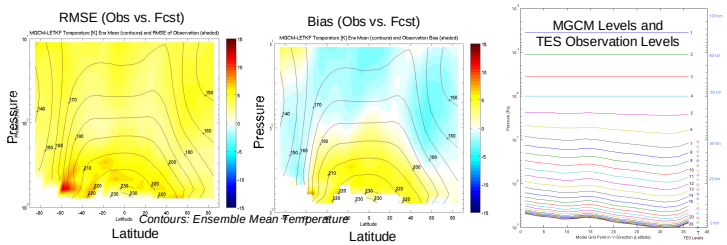
10% Multiplicative Inflation

10% Multiplicative Inflation
10% Additive Inflation

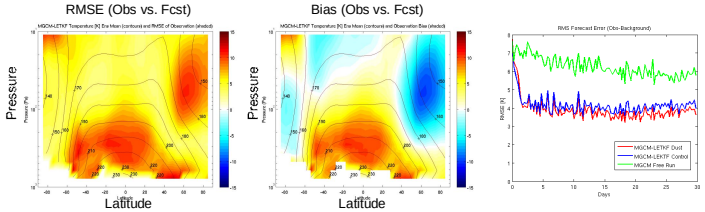
Online Adaptive Inflation
(53.2% Global Multiplicative)
Online Error Estimation (**2.7 K**)

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

System Performance for MGCM-LETKF with Dust Varying Among Ensemble Members:



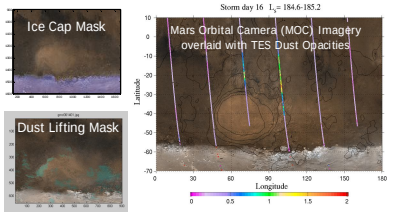
MGCM Free Run (How would the model without assimilation compare to observations?)



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

Future Work

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



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