The Atmosphere of Mars: Perspectives from Spacecraft and Models

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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

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

*Table Courtesy of Matthew Hoffman and John Wilson*
Seasons on Mars

$Ls = \text{Areocentric Longitude}$

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

- Hellas Basin
- Vastitas Borealis
- Olympus Mons
- Valles Marineris

~5 km Hemispheric Dichotomy in Elevation
Radiative effects of dust aerosol suspended in the atmosphere can strongly influence temperature profiles.
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.
GFDL Mars GCM

- Uses finite volume dynamical core
- Latitude-longitude grid
- 60x36 grid points (6° x 5.29° resolution)
- 28 vertical levels
- Hybrid $p/\sigma$ vertical coordinate
- Gaseous and condensed CO$_2$ cycle
- Tracers for dust and water vapor, with the option for dust radiative feedback
Martian Thermal Tide

- 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

Westerly Jets

NH Winter Solstice
Zonal Mean U-Wind

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.
Step 1: Create a long 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.

And Repeat…

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)
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.

Upper Levels (~60 km)

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.
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.

<table>
<thead>
<tr>
<th>Season</th>
<th>Ls</th>
<th>BV Day</th>
<th>Season Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-60</td>
<td>475-601</td>
<td>Boreal Post-Equinox</td>
</tr>
<tr>
<td>2</td>
<td>60-120</td>
<td>602-733</td>
<td>Austral Solstice</td>
</tr>
<tr>
<td>3</td>
<td>120-180</td>
<td>65-178</td>
<td>Austral Pre-Equinox</td>
</tr>
<tr>
<td>4</td>
<td>180-240</td>
<td>179-274</td>
<td>Austral Post-Equinox</td>
</tr>
<tr>
<td>5</td>
<td>240-300</td>
<td>275-368</td>
<td>Boreal Solstice</td>
</tr>
<tr>
<td>6</td>
<td>300-360</td>
<td>369-474</td>
<td>Boreal Pre-Equinox</td>
</tr>
</tbody>
</table>
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.
BV Kinetic Energy Equation

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

- 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 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).
Energy Equation Application: NH Pre-Equinox Season

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

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

 Courtesy NASA/JPL-Caltech
MGCM-LETKF-TES  Martian Atmosphere Reanalysis Project

Thermal Emission Spectrometer Temperature Profiles

MGCM
MGCM
MGCM

Mars Global Circulation Model

TES

LETKF

Local Ensemble Transform Kalman Filter

Forecast Ensemble

Analysis Ensemble

...
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)

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.
• 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.
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)

- 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

- 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.
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 →