Data Assimilation and Breeding for the Martian Atmosphere

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## Comparing Mars and Earth

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mars</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>$3.396 \times 10^6$ m</td>
<td>$6.378 \times 10^6$ m</td>
</tr>
<tr>
<td>Gravity</td>
<td>$3.72$ m $s^{-2}$</td>
<td>$9.81$ m $s^{-2}$</td>
</tr>
<tr>
<td>Solar Day</td>
<td>$88,775$ sec</td>
<td>$86,400$ sec</td>
</tr>
<tr>
<td>Year</td>
<td>$686.98$ earth days</td>
<td>$365.24$ earth days</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>$140$-$290$ K</td>
<td>$230$-$315$ K</td>
</tr>
</tbody>
</table>

*Table Courtesy of M. Hoffman*
Overview of Martian Climate

- Extreme Topography
- Hemispheric Dichotomy
- Seasonal Carbon Dioxide Ice Caps
- CO₂ and Water Ice Clouds
- Strong Diurnal Temperature Swings
- Regional and Planetary Dust Storms

Figure 4.2: Map of Mars’ surface topography, relative to an areopotential surface corresponding to a mean atmospheric surface pressure of 6.1 hPa, derived by the Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) team.
NASA / NOAA 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
- Tracers for dust and water vapor, with the option for dust radiative feedback
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 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…

These Differences are the Bred Vectors

Day 0    Day 1    …    Day 667    Day 668    …

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

MGCM Bred Vector Amplitude using 6-hour Rescaling Interval, 1 K Initial Perturbation

Season labels apply to Northern Hemisphere.
Day 060 ($L_s = 291$, Boreal Winter): After the initial perturbation has mostly decayed, sporadic weak BV activity is confined along the polar front to near the surface at 60N, and 0.01 hPa near the north pole.
Day 078 (Ls= 302, Boreal Winter): BV activity near surface temperature front begins to flare up.
Day 080 (Ls= 304, Boreal Winter): Just two days later, BV now extends vertically along the length of the front. Connection to the upper level tropics begins.
Day 175 (Ls= 358, near boreal vernal equinox): Typical winter BV activity along temperature front with upper level tropical connection. First hint of southern hemisphere activity.
Day 235 (Ls= 22, early boreal spring): Winter BV activity has begun to weaken, as the tropical connection has disappeared.
Day 240 (Ls= 230, early boreal spring): Southern hemisphere activity has now grown rapidly along austral front.
Day 430 (Ls= 116. austral mid-winter): Southern hemisphere BV activity now assumes full spatial extent.
Day 549 (near boreal autumn equinox): Signs BV of activity in the northern hemisphere have resumed.
Day 551 (Ls= 180, boreal autumn equinox): Activity in northern hemisphere has extended vertically.
Day 590 (mid boreal autumn): Activity in both hemispheres, but most intense along southern polar front.
Day 668 (Ls = 252, prior to boreal winter solstice): The seasons have returned full circle, with southern hemisphere activity fading and northern winter dominant.
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 and 2 most dominant, with occasional higher frequency signal.

Future Work:
• Implement energy equations to diagnose instability types
• Breeding with interactive dust scheme
Data Assimilation

- Optimally combines information from:
  - Atmospheric Model (NASA/NOAA Mars Global Circulation Model of John Wilson)
  - Observations (MGS TES Profiles)

- Using a state-of-the-art Ensemble Data Assimilation System
  - UMD’s Local Ensemble Transform Kalman Filter

- To depict as accurately as possible the state of the Martian atmosphere.
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
Simulated Observation Experiments  
(M. Hoffman et al.)

- Identical twin experiments with observations at TES levels and locations.
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.
Experiment Parameters

- **30 day assimilation**: Day 530 – Day 560
- 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
- **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
- **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
Free Run vs. 4D LETKF

- Plots show background (6-hour) temperature forecast RMSE as compared to observations for a free run of the MGCM (left) vs. 4D-LETKF (right). Curves are for Mars Hour 00, 06, 12, and 18; time progresses along x-axis.
Free Run (left) vs. 4D LETKF (right) 30-day error statistics
MGCM-LETKF final analysis ensemble spread.
Day 551 (boreal autumn equinox): Activity in northern hemisphere has extended vertically.
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:

- TES Radiance Assimilation
- Observation Error Estimation and System Tuning
- Dust Assimilation and Parameter Estimation
- Comparison to the Oxford Reanalysis