Grand Tour of Mars
(and some recent results)

Steven Greybush
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Weather Chaos
Group Meeting

Acknowledgments:
Eugenia Kalnay, Takemasa Miyoshi, Kayo Ide [UMD]
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Tim McConnochie, MCS Team, U.K. Mars Team, NASA grant NNX07AM97G

Image: Mars from Viking Orbiter, Courtesy of NASA
Comparing the Earth and Mars

<table>
<thead>
<tr>
<th>Variable</th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>6378 km</td>
<td>3396 km</td>
</tr>
<tr>
<td>Gravity</td>
<td>9.81 m/s²</td>
<td>3.72 m/s²</td>
</tr>
<tr>
<td>Solar Day</td>
<td>24 hours</td>
<td>24 hours 39 minutes</td>
</tr>
<tr>
<td>Year</td>
<td>365.24 earth days</td>
<td>686.98 earth days</td>
</tr>
<tr>
<td>Obliquity (Axial Tilt)</td>
<td>23.5 deg</td>
<td>25 deg</td>
</tr>
<tr>
<td>Primary Atmospheric Constituent</td>
<td>Nitrogen and Oxygen</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>Surface Pressure</td>
<td>101.300 Pa</td>
<td>600 Pa</td>
</tr>
<tr>
<td>Deformation Radius</td>
<td>1100 km</td>
<td>920 km</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>230-315 K</td>
<td>140-300 K</td>
</tr>
</tbody>
</table>

Table Courtesy of Matthew Hoffman and John Wilson

Image Courtesy of NASA
Seasons on Mars

$L_s = \text{Solar (Areocentric) Longitude}$

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

*Slide Courtesy of John Wilson*
Martian Topography

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

~5 km Hemispheric Dichotomy in Elevation
Mars Weather Phenomenon

- Dust Devils
- Water Ice Clouds (cirrus-like)
- Precipitation ("snowfall" detected aloft)
- Surface Frosts, Fogs
- Polar Caps – Water and CO$_2$ Ice
- Traveling Weather Systems
- Regional and Global Dust Storms

Image: View of Victoria Crater from Mars Rover Opportunity, Courtesy of NASA / JPL / Cornell University
Mars Orbital Camera (MOC) Image

Hellas Basin

Olympus Mons

Water Ice Clouds

Seasonal CO₂ Polar Ice Cap

Image Courtesy of Bruce Cantor / Malin Space Science
The Dust Storm Enigma

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.
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
Upcoming Mars Missions

• Mars Science Laboratory (MSL)
  – To be launched 2011, Arrive on Mars Aug. 2012 (“Curiosity” Rover)
  – Rover Environmental Monitoring Station (REMS) – Air and Ground Temperature, Winds, Surface Pressure, Relative Humidity, UV Radiation

• ExoMars
  – To be launched in 2016.
  – Will include an MCS-like instrument, and data assimilation is planned.
**TES (Thermal Emission Spectrometer)**  
**MCS (Mars Climate Sounder)**

<table>
<thead>
<tr>
<th>Thermal Emission Spectrometer (TES)</th>
<th>Mars Climate Sounder (MCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nadir sounder.</td>
<td>Limb sounder.</td>
</tr>
<tr>
<td>Temperature retrievals at 19 vertical levels up to 40 km; column dust opacity.</td>
<td>Temperature, dust, and water ice retrievals at 105 vertical levels up to 80 km.</td>
</tr>
<tr>
<td>Observation error estimated at 3 K; characteristics not well known.</td>
<td>Random error &lt; 1K at elevations below 50 km; estimated systematic error of 1-3 K.</td>
</tr>
</tbody>
</table>

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

- Uses finite volume dynamical core
- Latitude-longitude grid
- 60x36 grid points (6°x5.29° 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
As Revealed by the MGCM

- NH Winter Solstice Zonal Mean Temperature
- NH Spring Equinox Zonal Mean U-Wind
- NH Winter Solstice Zonal Mean Temperature

Adiabatic Warming from Global Hadley Cell Descent
Westerly Jets
Research Questions

• “Considering the unique characteristics of Mars and its observing systems, what is an optimal design of an ensemble data assimilation system for Mars?”
• “What are the locations, seasonal evolution, and physical origins of instabilities in the Martian atmosphere?”
• “How can insights from data assimilation aid remote sensing and model development for Mars, and improve understanding of phenomena such as water ice clouds and dust storms?”
• “How do analyses from assimilation compare to other reanalyses and independent observations, and what is the predictability horizon for Mars?”
Assimilation: Optimally Combining Observations with a Model

- Thermal Emission Spectrometer or Mars Climate Sounder Temperature Profiles
- TES or MCS
- MGCM
- MGCM
- MGCM
- Mars Global Circulation Model
- LETKF: Local Ensemble Transform Kalman Filter
- Forecast Ensemble
- Analysis Ensemble
- MGCM
- MGCM
- MGCM

Update: Temperature, U and V Wind, Surface Pressure
Improving LETKF Performance

- **Initial assimilation** with the LETKF provides significant improvement over freely running model.
- **Varying the dust distribution** among ensemble members, and using the adaptive inflation method (Miyoshi 2011) creates better ensemble spread.
- **Empirical bias correction** of the time mean analysis increment (Danforth et al., 2007) helps account for model errors and further improves performance.
Evaluating the Analyses

Free Run versus Observations (no data assimilation)

- Assimilation run is contrasted with a free run of the MGCM.
- 6-hour forecasts are compared to the latest observations.
- Analyses from assimilating simulated temperature observations at realistic (TES) locations compare well to the (known) truth for both temperature and wind (M. Hoffman et al., 2010).

- TES versus MCS.

- Longer (1-5 sol) forecasts versus observations.

- Evaluation of travelling waves in the analyses and forecasts.

- Comparison to other methods: radiance assimilation, OSS TES retrievals. (M. Hoffman et al., 2011).

- Comparison to the U.K. reanalysis (Montabone et al., 2005), and radio occultation measurements.
Assimilation without Bias Correction
Observation minus Forecast
(sols 10-20, after 10 sol spinup)

TES:

MCS:
(using version 3 retrievals)

Bias (Obs-Fcst)
RMSE
Assimilation with Empirical Bias Correction
Observation minus Forecast
(sols 10-20, after 10 sol spinup)

TES:

MCS:
(using version 3 retrievals)

Bias (Obs-Fcst)
RMSE
Latest Experiments

- Multi-Sol Forecasts and the Predictability Horizon
- Comparison of Analyses with U.K. Reanalysis, Radio Science
- Traveling Wave Analysis
- Breeding with realistic (TES) dust opacities
Forecasting Procedure

- **Free run** forecast (no observation information) using MGCM from Day 530-560.
- **Assimilation** of MY 25 TES data from Day 530-560.
- When applicable, calculate **bias** from mean analysis increment, Day 540-550, and apply every to model state every 6 hours.
- Create **forecasts** from Day 550 analysis.
- Compare forecasts to analyses and observations, Day 550-560, compute RMSE.
Forecast Performance vs. Obs

MGCM-LETKF RMSE of Forecast [K] Compared with Observations

- Freely Running Model (no assimilation): RMSE 5.8153
- Assimilation 6 hour forecasts from analyses (no bias correction): RMSE 3.7551
- Assimilation 6 hour forecasts from analyses (with bias correction): RMSE 3.7253
- 10-sol forecast from analysis (no bias correction): RMSE 6.3309
- 10-sol forecast from analysis (with bias correction): RMSE 4.9166
Observation – Forecast Bias

Averaged over a 10-sol forecast

No Bias Correction

With Bias Correction
Day 1 Forecast vs. Analysis (no Bias Correction)

- Surface Pressure RMSE
- Zonal Mean Temperature RMSE
- Zonal Mean U-Wind RMSE

<table>
<thead>
<tr>
<th>Forecast</th>
<th>Free Run</th>
<th>Forecast</th>
<th>Free Run</th>
<th>Forecast</th>
<th>Free Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Pressure</td>
<td></td>
<td>Zonal Mean Temperature</td>
<td></td>
<td>Zonal Mean U-Wind</td>
<td></td>
</tr>
</tbody>
</table>
Day 3 Forecast vs. Analysis
(no Bias Correction)

Surface Pressure RMSE

Zonal Mean Temperature RMSE

Zonal Mean U-Wind RMSE

Forecast

Free Run
Day 5 Forecast vs. Analysis (no Bias Correction)

Surface Pressure RMSE

Zonal Mean Temperature RMSE

Zonal Mean U-Wind RMSE

Forecast

Free Run
Day 1 Forecast vs. Analysis (with Bias Correction)

Surface Pressure RMSE

Zonal Mean Temperature RMSE

Zonal Mean U-Wind RMSE

Forecast

Free Run
Day 3 Forecast vs. Analysis (with Bias Correction)

Surface Pressure RMSE

Zonal Mean Temperature RMSE

Zonal Mean U-Wind RMSE

Forecast

Free Run
Day 5 Forecast vs. Analysis (with Bias Correction)

- Surface Pressure RMSE
- Zonal Mean Temperature RMSE
- Zonal Mean U-Wind RMSE
The U.K. and LETKF Analysis Systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>U.K. Reanalysis</th>
<th>LETKF Reanalysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assimilation Scheme</td>
<td>Analysis Correction Scheme (Lorenc et al., 1991), which is similar to nudging</td>
<td>Local Ensemble Transform Kalman Filter (LETKF; Hunt et al., 2007)</td>
</tr>
<tr>
<td>Update Frequency</td>
<td>Continuously (every model time step)</td>
<td>Assimilation cycle is 0.25 sol</td>
</tr>
<tr>
<td>Temporal Availability</td>
<td>Every 2 Mars hours</td>
<td>Every 6 Mars hours, or hourly as desired</td>
</tr>
<tr>
<td>Atmospheric Model</td>
<td>Oxford-LMD Mars model (Forget et al., 1999)</td>
<td>GFDL MGCM (Wilson et al., 2002; Hoffman et al., 2010)</td>
</tr>
<tr>
<td>Model Resolution</td>
<td>72 x 36 x 25 levels</td>
<td>60 x 36 x 28 levels</td>
</tr>
<tr>
<td>Vertical Coordinate</td>
<td>Sigma</td>
<td>Hybrid Sigma-Pressure</td>
</tr>
<tr>
<td>Temperature Data</td>
<td>PDS TES Profiles, with vertical averaging</td>
<td>PDS TES Profiles at TES levels</td>
</tr>
<tr>
<td>Dust Methodology</td>
<td>TES dust opacities directly inserted.</td>
<td>Initially, fixed dust opacity varied among ensemble members. Eventually, updated from observations.</td>
</tr>
<tr>
<td>Variables Updated</td>
<td>T, U, V, surface pressure, dust</td>
<td>T, U, V, surface pressure</td>
</tr>
<tr>
<td>Uncertainty Estimate</td>
<td>None</td>
<td>From Ensemble (16 members)</td>
</tr>
<tr>
<td>Localization Cutoff Radius</td>
<td>1200 km</td>
<td>1460 km (400 km gaussian * 3.65) horizontal</td>
</tr>
<tr>
<td>Availability</td>
<td>Entire TES Period; MCS</td>
<td>Intervals from MY 24, MY 25 for TES, MY 29 for MCS</td>
</tr>
</tbody>
</table>

- Analyses are compared over a 15 sol period in **N.H. autumn (L\textsubscript{s} 182.3 – 191.1) of MY 24**.
- TES observations from the PDS are assimilated.
- U.K. analyses (Montebone et al., 2005; Lewis et al., 2007) are interpolated to the MGCM grid.
Comparing the Analyses: Zonal Mean Statistics

- Zonal mean statistics of temperature differences between the analyses reveal a general agreement of the analyses, within 5 K in most of the domain.
- 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.
Comparing with the U.K. Analysis: Traveling Waves

- Analyses are compared over a 15 sol period in **N.H. autumn (Ls 182.3 - 191.1)** of **MY 24**.

- Hovmoller diagrams are a useful tool to evaluate the movement in space and time of travelling weather systems. This is a good test of the assimilation system, as traveling wave details are not easily discerned from sparse observations alone.

- Deviations from a zonal and temporal mean were used to calculate perturbation temperature fields at MGCM Level 20, or about 3km altitude, for latitude circles at 60°N and 60°S.

- Gray lines represent travelling waves from the LETKF hovmoller diagram, which have been copied atop the U.K. diagrams.

- The two analyses show generally good agreement on the phase of traveling waves, although the amplitudes are slightly different.
Radio Science (RS) occultation measurements (Hinson et al., 1999) can be used to derive temperature profiles, which serve as an independent data source to evaluate the analyses.

Here, profiles from the NH mid-latitudes (30°-50°N) are used.

RMSE is 5-10 K, except near the surface and at higher altitudes.

Both analyses have a warm bias compared to RS observations.
Breeding on Mars

Photograph of Martian Sunset taken from the Gusev crater, Courtesy of NASA
Upper levels are most active around the solstice, while near surface activity peaks in the transition seasons.

Wave 1 instabilities are dominate in upper levels, whereas waves 2-4 occur near the surface.

The atmosphere can rapidly grow from quiescent to active within a few days.
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.
**Instabilities: Bred Vectors and Ensemble Spread**

- **Bred vectors** characterize the spatial distribution, temporal evolution, and physical mechanisms of instabilities in the Martian atmosphere, which relate to the forecast errors resulting from uncertain initial conditions. (Greybush et al., in preparation)

- **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.

- Varying the dust distribution among ensemble members improves the ensemble spread in this region, and hence the performance of the data assimilation system.
MY24 TES Dust Opacity (contours) and Ice Cap Evolution (shaded) in the MGCM
Zonal Mean BV by Season, Hemispheric Scaling

Boreal Post-Equinox

Austral Solstice

Austral Pre-Equinox

Boreal Solstice

Boreal Pre-Equinox
Zonal Mean BV by Season, TES Dust

Boreal Post-Equinox

Austral Solstice

Austral Pre-Equinox

Austral Post-Equinox

Boreal Solstice

Boreal Pre-Equinox
Future Work

Creation of a long duration Mars atmosphere reanalysis for the TES and MCS eras, including temperature, dust and ice aerosol.

EOF-based retrieval assimilation that removes the influence of the prior and better represents degrees of freedom in observations, and considers vertical correlations (R. Hoffman, 2010) for OSS observations, or radiance assimilation.

Addition of a dust opacity analysis through assimilation of TES column opacities, MCS vertical profiles, and brightness temperatures (Wilson et al., 2011).

Improvement of the MGCM based upon insights from observations and assimilation products.

Investigation of travelling wave and dust storm characteristics.
Zonal Mean Temperatures at around Ls 160

**MCS Retrievals**  
MGCM w/Water Ice Clouds

**MGCM w/Topo Wave Drag**  
MGCM w/ both Clouds & Drag

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**Upgrades to MGCM:**

- improved parameterizations for surface dust lifting with tracer transport scheme
- Option to use seasonally-varying dust forcing from observations
- Radiatively active water ice clouds
- These will help improve agreement between the **MGCM** and **MCS**.

*Figure Courtesy of John Wilson*
Inspired by presentation by John Noble
MGCM-LETKF-TES  Martian Atmosphere Reanalysis Project

NOG Image Overlay with Temperature Perturbation (solid thick lines: hot red, cool blue) and Surface Pressure Perturbation (dashed thin lines: high blue, low red)
Hourly Time Series at MSL Sites
Higher Resolution Modeling

- Figure 3: Results from the SH spring (~Ls 209) from a global scale N180 (1.2x1.0 lon-lat, or ~30 km, resolution) MGCM simulation using a regular lon-lat grid at two different local times: early morning (left) and midday (right). The figure shows surface pressure (shaded, Pa), terrain (contours every 200 m) and low level winds (~1 km above surface; arrows, with maximum wind speed 20 m/s) in the region of the Holden Crater.

Figure Courtesy of John Wilson