Exploring Martian Weather through Data Assimilation

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Ross Hoffman, Matthew Hoffman
John Wilson
Features of Martian Weather

- Diurnal Cycle, Thermal Tides, Topography
- Traveling Weather Systems
- Water Ice Clouds
- Seasonal CO₂ Polar Ice Caps
- Dust Devils, Regional and Global Storms

Figure Courtesy of NASA/JPL and Malin Space Science

MGS Mars Orbital Camera (MOC) Visible Image
Features of Martian Weather

Inform Assimilation System Design

- Diurnal Cycle, Thermal Tides, Topography
- Traveling Weather Systems
- Water Ice Clouds
- Seasonal CO₂ Polar Ice Caps
- Dust Devils, Regional and Global Storms

- Optimal Window Length and Inflation
- Localization Scales, Verification Metrics
- Tuning Model Physics
- Enforcing CO₂ Conservation
- Representing Aerosols in Ensemble
### Features of Martian Weather

#### Inform Assimilation System Design and Motivate Science Questions

<table>
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<th>Martian Weather Features</th>
<th>Assimilation System Design Aspects</th>
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- What is the predictability window for Mars weather forecasting?
- What instabilities give rise to forecast errors and changes in wave regimes?
- How well are tides and traveling weather systems depicted in reanalyses, and can they be linked to dust lifting?
- What is the spatial distribution and time evolution of ice and dust aerosol?
- What mechanisms are responsible for global dust storm formation?
Components Needed to Create a Mars Reanalysis:

- GFDL Mars Global Climate Model (MGCM)
- LETKF Data Assimilation
- Spacecraft Observations: TES, MCS Retrievals

Spacecraft Horizontal Coverage in 6hrs

Spacecraft and Model Vertical Coverage
Regions of Chaotic and Stable Dynamical Error Growth: Implications for Ensemble Spread, Inflation

Contours: Temperature Ensemble Mean; Shaded: Temperature Ensemble Spread, Bred Vector, or Inflation
Mars TES/LETKF Impact on T Bias

Baseline Reanalysis:

Assimilating TES Temperatures with Fixed Dust Distribution, No Water Ice Clouds.

Adaptive Inflation (Miyoshi, 2011) and varying dust among ensemble members.

Gaussian “R-localization”: 600 km in horizontal, 0.4 logP in vertical.

Contours: Ensemble Mean Forecast

Shaded: Observation minus Forecast Bias
Mars TES/LETKF Impact on T Bias

Seasonal Dust Reanalysis:

Assimilating TES Temperatures with Seasonal Dust Distribution, No Water Ice Clouds. Distribution follows analytic formula (Montmessin et al., 2004) and is a function of season, latitude, and height.

Dust opacity varies among ensemble members according to scaling factor.

Contours: Ensemble Mean Forecast

Shaded: Observation minus Forecast Bias
Mars TES/LETKF Impact on T Bias

Reanalysis forced by TES Dust Opacities

Horizontal and vertical dust distribution determined by MGCM advection of tracers.

Dust injected/removed from boundary layer to match observations.

Ensemble varies strength of water ice clouds.

Contours: Ensemble Mean Forecast

Shaded: Observation minus Forecast Bias
Mars TES/LETKF Impact on T Bias

Reanalysis forced by TES Dust Opacities with diurnal Empirical Bias Correction using 10-sol window.

Contours: Ensemble Mean Forecast

Shaded: Observation minus Forecast Bias
Dust Aerosol Forcing

- How sensitive are temperature reanalyses to the choice of dust aerosol distribution?

Comparisons between free run and assimilation forecasts to TES nadir retrievals.
Traveling Waves and Dust

Simple Reanalysis: Fixed Dust No Bias Correction

Do reanalyses with different model configurations, dust specification, initial conditions, and data assimilation techniques converge on the same synoptic state of traveling waves?

It appears they may, although the details differ.

Advanced Reanalysis: TES Dust and Water Ice Clouds Empirical Bias Correction

3.5 km eddy T [shading], (u, v) [arrows], $p_s$ [contours]
Traveling Wave Hovmoller Plot

TES Dust Tracer Reanalysis Bias C

TES Seasdust Reanalysis Bias C

Reanalysis Travelling Waves 49° to 75° N
Wave Regimes on Mars

NH Fourier Timeseries

Seasdust Rean BC MEM 8

NH Fourier Timeseries

TES dust Rean BC

Seasdust Rean no BC

Seasdust Rean BC
### Improving Aerosol Representation

#### MCS Free Runs: Observation minus Model Bias

<table>
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<tr>
<th>Seasonal Dust, No Ice Cloud</th>
<th>Seasonal Dust + Ice Cloud</th>
<th>3 Tracers + Ice Cloud</th>
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<tr>
<td><img src="image1" alt="Seasonal Dust, No Ice Cloud" /></td>
<td><img src="image2" alt="Seasonal Dust + Ice Cloud" /></td>
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#### MCS Assimilation: Observation minus Model Bias

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**Challenges for GCMS:**

Mars GCMS do not yet handle detached dust layer very well.

Dust lifting is also difficult to determine due to observation limitations and finite surface dust reservoirs.
Empirical Bias Correction

• Assume that the time-mean analysis increment represents “missing physics” (for example, aerosol forcing) in the MGCM.
• Apply this correction prior to data assimilation every assimilation cycle. Assimilation then focuses on corrections to “errors of the day” rather than biases.
• Here we use 10-sol centered window diurnal biases.

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Strategies for Dust Assimilation

Dust can be injected/removed from the boundary layer to match analyzed opacity. Dust field is advected by tracers. 

*Challenge: how to distribute dust in vertical, among particle sizes.*

Determine dust field from observations using the LETKF: 
- dust column opacities (TES) and profiles (MCS) 
- temperature profiles 
- surface brightness temperatures 

And tune with variable localization. 

*Challenge: observation coverage is limited.*

Use parameter estimation to identify surface dust sources and sinks. 

*Challenge: sources evolve rapidly, need to be constrained by obs.*

Use dust lifting parameterizations (dust devil and surface wind stress) to model dust lifting based on analyzed meteorology. 

*Challenge: sensitive feedbacks between meteorology and dust field.*
Summary: MGCM-LETKF Mars Reanalysis Goals

• Innovate ensemble **data assimilation** methodology for the unique characteristics of the Mars atmosphere and its observing systems.

• Provide community with 4-D **synoptic states** of atmospheric and aerosol fields to explore science questions: traveling waves, dust storm evolution, etc.

• **Evaluate** reanalysis through comparison with other reanalyses and observation products.

• Improve **model** representation of dust and ice cloud aerosols through parameter estimation.

• Assess atmospheric **predictability** and analyzability.