ENSEMBLE MARS ATMOSPHERE REANALYSIS SYSTEM (EMARS)

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Introduction:

Data assimilation optimally combines spacecraft observations with short-term forecasts from an atmospheric model to produce a record of the atmospheric state and, with an ensemble, its uncertainties. When performed retroactively for a long period of time, this sequence of analyses is termed a reanalysis. The availability of Thermal Emission Spectrometer (TES) and Mars Climate Sounder (MCS) retrievals of temperature and aerosol opacities enables a comprehensive multiannual examination of Martian weather and climate, as data assimilation has proven to be an effective means of reconciling models with observations for Mars (Lewis et al., 2007; Hoffman et al., 2010; Lee et al., 2011; Navarro et al., 2013). We have used the Local Ensemble Transform Kalman Filter (LETKF), an advanced data assimilation system, to construct a sequence of synoptic maps (Figure 1) detailing the evolution of the temperature, wind, and surface pressure over the course of several Martian years (Mars Year 24 – 27, as well as during the MCS period).

Data and Methodology:

Spacecraft Observations. The first versions of our reanalysis assimilate Thermal Emission Spectrometer (TES) nadir temperature retrievals (Smith et al., 2001), downloaded from the Planetary Data System (PDS) website. Coverage is twice daily following a polar orbit, although profiles are somewhat smoothed in the vertical. We also use column dust opacity data to constrain the model aerosol. TES limb data are now available (Guzewich et al., 2013), extending coverage in the vertical.

AER has produced retrievals of the TES radiances using the Optimal Spectral Sampling (OSS) technique (Eluszkiewicz et al., 2008), and these have been evaluated compared to the PDS retrievals (Hoffman et al., 2012). These retrievals also provide averaging kernel information, enabling the method of Hoffman (2010) for removing the influence of the prior profile and vertical error correlations. This would also enable a pathway to interactive retrieval assimilation where forecasts from data assimilation provide an interactive prior, a technique that shares the advantages of radiance assimilation.

We have also assimilated Mars Climate Sounder (MCS) retrievals, which provide increased vertical extent and resolution for temperature, as well as vertical profiles of aerosols.

Model Configuration and Aerosol Scenarios. We use the GFDL Mars Global Climate Model (MGCM) for our simulations, currently with a lat/lon grid resolution of 5x6 degrees and 28 vertical levels. We employ several scenarios for aerosol. In the first, the dust distribution is prescribed following a smoothly varying function of latitude and season, and the Conrath (1975) profile in the vertical. In the second, the horizontal distribution matches the observed TES opacities as given by the Mars Climate Database dust scenarios (Montabone et al., 2013), while the vertical are still prescribed. The third uses radiatively active dust tracers in the MGCM with three size distributions to determine the vertical profile. Dust is added or subtracted to the lower atmosphere to match observed opacities, as an analogy to lifting and deposition (Kahre et al., 2009). Several experiments also employ radiatively active water ice clouds.

Data Assimilation System. We have developed an Ensemble Mars Atmosphere Reanalysis System (EMARS) based on the LETKF (Hunt et al., 2007). Each ensemble member represents a potential atmospheric state, spanning a range of possibilities, with the ensemble mean being the most probable and the ensemble spread reflecting the uncertainty. The LETKF also has the ability to estimate and improve model parameters.

We have improved the performance of this system by using spatially varying adaptive inflation (Miyoshi 2011) to tune the ensemble spread to agree with error statistics and diurnal empirical bias correction based on the time-averaged analysis increment to account for model errors (Greybush et al., 2012).

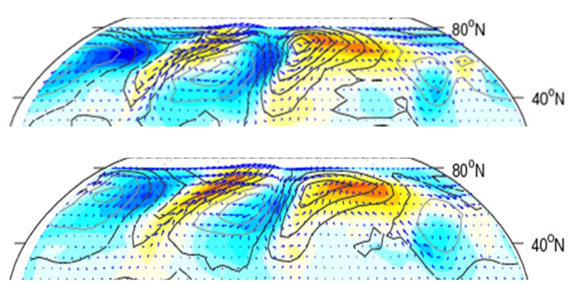

Figure 1: NH Synoptic map of reanalysis fields for MY 24 (~Ls 199°). Plotted are (~3.5 km altitude) eddy temperature (K; shaded), eddy wind vectors (m/s), and eddy surface pressure (contoured, positive in gray, negative in black). Top is with an analytic, seasonal dust distribution, bottom is forced by observed TES opacities. While the general synoptic wave patterns are similar, differences in detail reflect the impact of aerosol.

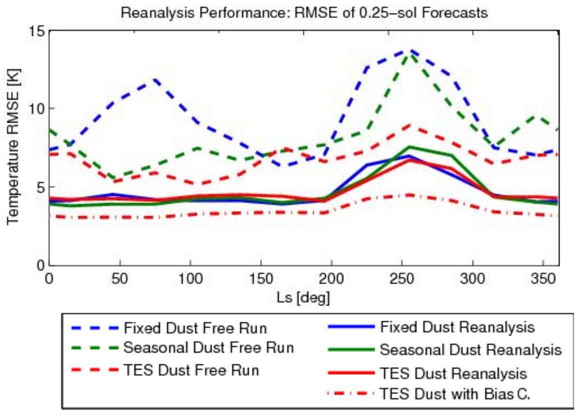

Figure 2: RMSE of 0.25 sol forecasts from free run model simulations and analyses compared to TES observations during MY 24-25.

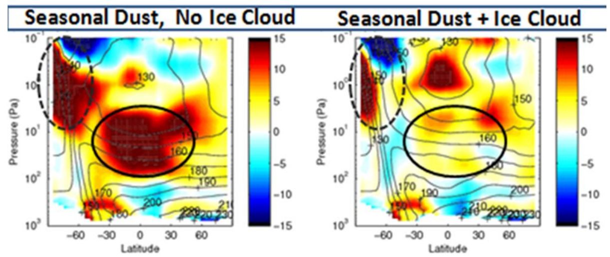

Figure 3: Inclusion of radiatively active water ice cloud greatly increases agreement between MGCM free run and MCS observations. Zonal mean temperatures (contours) and biases (shading) are plotted.

Results:

Reanalysis Evaluation. We evaluate the skill of short term forecasts (0.25 sol) initialized from analyses, and compare them to independent (in time) observations. These show reduced RMSE compared to a freely running model simulation (Figure 2). We have also performed a preliminary comparison with radio science profiles (Hinson et al., 2004), an independent dataset with high vertical resolution.

Sensitivity to Aerosols. Full-year TES experiments employing fixed dust opacities, seasonally varying dust opacities, and observed TES dust opacities show that while realistic dust distributions are essential to match observed temperatures with a free run simulation, analyses from data assimilation are more robust with respect to imperfections in aerosol distribution.

Traveling Waves. A consequence of successful reanalysis is a convergence of analyzed fields about a unique synoptic state. To examine this evidence, we compare weather maps of eddy temperature, surface pressure, and wind fields. Preliminary results indicate that ensemble member forecasts from within a single experiment, as well as ensemble means from experiments using different aerosol assumptions, are much more similar to each other than to freely running ensemble forecasts. Traveling wave climatologies, as evidenced by Hovmoller diagrams, show a distinct climatology in the reanalysis compared to the free run forecast. However, specific circulation features are dependent upon the correct aerosol specification (Figure 1).

Predictability. We have used the bred vector technique (Greybush et al., 2013) as well as longer range (10 sol) forecasts to examine the predictability of the Martian atmosphere. In agreement with Rogberg et al. (2010), midlatitudes are baroclinically unstable, whereas in the tropics the model is stable and forced by aerosol radiative heating. We have found that varying the aerosol distribution among ensemble members improves the ensemble spread and improves the performance of the system.

Mars Climate Sounder Assimilation. We have expanded our assimilation to include Mars Climate Sounder temperature retrievals (testing both along-track and cross-track geometries) at several times of year, and compared biases to those from TES assimilation. Inclusion of radiatively active water ice clouds and 3 dust tracers have improved agreement between the MGCM and MCS data (Figure 3). We have also conducted preliminary comparisons of free run simulations and MCS analysis dust and water ice vertical structure (Figure 4) to MCS profiles.

Tides and Water Ice Clouds. Representation of the diurnal cycle is another important component of our reanalysis. We found that using shorter (1-hour) as opposed to 6-hour assimilation windows more realistically reproduces all components of the thermal tide in the atmosphere (Zhao et al., 2013). Using data assimilation can also help compensate for missing aerosol heating (such as water ice clouds) in mid-levels of the model, creating diurnal and semi-diurnal tidal amplitudes in better agreement with observational studies (e.g. Kleinböhl et al., 2013).

Reanalysis Intercomparison. We have initiated an intercomparsion of EMARS with the Mars Analysis Correction Data Assimilation (MACDA) reanalysis (Montabone et al., 2011) during the TES period, with the goal of comparing both zonal mean temperature structures and travelling wave activity.

Conclusions:

In this study we have:

- Created an advanced data assimilation and numerical weather prediction system by coupling the Geophysical Fluid Dynamics Laboratory (GFDL) Mars Global Circulation Model (MGCM) with the Local Ensemble Transform Kalman Filter (LETKF).
- Successfully assimilated both nadir (TES) and limb (MCS) Mars temperature profiles, comparing to radio science profiles and other analyses.
- Generated a multiannual reanalysis of atmospheric temperatures, winds, and surface pressures, quantified their uncertainty using ensemble techniques, and examined predictability, traveling waves, thermal tides, and the impact of water ice clouds.

- Compared free runs and assimilations with observations to identify model biases that should be addressed. Aerosol distribution is a leading cause of bias (and RMSE) in analyses, and especially in forecasts, given the fast radiative time scale on Mars.

Our ongoing plans include directly assimilating dust and water ice aerosol in the reanalysis. Recent investigations have demonstrated the important role of detached dust layers (Heavens et al., 2011; Guzewich et al., 2013) and water ice clouds (Wilson et al., 2008; Madeleine et al., 2012) in the thermal structure on Mars. An improved depiction of aerosol horizontal, vertical, and temporal distributions, and therefore heating rates, will improve the atmospheric state in the reanalysis, and subsequent forecasts. We can also use data assimilation to estimate important model parameters, which may eventually lead to improvements in understanding and prediction of dust storms.

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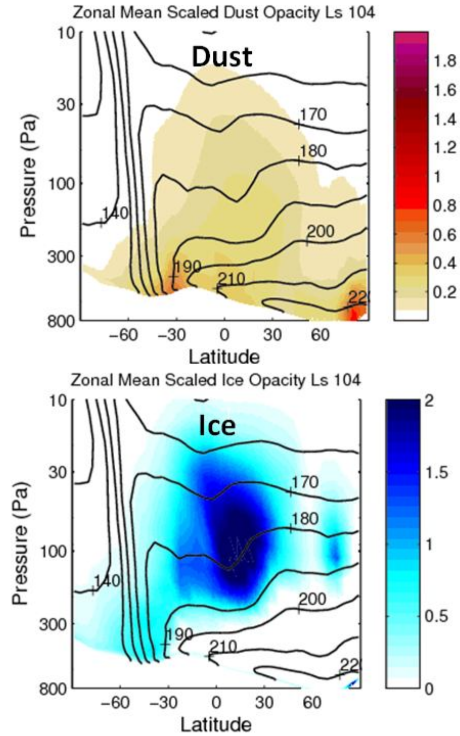

Figure 4: Latitude-vertical cross section of dust and ice aerosol (pressure normalized opacity) in the MGCM forecast using 3 radiatively active dust tracers and water ice clouds.

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