TRAVELING WEATHER SYSTEMS IN THE ENSEMBLE MARS ATMOSPHERE REANALYSIS SYSTEM (EMARS)

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Introduction:

The Ensemble Mars Atmosphere Reanalysis System (EMARS) combines insights from spacecraft observations and model simulations using data assimilation, producing a comprehensive, multi-annual record of Martian weather and its uncertainties. Temperature and aerosol retrievals from the Thermal Emission Spectrometer (TES) and Mars Climate Sounder (MCS) instruments are assimilated into the GFDL Mars Global Climate Model (MGCM) using the Local Ensemble Transform Kalman Filter (LETKF) system. The resulting product is a comprehensive gridded dataset of atmospheric properties—temperature, wind, surface pressure, and (dust and water ice cloud) aerosols—and their uncertainties spanning several Mars years. Data assimilation products are a valuable means of synthesizing observations and models to provide insights on Martian weather and climate (Lewis et al., 2007; Hoffman et al., 2010; Montabone et al., 2011; Lee et al., 2011; Greybush et al., 2012; Steele et al., 2014; Navarro et al., 2014).

Data and Methodology:

Spacecraft Observations. EMARS assimilates observations from the Mars Global Surveyor (MGS) and Mars Reconnaissance Orbiter (MRO) spacecraft, available from the Planetary Data System (PDS) website. Thermal Emission Spectrometer (TES) nadir temperature retrievals (Smith et al., 2001) follow a polar orbit with twice daily coverage. The standard retrieval process effectively smoothes the true atmospheric profile in the vertical, then mixes it with a climatological prior. We have the ability to create new TES retrievals (Hoffman et al., 2012) using the Optimal Spectral Sampling (OSS; Eluszkiewicz et al., 2008), which has the advantage of allowing for an interactive prior, and providing profile error statistics. Therefore, we have developed a methodology (outlined in R. Hoffman, 2010 and inspired by Rodgers 2003) that removes the influence of the prior, using the information contained in the averaging kernel of the retrievals. This methodology can be applied to retrievals that used a climatological prior, or a prior obtained from the short term forecasts from data assimilation (termed interactive retrievals). In the EOF retrieval formalism, standard retrievals are converted to observations that have zero mean, uncorrelated, and unit variance expected errors. The new observation operator is simply a weighted average of temperatures at retrieval pressure levels, which allows for a fair comparison of model and observation information. For interactive retrievals, the new priors from the data assimilation ensemble forecasts consider the additional information from the model regarding temperature and aerosol vertical distributions (and their covariances) and are not overly smoothed, allowing a more realistic retrieval despite the limited vertical degrees of freedom in TES.

Mars Climate Sounder (MCS) limb retrievals (Kleinboehl et al., 2009) provide increased vertical extent and resolution for temperature in both along-track and cross-track geometries, as well as vertical profiles of dust and water ice aerosol. The latest 2D retrievals (Kleinboehl et al., 2016) improve the retrievals in regions of strong temperature gradients, such as the polar vortex where traveling waves are found.

Model Configuration and Aerosol Scenarios. We use the GFDL Mars Global Climate Model (MGCM) for our simulations, currently with a lat/lon grid spacing of 5x6 degrees and 28 vertical levels. Aerosol horizontal distributions are constrained by spacecraft column opacities gridded by the Mars Climate Database dust scenarios (Montabone et al., 2015). The vertical distribution of dust evolves in the MGCM using radiatively active dust tracers with three sizes (and therefore differing sedimentation rates). Dust is added or subtracted to the lower atmosphere to match observed opacities, as an analogy to lifting and deposition (Kahre et al., 2009). Dust vertical structure can also be updated using the correlations between the thermal and aerosol fields (e.g. Navarro et al., 2014). Experiments employ radiatively active water ice clouds and a sub-grid-scale topographic gravity wave drag parameterization.

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, and provide a partial empirical correction for systematic model biases.

There is a synergy between reanalysis development and science investigations: varying dust and

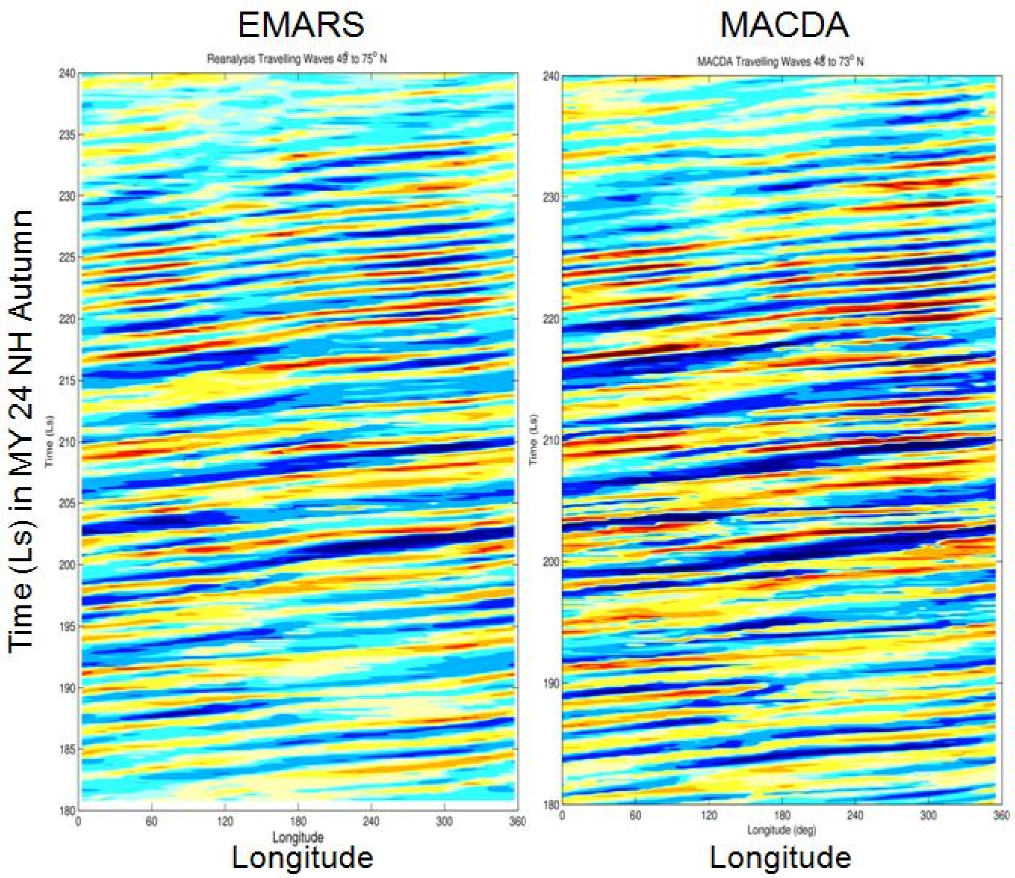

Figure 1: NH hovmoller diagram of reanalysis temperature eddies from EMARS (left) and MACDA (right) at ~3.5 km altitude for MY 24 Ls 180 - 240°. The phase and dominant wave regime are in general agreement.

water ice cloud amounts among ensemble members improves ensemble spread and analysis errors (Greybush et al., 2012); more frequent analyses improve the estimates of thermal tides (Zhao et al., 2015); and the vertical averaging of observations impacts the strength of traveling waves (Greybush et al., 2015).

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. The length of time for which forecasts initialized from analyses improve upon a free running model provide indications to the predictability of Martian weather (Zhao et al., 2015); traveling waves are baroclinically unstable, where as other regions of the Martian atmosphere are more stable and driven by aerosol vertical distributions (Greybush et al., 2013). We have also performed a preliminary comparison with radio science profiles (Hinson et al., 2004), an independent dataset with high vertical resolution. Waugh et al. (2016) compares the zonal mean tempature, wind, and potential vorticity structures in EMARS and the Mars Analysis Correction Data Assimilation (MACDA) version 1.0 reanalysis; these products are much more similar to each other (and hence observations) than freely running models in portions of the atmosphere where TES observations are available. We recognize the importance of feature-based validation of reanalyses; for example, examining the depiction of dust spatial and vertical structure, water ice cloud locations, seasonal surface pressure cycle and cap edge locations, stationary and traveling waves, and thermal tides.

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, and general agreement between the phase and wavenumber regime between MACDA and EMARS (e.g. Figure 1).

However, specific details of circulation features

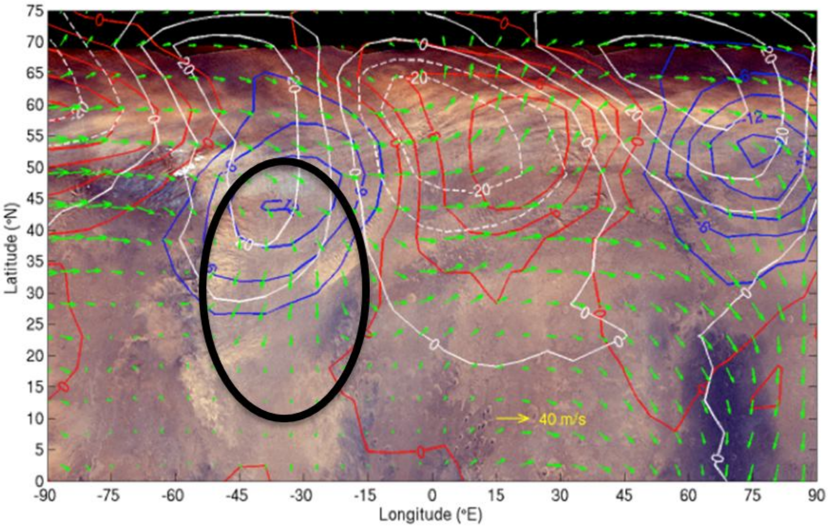

Figure 2: NH Synoptic map of sample EMARS reanalysis fields for cross-equatorial storm of MY 24 (~Ls 223.8°). Plotted are (~3.5 km altitude) eddy temperature (K; contoured, positive in red, negative in blue), eddy wind vectors (m/s), and eddy surface pressure (white contours, negative dashed). Fields are overlayed upon MOC visible imagery. Note circled dust front and southward advection of dust coincident with northerly winds.

are sensitive to several model, observation, and DA characteristics. These include the model zonal mean and stationary wave temperature structure, vertical specification of aerosol, and the CO2 cycle and cap edge locations. Applying vertical averaging to TES observations and the model state during assimilation produces larger amplitude traveling waves; this is because the TES retrievals are overly smoothed due of their limited degrees of freedom in the vertical, and do not fully resolve the vertical structure of shallow eddies. We are also comparing traveling waves between TES and MCS reanalyses to explore interannual variability and the impact of observing system upon depiction of wave structure.

Dust Storms. Plotting reanalysis fields with Mars Orbital Camera (MOC; Cantor et al., 2001) imagery can provide insights to the structure and development of dust storms (Mooring et al., 2015). For example, Figure 2 examines the development of a MY 24 NH autumn cross-equatorial storm. It is hypothesized that the interaction between a zonal wave 3 and thermal tide can help initiate these storms (e.g. Wang et al., 2013).

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 Climate Model (MGCM) with the Local Ensemble Transform Kalman Filter (LETKF).
- Successfully assimilated both nadir (TES) and limb (MCS) retrievals to create a multiannual reanalysis of atmospheric temperatures, winds, surface pressures, dust, and water ice clouds.
- Examined traveling weather systems in reanalyses; noting that reanalyses were much more similar to each other than freely running GCMS. We also explored the circulation patterns associated with dust storms, and compared to visual imagery.

Ongoing work is exploring the optimal methodology for updating dust and water ice aerosol vertical structure in the reanalysis. An improved depiction of aerosol horizontal, vertical, and temporal distributions, and therefore heating rates, will improve the atmospheric state (including the structure of traveling waves) 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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