MARTIAN ATMOSPHERE DATA ASSIMILATION OF TES AND MCS RETRIEVALS

S. J. Greybush, E. Kalnay, T. Miyoshi, K. Ide, *University of Maryland, College Park, MD, USA*., **M. J. Hoffman**, *Johns Hopkins University, Baltimore, MD, USA,* **J. Eluszkiewicz, R. Hoffman** *Atmospheric and Environmental Research, Lexington, MA, USA*., **R. J. Wilson**, *Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA*.

Introduction:

Temperature profiles retrieved from the Thermal Emission Spectrometer (TES) instrument on the Mars Global Surveyor spacecraft, as well as from the Mars Climate Sounder (MCS) aboard the Mars Reconnaissance Orbiter, are assimilated into a Mars Global Circulation Model (MGCM) using the Local Ensemble Transform Kalman Filter (LETKF). Data assimilation provides the optimal framework (Fig.1) for combining observations with models to accurately depict the state of the Martian atmosphere, and eventually creating a weather and climate reanalysis spanning several Martian years. The goals of this project include understanding the characteristics and locations of any temperature biases between spacecraft data and the model, improving physical parameterizations in Mars models to facilitate the match between observations and model output, and addressing scientific questions involving atmospheric predictability, the origins of dynamical instability, aerosol distribution, traveling wave activity, and genesis and decay of dust storms.

Mars Model:

This study employs the GFDL Mars Global Circulation Model (MGCM) developed by John Wilson (Wilson et al., 2002; Hoffman et al., 2010), which is based on a finite volume dynamical core. We selected 6°x5° (60x36) longitude-latitude resolution and 28 vertical levels with hybrid p / σ vertical coordinate, with roughly half the levels located in the lowest ~15 km, and with the highest level extending vertically in excess of 85 km above the surface (Fig. 2). The model includes radiatively active dust, with options for interactive dust parameterization with lifting and sedimentation; water ice clouds are optionally radiatively interactive. Greybush et al. (2010) used the breeding method to examine issues of predictability and error growth using the MGCM.

Assimilation System:

The Local Ensemble Transform Kalman Filter (LETKF; Hunt et al., 2007) is an efficient implementation of the Ensemble Kalman Filter (EnKF) suitable for operational Numerical Weather Prediction, and is competitive with state-of-the-art assimilation systems. With the LETKF, the analysis at a given grid point is determined from the background at that point plus a weighted sum of observation increments within a localization radius, and the analysis increment at a given grid point is a local linear combination of ensemble perturbations. Background, or forecast, errors are described by an ensemble of MGCM states, and evolve with the flow. This is an important advantage of ensemble data assimilation methods, and represents a significant advantage over the

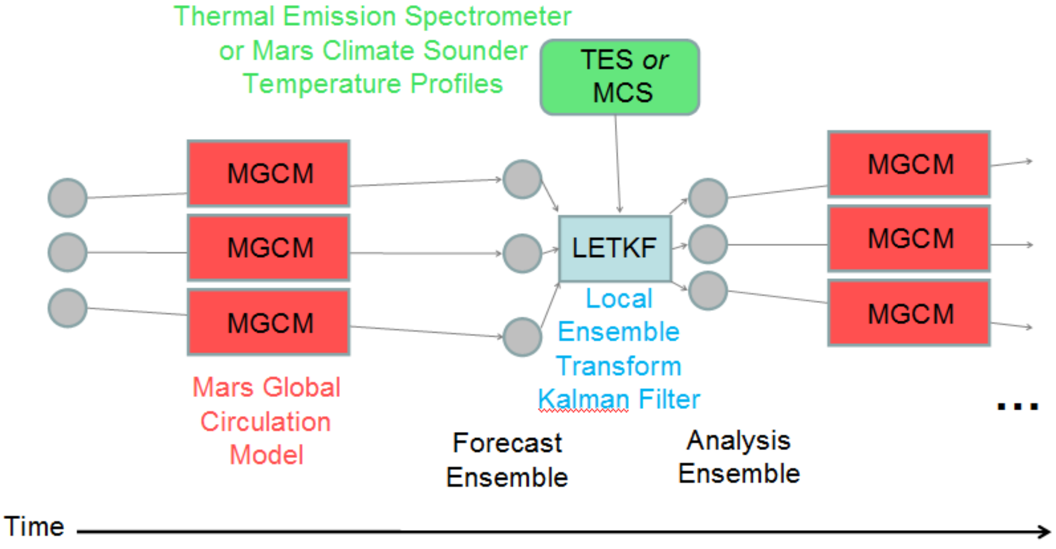

Figure 1: Diagram of the forecast-analysis cycle for ensemble data assimilation.

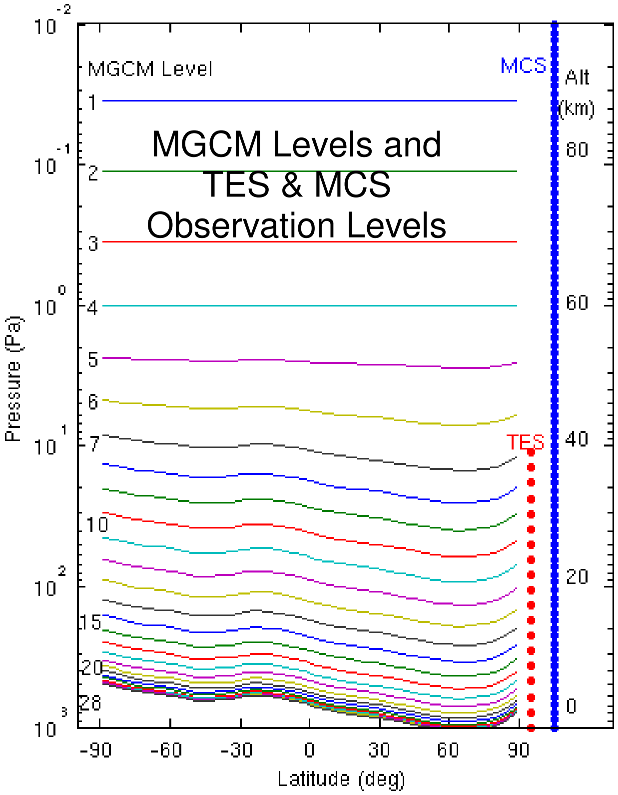

Figure 2: MGCM, TES, and MCS vertical levels.

Analysis Correction Scheme used in the TES Reanalysis of Lewis et al. (2007). Ensemble spread, representing forecast errors, is tuned using adaptive inflation techniques, as well as through the variation of dust in the ensemble. 4D-LETKF considers observations at correct hourly timeslot rather than assume that they were taken at 6-hourly intervals, which is important for the strong diurnal changes on Mars.

Observations:

Table 1: MCS and TES observations.

Thermal Emission Spectrometer (TES)	**Mars Climate Sounder (MCS)**
Observations from 1997-2006.	Observations from 2006-present.
Nadir sounder.	Limb sounder.
Temperature retrievals at 19 vertical levels up to 40 km; column dust opacity.	Temperature, dust, and water ice retrievals at 105 vertical levels up to 80 km.
Observation error estimated at 3 K; characteristics not well known.	Random error < 1K at elevations below 50 km; estimated systematic error of 1-3 K.

Table 1 summarizes the TES and MCS observations employed in this study. Observation errors have both random and systematic components, and include instrument error and errors of representativeness. Gaussian localization of observation errors in the LETKF ensures that an observation's influence wanes as one moves far away from the analysis grid point. Superobservations (one observation per grid point) combine nearby observations into a single value, and reduce the random component of observation error. For now, we consider each observation as independent, but we have a strategy to address vertical correlations and remove the influence of the prior (R. Hoffman et al., 2010). MCS retrievals (Kleinboehl et al., 2009) are version 3, which includes an important near-surface temperature correction. TES retrievals are initially obtained from the Planetary Data System (PDS; Smith et al., 2001), but a comparison (M. Hoffman et al., 2011) is underway with retrievals produced by the Optimal Spectral Sampling method (Eluszkiewicz et al., 2008).

Results:

M. Hoffman et al. (2010) used observing system simulation experiments with synthetic observations and a known truth to demonstrate that temperature observations create accurate analyses of both temperature and wind. Here, MCS and TES temperature profiles are assimilated to update temperature, wind, and surface pressure fields. Experiments occur over 30-sol time periods near the NH autumnal equinox. Performance is evaluated using short term forecasts compared to independent observations (Fig. 3), and the MCS analyses are compared to those generated by the assimilation of TES profiles during a similar Martian season. There are 16 ensemble members, taken initially from 16 previous model states (at 6-hour intervals). Gaussian localization parameters are set to 400 km in horizontal, 0.4 log P in vertical, and 3 hours in time.

A free run, in which the MGCM starting from the initial background ensemble mean runs without data assimilation, provides a baseline to assess performance. The initial assimilation uses a fixed background dust opacity of 0.3, and fixed 10% multiplicative inflation of ensemble spread. In the low level tropics, a region with little dynamical instability, ensemble spread was initially insufficient, leading to small analysis increments and large discrepancies between observations and forecasts. Ensemble members with varying dust opacities, along with adaptive inflation, improved the ensemble spread and performance, although for initial experiments dust opacities are temporally constant and not yet updated by observations.

Errors for TES and MCS experiments are generally < 5 K below 40 km, or where TES observations exist, and are dominated by bias. The largest random errors are along polar temperature fronts. Empirical

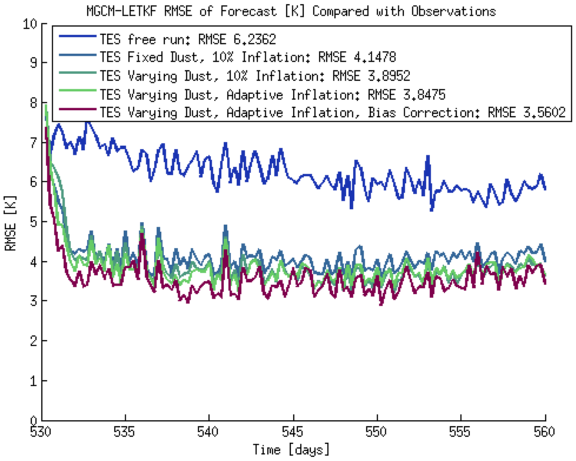

Figure 3: Performance of TES data assimilation experiments by comparing short term forecasts to observations.

bias correction (Danforth et al., 2007) of the MGCM based on analysis increments helps account for model error. Corrections (based on long-term differences between analyses and forecasts) are applied every analysis step, as if they were part of the model itself. As a result, bias and forecast error improve, especially in regions above 40 km (Fig. 4).

Conclusions and Continuing Work: The LETKF successfully assimilates spacecraft observations into the MGCM, with RMSE substantially below that of the freely running model (Fig. 3). Key to success is creating adequate ensemble spread through varying dust distributions and adaptive inflation, and addressing biases between observations and the model.

Initial biases between the MCS and MGCM have led to further model development. In particular, the addition of topographic gravity wave drag parameterization and radiatively active water ice clouds have done much to alleviate a cold bias in many GCM simulations at heights above 30 Pa at tropical and winter polar latitudes. Improvements in the RMSE and bias of assimilation efforts can be expected with improved parameterizations in the latest version of the MGCM, as well as by improving the dust and water ice distributions using observation information. Future efforts will focus on the representation of dust in the analyses, including direct assimilation of dust opacities from TES and MCS. One approach includes using retrieved surface

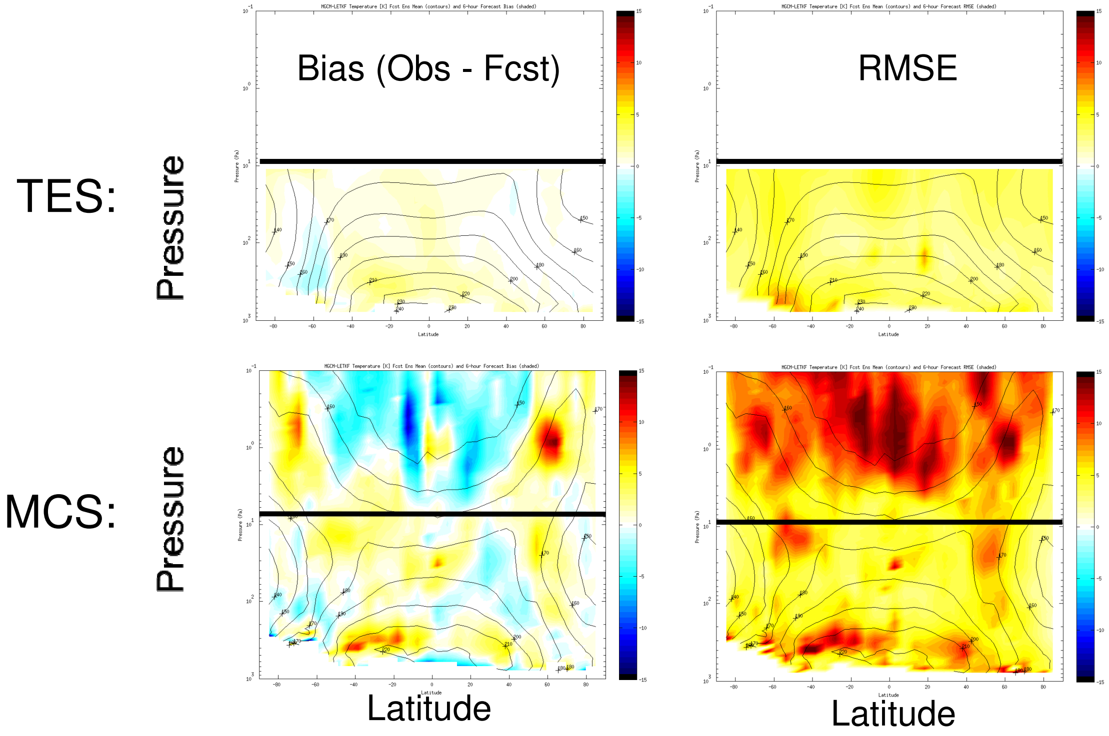

Figure 4: Comparison of 0.25-sol forecasts to observations for TES and MCS temperature profiles as a zonal average over sols 10-20 of assimilation. Contours are ensemble mean temperatures at observation locations [K]; shading is temperature bias or RMSE [K]. 4D-LETKF, adaptive inflation, varying ensemble dust opacities, and empirical bias correction are employed. Large biases in the upper levels for MCS experiments encouraged the development of topographic wave drag and radiatively active water ice cloud parameterizations in the MGCM, which are expected to significantly reduce these biases in future experiments.

brightness temperature to update dust opacity (Wilson, 2011), which is straightforward to accomplish with the LETKF where inter-variable covariances are readily obtained from the ensemble.

Analyses will be compared to the Oxford Reanalysis (Lewis et al., 2007), as well as Radio Occultation temperature profiles, and the analyses will be evaluated as to how well they portray travelling waves (Greybush et. al, 2011).

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