DATA ASSIMILATION DEVELOPMENTS FOR MARTIAN METEOROLOGY.

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Introduction

The primary goal of data assimilation in planetary meteorology is to maximize the return from remote sensing observations. This is done by applying physically derived constraints — from reasonable general circulation models — to the retrieval of the data. These data are accumulated over a period of time — the assimilation window — and are retrieved by a four-dimensional variational (4DVAR) technique which determines the model variables that give a best fit to the data. The resulting meteorological variables — some of which, like the wind fields, are only indirectly observed — are therefore consistent not only with the observations, but with the laws of physics as they are understood to apply to the atmosphere in question.

A number of improvements have been made in the assimilation technique and in the underlying general circulation model to enhancee their performance in the martian context. These improvements have been tested primarily through the assimilation of Mars Global Surveyor Thermal Emission Spectrometer (TES) temperature retrievals [Smith et al., 2001]. Temperature retrievals are used — although the direct retrieval of the infrared spectra is a preferred meteorological approach — because temperature residuals are more easily understood when evaluating model performance.

Observation Space Assimilation

An assimilation is necessarily a weighted average between model predictions and observations. Most of the effort typically goes into determining these weights. Observational errors are usually directly measurable from the data, but model forecast errors are another matter. This is especially true for other planets where the predictive models — general circulation models — are not validated. Thus, the second order error statistics — the model forecast covariances — are very hard to estimate. However, when the estimates are required in the observation space (i.e., when the primary assimilation variable is the observed quantity), it is possible to derive these statistics using the observations. The result is a transform of the Kalman filter (the optimal gain matrix for weighting between forecast and observations) with little computational cost.

This formulation leads to great freedom in a number of aspects of the assimilation. The window can range from an instantaneous assimilation of each datum as it is measured (i.e., sequential assimilation) to long periods of several days (which are starting to gain favor at numerical weather prediction centers because they minimize the sensitivity to assumptions about model errors [Fisher, 2005]. Also, it is no longer necessary to truncate the model so that the state is fully determined by observations within a radiative time scale. Of course, this freedom leads to the requirement for more testing of different model configurations. The results shown below are from a test of the relative merits of longer and shorter assimilation windows (1 sol vs. 2 MGS orbits) over some 800 sols.

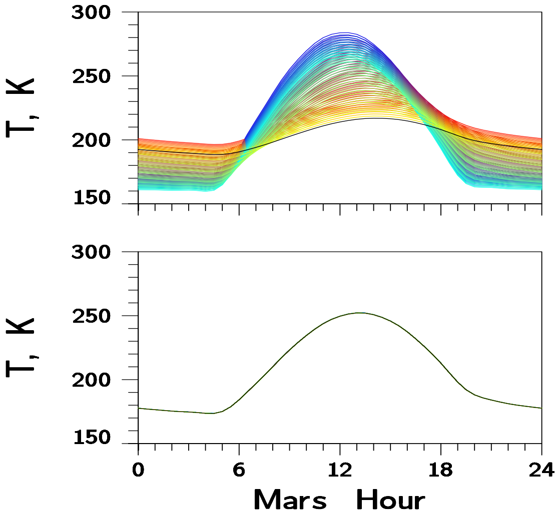

Figure 1: When temperatures are specified at 2 am and 2 pm, the ground temperature assimilation model successfully converges, albeit slowly, from any starting values of albedo and thermal inertia (top) to the curve from which the temperatures were derived (bottom). Convergence takes as many as 40 iterations of the conjugate gradient method. But this is fewer than the number required for assimilation of the atmospheric state.

Ground Temperature Model

The direct assimilation of infrared radiances is now standard at numerical weather prediction centers. This represents something of a challenge for Mars since the surface is a strong contributor to most of the channels in the 15 micrometer band that are used to determine atmospheric structure [Conrath et al., 2000]. Thus, a good model that reproduces the diurnal cycle of surface temperature is required. An analytical model that includes the absorption of solar energy, infrared emission, and thermal conduction has been developed and included in the assimilation cycle. It depends on two surface parameters — albedo and thermal inertia — and reproduces the curves of Mellon et al. [2000]. Figure 1 shows that

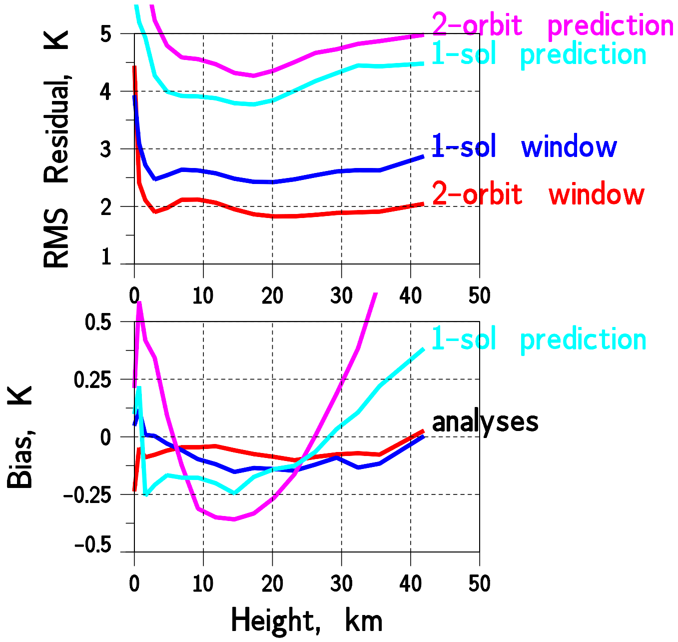

Figure 2: Results for 2 800-sol assimilations with different windows. Analyses are somewhat better for the shorter windows, but forecasts are worse. Root-mean-square residuals are of the same order as the TES Team's estimated retrieval uncertainty [Conrath et al., 2000].

the model converges to the proper values of albedo and thermal inertia when 2 am and 2 pm temperatures are specified.

Gravity Wave Control

Another challenge in assimilation modeling is the control of gravity waves — a major concern, since these waves are excited by adjustments to model fields during the course of an assimilation. Digital filtering is now used for this purpose. The traditional formulation of the baroclinic spectral model [Haltiner and Williams, 1980] uses averaged values of the divergence (the meteorological variable most closely related to gravity waves) in its semi-implicit integration of the temperature and surface pressure equations. However, the divergence itself is integrated without this averaging. (This shortcoming is obscured by a typo in the text.) Reformulating this equation leads to improved stability of the mean meridional streamfunction.

Results

Figure 2 shows that the bias (the average temperature residual,represented here as a function of height) is small for assimilated fields. The upper atmosphere bias of the 1-sol forecasts is larger (although still acceptably small). This may be due to remaining erroneous gravity wave activity in the model.

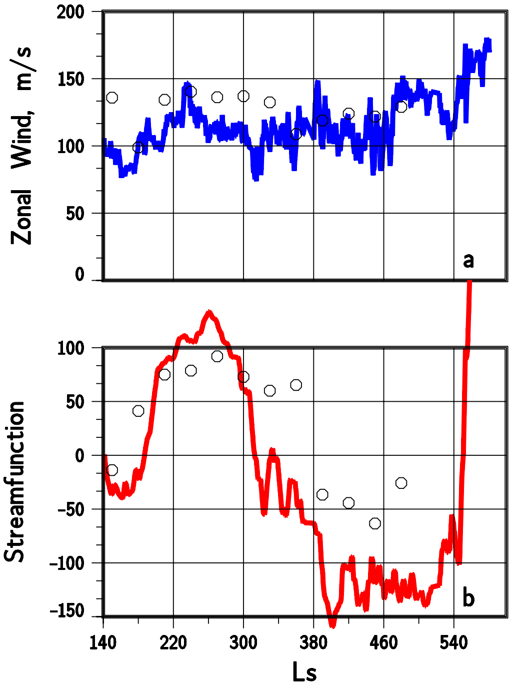

Figure 3: Peak zonal wind (a) and meridional streamfunction (b, in units of 10^8 kg s^{-1}) as a function of L_s during the first MGS year compared with selected values from the NASA Ames Mars Climate Catalog [R. M. Haberle, et al.].

Figure 2 also shows the root-mean-square temperature residuals as functions of height for the 2-orbit (red) and 1-sol (blue) assimilations. For some time intervals, the TES Team has flagged certain temperature retrievals as of poor quality. These retrievals are used along with the high quality retrievals in the data assimilations. However, they have not been used in the computation of the root-mean-square residuals shown in the red and magenta curves. When the poor quality data are included, root-mean-square errors are on the order of 4 K, about equal to the 1-sol prediction erors. This is consistent with the flagged data being good, but noisy (whether due to instrumental or retrieval effects). The smaller residuals obtained with the high quality data are consistent with the TES Team estimates of the intrinsic errors in their procedures [Conrath et al., 2000]. The cyan curves show the residual behavior of the 1-sol predictions. A challenge in choosing a window length for operational purposes is the fact that shorter window usually lead to better analyses, but poorer forecasts. So the choice of window depends in part on the purpose of the asimilation.

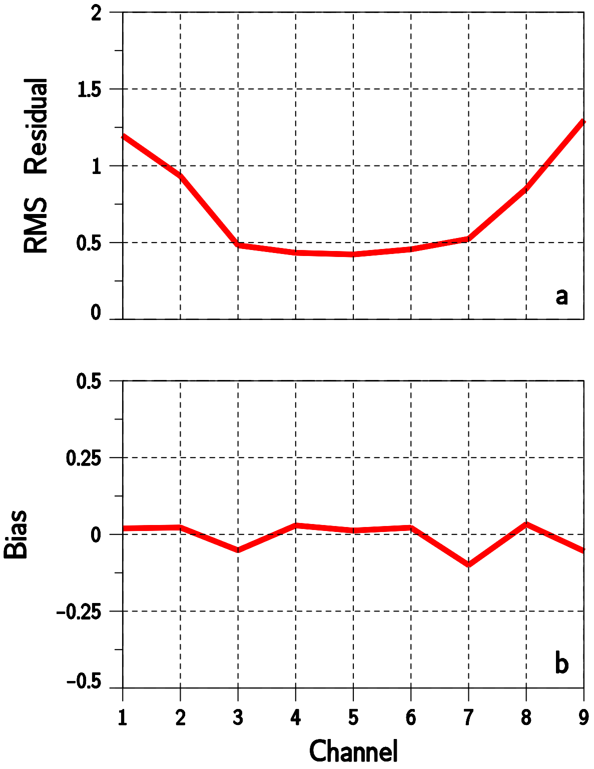

Figure 4: Statistical results for the direct assimilation of TES radiances. The channels correspond to TES channels 46–54 which bracket the 15 micrometer CO_2 band. Units are erg cm^{-2} s^{-1} $steradian^{-1} wavenumber^{-1}$

Figure 3 compares peak assimilated wind fields with the values computed in an ab initio general circulation model. It has been difficult to obtain direct measurements of Martian winds. So the assimilated winds are the closest thing to observed winds yet available for most purposes. There is a strong increase in atmospheric forcing and, hence, winds during the large (TES Year 2) dust storm at the end of the assimilation period.

The direct assimilation of infrared radiances is a goal of this project. A suitable two-stream, correlated-k radiative transfer code has been developed (with linearized and adjoint forms) and tested. Biases (average errors) are minimized by making slight adjustments in the assumed central wavelengths of the TES channels. A detailed comparison of the directly retrieved temperature profiles with the TES Team profiles will be presented in the near future.

Conclusion

Based on the results shown here, it appears that all the required model components are in place for the operational assimilation of martian meteorology from satellite data. The model will be used primarily in the direct assimilation of infrared radiances, as these require no a priori assumptions about atmospheric surface pressure or the smoothness of vertical temperature profiles. In addition, this direct assimilation is necessary to include TES limb observations in the calculations (in preparation for the primarily limb-viewing Mars Reconnaissance Orbiter Mars Climate Sounder) and is a preferred method for combining the results from disparate instruments (say, between Mars Global Surveyor and Mars Express).

The Mars Climate Sounder which is now approaching the planet is slated to be the first dedicated martian atmospheric sounder in an orbit suitable for operational meteorology. It is expected that all the required assimilation tools for the rapid generation of high-level data products will be in place by the time the instrument turns on. These high-level products — four-dimensional fields of temperature, pressure, and winds — are fundamental to the calibration and validation of the instrument against other observing systems (in the absence of ground truth) and to the use of atmospheric sounding observations in further scientific studies.

Acknowledgements

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References

Conrath, B. J., et al., 2000. Mars Global Surveyor Thermal Emission Spectrometer (TES) observations: Atmospheric temperatures during aerobraking and science phasing, *J. Geophys. Res.,* **105,** 9509–9519.

Fisher, M., 2005. Kalman filtering: the variational way, 4th WMO International Symposium on Assimilation of Observations in Meteorology and Oceanography, Prague, Czech Republic.

Haltiner, G. J., and R. T. Williams, 1980. *Numerical Prediction and Dynamic Meteorology,* Second Edition, John Wiley & Sons, New York, 477 pp.

Mellon, M. T., B. M. Jakosky, H. H. Kieffer, and P. R. Christensen, 2000. High-resolution thermal inertia mapping from the Mars Global Surveyor Thermal Emission Spectrometer, *Icarus,* **148,** 437–455.

Smith, M. D., J. C. Pearl, B. J. Conrath, and P. R. Christensen, 2001. Thermal Emission Spectrometer results: Mars atmospheric thermal structure and aerosol distribution, *J. Geophys. Res.* **106,** 23929–23945.