AN OPERATIONAL DATA ASSIMILATION SCHEME FOR THE MARTIAN ATMOSPHERE

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ABSTRACT

A meteorological data assimilation scheme has been developed for Mars, based on techniques used for the current operational scheme at the UK Meteorological Office (UKMO). The scheme has been designed to interface with a range of models of varying complexity, from a simple primitive equations model to a full martian general circulation model with detailed parameterizations of the most important physical processes. The scheme was originally intended to be used primarily for analysis of temperature profiles from the Pressure Modulator Infrared Radiometer (PMIRR) onboard the Mars Observer (MO) spacecraft. It is, however, capable of analysing any asynoptic, randomly-distributed dataset, which may include surface pressure, temperature, velocity or constituent data originating either from other past or future spacecraft missions or from models. It is proposed to use the scheme not only for interpretation of forthcoming data from future spacecraft but also for model inter-comparisons, for hind-casting earlier martian data for model validation and for data impact studies in the planning of new missions. Initial results have demonstrated successful assimilations of trial orbiter and lander data into models with different initial conditions and physics, although a large number of landers might be required if orbiter data were not available. An optimum approach would combine orbiter data with simultaneous measurements from a small number of landers.

MODELS AND DATA ASSIMILATION TECHNIQUE

Studies of a range of dynamical and physical phenomena in the martian atmosphere are hampered by the fact that previous spacecraft missions, and those planned for the near-future, such as polar orbiter replacements for MO which involve only one or two spacecraft, are by their nature only able to provide asynchronous coverage by remote sounding instruments. This can lead to severe ambiguities in interpretation of observations when studying synoptic-scale phenomena with time-scales of a few days. In an attempt to overcome such problems we propose to use data assimilation techniques, as currently employed for operational weather forecasting on the Earth, in conjunction with a martian general circulation model (MGCM).

Data assimilation is conducted using a modified form of the analysis correction (AC) scheme, which is in current operational use at the UKMO /1/, interfaced to several versions of the MGCM of varying complexity. The AC scheme is an approximation to the optimum analysis which involves a form of successive-correction iterated between each time step of the model. Continuous (asynoptic) repeated insertion is conducted sequentially, assimilating each measurement at the time and place it is valid without prior interpolation. Observational increments to the model are spread in time and space by empirically-determined functions with scales which depend on the difference between the current model time and the time at which the data is valid. As an observation's valid time approaches, its weight increases and the scale it affects becomes smaller. An observation is discarded about one hour after the model has passed its valid time. The weight of each observation is scaled by the relative magnitudes of observational and forecast model error. Within each cycle of the assimilation scheme each model variable is analysed sequentially (surface pressure, temperature, velocity and constituents, e.g. dust and/or water vapour) followed by the derivation of multi-variate increment fields for dynamical balance (using geostrophy and the thermal wind equation) in order to avoid losing much of the newly-introduced information. The analysis correction scheme has been found to produce improved analyses in data-sparse areas compared to the previous optimum interpolation scheme in use at the UKMO, primarily because observational increments are spread over larger areas /1/. It is also particularly suitable for the martian problem because the iterative technique places no requirement to cast all the observations to synoptic hours when they have in fact been made continuously.

The MGCM is based on a semi-spectral primitive equations model /2/, which, typically for assimilation runs, covers the surface to 80km altitude, using about 25 sigma levels in the vertical, and with a triangular spectral truncation at wavenumber 42 in the horizontal (T42), roughly equivalent to a grid spacing of 2.8 degrees in latitude and longitude. The full MGCM makes use of complicated physical parameterization schemes which are described in some more detail in a companion paper /3/. For the trial experiments described here a much simpler version of the model was used (the SGCM) in which surface drag was represented by Rayleigh friction and Newtonian relaxation (to a prescribed equilibrium temperature state) was used to represent radiative heating and cooling. The SGCM has been used for previous martian studies /4/. Here, for simplicity, the SGCM has been run at reduced resolution; T21 in the horizontal, 10 levels in the vertical up to 30km altitude and without topography to give a clearer spectrum for regular waves. It is still able to produce realistic-looking zonal mean states and regimes of both regular and irregular baroclinic waves in the winter hemisphere /5/.

SIMPLE TRIALS

The SGCM was run using a thermal equilibrium temperature state chosen to give flows representative of northern hemisphere winter solstice on Mars. The radiative time-scale was taken to be 2 sols (a sol is a martian solar day) and a time-scale of 3 sols was taken for Rayleigh drag in the lowest model level. These model parameters are appropriate for the martian atmosphere /4/ and under these conditions both a strong wavenumber 3 flow and an irregular state with weaker waves are both possible depending upon the initial conditions /5/. Temperature maps from both states are illustrated in Figure 1. The control run from which data was generated was a wavenumber 3 flow. This wave has a period of 3.9 ± 0.4 sols (the phase speed fluctuates between 25 and 35 degrees per sol) and a surface pressure peak-to-peak amplitude of about 40 Pa at the Viking Lander 2 (VL2) site (48^oN). While the period does not agree precisely with waves observed by VL2 /6/ or those seen in more complete models, e.g. /3/, it is in the correct range for baroclinic waves on Mars (2 to 5 sols) and the amplitude is similar. It thus provides a reasonable test for the assimilation scheme.

The errors in the amplitude and phase of the Y_3^3 (the zonal wavenumber 3, gravest meridional mode) spherical harmonic of temperature on the 520 Pa surface are used as diagnostics of these trials. Table 1 summarizes the results of the experiments described below by giving means and standard deviations of the wavenumber 3 component errors (the total amplitude of the mode in the control case is about 4K and fluctuates by up to 0.5K over a sol). Runs in the upper box used temperature profile data as from an orbiting remote sounding instrument, those in the lower box used surface pressure and temperature (at n sites for a run denoted Ln). Statistics were calculated from sol 10 to sol 20 after an assimilation began (at sol number 120).

Temperature Profile Data

Temperature profiles were taken 90 times per orbit for a polar orbiting satellite making 12.67 orbits per sol in the MO pattern. The number in the run codes used for these experiments refers to the time-scale for the Newtonian heating.

Varying initial conditions. A strong wave 3 state, 180 degrees out of phase with the control run (w2) and a weak wave state generated from different initial conditions (i2) were used as initial conditions for assimilations conducted with the same model parameters as the control run. In both cases a strong wave 3, in phase with the control run, was generated within a few sols of the beginning of assimilation.

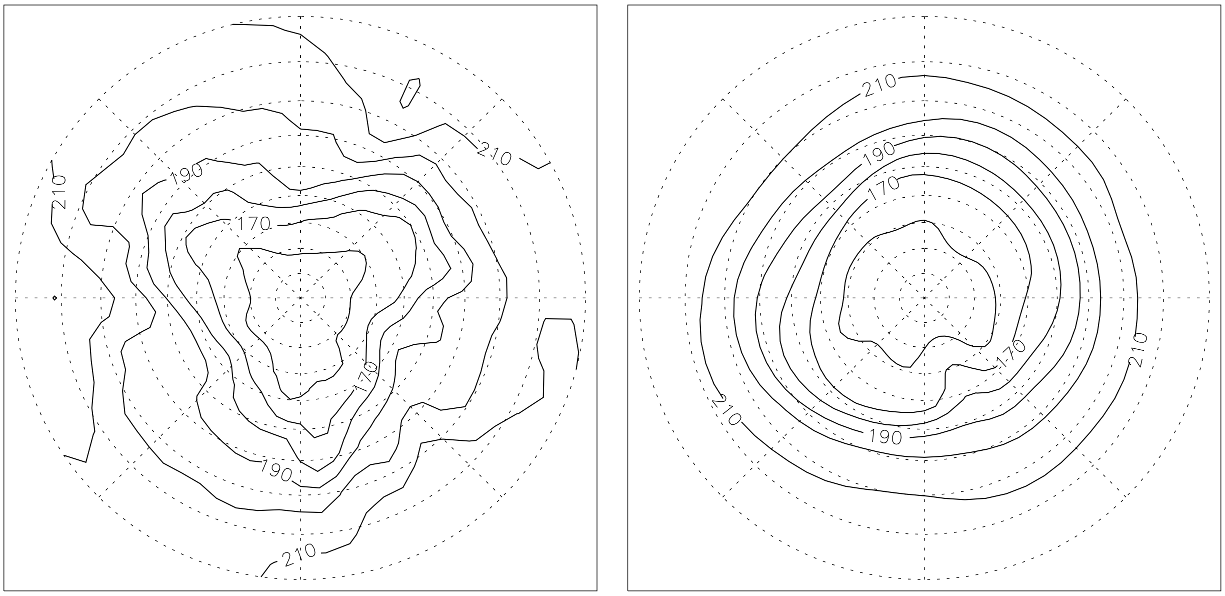

Fig. 1. Polar stereographic plots of northern hemisphere temperature on the 520 Pa surface for a strong wave 3 (left) and a weak wave (right). Contour interval is 10K.

TABLE 1 Errors in the Principal Wave 3 Component of Temperature on the 520 Pa Surface.

Run code	Amplitude error (K)	Phase error (degrees)
w2	0.0 ± 0.3	-1 ± 3
i1	-0.3 ± 0.2	4 ± 4
i2	-0.1 ± 0.2	0 ± 4
i4	-0.1 ± 0.4	-2 ± 3
i0	-0.1 ± 0.3	-7 ± 4
L2	-3.1 ± 0.4	52 ± 60
L8	-1.1 ± 0.6	38 ± 64
L16	-2.1 ± 0.4	21 ± 21
L32	-0.5 ± 0.7	9 ± 8

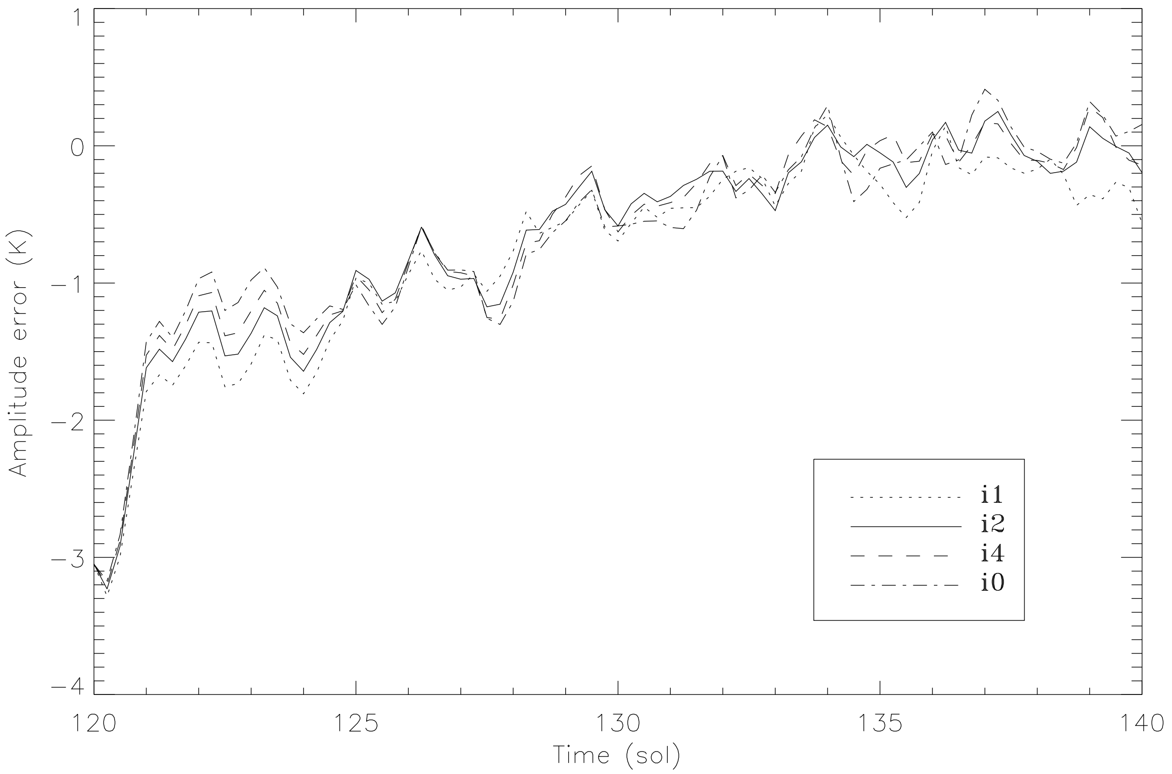

Fig. 2. Error in the amplitude of the principal wave 3 component for assimilations beginning at sol 120 with different Newtonian relaxation timescales. Run i2 has the same timescale as the control (2 sols), i1 has stronger heating (1 sol), i4 has weaker heating (4 sols) and i0 has no Newtonian heating term.

Varying model parameters. The time-scale of the Newtonian heating was varied in the model used in the assimilation run from 1 sol (i1) to 4 sols (i4), and heating was turned off completely for run i0. An irregular, weak state was used as the initial condition each time. In each case a strong wave 3 was produced with a strikingly similar time evolution to run i2 (Figure 2), showing insensitivity to the model heating once assimilation of temperature profiles is underway. Runs i1 and i0 are strong tests since it is not possible to produce or sustain a strong wave 3 with either very strong heating or with no heating term at all, in the absence of data assimilation. These results are encouraging in the light of the uncertainties (particularly in dust distribution and parameters) in the radiation scheme in the full model.

Surface Data Alone

Surface pressure and near-surface temperature data were taken 25 times per day at varying numbers of sites distributed evenly over both hemispheres in sin(latitude) and randomly in longitude. For the case of 2 sites the Viking Lander latitudes were used (22.5^oN and 48.0^oN). In principle, wind data could also have been assimilated, but the SGCM does not have a boundary layer scheme to predict near-surface winds. A weak wave state was used for initial conditions (lander data was more successful at correcting the phase of an already established wave 3 in the cases tried). It was found that 32 sites in total (of which only about 6 lie in northern mid-latitudes and record a strong signal from the wave) were needed to establish a strong wave 3 state in agreement with the control run. Assimilations were continued for 50 sols, but fewer landers only produced an irregular state with an enhanced wavenumber 3 component.

CONCLUSIONS AND FUTURE WORK

All the experiments with simulated orbiter data gave good agreement with the control experiment after a few sols of assimilation, while 32 simulated landers, if spread over the whole globe, seem to be needed to extract useful information about the wave in the absence of any orbiter data. It is important to note that the excellent degree of agreement in the trial orbiter data assimilations might not be achieved in practice. For example, there are no systematic errors in the simulated data, nor gaps in the coverage, and topographic and diurnal effects are absent. In addition the model which generates the data is the same as that into which the data is assimilated, though at least it has been shown that the results are insensitive to the magnitude (or even presence) of the radiative heating. However, the experiments do show that the concept of assimilation of polar orbiting spacecraft data into a model is potentially feasible and worthwhile, and that useful information may be extracted about baroclinic waves with periods and amplitudes comparable to those in the martian atmosphere. This suggests that successful analyses should be obtainable from remotely-sensed observations of the type planned for MO (and Mars Surveyor, etc.). In practice, simultaneous *in situ* measurements from a small number of landers might be expected to enhance the quality of such analyses and facilitate their verification.

Future work on the problem will include assimilations into a more realistic martian model, such as the full MGCM, and trials where more of the physical parameterization schemes (and uncertain parameters, such as the dust content of the atmosphere and amount of condensates stored in the polar caps) are changed between the data generating model and that used for the assimilation. This should lead on to inter-comparison with different GCMs. In terms of real observational data, the scheme will be tuned for future use with spacecraft missions such as those planned to replace MO. In the immediate future we hope also to use the scheme to attempt assimilations of temperature profiles obtained by infrared remote sounding from the Mariner 9 spacecraft, which are currently being re-analysed /7/.

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