Data Assimilation for Other Planets

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1 Introduction

The application of data assimilation methodology to terrestrial problems in meteorology, atmospheric physics and physical oceanography has already been described extensively within this book. Data assimilation, the combination of observations and numerical models which provide physical constraints, organize and propagate the observational information which is introduced, also offers significant potential advantages for the analysis of atmospheric data from other planets. The Solar System provides seven examples of thick neutral atmospheres in addition to that of the Earth: Mars, Venus and Saturn's moon Titan, which all have relatively large rocky cores surrounded by thinner atmospheres, like the Earth, and four largely gaseous Giant Planets, Jupiter, Saturn, Uranus and Neptune. In recent years satellites have been placed in orbit about Mars in particular, but also Venus, Jupiter and Saturn, in contrast to the relatively rapid fly-by missions in the initial stages of the exploration of the Solar System. These spacecraft provide the potential for long sequences of atmospheric observations. Together with the necessary advances in numerical modelling of planetary atmospheres, these new missions have provided an opportunity for the application of data assimilation techniques for the analysis of planetary observations. As described in this chapter, data assimilation has now been employed with some success in the context of the atmosphere of Mars and more ambitious studies are planned for the future. Assimilation in these unfamiliar and, compared to Earth, data-poor environments also provides valuable lessons for the development of terrestrial assimilation, especially in situations where it is vital to extract the maximum information from a limited observational record.

2 Motivation for the assimilation of extra-terrestrial data

The motivation behind the application of data assimilation to atmospheric data from other planets is in principle very similar to the motivation for its use on the Earth. Typical spacecraft observations of radiances at various wavelengths, most commonly in the infrared, must be interpreted and used to constrain the thermodynamic and dynamic state of the atmosphere under observation in a systematic way. In the past, this has typically been done by the retrieval of individual temperature profiles, for example, and by mapping and interpolation in space and time of either observed radiances (or brightness temperatures) or sets of individual retrieved profiles to obtain global fields. Simple balance relationships, such as the gradient wind approximation, have been used to derive estimates of further quantities such as zonal winds from longitudinally-averaged temperatures. Such straightforward procedures are justified in the case of relatively sparse observations of a planetary atmosphere which may be much less well understood than that of the Earth. As seen earlier in the book, in recent years the terrestrial meteorological and oceanographic community have benefited greatly from the application of more sophisticated data assimilation techniques to the relatively large number of observations available to them (see chapters in Part B, *Observations*). It is natural that planetary scientists would propose similar analyses to maximize the valuable information that can be extracted from the relatively smaller data sets that are available to them, as was done by several teams for Mars in the 1990s (*e.g.* Banfield *et al.* 1995; Lewis and Read 1995; Lewis *et al.* 1996, 1997; Houben 1999; Kass 1999; Zhang *et al.* 2001).

Planetary scientists do not yet have the strong motivation provided by the regular requirement to provide initial states for near-future weather forecasts, which has provided much of the impetus behind the development of data assimilation techniques for Earth (chapter *Numerical Weather Prediction*, Swinbank). As a consequence, the resources available for planetary modelling and data assimilation are much smaller and to date schemes have generally been developed by only a handful of individuals and small teams of researchers. Aside from this practical limitation, the atmospheres of other planets are simply much less well-understood than that of the Earth and in many cases no sufficiently realistic general circulation model (GCM) exists which may be constrained by observations. Observational and model error characteristics, error growth and inherent biases have all received very limited study, if they have been considered in the literature at all.

Data assimilation does, however, offer many potential benefits to planetary science, not least in offering the prospect of a systematic reanalysis of past and present spacecraft data. By using a physically self-consistent atmospheric model, data assimilation is also able to extract information about variables not directly observed, for example to provide a self-consistent set of global temperatures, winds and surface pressure even where only one or two of these atmospheric fields may be observed, or, more likely, the observations are in the form of radiances which require inversion to derive temperatures. In these cases, assimilation effectively offers a good “first guess” in the form of a model forecast of the atmospheric state which might be used with a forward model to predict radiances, or as the basis for a conventional atmospheric inversion.

As in terrestrial atmospheric science and physical oceanography, at the same time data assimilation provides a systematic method of testing and validating models, for example by the identification of regions or fields where the model predicts a consistent misfit with the observations (see chapter *The Role of the Model in the Data Assimilation System*, Rood). This is of particular value in planetary science where models are often at a quite early stage of development and it is not necessarily the case that experience of the Earth will carry over directly. Data assimilation also permits the intercomparison of observations made of different fields, or at different time and places by separate instruments, permitting the extraction of the maximum information by combining two different data sets in an objective way.

Having noted the use of assimilation for improving models, it is important that while the maximum information is extracted from the valuable and limited observational record for another planet, at the same time this record is not over-used. For example, a set of observations could be used to improve the model itself or to estimate the model state, but not both in a recursive fashion. It is possible that uncertain model parameters can be included formally in the model state and that both may be estimated at once. A practice in terrestrial numerical weather prediction is to accumulate records of model output statistics and to perform a linear regression between the prediction and subsequent verification as a means of improving the model based on very large numbers of observations (*e.g.* Kalnay 2003). This may not yet be possible for other planets, owing to the more limited observational record.

Although short-term weather forecasting for the near-surface meteorology of another planet is still a distant prospect, forecasts of some atmospheric properties and, perhaps most importantly, their likely variance are vital now for spacecraft and instrument design and planning. Uses include predictions of upper atmosphere density for satellite *aerobraking* and *aerocapture* (this is the use of the atmospheric friction around 100 km altitude and above to decelerate spacecraft to aid their capture into low planetary orbits), entry, descent and landing studies for atmospheric entry vehicles, and estimates of the range of surface conditions which will be experienced in the lifetime of landed spacecraft. Such forecasts are often made on the basis of past experience and climatology, but for other planets the latter can be unknown or involve unwarranted extrapolations from previous mission data relevant to different locations and times of year. Models are starting to be used as the basis for generating more comprehensive climatologies for Mars (Lewis *et al.* 1999; Justus *et al.* 2002), in particular for regions of the atmosphere, or under conditions which have not yet been observed in detail. Data assimilation will play an increasingly important role here as the means of constraining and improving these models at times when some observations are available.

3 Data assimilation for the atmosphere of Mars

The atmosphere of Mars is the most obvious first extra-terrestrial target for data assimilation, motivated both by its similarities to the atmosphere of the Earth and by the regular launch of spacecraft missions over the last decade, resulting in an increased observational data set and an increased need to better understand the atmosphere for mission operations, in particular for aerobraking, aerocapture and entry descent and landing.

Like the Earth, Mars is a largely solid planet with a radius of 3,389 km, surface gravity of 3.72 ms^{-2} and a solar day (*sol*) of 88,775 s, around 40 minutes longer than the day on Earth. The rotation axis of Mars is tilted at a similar angle to the plane of the ecliptic, 25.2° compared to 23.5° for Earth, and so Mars experiences a similar pattern of seasons over the year of 668.6 sols, almost twice as long as a year on Earth. The atmosphere is also largely transparent, but is composed of 95% carbon dioxide with a typical surface pressure of 610 Pa (the typical surface pressure on Earth is 101,300 Pa, or 1013 hPa). Temperatures can reach above the freezing point of water on a warm, summer's afternoon, but can also fall to 145 K in polar night, at which point carbon dioxide freezes out around the Winter Pole forming a large seasonal ice cap containing up to a third of the total mass of the atmosphere. Despite the differences in atmospheric composition and mass, the atmospheric pressure scale height is only a little larger (roughly 10 km compared to 7.5 km on Earth) and the horizontal deformation radius is about 1,000 km in both cases; the lower gravity on Mars compared to Earth is compensated by the lower specific gas constant for the carbon dioxide rich atmosphere, resulting in a rather similar static stability for the lower atmosphere on both planets.

Transient, baroclinic weather systems are observed in martian mid latitudes, especially in the Northern Hemisphere (Barnes 1981, 1980; Collins *et al.* 1996; Wilson *et al.* 2002; Banfield *et al.* 2004), on a similar scale to those seen on Earth but with typically one to four high and low pressure systems around a latitude circle owing to the smaller planetary radius. Intriguingly, these travelling waves on Mars appear to be much more regular, and sometimes almost periodic, than typical terrestrial mid latitude weather systems (Barnes 1980, 1981; Collins *et al.* 1996; Read and Lewis 2004).

The similarities of martian atmospheric dynamics to that of the Earth have led to the development of several Mars GCMs from the late 1960s onwards, typically derived from terrestrial models (for reviews see, *e.g.*, Zurek *et al.* 1992; Lewis 2003; Read and Lewis 2004 and references therein). The most advanced of these models are comparable in complexity with a terrestrial global model used for numerical weather prediction or for climate studies (see chapters *The Role of the Model in the Data Assimilation System*, Rood; *Reanalysis: Data Assimilation for Scientific Investigation of Climate*, Rood and Bosilovich).

Despite its similarities with the atmosphere of the Earth, at least two factors make that of Mars different from the perspective of data assimilation. Firstly, the lower atmospheric density, and hence lower heat capacity, on Mars means that the atmosphere responds very much more quickly to changes in radiative forcing. This is particularly true at times when the atmosphere of Mars contains large amounts of suspended dust, which absorbs visible radiation and heats the atmosphere. A typical radiative relaxation time scale for the lower martian atmosphere is around two sols (Goody and Belton 1967; Gierasch and Goody 1967, 1968), and may be as low as one sol when the atmosphere is dusty, an order of magnitude shorter than radiative relaxation times for the Earth's atmosphere. This means that a Mars GCM will respond very quickly to its own radiative forcing scheme and, if this is not precisely correct together with an accurate spatial and temporal dust distribution, the GCM may rapidly "forget" information introduced by assimilation of past data where there is an absence of current observations. It should be noted that there are considerable uncertainties in the radiative properties and size distribution of martian dust and consequently dust heating parametrizations in GCMs are likely to be subject to substantial errors.

Secondly, the observation that errors grow roughly exponentially with time in accordance with deterministic chaos theory on Earth (*e.g.* Ehrendorfer 1997; Toth 2001) may not necessarily be true on Mars, at least at some times of year when model simulations indicate that error growth can decay with time and the atmosphere appears highly predictable (Newman *et al.* 2004). The implications of this potentially greater predictability on Mars are yet to be fully explored.

In addition to a realistic numerical model, data assimilation requires a stream of observations and several early assimilation efforts for the martian atmosphere were motivated by the launch in 1992 of the ill-fated NASA Mars Observer (MO) spacecraft (Cunningham *et al.* 1992), lost around the time of orbital insertion in 1993. Like several subsequent NASA missions, MO was intended for a two-hourly sun-synchronous low polar orbit, passing over the Equator at 2:00 am and 2:00 pm local time, and it was this regular, repetitive mapping of the atmosphere that made data assimilation for Mars an attractive option. MO was followed by Mars Global Surveyor (MGS), launched in 1996, which re-flew some of the MO instruments, including notably for atmospheric observations the Thermal Emission Spectrometer (TES) (Christensen *et al.* 1992), which is an infrared sounder operating mainly in nadir mode, though with some limb observations. TES has produced a spectacular dataset covering almost three complete martian years from 1999–2004 and is the subject of several current data assimilation studies. TES nadir soundings typically allow the retrieval of temperature profiles between the surface and about 40 km with a vertical resolution of one scale height (10 km) or greater and total column opacities of dust and water ice (Conrath *et al.* 2000, 2002; Smith *et al.* 2000, 2001; Smith 2004), as well as various surface properties.

A second instrument from MO, the limb-sounding Pressure Modulator InfraRed Radiometer (McCleese *et al.* 1992) was re-flown on a second unsuccessful mission, Mars Climate Orbiter in 1998, but a new version of the limb-sounding radiometer, Mars Climate Sounder (MCS) (McCleese *et al.* 2007) is presently in orbit about Mars aboard the Mars Reconnaissance Orbiter. MCS has been mapping the martian atmosphere over at least one seasonal cycle. The principal advantages MCS will offer over TES for atmospheric assimilation are routine limb-sounding, with coverage up to about 80 km and half-scale height, 5 km, vertical resolution, with the ability to differentiate between dust, condensates and water vapour and to profile each in the vertical. Several groups are preparing to assimilate MCS data in the coming years.

It should also be noted that two other Mars spacecraft, NASA's 2001 Mars Odyssey (Saunders *et al.* 2004) and ESA's 2003 Mars Express (Schmidt 2003) have both provided fascinating remote sensing observations revealing much about the martian climate and surface, but to date observations from either mission have not been assimilated into a Mars GCM.

In direct contrast to Earth, at the time these orbital spacecraft have been operating there have been few, if any, surface-based *in situ* meteorological observations, with the notable exceptions of the instruments on the NASA Phoenix polar lander, operating five months in 2008, and the Mini-TES instruments on the Mars Exploration Rovers (Smith *et al.* 2006) which provide lower atmosphere profiles up to a few km in height. Crucially, there have been no systematic surface pressure measurements other than from Phoenix, from Mars Pathfinder or a few months in 1996 (Schofield *et al.* 1997) and the longer, multi-annual record from the Viking Landers in the late 1970s (Hess *et al.* 1980). This lack of pressure data makes it difficult to constrain the mass budget of the Mars GCMs and brings novel difficulties in data assimilation compared to the Earth, where surface pressure is a fundamental observation to be included in any meteorological analysis. Indeed, it might be argued that surface pressure is the most important observable quantity for constraining the whole troposphere in terrestrial atmospheric data assimilation (*e.g.* Anderson *et al.* 2005) and this emphasizes the need for more martian surface observations in future, although it is highly unlikely that there will be a sufficiently dense network of surface stations on Mars to constrain a model on their own in the foreseeable future.

3.1 Data assimilation schemes for Mars

Two approaches have been taken in developing data assimilation schemes to work with martian observations. On one hand, new schemes have been developed tailored specifically to exploit the characteristics of the data which are expected; normally remotely sensed temperature profiles from a regular two-hourly, polar orbit. On the other hand, terrestrial schemes with heritage in the numerical weather prediction community have been adapted and re-tuned for martian conditions.

Banfield *et al.* (1995) exploited the repetitive nature of the polar orbit to propose a variant on the full sequential Kalman filter (Kalman 1960), which is made computationally economic by only calculating the gain matrix once, and then holding it steady in time. (For a discussion on the Kalman filter see chapter *Mathematical Concepts of Data Assimilation*, Nichols.) The steady-state gains are computed once at the start of each assimilation experiment by an iterative technique and then applied throughout to each observation, making the gains a function of relative longitude between observation and model points. This was shown to work well in a highly idealized, single-layer primitive equation model, observing the mass field but not the velocity field.

The steady-state Kalman filter was later applied to TES mapping phase data (Zhang *et al.* 2001) using the NASA Ames Mars GCM (Pollack *et al.* 1990; Haberle *et al.* 1993). This study only assimilated ten sols of MGS mapping phase TES data, but was able to show a small improvement in the agreement between model and observations; although the success was only limited and the model response was degraded in south Polar Regions. There also seemed to be little evidence that the assimilation was converging sufficiently well to capture the transient waves. The problems experienced were attributed to problems with the assumed dust opacity and distribution in the GCM.

An alternative approach was taken by Houben (1999), who employed a Mars GCM with relatively low resolution, a spectral model with 17 Legendre modes in latitude, 7 waves in longitude and 16 vertical levels, and with highly simplified physical parametrizations including linear Newtonian cooling in place of a full radiation scheme. Houben was thus able to reduce the complexity of the model so that it could be constrained with the number of MGS observations available in one sol. Assimilation was accomplished by a four-dimensional variational technique, 4D-Var (Talagrand and Courtier 1987; Courtier and Talagrand 1987) (For a discussion on 4D-Var see chapter *Variational Assimilation*, Talagrand.). This study is notably complementary to other assimilation techniques which employ a full Mars GCM and assimilate data using a more empirical technique.

Kass (1999) used the NASA Ames Mars GCM, but with a form of assimilation based on optimal interpolation, OI (Bengtsson and Gustafsson 1971; Rutherford

1972). Kass assimilated TES temperature profiles over a 25-sol, 17-orbit period during MGS aerobraking using optimal interpolation. He found that the Winter Hemisphere jet was moved polewards and that the amplitude of waves became stronger compared to an independent experiment with the Mars GCM. He was also able to demonstrate that the transient component of the surface pressure field was modified in response to the assimilation of temperature data, in an interesting contrast to the terrestrial meteorological experience which suggests that surface pressure observations are crucial and tend to drive behaviour in the atmosphere above.

Another scheme which draws heavily on terrestrial experience with some success was developed by Lewis *et al.* (Lewis and Read 1995; Lewis *et al.* 1996, 1997) based closely on the analysis correction scheme (Lorenc *et al.* 1991), in operational use at the Meteorological Office (UK) at the time. This scheme is a form of the successive corrections method which has proved simple and robust in many trial studies with artificial data under martian conditions. Observations are spread in both space and time by the use of empirically-tuned functions and the relatively inexpensive data assimilation scheme is paired with a fully comprehensive Mars GCM (Forget *et al.* 1999; Lewis *et al.* 1999). Assimilation of the TES data using this technique during the MGS aerobraking hiatus has been described (Lewis *et al.* 2007), as has an analysis of the thermal tidal behaviour throughout the MGS mapping phase (Lewis and Barker 2005). The mapping phase assimilation has been validated by a cross-comparison of model temperature profiles sampled at the same time and place as profiles obtained by radio occultation, also using the MGS spacecraft (Montabone *et al.* 2006a). Focused studies have included investigations of martian dust storms (Montabone *et al.* 2005) and detailed reconstructions of the atmosphere at the time of recent entry probes (Montabone *et al.* 2006b). The results of this assimilation procedure are further validated by comparing the planetary waves in the assimilation with those from direct synoptic mapping analyses of the TES retrievals. The output from this assimilation over the full three martian years observed by MGS/TES is being made freely available and is the subject of many ongoing atmospheric investigations. For example, Wilson *et al.* (2008) use the statistical differences between the output of the assimilation and independent model experiments to infer potential longitudinal-mean errors in the model radiation budgets, in this case ascribed to the absence of equatorial water ice clouds in the independent model experiments.

With new MCS data in prospect and with the vast TES data set not yet fully exploited, new martian data assimilation schemes are also under development. These include applications of both variational and Ensemble Kalman filter schemes, which are now widely used at leading terrestrial data assimilation centres (*e.g.* Rabier 2005; Houtekamer and Mitchell 2005) – see also chapter *Mathematical Concepts of Data Assimilation* (Nichols). Research is also ongoing into direct assimilation of observed radiances rather than using pre-retrieved temperature profiles as most of the martian studies described above have done. Removing the need for a separate retrieval and linking the observed infrared radiance directly to the atmospheric state has many attractions, but is a challenging prospect particularly with a limb-sounding radiometer such as MCS. Chapters *Assimilation of Operational Data* (Andersson and

Thépaut) and *Constituent Assimilation* (Lahoz and Errera) discuss the direct assimilation of radiances from operational and research satellites on Earth.

3.2 Results from martian data assimilation

Some early results from martian data assimilation are illustrated in this section based on the assimilation of TES observations throughout the aerobraking hiatus and scientific and extended mapping phases, a period of almost three martian years, using the analysis correction scheme of Lewis *et al.* (2007). The full assimilation period is summarized by Fig. 1, which shows the assimilated dust optical depth in the visible, averaged over all longitudes and converted to an equivalent optical depth at a standard reference pressure of 610 Pa. The Mars Years (*MY*) are numbered here following an arbitrary scheme (following Clancy *et al.* 2000), and the time of year is indicated by *areocentric longitude*, L_S, an angle varying from 0°–360°, where L_S=0° is spring equinox, L_S=90° is summer solstice, L_S=180° is autumn equinox and L_S=270° is winter solstice (seasons are for the Northern Hemisphere of Mars). Figure 1 includes the aerobraking hiatus period (*MY23*, L_S=190°–260°), during which time the spacecraft orbital period was being reduced from 45 hours to 24 hours and the configuration was more difficult for atmospheric assimilation owing to the long orbital period and irregular and intermittent observational coverage. The subsequent 2-hour scientific mapping phase orbit provided more regular observations throughout almost three Martian years of operation (*MY24*, L_S=141° to *MY27*, L_S=72°).

The impact of the assimilation on the zonal mean state of the atmosphere, even in the least optimal aerobraking hiatus period is illustrated by the zonal-mean temperature and zonal winds in the assimilation during the *Noachis* dust storm period, a regional, moderate dust storm that began around *MY23*, L_S=225° in the martian Southern Hemisphere. Figure 2 shows the zonal mean state in the assimilation and Fig. 3 the differences between this and a model run with a dust state which is a close match to the mean conditions before the dust storm. Enhanced warming throughout the middle atmosphere at most latitudes is apparent, as is a strong polar warming above the North Pole, and enhancement of the polar westerly jet, thanks to the enhanced meridional circulation in the model; no observations were available in this region at this time.

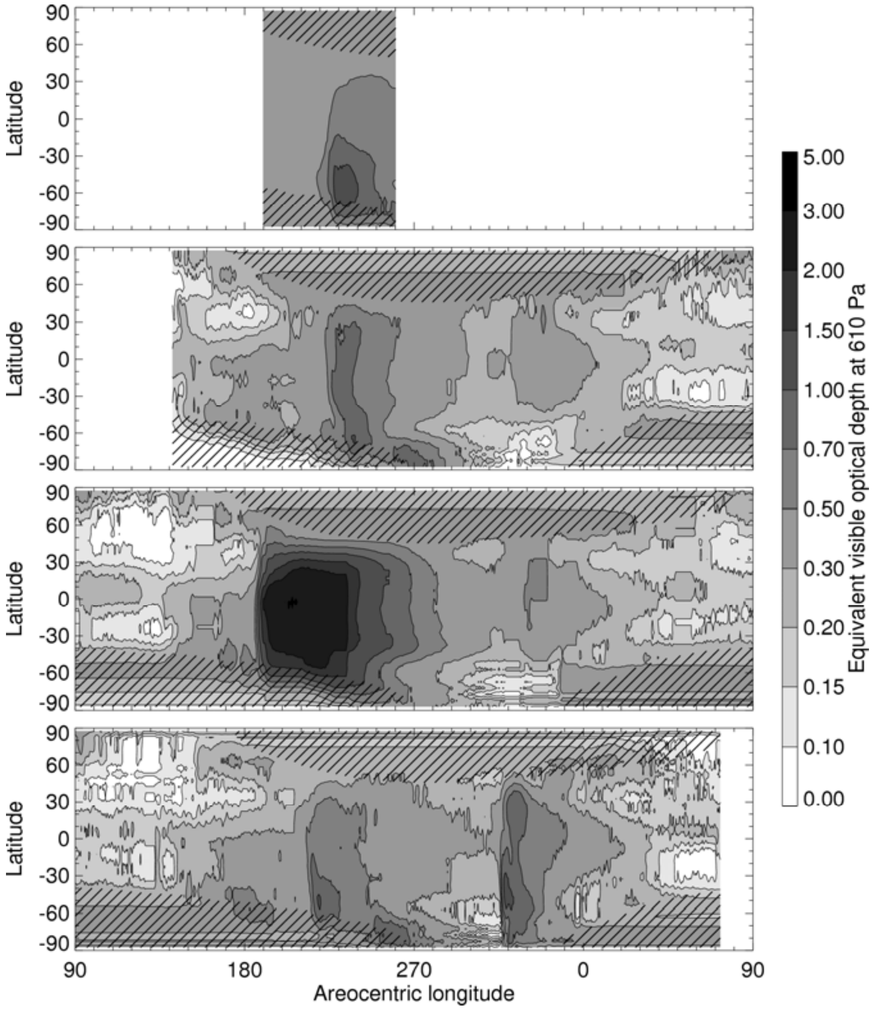

Fig.1. Assimilated dust optical depth at 610 Pa from the full period for which TES observations are available. Each panel shows one martian year, Mars Years (*MY*) 23-26 from upper panel down, with summer solstice at the left-hand edge (aerocentric longitude=90°). The hatched regions indicate where there are few, if any, total opacity observations (the mean surface temperature is below 160 K and there is insufficient thermal contrast between the atmosphere and surface to retrieve total atmospheric opacities).

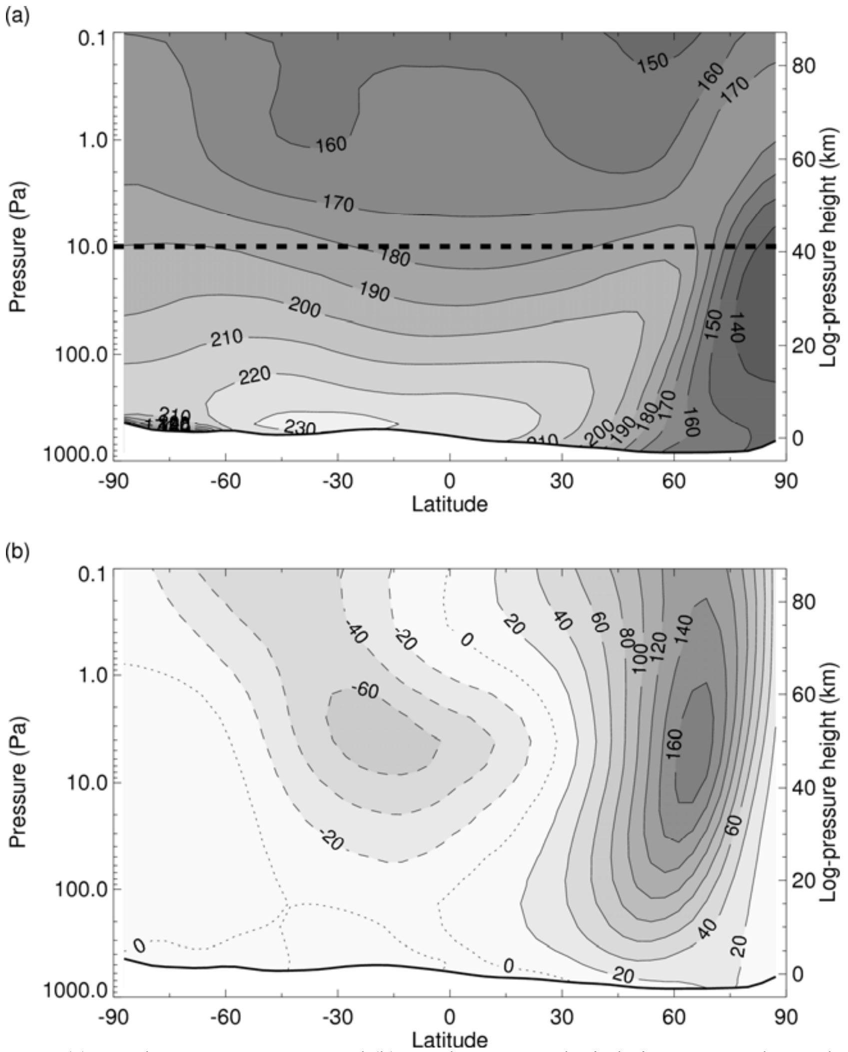

Fig. 2. (a) Zonal-mean temperature and (b) zonal-mean zonal wind, time-averaged over the period $L_S = 225°–233°$. The horizontal, dashed line indicates the approximate level above which no temperature data from the nadir soundings was available. The zero contour is dotted and negative contours dashed. Log-pressure height is defined as $-10\log(p/610\ \mathrm{Pa})$ km as an approximate conversion from pressure p to height above the 610 Pa level. Reprinted from Lewis *et al.* (2007), with permission from Elsevier.

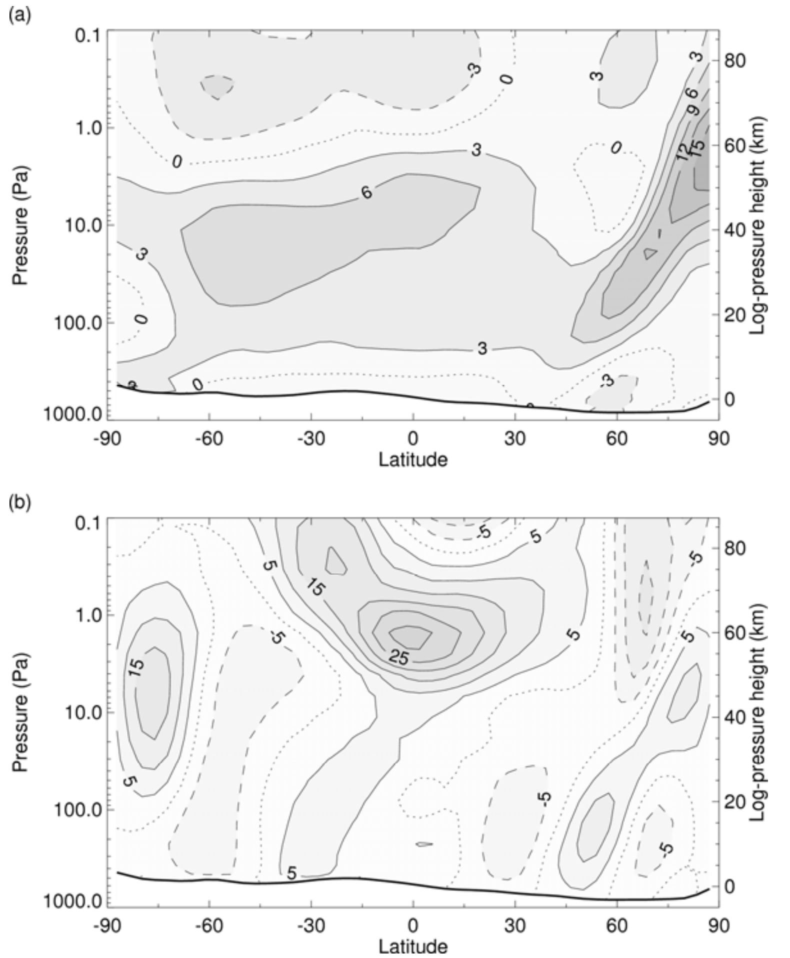

Fig. 3. Differences, assimilation minus a model run with no dust storm, in (a) zonal-mean temperature and (b) zonal-mean zonal wind, averaged over the period shown in Fig. 2. Positive values indicate that the assimilation gives higher values than the model. Reprinted from Lewis *et al.* (2007), with permission from Elsevier.

One major motivation for using assimilation techniques is in order to investigate the *transient wave* behaviour on Mars, which is difficult to interpret when the observations are made asynchronously from a single orbiting spacecraft. Lewis and Barker (2005) described the atmospheric thermal tide behaviour, an analysis which is extended by Figs. 4 and 5 here to show the diurnal and semidiurnal tidal amplitudes respectively throughout the MGS mapping phase. These amplitudes are difficult to analyse from the data directly, since at low latitudes only two local times of day are observed, but the model responds to the changing dust optical depth and exhibits very variable tidal behaviour compared to a model run with a steady, prescribed dust field. The correlation between the semidiurnal tide and optical depth (Fig. 1) is striking.

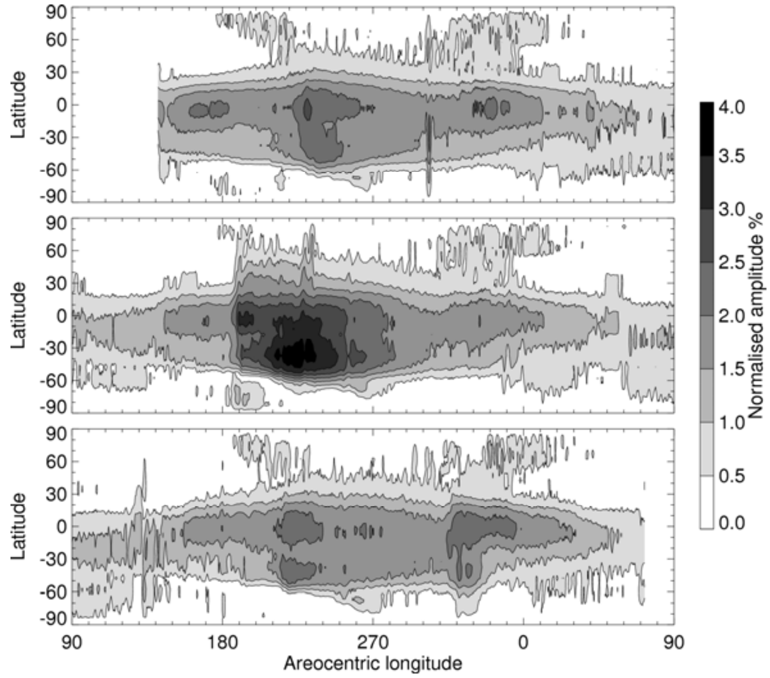

Fig. 4. The normalized amplitude of the surface pressure signature of the diurnal tide, shown as a function of latitude and time during the MGS mapping phase, the same period as the lower three panels of Fig. 1 (Mars Year, *MY* 24, L_S=141° to Mars Year, *MY* 27, L_S=72°).

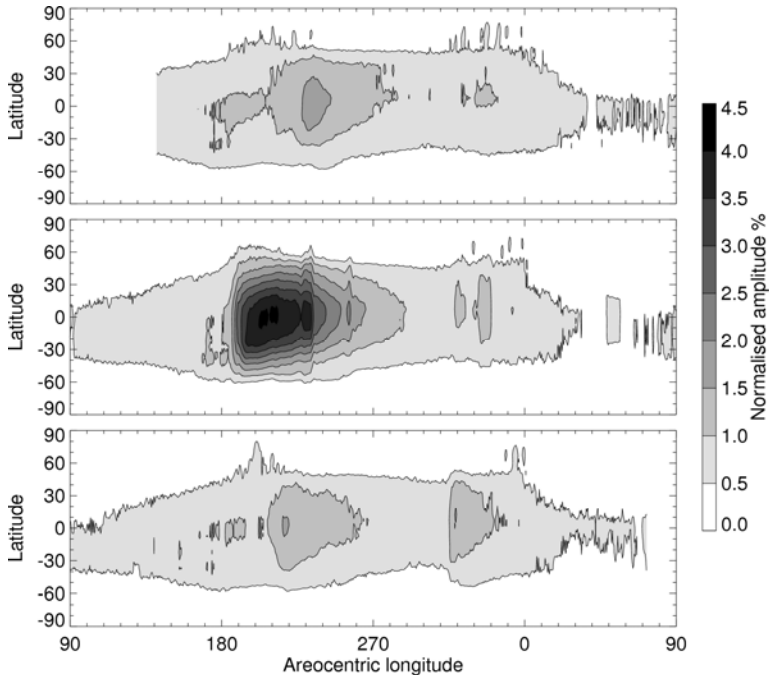

Fig. 5. The normalized amplitude of the surface pressure signature of the semidiurnal tide, as Fig. 4.

A principal advantage of data assimilation of data from a single, polar orbiting satellite is in its ability to reconstruct transient waves. The *Hovmoller diagrams* in Fig. 6 show (a) transient temperature on the 50 Pa pressure surface (~25 km altitude) and (b) transient pressure, corrected to the Mars reference datum to remove topographic signals. Both variables are shown at 62.5°N over the entire Northern Hemisphere winter period, L_S=180°–360°, of *MY* 24, the first year of the MGS scientific mapping phase period. The temperature and pressure have been time-filtered to remove tides and quasi-stationary features.

Transient waves can be seen to propagate eastwards in both panels of Fig. 6. These waves have low zonal wavenumbers, primarily 1–3, with wavenumber 1 dominating throughout much of this period. Of interest is the period around L_S=220°–260°, when the atmospheric temperature shows a strong, long-period wavenumber 1 signal. This is equivalent to a wobble in the polar vortex, the region of strong westerly winds which circulate the Winter Pole (for the analogue on Earth, see chapter *General Concepts in Dynamics and Meteorology*, Charlton_Perez *et al.*). If this moves to a position not centred over the geographic pole, it will appear as a wavenumber 1 wave as seen at any mid to high latitude. The long-period wavenumber 1 signal is detached from the weaker, shorter period (2–10 days) waves seen near the surface in the pressure signal. A modulation from these waves can still be seen in the temperature signal. At other times the waves are broadly coherent over this altitude range.

It is also notable that the waves near the surface are stronger after the autumn equinox and before the spring equinox, whereas the 50 Pa temperature signal peaks around winter solstice. This solsticial pause in the near-surface waves is seen to recur in all three years analysed.

There is a strong topographic influence on the strength of the waves, with maxima being consistently seen at longitudes corresponding to lowlands in *Acidalia*, *Utopia* and *Arcadia Planitia*, which break the longitudinal symmetry of Mars into regions reminiscent of storm zones on Earth.

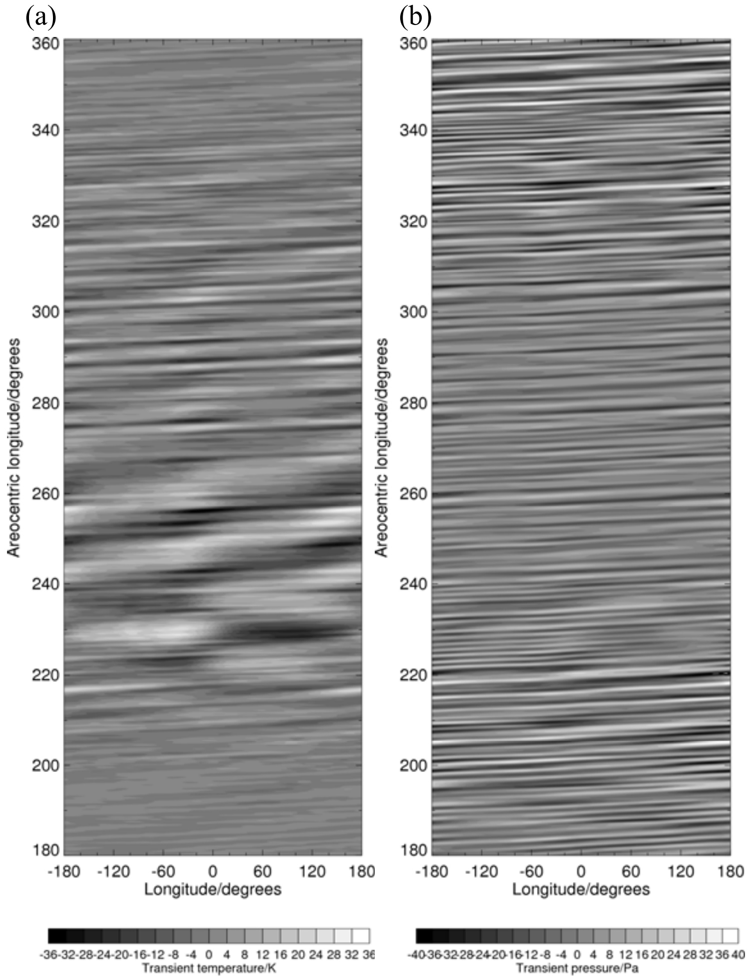

Fig. 6. (a) transient temperature on the 50 Pa pressure surface (~25 km altitude) and (b) transient pressure, corrected to the Mars reference datum to remove topographic signals at 62.5°N over the period, L_S=180°–360°, of *MY* 24.

4 Future prospects for other planets

To date, a formal process of data assimilation has not been attempted for any other planetary atmospheres, though the observations that are available are naturally used to inform and to constrain models. The most likely next application beyond Mars is to the atmosphere of Venus, with new ESA Venus Express observations now available (Titov *et al.* 2006) and recent advances in Venus GCMs (Yamamoto and Takahashi 2003, 2006; Lee *et al.* 2005, 2007; Hollingsworth *et al.* 2007; Lebonnois *et al.* 2009). The Venus models still have simplified physical parametrizations compared with the Mars and terrestrial GCMs and are not yet able to make accurate, quantitative predictions of, for example, equatorial winds. Venus, with its very long radiative relaxation timescale (varying from around an Earth day at the cloud tops to many years in the lower atmosphere) and slow rotation rate, which means that assumptions about *geostrophic balance* will not apply (see chapter *General Concepts in Meteorology and Dynamics*, Charlton-Perez *et al.*), will offer new challenges for data assimilation.

Data assimilation for the atmospheres of the Giant Planets is also a challenging prospect. Again, there are few complete global atmospheric models (Dowling *et al.* 1998, 2006), but there is now a substantial observational data set from the Galileo mission to Jupiter (Young 1998, 2000) and the Cassini mission to Saturn (Mitchell 2007). These missions have not provided the very repetitive coverage of the satellites observing Mars and Venus, but they have made multiple orbits and observed some atmospheric features repeatedly, so limited-area assimilations may become feasible at some point in the future.

5 Implications for terrestrial data assimilation

Although data assimilation for other planets is presently only in a nascent state, advances are happening rapidly. Planetary data assimilation has examples of both building on older, established terrestrial techniques and developing new ideas tailored to specific problems. In particular it demonstrates assimilation scheme performance in a very data-poor environment, perhaps more analogous to physical oceanographic applications than to terrestrial numerical weather forecasting. There are particular challenges in a planetary context, often with only poor knowledge of the dominant physical processes and with highly simplified models without a well-known climatology. A notable feature of the martian data assimilation studies outlined in this chapter, and most likely future planetary data assimilation studies, is their reliance on remotely-sensed observations from a single satellite at any one time with the lack of contemporaneous *in situ* measurements. That there has been at least some limited success reported is interesting with regard to the terrestrial problem. On Earth, surface and near-surface measurements are clearly of great importance for determining the state of the lower atmosphere and satellite observations have been introduced to terrestrial data assimilation schemes for numerical weather prediction at a later stage. The planetary problem is almost being tackled in reverse, with models now incorporating satellite data assimilation being used to form climate databases to assist in the entry, descent and landing process for spacecraft which will hopefully make the surface and *in situ* atmospheric measurements in future.

Acknowledgments

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