METEOROLOGY OF THE 2001 GLOBAL DUST STORM ON MARS IN AN ASSIMILATION OF THERMAL EMISSION SPECTROMETER DATA FROM MARS GLOBAL SURVEYOR. L. Montabone[1], O. Martinez-Alvarado[2], S. R. Lewis[1], P. L. Read[3], and M. D. Smith[4], [1]Dept. of Physics & Astronomy, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK (L.Montabone@open.ac.uk), [2]Oxford Centre for Industrial and Applied Mathematics, Mathematical Institute, University of Oxford, , 24-29 St. Giles, Oxford OX1 3LB, UK, [3]Dept. of Physics, University of Oxford, Atmospheric, Oceanic and Planetary Physics, Parks Road, Oxford OX1 3PU, UK, [4]NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Introduction: In late June 2001, Mars was enshrouded by a thick veil of dust which lasted for several months and obscured observations of its surface by spacecraft cameras and ground-based telescopes. The emergence and evolution of the 2001 global dust storm was well captured by NASA's Mars Global Surveyor (MGS) spacecraft, which was launched in 1997 and which is still in orbit around the planet.

Although the coverage of both the Mars Orbiter Camera (MOC) and the Thermal Emission Spectrometer (TES) aboard MGS is excellent during the dust storm event [1,2], no synoptic data maps are available, given the sun-synchronous orbit of the MGS spacecraft, which makes difficult to retrieve information on waves, such as traveling waves or thermal tides. Furthermore, the type of information which is available from MGS for the study of the global dust storm is mainly limited to temperature and dust opacity. No atmospheric wind or surface pressure data are available from the spacecraft observations.

The substantial dataset of TES thermal and dust opacity observations with good spatial and temporal coverage has allowed us to apply successfully a data assimilation technique to the study of Martian atmospheric dynamics [3, 4]. The advantage of such an approach, which combines modeling with a state-of-the-art Martian global circulation model (GCM) and observations, is to provide global, four-dimensional information on the atmospheric state, including those variables which are not directly observed, such as near-surface winds and surface pressure.

We report here on the assimilation of MGS/TES nadir thermal profiles and dust opacity observations into the UK Martian GCM (Oxford University/The Open University) [5], aimed at characterizing the meteorology at the time of the onset of the 2001 global dust storm (L_S~177°, MarsYear 25), during its rapid explosion (L_S~186°) and subsequent evolution until the start of the decay (L_S~212°).

Methods: Data assimilation is a technique which combines observations and numerical modeling to produce a best-fit to the real state by minimizing misfits between data and model results. This technique has been developed for the weather forecast on the Earth, and several mathematical approaches are available in the literature (Successive corrections, Kalman filter, 3D-Var, 4D-Var, etc.).

We make use of a sequential procedure known as the analysis correction scheme [6], a form of the successive corrections method which has proved simple and robust in trial studies with artificial data under Martian conditions. See the companion paper [7] in this volume for details on the technique and for references.

In this paper, we focus the analysis on the surface pressure and the near-surface wind stress (i.e., the wind stress calculated at the lowest layer in the model, which has an average height of 4.6 m) at the time of the 2001 global dust storm. These two variables are not directly observed by any instrument, but are obtained from the results of the assimilation of thermal profiles below 40 km altitude and infrared total dust opacity provided by MGS/TES.

The optical depths measured by TES in the infrared are transformed in equivalent visible optical depths by multiplying by a factor of 2.0 [8,9] before being assimilated into the GCM. Another assumption that we have to make, because of the lack of data, concerns the vertical distributon of the dust. We assume that the dust mixing ratio has an exponentially modulated decay with height, as detailed in [10,4].

Results: The dust storm witnessed by MGS in 2001 is one of the greatest ever seen and the only one for which many measurements exist so far. Thefore, studying the atmospheric and surface mechanisms is crucial for understanding the phenomenon of the initiation and evolution of the dust storms on Mars.

According to the results of the assimilation, confirmed by MOC, TES observations [1,11] and numerical simulations performed with the NASA Ames GCM [12], the working hypotheses for the development of the global (also called “planet-encircling”) dust storm are the following.

- Traveling waves along the southern cap edge are responsible for the small dust storms along the cap and the initial dust pulses into the Hellas basin between L_S~177° and L_S~184°.
- The dust lifted in Hellas moved north-eastward towards the area between the northern slopes of Hellas and the Isidis Planitia. There, the in-

teraction with the thermal tides may be involved in the explosive expansion at L_S~186°.

- The large cloud of dust moved eastward. The mean meridional circulation (Hadley cell) may play a significant role in this asymmetric migration of the initial cloud of dust.
- Secondary lifting centres were activated around Tharsis and in the plains south of the Tharsis ridge, namely in Syria, Solis and Daedalia, starting from L_S~189°. Again, the interaction of the initial cloud of dust which migrated eastward with the thermal tides may play a major role.
- The global circulation transported and diffused the lifted dust all around the planet, and the 2001 dust storm became global, or planet-encircling.

Figures 1 and 2 show the transient component of the surface pressure at L_S~177° along the southern cap edge, together with the associated near-surface wind stress. The low and high pressure patches propagate eastward and correlate well with patches of strong wind which may have lifted dust from the ice-free areas around the ice cap and gave rise to the observed small dust storms around the southern slopes of Hellas.

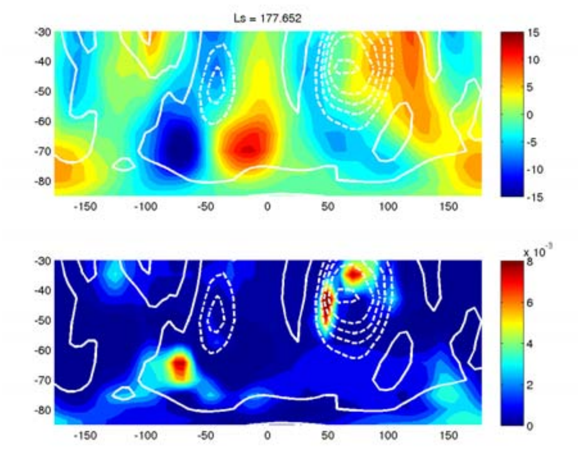

Figure 1: The upper panel shows the longitude-latitude transient component of the surface pressure at L_S~177° (local time is 6 p.m. at 0° longitude), the lower panel shows the corresponding near-surface wind stress. Units are Pascal for the surface pressure and N/m^2 for the wind stress. Solid and dashed lines represent the positive and negative topography.

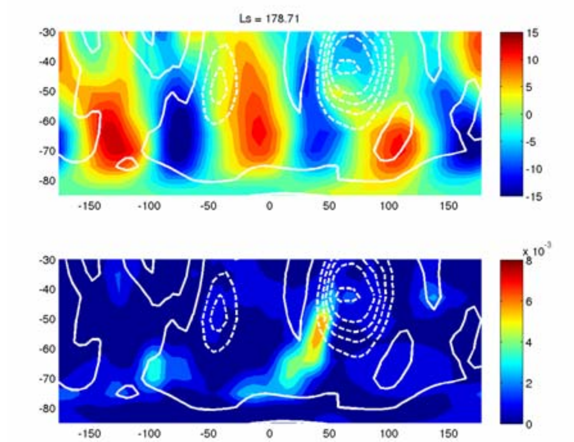

Figure 2: Same as in Fig. 1, but for L_S~177° when the local time is at 2 p.m. at 0° longitude.

The interaction of the initial small cloud of dust which moved north-eastward of Hellas and the thermal tides is illustrated in Fig. 3. This figure shows the diurnal, semidiurnal and Kelvin components of the surface pressure tidal modes around Hellas at the time of the explosive expansion of the storm. The three components are all in phase, thus producing a strong low pressure patch which correlates very well with the sudden increase of the dust optical depth (not shown here). This increase of the dust opacity is caused by the explosive increase of the dust lifting, which is produced by strong near-surface wind stress, as shown in Fig. 4.

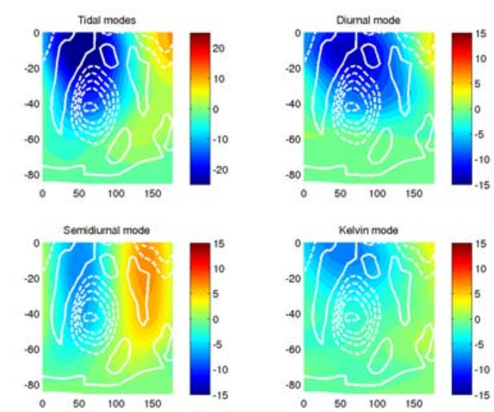

Figure 3: The upper left panel shows the surface pressure tidal component around Hellas at L_S=185.32° (local time is 12 p.m. at 0° longitude). The other panels show, respectively, the diurnal mode (upper right), the semi-diurnal mode (lower left) and the Kelvin mode (lower right). Units are Pascals; longitudes are in the x-axis and latitudes in the y-axis. Lines are for topography, as in Fig. 1.

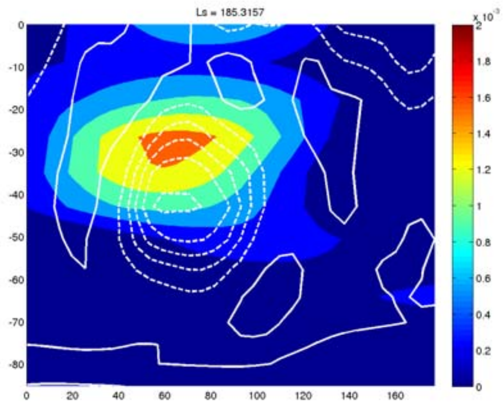

Figure 4: This picture shows the near-surface wind stress around Hellas for the time corresponding to Fig. 3 (L_S=185.32°, local time is 12 p.m. at 0° longitude). Units are in N/m^2; longitudes are in the x-axis and latitudes are in the y-axis. Lines are for topography, as in Fig. 1.

Future plans:

Future work will be devoted to activate a fully-coupled dust transport scheme within the assimilation in order to study the full cycle of dust lifting, transport and deposition during the 2001 global event.

Given the successful testing of high resolution model simulations (at better than one degree resolution), we also plan to perform high resolution assimilation experiments in order to investigate in detail the explosive behaviour of the storm around the northern slopes of Hellas and the activation of the secondary lifting centres in the Tharsis plains.

We are also analyzing the results of the assimilation for the period of the global dust storm using the Proper Orthogonal Decomposition (POD) technique. This is a statistical technique which allows the extraction of the most energetic modes of the atmosphere by maximising the total energy in each orthogonal mode. Ongoing work is being conducted to associate a physical meaning to the statistical results provided by the technique.

Future work will also take advantage of a better knowledge of the vertical structure of the dust distribution or at least of its vertical extent, which at the moment are inferred from indirect considerations of particle sedimentation and eddy mixing. The Mars Climate Sounder experiment on the 2005 Mars Reconnaissance Orbiter should provide such an improvement [13].

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