Reconstructing the weather on Mars at the time of the MERs and Beagle 2 landings

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[1] We reconstruct the temperature, wind and density structure of the atmosphere on Mars from the surface to 120 km altitude at the time of the landing of the two NASA Mars Exploration Rovers (MER), and ESA's "Beagle 2." This reconstruction is based on an assimilation of temperature and dust opacity observations from the Thermal Emission Spectrometer aboard the Mars Global Surveyor spacecraft into a general circulation model of the Martian atmosphere and, for the case of the MERs, on retrievals of temperature and density profiles from accelerometer data. For all landers, the reconstruction of the atmospheric state is compared with the climatological state predicted by the European Mars Climate Database (EMCD) for two different prescribed dust scenarios, with added large- and small-scale variability. This comparison exhibits good agreement for all three landers within the modeled variability, confirming a posteriori the accuracy of the climate forecasts by the EMCD. **Citation:** Montabone, L., S. R. Lewis, P. L. Read, and P. Withers (2006), Reconstructing the weather on Mars at the time of the MERs and Beagle 2 landings, *Geophys. Res. Lett.*, *33*, L19202, doi:10.1029/2006GL026565.

1. Introduction

[2] "Beagle 2" was the lander carried aboard ESA's Mars Express spacecraft, which was due to land in Isidis Planitia on Mars on December 25th, 2003 [*Bridges et al.*, 2003]. The lander was successfully released from the parent spacecraft on December 19th, six days before arrival at Mars. After its release, no communication with Beagle 2 was possible until landing. The planned contact with Beagle 2 after landing was never established and the lander was eventually declared lost.

[3] The NASA Mars Exploration Rover (MER) mission, on the other hand, successfully landed two rovers on Mars, "Spirit" and "Opportunity" respectively, on January 4th and 25th, 2004. Spirit landed in Gusev crater and Opportunity landed in Meridiani Planum; for example, see *Squyres and the Athena Team* [2004], *Arvidson et al.* [2006], and reference therein for overviews of the mission. Both the rovers were equipped with an accelerometer, and data recorded during the descent and landing have been analyzed to retrieve profiles of temperature, pressure and density.

[4] Entry, descent and landing (EDL) procedures for a spacecraft rely upon an estimate of atmospheric density as a function of height. This may be a reference profile, based on previous observations or, increasingly, may be based on mean climate and variability predictions from a numerical model. One example is the European Mars Climate Database (EMCD) [see *Lewis et al.*, 1999].

[5] Following the loss of Beagle 2, an internal inquiry was carried out to identify possible reasons for failure. Although no specific cause has been identified, the official report suggested that systematic errors in the predicted atmospheric characteristics provided by the models could leave scope for a resulting loss of the Beagle 2 mission during EDL [*Sims et al.*, 2004].

[6] This paper is a study of the weather conditions at the time and location of the landing of Beagle 2 and the two NASA rovers, and a comparison with the climatological state provided by the EMCD. This comparison is aimed at determining whether systematic errors might be present in the EMCD predicted climatology, which could affect its use for possible EDL design.

[7] For this comparison, profiles of temperature, density and wind velocity from the surface to 120 km altitude were retrieved by using a data assimilation technique, which makes use of observations of temperature and total dust infrared opacity provided by the Thermal Emission Spectrometer (TES) onboard the Mars Global Surveyor (MGS) spacecraft [*Smith et al.*, 2001; *Smith*, 2004, and references therein]. Independent retrievals of temperature and density profiles from accelerometer data during the landing of Spirit and Opportunity are also used. The reconstructed atmospheric state during the three landers' EDL is compared to the climate forecasts provided by the EMCD (version 3.2) for two different prescribed dust scenarios ("baseline" and "warm"), taking into account large and small scale variability.

2. Method

[8] A forecast of the climatological atmospheric conditions on Mars at a given time of year, position and local time can be obtained via the European Mars Climate Database developed jointly at Oxford University and Laboratoire de Météorologie Dynamique (LMD) in Paris. This is a database of statistics which describes the climate and surface environment of Mars based on multiannual integrations of the LMD/AOPP Mars General Circulation Model (MGCM) [see *Forget et al.*, 1999]. The database is described by *Lewis et al.* [1999] and at http://www-mars.lmd.jussieu.fr. In this paper, an ensemble of profiles of temperature, density and

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wind velocity are given for each lander, in order to take into account the variability of large scale (baroclinic waves) and small scale (gravity waves) processes using statistical-dynamical models. Two different prescribed dust scenarios were used: a scenario modeled on recent MGS observations with large dust storms removed (the "baseline" scenario, characterized by a relatively clear atmosphere at the time of the landings), and a dustier scenario modeled on mean Viking lander observations outside major dust storms (the "warm" scenario). The EMCD profiles were obtained along the trajectories of the MERs, which permits a close comparison between predictions and the entry observations, and above the presumed landing site of the failed Beagle 2. Density profiles at Spirit's landing site are corrected for altitude differences between the model topography and the high resolution (16 pixels/degree) MGS/MOLA topography. This difference is more than 1000 m at Spirit's landing site, resulting in a difference of $\sim$10% in surface pressure and density (derived using the ideal gas law). This equivalent correction is negligible at the other two landing sites.

[9] Data assimilation is an approach which has been made possible on Mars by the availability of a substantial data set of MGS measurements with good spatial and temporal coverage. The development and early applications of this technique for Mars have been carried out by *Banfield et al.* [1995], *Lewis and Read* [1995], *Houben* [1999], and *Zhang et al.* [2001]. The data assimilation technique that is used in this paper has been detailed by *Lewis et al.* [2006], and validated against radio occultation observations by *Montabone et al.* [2006]. In this paper, TES observations of temperature and total dust opacity in nadir mode (below about 40 km altitude) were assimilated into the Oxford version of the LMD/AOPP MGCM, as detailed by *Montabone et al.* [2006]. The spectral model of the Martian atmosphere (T31, 32 vertical levels in σ-coordinates, up to about 120 km altitude) makes use of a $5^\circ \times 5^\circ$ latitude-longitude physical grid. The vertical distribution of the dust in the model is prescribed, since no global observations were available in order to assimilate it directly. The measured infrared dust opacities were multiplied by a factor of 2.0 in order to produce equivalent visible opacities to be used by the model radiative transfer code [*Clancy et al.*, 2003]. Temperature, density, zonal and meridional wind profiles as a function of height above the surface were reconstructed along the trajectories of the MERs and above the presumed landing site of Beagle 2 from atmospheric entry (about 120 km altitude) down to the ground. The density profile at Spirit's landing site was corrected as detailed above.

[10] Trajectory reconstruction and retrieval of atmospheric density, pressure and temperature from data provided by accelerometers during EDL is a technique which has been implemented for several entry probes, landers and satellite aerobraking in the past [e.g., *Seiff and Kirk*, 1977; *Magalhães et al.*, 1999; *Withers et al.*, 2003]. In the present work, atmospheric densities along the two entry trajectories of Spirit and Opportunity were determined using the drag equation and measured spacecraft accelerations. Pressures and temperatures were then derived using the equation of hydrostatic equilibrium and the ideal gas law. Details of the method are given by *Withers and Smith* [2006].

3. Results

[11] Martian weather is strongly influenced by waves (stationary, transient, tidal and inertio-gravity) and dust storms. The former are responsible for day-to-day variability [*Leovy and Zurek*, 1979; *Banfield et al.*, 2000], while the latter are responsible for much of the interannual variability, owing to their strong impact on the thermal and dynamical state of the lower atmosphere due to absorption of visible radiation by dust particles [*Leovy*, 2001; *Newman et al.*, 2002; *Montabone et al.*, 2005]. Although large regional storms are generally concentrated around perihelion (which on Mars occurs at solar longitude $L_s = 251^\circ$), local storms can occur at any time of the year.

[12] Observations of infrared dust optical depth from TES over three Martian years illustrate the strong interannual variability of the dust loading into the atmosphere during MGS mapping phase [*Smith*, 2006]. In particular, at the time of the landing of Beagle 2 ($L_s = 322.0^\circ$, Martian year 26) and the two MERs ($L_s = 327.7^\circ$ and $L_s = 339.1^\circ$), TES zonally-averaged optical depth shows a peak due to the occurrence of regional storms started in Chryse Planitia and the region between Argyre and Hellas Planitias (Noachis Terra). As a consequence, the optical depth at the landing sites was slightly larger than expected compared to the previous two years of MGS observations, although not outside the expected long-term climatological variability.

[13] According to TES measurements close to the time of the MERs' EDL, the infrared total optical depth at the reference pressure of 610 Pa was respectively 0.34 at Spirit's landing site and 0.28 at Opportunity's [*Withers and Smith*, 2006]. The equivalent visible opacity inferred by the assimilation is about twice that of the measured infrared one, as expected. According to the assimilation, therefore, Beagle 2 should have experienced an equivalent visible total optical depth at 610 Pa of about 0.8 at the time of landing. Such visible opacities are much larger than the EMCD opacities of the baseline scenario at the corresponding time of year, which are 0.19 (Beagle 2), 0.18 (Spirit) and 0.17 (Opportunity). The opacities of the warm EMCD scenario (respectively 0.92, 0.78 and 0.74), however, agree better with the (equivalent visible) measured ones.

3.1. Mars Exploration Rovers

[14] Spirit landed on Mars at 175.48°E, 14.57°S, touching down at 14:25 (local true solar time), $L_s = 327.7^\circ$ (MY 26). Opportunity landed at 5.53°W, 1.95°S, touching down at 13:23, $L_s = 339.1^\circ$ (D. M. Kass et al., PDS volume MERIMU_0001, NASA Planetary Data System, MER1/MER2-M-IMU-4-EDL-V1.0, 2004, available at http://starbrite.jpl.nasa.gov/pds-explorer/dsidnode.jsp?nodename=ATMOS&datasetid=MER1/MER2-M-IMU-4-EDL-V1.0&volume=merimu _1001). The first impact on the surface for each rover occurred few minutes before these times.

[15] MGS/Mars Orbiter Camera (MOC) images show that the regional dust storms which started around $L_s = 315^\circ$ had already faded out, although an enhanced veil of dust was still present in the atmosphere, particularly at the

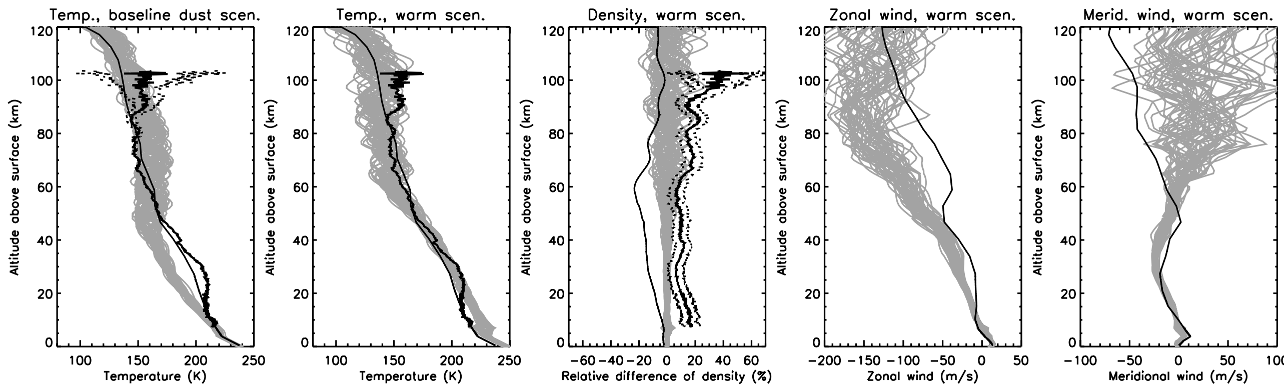

Figure 1. Temperature, density, zonal and meridional winds along the EDL trajectory of Spirit. The smooth, thin line is for assimilation, the thick line is for the retrieval from accelerometer data (dotted lines bound the corresponding $1-\sigma$ errors), and the light grey lines are from the EMCD. Two dust scenarios are shown for the temperature profiles of EMCD, as described in the text. Density and wind profiles are only shown for the warm scenario. Density is plotted as relative difference in per cent with respect to the average of EMCD densities.

time of the landing of Spirit. (You can find MOC images at http://www.msss.com/mars_images/moc/mer_weather/. See also auxiliary Figure S1[1].) As a consequence, the best fit of the actual temperature profiles in the lower atmosphere (below 50 km altitude) is obtained by using the warm EMCD dust scenario rather than the baseline scenario, especially for the case of Spirit (see Figure 1). For Opportunity, the fact that both the assimilation and the accelerometer temperature profiles are in better agreement with the baseline dust scenario above 90 km altitude might indicate that most of the dust had already moved to lower altitudes at that time (see Figure 2).

[16] Good agreement is found between the temperature profiles from the assimilation and those retrieved from the accelerometers. The agreement between the two techniques is particularly striking in the case of Spirit over the entire range of heights, well above the altitude at which TES nadir observations stop. Nevertheless, accelerometer retrievals appear to be warm-biased by up to 10 K compared with the assimilation between 20 and 50 km. Such a warm bias seems to be a common characteristic for all the Martian landers to which the accelerometer technique has been applied [*Withers and Smith*, 2006].

[17] In the case of Opportunity, the temperature shows an inversion at about 60 km altitude, which is only partially reproduced by the assimilation, and a second very strong inversion at about 85 km altitude, which is in anti-phase with the assimilation. In the model, this latter inversion, which is a signature of thermal tides, occurs 15 km lower than in the accelerometer profile at that local time. Since TES observations were only assimilated below 40 km, this could be an intrinsic model bias. Also the inversion at 60 km altitude is out of phase in the assimilation profile, but a similar inversion is present at that local time at nearby model longitudes. The inversion around 10 km altitude is neither present in the assimilation profile nor in the EMCD one. The vertical resolution of the model near the ground is fairly good (twelve model levels in the first scale height), therefore the fact that no hints of inversion are present could signify that either the horizontal resolution of the model is too coarse for showing such an inversion or the inversion is an artifact of the accelerometer retrieval. A definite answer is beyond the scope of this paper.

[18] As for density, the apparent 20% difference between the accelerometer profile and the profile from the assimilation in the case of Spirit is due to a large difference in the value of surface pressure derived by the two techniques. The assimilation yields a surface pressure of $p_s = 601$ Pa, whereas the estimate of p_s from the accelerometer data is 720 ± 110 Pa. The difference between these two pressure estimates, which accounts for a 20% difference in density, is only slightly larger than the $1-\sigma$ uncertainty in the estimate from accelerometer data. It is likely, however, that Spirit's estimate of p_s by accelerometer data is too high. It is worth noting that, despite this systematic difference, the two density profiles exhibit a similar shape.

[19] Densities are rather similar for all the profiles in the lower atmosphere in the case of Opportunity. Accelerometer and assimilation estimates are within ±10% of each other below 60 km altitude, and ±20% with respect to the average of EMCD densities. The upper part of the profiles diverge with respect to EMCD, but the agreement improves if the baseline dust scenario is used, as for temperature (within ±20%, not shown here). Moreover, the assimilation shows a behaviour very similar to the accelerometer density for the entire profile.

[20] Density is one of the critical variables for EDL design. The results shown here indicate that the EMCD is able to predict a density value within ±20% of the actual atmospheric density over most of the altitude range of EDL, if the full variability of the database is used (different dust scenarios, and large and small scale variability). In particular, this error reduces considerably below 20 km altitude, which is the critical range for parachute deployment, and remains within ±10%.

[21] Another critical factor in the choice of a landing site is wind. Measurements of winds are extremely rare on Mars, but assimilation can provide wind values that can be compared to the climate forecast of the EMCD. Wind profiles in

[1]Auxiliary material is available in the HTML. doi:10.1029/2006GL026565.

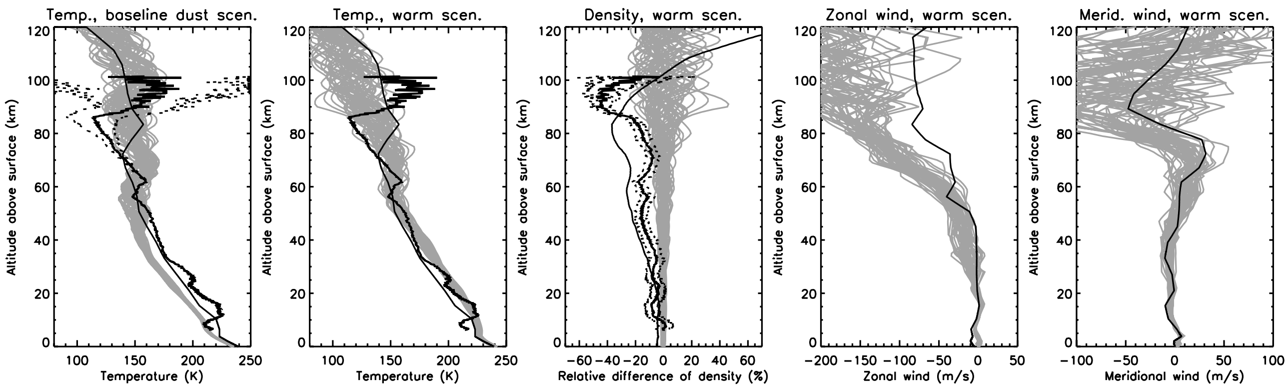

Figure 2. As Figure 1, for the case of Opportunity.

the assimilation and in the EMCD are generally in good agreement for the case of the two MERs, particularly in the lower atmosphere where TES observations are assimilated. Differences are evident in the upper parts of the profiles for the case of Spirit meridional wind and Opportunity zonal wind, but such differences are smaller if the EMCD baseline dust scenario is used (not shown here). While this is in accordance with the behaviour of temperature and density for Opportunity, the case of Spirit might indicate a high sensitivity of middle atmosphere wind (above 50 km altitude) to the dust loading in the lower atmosphere in the model.

3.2. Beagle 2

[22] According to the reconstructed landing point by *Bauske* [2004], Beagle 2 might have landed on the surface of Mars at 90.50°E, 11.53°N, impacting on the surface at 13:34 (local true solar time), $L_s = 322.0°$.

[23] Auxiliary Figure S1 mentioned above shows that two regional dust storms were active at the time of the landing, one in Meridiani Planum and the other one in Noachis Terra. Neither of them affected directly the landing site in Isidis Planitia, but certainly they contributed to increasing the amount of dust loading overall in the atmosphere. As a consequence, the EMCD ensemble of temperature profiles with the warm scenario is found to be in very good agreement with the assimilation along the whole range of EDL, within a few K (see Figure 3).

[24] Density is found to be within 10% with respect to EMCD average densities at all altitudes below 85 km, and within 5% below 20 km. Such a small error is within the nominal error for parachute deployment [*Sims et al.*, 2004]. Densities appear to be larger than expected above 85 km altitude, where a peak of almost 40% difference is reached around 100 km altitude. This difference is due to the steeper lapse rate of temperature in the assimilation compared to the EMCD above that altitude.

[25] It is remarkable that the density difference with respect to EMCD is around 10% below 25 km altitude even if one uses the baseline dust scenario (see the dashed line in Figure 3), which is clearly colder than the reconstructed atmospheric state between 10 and 55 km altitude. This suggests that the choice of the dust scenario should not have dramatically affected the critical operation of parachute deployment for Beagle 2. Nevertheless, the use of the baseline dust scenario (∼clear atmosphere) would introduce a significant difference in density with respect to the assimilation above 40 km altitude, with a peak of 70% around 70 km altitude.

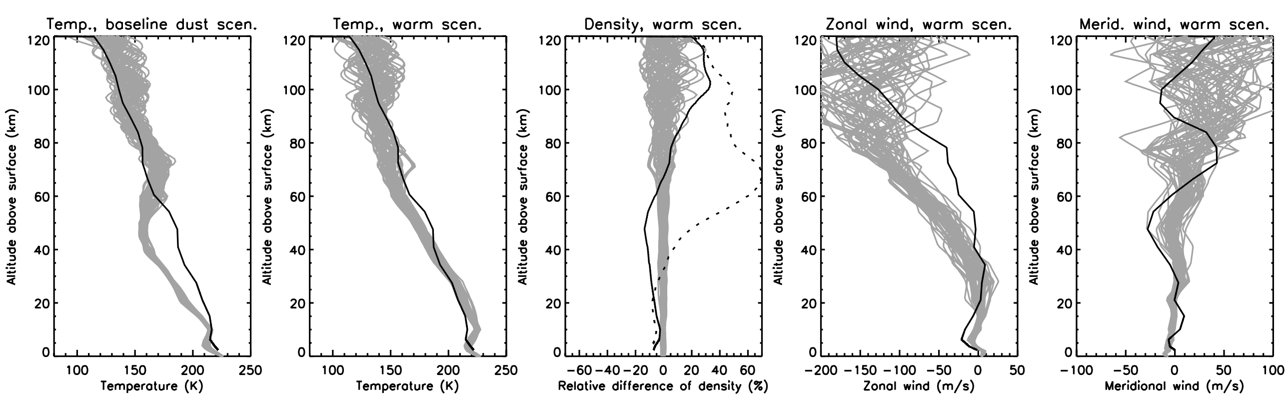

Figure 3. Temperature, density, zonal and meridional winds at the landing site of Beagle 2. The black solid lines are the reconstruction from the assimilation and the light grey lines are from the EMCD. Two dust scenarios are shown for the temperature profiles of EMCD, as in Figure 1. Density is plotted as relative difference in per cent with respect to the average of EMCD densities. The black solid line shows the difference between the assimilation and the mean EMCD warm dust scenario; the dashed line shows the difference between the assimilation and the mean EMCD baseline dust scenario. EMCD variability about the mean density (in grey) is shown for the warm scenario only.

[26] The reconstructed meridional wind strength is in close agreement with EMCD (for both dust scenarios), likewise the zonal wind, at least below 40 km altitude. No evidence for anomalous large scale wind is found in the lower atmosphere. The largest difference below 40 km altitude lies within an error of ± 10 m s^{-1}. This does not exclude possible strong gusts which might have affected the landing of Beagle 2 before touching down.

4. Conclusions

[27] Landing a spacecraft on Mars requires a good forecast of the weather conditions at the time and location where the landing might occur. This means relying on past observations and model forecasts. Data assimilation could play a more important role in the future, if this technique were to be implemented at the level of an operational forecast. This in turn needs frequent observations on global and local scales.

[28] Nevertheless, we have demonstrated in this paper that the reconstruction a posteriori of the weather at the time when Beagle 2 and the two MERs landed on Mars is in good agreement with the climatological state as provided by the EMCD, if the full variability predicted by this database is taken into account.

[29] In fact, no evidence for systematic errors in the EMCD climate forecast was found. The atmospheric dust loading was higher than that at the same point in the preceding two Mars years, but within the range of conditions which might be expected in the absence of a global dust storm. As a consequence, the reconstructed temperature, density and wind profiles generally agree better with the warm dust scenario than with the baseline one.

[30] These results highlight the importance of taking into account the full variability provided by the EMCD for critical applications such as EDL design, given the observed strong interannual variability of the Martian atmosphere.

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