Near-surface temperatures at proposed Mars Exploration Rover landing sites

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[1] Minimum nighttime temperatures at the Mars Exploration Rover (MER) landing sites may limit power available for science activities and thus mission lifetime. Here, 1 m air temperatures at the end of the nominal 90 sol primary mission are derived for the four primary and three previously considered MER landing sites based on Mars Global Surveyor Thermal Emission Spectrometer thermal inertia and albedo, estimated opacity, and predictions of air temperatures from a one-dimensional atmospheric model. Taking these results and mapping them onto the probability density distribution of the landing ellipses shows that of the air temperatures of the primary sites, Sinus Meridiani ("Hematite") is the coldest, with an 8% chance of encountering minimum nighttime temperatures below the 176 K value considered a practical limit for operations. Elysium and Gusev are at 7% and 3%, respectively, whereas Isidis has no computed temperatures below 191 K. For the Hematite site, preliminary observations and interpretations are also made using high-resolution Odyssey Thermal Imaging System predawn images. *INDEX TERMS:* 0350 Atmospheric Composition and Structure: Pressure, density, and temperature; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3346 Meteorology and Atmospheric Dynamics: Planetary meteorology (5445, 5739); 6225 Planetology: Solar System Objects: Mars; *KEYWORDS:* Mars, atmosphere, temperature, MER, surface, model

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1. Introduction

[2] Recent measurements of Mars, together with continually updated models, provide a variety of improved environmental parameters for the Martian surface and atmosphere. For example, accurate topography and slopes from the Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter experiment have led to more accurate prediction of winds in circulation models, as well as improved ability to model local thermal regimes. Accelerometer measurements made during aerobraking by MGS and Odyssey refine the understanding of density and wave phenomena above 100 km, for the benefit of future mission atmosphere entries. Of particular reference to this paper, thermal inertias, albedos and infrared dust opacities from the MGS Thermal Emission Spectrometer (TES) have improved thermal modeling of the surface and the bulk atmosphere.

[3] Among the atmospheric models of value are global circulation models (GCM), which cover the entire planet at limited spatial resolution, mesoscale models that focus on spatial subsets in order to capture local behavior, particularly topographic effects, and one-dimensional models that serve to model boundary layer behavior near the surface in the vertical dimension. Integrated together, these models provide capability to estimate a range of environmental parameters at scales from meters to thousands of kilometers. These products can be of critical importance in the design and operation of future Martian vehicles, both orbital or operating in the atmosphere or on the surface.

[4] A one-dimensional (altitude) model is used here because of its value in predicting near-surface temperatures that influence the power available for a Martian rover. Power is used for many purposes on a rover, including driving; communication; operating instruments; and maintaining component temperatures. Solar power replenishes the batteries. The input power available depends on sun angle (a function of latitude and season) and dust opacity, and also upon how much dust has built up on the solar panels. Power used to maintain temperature of the MER warm electronics box (WEB) and particularly external instruments at night can be important in cold environments. The Mars Exploration Rover (MER) mission has a stated mission lifetime of 3 months.

[5] Heat loss from the rovers is a mixture of radiative and convective mechanisms. The highest losses occur when it is coldest, at predawn, or approximately 0600 Mars local time. Predawn is the coldest time of day, both for the surface layer and near-surface air that is strongly coupled thermally to the surface. The high emissivity (ε) top surfaces of the vehicle

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lose substantial radiative heat to the cold, ~140 K, Martian sky. Bottom surfaces are cooled by radiation to the cold ground. The WEB is encased within the rover body and is covered by gilded kapton of $\varepsilon = 0.3-0.4$. Because of its insulated location and low emissivity casing, the WEB loses about 65–86% of its heat via convection, despite the low density of the Martian atmosphere. The atmospheric temperature at about 1 m above the surface is a fundamental parameter that ties into mission lifetime predictions. Engineering models estimate that night temperatures routinely below about 176 K (−97°C) substantially limit total mission lifetime below the goal of 3 months (K. Novak, personal communication, 2002, 2003). To provide such input for MER surface lifetime predictions, we estimate herein near-surface predawn temperatures for several MER candidate landing sites.

[6] The near-surface air temperature relevant to the rover depends primarily on surface temperature, which itself depends on albedo, thermal inertia, latitude, season (areocentric solar longitude, L_s), and dust opacity. Local slope also affects the surface insolation. Winds can modify air temperature, by advecting air from other thermal regimes. Nighttime drainage winds are a possible concern, operating for hours at the coldest times of day. However, significant mixing associated with winds can also bring warmer air from higher layers down to the surface. Detailed modeling of landing sites has been done by several mesoscale modeling groups [*Rafkin et al.*, 2001; *Toigo and Richardson*, 2002], primarily for estimation of winds affecting entry. Analysis and comparison of their surface air temperature predictions is beyond the scope of this paper.

[7] In this paper we estimate near-surface temperatures at 0600 Mars local time for several MER candidate landing sites. It should be emphasized that the entry and landing process for MER does not allow avoidance of small-scale features. Rather, this work permits a statistical determination of the likelihood that landing in a given large region, specified by the landing error ellipse, will produce problematical conditions.

2. Methods

[8] We present here two separate approaches for determining minimum nighttime near-surface air temperatures. In the first case, we employ albedo and thermal inertia map data derived from the MGS TES experiment brightness temperature spectra and solar band radiances, and apply these in a parameterized one-dimensional (1-D) atmosphere model to map minimum 1 m air temperatures. The TES data have a spatial resolution of about 3 × 6 km.

[9] The second approach uses much higher resolution (100 m) nighttime thermal mapping performed by the Odyssey Thermal Imaging System (THEMIS) experiment, and applies a process to correct those brightness temperature data for effects of surface emissivity, time of day, and seasonal variation. We then add thermal offsets from the 1-D model to arrive at the minimum air temperatures. This approach is a little more uncertain, in that the THEMIS data used are incompletely calibrated; the albedo employed for emissivity derivation is not mapped at as high a spatial resolution. The high spatial resolution may also be of little value if winds act to smooth the thermal behavior at the 100 m spatial scale. We consider this second approach a trial study and therefore apply it to just one THEMIS data strip going through the Hematite landing ellipse, which, at the time of writing, is considered the primary MER landing site candidate.

2.1. 1-D Temperature Modeling

[10] The one-dimensional model developed at NASA Ames Research Center is intended to reproduce boundary layer behavior observed by the Pathfinder and Viking landers' meteorology experiments. Surface thermal behavior is the starting point. Temperatures at a variety of levels are then predicted for all times of day.

[11] Modeled ground and near-surface air temperature results are generated with a one-dimensional (vertical) formulation of the NASA Ames Mars GCM [*Pollack et al.*, 1990; *Haberle et al.*, 1997, 1999]. In this one-dimensional mode, horizontal winds are set to zero, and results are generated at one specific latitude-longitude location. Temperatures are dependent upon: latitude, L_s, surface pressure (dependent upon topography), thermal inertia, albedo, and dust optical depth. The model formulation allows for input of each of these parameters for a site of interest. Sensitivity is investigated via changes in the more uncertain parameters.

[12] The model determines heating and cooling, and thus temperature, by accounting for absorption of solar (visible, near IR) radiation by both CO_2 gas and suspended dust and the absorption and emission of infrared radiation (within two bands, the 15 μm band and all others) by dust and CO_2. The surface is warmed or cooled by the net radiative flux at the atmosphere-surface boundary as well as sensible heat exchange with the atmosphere in contact with the surface. Additionally, vertical mixing is included, with its intensity dependent upon local stability considerations. The model also includes diffusion of heat into and out of the upper 0.25 m of the regolith. This depth accounts for the penetration of the diurnal thermal wave, but is less than the depth of the annual thermal wave penetration.

[13] The model faithfully reproduces the Viking lander and Mars Pathfinder lander observed near-surface air temperatures when the appropriate location, surface property, and dust opacity conditions are specified [*Haberle et al.*, 1997, 1999]. This ability of the model to reproduce the observed fields provides confidence that results applied to other potential landing sites are representative of the environment that would be experienced there for the correct surface characteristics.

[14] Numerical simulations included the diurnal radiation cycle, and were initialized with an isothermal profile from the surface to a model top pressure of 0.01 mbar (~6 scale heights). Simulations were executed for 20 sols, during which the seasonal date did not advance. The diurnal cycle equilibrated after ~12 sols, with subsequent sol-to-sol variations being less than 0.2 K for the diurnal minima and maxima. Typical diurnal behavior of near-surface air temperatures relative to surface temperature is portrayed in Figure 1 for the Meridiani landing site.

2.2. TES Albedo and Thermal Inertia

[15] The MGS TES experiment [*Christensen et al.*, 2001] measures surface temperature in the afternoon and early

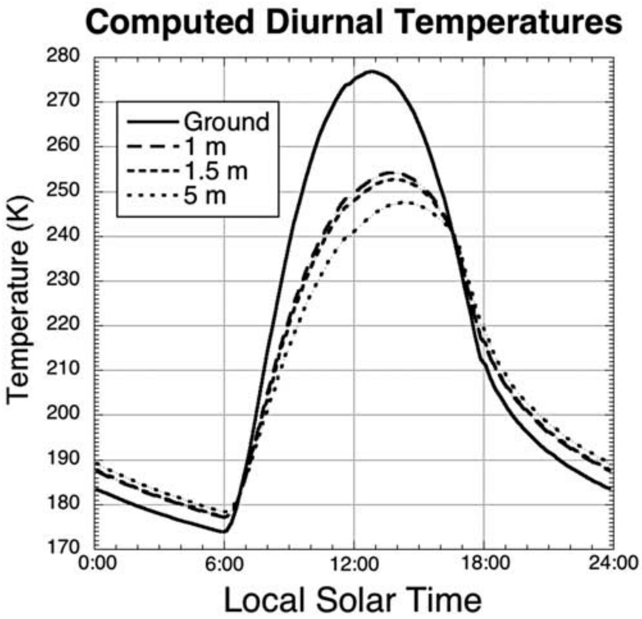

Figure 1. Diurnal behavior of one-dimensional atmosphere model temperatures for the surface and the near-surface atmosphere at the Sinus Meridiani ("Hematite") MER landing site near the end of its nominal mission. Five percent variations in the thermal inertia and albedo values produce potential ±1.5 K variations in the minimum calculated ground and near-surface air temperatures.

predawn hours using 6–40 μm spectroscopy with 3 × 6 km spatial resolution. Predawn temperatures are most sensitive to thermal inertia variation [*Mellon et al.*, 2000]. The experiment also carries a broadband reflected light channel employed to measure surface albedo at the same spatial resolution during the dayside passes. Essentially complete maps of Mars have been created by the TES team for both these parameters. For this work we employ maximum resolution maps of the MER landing sites that were prepared by S. Pelkey (personal communication, 2002) for study of the thermal properties of the sites. Thermal inertia and albedo are, of course, of separate interest in evaluating the surficial geology of Mars.

[16] Of additional value are the global dust opacities determined from the 9 μm silicate band absorption observed by the TES [*Smith et al.*, 2001]. Though variable in time, for the period of the MER mission, L_s 326°–24°, opacities are likely to be similar to those measured by MGS at comparable season during 1998 and 2000, unless a late dust storm season produces a high-opacity tail into that time frame. The worst case for low nighttime surface temperature is low opacity; we have assumed a value of 0.2 for the visual dust opacity for this work; this value is realistic for expected conditions at the MER sites.

2.3. Analysis Approach Using MGS TES Data

[17] The low-resolution TES data provide accurate mapping of thermal inertia (derived from brightness temperature) and albedo for the landing sites, and thus reliable estimates of the primary parameters affecting surface temperature. The spatial resolution is much smaller than the landing error ellipse size (~30 × 150 km), so we get a good indication of zones within the ellipses that may have anomalous low temperatures.

[18] In order to assess relative behavior at different sites, we created an albedo versus thermal inertia plot with the landing site data. Sites with the lowest temperatures will have low thermal inertia (typically dust shows the lowest values) and bright albedo (dust is bright relative to dust-free regions). Using the 1-D model, we calculated minimum air temperatures as a function of albedo and inertia for a variety of cases, and constructed contour lines of minimum air temperature in the A versus I plot (Figure 2). Using this plot, one can readily assess the likelihood of encountering seriously low temperatures in a given landing ellipse.

[19] For method 1, we have also compared the results of two separate models for surface temperature, to assess this contribution. *Mellon et al.* [2000] developed a surface thermal model that incorporates a good estimate of the contribution from the overlying atmosphere and its dust opacity-dependent downwelling flux. We believe this model gives perhaps the best current representation of the surface temperature. However, for estimation of the thermal behavior of the near-surface air, we find the Ames 1-D model probably superior, being designed specifically for this purpose. Perhaps the best estimate of minimal air temperatures would come from deriving the surface temperature for a given albedo/inertia/opacity condition using Mellon's model, and then offsetting to the air temperature using the Ames model runs for comparable settings. A direct comparison of minimum surface temperatures from Mellon and from the Ames for a common test case yielded a difference between them of 3 K, with Mellon's model being warmer. In the work below, we have used the Ames model alone.

2.4. Analysis Approach Using Odyssey THEMIS Data

[20] It is complex to process THEMIS measurements into minimum air temperatures (Figure 3). We must convert from brightness temperature to kinetic surface temperature. Then we apply a translation to 0600 hours local time, and a correction from the season of measurement to the season of interest. Finally, we apply an offset from the surface temperature to the temperature at 1 m.

[21] We start with THEMIS Band 9 (11.79 μm) brightness temperatures, obtained at about 03 hours local time. The THEMIS data were calculated assuming a surface emissivity of 1 and an atmospheric opacity of 0, which is the usual approach for representing brightness temperature. *Christensen* [1982] found a correlation between albedo and emissivity in Viking IR Thermal Mapper data. The correlation was similar at the IRTM 10–12 μm band to that for 18–24 μm. We have assumed that this correlation can be applied also at the THEMIS Band 9 wavelength. For the location of the THEMIS pixel, we look up mapped albedo from the TES data, which are necessarily at lower resolution than THEMIS. Emissivity is taken from the expression

$$\varepsilon = 0.884 + 0.412 * A,$$

but if $A > 0.28$, then $\varepsilon = 1$. In order to apply an emissivity, we must convert brightness temperature to radiance. That is

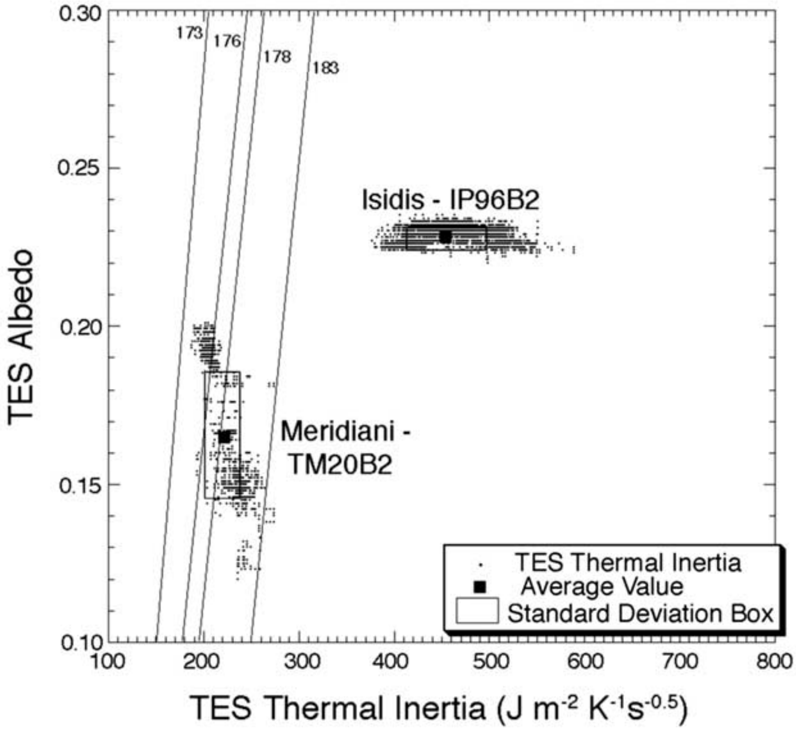

Figure 2. Contours of minimum diurnal 1 m air temperature (°C) in albedo/inertia space for latitude −2, season L_s 30, and dust opacity 0.2. The contours are defined by 1-D model runs for a grid of *A*/*I* points. The distribution of *A*/*I* points in the Meridiani ellipse indicates a fraction falling below the −97°C line (176 K). The Isidis location is far warmer.

done using a utility expression derived by the IRTM team for the IRTM 12 μm band. We then divide the radiance by the emissivity, and convert back to temperature units using the inverse IRTM formulation. The result is our kinetic temperature estimate. The application of emissivity leads to a maximum correction to the brightness temperature of about 2 K (4% in radiance). Note that the brighter the surface, the smaller the required correction.

[22] We then translate from the local time of the THEMIS measurements (3 hours) to the time of minimum temperature, which is 0600 LT at this season and latitude. This correction is applied based on the models developed by *Mellon et al.* [2000]; they show that for different thermal inertias, the temperature curves are essentially parallel in the predawn period, so we can apply a single correction (−1.7 K) for the range of thermal inertias encountered here.

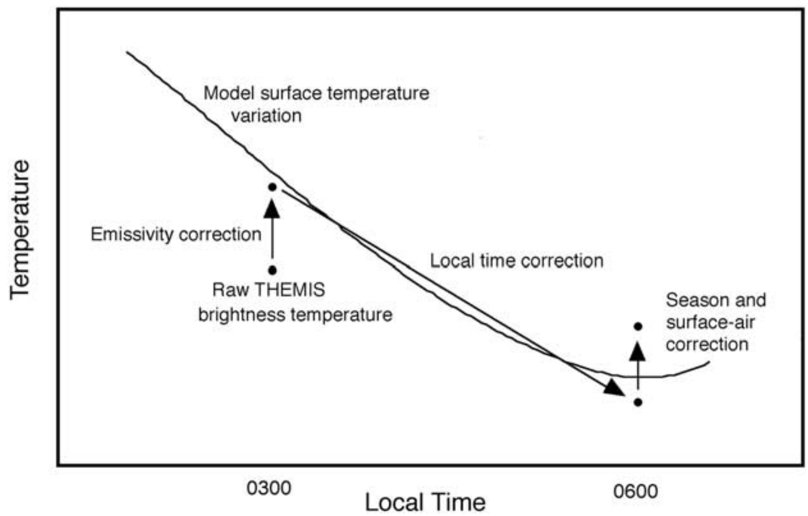

Figure 3. Correction of THEMIS nighttime brightness temperatures. We show the schematic effects of converting to surface kinetic temperature using nonunit emissivity, translating in local time and season, and allowing for the surface/air thermal offset.

Table 1. Errors in Computing Minima From THEMIS Data

	Error
Input temperatures	1–2
Emissivity	0.2
Local time	0.5
Season, K	1
Air offset, K	1

[23] The THEMIS data were acquired between L_s 330–350. The variation in model minimum air temperature across this range is about 0.5 K. In fact, that temperature undergoes a seasonal maximum value at about L_s 336; this is just the time when most of the THEMIS data were acquired. For MER, the worst case time period lies at the end of the nominal mission, at L_s 30. We use the 1-D model to translate temperature across this seasonal distance. The change is about -5.2 K.

[24] The final correction is the offset from surface to near-surface air temperature. In the Ames 1-D model runs, this value at 0600 LT is essentially independent of thermal inertia. The magnitude of the surface to 1 m air temperature difference is also nearly constant during the L_s range 336–30, at 3.1 K, the air being warmer than the surface. Physically, this effect is largely due to the surface having a superior ability to radiate to space.

[25] There is also a dependence on dust opacity. We employ here model runs for an opacity of 0.2, which is consistent with TES observations for this period during 1998 and 2000 [*Smith et al.*, 2001]. The worst case for MER is at such low opacities, when the nighttime radiative cooling to space is maximal.

[26] Several error sources of comparable magnitude contribute to the uncertainty in our derived minimum temperatures for the landing sites using THEMIS data. We list these in Table 1 for the second approach method. The nighttime data now have a quoted error of 1–2 K due to THEMIS calibration. A reasonable albedo error of 0.02 produces an emissivity error of 1%, leading to a brightness temperature error of 0.2 K. The model temperature time of day translation produces no more than 0.5 K variation for the range of inertia values encountered. The seasonal variation of the model is more difficult to assess; allowing 20% error over this 50° of L_s would yield an error of 1 K in that translation. The surface temperature offset depends likewise on many factors, but the value varies very little among model runs with differing input parameters. We assign 1 K error here as well. When combined, these sources of error lead to an overall estimated uncertainty of about 2–4 K in the nightly minima.

3. Results

3.1. Method 1: Using TES Albedo and Inertia

[27] The Hematite site is characterized by low albedos, so is not covered by substantial amounts of dust. However, the surface also shows low inertias, with the brightest areas – perhaps having the largest fractional coverage by dust, falling well below the −97°C limit for low nighttime temperatures (Figure 4). The standard deviation of minima

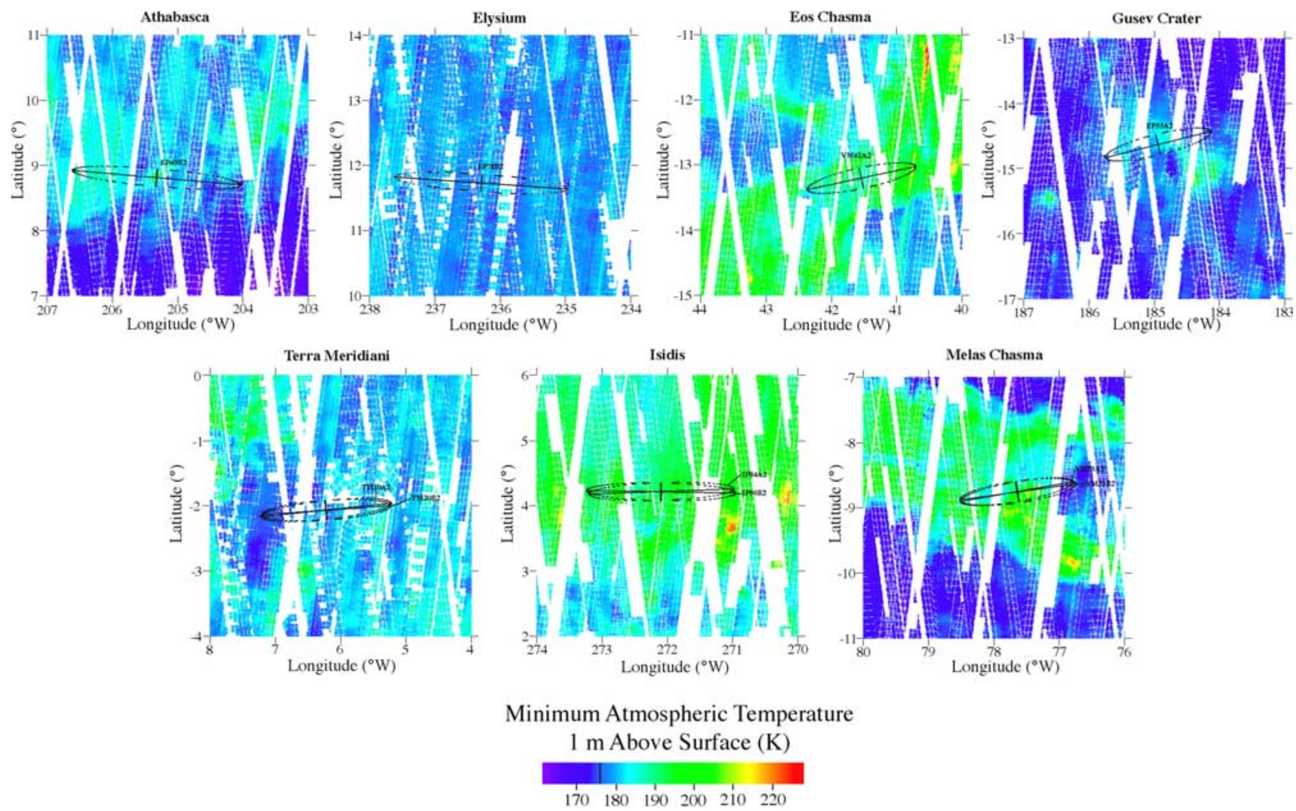

Figure 4. Maps of minimum air temperatures for the Mars Exploration Rover candidate landing sites; the ellipses are defined by 99% landing probability.

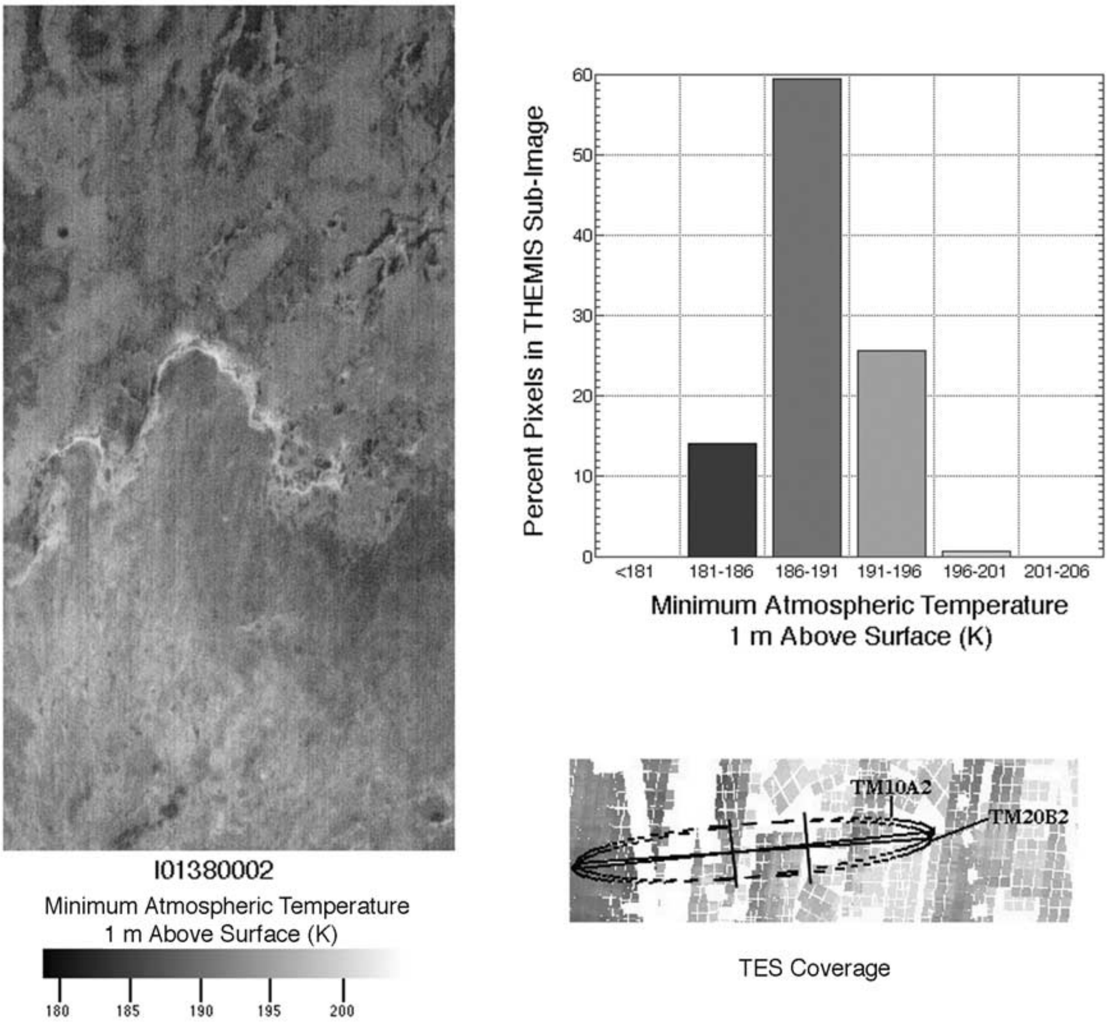

Figure 5. Map of minimum 1 m air temperatures for a portion of a single THEMIS predawn image (I01380002) within the Hematite landing ellipse. This image covers a region within the ellipse indicated by lines across the center of the map of TES temperatures (lower right). This distribution of temperatures is shown in the histogram.

within the ellipse is 2.3 K. We calculate that 8% of the landing ellipse will achieve such low temperatures near the end of the MER mission. Landing in such areas would imply energy limitation of rover operational lifetime.

[28] The brightest material within Gusev crater, which is likely dust deposits, also cools enough to create problematic nighttime air temperatures. The overall probability of encountering values below −97°C is 3%. The Isidis site contains generally higher thermal inertias, and consequently nighttime surface temperatures do not fall low enough to be of concern for mission lifetime. Elysium shows a very small range of values in *A*/*I* space, indicating a fairly uniform surface character. The few problematic data points fall nearer the ellipse center than for Hematite, and thus contribute more strongly to the overall probability of landing in such locations (7%).

3.2. Method 2: Using THEMIS Data

[29] The THEMIS data offer a very different picture of the thermal environment, in that minor variations in surface temperature at the 100 m spatial scale arising from thermal inertia differences translate directly into perceived variations in the minimum air temperature (Figure 5). The image shows a total temperature range of 23 K, and has a variance of 2 K. The similarity of the variance to that from the TES analysis is probably due to the smaller coverage of the THEMIS strip. We would expect greater spatial resolution to yield a better sampling of extreme values. The structure of the image implies that significant variation in thermal behavior is encountered within the potential driving range of the MER vehicles. The detailed variation may also be influenced by topography, which affects the daily insolation available, but as with albedo, the effect at night is likely smaller than for inertia.

[30] The mean predawn air temperature from the THEMIS strip for the Hematite site exceeds the mean for the whole ellipse using method 1 above by 10 K. Part of this is due to the strip occurring in a higher-inertia region of the ellipse. We also may see here calibration errors in these early-reported THEMIS temperature values; THEMIS data are not as easily calibrated as TES; subsequent data releases should show better agreement with TES data.

[31] Whether the surface air in fact behaves as shown in Figure 5 depends on what other factors can influence the temperature, especially wind. A significant regional wind would act to mix local inhomogeneities and average out the lowest values. A wind of sufficient magnitude would also serve to mix air from higher layers that at this time of day would be warmer; the surface layers cool more rapidly due to contact with the more efficiently cooling surface. In this sense, wind improves the minimum temperature picture for the rover. It becomes of high interest to see what mesoscale models predict for the finest-scale wind behavior. These models are available now for the first time in Martian science, and their interaction with our work may be a fruitful effort in the future.

[32] Coverage of the landing site ellipses by THEMIS is incomplete at the time of this writing, so a fuller spatial analysis of probabilities of encountering thermal regimes, like that possible with the TES data, will likewise be deferred.

4. Summary

[33] This work serves to demonstrate one way in which physical measurements of Mars can be applied to serve engineering needs for future missions. It is analogous to the process undergone for the Viking landers, in which orbital imaging and infrared data provided estimates of risk for landing based on extrapolation of low-resolution data, comparisons to terrestrial sites, and careful analysis of thermophysical models.

[34] For the Mars Exploration Rover mission in particular, the data indicate a small but real risk to the extended operation of a rover landing in certain parts of the Hematite and other landing ellipses.

[35] Combining data from MGS TES and Odyssey THEMIS with surface and atmospheric thermal models provides a fruitful way to estimate certain parameters of engineering value for the MER mission. Of particular interest here are the nightly minima in air temperatures near the 1 m level; these affect conductive cooling of the rover and consequently the power required to maintain internal temperatures at night.

[36] We find within the original Hematite landing ellipse numerous locations where the nightly minimum 1 m air temperature could fall below −97°C. The probability of landing in a region of concern for rover lifetime is 9%; the corresponding result for Gusev is 3%.

[37] **Acknowledgments.** We are grateful for the help of several individuals without whom this effort would have been much more difficult or impossible. S. Pelkey graciously provided TES thermal inertia and albedo maps for our use. R. Fergason did likewise with THEMIS images. M. Mellon gave insight and critique at many stages of this project. M. Adler coached us in the proper use and interpretations of the ellipse probability density distribution. K. Novak, who used these thermal models for surface lifetime predictions, provided information on rover cooling assumptions used by the MER engineers. We acknowledge the support of the Mars GCM group at NASA Ames. Finally, we acknowledge support of the MER Characterization Task in funding this study.

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