Available online at www.sciencedirect.com
SCIENCE DIRECT®

ELSEVIER

Icarus 180 (2006) 314–320

ICARUS

www.elsevier.com/locate/icarus

Surface and near-surface atmospheric temperatures for the Mars Exploration Rover landing sites

N. Spanovich [a,b,*], M.D. Smith [c], P.H. Smith [b], M.J. Wolff [d], P.R. Christensen [e], S.W. Squyres [f]

[a] *Jet Propulsion Laboratory, MS 264-422, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*
[b] *Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Boulevard, Tucson, AZ 85721, USA*
[c] *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[d] *Space Science Institute, 18970 Cavendish Road, Brookfield, WI 53045, USA*
[e] *Department of Geological Sciences, Arizona State University, PO Box 871404, Tempe, AZ 85287, USA*
[f] *Department of Astronomy, Cornell University, 406 Space Sciences, Ithaca, NY 14853, USA*

Received 19 January 2005; revised 4 August 2005

Available online 23 November 2005

Abstract

Downward-looking spectra of the martian surface from the Miniature Thermal Emission spectrometer (Mini-TES), onboard each of the two Mars Exploration Rovers, are modeled in order to retrieve surface and near-surface atmospheric temperatures. By fitting the observed radiance in the vicinity of the 15-μm CO_2 absorption feature, the surface temperature and the near-surface atmospheric temperature, approximately 1.1 m above the surface, are determined. The temperatures from the first 180 sols (martian days) of each surface mission are used to characterize the diurnal dependence of temperatures. The near-surface atmospheric temperatures are consistently 20 K cooler than the surface temperatures in the warmest part of each sol, which is 1300–1400 LTST (local true solar time) depending on the location. Seasonal cooling trends are seen in the data by displaying the temperatures as a function of sol. Long ground stares, 8.5 min in duration, show as much as 8 K fluctuation in the near-surface atmospheric temperatures during the early afternoon hours when the near-surface atmosphere is unstable.

Keywords: Mars, atmosphere; Mars, climate; Mars, surface

1. Introduction

Atmospheric temperatures within the lowest few meters above the martian surface are diagnostic of processes occurring within the planetary boundary layer that control the exchange of heat and momentum between the surface and atmosphere. This region of the atmosphere is also the environment in which the rovers operate. The Mars Exploration Rovers (MER) Athena payload (Squyres et al., 2003) does not contain a meteorology package (as did the Viking and Pathfinder landers) that can measure near-surface atmospheric temperature, pressure, and winds directly using in situ instruments. However, here we describe a new algorithm that uses the observed absorption in the 15-μm CO_2 band in downward-looking MER Miniature Thermal Emission spectrometer (Mini-TES) observations of the surface to retrieve the near-surface atmospheric temperature at about 1.1 m above the surface. Mini-TES is the first infrared spectrometer to take observations from the surface of Mars, and here we demonstrate the utility of this method for obtaining near-surface atmospheric temperatures. These near-surface atmospheric temperatures are complementary to the atmospheric temperatures retrieved from upward-looking observations, which are sensitive to temperatures between 20 m and 2 km above the surface (Smith et al., 2004).

Previous observations of near-surface atmospheric temperatures have been made by thermocouples mounted to masts on the two Viking landers (Hess et al., 1977) and the Pathfinder lander (Schofield et al., 1997) at heights of 0.25 to 1.6 m above the surface. Those observations have shown the large diurnal and seasonal variations in near-surface atmospheric tempera-

* Corresponding author. Fax: +1 818 393 2436.
E-mail address: nicole.spanovich@jpl.nasa.gov (N. Spanovich).

0019-1035/$ – see front matter
doi:10.1016/j.icarus.2005.09.014

tures that occur on Mars, as well as the fluctuations on shorter time scales that are caused by convective turbulence.

2. Data set and retrieval algorithm

2.1. Instrument

The Miniature Thermal Emission spectrometer (Mini-TES) is a Michelson interferometer operating in the thermal infrared with a spectral range from 340 to 1997 cm^{-1} (5–29 μm) in 167 spectral channels with a spectral resolution of 10 cm^{-1} (Christensen et al., 2003). The nominal angular field-of-view is 20 mrad, which at an angle of 20° below the horizon covers an area on the surface approximately 25 cm in diameter. Each Mini-TES spectrum takes two seconds to acquire with 1.8 s spent integrating. The combination of uncertainties associated with radiometric precision and random noise result in an expected radiance uncertainty of about 3×10^{-8} $W\,cm^{-2}\,ster^{-1}/cm^{-1}$, which corresponds to an equivalent temperature uncertainty of less than 0.3 K at 15 μm at a typical surface temperature of 250 K.

2.2. Data set

The data used for the retrieval of surface and near-surface atmospheric temperatures are "ground stares" taken by Mini-TES in which spectra are continuously taken of a single spot on the ground for a period of time. In this paper we examine the more than 800 ground stares observed during the first 180 sols of each of the two rover missions. Two types of ground stares, "short" and "long," were taken at a pointing of 20° below the horizon. To ensure accurate calculation of path lengths, angles translated into the local coordinate system of the rover were used in the retrieval process. The short ground stares, 10–20 s in duration, collect 5–10 spectra and are used to monitor the diurnal and seasonal variation of temperatures. Typically, one to four short ground stares were collected between 0800 and 1800 LTST (local true solar time). The long ground stares, 8.5 min in duration, collect 255 spectra and are used to look for any short time scale variations in the near-surface atmospheric temperature. Fourteen long ground stares have been collected on Opportunity and five on Spirit through sol 180 between 1000 and 1730 LTST. A total of 16 overnight observations, between 1800 and 0530 LTST, were taken by both rovers and usually had a pointing of 40° below the horizon to accommodate parallel efforts to derive thermal inertia of rocks and soil. No Mini-TES observations were collected between 0600 and 0750 LTST, when data from previous missions and models show the coldest temperatures (Schofield et al., 1997; Martin et al., 2003).

2.3. Retrieval algorithm

Near-surface atmospheric temperature is derived by modeling the observed radiance within the 15-μm CO_2 band. Gaseous absorption by CO_2 is modeled using the correlated-k approximation (Lacis and Oinas, 1991). Although not opaque at the spectral resolution of Mini-TES over the short path lengths observed, the 15-μm CO_2 absorption is strong enough to produce a spectral feature that is well above the level of instrument noise. Fig. 1 shows three examples from different local times of the

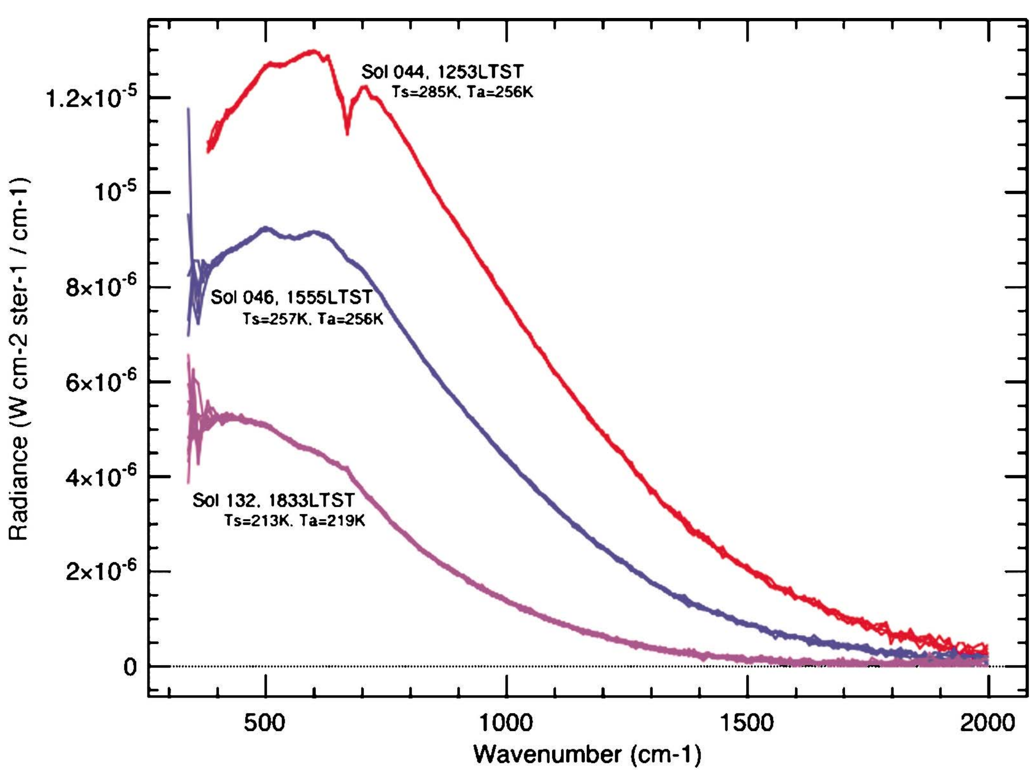

Fig. 1. Mini-TES ground spectra: Compilation of Mini-TES spectra for three different local times that show an absorption, isothermal, and emission case.

spectra that make up a short ground stare. The red lines show a set of five absorption spectra, taken at 1253 LTST with a surface temperature 29 K warmer than the near-surface temperature. The blue lines show a set of five spectra that are almost isothermal, which were taken in the late afternoon with temperature differences of 1 K. The purple lines show a set of ten emission spectra, taken at 1833 LTST, where the near-surface temperature was 6 K warmer than the surface temperature. These short ground stares have a smooth, nearly-blackbody shape that defines the surface temperature, while the CO_2 absorption centered at 667 cm^{-1} (15 μm) is used to retrieve near-surface atmospheric temperature. We model the observed radiance with a surface temperature and a single atmospheric temperature. Therefore, the retrieved near-surface atmospheric temperature is an average representative temperature along the path between the Mini-TES mast height of 1.5 m and the surface. To estimate the effective height of the representative temperature, synthetic spectra were computed from several assumed temperature profiles. The synthetic spectrum was run through the retrieval algorithm and the effective height was obtained by matching the retrieved near-surface temperature to the assumed temperature profile. The resulting effective height is 1.1 m about the surface. The effective height is relatively insensitive to changes in the elevation angle of the observation and the assumed temperature profile (e.g., superadiabatic vs inverted), varying by only about 1 cm. The surface temperature is derived simultaneously by matching the observed radiance of the spectral region immediately surrounding the CO_2 band.

2.4. Uncertainties

Uncertainties in the retrieved temperatures come from random noise and systematic calibration uncertainties in the Mini-TES instrument, and from approximations and assumptions made in the retrieval algorithm. The instrumental uncertainty can be estimated directly from the data by calculating the root-mean-square (rms) spectrum-to-spectrum variation of surface temperature in the long ground stares. While atmospheric turbulence can cause the near-surface atmospheric temperature to vary on short time scales (see Section 3.3), we expect surface temperature to vary only slowly and systematically. The observed rms surface temperature variations are 1–2 K. The systematic uncertainty introduced by the retrieval algorithm (e.g., use of the correlated-k approximation) is small compared to the instrumental uncertainty, and so we estimate the uncertainty in the retrieved surface and near-surface atmospheric temperatures as 1–2 K.

3. Results

3.1. Diurnal variations

Surface temperatures retrieved from Mini-TES spectra taken by Opportunity at Meridiani Planum (roughly 2° S, 6° W) follow a well-defined diurnal curve with peak temperatures occurring at about 1300 LTST, while the near-surface atmospheric temperatures peak at about 1430 LTST. Opportunity experienced a maximum daily surface temperature of 295 K and near-surface atmospheric temperature of 265 K at the beginning of the mission ($L_s = 339°$, southern hemisphere summer). Near-surface atmospheric temperatures at Meridiani were observed to rise more slowly than the surface temperature during the morning hours, but to fall off in the evening at a similar rate. Surface temperature remained warmer than the near-surface atmospheric temperature until 1630 LTST. At that time, the surface temperatures fell below the near-surface atmospheric temperatures and stayed that way throughout the late evening and overnight. The lack of pre-dawn observations only allows us to determine that the surface temperatures became warmer than the near-surface atmosphere again sometime between 0500 and 0750 LTST. The coldest overnight surface temperature observed by Opportunity was 175 K, and occurred at 0415 LTST on sol 137. Somewhat lower temperatures were undoubtedly experienced by the rover but were not recorded by Mini-TES because of the limited number of nighttime observations.

Temperatures retrieved from the Spirit rover at Gusev crater (roughly 15° S, 185° W) are similar to those at Meridiani, but there are differences caused by the difference in latitude, surface visible albedo, and thermal inertia. The surface temperature at Gusev increases more slowly in the morning and early afternoon hours than it does at Meridiani, with peak temperatures occurring at 1400 LTST. The near-surface atmospheric temperature variation mirrors that of the surface temperatures, but peaks at 1500 LTST. Spirit experienced a maximum surface temperature shortly after landing of 280 K and a near-surface atmospheric temperature of 260 K. The minimum observed overnight surface temperature at Gusev crater was 183 K at 0040 LTST on sol 180.

Since there were not enough short ground stares collected over any single sol to effectively produce a curve showing the diurnal variation of temperature, Figs. 2 and 3 show a combination of all of the short ground stares taken during the first 65 sols of each surface mission. The data are constrained to the first 65 sols to adequately show the shape of the diurnal curve without introducing seasonal effects (see Section 3.2). Opportunity (Fig. 2) data show well-defined curves with little scatter for both surface and near-surface atmospheric temperatures, while Spirit data (Fig. 3) show significant scatter. Since the seasonal effects were reduced by constraining the dataset, the majority of this scatter can be attributed small-scale variations in surface albedo and thermal inertia (i.e. rocks vs soil) at different rover locations, causing real changes in surface temperature. The ground stare observations were usually taken with no specific surface target selected, so the chances of having a mixed surface, including both rocks and soil, in the Mini-TES field of view are high. It is this rock/soil mixture that accounts for a large part of the dispersion seen in the Spirit dataset. The Meridiani site has a more homogeneous surface with a smaller chance of rocks being present in the field of view, and therefore produces a dataset with less dispersion.

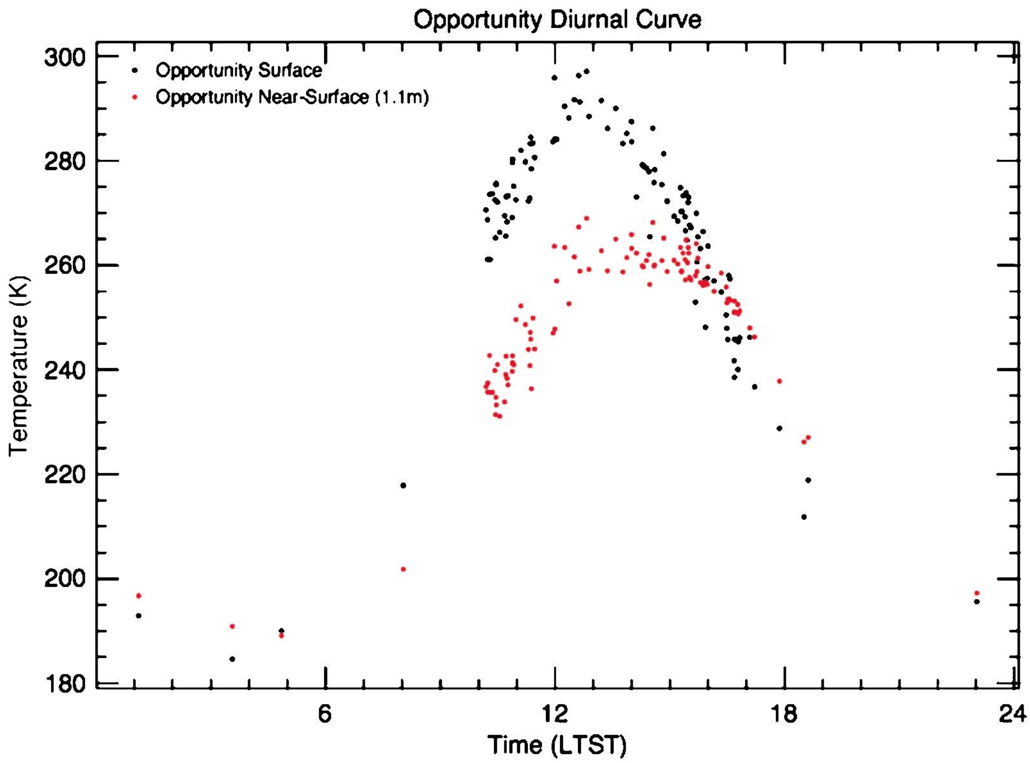

Fig. 2. Opportunity diurnal curve: Surface (black) temperature and near-surface (red) atmospheric temperature (1.1 m) retrieved from the first 65 sols of Mini-TES spectra as a function of local time. The data are constrained to the first 65 sols to reduce scatter due to the seasonal cooling. The estimated uncertainty in each retrieved temperature is 1–2 K. Notice that the surface temperature drops below the near-surface atmospheric temperature in the evening and overnight hours.

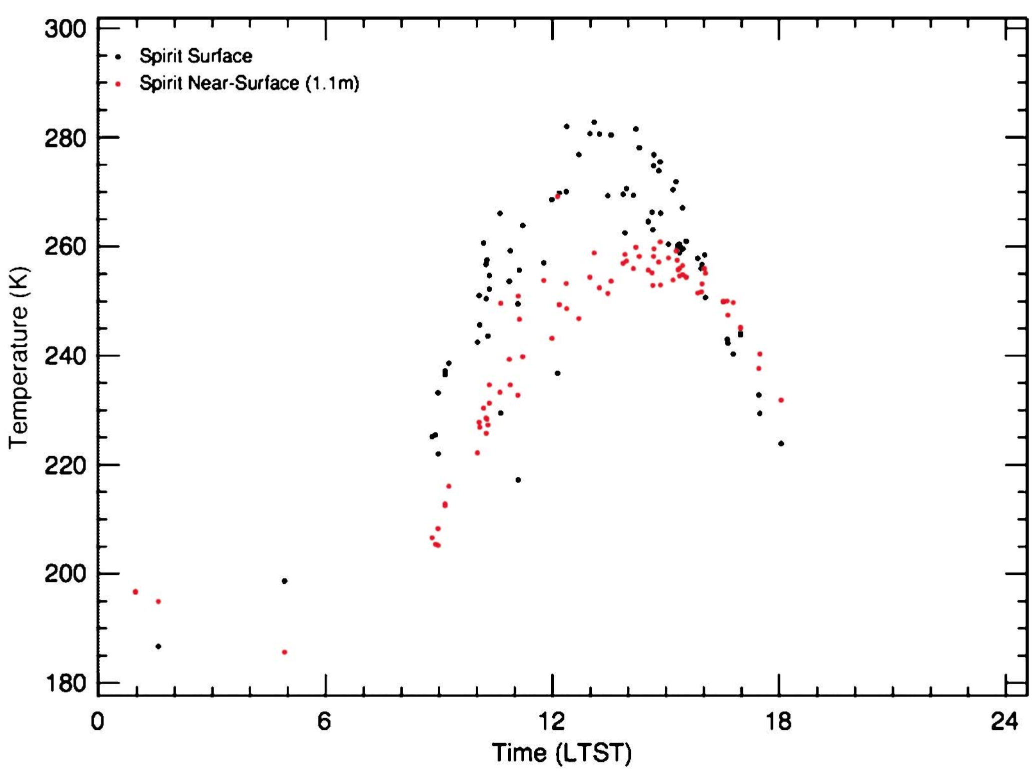

Fig. 3. Spirit diurnal curve: Surface (black) temperature and near-surface (red) atmospheric temperature (1.1 m) retrieved from the first 65 sols of Mini-TES spectra as a function of local time. The data are constrained to the first 65 sols to reduce the scatter that is due to the seasonal cooling. The estimated uncertainty in each retrieved temperature is 1–2 K.

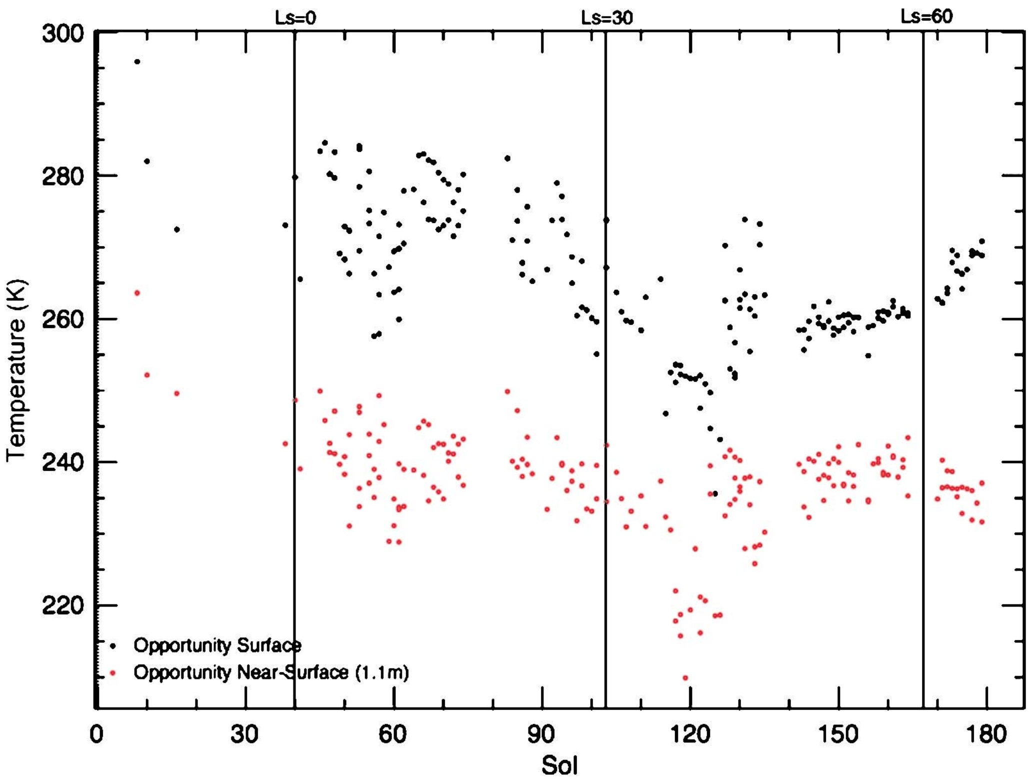

Fig. 4. Opportunity seasonal plot: Surface (black) temperature and near-surface (red) atmospheric temperature (1.1 m) retrieved from the first 180 sols of Mini-TES spectra as a function of sol. To reduce the scatter from diurnal variations, the data are constrained to local times between 1030 and 1230 LTST. Distinct changes to the surface temperatures can be linked to specific events during the Opportunity traverse. Opportunity began ingress into Endurance crater around sol 132 and the parameters of all atmospheric Mini-TES observations were changed.

3.2. Seasonal variations

The data presented here, spanning from the middle of martian southern hemisphere summer ($L_s = 327°$) to the end of southern-hemisphere fall ($L_s \sim 60°$), show the expected cooling trend experienced by the two rovers as the seasons changed. Figs. 4 and 5 show the seasonal curve spanning all 180 sols for the Meridiani and Gusev sites, respectively. Each dataset has been constrained to a certain local time range to reduce the scatter from changes over a diurnal cycle. Fig. 4, showing Opportunity data, has been constrained to local times between 1030 and 1230 LTST and Fig. 5, showing Spirit data, has been constrained to local times between 1200 and 1500 LTST. These local times were chosen because they contain the greatest number of observations that best represent the seasonal effect on the temperatures. The Spirit and Opportunity landing sites experienced similar rates of cooling for both surface and near-surface temperatures. Afternoon near-surface atmospheric temperatures decreased by 0.14 $\mathrm{K\,sol^{-1}}$ at Meridiani, and by 0.17 $\mathrm{K\,sol^{-1}}$ at Gusev. The surface temperature decreased by about 0.21 $\mathrm{K\,sol^{-1}}$ at both sites.

3.3. Short time scale variations

Long ground stares were designed to look at variations in the near-surface atmospheric temperatures on time scales ranging from two seconds to several minutes. Long ground stares were taken at different local times throughout the daytime hours to look at the diurnal variation of temperature fluctuations. The same retrieval process that is used for the short ground stares, is also used for the long ground stares, but with the slight adjustment that the temperatures are retrieved for each individual spectrum instead of for the average of all spectra in a stare. This provides an independent measure of the surface and near-surface atmospheric temperatures every two seconds for a period of 8.5 min. Fig. 6 shows the near-surface atmospheric temperatures from these long ground stares, taken on Opportunity, at different local times. Morning and late afternoon observations have little to no temperature fluctuations as is seen in the green curve taken at 1714 LTST. The combined noise level, approximately 1 to 2 K, in the observations and retrieval are illustrated in the late afternoon green curve and the red surface temperature curve. The larger fluctuations, up to 8 K, seen in the other curves are caused by real temperature variations within the lowest 1.5 m of the atmosphere. The fluctuations have maximum amplitude and occur most often during the afternoon between 1200 and 1500 LTST, when the atmosphere is unstable due to convective motions (Smith et al., 2004).

4. Discussion

4.1. Comparison with Viking Lander and Pathfinder observations

Direct comparison of the near-surface atmospheric temperatures derived from Mini-TES observations with those from

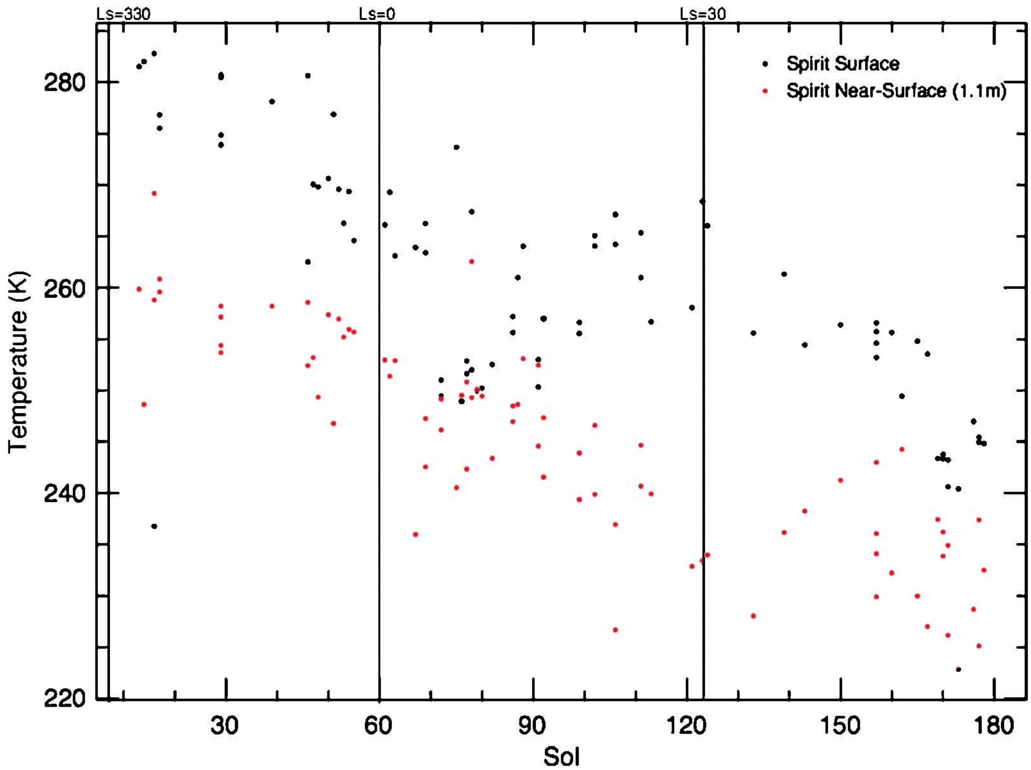

Fig. 5. Spirit seasonal plot: Surface (black) temperature and near-surface (red) atmospheric temperature (1.1 m) retrieved from the first 180 sols of Mini-TES spectra as a function of sol. To reduce the scatter from diurnal variations, the data are constrained to local times between 1200 and 1500 LTST. Cooling trends of 0.21 and 0.17 K sol^{-1} are observed for surface and near-surface atmospheric temperatures, respectively. The estimated uncertainty in each retrieved temperature is 1–2 K.

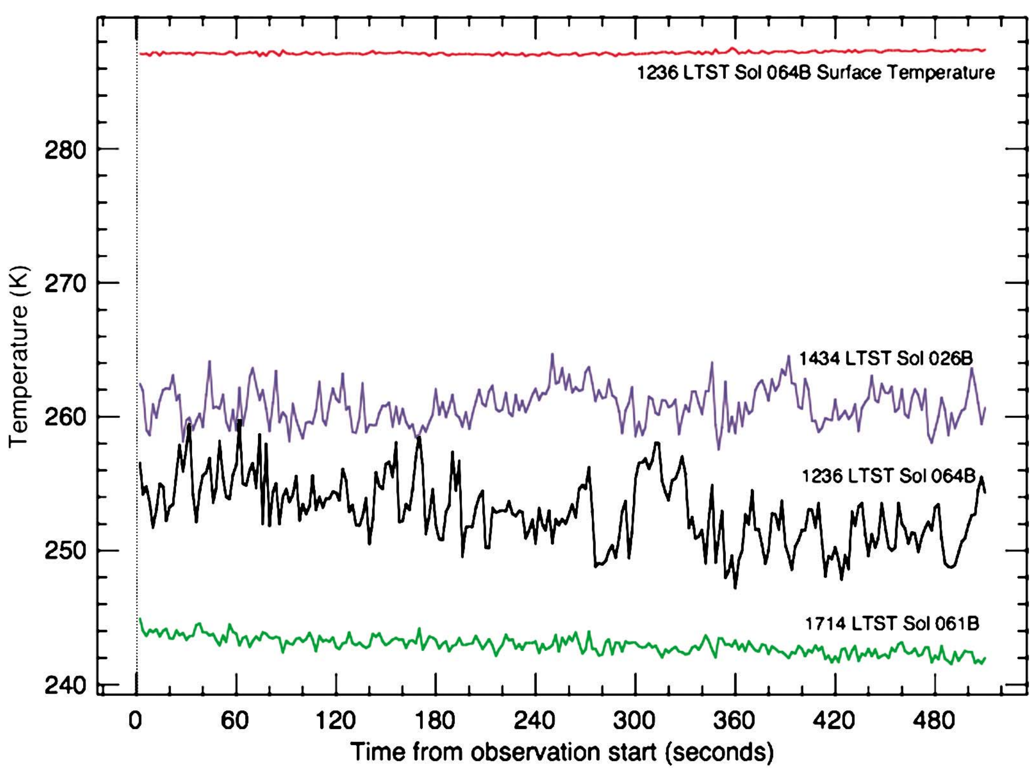

Fig. 6. Opportunity long ground stares: This plot shows several “long ground stare” observations from various local times. These observations are 8.5 min in duration with spectra being recorded every two seconds. The near-surface (1.1 m) atmospheric temperatures are retrieved from individual spectra and show that the afternoon hours are the most convectively active and have the largest temperature fluctuations. The 1–2 K fluctuation apparent in the red curve, collected at 1236 LTST of the surface temperature, is representative of the uncertainty in both the observation and retrieval.

Viking (Tillman, 1988) and Pathfinder (Schofield et al., 1997) measurements is complicated by differences in landing site locations (22° N for Viking Lander 1 and Pathfinder, 48° N for Viking Lander 2) and thermal characteristics. However, the general trends observed at the two MER sites are consistent with those of previous missions. Specifically, the near-surface atmospheric temperatures peak near 1500 local time, with minima located in the 0500–0800 local time interval (exact time of minimum varies with season). The seasonal trend of atmospheric temperature for a given local time also possesses the same gross behavior among the landing sites, but the large variations in solar insolation (approximately 40% from perihelion to aphelion) for the same season in the northern and southern hemispheres can produce distinct differences in the cooling and warming rates.

4.2. Comparison with upward-looking Mini-TES observations

Near-surface atmospheric temperatures retrieved from downward-looking Mini-TES spectra extend the range of retrievals from upward-looking Mini-TES spectra, which are sensitive to temperatures between 20 m and 2 km above the surface (Smith et al., 2004). The peak diurnal temperature at 1.1 m occurs later than that for the surface, but earlier than that at 20 m. Overnight temperatures at 1.1 m are warmer than the surface, but cooler than those at 20 m indicating that the nighttime inversion layer extends down to at least the 1.1 m level. The large daytime temperature difference between 1.1 and 20 m, and the even larger difference between the surface and 1.1 m, shows that the daytime superadiabatic layer becomes even more unstable closer to the surface.

4.3. Comparison with modeled temperatures

Comparisons with model predictions of near-surface temperatures at the MER landing sites (Martin et al., 2003) show generally good agreement, but also some significant differences. Mid-afternoon times generally have the poorest fit, but residuals rarely exceed 15 K. The Martin et al. (2003) model uses thermal inertia and albedo estimates based on orbital data, which are somewhat different than the values derived directly from rover data (Golombek et al., 2005). This difference in parameters can account for much of the discrepancy between the modeled and observed temperatures. Martin et al. (2003) used the models to predict that Spirit would have a 3% chance of encountering temperatures below 176 K at 1 m, and Opportunity a 7% chance. Based on the Mini-TES data collected, retrieved temperatures at 1.1 m from Spirit never fell below 183 K, but no observations were taken during the very coldest (predawn) times. Likewise, retrieved temperatures at 1.1 m from Opportunity were also never as cold as 176 K, but very few overnight observations were taken in the season when temperatures are generally coldest (Smith, 2004).

References

Christensen, P.R., and 19 colleagues, 2003. Miniature Thermal Emission Spectrometer for the Mars Exploration Rovers. J. Geophys. Res. 108 (E12), doi:10.1029/2003JE002117.

Golombek, M.P., Arvidson, R.E., Bell III, J.F., Christensen, P.R., Crisp, J.A., Crumpler, L.S., Ehlmann, B.L., Fergason, R.L., Grant, J.A., Greeley, R., Haldemann, A.F.C., Kass, D.M., Parker, T.J., Schofield, J.T., Squyres, S.W., Zurek, R.W., 2005. Assessment of Mars Exploration Rover landing site predictions and implications for climate change. Nature. In press.

Hess, S.L., Henry, R.M., Leovy, C.B., Ryan, J.A., Tillman, J.E., 1977. Meteorological results from the surface of Mars: Viking 1 and 2. J. Geophys. Res. 82, 4559–4574.

Lacis, A.A., Oinas, V., 1991. A description of the correlated *k* distributed method for modeling nongray gaseous absorption, thermal emission, and multiple scattering in vertically inhomogeneous atmospheres. J. Geophys. Res. 96, 9027–9063.

Martin, T.Z., Bridges, N.T., Murphy, J.R., 2003. Near-surface temperatures at proposed Mars Exploration Rover landing sites. J. Geophys. Res. 108 (E12), doi:10.1029/2003JE002063. 8089.

Schofield, J.T., Barnes, J.R., Crisp, D., Haberle, R.M., Larsen, S., Magalhães, J.A., Murphy, J.R., Seiff, A., Wilson, G., 1997. The Mars Pathfinder atmospheric structure investigation/meteorology (ASI/MET) experiment. Science 278, 1752–1757.

Smith, M.D., 2004. Interannual variability in TES atmospheric observations of Mars during 1999–2003. Icarus 167, 148–165.

Smith, M.D., Wolff, M.J., Lemmon, M.T., Spanovich, N., Banfield, D., Budney, C.J., Clancy, R.T., Ghosh, A., Landis, G.A., Smith, P., Whitney, B., Christensen, P.R., Squyres, S.W., 2004. First atmospheric science results from the Mars Exploration Rovers Mini-TES. Science 306, 1750–1753.

Squyres, S.W., Arvidson, R.E., Baumgartner, E.T., Bell III, J.F., Christensen, P.R., Gorevan, S., Herkenhoff, K.E., Klingelhöfer, G., Bo Madsen, M., Morris, R.V., Rieder, R., Romero, R.A., 2003. Athena Mars Rover science investigation. J. Geophys. Res. 108 (E12), doi:10.1029/2003JE002121.

Tillman, J.E., 1988. Mars global atmospheric oscillations—Annually synchronized, transient normal-mode oscillations and the triggering of global dust storms. J. Geophys. Res. 93, 9433–9451.