MARS EXPLORATION ROVERS MINI-TES OBSERVATIONS OF BOUNDARY LAYER TEMPERATURES AND AEROSOL OPTICAL DEPTH

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Introduction:

Spectra returned by the Miniature Thermal Emission Spectrometer (Mini-TES) on-board the *Spirit* and *Opportunity* Mars Exploration Rovers give the first view of the Martian surface and atmosphere in the thermal infrared from the surface of Mars. Upward-looking observations by Mini-TES allow the temperature profile within the lowest 2 km of the planetary boundary layer (PBL) to be retrieved. The PBL is the portion of the atmosphere that directly interacts with the surface, responding to forcings such as frictional drag and surface heating. Atmospheric temperatures retrieved from orbital observations do not have sufficient vertical resolution to resolve the PBL. Mini-TES observations are important because they provide a glimpse of the convective and turbulent behavior of the temperature perturbations in the PBL, and these processes control the transfer of heat, momentum, and molecular species across the surface-atmosphere interface. Retrieved PBL temperature profiles also provide valuable constraints for the validation of both global and mesoscale Martian atmospheric models. Initial atmospheric results from Mini-TES are reported by *Smith et al.* [2004] and *Spanovich et al.* [2005].

Mini-TES Data Characteristics:

Mini-TES is a Michelson interferometer with 167 spectral channels covering the spectral range from 340 to 1997 cm^{-1} (5–29 μm) with a spectral resolution of 10 cm^{-1} (see *Christensen et al.* [2003] for further details about the instrument). The nominal angular resolution is 20 mrad. A pointing mirror allows Mini-TES to view elevation angles up to 30° above the plane of the rover deck.

We acquired repeated atmospheric observations at different times of day on each sol in an attempt to obtain diurnal and seasonal coverage. Because resources (energy, download data volume, and time duration) on the rovers are limited and are shared between instruments and science interests, actual coverage is limited outside of "nominal" observations near noon and mid- to late-afternoon, which we obtained almost every sol (Martian day). In particular, observations during the night are very expensive in terms of power and were taken only sporadically. As of early December 2005, each rover had taken roughly 2000 Mini-TES atmospheric observations over a period of one Martian year (669 sols).

Each Mini-TES "atmospheric observation" consists of 100–1000 individual spectra, which are acquired every two seconds. The spectra are taken either as a "stare" at one elevation angle (typically aimed as high above the horizon as possible), or as an "elevation scan", where a set of spectra are taken at several different elevation angles. The most common elevation scan takes 100 spectra at each of three elevation angles, 10°, 20°, and 30° above the plane of the rover deck. In addition to the upward-looking spectra described above, a short set of downward-looking spectra is taken of the surface as a part of each atmospheric observation. These spectra are used to obtain surface temperature and a representative temperature in the path between the rover mast height (1.5 m) and the surface (see *Spanovich et al.* [2005] for further details). Special campaigns to coordinate observations with the overflight of orbiting spacecraft (Mars Global Surveyor and Mars Express) were also performed.

Retrieval Methods:

The retrieval of atmospheric temperatures was performed using a constrained linear inversion of the observed radiance in the 15-μm CO_2 band following the approach of *Smith et al.* [1996]. The retrieval is sensitive to temperatures between about 20 m and 2 km above the surface. The vertical resolution at a given height is about equal to the height above the surface. The typical elevation angle of 30° above the horizon used by Mini-TES means that atmospheric temperatures are retrieved along a slant path away from the rover, so the temperature at 2 km altitude is representative of a location 4 km away horizontally from the rover. Because there are no atmospheric pressure sensors on-board the rovers, surface pressure was estimated by using the modeling results of Mars Global Circulation Models (model results provided by R. M. Haberle and R. J. Wilson, personal communication, 2003 and 2004).

Aerosol optical depth was retrieved along with atmospheric temperatures in an iterative fashion. In the upward-looking geometry scattering is important, so aerosol scattering is included using the two-stream approximation. The spectral dependence of aerosol absorption and scattering coefficients were fit using the Mini-TES data themselves, with guidance from TES analysis [e.g. *Smith* 2004; *Wolff and Clancy* 2003; *Bandfield and Smith* 2003]. Although Mini-TES is only sensitive to atmospheric temperature within 2 km of the surface, the absorptions caused by atmospheric aerosols are not opaque, so Mini-TES spectra are sensitive to the entire column abundance of aerosols and the retrieval requires extended temperature profiles from TES (either concurrent observations or averages from TES climatology). The retrieval algorithm supports the use of arbitrary vertical profiles for dust, but we have used well-mixed for these results.

Uncertainty in the retrieved temperatures and aerosol optical depth includes contributions from the random and systematic errors in the instrument and calibration, and from systematic errors inherent in the retrieval process. Propagation of instrument errors [*Christensen et al.* 2003] is straightforward and results in relatively small uncertainties for temperatures (<0.5 K) and optical depth (<0.02). The uncertainty introduced by the assumptions inherent in the retrieval process (e.g., use of modeled surface pressure and the amount of vertical smoothing used to keep the retrieval algorithm stable) is more difficult to quantify. Complicating the above are additional systematic errors caused by instrumental effects such as the accumulation of dust on the instrument optics, drift in the instrument response function, and the loss of important temperature sensors in the instrument. On the basis of numerical experiments and our experience with this and similar datasets [e.g. *Conrath et al.* 2000; *Wolff and Clnacy* 2003; *Smith* 2004; *Smith et al.* 2004l *Spanovich et al.* 2005] we estimate the uncertainty in retrieved temperatures to be 2 K near the surface, increasing to 4 K at the upper boundary (2 km), and the uncertainty in aerosol optical depth to be 0.03 or 10%, whichever is larger.

Overview of Mini-TES Observations:

The results presented here were derived using data covering one Martian year of observations from each rover. For *Spirit*, the time period covered is from 8 January 2004 (sol 5, Mars Year 26 Ls=330°) to 25 November 2004 (sol 674, Mars Year 27 Ls=330°). For *Opportunity*, the time period covered is from 30 January 2004 (sol 6, Mars Year 26, Ls=342°) to 28 November 2004 (sol 656, Mars Year 27, Ls=332°).

Figure 1 shows typical temperature profiles from the *Spirit* rover (profiles from *Opportunity* look very similar). There is a large and systematic change in the retrieved thermal structure throughout a sol. At all levels, atmospheric temperatures are minima at dawn, increase throughout the morning and early afternoon, reach maxima in the mid-afternoon, decrease rapidly in the early evening, and then decrease more slowly throughout the night. This cycle is most dramatic in the lowest 100 m above the surface. From morning until early afternoon, atmospheric temperatures nearest the surface rapidly rise, formatting a superadiabatic layer extending to more than 100 m above the surface. The lapse rate in this layer far exceeds the adiabatic value, thus creating unstable conditions. Convective motions in the thin atmosphere cannot transfer heat from the surface layer quickly enough to sustain an adiabatic lapse rate, such that the superadiabatic layer persists throughout the afternoon, with resulting turbulent motions. Between 16:00 and 17:00 local time, the superadiabatic layer collapses and is quickly replaced by a stable inversion layer. The inversion layer continues to grow in amplitude and depth throughout the night, until it dissipates after dawn the next morning.

Figure 2 shows the turbulent motions associated with convection in the form of large temperature fluctuations on short time scales. The activity persists throughout the daytime hours and is highly variable from day to day. Peak-to-peak amplitude of the temperature fluctuations is as high as 5 K, with typical a typical time scale of 15–30 seconds. Nearly all of the activity is confined to the superadiabatic layer, but the largest fluctuations can sometimes penetrate into the neutrally-stable region above.

Figure 3 shows the seasonal variation of temperatures 30 m above the surface for the *Spirit* rover. The seasonal variation of *Opportunity* temperatures is very similar. Minimum temperatures were recorded around Ls=80°, and maximum temperatures at Ls=220°. There are no large jumps in temperatures (e.g. >10 K) associated with dust activity.

Figure 4 shows the seasonal variation of dust optical depth at *Spirit* and *Opportunity*. Shown is normal-incidence column dust optical depth from the surface to infinity at 1075 cm^{-1}. The two rovers landed during the decay of a large regional dust storm in December 2003 (see my abstract on TES observations). Both rovers observed low dust loading through the aphelion season until Ls=140° when dust activity dramatically returned at both sites. Throughout the period from Ls=140° to 330° both rovers observed numerous episodes of both local (observed by only one rover) and regional (observed by both rovers) dust storms. The Mars Year 27 dust storm season was quite moderate, with no global-scale dust storms of the magnitude of the 2001 storm (Mars Year 25).

Summary:

Mini-TES atmospheric observations have given an unprecedented look at the vertical and seasonal variation of temperatures within the PBL. As of early December 2005, the Mini-TES instruments on both rovers are operational and continue to provide atmospheric observations. Further observations by Mini-TES will enable comparisons between consecutive Martian years.

References:

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Wolff and Clancy 2003. *J.Geophys. Res.* **108**, doi:10.1029/2003JE002057.

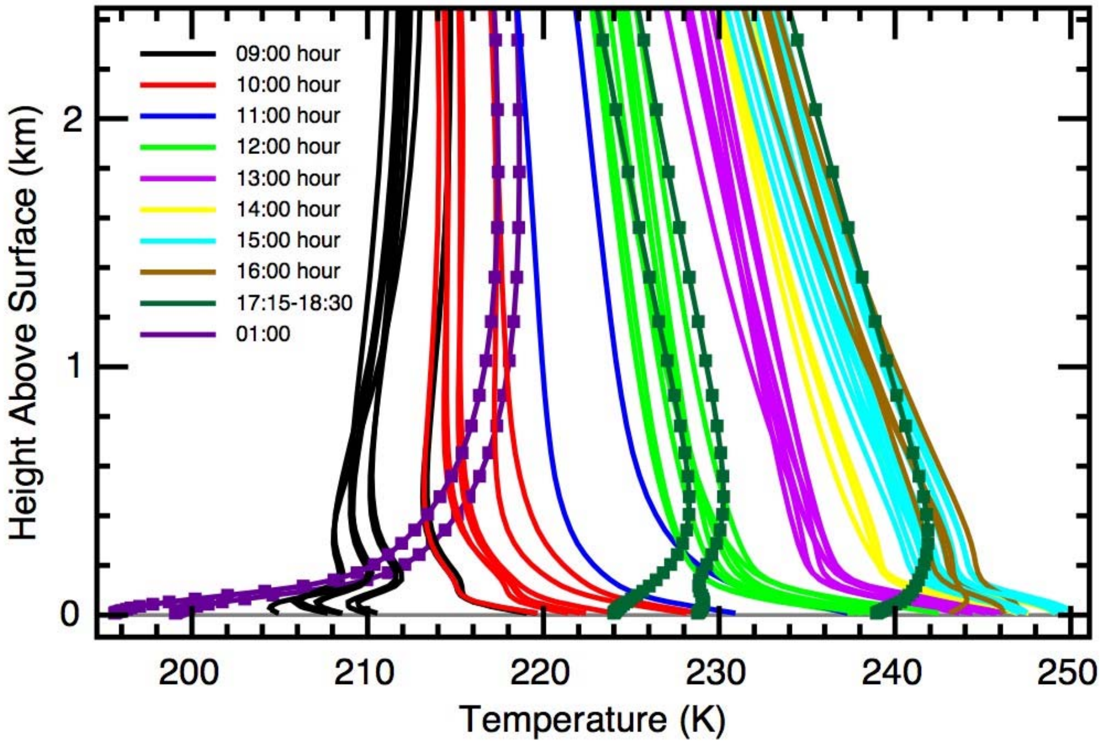

Figure 1. Atmospheric temperature as a function of height from *Spirit* sols 39 to 57 (Ls=348°–358°). Note the large diurnal variation and superadiabatic layer near the surface. Figure from *Smith et al.* [2004].

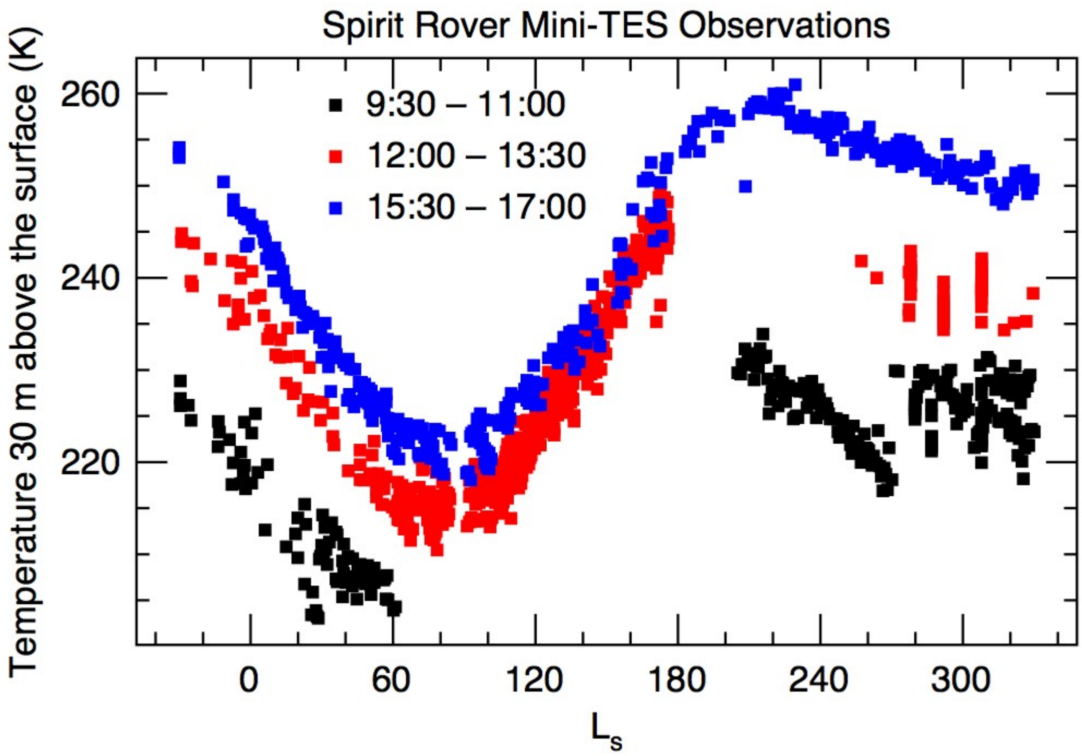

Figure 2. Seasonal trend of temperatures 30 m above the surface for the *Spirit* rover for three different ranges of local time. The jump in the morning temperatures at Ls=270° is caused by a shift to later local time within the time range, not a seasonal increase in temperature. The vertical bars in the midday observations at Ls=270°–310° are long sets of observations that span the entire local time range (12:00–13:30) on a single sol.

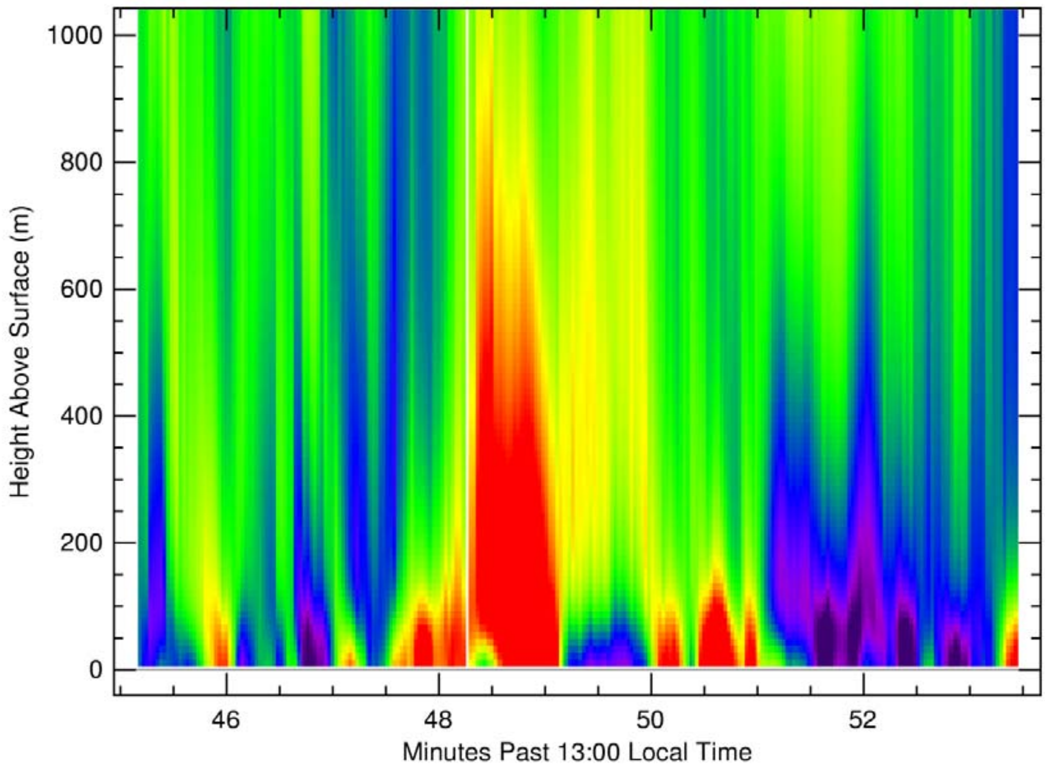

Figure 3. Perturbations in atmospheric temperature as a function of time and height after removal of the time-mean at each height as observed by *Opportunity* on sol 27 (Ls=353°). Red and orange indicate warmer than average temperatures, green indicates near-average, and blue and purple indicate colder then average temperature. The peak-to-peak amplitude of the fluctuations is as much as 5 K.

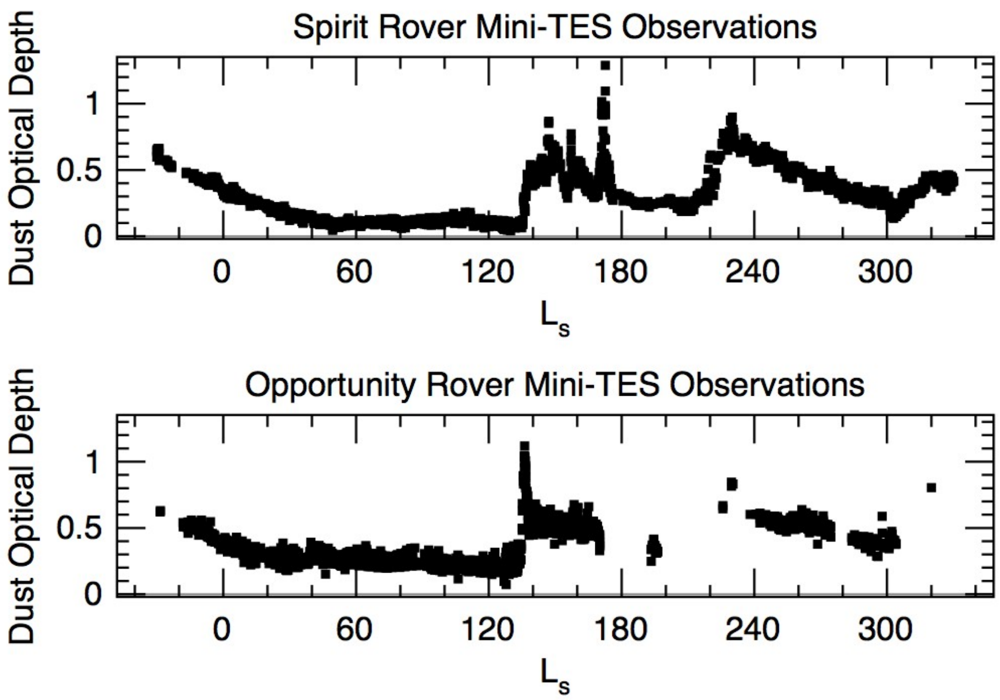

Figure 4. Seasonal trend of dust aerosol optical depth (at 1075 cm^{-1}) for both *Spirit* (top) and *Opportunity* (bottom). The two rovers landed during the clearing phase of a large regional dust storm. Significant dust activity began at both sites at around Ls=140°, with numerous episodes of local (seen in only one rover) and regional

(seen in both rovers) dust storms throughout the perihelion season.