



Sensitivity of Simulated Martian Atmospheric Temperature to Prescribed Dust Opacity Distribution: Comparisons of Model Results With Reconstructed Data From Past Mars Missions

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Introduction

The design of Entry, Descent, and Landing (EDL) activities at Mars requires comprehensive characterization of the atmospheric variability. The preflight prediction and the actual landing location of Mars Exploration Rover Opportunity (MER-B) are shown in **Figure 1**. The landing of both MERs further downrange from the targeted sites raised concern about the veracity of the preflight atmospheric characterization.

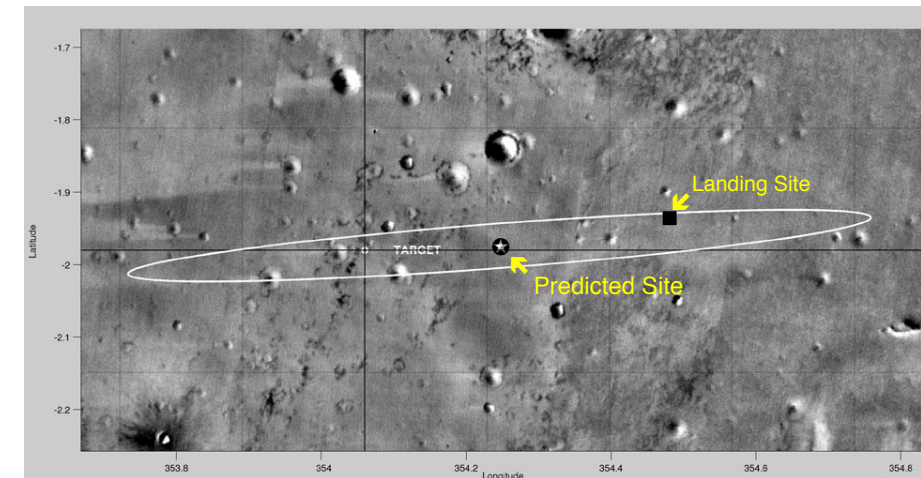


Fig.1. MER-B Landing Ellipse
(Image Credit: NASA/JPL/ASU)

Regional dust storm activity prior to the MER landings is a possible source of atmospheric perturbations.

Atmospheric models are useful tools for testing the impact of dust perturbations using data from past missions and for developing more realistic characterization needed for future missions.

We use Mars Weather Research and Forecasting (MarsWRF) model with different opacity specifications and reconstruction of the MER EDL data to see to what extent the model captures the atmospheric variability.

MarsWRF Model

MarsWRF is a part of the PlanetWRF model, which is based on the NCAR WRF model. A full description of the model formulation is given in Richardson et al. (JGR, 2007). Briefly, the main features are the following:

- Fully compressible and non-Hydrostatic simulation of the atmosphere on a finite difference grid.
- Surface energy balance includes treatment of CO₂ ice condensation/sublimation and resultant changes in the atmospheric mass.
- Medium Range Forecast (MRF) Planetary Boundary Layer scheme for surface layer exchange and PBL mixing of heat and momentum.
- Radiative heating of the surface and atmosphere evaluated with “k-distribution” radiative transfer model (Mischna et al., JGR 2012).
- Dust opacity distribution from MCD-MGS scenario or TES_Limb data

Following modifications are made for this study

- TES_Limb profiles and TES nadir IR opacities provided by Tim McConnochie
- A factor of 1.3 to convert TES nadir IR absorption opacity to extinction opacity.
- TES Limb opacity profile extended to the surface assuming a constant mixing ratio below an overhead opacity of 0.25 (Guzewich, JGR 2013), and then scaled using the TES Nadir total IR opacity.
- Created data files of dust opacity profiles for each of the Mars years from 24 to 27, and also a TES climatology data file made up of the median values of dust opacities.
- Regenerated dust optical properties using updated complex refractive indices for dust particles, from Mike Wolff.
- Assumed spherical particles with an effective radius of 1.5 μ and an effective variance of 0.3.

MarsWRF (contd)

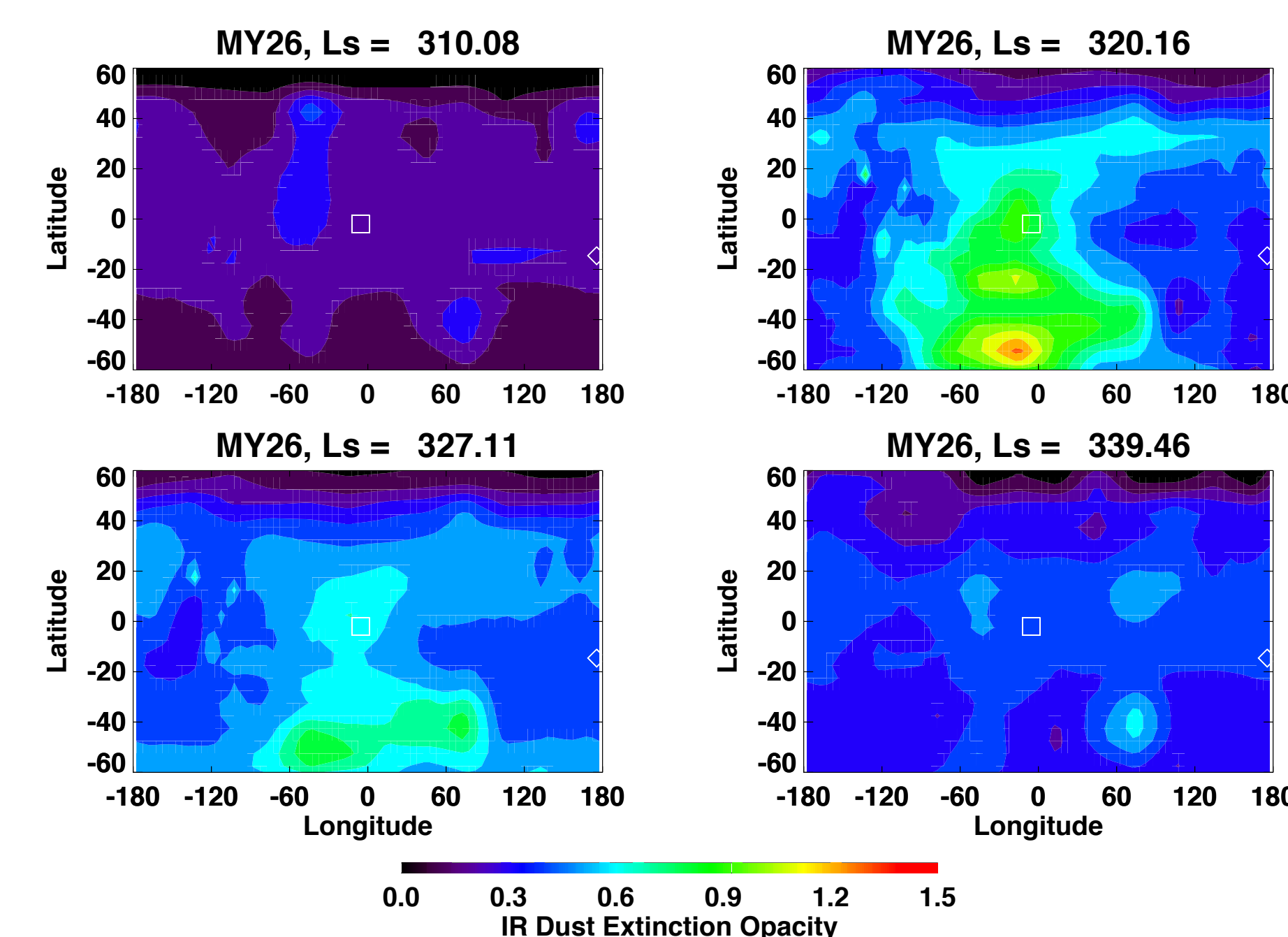


Fig.2. Total dust extinction opacity based on TES Nadir data from MY26. MER_A and B landing sites are denoted by diamond and square symbols.

Figure 2 shows maps of dust total opacity distribution from MY26 data file based on TES 9.3 μ measurements. The landing site of Spirit is indicated by diamond symbol (175.5E, 14.6S, LS=327.7) and that of Opportunity is shown by square symbol (5.5W, 1.9S, LS=339.1).

The onset of a regional dust storm and its decay are seen in these panels. Extinction opacity is about 0.4 at the location and time of MER-A landing. Longitudinal variation is significant as seen in the lower left panel. Lower right panel shows that closer to the time of MER-B landing, the opacity distribution is fairly well mixed in the zonal direction.

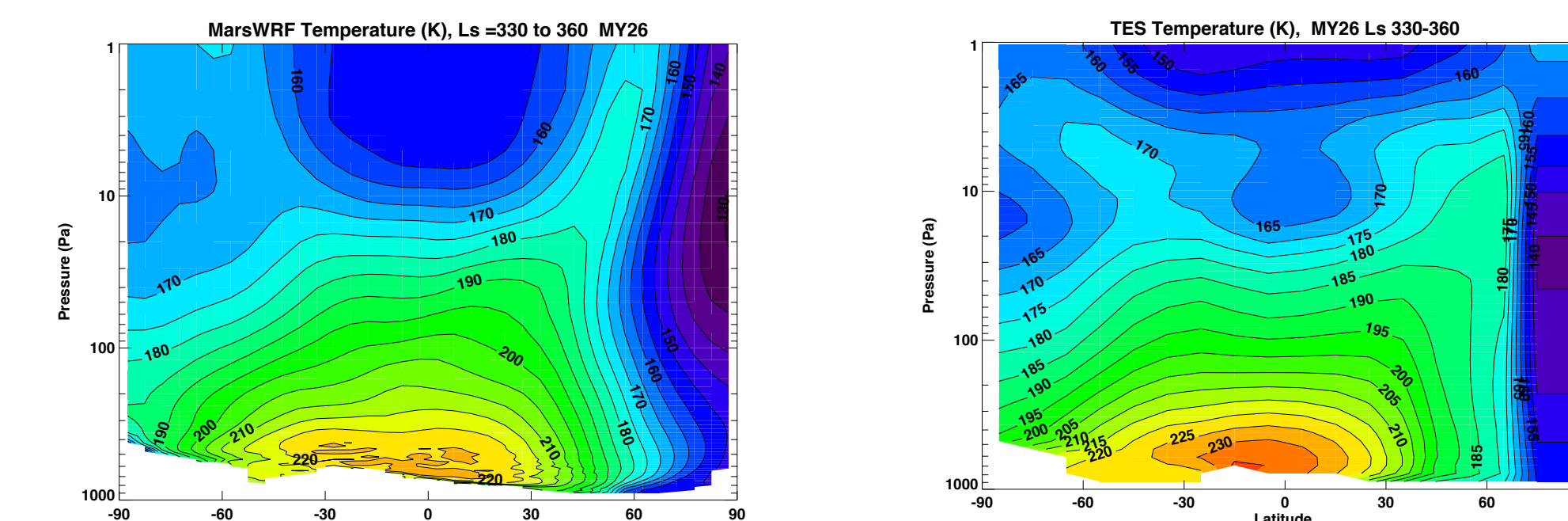


Fig. 3. Zonal average daytime temperature for LS=330 to 360. MarsWRF results (left) and TES data (right)

Figure 3 shows a comparison of zonally averaged temperature between 12 noon and 15:00 hours local time from the global run of MarsWRF using MY26 opacity with zonally averaged MY26 daytime temperature from TES for LS range 330 – 360.

The overall agreement between the simulated and observed temperature is good. The model is warmer by about 5° in the tropics near 100 Pa. Above 10 Pa the model is cooler. This could be partly due to the absence of water-ice cloud in this version of the model. The structure seen in the model tropical lower atmosphere is not apparent in the TES data. The vertical resolution of the TES measurement may not be enough to capture such features.

MarsWRF Nested Model

We use the nested version of MarsWRF for simulating the atmospheric conditions during the landing of MERs. Main features of the nested model are :

- GCM with 5° x 5° resolution is the mother domain
- Equal mass vertical grid with 40 intervals

MarsWRF Nested Model

- 3 levels of nesting with grid ratio of 3 centered near the landing site
- Time step in the nest 1/3 of the parent domain time step
- 3 different opacity specifications, MCD-MGS, TES_Climatology, and TES_MY26.
- Results from the highest resolution nest are used

Figure 4 compares the dust mixing ratio profiles from the 3 dust data files. Dust mixing ratios are given by the pressure derivatives of the opacity in (Pa)⁻¹ units. MCD-MGS specification has a constant mixing ratio profile. TES_Limb data indicate enhancement of dust above 200 Pa, with MY26 showing a larger increase during MER-A landing.

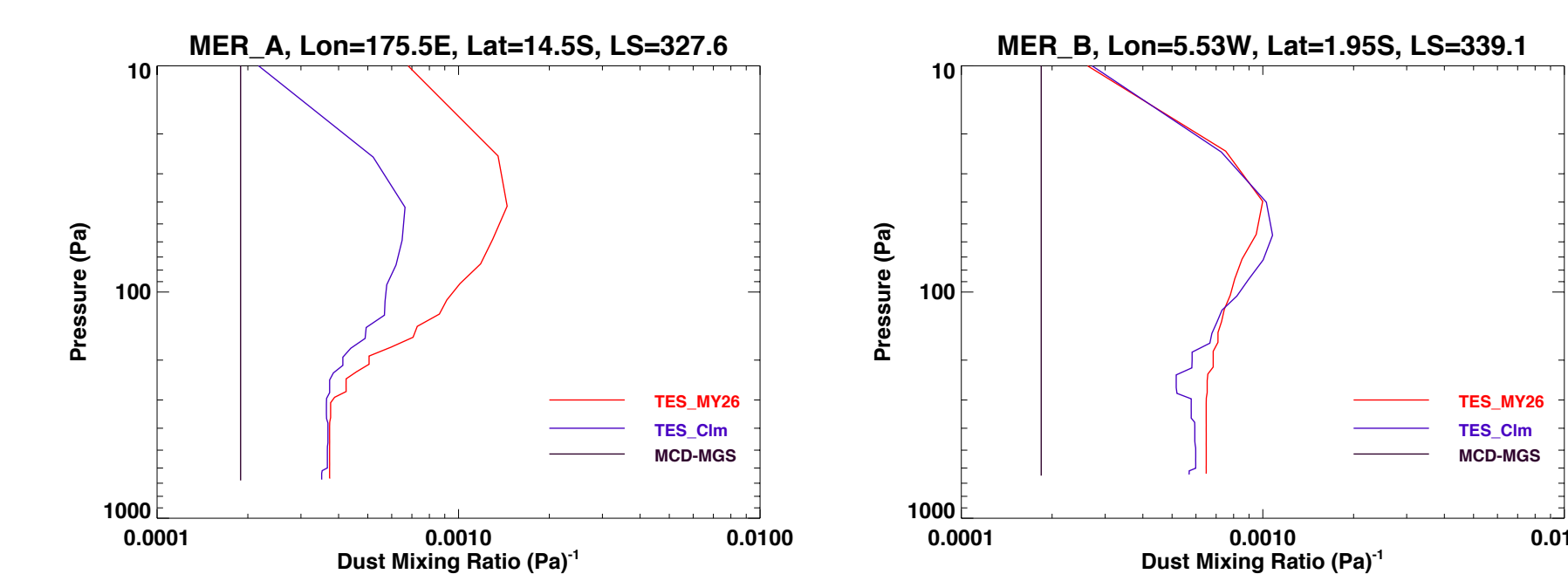


Fig.4. Dust mixing ratio (Pa)⁻¹ at MER-A and B landing sites

Following figures show,

- The pre-flight nominal (Black line) and perturbation profiles (Green shade) based on a random Martian atmospheric profile generation procedure using TES data from previous years.
- Reconstructions (Blue line) based on the density profiles derived from the accelerometer measurements made by the rovers during the entry.
- MarsWRF nested model results (Red lines) from a region about 2.8°x1.1° near the landing site and within 1 hour prior to local time of landing.

MER-A

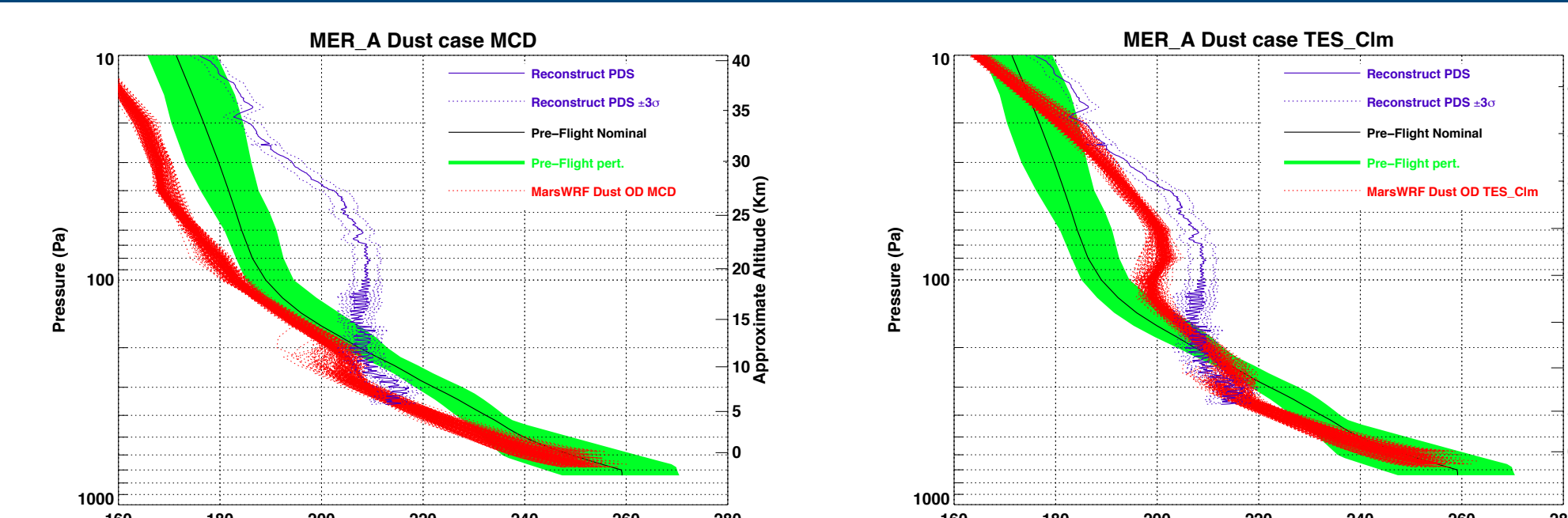


Fig. 5a

Fig. 5b

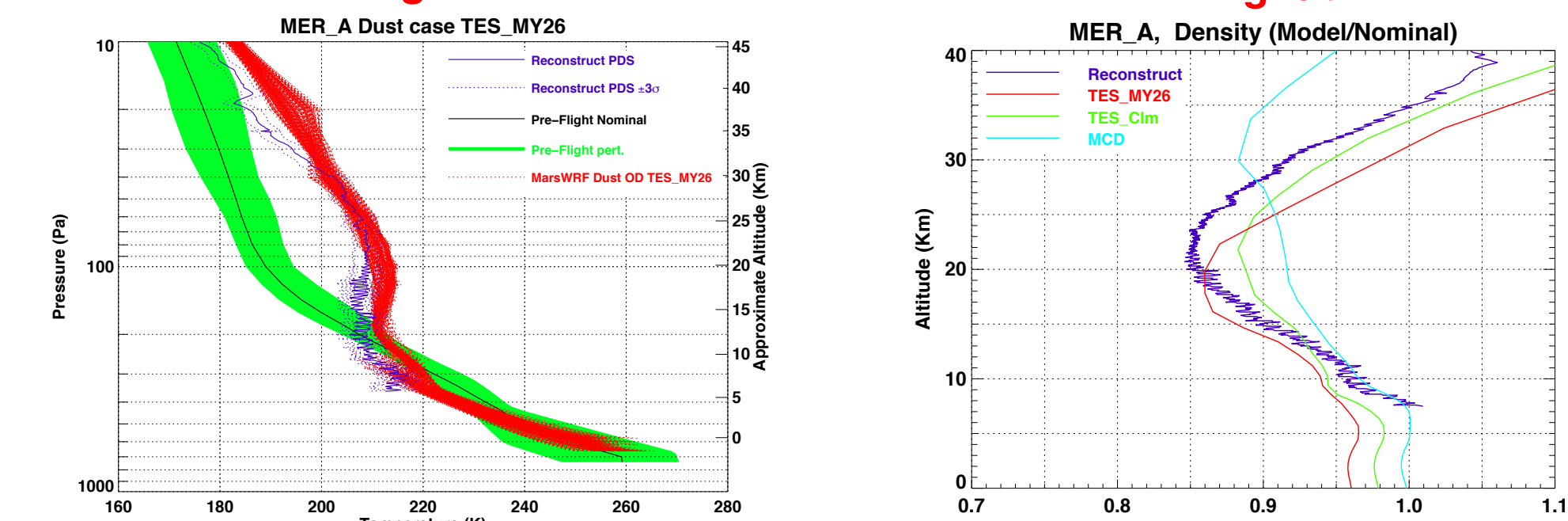


Fig. 5c

Fig. 5d

For MER_A, the reconstructed temperature is much warmer than the pre-flight predictions in the 200 to 20 Pa region. MarsWRF results (5a) for MCD opacity are cooler than the pre-flight model specifications. The use of TES_Clm dust opacity results in warmer temperatures (5b). The nearly isothermal feature of the profile is also reproduced. For the MY26 case (5c), the model is slightly warmer than the reconstruction but the shape of the temperature profile is in good agreement. The enhancement in dust opacity due to the regional storm in MY26

MER-A (contd)

prior to the landing of MER_A definitely played a major role in perturbing the atmospheric structure. Density perturbations are of primary interest to EDL activities. The density profile from the models as a fraction of the pre-flight nominal density is shown in **Figure 5d**. Between 10 and 30 km all models show reduced density compared to the nominal atmosphere. The peak reduction indicated by reconstructed data is about 15% near 20 km. MarsWRF with MY26 opacity is about 14% less dense than the nominal case. The MCD and TES_Clm cases also show -8 and -12% density differences relative to the nominal.

MER-B

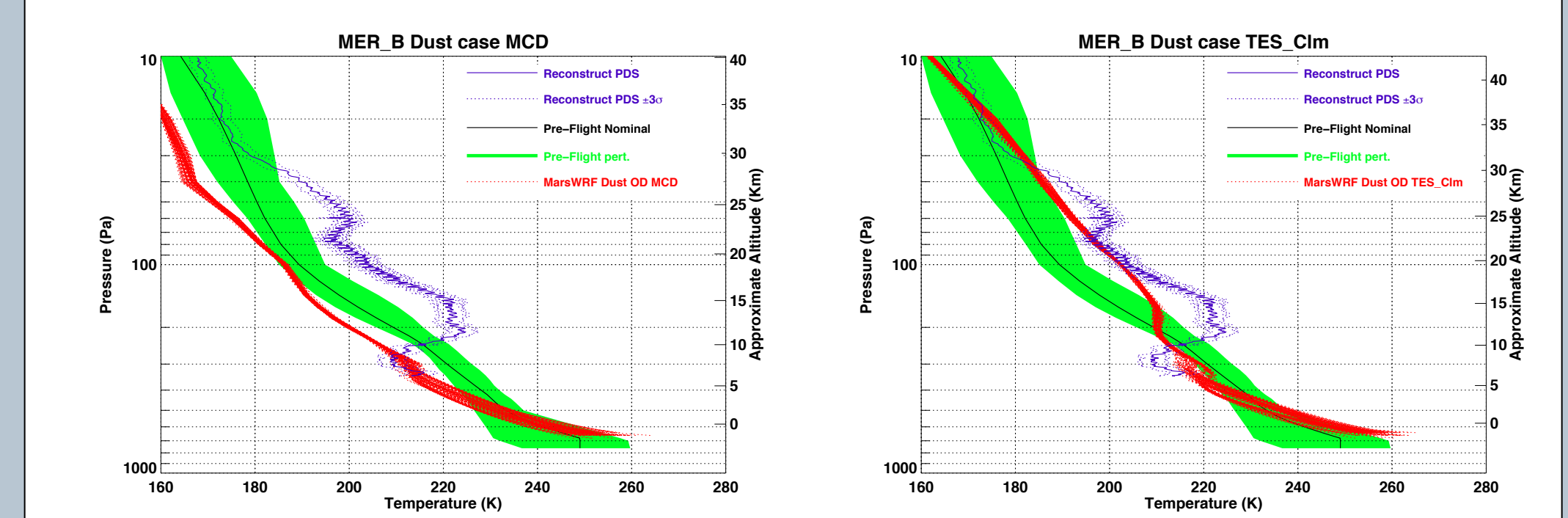


Fig. 6a

Fig. 6b

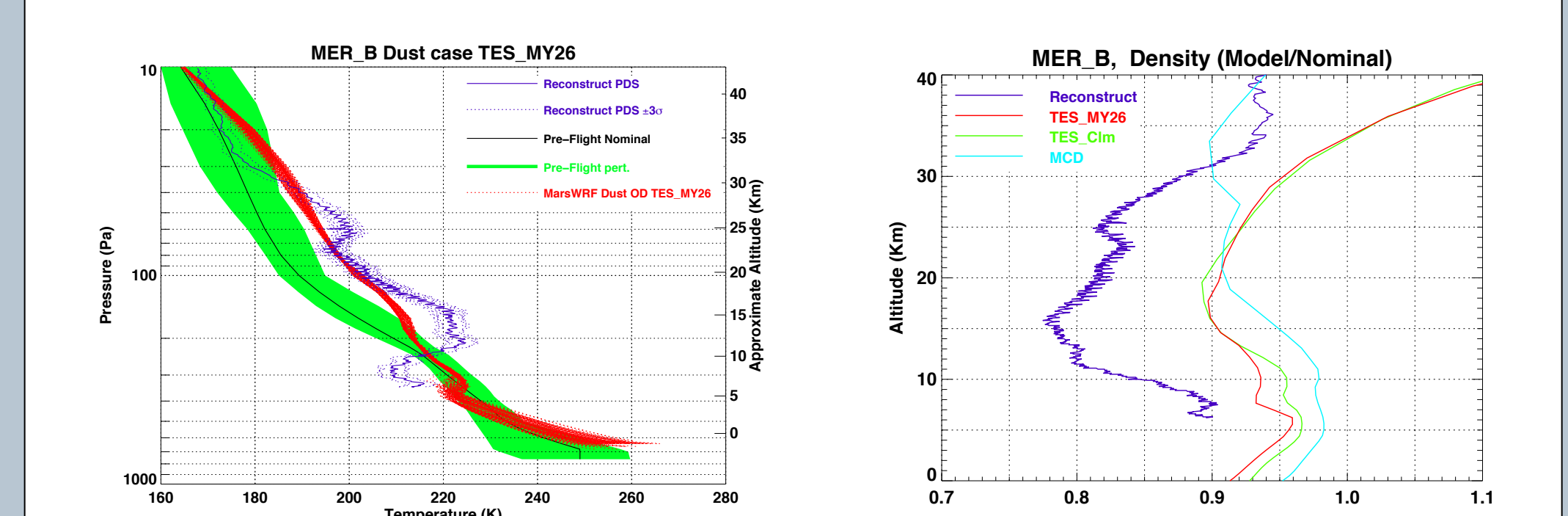


Fig. 6c

Fig. 6d

Reconstructed temperature from MER-B EDL shows a strong inversion above 300 Pa and another maximum near 60 Pa. MarsWRF model (6a) with MCD opacity is cooler than the nominal. Models with TES_Clm and TES_MY26 opacities (6b and 6c) clearly show warmer conditions like the reconstruction, a result of the enhanced dust mixing ratio above 200 Pa shown in **Figure 4**. There is a hint of an inversion near 300 Pa in the MY26 case, but the models do not reproduce the local maxima seen in the reconstruction. Density reduction for the reconstruction is nearly double that for the MarsWRF (6d). It should be noted that the TES_Limb retrieval of dust mixing ratio has a 10 km vertical resolution and variations in the dust mixing ratio on a finer vertical scale will not be captured by the retrieval. Uncertainties in the reconstruction of the EDL data could also play a role in the differences seen in the comparisons with the model results for both MER-A and MER_B simulations.

Summary

Temperature profiles from MarsWRF model simulations with different dust opacity specifications are compared with the reconstructions of EDL data from MER-A and MER-B missions. The use of TES Limb data for vertical distribution of dust opacity along with the nadir data for total opacity yields model results in good agreement with the reconstruction. Enhanced opacities, due to regional dust storm in the case of MER missions, perturb the temperature and the density profiles. Observations from past missions can be used in conjunction with models to develop characterization of atmospheric variability needed for EDL design activities of future missions.