OBSERVATIONS OF LARGE DUST STORMS DURING THE MARTIAN DUSTY SEASON

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Introduction:

We investigate the occurrence of large significant dust storms during the martian dusty season—southern spring and summer (Ls 180° to 360°). While there is extensive variability in the occurrence of dust storms [e.g. Zurek and Martin, 1993], there is a striking similarity in the overall behavior of the atmosphere, at least in years without a global dust event.

In this work, we focus on dust storms that perturb the temperature structure throughout the atmosphere. These are storms that loft dust well above the convective boundary layer into the lower atmosphere (between ~10 km and ~50 km).

We use data from MCS (on MRO) and TES (on MGS). This provides observations over seven Mars Years (MY 24 to MY 26 from TES and MY 28 to MY 31 from MCS). In two years (MY 25 and MY 28), global dust events occurred. In the other five years, there were only large regional dust storms.

Analysis Approach:

We use a relatively simple approach to identify and categorize the significant dust events while filtering out the local dust storms. We examine the zonal mean temperatures at 50 Pa (~25 km) over the season of interest.

The zonal mean essentially filters out the small storms by averaging any weak signature they might have. It also directly examines the impact on the global atmospheric structure. 50 Pa (~25 km) was selected to require the storm to affect more than just the boundary layer. In addition, storms that noticeably affected the temperatures at 50 Pa are the ones that have a regional or global impact on the atmospheric structure. It is also a region where both instruments can generally provide high quality retrieved temperatures.

The zonal mean was selected to require the storms to either have a very strong impact in one part or (as is often the case) affect the temperatures in an entire latitude band. Likewise, using a 2° Ls temporal bin (~4 sols) significantly reduces the impact of a local storms since they usually only last a sol [Cantor *et al.,* 2001]. In particular, the averaging should filter out the "Rocket Dust Storms" [Spiga *et al.,* 2013] seen in models that may allow local storms to loft dust to ~25 km. The binning criteria were also selected to provide adequate resolution to actually resolve and analyze the progress of the atmospheric impact of the storm.

Datasets:

We have taken the temperature retrievals from each of the instruments and binned them into latitutde/Ls bins. While both instruments are measuring atmospheric temperature they are using different techniques (nadir versus limb sounding) and are on different platforms. For purposes of this work, we find any subtle differences between the two datasets are not a concern. The binning was selected independently for each dataset. It was optimized to be as fine as possible while matching each dataset's intrinsic properties.

Mars Climate Sounder. MCS is an infrared 9 channel limb staring radiometer [McCleese *et al.,* 2007]. The retrieval algorithm [Kleinböhl *et al.,* 2009, and Kleinböhl *et al.,* 2011] produces vertical profiles of temperature, dust and water ice extinction versus pressure. The MCS detectors have a 5 km vertical resolution on the limb, providing a half scale height resolution. The retrieved profiles generally extend from the surface to ~80 km.

The retrievals were binned in 5° latitude by 2° Ls bins. MCS is on the MRO orbiter in a near polar sun-synchronous orbit with a local mean solar time of 3 AM/3 PM at the equator [Zurek and Smrekar, 2007]. The MCS observations start at Ls = 110° in MY 28 and continue to the present.

Thermal Emission Spectrometer. TES is primarily a nadir sounding infrared spectrometer with 6 cm^{-1} or 12 cm^{-1} resolution [Christensen *et al.*, 2001]. The retrieval algorithm produces vertical profiles of temperature and column integrated dust and water ice and water vapor opacities [Conrath *et al.*, 2000 and Smith, 2004]. For this work we have only used the nadir geometry TES observations. The spectral resolution in the nadir geometry provide a one scale height vertical resolution and coverage from the surface to ~40 km.

The TES retrievals were binned into 2° latitude by 2° Ls bins. TES is on the MGS orbiter in a near polar sun-synchronous orbit with a local mean solar time of 2 AM/2 PM at the equator. The TES observations start at the beginning of the mission, Ls = 102° in MY 24. They continue through to Ls = 82° in MY 27.

Storm Identification and Characterization:

Dust storms are generally qualitatively obvious in the zonal mean temperature field. However, to quantitatively define them, we used a 200 K contour of the daytime temperatures. This provides a good definition of the latitudinal and temporal extent of the storms. It also is a clear increase from the pre-storm unperturbed background conditions. Almost all of the significant storms reach zonal mean temperatures above 200 K. In the case of two particularly weak seasonally late storms (MY 24 and MY 30), we instead used a daytime 197 K contour to better define the extent of the storm. In both cases, this produced a better match for the disturbed region due to the relatively cold environment at the time of the storm.

For most storms, the temperature increase at the onset of the storm is rapid. Thus the identified starting Ls is not sensitive to the selected contour and 200 K is usually near the time of the steepest temperature increase. The end of some of the storms is not as well defined. This is due to the relatively long decay time as the dust settles and the perturbed atmosphere returns to a non-storm seasonal state. In many cases, the atmosphere remains above ~185 K for extended periods and it is not possible to account for seasonal trends. 200 K represents the transition of the atmosphere from significantly perturbed to modestly elevated temperatures. So for simplicity, we generally used the same value for defining the "end" of the storm. Likewise, we generally use the 200 K contour to define the latitudinal extent of the storm at its peak.

In some cases, a second dust event starts while the first one is still decaying and the temperature never falls below 200 K. There is usually a temperature minimum, which we use to separate the two. The separation is often more obvious in the nighttime zonal mean temperature structure. While the second event could be treated as a second phase of the first one, this becomes complicated and equally arbitrary due to the long decay after any of the storms. A finer examination of the data also reveals that the two events usually do have significantly different characteristics, especially in terms of the impact on the global atmospheric structure. We find that it is more illuminating to separate the two events.

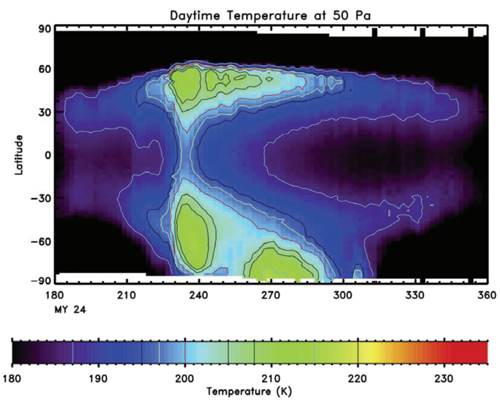

Figure 1. Daytime zonal mean temperatures versus season from TES at 50 Pa, Ls 180° to 360°, for MY 24. The red contour at 200 K and orange one at 197 K are to define the storms, other contours help define the overall storm and background behavior.

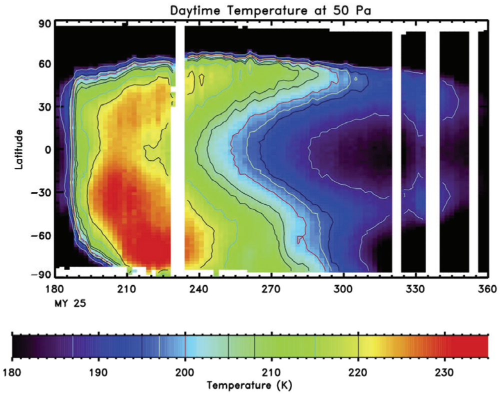

Figure 2. Daytime zonal mean temperatures versus season from TES at 50 Pa, Ls 180° to 360°, for MY 25.

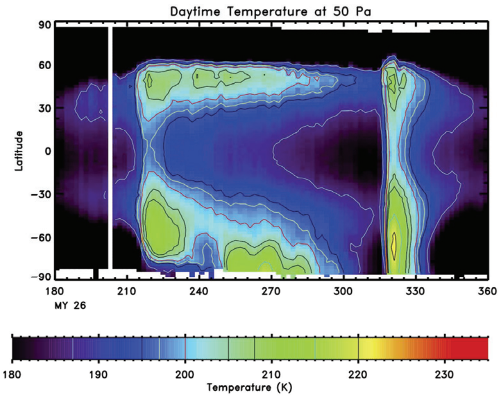

Figure 3. Daytime zonal mean temperatures versus season from TES at 50 Pa, Ls 180° to 360°, for MY 26.

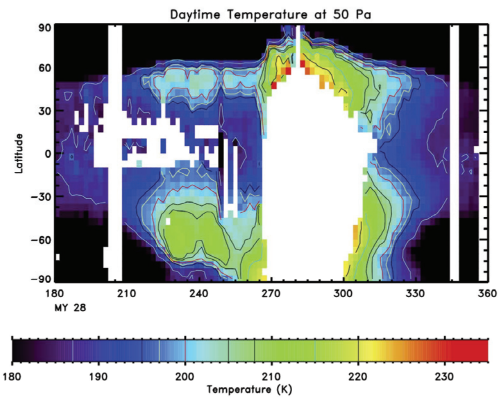

Figure 4. Daytime zonal mean temperatures versus season from MCS at 50 Pa, Ls 180° to 360°, for MY 28. The dust is too opaque in a limb path at 50 Pa for successful limb temperature retrievals during most of the global dust storm.

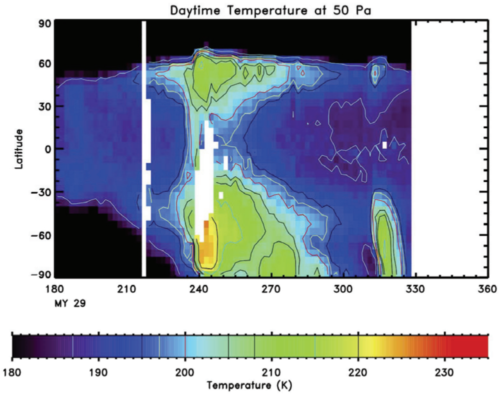

Figure 5. Daytime zonal mean temperatures versus season from MCS at 50 Pa, Ls 180° to 360°, for MY 29.

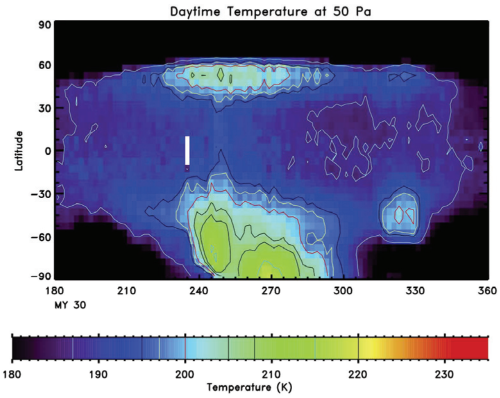

Figure 6. Daytime zonal mean temperatures versus season from MCS at 50 Pa, Ls 180° to 360°, for MY 30.

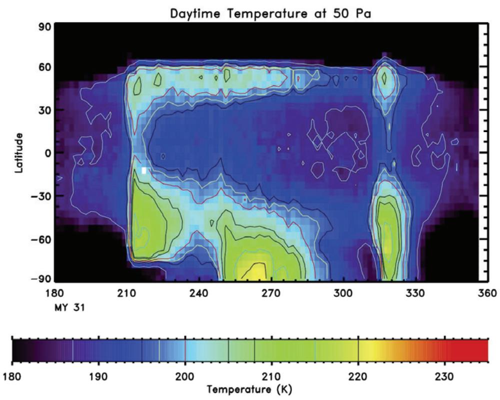

Figure 7. Daytime zonal mean temperatures versus season from MCS at 50 Pa, Ls 180° to 360°, for MY 31.

Dust Storm Behavior:

Examining all of the available Mars Years reveals a few trends and similarities among the dust events. In particular, there is a strong inter-annual similarity in the pattern of regional dust storms in the years without a global dust storm.

Regional dust storms. In the years without a global dust storm, there appear to be three large regional dust storms each year. We have labeled the events A, B and C in chronological order (see figure 8). Key parameters for each of the storms have been assembled from the five years of available data (table 1). Given the small sample and the dynamical nature of the atmosphere, it is likely that some individual storms can exceed these parameters

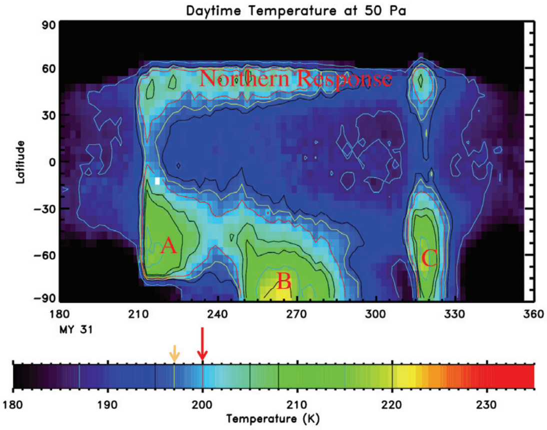

Figure 8. Same as fig. 7, with the storms labeled. The arrows represent the contour values used to define the extent of each storm.

Table 1. Generalized Regional Storm Parameters. These have been rounded to help account for the limited sampling available from the current observations.

	A Storm	B Storm	C Storm
Starting Ls	210° - 240°	245° - 260°	305° - 320°
Duration (deg Ls)	15° - 45°	30° - 45°	3° - 15°
Ending Ls	235° - 270°	285° - 295°	308° - 335°
Average Peak Temperature	217 K	218 K	212 K
Peak Temperature Range	210 K – 230 K	210 K – 225 K	200 K – 225 K

The A storm is usually a fairly classic regional or planet encircling southern hemisphere dust event. The actual instability that initiates the storm probably forms earlier. It is likely to be a small storm that develops along the northern baroclinc zone and then follows one of the storm tracks down and across the equator [e.g. Wang *et al.,* 2005]. In the southern hemisphere it then triggers the significant dust lifting leading to the regional activity.

The A storm will warm the atmosphere at all latitudes although in MY30 the effect in the northern tropics is very small. The tropical warming is significantly less than that in either polar region. In most years, it does not exceed 200 K. All of the A storms trigger dynamical heating in the northern hemisphere. The northern signature often lasts longer than the main dust heating in the southern hemisphere. While there may be small amounts of dust transported to the northern hemisphere (as very high altitude thin hazes), most of the northern warming appears to be dynamical. The nighttime shows very similar patterns and temperatures, pointing to a dynamical origin.

The end of the A storm is usually poorly defined, although typically occurring prior to the solstice. It tends to decay slowly and the decaying tail often merges with the start of the B storm. This is especially the case for A storms that start late in the year. The two storms are often more distinct in the nighttime data. The poorly defined end of the A events is due to the fact that they usually leave a long lasting dust haze in the lower atmosphere. The haze is spread zonally and continues to warm the atmosphere as it slowly sediments out.

The B dust storm is a southern polar event. It generally starts to manifest itself in the zonal mean temperatures at or near the south pole. The storm is probably the signature of a large seasonal cap edge storm, but it may be the combined effect of multiple dust storms or possibly sustained by subsequent cap edge storms.

The "B" storm always initiates in a significantly perturbed atmosphere that is still warm due to the activity from the "A" storm. It appears to start just after perihelion (Ls = 251°) in most years. The initiation near perihelion may be more a coincidence than an actual driving factor. The timing of the B storm may be more due to the location of the seasonal cap edge, where it appears to originate, and the associated circulation. The "B" events have a relatively long rise time and reach their peak right around the southern summer solstice. Unlike the first event of the year, the response to the "B" events is confined poleward of the southern mid-latitudes. "B" events do not seem to trigger a northern dynamical response, however there is still noticeable northern warming from the "A" event that continues to decay throughout the "B" event.

The "C" storm is quite similar to the "A" storm in that it is usually a fairly classic regional or planet encircling southern hemisphere dust event. It is, however, the most variable of the three storms, ranging from almost non-existent in MY 24 to the strongest storm for the year (MY 26). It starts well after the end of the "B" storm every year.

The "C" storms are also very short storms, lasting at most 15 degrees of Ls. The "C" events tend to have correspondingly short rise times once they initiate. This may be a reflection of the late season when they occur, with reduced sunlight due to being further from perihelion. Most of the "C" storms produce a dynamical response in the northern hemisphere. In many cases the response is quite weak (at least in a zonal mean sense) and it is non-existent in MY 24 (when the primary storm was very weak).

Global dust storms. It is difficult to say much concerning global dust storms since only two have occurred (so far) in the years observed by TES and MCS. They appear to be highly variable and do not seem to fit into the annual pattern of the regional storms. However, the two global dust storms in the datasets are very distinct from the regional storms in their characteristics. Both have zonal mean peak temperatures exceeding 235 K, at least 5 K warmer than any regional storm. The initial phases are latitudinally broader and more rapid than the regional storms. However, the overall rise time tends to be longer than for other storms (25° to 30° of Ls). The storms exhibit very strong warming in the tropics and northern mid-latitudes, which otherwise do not exceed 205 K. They also last at least 20° Ls longer than any of the regional storms.

In MY 25, the global storm occurs before the start of any regional storms (perhaps defining an earlier possible start season for the A storm). In MY 28, the global storm occurs in the middle of the regional B storm, after a classic appearing regional A storm.

One possible interpretation is that the global storms are not related to the regional storms that occur in other years. They are imprinted on a "standard" dust storm pattern, but wipe out any storms that occur after they start. Based on the limited observations, it is also possible the global storms could instead be associated with the A and B events.

References: Cantor *et al.* (2001), *JGR* 106, doi: 10.1029/2000JE001310; Christensen *et al.* (2001), *JGR* 106, 23823-23871; Conrath *et al.,* (2000), *JGR* 105, 9509-9520; Kleinböhl *et al.* (2009), *JGR 114*, E10006, doi: 10.1029/2009JE003358; Kleinböhl *et al.* (2011), *JQRST 112*, 1568-1580; McCleese *et al.* (2007), *JGR, 112,* E05S06 doi: 10.1029/2006JE002790; Smith (2004), *Icarus* 167, 148-165; Spiga *et al.* (2013), *JGR 118*, doi: 10.1002/jgre.20104; Wang *et al*. (2005), *JGR 110*, E07005, doi: 10.1029/2005JE002423; Zurek and Martin (1993), *JGR* 98, 2347-2399; Zurek and Smrekar (2007), *JGR, 112,* E05S01, doi: 10.1029/2006JE002701.

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