BRIDGING THE SCALES: WHAT LOCAL DUST STORMS CAN TELL US ABOUT REGIONAL AND GLOBAL DUST EVENTS AND VICE VERSA

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Introduction:
Dust storms on Mars can affect areas as small as a few square kilometers and as large as the surface area of the planet [1]. The largest of these storms, the multi-centric global dust events of southern spring and summer, long have been an object of intense scientific interest [2]. However, the complexity of their structure and evolution carefully documented in recent decades seems to have obstructed theoretical studies of their dynamics since the Viking era with the possible exception of the dynamics underlying their interannual variability [e.g., 3,4].

At the same time, the development of mesoscale models for the Martian atmosphere has enabled the simulation of smaller-scale dust storm activity [5,6]. Mesoscale modeling has led to new hypotheses about how dust storms grow, are maintained, and decay as well as about the role of dust storms in atmospheric vertical transport. However, the observational constraints on mesoscale simulations of dust storms are typically not very strong, because studies of local dust storms (with a couple of exceptions) mostly have focused on climatology and connection to large-scale dynamics rather than dust storm structure. Nevertheless, mesoscale modeling and past climatological work have been exceptionally valuable and remain the essential foundation and complement for the work we will describe here.

The purpose of this abstract is to discuss five structural elements that global and regional dust events can share with some local dust storms and propose possible questions/hypotheses/mysteries that could be addressed by further modeling and observations. These are: (1) a negative dayside surface temperature anomaly; (2) positive nightside surface temperature anomaly/nightside survival; (3) banding/texture; (4) detached dust layers (DDLs); and (5) limb castellations. The presentation will discuss some of the highlighted observations in greater detail.

Negative Dayside Surface Temperature Anomaly: Scattering and absorption by dust reduces the amount of sunlight that reaches the surface. The result is a strong association of dust storms with surface temperatures much cooler than the surrounding environment. Negative dayside temperature anomalies are well documented for the 2001 global dust event [7,8], but they easily can be seen in other events (Fig. 1).

An outstanding question about these anomalies is how contiguous they are with the area obscured by dust and how quickly the presence or absence of dust opacity will impact surface temperature. Consider strong winds at the top of the boundary layer moving over an area. If there is strong boundary layer convection, some of those winds may be mixed to the surface and mobilize dust. However, that dust then will suppress boundary layer convection [9]. Storm development thus will be dependent on the relative position of the winds aloft and the negative surface temperature anomaly associated with dust mobilization and the advected dust in the boundary layer. Thus, the interplay between these factors could explain variability in local dust storm size.

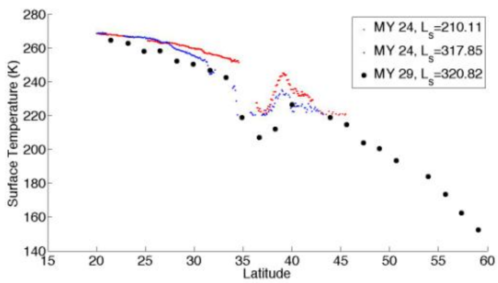

Figure 1: *Negative dayside temperature anomalies associated with local dust storms in NW Amazonis—SE Arcadia Planitiae*

Positive Nightside Surface Temperature Anomaly: At night, downwelling radiation from dust warms the surface, resulting in a positive nightside surface temperature anomaly [10]. A simple demonstration of this can be seen in northwestern Hellas during the MY 25 global dust event (Fig. 2), when nightside temperatures increased by ~ 20 K in a few sols just as the storm expanded from Hellas [7]. Part of this increase is seasonal, but ~10 K is due to the storm (Fig. 2).

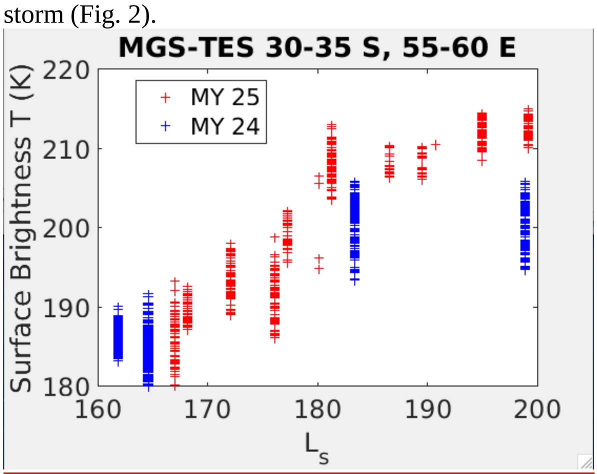

Figure 2: *Nightside surface brightness temperatures over NW Hellas Planitia during the MY 25 global dust event and the non-dust storm year of MY 24.*

It is possible that such anomalies are detectable in association with local dust storm activity that survives from the daytime of one sol to the next. An example is shown in Fig. 3. The sudden increase in surface temperature near 20° N might be expected when observing a large, deep crater but the area is relatively free of craters of the appropriate diameter. Examination of data over multiple years suggests surface temperatures were ~8 K above normal.

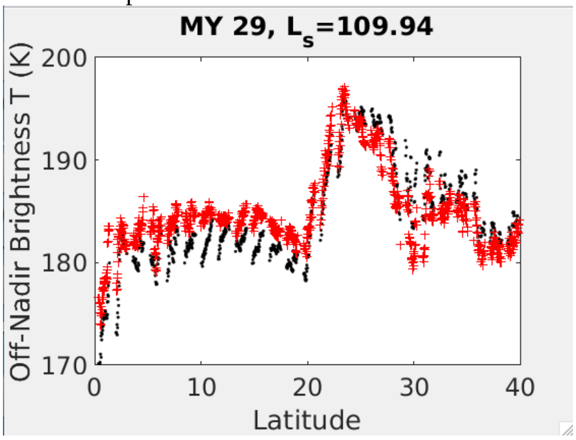

Figure 3: *Increase in nightside brightness temperatures in Mars Climate Sounder off-nadir observations over SE Utopia Planitia. A local dust storm is present in the area in visible imagery on the day prior and subsequent to these observations. Black dots indicate A5 channel observations, while red crosses indicate B1 channel observations.*

The dynamical significance of these anomalies is related to their implications for dust storm thermodynamics. Dust storms that are broadly warmer than their environment at night can generate positive work and maintain a circulation in the absence of external forcing [5]. Monitoring these anomalies in association with "outflow" temperatures downstream of the circulation may be helpful for understanding changes in dust storm intensity.

Banding/Texture: Dust storms of all sizes have an appearance in visible imagery that ranges somewhere between distinct structures/banding and indistinct haze. The former appearance, especially at the mesoscale, has been named "texture" [11] and is thought to be indicative of areas of intense dust lifting and/or convective transport [7,11].

The puffy texture that is particularly evident in Fig. 4a has been interpreted as cumulus-type convection [7]. Preliminary study suggests that the banded texture in Fig. 4c is analogous to shallow convective mixed layer rolls in the Earth's atmosphere, but the exact analogy remains under investigation [12].

The significance of texture is twofold. First, if particular textures can be connected to atmospheric column/profiling data, it may be possible to use texture as a proxy for structural aspects of a given storm, such as the type of convective activity present. Second, the structural aspects of storms that can be inferred may be relevant to the external forcing underlying the storm or the processes that allow the storm to maintain itself.

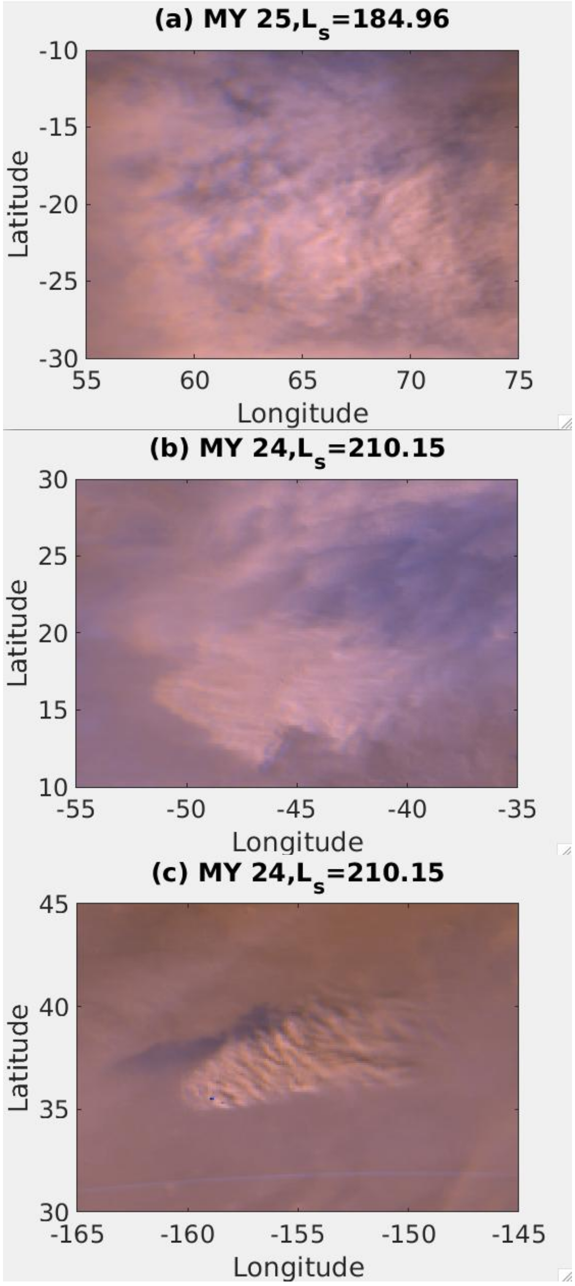

Figure 4: *Examples of texture in dust storms (MOC images described in [13]): (a) during the expansion phase of the global dust event of MY 25; (b) a regional dust storm in MY 24; (c) a local dust storm in MY 24.*

Detached Dust Layers (DDLs): DDLs (distinct local maxima in dust mass mixing ratio) are commonly observed in Mars's atmosphere in many places and seasons at altitudes between 15 and 75 km above the surface [13 and refs. therein]. Modeling suggests that DDLs can be formed by convection within dust storms [6].

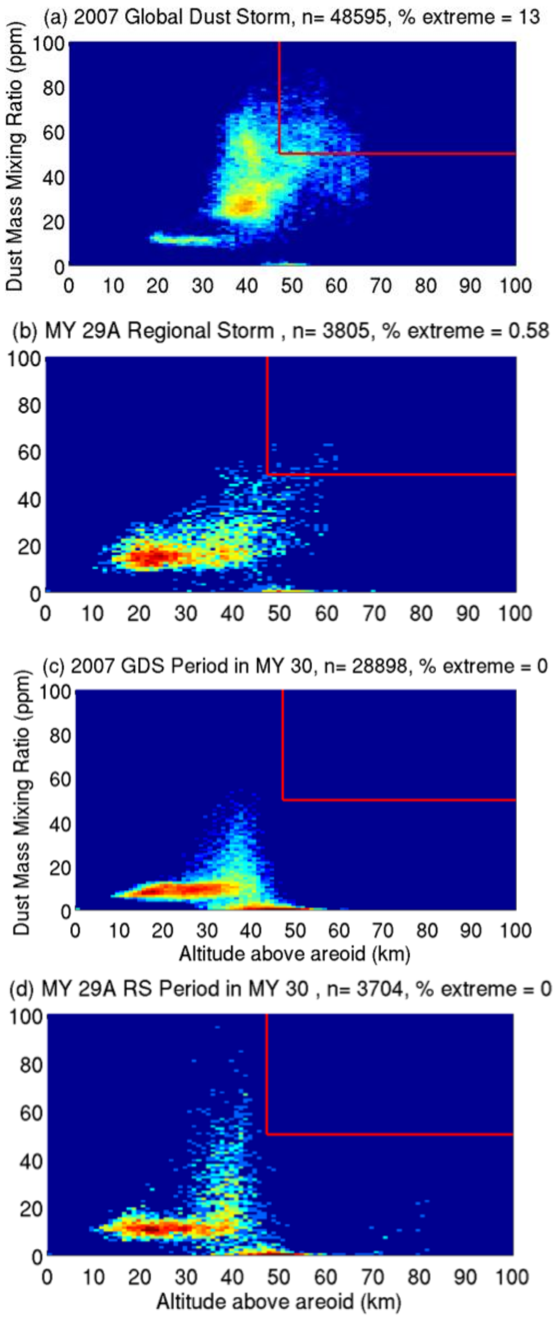

Figure 5: *Distribution of the peak dust mass mixing ratio inferred from MCS dayside retrievals in altitude above the areoid (km)-dust mass mixing ratio (ppm) space for the periods indicated. The extreme detached dust layer criterion is indicated by a red box. The color scale is logarithmic. The darkest blue is* 10^{-3} *% and the deepest red is 1 %* [14].

Observations so far have identified a variety of DDL activity in association with dust storms. The association of DDLs with regional and global dust events is best illustrated by Figs. 5a-d. In quiescent periods (Figs. 5c-d), most DDLs form a climatological layer of 5–15 ppm at 10-35 km above the areoid. A small number of higher mass mixing ratio layers are observed in the 30–45 km, which may be due to convection in local dust storm activity or have some other explanation.

However, during global and regional dust storm activity, this mysterious region of DDLs grows in abundance, mass mixing ratio, and altitude. The vast majority of extreme DDLs (at least 50 km above the areoid and 50 ppm dust mass mixing ratio) observed by MCS occurred during global dust storm activity [14] (Figs. 5a-b).

Attributing DDLs in global and regional dust events to areas of dust lifting in visible imagery is not straightforward. Like the high altitude warming associated with large dust storms [e.g., 15], there appears to be significant displacement between where dust is lifted (as indicated by visible imagery and surface thermal anomalies) and where DDLs are observed. One possible explanation is that large amounts of dust are being injected into the atmosphere at altitudes at which they obscure the limb (inhibiting retrieval) and then are advected away from the lifting region. Along the way, they rise, as a result of their initial positive buoyancy and/or the solar escalator mechanism [16], to an altitude where they can be observed.

One argument for this explanation comes from unusually strong local dust storm activity during MY 29, in which dust is not retrieved until approximately 40 km above the surface. Nevertheless, a significant detached dust layer is observed to the north of the storm. Limb radiance observations and possibly visible imagery suggest the presence of a 40 km deep storm rather than a thin detached dust layer below 40 km.

DDLs during regional and global dust storm activity also suggest that deep convection in these storms persists from sol to sol. There are several known instances in which multiple detached dust layers are observed in the same set of profiles. The separation between layers and spreading of dust within layers suggests that at least two separate sols of deep convective activity are recorded.

Extreme DDL activity is exceptionally observed outside of global or regional dust storm activity. The vast majority of these exceptions are attributable to local dust storms interacting with Olympus Mons, Arsia Mons, and possibly other nearby volcanoes. This type of extreme DDL formation event remains challenging to understand. On one hand, the layers themselves are unambiguous. They are clearly distinguished from ice clouds at lower altitudes. In addition, the dust storms responsible for their genesis are sometimes apparent in visible imagery, either as the well-known spiral cloud on Arsia Mons [17] or as a possible area of dust lifting along the southern flank of Olympus Mons. On the other hand, many of these layers are observed in conjunction with extremely thick water ice clouds in the absence of apparent dust storm activity.

Limb Castellations: Normally, brightness of the limb decreases with altitude as emission and scattering decrease with distance from the surface, air density, and aerosol density. Limb castellations depart from this rule and form high aspect ratio projections of radiance at higher altitude than the background. In MCS observations, they are of particular interest when they are present in the dust-sensitive A5 channel. And therefore instruments, such as IUVS on board MAVEN or limb-observing instruments on ExoMars TGO, could observe limb castellations in this sense as long as it is possible to distinguish between dust and condensates.

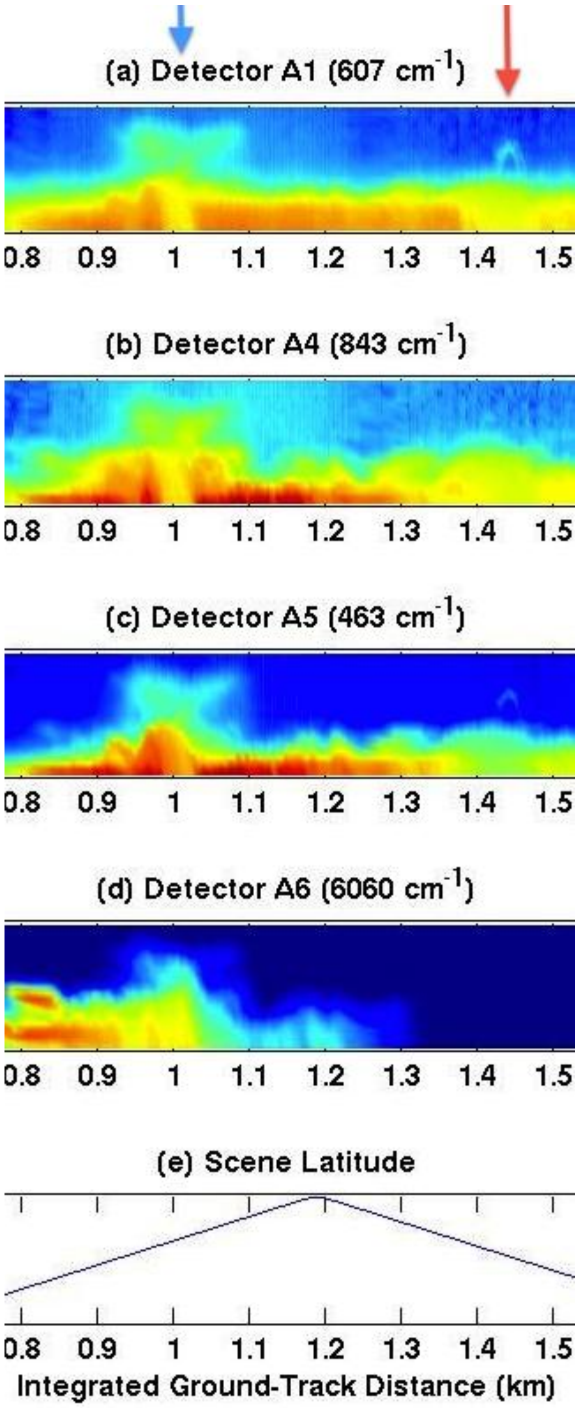

Figure 6: *A limb castellation in MCS observations of Mars's limb is indicated by the blue arrow. The unlabeled y-axis is detector altitude (km) ranging from 0 to 100 km, excerpted from [14]. The x-axis is in* 10^4 *km*

Observationally, limb castellations are connected with extreme detached dust layers. In the ideal case, limb castellations are retrieved as extreme detached dust layers. In other cases, only the sides of limb castellations are retrieved as resolved layers. In several cases, limb castellations are retrieved as unresolved caps of high dust and/or water ice opacity.

Dynamically, limb castellations may be the high intensity tail of dust-driven convection in Mars's atmosphere. They are therefore the best view of the deep convection that is generating extreme DDLs in global, regional, and orographic local dust storm events. Several local orographic events are associated with two limb castellations, while the MY 28 global dust event is associated with seven. A small number of limb castellations associated with non-orographic local dust storms are known.

The best-defined limb castellations are strongly concentrated in two areas: the mid-latitudes between Hellas and Argyre and the area around Tharsis. Limb castellations contemporary with regional dust storm activity are observed in the former area, while those attributed to local orographic events are observed in the latter area. Notably, limb castellations in the MY 28 global dust storm were observed in two phases: the first in the former area early in the storm and the second in the latter area 15 sols later. These insights may be helpful in understanding how they form and their significance for dust storm dynamics in general.

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