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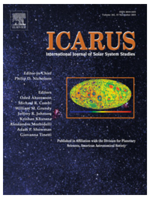

The cascade from local to global dust storms on Mars: Temporal and spatial thresholds on thermal and dynamical feedback

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ABSTRACT

We use the MarsWRF general circulation model to examine the temporal and spatial response of the atmosphere to idealized local and regional dust storm radiative heating. The ability of storms to modify the atmosphere away from the location of dust heating is a likely prerequisite for dynamical feedbacks that aid the growth of storms beyond the local scale, while the ability of storms to modify the atmosphere after the cessation of dust radiative heating is potentially important in preconditioning the atmosphere prior to large scale storms. Experiments were conducted over a range of static, prescribed storm sizes, durations, optical depth strengths, locations, and vertical extents of dust heating. Our results show that for typical sizes (order 10^5 km^2) and durations (1–10 sols) of local dust storms, modification of the atmosphere is less than the typical variability of the unperturbed (storm-free) state. Even if imposed on regional storm length scales (order 10^6 km^2), a 1-sol duration storm similarly does not significantly modify the background atmosphere. Only when imposed for 10 sols does a regional dust storm create a significant impact on the background atmosphere, allowing for the possibility of self-induced dynamical storm growth. These results suggest a prototype for how the subjective observational categorization of storms may be related to objective dynamical growth feedbacks that only become available to storms after they achieve a threshold size and duration, or if they grow into an atmosphere preconditioned by a prior large and sustained storm.

1. Introduction

Dust storms on Mars are observed to exhibit a wide range of sizes, durations, and optical thicknesses (Briggs et al., 1979; Martin and Richardson, 1993; Martin and Zurek, 1993; Cantor et al., 2001; Wang and Richardson, 2015; Guzewich et al., 2015, 2017; Kass et al., 2016; Kulowski et al., 2017). Colloquially these storms have been grouped based primarily on their size, with references to “local”, “regional”, and “planet-encircling” (or “global” or “great”) being common (e.g., Martin and Zurek, 1993). Based upon the extensive and nearly continuous dataset available from Mars Global Surveyor (MGS) through to Mars Reconnaissance Orbiter (MRO), other additional categorizations have been suggested based on both the spatial and temporal extent of the storm (Cantor et al., 2001), the seasonal date of large regional and global storm onset (Kass et al., 2016), or the location and mechanism of regional storm evolution (Wang and Richardson, 2015). Local dust storms are the most common occurring storm and their characteristics and spatial and temporal distribution have been examined in some detail (Cantor et al., 2001; Guzewich et al., 2015, 2017; Kulowski et al., 2017).

An important question prompted by the creation of these subjective categories is: to what extent do storms actually cluster into different “types” of storms and what physical mechanisms might exist that cause such clustering? For example, are the local and regional storms shown in Fig. 1 merely self-similar structures of different sizes or are there distinct dynamics that control these structures such that they are truly separate classes of storm? To illustrate this dichotomy, it might be argued that on the one hand the spectrum of storm sizes is a continuum and that the grouping of storms into labeled categories is an arbitrary, subjective, and “fuzzy” discretization of a natural, continuous distribution. A corollary of this argument would be that there are no threshold size- or

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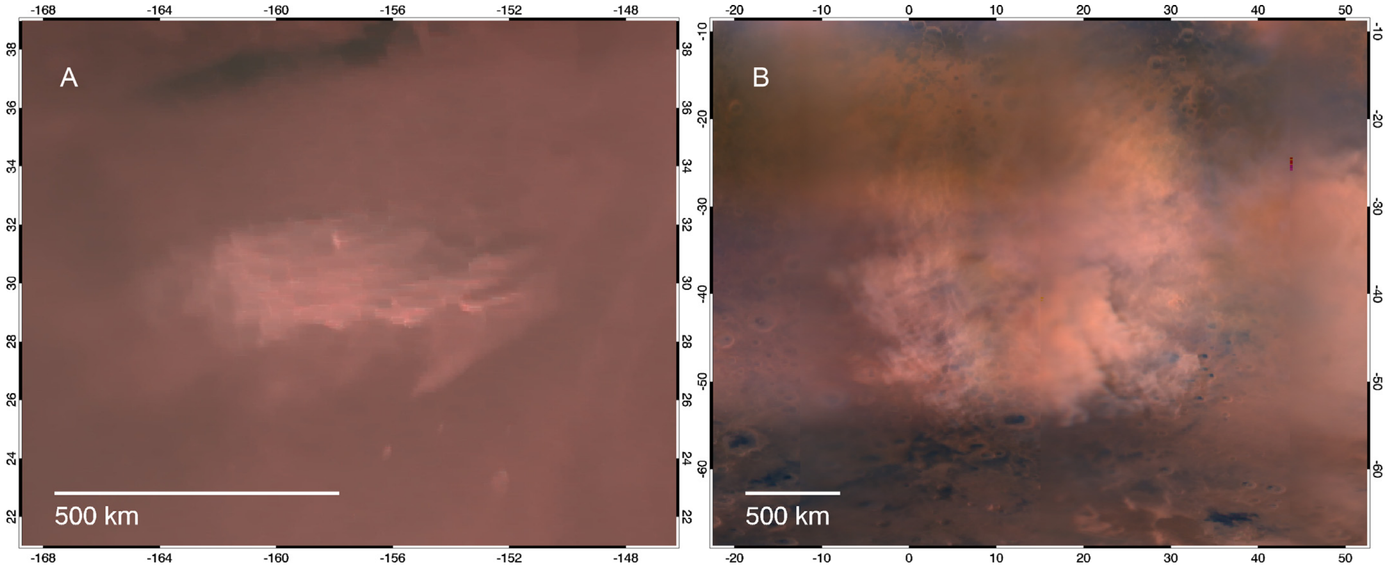

Fig. 1. Examples of (A) local and (B) regional dust storms seen in the Mars Daily Global Maps (MDGMs) assembled from Mars Reconnaissance Orbiter (MRO) Mars Color Imager (MARCI) camera images. (A) Local storm near Amazonis Planitia in MDGM B10_day27, Ls=291.9°. (B) Regional storm over Noachis Terra, west of Hellas, in MDGM B11_day27, Ls=309.7°. Boxes around each image show latitude and longitude intervals, while scale bars at the lower left of each image show the difference in relative size between the two storms. The scale bars are shown as a 500 km reference distance corresponding to the central latitude of each image. Note that both images use a simple cylindrical map projection and hence the 500 km scale bar changes in projected length at different latitudes; in particular, in case (B) the latitudinal variation of over 60° in the image means that the 500 km scale bar will change by approximately a factor of 3 between the top and the bottom of the image.

time-dependent feedbacks for storm development. Instead, there would be a dependence on stochastic parameters (e.g., background winds, supply of dust, etc.), and that, at an extreme, there would be only a very weak positive feedback on dust lifting, otherwise all storms would eventually grow to the largest extent. On the other hand, the contrary argument would be that the storm categories truly reflect deeper and objective divisions in the actual dust storm population. The corollary in this case would be that real physical mechanisms within the atmosphere must provide threshold (size and duration) and/or location dependent “gates” that allow storms to change from one category to another and create the gaps (the transitional pathways) between the categories. In this latter case, dust storm growth would represent a true cascade as new modes of growth became available to storms depending upon their size, duration, history, and location.

Some evidence that objective categorical definition has merit, at least in the case of distinct global dust storms, is provided by numerical modeling of global dust storm onset (Haberle et al., 1982; Schneider, 1983; Wilson, 1997; Newman et al., 2002; Basu et al., 2004). These models show that the presence of sufficient dust in the atmosphere fundamentally reconfigures the general circulation, with a significant expansion and intensification of the overturning (“Hadley”) circulation. Further support for objective categorical distinction of storms is provided by the frontal/tidal mechanism for the development of “flushing” storms (Wang et al., 2003), where a distinct morphological subcategory of regional storms has been linked to a specific regional and seasonal window (the northern mid-latitudes in northern autumn and winter), and to a specific transitional mechanism (the constructive interference of the thermal tide with baroclinic frontal storms).

A generalization of the question of storm categorization is whether thresholds exist such that as storms grow they gain access to additional and potentially faster mechanisms of growth that are not available to smaller storms. The activation of such extra mechanisms of growth would then provide the physical distinctions between different storm type categories. Most local dust storms, which widely occur near the cap edge, at surface thermophysical property boundaries, and in association with local topography, generally dissipate within a few sols (e.g., Cantor et al., 2001; Guzewich et al., 2015; 2017; Kulowski et al., 2017). This suggests that the intrinsic growth mechanisms that are available to small storms are relatively slow compared to changes in the externally imposed thermal and wind state. Indeed, it is not clear how much of local storm growth is due to intrinsic feedbacks (such as an expanding periphery of dust lifting) and how much is due to changes in the externally imposed wind field independent of the dust storm (e.g., the apparent lack of feedback in the storms examined by Heavens (2017)). Irrespective of how the smaller storms initially grow, the question addressed in this paper is whether the ability of a storm to influence the atmosphere at some distance from the area of dust heating, and/or at some time after cessation of dust heating, changes significantly for storms above some threshold size, duration, and/or dust opacity. Distal influence then opens the possibility of distal feedback mechanisms of storm growth (e.g., more rapid expansion of the existing lifting area, activation of new lifting centers, increased rates of dust advection, deeper vertical mixing of dust, etc.) that are not available to smaller storms and would create a dynamically meaningful distinction between large local and small regional storms. Similarly, a lasting modification of the atmosphere by one storm that aids the growth of a subsequent storm allows for the physical categorization of sequential activation storms, as observationally described by Wang and Richardson (2015) and that may have been important in the origin of the 2001 global storm (Strausberg et al., 2005).

In this paper, we examine the scale-dependent feedback between local and regional dust storms and the regional and global atmosphere. We limit the study to consideration of only the thermal and dynamical feedback on the atmosphere in order to limit the investigation to feedbacks associated with the distal dynamical response of the circulation to the storm. We do not treat advection of dust aerosols nor the activation of additional dust lifting centers beyond the area of the originally imposed storm. We use a general circulation model (GCM) to examine the thermal and dynamical response of the atmosphere to the imposition of static dust storms (simulated as regions of increased dust optical depth) of differing physical extent, duration, and total optical depth. The strength of