**FORECASTING DUST STORMS ON MARS: A SHORT REVIEW.**

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**Introduction:** Martian mineral dust is radiatively active and mostly absorbs short-wavelength (solar) radiation and, to a lesser extent, long-wavelength (thermal infrared) radiation. The dust cycle is currently considered to be the key process controlling the varia-bility of the Martian climate at inter-annual and seasonal time scales, as well as the weather variability at much shorter time scales. The atmospheric thermal and dynamical structures, and the transport of aerosols and chemical species, are all strongly dependent on the dust spatio-temporal distribution. Dust storms are the effect of strong and extended dust lifting by near-surface winds, and the behavior of dust clouds aloft both depends on and impacts the atmospheric circulation. The dust particles can represent a problem for surface mechanical and electrical systems and even for the health of future Martian astronauts.

Therefore, the spatial and temporal distributions of dust aerosol are essential observables for any fundamental or applied study related to the Martian atmosphere, including weather monitoring and forecast for robotic and possible future human exploration missions.

In this article we provide a short review focusing on the current and future capabilities of forecasting Martian dust storms.

**Dust storms classification:** Although small-scale dust storms can occur at any time during a Martian year, observations show that it is during northern autumn and winter (within the "High Dust Loading" –HDL- season, see [1, 2]) that the dust lifting increases, raising the probability of observing small (sizes of few tens kilometres across) and large (sizes of few hundreds kilometres across) dust storms. This well observed phenomenon coincides with the greater forcing in the atmosphere during the period around perihelion, which on Mars occurs at $L_S = 251°$.

Although there is not an officially accepted nomenclature and classification of dust storms (especially for historical events), [3] showed that one can define a clear size-duration relationship by which one can distinguish three (or four) types of dust storms. "**Local dust storms**" are events that create a thick atmospheric dust loading over an area smaller than 1.6·106 km2. They tend to systematically last less than 3 sols. "**Regional dust storms**" are events in which the atmospheric dust loading is important over an area larger than 1.6·106 km2, lasting for more than 3 sols. "**Planet-encircling dust storms**" are referred to those multi-regional dust storm events that spread mineral dust in the atmosphere at all longitudes (although not necessarily at all latitudes and not necessarily simultaneously), thus engulfing the planet at global scale for several months. The lifting of dust from the ground, though, does not occur at global scale, but rather at regional scale. This classification could be completed by the "**Dust devils**", created by the convective activity during daytime, with diameters of less than 1 km and which last less than 10 minutes. It is convenient to distinguish the different types of dust events when studying the likeliness of being affected by such an event for robotic or human missions..

**Current capability for dust storm forecast:** A typical question that is frequently asked to Mars' atmosphere experts is about the possibility of forecasting dust storm events, and in particular the occurrence of a planet-encircling dust storm.

Weather forecasting on Mars is very different from that on the Earth. When compared to Earth, the specificities of the Martian atmosphere (low atmospheric density, water in trace quantities, absence of oceans) provide Mars with a (generally speaking) very predictable weather. For a large portion of the year, flow instabilities in the Martian atmosphere do not grow [4, 5]. On the contrary, this situation is not likely to occur on Earth, where the atmosphere is intrinsically more chaotic. Paradoxically, this makes the prediction of the state of the Martian atmosphere with models more problematic in a certain sense, because the main source of disagreement between model and observations are possibly unknown biases (whether model or observational biases), rather than more or less known flow instabilities [6].

While forecasting the atmospheric state (i.e temperatures and winds) when the atmosphere is clear of dust is an achievable task in a large portion of the atmosphere and at most times, it becomes a much more difficult enterprise when dust storms occur. The main reason comes from the fact that, at the current state of knowledge on the Martian dust cycle, the prediction of the onset of dust storms is not yet reliable. Several factors contribute to make this prediction as such:

- The lack of deep understanding of the mechanisms of dust lifting, including the effects of dynamical thresholds [7], electric fields, sand-dust interaction, vertical fluxes;

• The lack of knowledge on the time-variable reservoirs of surface dust available to be lifted (including the possibility of differentiating between "fresh dust" and compacted layers);

• The approximate knowledge of the dust particle sizes injected in the turbulent boundary layer and beyond;

• The approximate understanding of the radiative/dynamical feedback that make a local storm transform into a regional one, and ultimately into a planetary-scale storm, within a short time-scale (usually just a few sols).

Once dust is airborne, the transport and sedimentation processes are much better constrained than lifting and atmospheric injection. Furthermore, the radiative impact of dust has been the object of several recent improvements [8, 9]. Provided the size distribution of the airborne dust is known within reasonable uncertainties, models can forecast the distribution of dust particles and the feedback on the thermal and wind structure. Paradoxically, it would therefore be easier to forecast the evolution of a dust storm that initiated a few sols before, say, the Entry Descent and Landing (EDL) of a vehicle, than to forecast the possible onset of a storm that presented no signs in the preceding sols. .

**The specificity of planetary-scale dust storms:** When a global-scale, planet-encircling dust storm occurs, the Martian environment switches to a new regime which strongly differs from other periods and other years from the point of view of density, temperature, and wind profiles, surface luminosity, etc. These storms typically last for several months, and must be accounted for when designing and planning a mission to Mars. However, one should note that the word "dust storm" in this case can be misleading in the sense that on most of the planet strong surface winds are not expected. In fact, as a result of the change in atmospheric stability, in many locations the surface winds can be weaker than usual within the area covered by a "dust storm", except at the edges where temperature contrasts are the strongest. Even the word "global" can be misleading, because these storms are born when several, often separated regional-scale dust storms occur together, and a large amount of dust injected beyond the atmospheric boundary layer is transported by large-scale winds to engulf most of the planet. The role of possible "transient teleconnection events" (i.e. rapid changes of atmospheric state induced by a localized occurrence that contribute to trigger another occurrence at distance) has been put forward to account for the onset of multiple separated regional storms in the case of the MY25 global-scale storm [10, 11], but at present it would require more extensive work to be validated and generalized.

If forecasting the onset of a local or regional dust storm is difficult, forecasting the onset of a dust storm that attains the planetary scale –i.e. encircles all longitudes within a large latitudinal band– is even more difficult at the current state of the knowledge. Planet-encircling dust storms develop suddenly, rapidly, as a combination of multiple regional storms at locations possibly far apart. The atmospheric dust loading usually increases explosively by more than 5-fold within 10 sols, reaches a peak within 30-40 sols before dust lifting is shut down, then decays slowly over a long period of time (even longer than 150 sols, depending on the peak value) after sedimentation prevails, to eventually attain typical background values again.

Five confirmed global dust storms have been observed by instruments either in Mars orbit or on the Martian surface –one in 1971 (MY 9; Mariner 9), two in 1977 (MY 12; Viking), one in 2001 (MY 25; MGS), and one in 2007 (MY 28; MRO/Mars Odyssey/MEX). One additional storm, in 1982 (MY 15) was identified from Viking lander 1 pressure observations and two more confirmed storms –one in 1956 (MY 1) and one in 1973 (MY 10)– are well documented in the ground-based telescopic record. On this basis, a very rough estimation of the probability of the onset of a global-scale dust storm within a given week (7 sols) during the ~250 sols between $L_S$=180° and 330° (within the HDL season) over Martian years 1-32 yields a probability of the order of 1% [i.e. 8 storms /(32 Martian years *(250 sols/7 sols)) = 0.7% < 1%]. It must be stressed that this very general and roughly calculated value of probability does not take into account the increase or decrease of probability depending on the specific season and location, nor it takes into account the fact that the probability distribution of global-scale dust storms likely follows that of extreme episodic events rather than a classic Gaussian probability, therefore inferring probability values from past frequencies might not be a valid approach, as much as it is not valid, for instance, in the cases of the stock market and earthquake forecast.

The main difficulties in forecasting the onset of what can become a planet-encircling dust storm are:

• These kind of storms can start as a local or regional-scale storm with no apparent preferential location within an extended band of latitudes (excluding the high latitudes);

• They do not have preferential solar longitudes, although they seem to cluster around northern hemisphere autumn equinox (equinoctial storms) and winter solstice (solstitial storms);

• They do not seemingly have a preferential time interval between two consecutive occurrences (e.g. two of such storms occurred in MY 12, but three Martian years passed between the one in MY 25 and the one in

MY 28, and none occurred for the last 4 years –possibly 5, if including the currently ending MY 33).

- The dust loading background in the sols preceding the onset of a planet-encircling dust storm may look very similar to the one present at the same season in years without global-scale storms. The simple monitoring of dust opacity, therefore, might not be sufficient if it is not associated to the monitoring of dynamical variables such as temperature, pressure, and (possibly derived) winds.

**Future capability for dust storm forecast:** A promising technique for forecasting dust storms is "data assimilation", which consists in combining all available information to reconstruct a best estimate of the state of the atmosphere. The information comes from two sources of data: observations by instrument(s) and results from a numerical model of the considered system. Thus, assimilation can be seen as an (optimal) extrapolation or interpolation of observations in space and time using a numerical model. The current research in assimilation for Mars' atmosphere has focused on nudging (Analysis Correction scheme) and ensemble Kalman filtering. All in all, these schemes are not mature enough yet to be used for the purpose of predictability of dust storms. Promising results using the assimilation of temperature and aerosol observations could lead to prediction of the evolution of dust days in advance, once it has already been lifted, injected and observed in the atmosphere. This is made possible by the capability of a numerical model to efficiently simulate the horizontal and vertical transport of dust on a global scale. However, the complexity of dust lifting and atmospheric injection mechanisms (see e.g. [7, 12]) and the lack of continuous synoptic observations, which induce a lack of understanding of the onset of dust storms, are the main reasons why it is quite unlikely to have soon an assimilation tool that is fully able to predict the occurrence of a dust storm.

Finally, we would like to mention that none of the missions to Mars so far has been able to provide both continuous and synoptic monitoring of Martian aerosols, which would allow for studying their dynamics in detail. A truly innovative method to obtain continuous synoptic observations of the dust distribution (at least the horizontal one) would be to use a Mars-stationary (areostationary) satellite rather than a polar orbiter.

Frequent and extended observations of large portions of the Mars' atmosphere allow to properly monitor and understand the rapidly evolving dynamics of the aerosols -intrinsically linked to the atmospheric thermodynamics and circulation. An areostationary satellite, similarly to a geostationary one, can continuously monitor changes in a region of the planet at least 60° wide centered at the equator, affected by meteorological phenomena such as the formation and evolution of Martian dust storms as well as water ice clouds, and evolving surface characteristics. Nonetheless it is not well positioned to observe the vertical structure of the aerosol distributions.

For Mars, the areostationary altitude is 17,031.5 km above the equator (semi-major axis = 20,428.5 km). The sub-spacecraft point is at 0° latitude at the chosen longitude, and the satellite can observe the surface up to 80° away from it, although the portion of the disk useful for scientific purposes might be limited to about 60° away. The view of Mars from areostationary orbit is similar to that shown in Fig. 1 where a regional storm that developed in Martian year 24 is seen as from the point of view of such an orbit.

**Acknowledgments:** The authors (LM in particular) are grateful for funding from the French "Centre National d'Etudes Spatiale" (CNES) and from the "European Space Agency" (ESA) to carry out part of the study presented in this paper. LM also acknowledges funding support to improve dust climatologies from NASA's "Planetary Data Archiving, Restoration, and Tools" (PDART) program under grant no. NNX15AN06G.

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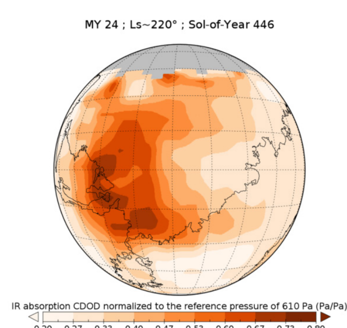


**Figure 1.**