The Spatial and Temporal Distribution of Dust in the Atmosphere of Mars. Richard W. Zurek, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Mail Stop 321-690, Pasadena, CA 91109. *Richard.W.Zurek@jpl.nasa.gov*

Introduction: The presence of dust in the atmosphere of Mars profoundly influences its density-temperature structure and wind patterns, as well as the surface environment. The absorption of solar radiation during the day and the exchange of infrared radiation both day and night provides a powerful thermodynamic drive for atmospheric circulation. In many respects, dust is the heat reservoir for the non-polar Mars atmosphere in that its redistribution and subsequent radiative heating and cooling alter vertical and horizontal temperature and pressure gradients. This provides a major feedback for the system: Winds lift dust into the atmosphere and heating of the dust alters pressure and temperature at a given height and these changes drive winds.

Atmospheric dust affects the environment in other ways, as well. Dust aerosols serve as nucleation centers for the condensation of water and carbon dioxide ice. These condensate clouds, optically thin outside the winter polar region, also affect the environment, primarily through their infrared radiative effects, but also by scavenging water and the dust itself from the atmosphere. In the polar regions, dust particles can nucleate carbon dioxide snow whose fall-out affects the surface ice properties, particularly in the south.

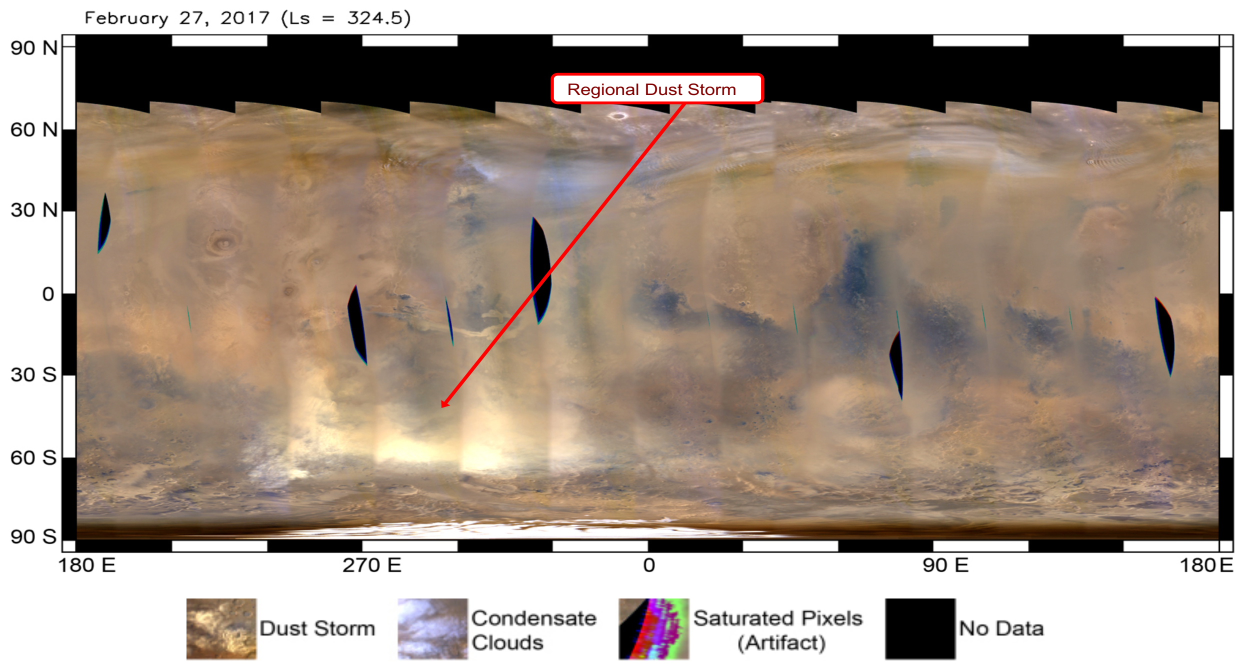
Dust Entry into the Atmosphere: Dust enters the atmosphere wherever it is present and winds are strong enough to lift it. This can occur by winds blowing across the surface through saltation of sand-size grains and lofting of the finer particles they dislodge, but also by mesoscale low pressure vortices whose entrainment of dust forms dust devils across much of the planet.

The strongest winds near the surface occur at the edges of the polar caps where strong temperature/pressure gradients occur across the boundaries of bare ground and icy surfaces. Undulation of these jet streams can spawn local storms which concentrate the winds along fronts or convective rolls. When these are strong enough, dust is actively raised and the storm is now a local dust storm. Generated at high latitudes, some of these local dust storms move to lower latitudes and thus affect much of the planet. On occasion these storms can grow, or centers of activity can coalesce, to cover large portions of the planet. Events covering ~10^6 km^2 are classified as regional storms and a handful of these can produce hazes that encircle the planet. During the present epoch, these regional and planet-encircling events occur in the southern hemisphere during its spring and summer, often triggered by local dust storms generated near the northern winter polar vortex that then travel south through the great northern basins (primarily Acidalia and Utopia), eventually crossing the equator.

Observations of Dust Distribution: Telescopic observers of Mars glimpsed such storms on occasion as movable “yellow clouds”. Today we have the benefit of ~20 years of practically continuous coverage of the weather of Mars, including these storms, thanks to the daily global coverage of the Mars Global Surveyor (MGS) Mars Orbiter Wide Angle Camera (MOC-WA) and its successor, the Mars Reconnaissance Orbiter (MRO) Mars Color Imager (MARCI[1,2]). Figure 1 shows recent daily global maps from the latter. MARCI looks limb to limb across the near polar spacecraft ground track. This, of course, is not a true synoptic view of Mars; all areas are not seen at one moment in time. Instead, the map is a composite of swaths imaged on the 12-13 orbits MRO makes each day. This means that the center of each swath is near 3 p.m. local time while the edges are closer to 1.5 hours earlier and later, so that the phase angle of the Sun varies significantly from left to right across the swath, giving rise to the visible discontinuities across the map. Similar maps of column dust opacity are made on a less frequent basis from IR radiometers[3]; e.g., the Mars Odyssey (ODY) THEMIS instrument. Maps of dust extinction and temperature can also be made for different pressure levels from globally sampled limb profiles retrieved from MRO Mars Climate Sounder data[4].

Readily apparent on many of the daily visual image maps are the local dust storms in both hemispheres, typically moving in the jet streams along the edge of the polar caps. On occasion these local storms can bloom into regional events, usually in the southern hemisphere, during a “great dust storm season”[5] that spans much of southern spring and summer. In the south such regional storms arise by expansion or coalesce of local storms as they move from the seasonally varying polar cap edge into southern mid-latitudes. From the north, a local storm may move out of high latitudes and across the equator where it may develop into a regional storm once it reached the southern mid-latitudes.

Figure 1: MARCI Daily Global Map for late southern summer in Mars Year 33. A large regional dust event is shown. The black gores (no data) are produced when the MRO spacecraft rolls to the left or right to target observations by high-spatial-resolution imagers. Also, the winter (north) pole is still in polar night. (Malin & Cantor, Malin Space Sciences Systems, all rights reserved).



Dust Storm Pathways and Evolution: Local dust storms can occur in any season and can affect nearly any place on the planet, but there are preferred storm tracks where local storms more frequently move from the high latitudes of storm generation towards the equator. Model simulations show that the tracks for the northern dust storms are due in large part to the channeling by topography of essentially western boundary currents in the large basins. Whether these local storms cross the equator can depend on the time of day, as the large-scale winds at low latitudes have a significant diurnal variation, opposing or amplifying the storm movement, producing a "tidal (time-of-day) gate"[6].

The cause of local dust storms expanding into regional events is not understood. There are examples of apparently identical local dust storms in two different Mars years but otherwise at the same season and traveling the same path; one grows into a regional event, the other does not. Possibly, it has to do with the vertical penetration of the storm.

Most local dust storms have little temperature signature above the planetary boundary layer. However, once dust is lofted higher into the atmosphere, it will be transported away from the active dust-raising centers, producing a haze expanding longitudinally with both in situ and wide-ranging temperature effects observable using atmospheric infrared sounders[3,4].

There is a pattern during the southern spring and summer seasons, when Mars is near perihelion and solar heating is greatest, of typically 3 regional events, of varying size (Fig. 2)[7]. In some, but certainly not all Mars years, a regional storm will expand such that the dust haze produced by spatially limited dust raising centers spans essentially all longitudes, producing a planet-encircling, hemispheric or even global dust storm. Historically, the planetary-scale dust events appeared to occur every 3-4 Mars years[5]. This is consistent with events recently observed in 2001 and 2007 (MY 25 and 28). However, there have been no planet-encircling dust events in the last 5 Mars years.

During these events, dust is lofted to quite high altitudes (> 70 km for the 1971 global dust storm).

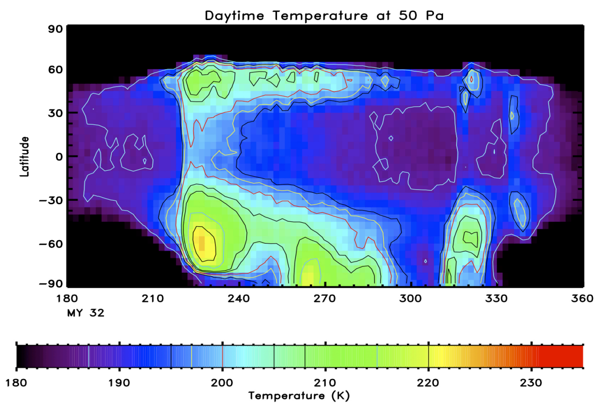


Figure 2: MRO Mars Climate Sounder temperatures at ~25 km altitude showing the direct response of solar heating of regional dust storms in the southern hemisphere and their indirect dynamical (adiabatic) heating in the north. (Kass et al., 2016).

Clearing of the atmosphere after these events takes several months, while regional dust storms may affect the atmosphere for a few weeks and local storms for one to a few days. The clearing of the dust is not necessarily uniform, horizontally or vertically, subject to the large-scale atmospheric circulation. Even the background dust haze produced by more local processes or the tails of these dust events is not uniformly mixed with height[8].

The potential effects of dust on human missions are several:

- Dust can be anywhere on the planet, but some surface areas and some atmospheric zones are known to be particularly troublesome. As shown in Fig. 3, even during the clearest periods, there is some background dust haze.
- Dust falling from the atmosphere does degrade the efficiency of solar panels such as those on the Mars Exploration Rovers. Fortunately, winds can remove such dust on occasion, which accounts for the multi-year longevity of the solar-powered rovers. During local and more expansive dust events, solar power at the surface can be substantially reduced.
- The surface thermal environment also changes: Daytime temperatures are lower (less sunlight reaches the surface) while nighttime temperatures are warmer due to (infrared radiation by the atmospheric dust, a "greenhouse" warming effect).
- Dust alters the vertical density profile, modifying the environment for entry and landing and aeromaneuvering; the atmosphere can "bloom" even at high altitudes, affecting aerobraking spacecraft.

Dust Uncertainties: Major uncertainties about the dust distribution are:

- As noted earlier, the full process by which dust storms are generated and evolved are not fully understood; modeling of these developments is known to be deficient in simulating the numbers of events in a given year and in predicting their evolution to larger scales, when that occurs.
- In particular, interannual variability of the largest events has not been successfully replicated.
- Dust reservoirs (i.e., places where dust can be injected into the atmosphere by seasonal winds) are not well delineated; it is possible that some interannual variation is caused by previous removal of the movable dust.

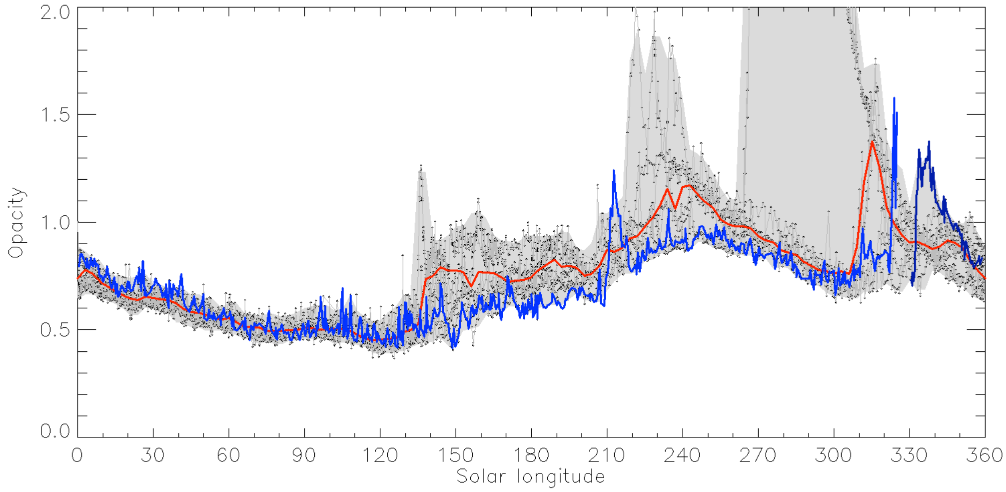
Needed Measurements: Measurements that could improve our understanding of the temporal and spatial distribution of dust in the Mars atmosphere include:

- Continued observation of the global weather and climate of the Mars atmosphere, requiring extended measurements of the current visual imaging and IR temperature/aerosol sounding. New observations, particularly of:
    - Atmospheric temperatures and water vapor, especially near the surface and even in the presence of dust (e.g., at microwave or submillimeter wavelengths).
    - Winds at multiple altitudes, perhaps using active devices like lidar or passive observation of the Doppler shift of emission line features (to model dust redistribution).
    - Detailed characterization of particle composition, size and electrical properties, either in situ or on returned sample materials (to improve physical parameterizations).
    - Storm (weather) prediction desired to support humans on the surface will require a combination of orbital and surface meteorological observations.

Atmospheric Models: Also needed are improved Atmospheric General Circulation Models:

- Fully radiative-dynamic interactive codes (i.e., dust is not prescribed, but is transported and radiatively active).
- Improved dust lifting & removal parameterizations.

Figure 3: Column Dust Opacity above the Opportunity Rover for 2004-2017. Blue line is for last Mars year; red is the median in approximately weekly steps for all years. Gray shaded area includes 95% of all values. (M. Lemmon, Texas A&M University)



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