

The Mars Global Dust Storm of 2018

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Mars is a dusty planet. Wind often lifts dust from the surface into the air forming clouds of dust at different locations across Mars. These dust storms typically last up to a couple days and grow to a few hundred km in size. However, once in a long while when conditions are just right, localized dust storms can interact in a way that optically thick suspended dust covers nearly the entire planet remaining aloft for weeks to months. These global-scale dust storms are the most dramatic of all weather phenomena on Mars, greatly altering the thermal structure and dynamics of the Martian atmosphere and significantly changing the global distribution of surface dust. Such a global-scale dust storm occurred during the summer of 2018, the first such event since 2007. The global dust storm was observed by an international fleet of spacecraft in Mars orbit and on the surface of Mars providing an unprecedented view of the initiation, growth, and decay of the storm as well as the physical properties of the dust during the storm's evolution. The 2018 global-scale dust storm was observed to grow from several localized dust-lifting centers with wind-blown dust suspended in the atmosphere encircling Mars after about two weeks of activity. Dust column optical depths recorded by the Opportunity and Curiosity rovers on the surface were the highest ever recorded on Mars. Peak global intensity of the dust storm was reached in early July 2018. Over the next couple months, the dust settled out and the atmosphere returned to its climatological average. Only a small number of global-scale dust storms have been observed on Mars, and so detailed analysis of the observations of this storm will provide important new insight into how these events occur and their effect on the current Mars climate.

Nomenclature

L_s	=	areocentric solar longitude, a measure of the season on Mars
τ	=	dust column-integrated optical depth

I. Introduction

THE presence of dust is ubiquitous on Mars and it has long been recognized to play a crucial role in the current Martian climate¹⁻⁶. Observations of dust suspended in the Mars atmosphere go back to early telescopic records of “yellow clouds” that would sometimes obscure the familiar surface markings⁷. These clouds of dust typically measure up to a several hundreds of km in size, and most of the time these clouds are observed to form, evolve, and then dissipate over the course of a few days. During the portion of the year near perihelion when there is maximum solar input to drive atmospheric motions, there is usually a succession of many of these “local-scale” dust storms, the combination of which can generate enough suspended dust to create a regional-scale pall of dust covering a continent-sized portion of the globe. The visible-wavelength optical depth of the dust can exceed unity in the regions where dust clouds are thickest. In this nominal case the gravitational settling of dust soon overcomes the raising of new dust from the surface, and the overall dust loading of the atmosphere begins to fall. As the season progresses and Mars recedes from the Sun, the amount of dust raising further subsides and eventually an equilibrium is reached where gravitational settling of the dust is balanced by a background of small-scale local dust storms and dust devils with the optical depth of dust typically around $\tau=0.4$ ⁸.

In rare cases, however, conditions are just right for an interaction between the local- and regional-scale dust storms that prolongs the growth of dust lifting and incites new centers of dust lifting to form at a number of different sites around Mars. As this chain reaction of dust injection into the atmosphere occurs, winds aloft distribute the dust around the planet over a timescale of a week or two so that a thick blanket of airborne dust encircles the planet. This is a so-called “global dust storm⁹.” Such a global dust storm occurred during the summer of 2018¹⁰. Figure 1 shows

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images taken from Mars orbit before and during the global dust storm¹¹. Surface features that are easily recognizable before the global dust storm were no longer apparent during the storm. These global storms can nearly completely obscure the planet with the dust optical depth reaching $\tau=5$ or more over a global scale, with localized values measured at $\tau=10$ or even higher. Eventually, new dust lifting subsides and the dust slowly falls out of the atmosphere, but this process can take months until the atmospheric dust loading has returned to nominal climatological levels once again.

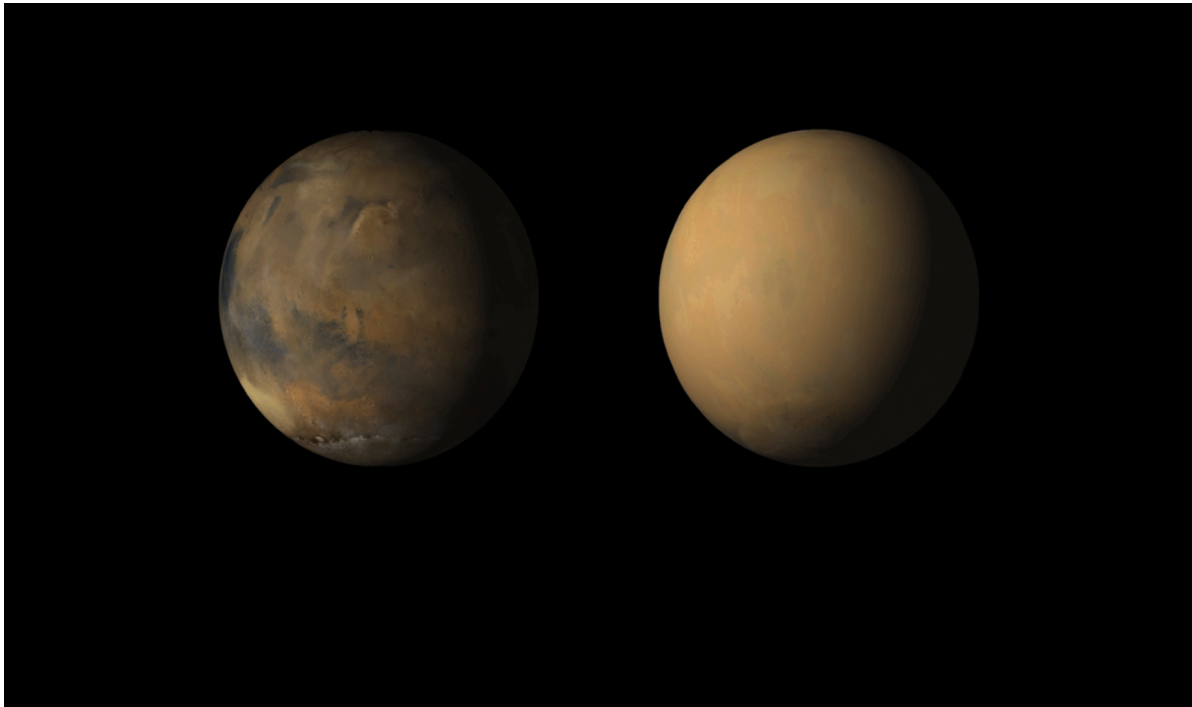


Figure 1. A view of Mars before (left) and during (right) the global dust storm of 2018 as imaged by the Mars Color Imager (MARCI) on-board the Mars Reconnaissance Orbiter. The image at left was taken 28 May 2018 ($L_s=183^\circ$), just before the beginning of the global dust storm. The image at right was taken 1 July 2018 ($L_s=203^\circ$) at the height of the dust storm. Suspended dust from the storm completely obscures surface markings apparent in the image at left. Image Credit: NASA/JPL-Caltech/MSSS.

As mentioned earlier, Mars has distinct seasons. Seasons on Mars are described in terms of the areocentric longitude, or L_s , of Mars in its orbit around the Sun. The value $L_s=0^\circ$ is defined by the Northern Hemisphere vernal equinox. Likewise, in the Northern Hemisphere $L_s=90^\circ$ marks the date of summer solstice, $L_s=180^\circ$ is the date of the autumnal equinox, and $L_s=270^\circ$ is the date of the winter solstice. In the current epoch, Mars perihelion (its closest approach to the Sun) is at $L_s=251^\circ$. This is important because the relatively large eccentricity of the Martian orbit (0.09) means that Mars receives roughly 40% more solar flux at perihelion than it does at aphelion, its furthest point from the Sun. At low latitudes, this drives seasons that are aligned more with the difference between perihelion and aphelion than the summer vs. winter seasons that are familiar from terrestrial experience. Very roughly, the Martian year can be divided between a relatively warm and dusty “perihelion season” between $L_s=180^\circ$ and 360° , and a relatively cool and less dusty “aphelion season” between $L_s=0^\circ$ and 180° . Because the seasonal date of perihelion ($L_s=251^\circ$) is close to the summer solstice in the Southern Hemisphere ($L_s=270^\circ$), the orbital seasons (perihelion/aphelion) and obliquity seasons (summer/winter) align causing a greater annual variation in temperatures than in the north^{12,13}.

While there is some amount of dust suspended in the Martian atmosphere during all seasons¹², the activity that raises dust from the surface to form dust storms is far more common during the perihelion season when solar input is larger. And, the occurrence of global dust storms appears to be restricted solely to the perihelion season. Figure 2 shows the seasonal date of all observed global dust storms on Mars over the past 100 years^{7,14,15}. To differentiate

between different Martian years, a consensus has arisen¹⁶ to label Mars Years (MY), beginning with MY 1 defined as the Mars Year with the first global dust storm observed in the modern age in 1957. The beginning of a new Mars Year is defined by $L_s=0^\circ$, and thus, Mars Year 1 (MY 1) began on 11 April 1955. The global dust storm from summer 2018 occurred in MY 34, and the current Mars Year is 35, which began on 23 March 2019.

In Fig. 2, it is apparent that every observed global storm has occurred during the perihelion season within the range of seasonal dates $L_s=185^\circ$ to 315° , or within about 65° of the perihelion date. With only 11 recorded global dust storms it is difficult to draw any firm conclusions about the distribution within that period, but there appear to be three clusters or groups, with one group having an early onset before $L_s=220^\circ$, a second group clustered near perihelion at $L_s=250^\circ$ – 270° , and a third group occurring late in the interval near $L_s=310^\circ$.

The physical mechanism behind the growth of local and regional scale dust storms into a global scale storm is still not well understood⁶. Indeed, it appears likely that it is a combination of many different phenomena with complex positive and negative feedbacks that leads to the growth and evolution of a global scale storm. It is apparent from a quick look at the Mars Years listed in Fig. 2 that global dust storms do not happen every Mars Year. Indeed, the occurrence of global storms is stochastic with the probability for a global storm being roughly 25% for any given Mars Year. Global storms can happen on two consecutive years (e.g., MY 9 and 10), and there has even been one occurrence of two global storms happening during the same Mars Year (MY 12), which was observed in 1977 by the Viking orbiters and landers¹⁷. More common is a gap of several Mars Years between global storms. In fact, the last global dust storm before the 2008 (MY 34) storm occurred in 2007, six Mars Years previously (MY 28). It is still a matter of intense active research to determine the root cause for this intermittent and seemingly random behavior in the occurrence of global dust storms. It may be that some reservoir of surface dust needs time to be replenished before another global storm can occur. Others have suggested that the phasing of a spin-orbit coupling forcing term may explain much of the variation from one Mars Year to the next¹⁵. We are only beginning to fully appreciate the complexity of the Mars system and the intricate and complex interactions between atmospheric dust, clouds, dynamics, and photochemistry, and it is likely that the observed interannual variation in the size and occurrence of dust storms is caused by a number of interacting phenomena.

Figure 3 further illustrates and summarizes the points made in this introduction. Here is shown daytime atmospheric temperatures at about 25 km altitude as retrieved from thermal infrared observations made by the Thermal Emission Spectrometer (TES), which was on-board the Mars Global Surveyor (MGS) orbiter, and the Thermal Emission Imaging System (THEMIS), which is on-board the currently operating Mars Odyssey orbiter. Together, observations from TES¹⁸ (MY 24-26) and THEMIS¹⁹ (MY 26-present) now span more than 10 Mars Years, which allows the annual patterns and the interannual variations to be easily seen. At low latitudes, the cool aphelion ($L_s=0^\circ$ - 180°) contrasts with the warmer perihelion ($L_s=180^\circ$ - 360°) season. It is also apparent that the interannual variation from one Mars Year to the next is confined mostly to the perihelion season. This is primarily driven by interannual variation in the amount of dust loading in the atmosphere. Dust suspended in the atmosphere absorbs solar radiation warming the atmosphere. A greater optical depth of dust directly leads to higher observed atmospheric temperatures at local time and altitude of these observations. In Fig. 3 we can see that the three most

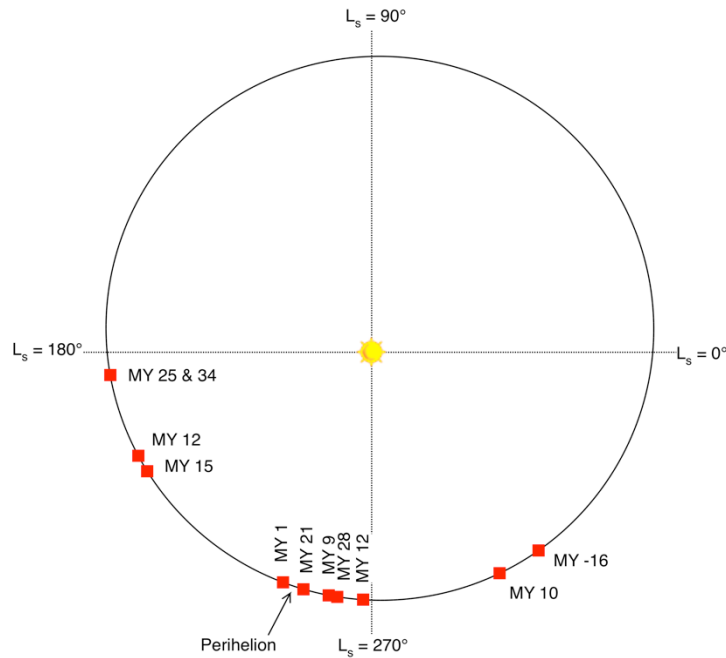


Figure 2. The timing of observed global dust storms on Mars is concentrated in the season near perihelion. The global dust storm of 2018 (MY 34) occurred early in the seasonal window where such storms have been observed to occur.

recent global storms have occurred during MY 25, 28, and 34, which are Earth years 2001, 2007, and 2018. Those three Mars Years have significantly higher atmospheric temperatures than the other Mars Years. It is also interesting that no two Mars Years are alike. The seasonal date of the MY 28 storm was much later than the MY 25 and 34 storms. And, even those Mars Years without a global scale storm show significant differences in the timing and strength of the regional scale storms that produce the warmings shown in this plot.

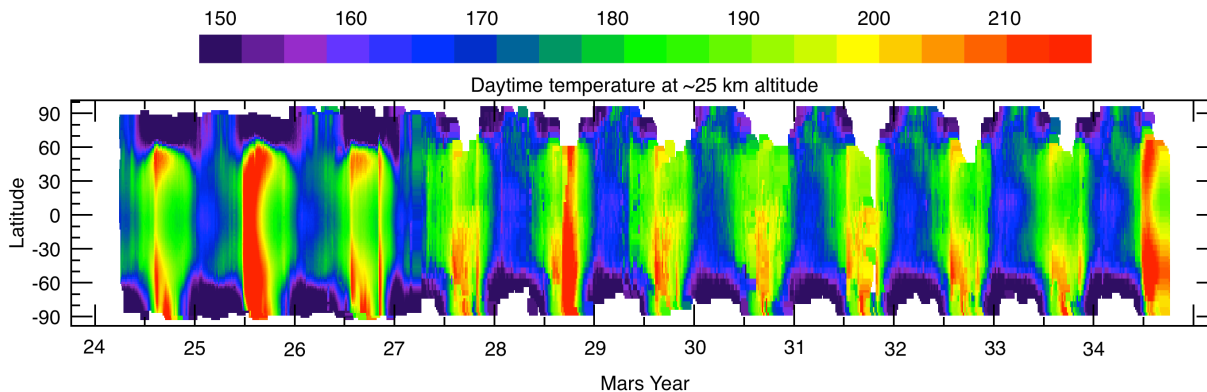


Figure 3. Daytime atmospheric temperature on Mars at ~25 km altitude as observed by the TES and THEMIS instruments over a time period of 10 Mars Years. Global dust storms are indicated by the large thermal response observed during Mars Years 25, 28, and 34. Other Mars Years had smaller, regional-scale dust storms, but no global storm.

For the remainder of this paper, we will focus on a description of spacecraft observations of the most recent global dust storm, which occurred in MY 34, or the summer of 2018. This storm was observed by a number of different spacecraft, both from orbit and from rovers on the surface giving us an unprecedented view of the initiation, growth and decay of one of these rare events.

II. Observations of the 2018 global dust storm

A. Overview and Narrative of the storm’s evolution

As with all Mars global dust storms, the global storm of 2018 began as a series of typical local-scale dust storms^{10,20}. In the earliest stages of development, it is never obvious whether a given dust event will grow to global scale covering nearly the entire planet or remain at the more typical regional scale of up to a couple thousand km. At the beginning of the perihelion season ($L_s=180^\circ$), dust activity is typically just beginning to increase in frequency and intensity, and the global average dust loading, or optical depth, also begins to increase. As is common during this season, at the end of May 2018 (MY 34, $L_s=185^\circ$) the daily global observations performed from orbit by the MARCI instrument showed the formation of a local dust storm on the edge of the seasonally growing north polar ice cap²⁰. Because of the strong thermal contrast between regolith and ice-covered surfaces, small-scale dust storms often arise along the edge of the seasonal polar ice caps in both hemispheres²¹.

The local dust storms that form along the edge of the northern polar cap in this season are often transient events lasting no longer than a day or two. However, conditions were right for this particular storm to intensify and grow in areal extent as prevailing winds carried it southward along a “storm track” toward lower latitudes. By 2 June 2018, the storm had reached the Mars Exploration Rover “Opportunity” located in Meridiani Planum near the equator. The storm continued to intensify and spread to the east. The optical depth as measured by Opportunity spiked, increasing from the nominal seasonal value of somewhat less than $\tau \sim 1$ to a lower limit of $\tau > 10.7$, the highest ever dust optical depth measured at Mars²². Ultimately, this proved fatal to the solar powered Opportunity rover, which entered a low-power fault condition and was never heard from again.

The dust storm, which had now attained regional scale stalled over the Opportunity site and continued to slowly grow in size and evolve²³. New centers of dust lifting arose to replace others that dissipated. Airborne dust was advected eastward by the prevailing winds with the effect that the dust cloud slowly grew to cover additional regions. On 12 June 2018 ($L_s=192^\circ$) the edge of the growing dust storm reached the longitude of the Mars Science

Laboratory (MSL) “Curiosity” rover, also located near the equator but 180° in longitude away from Opportunity. Figure 4 shows the rapid increase in dust optical depth as measured by direct imaging of the Sun by the Mast Camera on-board the Curiosity rover¹⁰. Over the course of approximately a week the dust optical depth increased by an order of magnitude reaching a maximum value of $\tau=8.5$. Because Curiosity is nuclear powered it was able to survive the dust storm and provide a wealth of meteorological data throughout the growth and decay of the storm.

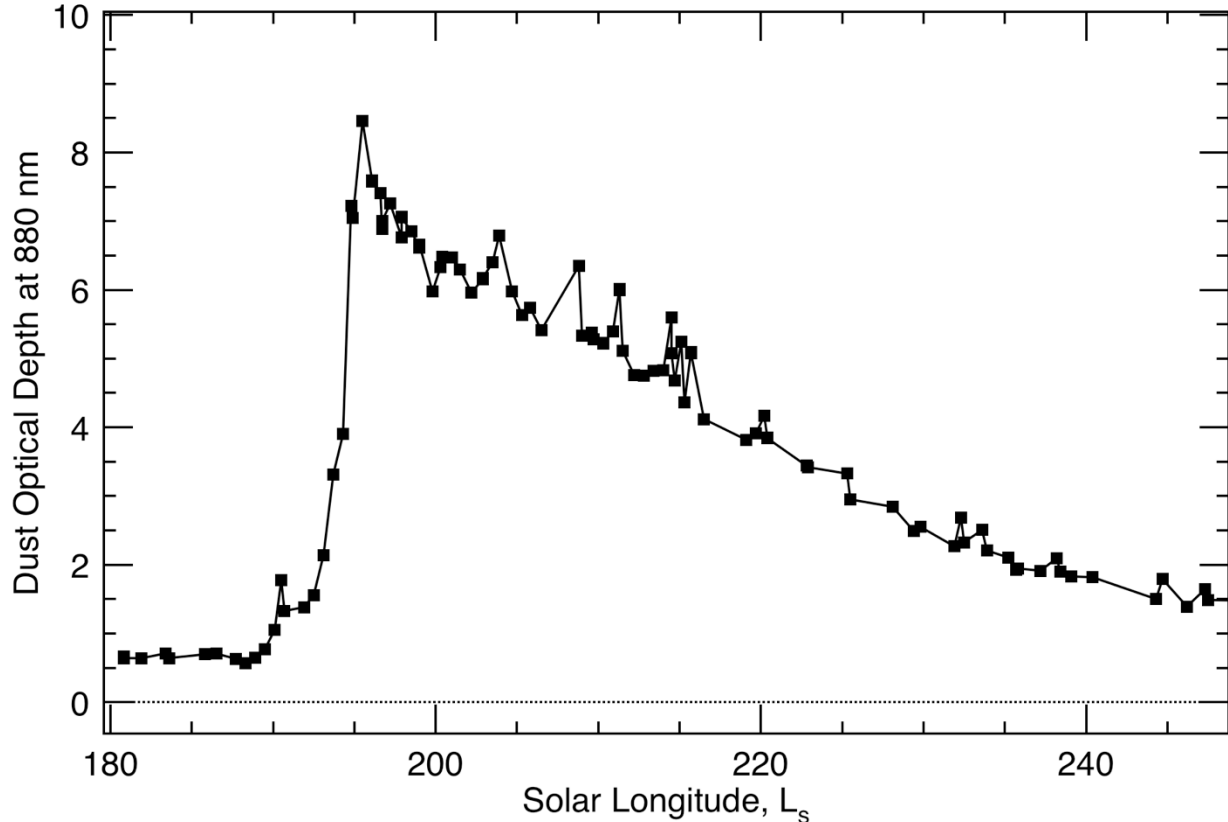


Figure 4. The column dust optical depth at 880 nm wavelength observed by direct solar imaging by the Mars Science Laboratory (“Curiosity” rover) Mast Camera. The dust optical depth at Gale Crater jumped rapidly once the cloud of dust spread over the Curiosity rover site. The optical depth subsequently decayed back to nominal values as dust gravitationally settled out of the atmosphere.

Active dust lifting spread into the Southern Hemisphere and the cloud of airborne dust was advected further eastward. On 20 June 2018 ($L_s=197^\circ$) the dust cloud completed its circumnavigation of Mars so that the storm now encircled the globe and could be officially called a global-scale dust storm. The peak dust optical depth at any given location on Mars varies, but observations from orbit²⁴ show that the peak global dust loading occurred shortly after $L_s=200^\circ$, at which time new active dust lifting began to abate and the long process of the dust gravitationally settling out of the atmosphere began to outpace new lifting of dust. As can be seen in Fig. 4, the micron-sized dust particles, which may be lofted more than 50 km into the atmosphere during a global storm²⁵, take weeks or months to settle out. Here, 20° of L_s is just over one month of Earth time. The decrease in dust optical depth observed by Curiosity (Fig. 4) is well represented by an exponential decay with a time scale of 43 sols (length of a day on Mars) or 44 Earth days¹⁰. By mid-September 2018 ($L_s=250^\circ$) atmospheric dust optical depth and temperatures had returned to nominal climatological values¹⁶ for that season, marking the end of the 2018 global dust storm.

B. Effects of the Global Dust Storm on the Martian Atmosphere

The injection of that quantity of dust into the atmosphere has a profound effect on the dynamics and meteorology of the Mars atmosphere⁶. For example, Fig. 5 shows a few of the observations during the global dust storm taken by the Rover Environmental Monitoring Station (REMS) on-board the Curiosity rover¹⁰. A set of upward-looking

photodiodes monitors the levels of UV radiation reaching the rover. Shown in the top panel of Fig. 5 is the daily maximum intensity of UV radiation observed at the rover. As the cloud of dust moved over the rover and intensified, the observed UV radiation dropped by 97% mirroring the increase in dust optical depth shown in Fig. 4. Images taken by the rover (not shown here) became increasingly dark and the visibility of distant objects became reduced to the point where normal imaging campaigns were suspended until after the storm. Suspended dust in the atmosphere absorbs sunlight that otherwise would have reached the surface thereby increasing atmospheric temperatures and decreasing surface temperatures during daytime hours. The opposite occurs during the night as radiation from the warm atmosphere keeps the surface warmer than it would be without the dust. This is illustrated in the bottom panel of Fig. 5, which shows the minimum and maximum daily surface temperatures recorded by REMS. The diurnal range of surface temperature rapidly dropped from a value of almost 100 K, typical of this location and season, to about 40 K during the peak of the storm. The diurnal range of near-surface atmospheric temperatures observed by REMS was also observed to decrease by about 40 K at the arrival of the global storm at Gale Crater. Other effects caused by the dust storm that were observed by the Curiosity rover included an increase in the effective radius of dust particles above the rover, a pause in dust devil activity during the dustiest portion of the storm, and a strong enhancement in the amplitude of atmospheric tides¹⁰. All of this occurred despite there being no evidence of active local dust lifting at the Curiosity site in Gale Crater itself during the storm.

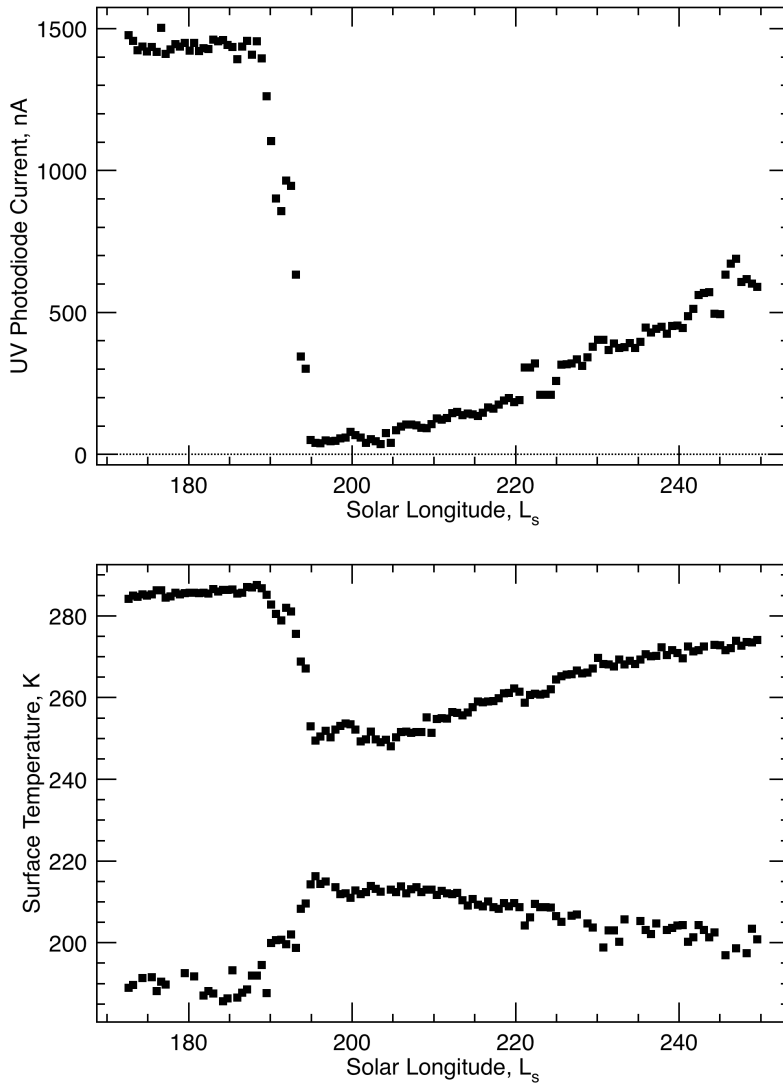


Figure 5. The amount of UV radiation (top) and the daily surface temperature minima and maxima (bottom) as observed by the REMS instrument on the MSL Curiosity rover. The abrupt onset of the global storm is seen by a 97% reduction in the amount of UV radiation and a drastic reduction in the range of surface temperatures observed over the diurnal cycle. Suspended dust blocks sunlight during the day cooling the surface, but re-radiates during the night warming the surface.

The global reach of the effects of this dust storm is illustrated in Fig. 6. Shown in the figure is the year-over-year difference in daytime atmospheric temperature (at ~25 km altitude) caused by the 2018 global storm as a function of season (L_s) and latitude as observed by the THEMIS instrument on the Mars Odyssey orbiter²⁶. The temperature difference is given by the temperature during MY 34 (the year of the global dust storm) minus the temperature during MY 33 (a year without a global dust storm). Before the onset of the global storm (L_s earlier than 185°) and after conditions had returned to seasonal norms (L_s later than about 250°) the temperature difference is essentially zero, as expected. During the

global dust storm, the THEMIS observations show that temperatures increased on a global scale by more than 20 K, reaching a peak value around $L_s=205^\circ$. At some latitudes in the Southern Hemisphere the observed temperature increase was more than 40 K. This warming is a combination of the direct solar heating through the absorption of sunlight by the dust and heating caused by a change and intensification of patterns in the global circulation. Even before dust spreads to all latitudes, the dust near the equator (for example) will intensify the strength of the Hadley circulation leading to an increase in the dynamical heating associated with the downward motions of the Hadley cell at latitudes far from the dusty region⁶. This effect can be seen in Fig. 6 by the greater temperature changes at 60° north and south latitude (the latitude of the descending branch of the Hadley circulation) than at tropical latitudes where the dust optical depth was observed to be greatest. This effect happens even during years without a global dust storm¹³. Recalling Fig. 2, we see a similar effect (although of lesser amplitude) nearly every Mars Year regardless of whether there was a global dust storm or not. This is perhaps most clearly seen for a non-global dust storm year in MY 24.

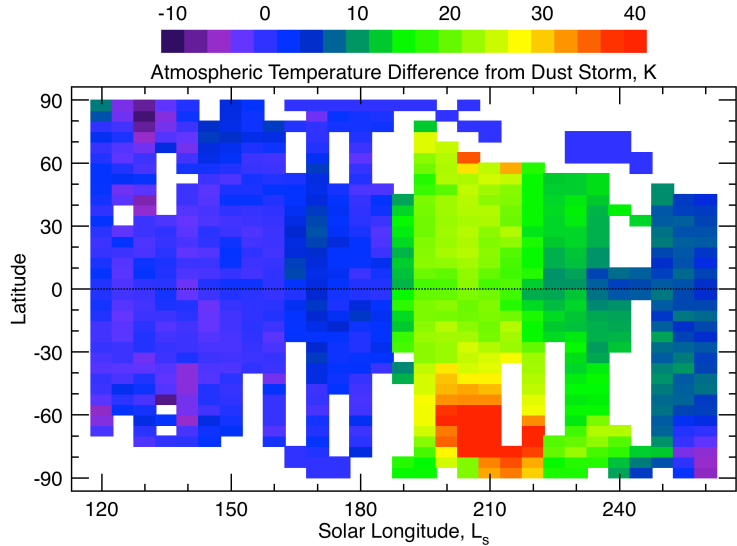


Figure 6. The year-over-year change in daytime atmospheric temperature observed by THEMIS. Shown is the MY 34 (global dust storm) temperature minus the MY 33 (no global dust storm) temperature. The presence of dust significantly affects the overall thermal structure of the atmosphere. The local time of these observations is about 7:15 PM.

The temperature differences shown in Fig. 6 are for a local time of about 7:15 PM, or shortly after sunset. Observations by THEMIS at 7:15 AM local time reveal that the temperature difference caused by the global dust storm had a somewhat smaller amplitude ($\sim 15\text{--}25$ K) that was greatest at low northern latitudes²⁶. This difference in the thermal effect of the dust storm at different local times (and at different altitudes) is caused by the relative phase of the solar atmospheric tides.

The effect of the global dust storm on the surface temperatures retrieved from THEMIS observations are a bit more difficult to interpret since the 7:15 AM/PM local time of observation is very near the thermal crossover time between the expected daytime cooling and nighttime warming of the surface from the overlying dust. Indeed, there is only a slight warming ($\ll 10$ K) of the surface observed at 7:15 PM, mostly at low northern latitudes. The morning (7:15 AM) observations show ~ 15 K cooling in the Southern Hemisphere, but little change in the Northern Hemisphere²⁶.

III. Conclusion

Global dust storms are among the most dramatic weather events observed at Mars. The global dust storm observed during the summer of 2018 (Mars Year 34) provides an excellent example of one of these rare events. Dust storms with this global scale profoundly affect all aspects of the atmosphere state of Mars, and these effects last for more than a month. Only a handful of global dust storms has ever been observed and each one is unique in its seasonal timing and in the particular way in which it initiates and grows to global scale. We are fortunate that a large number of spacecraft were in place to observe this storm, both from orbit and from the surface. Detailed analysis of these observations is currently underway and promises to provide new and important insights into the physical processes that drive these storms.

Acknowledgments

The authors gratefully acknowledge financial support from the Mars Science Laboratory Participating Scientist program and the Mars Odyssey Participating Science program.

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