1. Introduction

Spacecraft observations of martian “planet-encircling” or “global” dust storms extend back to Mariner 9, which famously arrived during the 1971 (Mars Year [MY] 9) global dust storm (GDS) and watched the storm decay from orbit (Conrath et al., 1973; C. B. Leovy et al., 1971; Pang & Hord, 1973). Later, GDSs were studied by the Viking orbiters and landers in 1977 (MY12; Briggs et al., 1979; Ryan & Sharman, 1981), Mars Global Surveyor in 2001 (MY25; M. D. Smith, 2004), and Mars Reconnaissance Orbiter (MRO) (S. D. Guzewich et al., 2017; Heavens et al., 2019a; Wang & Richardson, 2015), Mars Odyssey (M. D. Smith, 2009), the Mars Exploration Rovers (Lemmon et al., 2015), and Mars Express (Fedorova et al., 2018; Wolkenberg et al., 2018, 2020) in 2007 (MY28).

The GDS of 2018 (MY34) presented an unprecedented opportunity to study these rare and fascinating events that are unique in the Solar System. Eight spacecraft were on the surface or in orbit around the planet at the start of the storm, before the fatal reduction in sunlight ended the Opportunity rover’s mission more than 14 years after its landing. Prior to its failure, Opportunity recorded the highest visible-band atmospheric dust opacity ever measured on the surface of Mars (>10). This special collection reflects studies of this GDS using data from six of the remaining seven spacecraft and Earth-based telescopes that observed the growth, peak, and decay of the storm, and using modeling and theoretical work related to this particular dust storm and comparing it to other martian dust storms.

2. Storm Evolution and Timeline

The first widely confirmed GDS was observed by means of ground-based telescopes in 1956/MY1 (Martin & Zurek, 1993). The 2018 (MY34) GDS was an equinoctial GDS, starting at approximately $L_s = 185^\circ$ (S. D. Guzewich et al., 2019; Kass et al., 2019; Sánchez-Lavega et al., 2019). This was very nearly the same time of...
year at which the 2001 (MY25) GDS began, hence these two storms represent the earliest-starting GDSs on record (Figure 1; Shirley et al., 2020a).

However, the MY34 storm was unique in its initiation in the northern hemisphere. All previous storms on record have been initiated in the southern hemisphere (although a specific initiation date and location is not always uniquely determined in the literature). This conforms with our (limited) knowledge about how GDSs develop, which have been generally centered on the seasons (southern hemisphere spring and summer) with the warmest and most vigorous atmospheric circulation that Mars experiences each year. Instead, the MY34 storm grew through a series of precursor storms in the northern hemisphere storm tracks that expanded south slowly toward the equator. Despite this unique feature, there are similarities with the growth trajectory of other GDSs (such as 2007/MY28) which may have been initiated by “flushing” dust storms that cross the equator from the Acidalia/Chryse Planitia corridor (Wang et al., 2003). However, the MY34 precursor storms never directly crossed the equator. Rather, (seemingly) independent southern polar cap edge dust lifting began and eventually merged with the northern hemisphere and equatorial storm region to encircle the planet (Montabone et al., 2020). This perhaps explains the comparatively methodical growth and expansion of the MY34 storm relative to previously observed GDSs (particularly MY25 and MY28) which underwent explosive growth and expansion in the period of a few sols. This first growth phase of the storm was centered near Chryse Planitia and Meridiani Planum, which resulted in the eventual failure of the Opportunity rover.

During the equinox season, near \( L_s = 180^\circ \), the martian atmospheric circulation consists of two meridional overturning (Hadley) cells, each with their rising branches near the equator and descending branches in the mid-latitudes of each hemisphere. As southern hemisphere spring approaches the summer solstice (\( L_s = 270^\circ \)), this morphs into a single-celled Hadley circulation with a rising branch in the southern mid-latitudes and descending branch in the northern mid-latitudes. The initial phase of the MY34 storm occurred during the equinox season and spread dust throughout the northern hemisphere with the aid of a strengthened Hadley circulation (as shown by several modeling studies, see below for details). The growing southern polar cap edge dust lifting regions later sent dust over Gale Crater, where the Mars Science Laboratory Curiosity rover was exploring the Vera Rubin Ridge (S. D. Guzewich et al., 2019). It also strengthened the atmospheric circulation and enhanced atmospheric thermal tides, which facilitated rapid spread of dust around the planet as shown in the Ensemble Mars Atmospheric Reanalysis using the Geophysical Fluid Dynamics Laboratory's Community Atmosphere Model (Guzewich et al., 2020b).
The strengthened Hadley circulation lofted dust to very high altitudes, \( \sim 70 \) km, and led to almost anvil-cloud-like distributions of dust in the middle and upper atmosphere. Additionally, this seasonally atypically strong Hadley circulation produced dynamical heating of mid-altitude air at high latitudes in both hemispheres due to adiabatic warming in the descending branches of the equinoctial circulation (Shirley et al., 2020b). Indeed, both observations (Kass et al., 2019) and modeling (e.g., Bertrand et al. [2020] with the GFDL/NASA Ames GCM) demonstrate this rapid strengthening of the northern hemisphere Hadley circulation (with a rising branch starting near the equator that moved southward during the storm’s progression). Under typical seasonal evolution, this southward migration of the rising branch of the Hadley circulation would have occurred later in the spring season.

Following this first burst of activity (\( \sim L_s = 185^\circ - 192^\circ \)), it seemed plausible that the dust in the atmosphere would begin to settle out of the atmosphere and the MY34 storm would have been better defined as a “large regional” dust storm. Heavens et al. (2019b) noted that “The altitude of significant dust transport almost declined to prestorm levels...” near \( L_s = 194^\circ \). This brief pause or reduction in dust lifting can be seen in globally averaged dust opacity (e.g., Figures 7 and 10 by Montabone et al. [2020]) as a “knee” or change in slope of the opacity growth curve. However, a secondary “storm within a storm” (Montabone et al., 2020) over Tharsis that began at \( L_s = 197^\circ \) injected massive amounts of dust into the atmosphere and made the storm truly “global” or “planet-encircling.” This pause and then secondary expansion from the Tharsis dust lifting can be seen in Figure 2 from Smith (2019) using Mars Odyssey Thermal Emission Spectrometer retrievals of column dust optical depth.

Bertrand et al. (2020) convincingly show that Hadley cell strengthening led to the Tharsis dust being lifted to very high altitudes (60–80 km) over a broad region. This high altitude dust injection was distinct in

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**Figure 7.** Figures 1a and 1b reproduced from Connour et al. (2020). (a) Projection of a latitudinally continuous twilight cloud band taken shortly after the start of the mature phase of the GDS (MAVEN orbit 7281; \( L_s = 200^\circ \)). This false-color projection represents what each swath would have looked like when viewed from the position of the spacecraft at apoapsis. The black dashed line denotes the location of the terminator, and the gray box denotes the bounds of Figure 1b. (b) Minimum illuminated altitudes of the cloud band. Solar zenith angles were converted into minimum altitudes at which these aerosols must be directly illuminated, which reveals that bands often reached altitudes of at least 40–50 km.
behavior from more mesoscale phenomena (e.g., “rocket dust storms”; Spiga et al. [2013]) that may produce detached dust layers in the middle atmosphere under normal dust conditions. Heavens et al. (2019b) and Bertrand et al. (2020) both note that this dust lifting was vigorously convective. This period of lifting after \( L_s = 197° \) was also distinct from “dusty deep convection” that was seen over Tharsis prior to this dust lifting region expanding and becoming the primary source of dust for the storm (see below; Heavens et al. [2019b]). The storm peaked, as measured by global atmospheric dust loading and middle atmospheric temperature, around \( L_s = 205° – 210° \) (Bertrand et al., 2020; Kass et al., 2019; Montabone et al., 2020; M. D. Smith, 2019). After that point, it appears that dust sedimentation and deposition dominated behavior globally, which continued until dust returned to climatologically typical levels near \( L_s = 250° \).

The long decay phase of the storm, from \( L_s = 210° – 250° \), provides another point of comparison with previous GDSs. Kass et al. (2019), Smith (2019), and Wolkenberg et al. (2020) all note that the MY34 storm decayed faster than either the MY25 or MY28 storms. However, the Curiosity rover observed a decay timescale of column dust opacity identical to that observed by the Spirit and Opportunity rovers during the MY28 storm (S. D. Guzewich et al., 2019). Reconciling those disparate observations likely falls to regional versus global perspectives, as Curiosity was never near the core of major dust lifting centers. The decay rate of global storms is plausibly driven by a combination of atmospheric circulation structure and strength, height of dust during the storm, and dust particle size distribution, all of which help determine the timescale for a dust particle to sediment out of the atmosphere to the surface. For MY34, we know that dust was lifted to great altitudes (e.g., Heavens et al. [2019b]) and we know that dust particle sizes were very large (at least over Gale Crater; Lemmon et al. [2019]). Bertrand et al. (2020) noted that the storm’s decay timescale was particularly sensitive to dust particle size in their simulations. One factor that appears distinct for MY34 relative to the MY25 and MY28 storms (for which we have the most comprehensive data and modeling for comparison; e.g., see Smith [2004] for the MY25 thermal structure) is the atmospheric circulation structure, with a rapid strengthening of the northern hemisphere Hadley cell’s rising branch near the equator in southern hemisphere spring. Future work should investigate whether the seasonally driven evolution of this structure, coupled with the decay of the GDS, could have resulted in a faster storm decay relative to the MY25 and MY28 storms which were centered in the seasonally favored southern hemisphere mid-latitudes. Similarly, globally heterogeneous surface dust populations, with different particle size distributions lifted during different GDSs, should be explored.

MY34 also provided an important control experiment for understanding how some storms become global, while others remain regional. Soon after the InSight lander arrived at Elysium Planitia, a strong regional dust storm developed at \( L_s = 320° \) (Banfield et al., 2020). This storm began in western Chryse Planitia, near where the GDS had begun just months before (Montabone et al., 2020). This is an important note, as surface dust source exhaustion from dust storms and the “recharge” timescale from airfall dust, is an ongoing topic of study and speculation, as discussed by, for example, Bertrand et al. (2020) for the GDS. This regional storm spread dust around the planet in both hemispheres, but the storm ceased dust lifting and decayed on a timescale of days to weeks rather than months. Some observations of these storms have helped distinguish global from regional storms and perhaps provide criteria to anticipate global expansion of a storm in the future. Kass et al. (2019) note that daytime 50 Pa temperatures exceed 235 K in global storms, more than 10 K higher than regional storms, and a temperature > 220 K in the tropics is even more discriminatory (observed regional storms have never exceeded 205 K). Additionally, the rapid expansion of 50 Pa warming (>200 K from 45°S-45°N within 2° of solar longitude) is also unique to global storms in the Mars Climate Sounder (MCS) record.
3. Perspective From the Surface

Curiosity’s measurements in Gale Crater with the Rover Environmental Monitoring Station (REMS) were the first surface meteorological measurements to be made during a major dust storm since the Viking landers and the first ever near the equator during such a storm (S. D. Guzewich et al., 2019; Viúdez-Moreiras et al., 2019). The initial phase of storm growth near Opportunity’s location in Meridiani Planum did not substantively impact local conditions in Gale Crater. Dust lifted in the southern hemisphere eventually reached Gale after $L_s = 192^\circ$, which eventually resulted in a peak dust optical depth of $\sim 8.5$ (S. D. Guzewich et al., 2019). This dust optical depth reduced ultraviolet light at the surface by $\sim 90\%$, lowering the daytime air and ground temperatures. Nighttime temperatures warmed due to increased downwelling infrared radiation from the dust (Figure 3, Viúdez-Moreiras et al. [2019]). This reduction in the diurnal surface temperature range was also seen globally from orbit. Streeter et al. (2020) use the Open University’s Mars GCM to show that nighttime warming from longwave dust emission more than compensated for daytime reductions in shortwave insolation, resulting in a general increase in diurnally averaged temperatures. This, however, is modulated by the thermal inertia of an individual location. Comparing with the MY28 storm, Wolkenberg et al. (2020) demonstrate that surface temperatures converge to near 250 K once 9 $\mu$m dust opacity exceeds 1–2 and Streeter et al. (2020) also find asymptotic behavior of daytime surface temperatures at increasing dust opacity.

Atmospheric pressure tides responded dramatically, with the semidiurnal tide (long known to be responsive to globally integrated dust loading [C. B. Leovy and Zurek, 1979; Wilson & Hamilton, 1996]) briefly becoming stronger than the diurnal tide in Gale Crater. The global response of the martian water cycle to such storms is becoming clearer (see below), but never before had humidity been measured in situ during a GDS. In Gale Crater, the humidity decreased due to the warmer nighttime temperatures, but the amount of water vapor itself increased sharply (by almost a factor of 2) with the arrival of significant dust opacity before
decreasing again to prestorm levels after ∼40 sols (Figure 3, Viúdez-Moreiras et al. [2019]). The mechanism behind these fluctuations is unknown, but needs to be understood in the context of higher water vapor mixing ratios seen by Curiosity in MY34 relative to previous years.

The structure seen in water vapor mixing ratio, air temperature, and even pressure is reflective of two pulses of dust that entered Gale Crater. Smith et al. (2019) show that across-crater dust extinction (extinction as measured along a line-of-sight from the Curiosity rover to the Gale Crater rim) was an order of magnitude higher than anything measured prior to the GDS. Horizontal visibility dropped to <3 km, whereas it normally equals or exceeds 30 km and sometimes 70 km or more. The peak in across-crater dust extinction was also 3–5 sols after the column dust opacity peak. And while the atmospheric column dust opacity showed a generally steady decline of dust opacity after the initial peak (S. D. Guzewich et al., 2019), the across-crater dust extinction had a second peak ∼25 sols after the initial wave of dust. In conjunction with the REMS variables, this points to dynamical behavior of dust moving above the crater and then sedimenting to lower altitudes within the crater over time. This behavior is further supported by analysis of dust particle sizes, which corroborate the two-peaked pattern of across-crater dust extinction (Lemmon et al., 2019). In combination, Guzewich et al. (2019), Lemmon et al. (2019), Smith et al. (2019), and Viúdez-Moreiras et al. (2019) show that the first wave of dust predominantly passed above Gale Crater with dust particle effective radii as high as 8 μm, the largest ever observed in Mars’ atmosphere. Given Mars’ thin atmosphere, dust particles with such large effective radii should sediment to the surface on very short timescales (hours or sols) unless there is some compensating upward vertical motion in the atmosphere, suggesting such strong upward motions were present during the storm as the particles were transported away from their surface source regions. The lack of any clear signs of local dust lifting within Gale Crater by wind stress or dust devil lifting (S. D. Guzewich et al., 2019) imply that these very large particles were transported aloft over hundreds to thousands of kilometers distance, emphasizing the vigorous and highly anomalous dynamics that were likely ongoing within the storm relative to seasonally typical conditions. These large dust particles sedimented quickly to lower altitudes within the crater, producing a delayed peak in across-crater dust extinction. Then a second phase of the storm arrived at Gale Crater ∼25 sols later, but this phase did not make a clear change to the column dust opacity and was only noted by an increase in across-crater dust extinction and a second increase in dust particle effective radius (Lemmon et al., 2019; C. L. Smith et al., 2019).

4. Upper Atmosphere Response

Recent work prior to the MY34 GDS showed that dust storms likely have a disproportionate effect on Mars’ loss of water to space in the modern climate epoch (Chaffin et al., 2014, 2017; Fedorova et al., 2018; Heavens et al., 2018). The presence of the MRO, Mars Atmosphere and Volatile Evolution mission (MAVEN), and the ExoMars/Trace Gas Orbiter (TGO) simultaneously during a GDS provided an opportunity to watch this behavior through the entire atmospheric column and diagnose the mechanisms that lift water to high altitude, where it can be photodissociated to be a direct source of hydrogen atoms in the thermosphere. Aoki et al. (2019) show that great amounts of water were lifted to altitudes as high as 100 km during the storm. Using solar occultation, the Nadir and Occultation for MArs Discovery (NOMAD) instrument onboard TGO can measure water vapor abundance with high precision and vertical resolution. As seen in Figure 4, this change occurred rapidly after the storm began and persisted through its duration. Similar, if less intense, behavior interestingly occurred during the late winter large regional dust storm in MY34 (Aoki et al., 2019).

Neary et al. (2020) use the Global Environmental Multiscale (GEM)-Mars GCM to diagnose the mechanisms behind the dramatic increase in high-altitude water vapor described by Aoki et al. (2019). They find that although the atmospheric circulation is deepened and strengthened during the storm, it alone is not sufficient to transport water vapor to such high altitudes. More directly, they find that the altitude of the hygropause is driven by the vertical profile of dust. The hygropause is the altitude above which water vapor and ice “content rapidly decreases to effectively zero” (Heavens et al., 2018) and is typically near 50 km altitude. Increased high-altitude dust during the storm warms the middle atmosphere and thus shifts the hygropause to much higher altitudes, letting water vapor reach altitudes where it is photodissociated.
Figure 4. Figure 6 reproduced from Aoki et al. (2019). Latitudinal variation of the water vapor vertical profiles retrieved from NOMAD data (the top panels of [a–e]), and predicted by the Global Environmental Multiscale (GEM)-Mars climate model for nondust storm conditions (the bottom panels of [a–e]). The seasonal ranges shown are (a) $L_s = 160°–195°$ (before the global dust storm), (b) $L_s = 195°–202°$ (during the growth phase of the storm), (c) $L_s = 210°–220°$ (during the mature phase of the storm), (d) $L_s = 220°–240°$ (during the decay phase of the storm), and (e) $L_s = 240°–260°$ (during the decay phase of the storm). The retrievals and GEM-Mars predictions are binned in 5° latitude × 1 km altitude grid and averaged over the $L_s$ range given and all longitudes.
The Atmospheric Chemistry Suite also onboard TGO similarly saw water ice clouds at exceptionally high altitudes, greater than 90 km during the storm, with water ice particle effective radii (∼1.5 μm) typical of much lower altitudes (Stcherbinine et al., 2020). As in the case of Curiosity (Section 3), these large particle effective radii at high altitudes imply that strong upward motion was likely occurring within the storm relative to seasonally typical conditions.

The effects of the storm reached into the ionosphere and thermosphere. Heating of the lower atmosphere by the dust storm causes the entire atmosphere to expand, which raises ionospheric altitudes. This phenomenon was previously found in Mariner 9 observations of the 1971/MY9 GDS (Hantsch & Bauer, 1990).

This increase in ionospheric peak altitude was again found during the MY34 GDS using a variety of spacecraft and techniques. Felici et al. (2020) note a 10–15 km increase in peak ionospheric altitude using MAVEN radio occultation retrievals (Figure 5). Girazian et al. (2020) see similar behavior with the Mars Express Mars Advanced Radar for Sub-surface and Ionosphere Sounding and contextualize that change with the long observation history of Mars Express through multiple large regional dust storms and two GDSs. The ionospheric peak altitude was also highly variable following the initial global expansion in late June 2018. This change in ionospheric altitude alters the chemical composition of the upper atmosphere during the storm. While the upward shift in the ionosphere increases the production of hot oxygen (“hot O”), the expansion of the neutral atmosphere increases its collisional loss. In combination, this reduced the oxygen escape rate during the storm by ∼28% (Lee et al., 2020).

Heating and expansion of the neutral martian atmosphere was also observed. This was manifested in a near-doubling of CO₂ density on the planet’s nightside at thermospheric altitudes (110 km) seen by MAVEN (Chaufray et al., 2020). MAVEN observed a near 20 K temperature increase in the thermosphere, while also seeing cooling at equatorial latitudes near the start of the storm due to adiabatic cooling in strong upward motion (Jain et al., 2020). These density and temperature changes were used to diagnose the atmospheric circulation, and indicate that a two-cell meridional circulation was still present during the storm (as was also seen in the lower atmosphere, Section 2) which created dynamical warming in the northern hemisphere (Girazian et al., 2020; Jain et al., 2020).

5. New Phenomena

The diversity of observations of the storm—diversity of location, instrument, and local time coverage—allowed a number of new phenomena to be discovered. Since the MY28 GDS, the MCS began a “cross-track” observation to access a larger local time range. These observations helped identify a dramatic diurnal variation in dust during the global storm, particularly at high southern latitudes. Kleinböhl et al. (2020) demonstrate 20–40 km changes of the effective dust “top” between morning and afternoon and link this behavior to an enhanced diurnal tide during the storm. Indeed, they show that the remnant southern winter polar vortex rotated fully around the pole each day as the diurnal tide propagated westward, and replicate this behavior with the Laboratoire de Météorologie Dynamique (LMD) Mars GCM. This remnant polar vortex, with high potential vorticity, was somewhat impervious to mixing with the exterior low potential vorticity and dusty atmosphere. Hernández-Bernal et al. (2019) use Mars Express camera images to show graceful dust streamers crossing the day-night terminator over the south pole, illuminated later than the surface due to their high altitude (Figure 6). Their shape and movement, which could be tracked over multiple images, serve as tracers of polar atmospheric dynamics during the storm. Hence, these arcs of dust may be structured by filaments of potential vorticity within the polar vortex and thus provide a visual complement to the study of the dynamics of the vortex during the storm. Hernández-Bernal et al. (2019) also use cloud-tracking to produce estimates of wind velocity, which show the circulation of the atmosphere within and around...
the polar vortex during the storm. Direct wind measurements are otherwise entirely lacking during the storm and thus this provides a unique insight. They find wind speeds are typically near 60 m/s, but with some as high as 100 m/s, at the altitude of the dust cloud tops.

MAVEN also observed a new phenomenon near the day-night terminator. Connour et al. (2020) discover a persistent water ice cloud band along and just beyond the evening terminator that sometimes spanned 6,000 km in latitude (Figure 7). Modeling with the LMD Mars GCM indicate that altered atmospheric tides during the storm produced colder conditions near the dawn and dusk terminators, facilitating the formation of expansive water ice clouds. MAVEN’s orbit precluded confirmation of corresponding morning terminator clouds. Changing patterns of atmospheric water vapor and water ice clouds during GDSs is an ongoing topic of research and this discovery provides a new and unique insight into this question by expanding observing local times to dusk.

In the upper atmosphere, MAVEN was able to also measure how the bulk composition of the atmosphere changed in response to the storm. As stated above, the thermosphere warmed and expanded during the storm, leading to higher atmospheric densities (Chaufray et al., 2020). In conjunction, CO₂ and Ar densities increased in the thermosphere, but surprisingly, atomic O density decreased by 20% (Elrod et al., 2020). Thus far, there is no explanation for this change but this implies that unknown dynamical and/or photochemical activities were occurring within the thermosphere as the storm expanded near the surface. This result could have important ramifications for martian atmospheric escape, both in the present and in the past. Future work is needed to determine the robustness of this O density decline and how it could impact Mars’ atmospheric evolution through time. Recall that Lee et al. (2020) find a 28% decrease in the escape of ionized hot O during the storm.

Atmospheric modeling helped expand and contextualize many of the results presented in this special collection. The increasing sophistication of Mars atmospheric modeling, like the expansion of spacecraft observations, has also led to new insights. Of particular note, Bertrand et al. (2020) use tracer tagging to watch how dust particles are lifted, transported, sedimented, and re-lifted during their simulation of the MY34 GDS. They show that transfer of dust between the Tharsis region and Arabia Terra/Terra Sabeae may have helped precondition the Tharsis region for the “storm within the storm” that Montabone et al. (2020) find expanded the storm to global proportions. Understanding the dynamics of how dust is moved through different surface reservoirs may be of critical importance to understanding why some storms become global while most do not.

6. Conclusions

The 2018/MY34 planet-encircling dust storm provided a unique opportunity to study these iconic martian events. This introduction and the works included in this special collection serve as a foundation for future analysis of this storm, comparison with previous and future storms, and critical data points to understand how GDSs develop and shape the modern climate. The upcoming arrival of new spacecraft, the continued advance of modeling and theoretical understanding, and eventual human exploration will surely provide additional insights to understanding Mars’ modern climate and its unique planet-wide dust storms.
Data Availability Statement

Data were not used, nor created for this research.

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