INSIDE AN ACTIVE MARTIAN STORM IN JEZERO CRATER

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Introduction:

Martian dust storms are a key part of the current climate that remain poorly predictable [1]. They range in scale from local to planet-encircling dust events (PEDE). Orbital data have been used to track and classify storms, showing patterns in where and when storms occur and move [2-3]. Yet there is no predictor of why one local storm grows to regional and another dies, or one regional storm triggers or joins a PEDE and another dissipates.

In situ data on storm processes is a necessary element to develop a complete picture of storm evolution. While landers and rovers have experienced dust storms or been impacted by the lifted dust, there has been no prior comprehensive collection of meteorological data within the active lifting area of a storm. The Viking landers documented the effects of planetary scale events, including winds associated with storm onset at VL1, without documenting local lifting or activity [4]. The Spirit and Opportunity rovers, without meteorological capabilities, experienced local, regional, and planetary events [5]. Local events passed before additional imaging could be commanded, while the regional events were associated with a reduction in local dust lifting [5-6]. While the 2008 PEDE involved a dynamic environment at each site, the solar-powered rovers had reduced operations [5]. The Curiosity rover experienced optical depths of 9 yet saw only a reduction in local activity [7].

During January 2022, a regional dust storm affected the Perseverance, InSight, and Curiosity sites, causing the solar-powered InSight to cease operations for several days. We report on the events at the Perseverance site in Jezero crater: six sols of dynamic and dusty weather that erased rover tracks, cleaned some surfaces, dirtied others, and partly damaged the rover's wind sensors.

Data and methods:

The Perseverance rover landed on 19 February 2021 in Jezero crater, at 18.4°E longitude, 77.5°N latitude. Among its instruments were several cameras and a meteorology package. Mastcam-Z is a multispectral, stereo camera pair with zoom lenses [8]. Navcam is a color, stereo camera pair with a wide field of view (FOV) and the front and rear Hazcams are each color, stereo camera pairs with fisheye lenses [9]. MEDA, the Mars Environmental Dynamics Analyzer, is a meteorological package that measures pressure, temperature, winds, ultraviolet, visible, and infrared fluxes and radiances, optical depth, and humidity; it includes a zenith-looking fisheye camera, Skycam, as part of its Radiations and Dust Sensor (RDS) [10].

Meteorology. MEDA functions independently of rover wake-sleep cycles at a cadence that is specified in observation tables. Typical behavior was to measure with all sensors (excluding the camera) at 1 Hz, for a minimum of 5 minutes of each Mars-hour (1.03 hours) and to run continuously for even hours on even sols and odd hours on odd sols. Additional data collection was commanded during the storm.

Optical depth. Mastcam-Z measured dust optical depth via Sun imaging using solar filters (neutral density filters combined with a narrow 880-nm filter for the right camera and a short-pass filter to get red, green, and blue optical depths for the left camera). Solar images were calibrated to radiance on sensor [11] and then solar flux was calculated and used to determine atmospheric extinction (see also [5]).

Skycam's 126° diameter view of the sky is partly obscured by a neutral density annulus, allowing direct solar imaging in mid-morning and mid-afternoon. Due to the limited range of solar elevations, Skycam optical depths were calibrated to match Mastcam-Z near-infrared optical depths using measurements close in time. (Skycam has been zenith-looking and uncovered and has accumulated dust on the optics.)

MEDA sensor data were also used to determine optical depth. TIRS (Thermal Infrared Radiometer) measures broadband and 15-µm radiance, which have been used to derive 9- µm dust optical depth [12]. The RDS-Top-7 photodiode measures broadband solar downward flux with an approximately Lambertian response. The rover was stationary over sols 289-327, and the TOP7 flux was calibrated to optical depth using a simple 2-stream model to tune the results to match the Mastcam-Z 880-nm channel.

Site imaging. Upon arrival at the site, the rover acquired a site and rover deck panorama with Navcam, as well as images of the area immediately in front of and behind the rover with Hazcam. During the next sols, a site panorama was acquired with Mastcam-Z. All the scene was acquired with the 34-mm

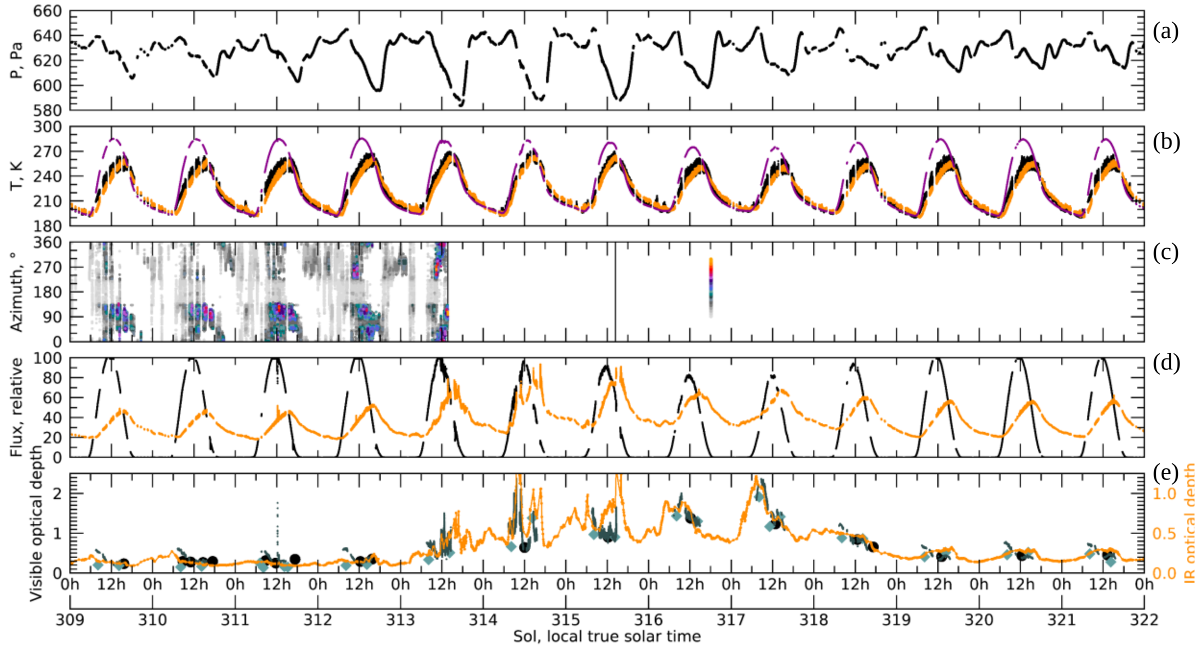

Figure 1. Meteorology summary from the start of sol 309 to the end of sol 321. (a) Pressure; (b) Temperature for surface (magenta), local air (black), and lower 200 m (orange); (c) wind direction, with speed shown using color-bar with a linear scale from 0-20+ m/s, and vertical lines showing the two boom failures; (d) fluxes in broadband visible (black, saturated near noon outside of storm) and thermal infrared (orange), shown on an arbitrary scale; (e) visible optical depth from Mastcam-Z (black circles), Skycam (blue diamonds), RDS (dark gray line fragments); and TIRS 9-µm optical depth (orange, scale 2x different).

zoom setting; many areas were imaged at zooms as high as 110-mm (resulting in 3x better spatial resolution). Hazcam images were acquired episodically to support contact and proximity science operations. Once the storm was recognized, additional Hazcams were acquired to assess the storm's impact. In addition, the Navcam and the 34-mm Mastcam-Z site panoramas were repeated after the storm. Albedo was monitored by MEDA's RDS and TIRS [13].

While at the site, Navcam acquired quasi-periodic environmental survey images. These included dust devil surveys (DDS), which used 3 monochrome images at each of 5 aims to survey the complete horizon for motion; dust devil movies (DDM) which used 21-45 monochrome exposures at a single aim to find and track motion; cloud surveys , which used 5 color images to mosaic nearly the full sky hemisphere; and cloud movies, which were 8 color images at a single aim [14,15]. The 'dust devil' activities were sub-framed for the horizon at the full width of the FOV, while the 'cloud' activities used full 96°x72° FOV.

Results:

The team was aware that a storm existed, but not that it would come to Jezero, when the sol 312-313 plan was made, but sol 313 included an unusually large amount of MEDA data due to available power and projected downlink volume. By the time the sol 314 plan was made, the team was aware of unusual activity. Extra environmental monitoring was included in that and subsequent plans, but the rover also continued with rock-coring operations.

Progression of the storm. Figure 1 shows key meteorological measurements through the storm. Generally normal behavior was seen pre-storm (sols 309-312). The pressure profile showed tides [16] and a vortex near noon on sol 311 (see also [17]). Pressure tides increased in magnitude over sols 311-313, due to the storm's atmospheric heating even while distant. The pressure profile returned to normal by sol 321.

The storm moved into Jezero crater late in the morning of sol 313. About 10 AM, the winds increased in strength, with gusts >15 m/s, and turned clockwise around the site over several hours. During 11:30-12:00, the winds were ~6 m/s from the north; imaging showed a mottled sky with rolling dust clouds, variable shadowing, and extreme dust lifting activity. The DDS and DDM combined (see Fig. 2) over 11:35-11:59 to show 14 dust devils, more than any previous sol; 3 indeterminate dust lifting events; and 4 dust-carrying gust events, more than previously identified (cf., [14,18]). In late morning, RDS showed sky darkening in the north, followed by erratic brightness. The RDS showed 10% brightness variations over several minute periods from shadowing and local dust lifting. While dust devils moved S near noon, high-altitude dust clouds moved north (west of the rover) and south (east of the rover), suggesting CW motion or complex dynamics at 10s km scale.

The afternoon of sol 313 had the deepest pressure minimum, and through the day the optical depth increased and became variable. After noon, the winds rotated CW until they were roughly easterly. At 13:42 LTST, winds peaked at 22 m/s from 110° as a west-

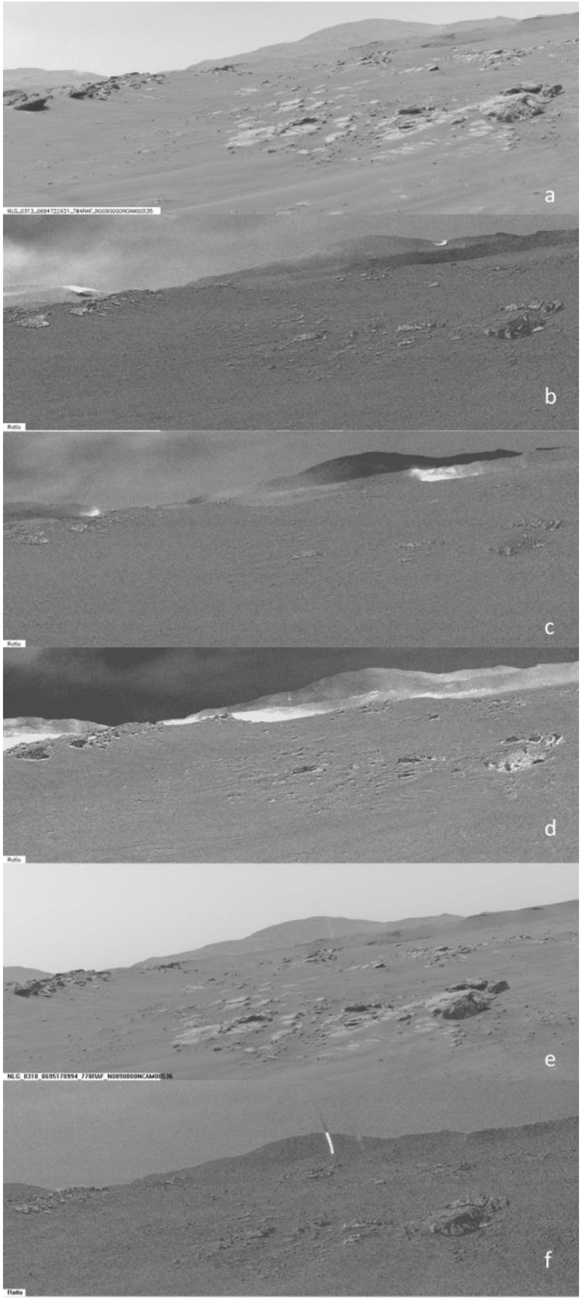

Figure 2. Dust activity seen in Navcam frames: (a) sol 313, ncam00535, azimuth 305°; (b) same frame after mean frame removal; (c, d) additional frames after mean frame removal; (e) sol 318, ncam00536, azimuth 310°; (f) same frame after mean frame removal.

moving, CW-rotating vortex passed to the north, when the wind sensor on boom 2 stopped reporting due to damage from blown debris. During the afternoon, visibility across the crater dropped as dust increased in the boundary layer.

Sols 314-315 had a high and variable optical depth through the day, with elevated but more moderate IR optical depth at night. On sol 315, the other WS boom stopped reporting at 14:24 LTST. That time was coincident with a 200-s optical depth spike that may have been due to local gusting. Visibility remained below normal, but not as much as implied by column optical depth: while visible optical depth >2 implied near-surface extinction >0.2 km^{-1} for a well-mixed atmosphere), a hill 40 km to the east remained barely visible even on sol 315, implying opacity <0.1 km^{-1}. Thus, the boundary layer was dust-depleted by a factor of ~2 compared to the air above during sols 313-316. Local dust lifting, while significant, remained small compared to the storm's total dust load.

Over sols 316-319, storm activity receded, followed by reductions in dust amount. Visibility was improved on sols 316-318; the boundary layer was dust-depleted by a factor of 3-4 by sol 318 as the crater cleared faster than the air above. Despite that, daytime optical depths remained elevated on sols 316-317, but decreased on sol 318 to become normal on 319. Dust lifting events were seen in 4 of 7 DDS+DDM sequences over sols 314-318. The wind remained variable, as dust devils were observed moving south at 13:00 on sol 318. At the dawn pressure maximum on sols 319 and 320, pressure oscillations with 9- and 15-minute periods were observed, possibly gravity waves caused by the storm to the east.

The daytime maximum surface temperature was reduced by ~10 K on sols 316-7, while the overnight low was highest around sol 315 [19]. 1.5-m and lowest-200-m peak air temperature increased several K on sols 312-5 and were depressed on 317.

Prior to the storm, high-altitude ice contributed to excess visible optical depth in the mornings; however, during the storm the 9-μm dust optical depth was generally ½ of the visible optical depth [12]. Residual differences may relate to changes in the vertical distribution of the dust, with relatively enhanced IR opacity when dust filled the crater.

Storm-induced changes. There were multiple instances in which winds from different directions, primarily east, were strong enough to mobilize sand and dust. Rover-disturbed areas, no longer in equilibrium with the environment, were affected the most. Small-scale ripples were mobilized, and local deflation and deposition occurred on natural surfaces and the rover.

Sol 316 rear Hazcam images showed substantial modification and erasure of tracks to the NE (Fig. 3),

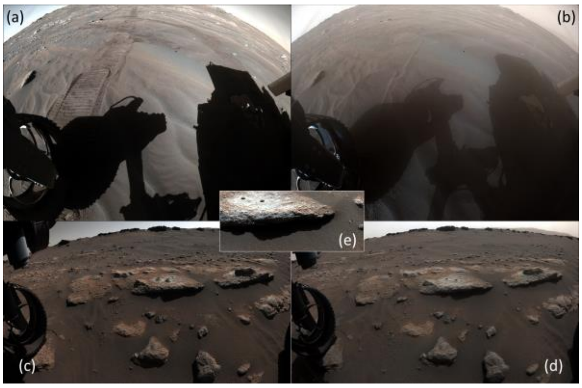

Figure 3. Changes immediately around the rover as seen in Rear (a, sol 286; b, sol 316) and Front Hazcam (c, sol 311; d, sol 315; e, sol 322).

and the optics became dust coated. Front Hazcam images on sol 314 showed removal of material from one abrasion site and two drill holes, as well as changes in other rover-modified terrain, by winds from the east. Additional removal occurred between ~13:00 on sols 314 and 315, and the cuttings were later scoured by winds from ENE before sol 320.

Site imaging after the storm (Fig. 4) showed a series of changes. (1) The rover itself was affected. The deck had a substantial increase in its sand load (at least some of which was last modified by winds from the west, based on piling against obstacles). Wheels were scoured clean. Clods were removed from the deck near the Mastcam-Z calibration target on sol 311-312 (possibly during a pre-storm vortex) and 314-315. Over 315-316 there was a debris dump on the targets, but material was removed from magnets by winds from the SE (Fig. 4g). (2) Rover-modified terrain was substantially reworked. Tracks to the east, south, and west were impacted. Some tracks disappeared; others were smoothed by motion of sand. (3) Small ripples all around the rover moved westward, and sand moved on rocks. Notably, undisturbed features other than small ripples were unmodified. While the storm was significant for disturbed material and loose sand, equilibrium materials were unimpressed.

Conclusions:

A significant dust storm impacted the Perseverance site for 6 sols. The leading edge of the storm brought a dynamic local environment on the first sol, unlike prior *in situ* storm encounters [4,5,7]. The next two sols brought high dust loads within the crater. Over the last 3 sols, the crater cleared faster than the column dust optical depth, suggesting the rover was experiencing outflow from increasingly distant lifting. During the storm's approach, winds rotated around the area clockwise, increased in speed, and drove dust devils and dusty gusts. As the storm's leading edge went over the site, there were high and variable daytime optical depths, warmer overnight and cooler daytime temperatures, and variable sky brightness due to clouds of dust. Vortices continued to form, and in multiple events sand was mobilized in ripples, sand and/or finer material was transported to the rover deck and likely damaged the MEDA wind sensors, and rover modifications to the terrain were erased or reworked by winds. No winds >22 m/s were measured, but larger winds may have occurred after the loss of the wind sensor.

References:

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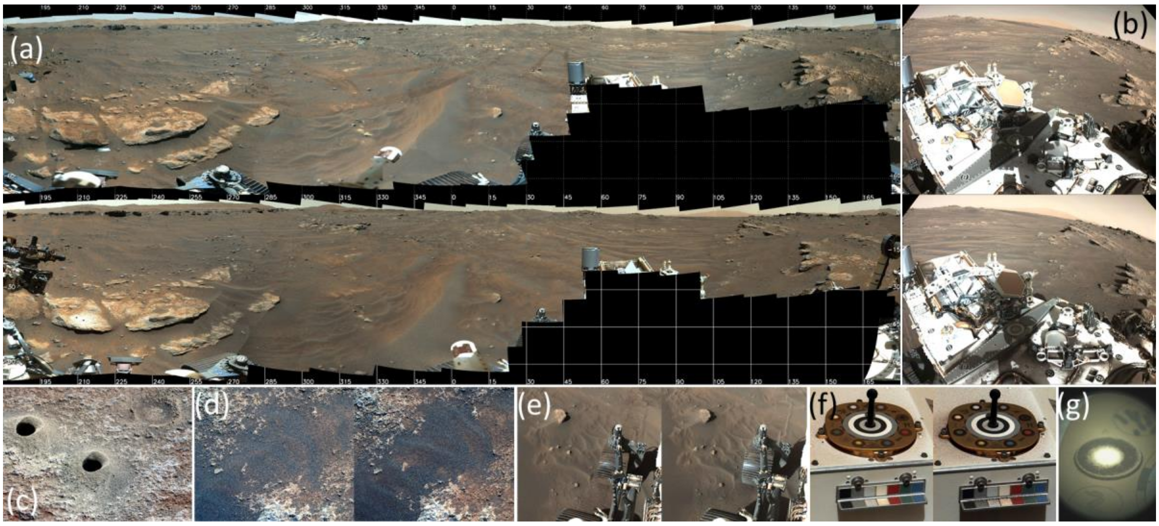

Figure 4. Changes in the rover site are shown in (a) sol 286-310 (top) and 321 (bottom) Mastcam-Z panoramas; (b) Navcam deck images on sols 286 (top) and 321 (bottom); (c) sol 318 Mastcam-Z 110-mm image of drill cuttings removal; (d) Mastcam-Z 110-mm image of ripple migration from sol 290 (left) to 320 (right); (e) Navcam images showing tracks, ripples, and sand-blasting of wheels, sol 286 (left) and 321 (right); (f) Mastcam-Z calibration target images shown debris deposition and wind effects; and (g) a calibration target detail with Supercam [20] image showing removal of dust from the magnet by winds from SE (right).