Winds at the Mars 2020 landing site.
Part 1: Near-surface wind patterns at Jezero crater

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ABSTRACT

This is the first part of a two-part paper. NASA's Mars 2020 Perseverance rover measured winds on the Jezero crater floor close to the delta of an ancient river. A mostly repeatable diurnal cycle was observed and presented two regimes: (i) a convective regime, from dawn to sunset, with average easterly to southeasterly winds, during which maximum wind speeds were measured, and (ii) a nighttime regime with westerly-northwesterly winds followed by a relatively calm period with highly variable wind directions as a function of sol and time of night. The timing and magnitude of the observed regimes is consistent with primary control by regional and local slope flows. Data suggest that the surface circulation at Jezero region is highly unaffected by large-scale circulation except during particular periods in the diurnal cycle or, generally, during dust storms. Consequently, the seasonal variability in northern spring and summer seasons was weak. However, sol-to-sol and seasonal variability were measured, most of it during certain nighttime periods. Traveling waves consistent with baroclinic instability were clearly observed in surface winds at L_s~75º. The early MY36/2022 regional dust storm at L_s~153º disturbed the wind patterns with changes suggesting enhanced tidal flows. After sunset, the dust storm also produced detectable gravity wave activity, increasing the mixing in the nighttime planetary boundary layer during storm conditions.

PLAIN LANGUAGE SUMMARY

This is the first part of a two-part paper. NASA's Mars 2020 Perseverance rover landed close to the western rim of Jezero crater (18.44ºN, 77.45ºE) on Feb 18, 2021. The wind data acquired by the rover measured a mostly repeatable diurnal cycle with two regimes: (i) a convective regime, from dawn to sunset, with average easterly to southeasterly winds, in which maximum wind speeds were measured, and (ii) a nighttime regime with westerly-northwesterly winds followed by a relatively calm period with highly variable wind directions as a function of sol and time of night. The timing and magnitude of the observed regimes is consistent with primary control by regional and local slope flows, as has been observed to varying degrees at other landing sites on Mars. Data suggest that the surface circulation at Jezero is highly unaffected by large-scale circulation, except during particular periods. An early regional dust storm prior to fall equinox also disturbed wind patterns, with changes suggesting the strengthening of flows linked to large-scale atmospheric oscillations called tides. The latter are primarily driven by the daily pattern of solar heating around Mars and its interaction with topography.

KEY POINTS:

1. A mostly repeatable diurnal cycle is consistent with primary control by regional and local slope flows.
2. Great sub-diurnal and sol-to-sol variability was observed during the calm period at night.
3. Atmospheric and gravity waves were observed, along with the probable effect of enhanced tidal flows.

1. INTRODUCTION

NASA's Mars 2020 Perseverance rover successfully landed close to the western rim of Jezero crater (18.44ºN, 77.45ºE) on February 18, 2021 (areocentric solar longitude, L_s ~5º). The rover is seeking signs of potential ancient life on Mars and preparing, for the first time, a set of samples for possible return to Earth (Farley et al., 2020). Among the mission objectives, Mars 2020 should enable future Mars exploration focused on manned missions, with a characterization of the atmospheric environment. To fulfill this requirement, the Mars Environmental Dynamics Analyzer (MEDA) instrument (Rodríguez-Manfredi et al., 2021) on board Perseverance rover includes a wind sensor that combines with other meteorological measurements to allow the characterization of the atmospheric environment of Jezero crater and obtain insight into the processes that drive the Martian atmosphere.

Near-surface winds are a key mechanism for the exchange of heat, mass and momentum between the surface and the atmosphere. On Mars, suspended dust in the atmosphere drives weather and climate. Therefore, comprehensive knowledge of the surface wind patterns is desirable to fully understand the weather and climate of the planet, as well as how dust storms originate and develop. To date, however, few missions have measured the surface winds on Mars, and their measurement has been complex and sometimes constrained by instrumentation issues. The first measurements of the Martian winds were taken by the Viking Landers (VL) in the 1970s at 22.5ºN 48ºW (VL-1) and at 48ºN 134ºE (VL-2). Those missions observed light winds of a few meters per second with a marked rotation in the diurnal cycle. They also reported dramatic changes as a function of season and in the presence of dust events, which were attributed to variable regional slope flows, diurnally varying planetary boundary layer (PBL) coupling, large-scale circulation, thermal tides and baroclinic waves (Hess et al., 1977; Ryan et al., 1978; Barnes et al., 1980; Murphy et al., 1990).

Twenty years later, the Mars Pathfinder mission again measured Martian surface winds. The Pathfinder lander acquired sparse wind data during several sols and enabled the first direct measurements of near-surface wind profiles on Mars, including a determination of aerodynamic roughness length and wind friction speeds (Sullivan et al., 2000). Later, the Phoenix lander measured winds (Holstein et al., 2010) in the polar region (68.2ºN 125.8ºW) and at various heights during ~150 mission sols, showing highly variable diurnal conditions due to the daytime convective turbulence and reporting wind patterns possibly driven by thermal tides and weather systems. The Mars Science Laboratory (MSL) measured surface winds at Gale crater, but the retrieval presented problems due to damage to the wind sensor during MSL's landing. A comprehensive diurnal and seasonal surface wind characterization was presented covering the two Mars years over which the wind sensor operated, in the northwest crater floor and on the northwestern slopes of Aeolis Mons. Wind data showed that the patterns at Gale crater are driven mostly by local slope winds on Aeolis Mons, in accordance with mesoscale model predictions (Tyler et al., 2013; Raftkin et al., 2016; Pla-García et al., 2016; Newman et al., 2017; Viúdez-Moreiras et al., 2019a; 2019b). To date, these wind patterns are the most complex ever seen on Mars, due to strong constructive and destructive interactions between different scales variably affecting the near-surface atmosphere in the crater. Wind-driven erosion signatures and sand transport have also been repeatedly observed by the mission (e.g., Sullivan & Kok; 2017; Schieber et al., 2021; Vasavada, 2022 and references therein). Local winds in Gale crater have been proposed to drive the abundance of methane detected by MSL near the surface, and could even induce advective flows in the regolith (e.g. Webster et al., 2018; Etiope & Oehler; 2019; Viúdez-Moreiras et al., 2020a; 2021).

InSight landed in Elysium Planitia (~4.5°N 136°E) right after the decay of the MY34/2018 Global Dust Storm (GDS) and before the onset of the MY34/2019 Large Dust Storm (LDS) (e.g. Montabone et al., 2020). Before and after the storm began, the observed wind patterns resulted from the interaction between regional and local slope flows induced by topography, together producing a diurnal perturbation superimposed on a mean flow, dominated by the Hadley cell but with modifications due to channeling effects from the regional topography (Banfield et al., 2020; Viúdez-Moreiras et al., 2020b). Pressure tides were strongly affected by the LDS and produced a dramatic change in the wind patterns that was attributed to enhanced tidal flows. InSight's surface wind measurements have also been crucial for aeolian studies. Aeolian changes at InSight's landing site in Elysium Planitia were infrequent and probably primarily driven by high wind speeds inside convective vortices (Charalambous et al., 2021). The effect of ambient wind speeds on convective vortex encounters was also observed (Spiga et al., 2021) and wind measurements inside vortices were reported, complementing those observed by MSL (Banfield et al., 2020; Spiga et al., 2021; Kahanpää & Viúdez-Moreiras, 2021).

Mars 2020 has detected a rich dynamic atmosphere and aeolian environment in Jezero crater with dust lifting mainly produced by the passage of convective vortices and convection cells (Newman et al., 2022;

Bell et al., under review; Rodríguez-Manfredi et al., under review). Measurements obtained during the first few sols of the mission suggested that wind patterns are mainly controlled by regional and local slope flows. Perseverance also characterized an early MY36/2022 regional dust storm in January 2022, which produced several dust-lifting events (Lemmon et al., this issue). The strong aeolian activity observed at Jezero has produced side effects on the instrumentation. The Mars 2020 wind sensor has been systematically damaged throughout the mission, although efforts are being made to partially recover most of the functionality. Furthermore, Mars 2020 has deployed, for the first time, an unmanned aerial vehicle on another planet, the Ingenuity helicopter (Farley et al., 2020; Balaram et al., 2021), whose safety is strongly dependent on atmospheric conditions. Together with the InSight's wind sensor, the Mars 2020 wind sensor is currently operating on the Martian surface.

In this two-part paper, we present the winds at the Mars 2020 landing site on the Jezero crater floor. This part focuses on the Mars 2020 MEDA wind measurements, describing the mechanisms that may be involved in the near-surface wind patterns at Jezero and presenting the observed winds throughout the mission from the diurnal to the seasonal scales, including the effects of the MY36/2022 regional dust storm on the near-surface circulation at Jezero. The second part presents the observed wind variability focusing on the sub-diurnal scale. This first part is structured as follows: Section 2 describes the MEDA wind sensor observations and the support that the wind measurements provided for the first Ingenuity flights. Section 3 introduces the mechanisms that may affect the near-surface wind patterns at Jezero crater. Section 4 shows the diurnal cycle of winds at Jezero, and Section 5 the sol-to-sol and seasonal cycle for the period covered by the sensor. Section 6 presents the effects of the MY36/2022 regional dust storm. Finally, Section 7 presents the conclusions.

2. METHODS: THE MARS 2020 MEDA WIND SENSOR AND OBSERVATIONS

2.1 The Mars 2020 MEDA wind sensor

The Mars 2020 MEDA wind sensor (WS) consists of two booms (WS1 and WS2) angled at 120° to each other and mounted on the Perseverance's Remote Sensing Mast (RSM), as shown in Fig. 1. WS1 points to the direction of the rover movement with a displacement of 6º in azimuth (Rodríguez-Manfredi et al., 2021), with the WS2 rotated 120º clockwise to the WS1. The WS measures winds by thermal anemometry, as in the Viking landers, MSL and InSight WS (Hess et al., 1977; Gómez-Elvira et al., 2012; Banfield et al., 2020), using thin-film resistors patterned on the surface of a silicon chip. Placed at 1.5 m above the ground, each boom has six sensor boards angled differently to the incoming wind direction, in different planes. The six sensor boards included on each boom allow for substantial redundancy in wind retrieval and enable accurate measurement of vertical winds, significantly improving the preceding designs implemented in the MSL and in the InSight wind sensors.

As in previous missions, the measured winds can be affected by the rover or platform itself, i.e., the ambient winds can be perturbed by the presence of the rover and thus the measured winds could differ from the ambient winds. The Perseverance rover is mostly similar to the MSL Curiosity rover in terms of both the platform and in the sensor allocation, with the RSM being the main source of perturbation. The position of the booms allows for the selection of the best boom for an incoming wind direction. On MSL, based on thorough CFD modeling and examination of REMS wind measurements after the sensor damage during MSL's landing, accurate wind speeds and directions were retrieved only for winds coming from the front boom hemisphere with incident wind angles between −90° and +90° relative to the boom (Gómez-Elvira et al., 2012; Viúdez-Moreiras et al., 2019a). Perseverance WS2 was designed to minimize the RSM perturbation and other disturbances by using a larger WS2 boom (393 mm versus 170 mm). Allocation and mechanical constraints on the Perseverance rover to be experienced during the cruise stage prevented the inclusion of a fixed WS2, which led to the development of a deployable boom once on the Martian surface. Thus, the sensors are farther from the RSM, allowing wider incident angles to be retrieved, particularly those of the WS2 boom, thus strongly minimizing the uncertainties in the rear hemisphere of the rover. Individual wind speeds and directions were estimated at each boom from all six sensor boards based on a wind tunnel calibration database augmented by CFD modeling, correcting potential disturbances from the RSM and its appendages, and combined according to the incident wind direction.

Mars 2020 wind data incorporates a relatively new issue that must be considered. The radioisotope thermoelectric generator (RTG) generates a thermal plume that could perturb the flow towards the sensors if the incoming wind direction comes from the rover's rear hemisphere. This thermal disturbance was not involved in the MSL REMS data, given that only the front pointing wind sensor boom was available to retrieve winds due to damage on the rear boom at MSL's landing. The RTG can provoke disturbances in the wind measurements, mainly in wind speeds. Thus, winds coming from the rear angles close to the RTG were not considered in this study. Fortunately, as in MSL, the rover moves regularly, so the attitude changes accordingly and the winds are sampled from every direction throughout the mission, despite gaps that are present if the rover is placed for long time at the same attitude.

MEDA WS can characterize the horizontal component of the wind at the sensor location with a resolution of at least 0.5 ms^{-1} in speed in the 0-10 ms^{-1} range, and of 1 ms^{-1} for wind speeds above 10 ms^{-1} up to 40 ms^{-1}. The performance decreases for temperatures greater than 223 K, reaching 1.25 ms^{-1} resolution at 293 K.

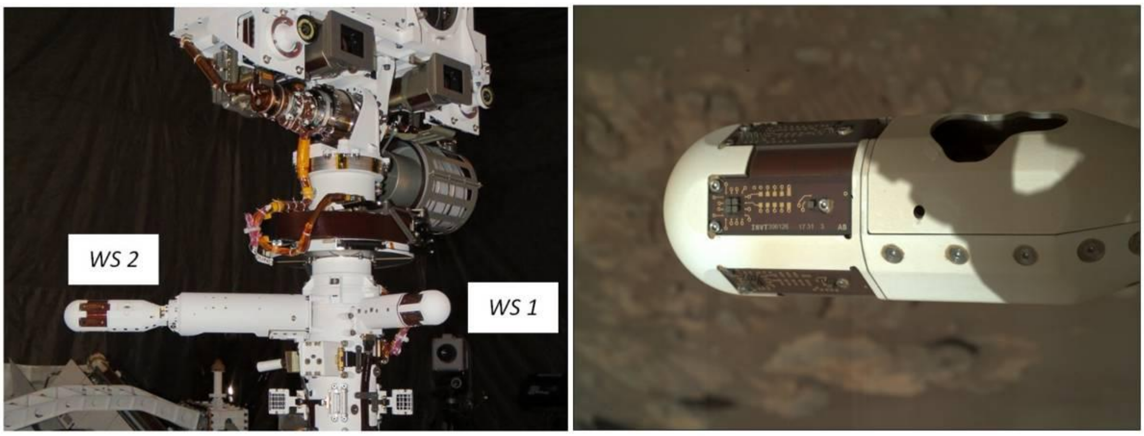


Fig. 1: (**left**) MEDA wind sensor booms (WS1 and WS2) on Mars 2020 Perseverance's Remote Sensing Mast (RSM) (**right**) MEDA WS2 captured on the Martian surface by the SHERLOC WATSON camera, onboard Perseverance, as part of the study performed after the event on sol 313. Credit: NASA/JPL-Caltech.

2.2 The Mars 2020 wind measurements and observations

The MEDA instrument performed eventual measurements beginning with sol 1, and starting systematic operations on sol 28 (Fig. 2). The MEDA WS2 was deployed on sol 10 (Feb 28, 2021). Discrepancies in the obtained results on Mars and the malfunction of a sensor board on WS2 delayed the start of WS operations to sol 36. Mars 2020 operational constraints limited the measurements in the first sols, focusing the observations on supporting the Ingenuity helicopter flights, particularly to select the best time of the day to minimize the risks for the first flights. The primary helicopter campaign concluded on sol 75, thus starting nominal wind observations, including additional coverage of morning, night-fall and nighttime since then. MEDA measurements were acquired for even or odd Martian hours, alternatively, from sol to sol, in Martian local mean solar time (LMST). In addition to these background hourly measurements, extended blocks may be included in each plan considering the operational constraints of the Perseverance rover. A potential issue between the WS and the antenna of the rover meant that the WS had to be turned off during the ultra high frequency (UHF) communication passes of the satellites, thus losing those wind observations.

Given the high sub-diurnal, diurnal and intersol variability inherent in winds, this sampling, together with significant gaps due to the satellite passes, prevented proper characterization of certain features in the wind data. Measurement cadence was increased at sol 281 after optimizing wind observations in the Mars 2020 tactical plans. The arrival of the MY36/2022 regional dust storm led to the activation of the dust storm campaign on sol 311 (Fig. 2), with continuous observations along several hours, significantly enhancing the wind data over those sols. Observations began at a 2 Hz sampling frequency, lowered to 1 Hz after sol 152, due to the need to extend the observation times while maintaining the operational constraints on data volume.

Flying debris is known to damage instrumentation in the severe conditions present on the Martian surface. MSL REMS WS was damaged during MSL's landing, due to flying debris making one of the two sensor booms inoperative. Dust aerosol impacts occurring due to the strong winds observed during the latest operational period of the sensor (around the southern spring equinox while approaching Aeolis Mons) are believed to be the responsible for the final REMS WS sensor failure on MSL after ~1500 sols of the mission (Viúdez-Moreiras et al., 2019a; 2019b). As a result of the MY36/2022 regional dust storm, the convective and aeolian activity at Jezero increased dramatically. A close encounter with a dust devil on sol 313 at 13:42 h LTST further damaged WS2 (see the companion paper, part 2). Two sols later (sol 315 at 14:24 h LTST), damage was produced on WS1 and the MEDA WS was unavailable to provide wind data, leaving only three operative sensor boards: one on WS2 and two on WS1. The sensor was turned off while an engineering analysis was performed. Detailed images obtained with the Mars 2020 cameras (Fig. 1) on sol 339 suggested damage on the board wires due to the impacts of lifted dust. The sensor was again turned on, on sol 342, although without retrieving wind data products. Further damage on other boards during the regional dust storm was detected, continuing at sol 413 and making the sensor inoperative to retrieve data without major modifications to the pipeline and additional calibration tests in the wind tunnel. It is expected that wind data from sol 342 to 413, and possibly data since sol 413, will be available when the retrieval algorithm for each boom is modified to focus on the non-damaged boards of the sensor, although greater uncertainty in the wind data will be involved in the retrievals.

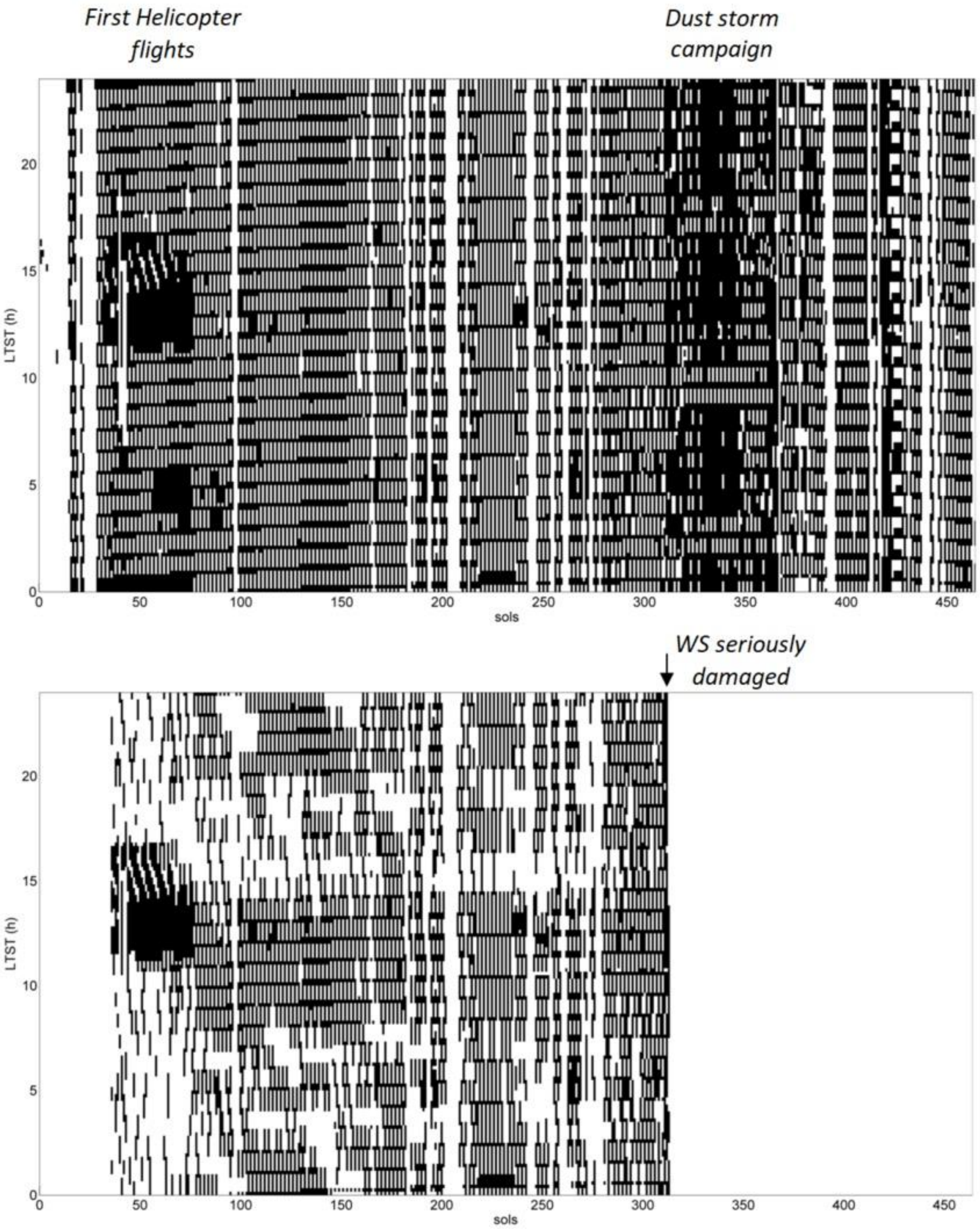


Fig. 2: (**top**) MEDA instrument observations performed until sol 450, as a function of LTST. The special campaigns to support the first helicopter flights (sol 28-75) and to widely cover the 2022/MY36 regional dust storm (sol 311-364) are highlighted. (**bottom**) MEDA instrument observations including WS measurements over the same period. The WS measurements started on sol 35 after the commissioning period. The WS was damaged during periods of high convective activity, probably by suspended dust, on sol 313 (WS2) and 315 (WS1).

2.3 Dust devil trajectories as a background wind proxy

In the absence of a working wind sensor, surface winds may be inferred, under particular conditions, from other sensors and/or from their interaction with surface. We have attempted to obtain some information on surface winds from dust devil Navcam surveys or movies after the wind sensor damage. Some surveys or movies detected the passage of dust devils (DDs) and, if conditions were appropriate, it was possible to estimate the trajectory of DDs from cameras. Terrestrial field measurements showed that dust devil horizontal speed is in agreement with wind speeds a few tens of meters above the surface, and that their horizontal direction closely matches background wind directions (Stanzel et al 2008; Balme et al., 2012). Therefore, assuming that DDs move with the background winds (e.g., Stanzel et al 2008; Reiss et al., 2014), the background wind direction can be inferred. Buoyancy-driven turbulent activity present in the PBL during the day can deviate local winds from the background wind, producing continuous disturbances (see companion paper, part 2); thus DD trajectories may deviate from the average wind in some cases.

Dust lifting events were detected in Navcam surveys or movies. Each comprised 96x19° subframed images of 1280x240 pixels. For movies, one aim was used for 21 images over ~90 s. For surveys, 5 aims were imaged 3 times, with ~4 s between images at one aim. Images were processed following Greeley et al. (2006) by constructing a mean or median frame and subtracting that frame from each image at the same pointing (per-pixel median frames were used for sets of 3). Images were inspected for changing features, all of which were visually confirmed to be lifted dust in motion (excluding obvious illumination artifacts). All reported dust detections were consistent with dust devils except one on sol 472, which had an amorphous, gust-like appearance. For each sequence with dust lifting, wind direction was assessed visually. Transverse (azimuthal) motion was measured, and radial motion was inferred where possible. Uncertainties range from unconstrained radial motion (45°) to well-constrained radial motion (15°); when multiple dust devils were tracked in one sequence, all were used to infer an average wind motion (Stanzel et al 2008).

2.4 MEDA wind measurements supported the first flights on Mars

The successful landing of Perseverance on Mars brought with it a partner, the technology demonstration helicopter Ingenuity (Farley et al., 2020; Balaram et al., 2021), designed to demonstrate the capability of powered flight in the Martian environment. Given the a priori absence of atmospheric information in Jezero crater, and the need to understand both density and wind conditions in the local environment, a significant modeling effort was pursued, prior to landing, in order to constrain the expected flight environment (e.g., Mischna et al., 2021). Upon landing, the mission timeline dictated an early demonstration of Ingenuity*'s* capabilities, and it was expected that the first flights would occur prior to full commissioning of the MEDA wind sensor (the air temperature and pressure sensors were commissioned sufficiently early so as to provide useful density information early in the mission).

Due to engineering constraints on Ingenuity, flights could initially only occur during late morning and afternoon, to ensure adequate temperatures for helicopter electronics (dictating the start of the window), and a sufficient battery state of charge to support helicopter heating during the subsequent overnight period (dictating the end of the window). Thus, the initial activities sought to assess the wind environment between 10 h and 17 h LMST. Initial assessment of wind speed and direction was performed beginning on sol 38 of the mission using calibrated MEDA wind sensor data, and showed two consistent diurnal trends. First, there was an observed pattern of increasing mean wind speed over the course of the study window, from ~5 m/s at 10 h LMST to peak winds of ~11 m/s by 17 h LMST (see the companion paper, part 2), in agreement with numerical modeling estimates of large-scale wind speed. The Ingenuity helicopter had previously been tested against mean wind speeds of up to 11.2 m/s prior to launch, with satisfactory performance, and so the MEDA mean wind speed measurements were not considered a significant constraint on flight time. Second, wind speed variability, or small-scale turbulent activity, decreased modestly throughout the sol, showing a broader range of wind speeds during the late morning and mid-sol period ($\sigma_v < 4$ m/s), with a narrowing range (σ_v ~2 m/s) after ~15.5 h LMST (see the companion paper, part 2). This, too, was consistent with modeling studies, and reflects the growth of larger-scale convective cells at the expense of small-scale, turbulent motions. Wind direction was not considered a significant constraint on Ingenuity operations, but was monitored for later assessment of helicopter performance.

Based in large part on this input from the MEDA wind sensor, early Ingenuity flights, starting with the first, historic flight on sol 58, were performed at 12.5 h LMST, this time being seen as a suitable balance between lower mean wind and moderate potential for turbulent motion, thus minimizing atmospheric risks to helicopter activities. Table 1 shows the atmospheric conditions during the first flight of Ingenuity, in which there are wind data available. Fig. 4 shows the trajectories for each flight. Mean wind speed during the flights was 4.6 m/s at 1.5 m (7.3 m/s at 10 m assuming a neutrally stable atmosphere, which probably overestimates wind speeds), with a mean pressure and temperature of 725 Pa and 238 K, respectively.

As the team gained confidence in Ingenuity's performance, flights later in the sol were performed, as MEDA continued to return data consistent with the previously observed trends. Following each flight, data were requested from the MEDA team, spanning the period of flight, for later comparison to flight performance logs, to identify any possible environmental conditions which might have led to off-nominal helicopter behavior (though no such conditions were observed).

F	Earth Date (UTC)	L_s (deg)	sol	LTST (h)	Flight duration (sec)	P_{srf} (Pa)	$T_{1.5m}$ (K)	$\rho_{1.5m}$ (kg/m^3)	$\phi_{1.5m}$	$\sigma_{\phi 1.5m}$	$v_{1.5m}$	$\sigma_{v1.5m}$	max $v_{1.5m}$	min $v_{1.5m}$
01	19 April 2021 07:34	33.5	58.5	12.26	40	748.4	235.8	0.0165	142.1	25.5	5.6	1.8	10.0	1.6
02	22 April 2021 09:33	34.9	61.5	12.29	52	748.6	235.9	0.0165	62.8	56.5	4.0	1.9	9.6	0.2
03	25 April 2021 11:31	36.3	64.5	12.29	80	746.5	236.8	0.0164	85.7	64.1	4.4	1.7	11.2	0.5
04	30 April 2021 14:49	38.7	69.5	12.32	117	748.1	235.3	0.0166	113.9	43.8	4.3	1.7	8.4	0.7
06	23 May 2021 05:20	48.8	91.5	12.45	140	751.7	236.0	0.0166	-39.9	79.2	3.3	1.9	8.9	0.4
07	08 June 2021 15:54	56	107.5	12.54	63	754.8	237.3	0.0166	110.2	39.6	4.6	2.4	12.2	0.3
08	22 June 2021 00:27	61.9	120.5	12.57	77	752.6	238.0	0.0165	78.3	20.0	6.4	2.8	19.1	1.0
12	16 August 2021 12:57	86.1	174.6	13.60	170	715.8	245.2	0.0152	109.6	32.8	3.6	1.3	8.4	0.4
14	24 Oct 2021 08:18	117.1	241.5	12.92	23	650.7	242.3	0.0140	64.5	31.6	5.7	2.1	11.9	1.0
16	21 Nov 2021 02:09	130.2	268.5	13.02	108	633.7	240.5	0.0137	42.4	34.0	3.9	1.5	7.9	0.7

Table 1: Atmospheric conditions and winds during the Ingenuity helicopter flights with available MEDA wind data. Pressure (P_{srf}), temperature ($T_{1.5m}$) and estimated density ($\rho_{1.5m}$) at 1.5 m are included, as well as mean and standard deviation of wind direction ($\phi_{1.5m}$ and $\sigma_{\phi 1.5m}$) and speed ($v_{1.5m}$ and $\sigma_{v1.5m}$) as measured by MEDA. Also, maximum and minimum wind speeds obtained by MEDA during the flights are shown.

3. INFLUENCES ON THE JEZERO CRATER CIRCULATION

Surface wind patterns in the tropical region of Mars could be the consequence of complex interactions between slope flows, on regional and local scales, and the large-scale circulation, dominated by Hadley cell flows, thermal tides and other planetary waves. In addition, other topographic influences, microscale flows, turbulence and wave activity modify this situation.

Jezero is an impact crater of 45 km in diameter and more than 500 m deep from the surroundings, with crater rims elevated ~800 m to the W and ~1 km to the S above the crater floor (e.g., Schon et al., 2012). Jezero is located on the northwestern slopes of Isidis basin (Fig. 3), a region presenting a steep slope (~0.7° downward towards ~120° of azimuth, clockwise from the north). This slope suggests strong near-surface regional flows in the area. In fact, the Isidis regional slope in the Jezero region is significantly greater than the <0.1° general slope of other landing sites, e.g., for Viking Lander 1 and InSight, where wind patterns were significantly shaped by regional slope flows (e.g., Hess et al., 1977; Banfield et al., 2020; Viúdez-Moreiras et al., 2020). Thus, it was expected pre-landing that the regional flows on the Isidis basin slopes may shape the surface wind patterns.

Additionally, local dynamics were expected in Jezero crater. To date, the only mission to measure winds in a region with significant topography at the local scale was MSL, which operates inside Gale crater. MSL observed wind patterns shaped by local slope flows related to both the rim of the crater and the mountain in the center of Gale (Newman et al., 2017; Viúdez-Moreiras et al., 2019a). Perseverance's landing site is close to the western-northwestern rims of Jezero crater, where slope flows are expected to develop. However, Jezero crater is smaller and far shallower than Gale crater, and does not contain a central mound, so the potential relevance of local slopes on wind patterns should be addressed by observations and modeling.

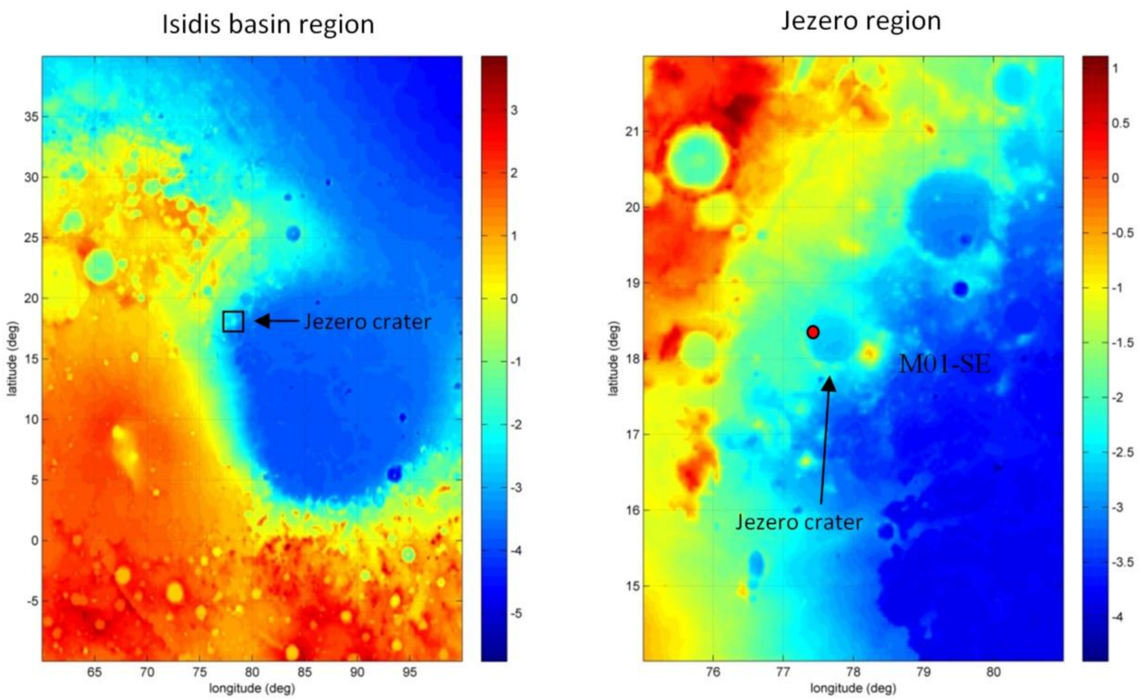
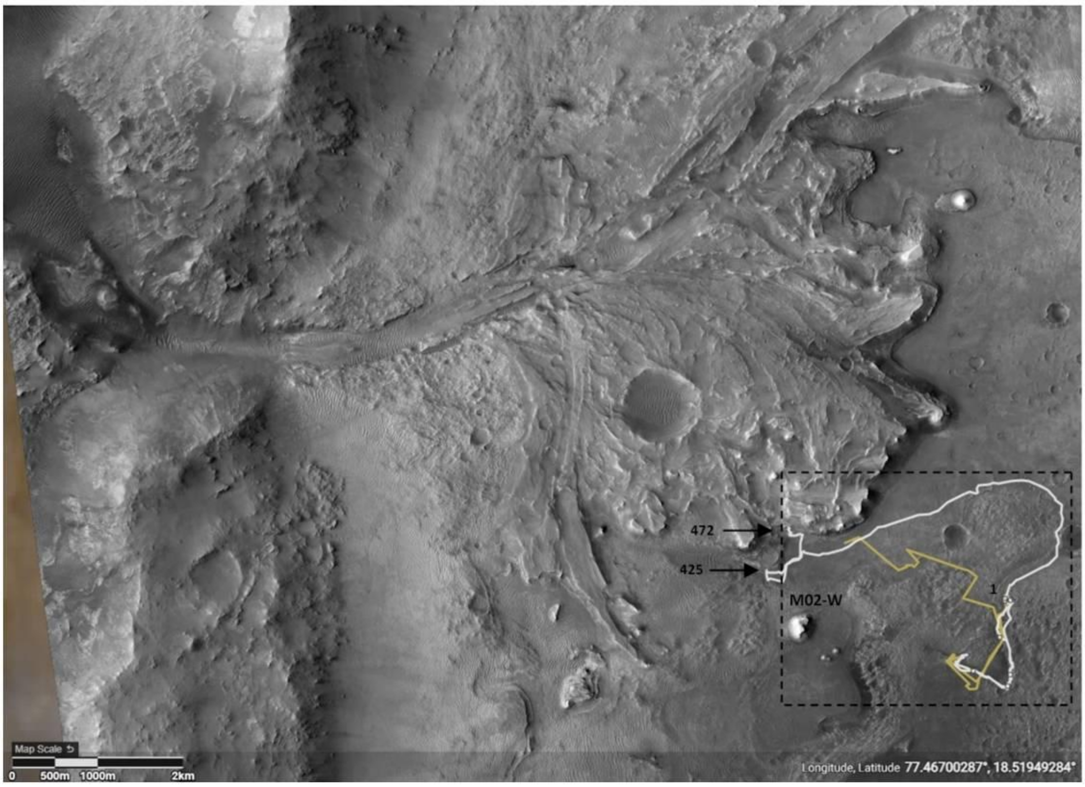


Fig. 3: (left) MOLA topography for the Isidis basin region. (**right**) Enlargement for the Jezero crater region. Perseverance's location is highlighted with a red circle close to the northwest crater rim of Jezero crater. Altitude is shown in kilometers both in left and in right panels.



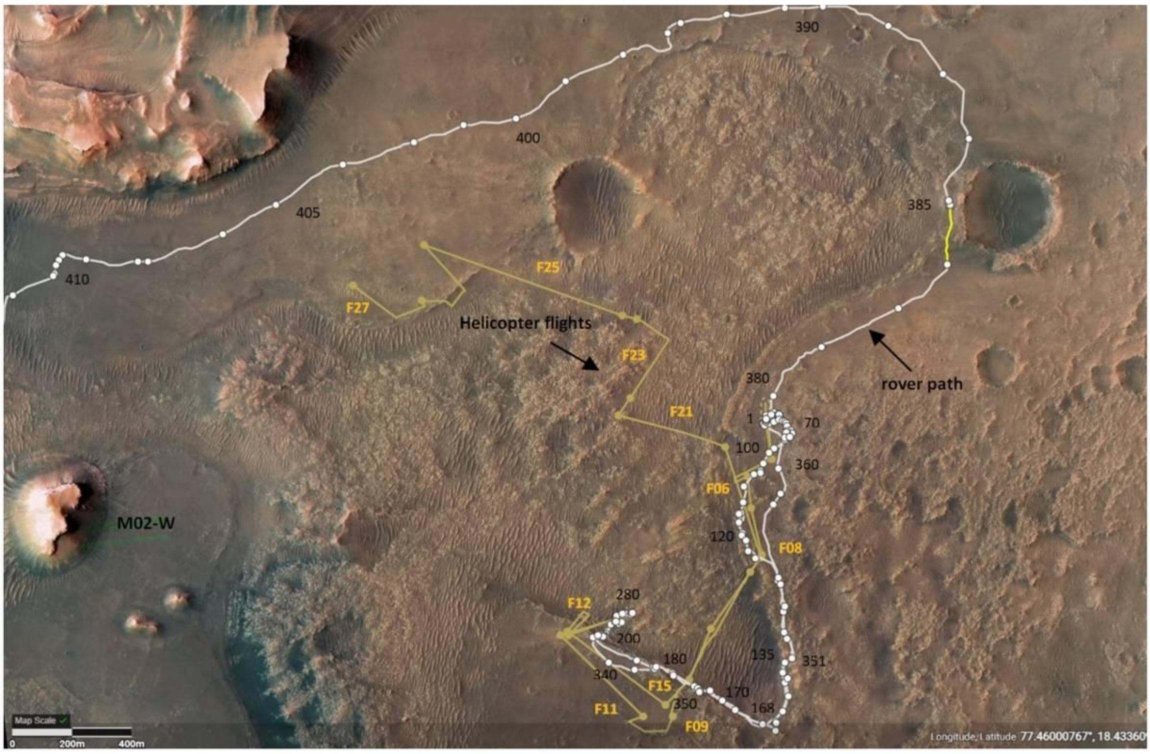


Fig. 4: High resolution images of the landing site location close to the western crater rim, taken from Mars Reconnaissance Orbiter (MRO). (**top**) crater rim and Jezero's delta (**bottom**) Enlargement of the southeastern region around the Mars 2020 landing site. The Perseverance rover and the Ingenuity helicopter trajectories as far as sol 410 are highlighted in the bottom panel in white and yellow colors, respectively. Mission sols are included in black and helicopter flights are labeled in yellow.

Other influence in the observed wind patterns by a mobile platform is the change in location throughout its traverse, that is, surface winds are observed in this case by a rover instead of by a fixed platform. It enables its wind data to also shed light on changes to wind patterns with location, although there is difficulty differentiating these variations with seasonal variations if the same location has not been sampled multiple times. A precedent exists only on Mars. The Curiosity rover traveled many kilometers from the bottom of the northwest region of Gale crater towards Aeolis Mons, a feature of more than 5 km altitude at the center of the crater. Along its traverse, the rover characterized the Bagnold Dune field around local winter in the third Martian year of operations (Newman et al., 2017) and measured upslope winds during the daytime getting stronger as it climbed Aeolis Mons (Viúdez-Moreiras et al., 2019a; 2019b).

After exploring the delta remnant inside the crater, Perseverance will drive to the rim and out of Jezero, likely driving to explore regions to the southwest. Different local dynamics are expected both closer to the rim, where local downslope flows at night are expected to be much stronger, and outside the crater. In addition, channeling effects and flow deviations closer to the crater rim and delta walls can be observed in satellite images through analysis of the aeolian features (Fig. 4 bottom). This is particularly easy to observe close to topographical features such as to the left of the mountain located to the west (hereafter M02-W, Fig. 4 bottom). Focusing on Perseverance's trajectory, significant deviations from the prevailing winds can be expected at least between sol 380 and 385 (where aeolian indicators suggest dominant west-northwesterly winds instead of the prevailing west-southwesterly winds), and between sol 400 and 408 (where aeolian indicators suggest channeling effects by small-scale topography, and dominant northwesterly winds, Fig. 4 bottom). After sol 410, the rover is very close to the delta walls (Fig. 4 top), which may also imply disturbances in the observed winds. However, during the first 315 sols of the mission, that is, the timescale currently covered by the wind sensor, the rover moved within a region of only ~1 km^2 (Fig. 4 bottom), in which strong variability neither in topography nor atmospheric dynamics is expected. Therefore, we initially assume that the observed variability is due to the different temporal scales and dust events.

4. DIURNAL VARIATION OF SURFACE WINDS AT JEZERO

4.1 Observed diurnal wind patterns

The Perseverance rover measured surface winds at Jezero during the first 315 sols of the mission, with observations starting at sol 35 (Section 2). This corresponds to areocentric solar longitudes (L_s) from ~22º to ~153º, i.e., much of northern spring (L_s = 0 - 90º) and summer (L_s = 90 - 180º).

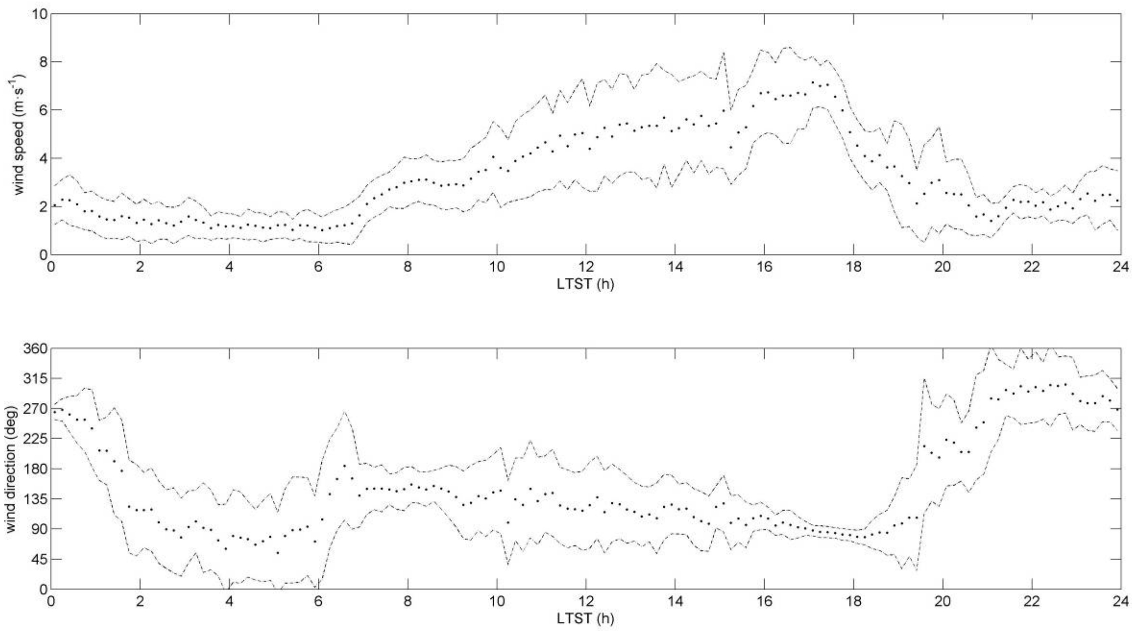


Fig. 5: Diurnal variation in wind speed and direction as a function of local true solar time (LTST) over a period of 40 sols close to the northern summer solstice. The direction from which the wind is blowing is shown, following the standard meteorological convention. 10 min averages are shown as dotted line, with the ± one standard deviation shown in dashed lines.

The observed wind patterns at Jezero presented minor sol-to-sol variations that were generally overwhelmed by the diurnal variations, in accordance with observations from previous missions on Mars outside the dust storm season (e.g., Hess et al., 1977; Banfield et al., 2020). The acquisition strategy involved in Mars 2020 operations (Section 2) prevented complete measurement of the diurnal cycle in a single sol; therefore, multiple sols were necessary to fill the gaps, which were particularly of concern during the afternoon due to more gaps at that time (Fig. 2). No major variability was observed in the general shape of the diurnal cycle within the period of observation. Conversely, a mostly repeatable diurnal cycle was measured, with minor long-term variability (detailed in the next subsection).

The observed diurnal cycle of winds presented two regimes: (i) a daytime or convective regime, from dawn to sunset, with average easterly to southeasterly winds in which maximum wind speeds were measured, and (ii) a nighttime regime with a period of W-NW winds followed by a relatively calm period until sunrise with highly variable wind directions as a function of sol and time of night. In addition, two transition periods occurred between the daytime and nighttime regimes. Fig. 5 shows the diurnal variation in wind speed and direction, averaged in ten-minute windows over a period of 40 sols close to the northern summer solstice, which is illustrative of the observed diurnal cycle throughout the first 315 sols of the mission.

Over this sol period, winds were southeasterlies during the morning when the PBL was developing. They gradually rotated east as the day progressed, at the same time that wind speed strongly increased. Maximum ten-minute-average wind speeds of ~7 ms^{-1} were measured during the late afternoon (~17 h LTST), when winds were easterlies. This corresponds to the time of sol when the solar heating that drives daytime upslope winds had lasted for several hours but was declining and would shortly be very low at sunset (~18.5 h LTST). In addition, the wind variability, both in wind speed and direction, was strongly reduced in the afternoon, when the PBL was fully developed and when turbulence was likely dominated by larger eddies. Winds remained as east-northeasterlies in the afternoon while wind speed decreased abruptly at 17.5 h. After sunset, wind speeds continued decreasing whilst winds inverted the rotation that presented throughout the daytime, rotating clockwise by a few degrees from east-northeasterlies to east-southeasterlies from 18.5 h to 19.5 h. At 19.5 h, the daytime convective regime had ceased, and wind speeds were weak, at 2 - 3 ms^{-1}. The winds then dramatically rotated clockwise from easterlies to west-northwesterlies, between 19.5 h and 21.5 h. This rotation was coincident with a wind speed spike in some sols that lasted for roughly an hour. Wind directions were then stable for ~2 hours with a slight shift towards westerlies. After ~21.5 h, wind speeds gradually increased, peaking with a local maximum around midnight. A subsequent decrease produced the minimum wind speeds reached during the diurnal cycle, ~1 ms^{-1}, in a period characterized by a counter-clockwise rotation toward easterlies and with pronounced variability in wind direction, comparable to that observed during the day. This period was characterized as well by a strong sol-to-sol variability (see Section 5). Finally, half an hour after dawn (~5.5 h LTST), winds rotated clockwise to S-SE and increased in intensity as the PBL developed, completing the diurnal cycle.

Notably, the observed variability represented in Fig. 5 by the standard deviation of wind speed and direction as a function of LTST described above could, a priori, be due to both intrasol (sub-diurnal) and intersol variations, given that 40 sols were averaged in this figure. Further analysis of such variability shows that, in general, intrasol variability dominates during the daytime convective regime (turbulence scale), while intersol variability dominates the ensembled multi-sol pattern during the night regime.

4.2 Mechanisms affecting the diurnal cycle in the near-surface wind patterns

The timing and magnitude of the observed regimes is consistent with control by slope flows. During the daytime, mean wind direction matched the regional upslope of Isidis basin at Jezero region and the Jezero crater rim slope (Fig. 4), although the wind direction shifted by ~30º north once the upslope winds were fully developed in the late afternoon. This could be explained by upslope flows being perturbed by the topography at Jezero region, together with the effect of local upslope flows. A full rotation of winds was produced after sunset, when near-surface thermal gradients started to reverse after their daytime maxima. Winds presented a similar orientation but in an opposite sense after rotation, i.e., at that time the wind direction roughly matched the downslope of Isidis basin around the Jezero region and the crater rim slope. The pre-landing general circulation model (GCM) and mesoscale simulations predicted strong control by regional and/or local winds (Newman et al., 2021; Pla-García et al., 2021), consistent with the first observations by Mars 2020 (Newman et al., 2022; Rodríguez-Manfredi et al., 2022). The modeled winds usually ranged from northeasterlies to south-southeasterlies during the daytime, rotating to westerlies/northwesterlies after sunset. The fact that the direction of the slopes of Isidis basin and Jezero crater's western rim are similar makes discerning the mechanism that modulates the diurnal cycle at the landing site difficult. Newman et al. (2021) suggested that largely similar wind patterns between the high- and low-resolution simulations tested in the study during the daytime could indicate that the slopes of Jezero crater, itself, cannot drive the winds during the daytime, as the local scale is not resolved in the latter simulations. In any case, the low-resolution simulations may be shifting the daytime wind direction by some degree, due to the variability in the Isidis basin slope direction at Jezero region (Fig. 3), thus artificially mimicking the potential effect local anabatic winds have on the wind pattern. On the other hand, given the small size of Jezero crater (less than 50 km), it is expected that upslope flows on the eastern crater rim and on the mountain located close to the southeastern crater rim of Jezero (hereafter M01-SE, see Fig. 3) would act in opposition to the regional flow, consequently producing effects at the landing site location. In that case, local forcing would produce complex constructive and destructive interactions in the near-surface winds.

The gradual increase in wind speeds and the shift in wind direction as the daytime timeslot progressed can be interpreted as the result of the gradual and different increase in the relative strength of regional and local slope flows as the PBL develops, as reproduced in the model simulations to some extent. Therefore, regional and local upslope flows would dominate during the daytime. Also, the importance of tidal flows cannot be ruled out during the daytime. However, the complex structure of tidal flows and the weak diurnal and semidiurnal tides at Jezero (Rodríguez-Manfredi et al., 2022), together with their representation in models being sensitive to the three-dimensional dust distribution used, complicates discerning the relative contribution of tidal flows under nominal conditions.

The vertical extent of the slope winds and the gradual coupling with winds aloft should also be considered. The unstable daytime PBL present in the Martian atmosphere quickly transports momentum between the near-surface and the atmosphere several kilometers above. Hess et al. (1977) attributed the behavior observed by VL1 to a combination of near-surface slope flows, peaking in the mid-afternoon, and maximum turbulent coupling with the winds aloft, peaking in late afternoon and acting constructively with the former. In addition, analysis of the wind data acquired by the InSight Lander at Elysium Planitia suggested that the reduction, or perhaps entire lack, of significant coupling during the nighttime could have allowed downslope flows to develop, producing surface winds opposite to the strong winds from the general circulation present during the northern summer in Elysium Planitia.

We performed MarsWRF GCM simulations in order to test the possible coupling of large-scale winds into near-surface winds in the Jezero region, with the same version and setup successfully applied to previous studies for the Gale crater region (Newman et al., 2017; Richardson & Newman, 2018; Viúdez-Moreiras, 2021), but using here only the global domain. We focused on the evaluation of the interference between the large-scale and the regional slope winds on the northwestern slopes of Isidis basin, so it is not necessary to resolve the local circulation at Jezero crater. These simulations show that surface winds on the slopes of the Isidis basin are mostly insensitive to the higher winds in and above the PBL, due to the strength of daytime slope flows on Isidis's slopes.

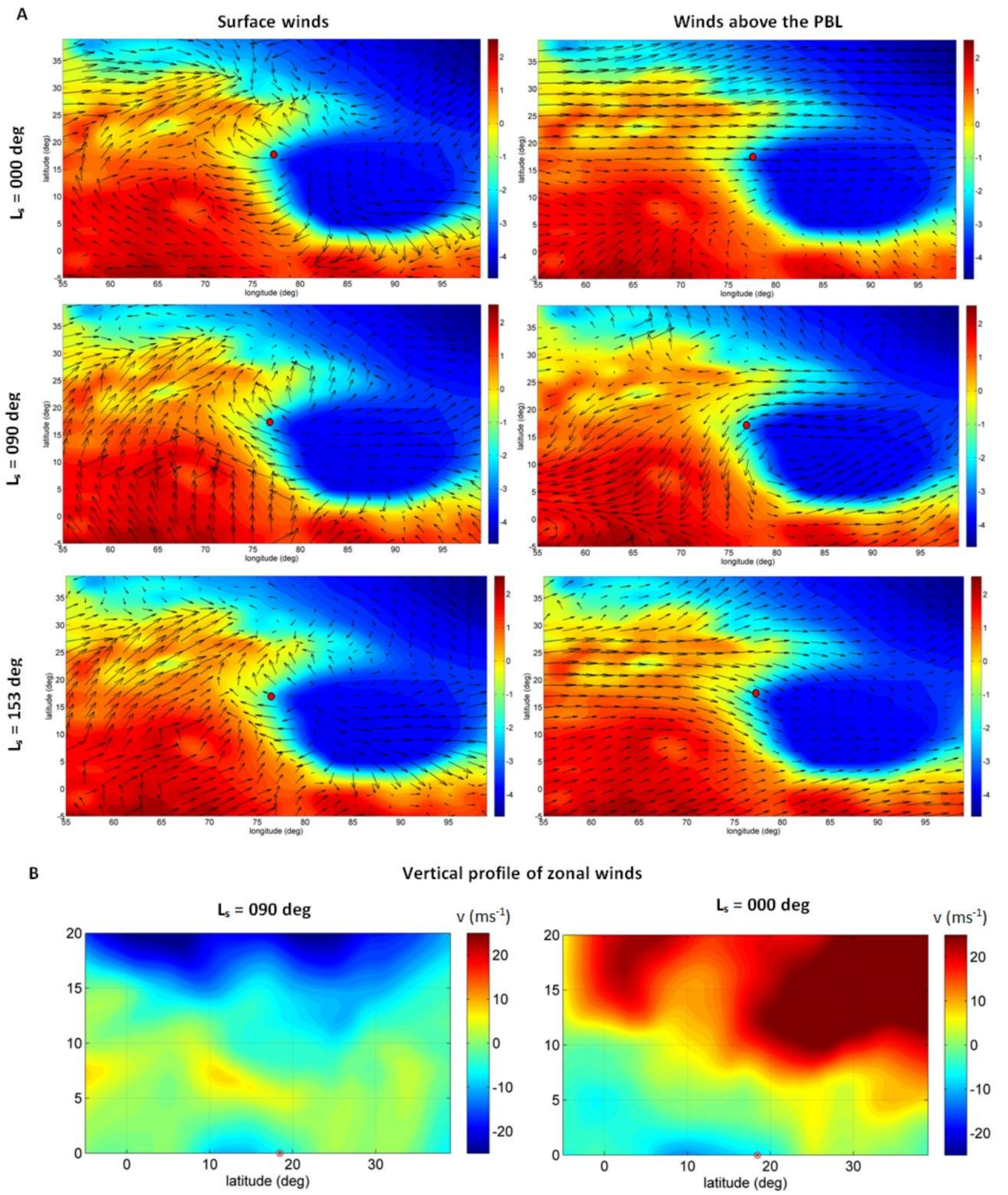


Fig. 6: (A) Wind field at midday in the Isidis basin region from MarsWRF GCM simulations at northern spring equinox (top), summer solstice (middle) and at L_s=153º (bottom), averaging ±5 sols. Surface winds and winds above the PBL (10 km) are shown in the left and in the right columns, respectively (see text). **(B)** Midday vertical profile of zonal winds at the landing site's longitude. Pseudo-altitude in km. The wind speed axis is constrained to ±25 ms^{-1} to better observe the range in Isidis basin. Jezero crater is shown by a red dot.

The effect of mid-latitude westerly winds above the PBL can be observed outside summer (Fig. 6), indicated by the strong westerly circumpolar winds that reach the Isidis basin latitudes, and that are variably disturbed by tidal flows along the day. Within the jet streams, these winds can present velocities greater than 100 ms^{-1} at high altitudes (Mitchell et al., 2015), and reach lower latitudes nearer the surface with reduced wind speeds. Simulations presented in Fig. 6 show that the daytime PBL at Jezero's region is subjected around the equinoxes to mid-latitude westerly winds that oppose the regional upslope near-surface flows. These strong winds are slightly disturbed by tidal flows along the day. Conversely, around the northern summer solstice these westerly winds are not present and winds above the PBL are dominated by tidal flows, which act constructively to the near-surface winds during most of the daytime, particularly during morning and midday. The vertical extent of the surface regional upslope winds produces even strong winds at a couple of kilometers above the surface during the daytime (Fig. 6B). The PBL reaches in the afternoon ~8 km at northern summer and ~5 km close to the equinoxes, achieving greater values at the fall equinox than at the spring equinox. However, although the winds above the PBL can strongly affect the high layers within the Isidis basin's PBL (Fig. 6B), simulations suggest that the effect on the surface winds by the winds above the PBL is minor, even when winds above the PBL flow in opposite directions to the surface winds (Fig. 6A), due to the intense daytime regional slope flows present in the Isidis basin's slopes. Most of the slight differences observed in the near-surface patterns on the Isidis basin western slopes could be attributed to the return branch of the Hadley cell. These results are in agreement with the weak southerly shift in surface winds observed in several model pre-landing predictions for Jezero around southern summer (Newman et al., 2021), which may be attributed to the Hadley cell circulation, although other models do not present such a shift. It illustrates how the steep slopes of Isidis basin would be contributing to isolation of the circulation from the large-scale dynamics in the Jezero region.

The nighttime regime presents several interesting features, with some differences from the daytime scenario. An interesting feature is the effect of the nighttime PBL structure on the near-surface winds. While the daytime PBL quickly transports and mixes momentum between surface and several kilometers of height, the nighttime PBL is much shallower, maximizing the effect of small topographic features in their surroundings that may reinforce mechanical turbulence in these areas and affect the downslope wind intensity and direction. The Jezero region and Jezero crater itself contain significant topography (Fig. 2) that could dramatically affect the nighttime patterns in the mesoscale (~10^2-10^4 m) and in the microscale (~10s of m and smaller). The first part of the night, from sunset to 01 h LTST, was characterized by relatively stable westerly/northwesterly winds that peaked around midnight as a likely result of downslope winds peaking at that time. However, this is not what is expected from regional downslope flows, which should peak right before sunrise, as the thermal conditions that drive katabatic flows (i.e., surface cooling along slopes) grow overnight. Pre-landing atmospheric modeling from lower-resolution simulations (i.e., that did not resolve the topography of Jezero crater) predicted that regional slope flows at the Perseverance landing site would, in general, grow during most of the night, reaching peak values shortly before sunrise (Newman et al., 2021), which is not at all what is observed. Atmospheric modeling from higher-resolution simulations (i.e., that did resolve the crater topography) predicted a spread of results, with the MarsWRF modeling reproducing the observed peak around the midnight followed by a drop in wind speed to low values by 02 h to 03 h. MarsWRF also shows that winds aligned with the Isidis basin downslope direction are, on average, present across this general region at night, but are absent from the center of Jezero crater, with the strongest winds (both in the crater and outside) instead linked to smaller-scale topography, including strong downslope winds around the western crater rim. This supports the hypothesis that regional downslope winds are weakened by the Jezero topography and that local downslope winds on the western crater rim dominate during this timeslot (e.g., Newman et al., 2022).

After 01 h LTST, winds decreased in intensity and rotated counter-clockwise to variable directions, although easterly winds dominate, with dramatic variability over most of the night (Fig. 5 and Fig. 7). This reduction in the relative strength of the crater rim downslope winds was probably enhancing the effect of another mechanism that was competing with the previous one. An analysis of the topography around the landing site and the prevailing wind directions in this period indicate that the best candidates to provoke such easterly flows should be the downslope winds at the eastern crater rim, possibly reinforced by downslope flows on M01-SE. Such flows would compete with the western and other crater rim flows, provoking convergent flows on the crater floor and periods of high mechanical turbulence and wind variability. The nocturnal dynamics may also increase the likelihood of low-level jets at the nocturnal inversion interface perhaps affecting the Perseverance's landing site in particular times (Pla-García et al., this issue). The very low wind speeds observed during this period of the night suggests that these convergent flows are very weak or a destructive interaction around the landing site dominates the atmospheric dynamics, provoking a calm region on the crater floor, at least at the Perseverance landing site. The calm period observed in Jezero crater at night resembles what was observed in the early morning at Gale crater, where the available data showed very low wind speeds (Viúdez-Moreiras et al., 2019a; 2019b) probably driven by a similar mechanism (in that case due to downslope flows in Aeolis Mons and the northern crater rims, greatly isolated from the regional and large-scale circulation).

5. SOL-TO-SOL AND SEASONAL VARIABILITY IN WINDS

5.1 Potential mechanisms affecting the seasonal cycle in the near-surface wind patterns at Jezero

The general circulation at the time of Perseverance's landing (L_s ~5°) is characterized by a weak equinoctial Hadley cell circulation, when the return branch of the northern cell would produce zonal-mean near-surface northerly winds at Jezero's latitude. Thermal tides and planetary waves are also affecting the large-scale circulation. In addition, strong westerly circumpolar winds aloft in the area reaching the PBL can be observed in the simulations (Section 4.2 and Fig. 6).

The situation changes as the season progresses. Together with possible changes in the intensity of regional and local slope flows, and seasonal variations in tides and planetary waves, the dual cell becomes a single cell that is already developed by summer solstice (L_s 90°) with upwelling (downwelling) at northern (southern) mid-latitudes, producing near-surface southerly winds in the zonal mean. The effect of the Hadley cell on surface winds is to a greater or lesser extent evident in the surface wind data of past missions. Viking 1 data suggested a transition from regional topographic to global Hadley circulation control of the winds above the landing site, with a remarkable effect on the surface winds measured by the lander (Murphy et al., 1990). The MSL wind data confirmed model simulations that predicted the large-scale, synoptic (>100s of km in scale) flow has a much stronger influence at Gale Crater during the summer and winter seasons when a single Hadley cell exists in the zonal mean (Rafkin et al., 2016; Newman et al., 2017; Viúdez-Moreiras et al., 2019a). InSight data at Elysium Planitia indicated that the observed wind patterns resulted from the interaction between regional and local slope flows induced by topography, which all produced a diurnal perturbation superimposed on a mean flow, dominated by a combined effect of the Hadley cell and channeling effects from the regional topography (Banfield et al., 2020; Viúdez-Moreiras et al., 2020). However, although evident, the effect of meridional circulation in Mars 2020 wind data is difficult to observe due to the dominance of regional and local slope flows and the lack of measurements in southern summer, the season when the mean meridional circulation is at its strongest (e.g., Richardson & Wilson, 2002). Also, it is possible that the topography and variability in the terrain properties of this region could be influencing the behavior of the meridional circulation from the zonal mean.

5.2 Observed sol-to-sol and seasonal variability in daytime winds

Fig. 7 presents the wind roses for three L_s ranges and seven periods of the day or diurnal timeslots. The latter are chosen to combine hours with similar wind patterns, taking into account that the inherent complexity of the surface wind patterns may imply variations within the diurnal timeslot, as we will describe in that case. We use the same timeslots and nomenclature as presented in Viúdez-Moreiras et al. (2019a; 2019b) for Gale crater. The diurnal timeslots are: (i) morning (DW), from 07:00 to 10:00 LTST, (ii) midday (MD), from 10:00 to 15:00 LTST, (iii) afternoon (DL), from 15:00 to 18:00 LTST, (iv) night-fall (NF), from 18:00 to 21:00 LTST, (v) night (NL-1), from 21:00 to 24:00 LTST, (vi) midnight (NL-2), from 00:00 to 03:00 LTST, and (vii) early morning (EM), from 03:00 to 07:00 LTST. The time evolution of wind speed and direction are presented in Fig. 8 for selected diurnal timeslots, similar to those used in Fig. 7 but with slight modifications to allow for a better representation of the data as a function of season given short-term data gaps present in certain periods.

One-sol averages give more information about different dynamic processes that affect particular periods of time, but the significant gaps involved in the wind data (particularly between 16-17 h and 16-18 h LTST in the early sols of the mission) make it difficult to study the sol-to-sol variability systematically. Therefore, 5-sol average wind speeds and directions as a function of sol are presented in Fig. 8.

Overall, the seasonal variability for the winds observed by Mars 2020 between the northern spring and the summer season was weak (Fig. 7), without dramatic variations, in agreement with the dominance of the regional and local scales in the surface wind patterns (Section 3).

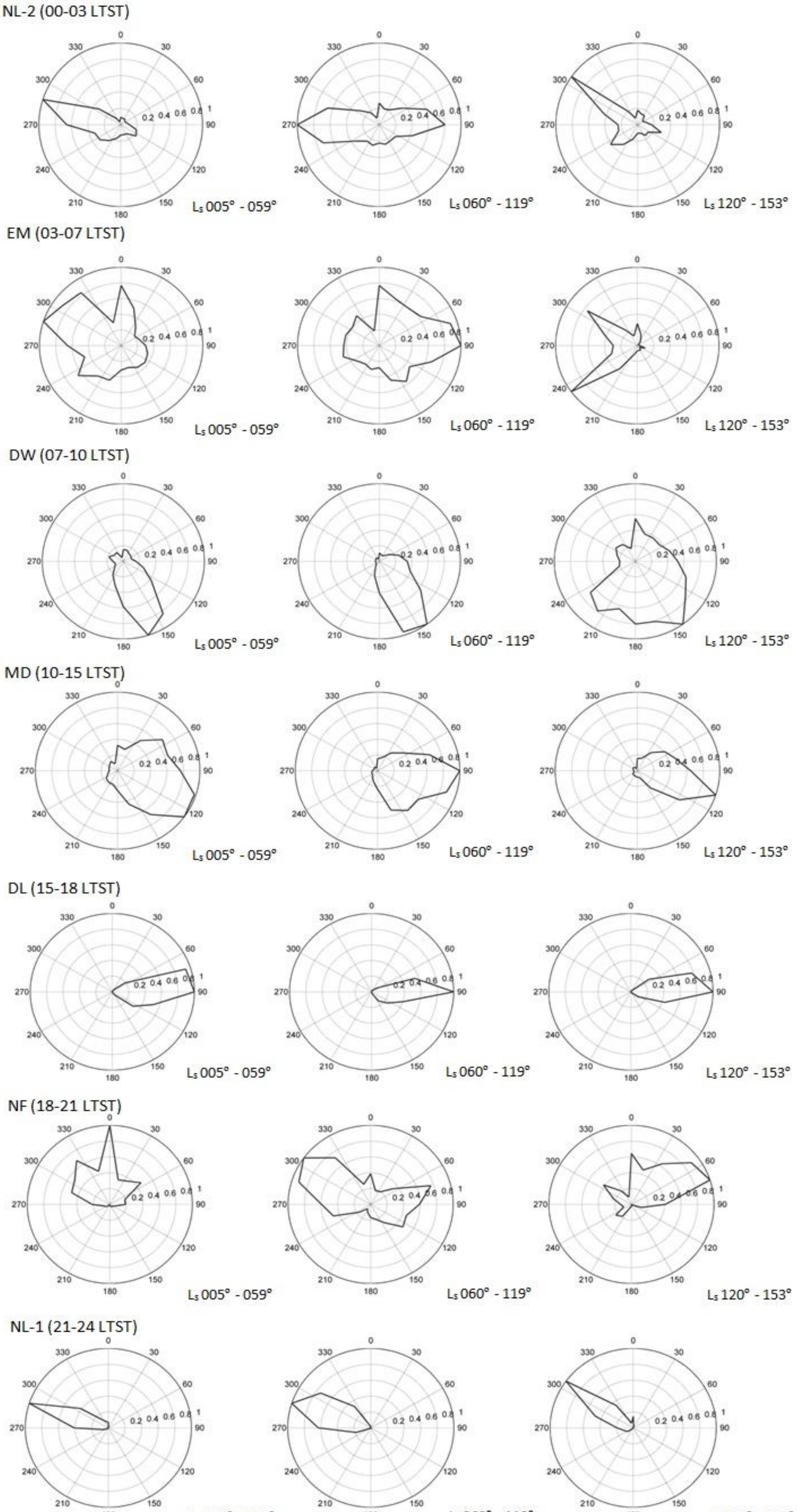


Fig. 7: Wind roses as a function of areocentric solar longitude (L_s) and time of the day until the wind sensor failure on sol 315 (L_s ~153°). The direction from which the wind is blowing is shown, following the standard meteorological convention.

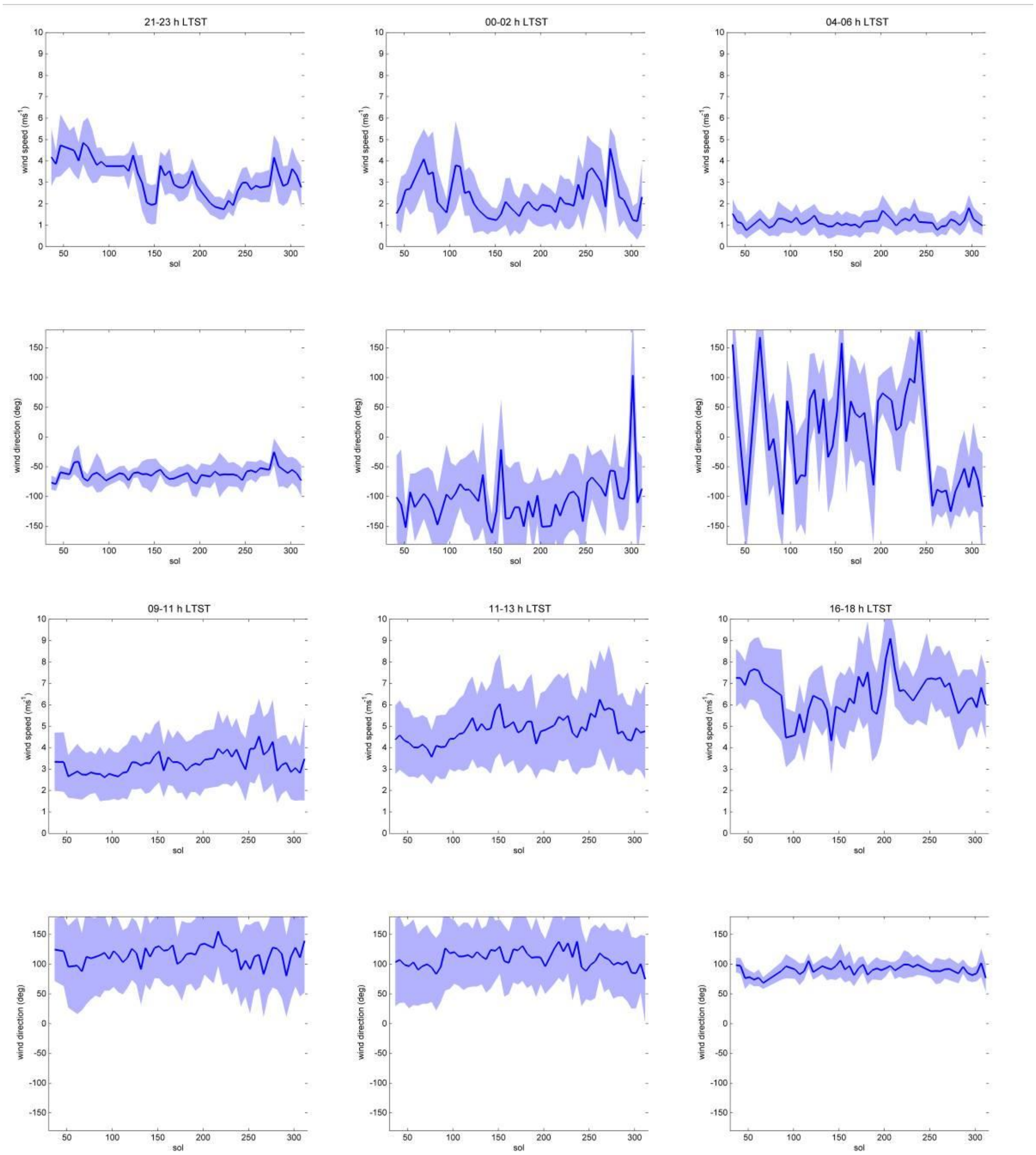


Fig. 8: Evolution in 5-sol average wind speeds and directions as a function of sol for different diurnal timeslots during the nighttime and daytime, with the ± one standard deviation shown by the light blue shading.

During midday (MD diurnal timeslot in Fig. 7), when upslope winds were developing, prevailing southeasterly winds were measured during early spring. Significant sub-hourly variability was observed mainly due to turbulent scales (see the companion paper, part 2), which included measuring northeasterly and south-southeasterly winds at certain times. These variations overwhelmed intrasol and seasonal variations (Fig. 8). Over the summer solstice, prevailing winds turned to east and east-southeasterlies. The seasonal variation of wind speeds peaked at that season (see the companion paper, part 2). During the afternoon (DL diurnal timeslot in Fig. 7), the full development of regional slope flows overwhelmed the effect of other potential mechanisms in the large-scale, maintaining roughly constant behavior in wind directions as a function of season. The low variability in wind direction that characterized this timeslot, probably due to the reduction in short term eddies as the PBL was fully developed (Section 4), was maintained as a function of season.

The nightfall (NF) diurnal timeslot in Fig. 7 (18:00-21:00) is a period of transition between anabatic upslope winds and katabatic downslope winds, and shows strong sensitivity to season. Counter-clockwise rotation started in the first sols of the mission at ~18 h LTST (sunset at ~18.25 h LTST), with northerly winds at 19.5 h LTST, and north-northwesterly winds at 22.5 h LTST as a result of local downslope winds dominating at that time. As the mission progressed, the transition began later and occurred more rapidly. Right before the summer solstice, the rotation was suddenly executed at 19 h - 19.5 h LTST (sunset at ~18.5 h LTST). Right after the solstice, the sign reversed, that is, the rotation was performed clockwise and the transition was very slow (Fig. 5). At mid-summer, the transition reversed again to counter-clockwise rotation but with longer timescales typically observed in the first sols of the mission and beginning a bit later. This seasonal behavior in the transition between upslope and downslope winds could be related to a coupled effect of Hadley cell return flow and thermal tides. In fact, more southerly winds are expected as approaching toward solstice, which is consistent with the change to a clockwise rotation. However, the different behavior between pre-solstice and post-solstice would need the effect of another mechanism acting together. As described, thermal tides produce variable tidal forcing as a function of time of day and as a function of season. We observe significant changes in the phase of the diurnal pressure mode and also a peak in the amplitude of the semidiurnal pressure mode after the summer solstice (Rodríguez-Manfredi et al., 2022; Sánchez-Lavega et al., this issue). These changes suggest disturbances in tidal flows at that season which could relate with the different behavior in the rotation at that period.

5.3 Sol-to-sol and seasonal variability in nighttime winds

West-northwesterly downslope winds were fully developed in the first part of the NL-1 timeslot in Fig. 7 (21-24 h LTST), which remained roughly constant throughout the mission and presented very little variability in wind direction, similarly to that produced with the counterpart daytime upslope winds during the afternoon. However, the longer rotation duration at midsummer from the daytime winds coincided with a slight shift in the wind directions to northwesterly winds; that is, the local downslope winds had a greater northerly component as the summer progressed. The intensity of midnight wind speeds, affecting the NL-1 and NL-2 timeslots, reduced to one half of the 4 – 5 ms^{-1} observed at the beginning of the mission. Stable atmospheric conditions during the night likely promoted the effect of topography on surface flows; and significant topographic features in the surroundings such as the delta walls and crater rims, but also M02-W (Fig. 4), could result in spatial differences in nighttime flow among rover locations as the mission progressed. In fact, extreme shifts in wind direction can be inferred from aeolian signatures in the MRO images close to the delta and in other topographical features (Fig. 4), with the delta walls producing what appears to be a channel effect in the surface flows on the area (Section 3).

However, the observed variability as the mission progressed is mostly attributed to seasonal variations (Section 3). It would include the effect of the large-scale circulation on the regional and local scale during nighttime. Convergent local downslope flows on the crater floor during NL-1 and part of NL-2 were probably competing, in the context of prevailing regional downslope flows from the west-northwest, and with local downslope flows from the east-southeast likely reinforced by M01-SE. A single cross-equatorial Hadley cell that develop around summer solstice would produce zonal-mean southerly winds near the surface; these could compete with the slope flows, reducing the intensity of the regional downslope flows in this region (northwesterly flows), in addition to local slope flows with such meridional and zonal wind components, hence enhancing the effect of east-southeasterly local downslope winds. This situation would reduce the strength of the northwesterly winds around midnight, as described earlier, and it was likely the responsible for the winds from the east-southeast observed at the Mars 2020 landing site around the summer solstice (Fig. 7, EM timeslot).

The second part of the night (NL-2 diurnal timeslot in Fig. 7, 00-03 h LTST) contains another transition in which the intensity of the downslope winds in the crater rim decreased, starting a calm period extending as late as the sunrise (Section 4). The NL-2 and EM diurnal timeslots in Fig. 7 involved the greatest wind variability observed in the diurnal cycle, both in wind direction and in the relative wind speed variability (see the companion paper, part 2). During the first sols of the mission, the local downslope flows reduced their activity well enough to produce a counter-clockwise rotation towards easterlies at the end of NL-2.

Weak easterly winds developed in some sols at the end of this timeslot, while other sols had variable winds during the calm period. Around summer solstice, the reduction in the intensity of downslope flows and the subsequent rotation to easterly winds were more established, taking place in the middle/end of NL-2. After L_s 120º, the situation was the reverse of that observed in the first sols of the mission. Some sols maintained the downslope flows more often than others. This curious effect can be seen in Fig. 8 (00 – 02 h LTST). The dramatic increases between sol 60 – 80 and between sols 110 – 120, as well as some periods between sols 250 and 280, are the result of variable downslope flows that have an influence longer into the calm period during the night and early morning (NL-2 and EM timeslots), and can be related to the lack of a competing mechanism such as the Hadley cell circulation, which is present around the summer solstice.

The EM timeslot (03-07 h LTST) in Fig. 7 involved the greatest variability due to a combined effect of intersol and intrasol variations. After L_s 120º, westerly winds developed again around 5 h LTST, but with much less intensity than those observed at midnight, before the development of upslope winds in the morning (see the DW, 07:00-10:00 LTST, timeslot in Fig. 7). As described above and in Section 4, these rich nocturnal dynamics could result from downslope flows at the eastern crater rim, possibly reinforced by downslope flows on M01-SE. Such flows, likely promoted around southern summer by the Hadley cell, would compete with the western and other crater rim flows, provoking destructive interaction by convergent flows on the crater floor, and periods with high mechanical turbulence and, hence, wind variability. The dramatic seasonal rotation observed during this timeslot (Fig. 7) suggests large-scale interference in the Jezero region circulation.

5.4 Atmospheric waves as a source of sol-to-sol wind variability

Most of the intersol variability is the result of stochastic variations produced by turbulence and interactions with the different scales. However, part of the observed intersol variability in winds can be associated with atmospheric travelling waves, possibly baroclinic. The effects of baroclinic waves were clearly observed in the Viking Lander wind data, particularly by VL-2, which landed at 48ºN, but also in VL-1, which landed at 22.5ºN (e.g. Barnes et al., 1980; 1984). These disturbances have also been observed in the InSight wind data (Banfield et al., 2020), which landed in equatorial latitudes. Mars 2020 has detected travelling waves in the pressure and temperature data (Battalio, 2021; Rodríguez-Manfredi et al., under review; Sánchez-

Lavega et al., this issue), with variable periods during the mission. MEDA wind data is constrained between L_s ~22º and L_s ~153º and have many gaps (Section 2) particularly in the first sols of the mission, which challenge the detection of travelling waves. After detailed analysis of the wind data, we are reporting the effects of travelling waves on the surface winds at Jezero.

There are several sol periods with a predominant period of oscillation; they are mostly weak and uncorrelated with pressure. However, a strong peak appears in the frequency analysis between sols 130 and 170 both for wind and pressure variables, corresponding to waves of 4.4-sol period with ~0.6 ms^{-1} amplitude both in wind speed and pressure. Fig. 9 shows the wind and pressure detrended signals (top and bottom, respectively) around sol 150 (L_s~75º, northern spring). This sol period is characterized by a clear harmonic in the signal. As noted, other sol periods show more variability and weak peaks in the wind spectra that are usually not well correlated with pressure. This could be influenced by the data gaps in the Mars 2020 wind data. However, given the gaps present in the data, it is expected that longer periods would also be affected by travelling waves.

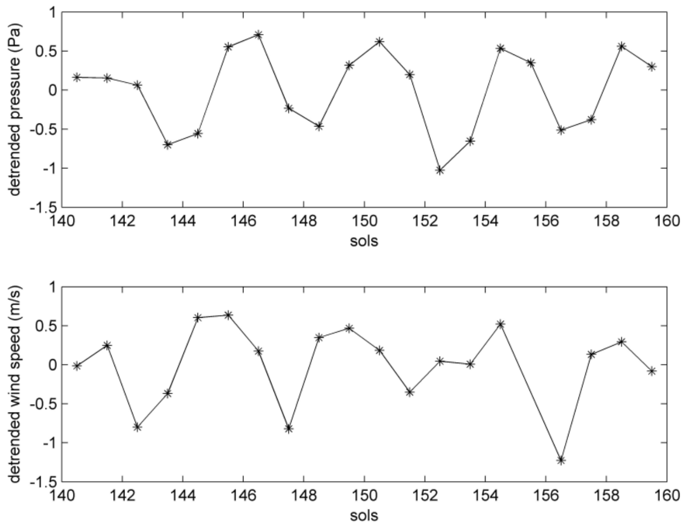


Fig. 9: Detection of oscillations probably related to travelling waves in the Mars 2020 wind data. Detrended pressure (**top**) and wind (**bottom**) signals are shown around sol 150 (northern spring), after removing the subdiurnal variation related to thermal tides, regional/local flows and other mesoscale variations, and turbulence. In addition, seasonal variations such as those produced by the CO_2 cycle are removed as well. An oscillation period of ~4.4 sols is observed both in wind and pressure data.

6. EFFECTS OF THE MY36/2022 REGIONAL DUST STORM ON THE SURFACE WINDS

An early regional dust storm (RDS) affected Mars in January 2022 (MY36, L_s~153º). The storm passed over Jezero crater on January 5 on mission sol 313, increased opacity to values greater than 1.5 on sols 314 – 317 from pre-storm values lower than 0.5, and persisted with variable opacities until sol 319 (Lemmon et al., 2022; Smith et al., 2022). This event was the most intense observed by a surface mission since the MY34/2019 large dust storm (LDS) that affected InSight's landing site at Elysium Planitia and MSL's landing site at Gale crater (Viúdez-Moreiras et al., 2020c). However, the MY36/2022 storm duration (six sols) was much shorter than the LDS duration (whose most noticeable disturbances ended a month after the first effects were observed, and high levels of dust remained in the atmosphere for several sols, see Fig. 8 in Viúdez-Moreiras et al., 2020c), more in agreement with the durations of typical regional dust storms. Pressure tides and near-surface temperatures were strongly affected at the Perseverance landing site, similar to what was observed during previous storms (e.g., Ryan & Henry, 1979; Zurek & Leovy, 1981; Wilson & Hamilton, 1996; Lewis & Barker, 2005; Guzewich et al., 2016; Viúdez-Moreiras, 2019c; 2020c). However, Perseverance was the first mission to make meteorological observations at a location with active storm dust lifting; previous missions were either not located in active dust lifting centers, did not carry meteorological sensors, and/or could not operate during a storm due to being solar powered. This enabled Perseverance to study the strong aeolian activity (both dust lifting and sand motion) associated with the storm, including the deposition of surface grains on the rover deck (Lemmon et al., 2022).

As described in Section 2, a close encounter with a dust devil on sol 313 at 13:42 LTST further damaged WS2. Two sols later (sol 315 at 14:24 LTST), WS1 also experienced damage. The MEDA WS was unavailable to provide wind data. The wind sensor was then kept off for several tens of sols, including over the remaining storm period. However, wind changes during the onset of the storm at Jezero were able to be measured.

Prior to the storm, on sols 310-311, the diurnal cycle of winds (Fig. 9) was similar to that observed throughout the mission (Section 4), with the characteristic rotation between daytime and nighttime regimes consistent with slope flow control. Winds were east-southeasterlies during the daytime, peaking in the afternoon as usual, and then started to rotate progressively at ~17 h LTST towards westerlies. Between 20 h and 21 h LTST, when winds were slowly rotating from upslope to downslope, strong winds developed with wind speeds comparable to those measured in most of the daytime (but northerlies instead of the daytime's prevailing east-southeasterlies). This increase in wind speed after sunset was observed intermittently throughout the mission, but was more pronounced after sol ~300. By contrast, nighttime winds were weaker for sols 311-314 (Fig. 10).

On sol 312, the effects of the dust storm were clearly observed in the wind data, with southwesterlies between 10 h and 11.5 h LTST rather than the usual southeasterlies observed, i.e., the zonal winds were opposite in direction to those observed under nominal conditions (outside the dust storm). Winds abruptly rotated to southeasterlies at 11.5 h and remained mostly as usual in the afternoon. On sol 313, the disturbances were more dramatic, with a smooth clockwise rotation from southwesterlies to easterlies between 10 h and ~14 h LTST, and with stronger wind speeds than usual over this period, comparable to the peak speeds typically measured later in the afternoon. Due to the damage to WS2 at that time, which caused the WS to turn off for several sols, no wind data were taken during the afternoon under storm conditions; hence the peak wind speeds during the storm may not have been captured. At night, the data extracted from the remaining operating boom suggested that downslope westerly flows were much more intense than under nominal conditions, reaching 7 ms^{-1} at midnight.

Changes to the surface wind pattern during a dust storm can arise from several different mechanisms, as discussed, e.g., in Viúdez-Moreiras et al. (2020). First, a dust storm can locally (or even regionally/globally) modify the atmospheric static stability (e.g., Zurek, 1976) and thus the coupling between winds aloft and near the surface. Second, once the dust storm has grown enough (this will also depend on its location) that it influences the large-scale pattern of solar heating, it can enhance the strength of the zonal mean meridional (Hadley cell) global circulation (Basu et al., 2006; Heavens et al., 2011; Kass et al., 2016). Third, and typically at the same stage of growth as in the latter case, it can increase the strength of thermal tides and thus tidal flows (e.g., Zurek & Leovy, 1981; Wilson & Hamilton, 1996). Indeed, such tidal enhancement has been linked to the broadening and strengthening of the summer solstice Hadley cell (Wilson & Hamilton, 1996).

At L_s 153º, the Hadley cell is transitioning from the solsticial southern winter cell to a weak, dual cell, equinoctial circulation. Simulations with the MarsWRF GCM for L_s~153º, presented in Fig. 6, show, without the effects of a dust storm, surface winds fully driven by regional slope flows on the Jezero region in the Isidis basin slopes (the simulations do not resolve Jezero crater, which presents similar local slopes at Perseverance's location (W vs. NW), hence, a similar direction in the daytime anabatic winds). Simulations suggest that winds above the PBL are northwesterlies on average on the Isidis basin northwestern slopes throughout these sols, opposing the near-surface slope flows. These results are not consistent with dust storm observations, which suggest a mechanism producing high wind speeds instead of acting destructively. The observed clockwise rotation around noon from southwesterlies to easterlies between 10 h and ~14 h LTST in sols 312 and 313 is also inconsistent with an enhanced Hadley cell circulation, which should promote a particular meridional component in surface winds, instead of variable northerlies or southerlies separated by a few hours. Conversely, changes are in agreement with what is expected by thermal tides, as was observed in previous storms. Thus, enhanced tidal flows likely affected the surface wind patterns at Jezero, producing a dramatic clockwise rotation from southwesterlies to easterlies around midday and in less than 4 hours. In fact, thermal tides were strongly affected during the dust storm. Both the diurnal and the semidiurnal pressure modes were doubled between sols 310 and 313, driving higher diurnal pressure amplitudes during this period. The changes included dramatic disturbances in phase, as is usual during these events (e.g., Ryan & Henry, 1979; Leovy & Zurek, 1979; Zurek & Martin, 1993). The further deviation in the nominal wind patterns as diurnal and semidiurnal modes enhance and storm progresses supports this hypothesis.

The nighttime regime in sols 311 - 313, before the calm period, was affected by significant low-frequency oscillations (Fig. 10 and Fig. 11), probably due to gravity waves. These oscillations were observed after the sunset, when downslope winds developed, and remained until midnight, with periods of 50±10 min, and ~0.75±0.25 m/s of amplitude in the zonal and meridional components of surface winds, with a small counterpart in pressure (~0.5 Pa) and temperature (~1 K) perturbations. Winds were, at that time, west-northwesterlies on sol 311, west-southwesterlies on sol 312 and west-northwesterlies on sol 313. Oscillations were better observed on sol 313 and in the zonal winds, likely as a result of the detrending procedure and the small relative uncertainties in the zonal component of surface winds (Fig. 11). On that sol, there was a ~15 min shift in the zonal and meridional signals, that is, they were ~90º out of phase, while the phase difference between winds and pressure was ~180º. The relatively long period of these waves suggests that the origin is not local. Neglecting Coriolis forces and assuming a linear relationship between wind and pressure perturbations at first order (Coleman & Knupp, 2010; Banfield et al., 2020), the phase speed, c, can be computed by $c = u + P'/(\rho \cdot u')$, where u is the wind speed, ρ is the atmospheric density and P' and u' are the pressure and wind perturbations, respectively. It leads to phase speeds of 26-

28 ms^{-1} and horizontal wavelengths of 70-90 km. Therefore, we suggest that the origin of these waves may be the slopes of Isidis basin, possibly due to topographical effects or wind shear between regional downslope winds and the general circulation disturbed by enhanced tidal flows. The enhancement of the wave activity during the MY36/2022 regional dust storm at Jezero agrees with data from previous missions, which showed near-surface wave activity enhancement in dust storm periods (Banfield et al., 2020; Guzewich et al., 2021). Gravity waves have a strong relevance for atmospheric dynamics including mixing of energy, momentum and species in the very stable Martian nighttime PBL during dust storm conditions, as well as in the thermal structure of the atmosphere and, hence, in circulation (e.g., Barnes, 1980; Fritts & Alexander, 2003; Heavens et al., 2020 and references therein).

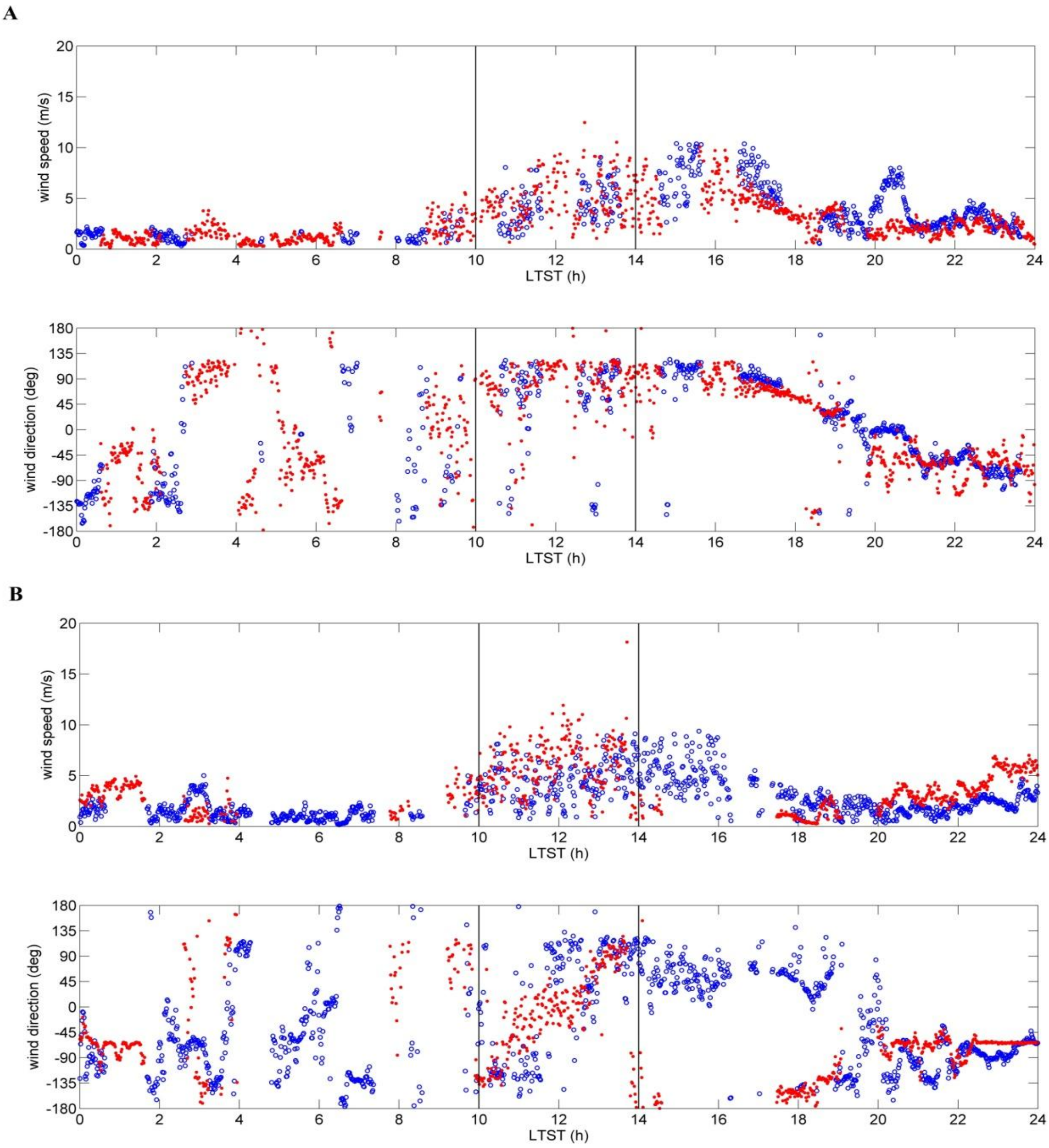


Fig. 10: Wind speed and direction (1 min averages) for (**A**) sols 310 and 311 (pre-storm conditions; in blue and red, respectively) and (**B**) sols 312 and 313 (storm onset at Jezero; in blue and red, respectively). Vertical lines show 10:00 and 12:00 LTST delimiting the period where the tidal winds were likely to produce the major change in winds during the storm. The direction from which the wind is blowing is shown, as in Fig. 5, following the standard meteorological convention; although here in a [-180,180] range to better visualize the wind rotation at sol 313.

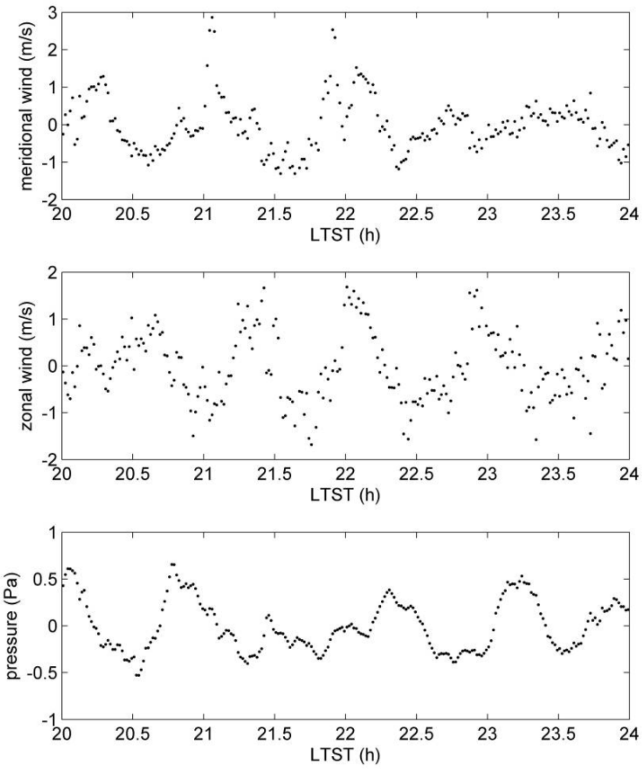


Fig. 11: Waves observed at night during the regional dust storm, while downslope flows developed in Isidis basin and Jezero crater. Time evolution is shown as a function of local true solar time (LTST). Both pressure and wind were detrended subtracting a running average of $4\cdot10^3$ s from 1-min average signals.

Sols 314 and 315, before the further damage to the WS, were mostly lost in terms of data, which was operating with only one working WS boom (pointing toward the front of the rover) and was a period when the rover heading was to the southwest, meaning that the remaining boom was unable to capture the prevailing daytime winds. However, the available data suggest that morning winds continued to be southwesterlies, as on sol 313, with maximum minute-averaged wind speeds close to 8 ms^{-1}, in agreement with previous sols. Nighttime downslope winds appeared to develop on sol 314 as usual, although the available data prevents knowing if wave activity occurred as in previous sols.

Wind speeds deserve a special mention. Summarizing what was observed regarding wind speeds during the onset of the storm at Jezero, mean winds appeared to be slightly greater during the storm than in pre-storm conditions. On the other hand, vortex activity strongly increased during the storm, particularly in early stages (Lemmon et al., 2022), and provoked a higher probability of close encounters. One of these encounters at sol 313, 13:42 LTST, produced an intense wind gust that damaged the wind sensor. This gust can be seen in Fig. 10 in the two measurements that depart from the average on sol 313. The companion paper (part 2) will detail this event.

As described, no wind data are available after sol 315 (L_s 153º) and, therefore, there is no direct information on wind patterns after the storm. Model simulations predict similar behavior in near-surface wind patterns as the season progresses (Newman et al., 2021; Pla-García et al., 2021); they differ, in general, only in the strength of daytime and nighttime winds (with daytime winds being weaker in the northern winter). However, the modeled wind directions are mostly unaffected, showing easterly and south easterly winds at midday.

Mission sol	Ls (deg)	LMST (h)	Event notes	Inferred background wind direction (deg)
323	157.9	12:50		90 ±30
327	160	12:33		135 ±15
347	170.9	12:42	The apparent motion is slight toward 305 with wobbling	125 ±15
362	179.5	15:38		100 ±20
364	180.6	12:20	Slight movement	160 ±30
365	181.2	13:08		135 ±45
368	183	12:04		90 ±45
370	184.1	11:37	Dust devils seem to converge and get closer	10 ±15
372	185.3	11:40	Multiple dust devils move away from rover	10 ±15
373	185.9	11:56		180 ±30
373	185.9	11:58	Slight movement	150 ±15
380	190	15:50	Very distant dust devils	indeterminate
383	191.8	11:40	Very distant dust devils	indeterminate
407	206.5	15:00	Sense of movement is uncertain	60 ±30 or 240 ±30
425	217.7	13:40	Nearby DD	65 ±15
472	248.1	12:25	Distant dust devil and nearby dust cloud move toward rover	120 ±15
473	248.7	12:07	Two distant dust devils converge	120 ±15

Table 2: Inferred wind direction from dust lifting events detected in Navcam surveys or movies. Mission sol, areocentric solar longitude (L_s), local mean solar time (LMST) and event notes are included together with the inferred background wind direction. The direction from which the wind is blowing is shown, following the standard meteorological convention.

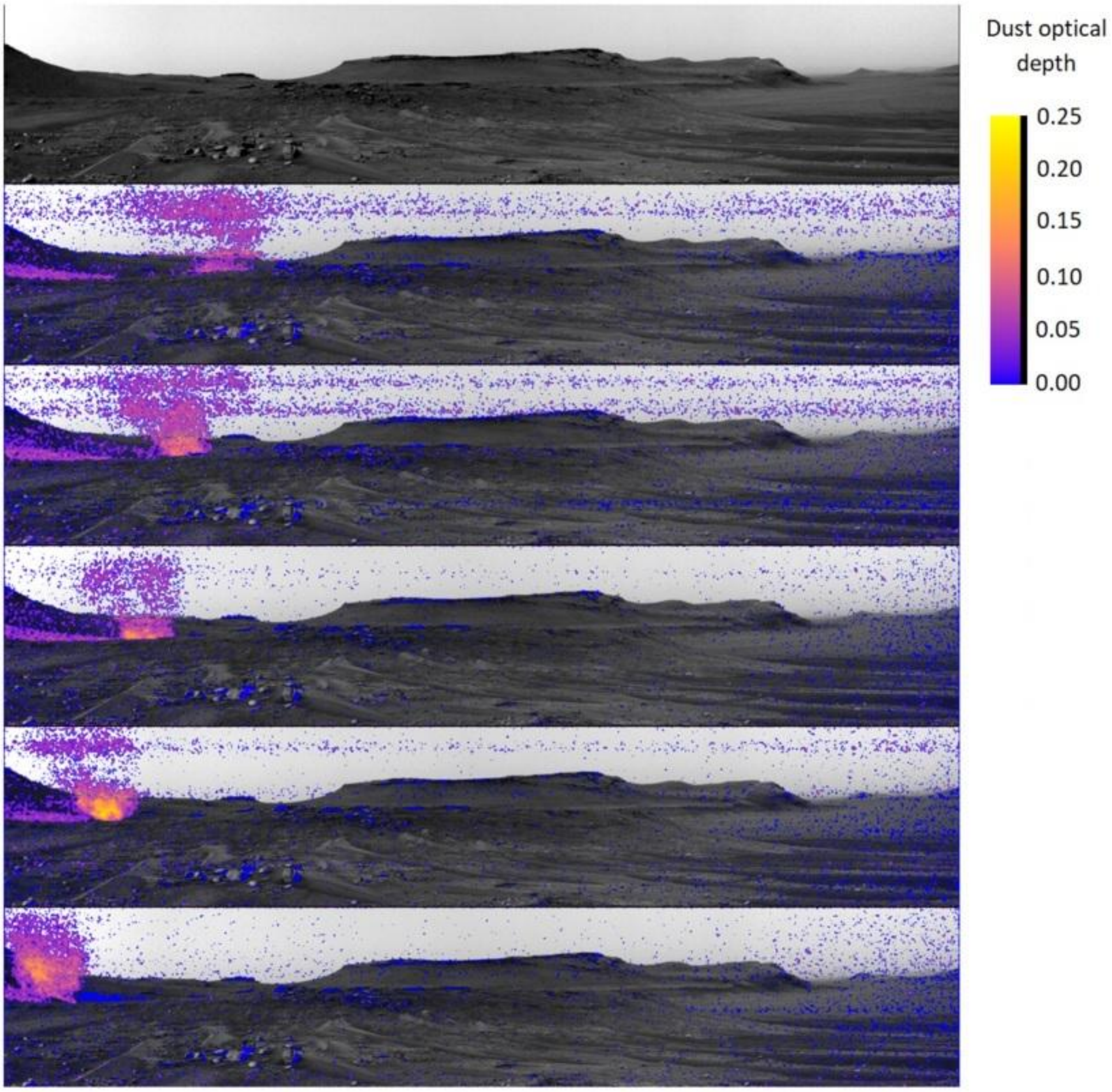


Fig. 12: Enhanced color images for the event at sol 425, corresponding with a dust devil moving WNW, 300±20 m away the rover, at 5.2±0.5 m/s. Dust optical depth is included. Delta walls are likely affecting background winds at that location, leading to west-northwesterly winds.

As described in Section 2, in the absence of a working wind sensor, surface winds may be inferred, under particular conditions, from other sensors and/or from their interaction with surface. We have attempted to obtain some information on surface winds from dust devil Navcam surveys or movies after the wind sensor damage. The wind direction estimations, acquired around noon local time or shifted to the afternoon, are presented in Table 2. It was possible to infer the DD trajectory in 15 events, from sol 323 (L_s 158º) to sol 473 (L_s 249º). The only reported events to have well-constrained distance and radial motion were on sol 425 and 472: the first, shown in Fig. 12, was a 32±3 m diameter dust devil moving WSW, 300±20 m away, at 5.2±0.5 m/s; the second was a 20-40 m length gust on sol 472 moving WNW at 14±4 m/s. The surveys showed diurnal wind directions that are consistent with the MEDA data before sol 313 and with the model simulations. On average, wind directions were southeasterlies around the fall equinox and easterlies at autumn, with significant deviations probably due to the daytime turbulence, mainly around the fall equinox. These empirical results confirm that winds continued to be slope-driven during the late summer and fall seasons. Additionally, it is likely that the topography affected the background wind patterns as the rover approached the delta walls (Section 3), as can be seen in the winds inferred from surveys near sol 400, which lead to west-northwesterly winds. It opens the possibility of expanding our knowledge of surface wind patterns with other wind indicators as the mission progresses, thus complementing the wind sensor data.

7. SUMMARY AND CONCLUSIONS

This paper presents the observed wind patterns at Perseverance's landing site, on the Jezero crater floor close to the delta of an ancient river. The contemporaneous wind measurements in Jezero have also supported the first flights of an unmanned aerial vehicle, the Ingenuity helicopter, on Mars.

The observed wind patterns at Jezero presented minor sol-to-sol variations generally overwhelmed by diurnal variations, in accordance with observations by previous missions on Mars outside the dust storm season. No significant variability was observed in the general shape of the diurnal cycle during the observation period. Conversely, a mostly repeatable diurnal cycle was measured and presented two regimes: (i) a daytime or convective regime, from dawn to sunset, with average easterly to southeasterly winds and where maximum wind speeds were measured, and (ii) a nighttime regime with a period of westerly/northwesterly winds followed by a period of relative calm until sunrise with highly variable wind directions as a function of sol and time of night. The timing and magnitude of the observed regimes is consistent with control by slope flows.

The fact that the slopes of Isidis basin and the Jezero crater western rim have a nearly similar direction complicates the discernment of which mechanism is modulating the diurnal cycle at the landing site. During the daytime, the gradual increase in wind speeds and the shift in wind direction as the daytime timeslot progressed can be interpreted as the result of the gradual and different increase in the relative strength of regional and local slope flows. During the night, the thin PBL depth maximizes the effect of smaller topographic features near the rover, therefore affecting the intensity of the regional-scale downslope winds in these areas and increasing mechanical turbulence. The Jezero region and the crater itself present significant topography that could dramatically affect the nighttime patterns in the mesoscale and in the microscale. The first part of the night, from sunset to ~01 h LTST, was characterized by quite stable westerly/northwesterly winds, peaking around midnight as a likely result of downslope winds peaking at that time, which is reproduced by pre-landing simulations. After ~01 h LTST, winds decreased in intensity and rotated counter-clockwise to roughly easterlies, with a dramatic variability during most of the nighttime. This reduction in the relative intensity of the crater rim downslope winds at the rover's location would enhance the effect of competing mechanisms, likely downslope winds at the eastern crater rim reinforced by downslope flows on M01-SE. The great sub-diurnal and sol-to-sol variability observed by Mars 2020 was consistent with an increase in mechanical turbulence caused by these convergent flows on the crater floor. The very low wind speeds observed during the early morning suggests that these flows were very weak and/or that a destructive interaction around the landing site was dominating the atmospheric dynamics, inducing a calm region on the crater floor.

Data suggest that the surface circulation at Jezero is highly unaffected by large-scale circulation, except during particular periods in the diurnal cycle or, more generally, during dust storms conditions. As a result, the seasonal variability for the winds observed by Mars 2020 between the northern spring and the summer season was weak, without dramatic variations. However, sol-to-sol and seasonal effects were observed by Perseverance rover, most of them at periods during the night. One of these particular periods in the diurnal cycle is the transition from daytime to nighttime. In the first sols of the mission, the transition from daytime to nighttime wind directions involved a counter-clockwise rotation, but this reversed to a clockwise rotation as the mission progressed. The duration of the transition was also long close to the equinoxes, lasting several hours, and sharp around the summer solstice. This seasonal behavior in the transition between upslope and downslope winds could be related to a coupled effect of Hadley cell return flow and thermal tides. Between 20 h and 21 h LTST, when winds were slowly rotating from upslope to downslope, strong winds developed, producing sometimes wind speeds comparable in some cases to those measured in most of the daytime, but with different directions from the prevailing southeasterlies. Also, nighttime downslope flows lasted variable durations. After peaking at midnight, they intermittently reached Perseverance's location in some sols of the mission, and in others the calm period was present earlier. During this nighttime period and in early morning, seasonal variations suggest large-scale interactions with the regional and local circulation.

Although the sol-to-sol variations were weak on average, travelling wave activity was observed on surface winds at Jezero. A strong peak appeared between sols 130 and 170, corresponding to waves of 4.4 sol period and ~0.5 ms^{-1} of amplitude in wind speed. Given the gaps present on the Mars 2020 wind data, it is expected that longer periods would also be affected by baroclinic instability.

An early regional dust storm (MY36/2022) affected Mars on January 2022 (L_s~153º). The optical depth in Jezero crater showed significant effects on sol 313. A close encounter with a dust devil on this sol damaged the wind sensor, and further damage on sol 315 meant that no wind data are available for the remaining storm period. However, the onset of the storm at Jezero was captured, and showed dramatic perturbations in wind directions compatible with tidal flows produced by enhanced thermal tides, and increased wind speeds both during day and night. The nighttime regime on sols 311 - 313 was affected by significant low-frequency oscillations, suspected to be from gravity waves. The relatively long period of these waves suggests that the origin is not local. We suggest that the origin of these waves may be the slopes of Isidis basin, possibly due to topographical effects or wind shear between regional downslope winds and the general circulation disturbed by enhanced tidal flows. The enhancement of wave activity during the regional dust storm at Jezero agrees with results of previous missions and is highly relevant for atmospheric dynamics including mixing of energy, momentum and species in the nighttime PBL during dust storm conditions.

There are no wind data after the storm at L_s 153º. In the absence of a working wind sensor, surface winds may be inferred, under particular conditions, from other sensors and/or from their interaction with surface. We have attempted to obtain some information on surface winds from dust devil movies (DDMs) taken by the rover's cameras. On average, wind directions were southeasterlies around the fall equinox and easterlies in autumn. These empirical results confirm that winds continued to be slope-driven during the late summer and fall seasons, opening the possibility of extending the wind dataset with other wind indicators as the mission progresses. Additionally, it is likely that the topography affected the background wind patterns as the rover approached the delta walls.

DATA AVAILABILITY AND OPEN RESEARCH

The data used in this work are publicly available in the NASA's Planetary Data System (PDS) (https://pds.nasa.gov/).

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