The Atmosphere of Mars as Observed by InSight

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The atmosphere of Mars is thin, though rich in dust aerosols, and covers a dry surface. As such, Mars provides an opportunity to expand our knowledge of atmospheres beyond that attainable from Earth's. The InSight (Interior exploration using Seismic Investigations, Geodesy and Heat Transport) lander is measuring Mars's atmosphere with unprecedented continuity, accuracy, and sampling frequency. Here we show that InSight unveils new atmospheric phenomena at Mars, especially in the higher-frequency range, and extends our understanding of Mars' meteorology at all scales. InSight is uniquely sensitive to large-scale and regional weather and obtained detailed in-situ coverage of a regional dust storm on Mars. Images have enabled high-altitude wind speeds to be measured and revealed airglow – faint emissions produced by photochemical reactions – in the middle atmosphere. InSight observations have shown a paradox of aeolian science on Mars: despite having the largest recorded martian vortex activity and dust devil tracks close to the lander, no visible dust devils have been seen. Meteorological measurements have produced a catalogue of atmospheric gravity waves, including bores (soliton-like waves). From these measurements, we have discovered martian infrasound and unexpected similarities between atmospheric turbulence on Earth and Mars. We suggest that the observations of Mars's atmosphere by InSight will be key for prediction capabilities and future exploration.

The atmosphere of Mars has an average pressure 0.6% of Earth's. It lacks moist convection but responds strongly to airborne dust heating. Mars' unique atmospheric regime offers the opportunity to study meteorological phenomena from the planetary scales (thermal tides, baroclinic instability, dust storms) to the regional scales (slope winds, gravity waves) and the local scales (turbulence), all of which are expected to be stronger than on Earth[1]. Mars also has unearthly characteristics, such as the main atmospheric component, CO_2, condensing on the martian polar regions[2] and in the middle atmosphere[3].

Outstanding questions about Mars' atmosphere remain open. What is the subtle balance of phenomena accounting for the atmospheric variability at a given location on Mars? How is dust lifted from the surface? How can we use Mars as a laboratory to explore key meteorological phenomena on Earth? To address those questions, *in situ* temporal coverage at Mars' surface is crucial to provide ground truth for martian atmospheric models and to supplement orbital observations, which at a given location on Mars provide infrequent coverage and sense mostly the middle-to-upper atmosphere. Previous lander missions conducted atmospheric measurements at the surface of Mars[4,5], yet no continuous measurements by a high-sensitivity meteorological station able to monitor atmosphere processes across a range of scales, from large-scale weather to small-scale turbulence, have been performed.

After successful entry and descent (Figure 1a), the InSight mission landed at 4.5°N 135.6°E in Elysium Planitia on Mars in northern winter (Extended Data Figures 1 and 2). The first 200 martian solar days (sols, 88775 s) of atmospheric measurements demonstrate how InSight can both unveil atmospheric phenomena never measured at the surface of Mars and explore known phenomena with a fresh perspective. The InSight lander is the first continuously operating weather station at the surface of Mars (Figure 1b) and the first to feature a high-frequency high-precision pressure sensor[6,7] (see *Methods*). Moreover, InSight's wind measurement capabilities, with two operating medium-frequency wind sensors, are only matched by those of the Viking landers; quantitative wind measurements on board all other previous missions[4] were either lacking[8], at low sampling frequency[9], or made difficult by damage during landing on Mars[10]. New perspectives for atmospheric science are also opened by using the wind- and pressure-induced "noise" in the signal acquired by the InSight SEIS seismometers[7,11,12].

1 Large-scale atmospheric phenomena

Mars has daily weather variations, as evidenced from landers[9,13] and orbiters[14], resulting from mid-latitude planetary waves, caused by baroclinic instability related to seasonal equator-to-pole temperature gradients. Contrary to Earth, the behaviour of the martian atmosphere in the mid-latitudes is simply governed by alternating dominant baroclinic modes, for reasons still unclear[15]. Surprisingly, InSight's high-sensitivity tropical pressure measurements are a valuable reference to study baroclinic instability in the mid-latitudes. When seasonal and diurnal trends are removed from InSight's pressure and wind measurements (Figure 3), a clear 2.5-sol-period wave pattern is detected in the first 40 sols of the mission, corresponding to the peak amplitude of northern winter's mid-latitudes' transient waves[16], later changing to a 5-6-sol period at the end of northern winter and a 4-sol period in northern spring (see Extended Data Figure 3). Baroclinic waves at equatorial latitudes were previously detected using Curiosity data[17], but by comparison the InSight measurements, with improved sensitivity and continuity, are remarkably clear and regular.

In Mars' thin, sunlight-controlled atmosphere, weather is impacted by airborne dust. InSight is the first wind-measuring weather station, since the Viking landers forty years ago[18], to experience the impact of a regional-scale dust storm. The storm started on the other side of Mars[19] before spreading dust around the planet and doubling the atmospheric dust optical depth at InSight between sols 40 to 50 (Figure 1c). Consequently, and as expected from theory[1], the diurnally-repeating pressure variation increased as both the diurnal and semi-diurnal tidal components amplified. In addition, the diurnal cycle of wind direction changed from a small angular fluctuation, to a complete counterclockwise rotation over a sol (Figure 2d). During this regional dust storm, the synoptic variability in pressure and wind (Figures 3a and 3b) was deeply impacted and transitioned from a well-identified 2.5-sol mode to longer-period modes (7- to 10-sol periods, Figure 3 and Extended Data Figure 3b). This transition is thought to act as a negative feedback for the development of dust storms on Mars[20,21].

InSight's ability to monitor meteorological phenomena at larger horizontal scales than its immediate surroundings also includes the vertical dimension for middle-atmosphere processes through color imaging capabilities. InSight's cameras, operating just after sunset, observed noctilucent clouds[3,8] at the transition between northern winter and spring (Figure 1d). Given the position of the Sun, these clouds must have been at least 50 kilometers above the surface to be illuminated. Past orbital detection of mesospheric clouds at this altitude and season suggests either water-ice or carbon-dioxide-ice clouds[22,23]. Cloud motions indicate east-southeasterly wind speeds of 40-60 m/s assuming 60 km altitude – an altitude at which wind speed has seldom been evaluated on Mars[24,25]. Furthermore, nighttime imaging showed that sky brightness persisted long after twilight, not attributable to moonlight. The relative contributions in the IDC's color filters were consistent with a 577.8 nm airglow of order 10 Rayleighs. This airglow, produced by photochemical reactions in the upper atmosphere, was expected but never previously confirmed on Mars[26].

2 Diurnal and sub-diurnal variability

Mars, with its uniquely low average surface pressure, highlights an end-member case of sunlight control of the diurnal cycle, particularly as compared to Earth. This causes on Mars: 1. atmospheric thermal tides an order of magnitude stronger,[27], especially in low-latitudes; 2. more sustained daytime upslope / nighttime downslope flows[28], especially over steep slopes[29]; 3. a much sharper contrast between the strong daytime, buoyancy-driven, convective turbulence and the moderate nighttime, shear-driven, mechanical turbulence[30].

InSight's atmospheric measurements allow this picture, drawn from existing observations, to be refined. Consistent with previous measurements[2,31] and modeling[7,32], InSight has recorded a diurnally-repeating cycle of pressure (Figure 2a) showing the major impact of diurnal and semi-diurnal thermal tides on the martian atmosphere. This makes thermal tides the best candidate to explain the large diurnal deviation in wind direction, recorded by InSight's wind sensors (Figure 2d) and consistently inferred by SEIS seismometers from wind-induced perturbations. Nevertheless, despite the fact that InSight landed on a nearly-flat plain, the diurnal cycle of wind direction measured by InSight appears to be due primarily to flows induced by the nearby gentle regional slope rather than thermal tides. Afternoon winds are upslope (from NE) and nighttime winds are downslope (from SW), except when the prevailing large-scale winds from NW are strong enough to dominate (Figure 2d). While global climate modeling using realistic topography reproduces these diurnal winds, artificially flattening the local plains around InSight in the model causes them to disappear (Extended Data Figure 4).

Gravity waves, which have buoyancy as their restoring force, are the dominant process governing the variability in planetary atmospheres at regional spatial scales and timescales of several hundred seconds[33]; their propagation and breaking also impacts large-scale wind and temperature in the upper atmosphere[34]. Both gravity wave oscillations, with vertical wavelengths of a couple kilometers[35], and dry adiabatic layers at mesospheric altitudes 60-70 km, denoting gravity-wave breaking and subsequent heat mixing, are detectable in the temperature profile acquired during InSight's entry, descent and landing (Figure 1a). On the detection of gravity waves, the continuous fine-sensitivity coverage by InSight's pressure sensor fills a gap left by previous studies: orbital observations can only provide infrequent coverage at a given location[36,37] and *in situ* observations are limited to the specific setting of Curiosity[5,38] within Gale Crater whose nearby rims are the likely wave source[39]. Located in the flat plains of Elysium Planitia, the InSight pressure measurements exhibit numerous examples of 300-800 s gravity-wave pressure fluctuations from early evening to late at night (Figure 4a), sometimes reaching 2 Pa peak-to-peak. Furthermore, in rare instances in the middle of the night, InSight captured yet undetected simultaneous and coherent gravity-wave fluctuations of pressure and wind with long periods $\sim$1500 s and estimated horizontal wavelengths $\sim$25–35 km and phase speeds $\sim$15–25 m/s (see *Methods* and Extended Data Figures 5 and 6). InSight demonstrates convincingly that the gravity-wave activity 1. systematically peaks in the evening and early night; 2. appears absent in daytime; 3. is highly variable from one sol to another; 4. undergoes significant seasonal variability: for instance, two successive wave trains often detected each sol from sol 120 to 150 are followed by almost no detected waves from sol 150 to 200. The intense gravity-wave activity at the InSight landing site, far from any topographical obstacles, indicates that waves either originate from strong winds interacting with sharp topographic features at particularly large distances, or that non-orographic sources (e.g., jet acceleration, convection) are involved.

In the decaying phase of the sol-40 regional dust storm, InSight detected for the first time on Mars a signal reminiscent of terrestrial atmospheric bores and solitary waves (Figure 4b), caused on Earth by the propagation of a cold front leading e.g. to "Morning Glory" clouds[40]. On Mars, modeling studies have proposed bores as an explanation for enigmatic elongated clouds[41] and hydraulic-jump analogs of low-latitude bores as instrumental for the migration of water-ice in martian polar regions[42]. During the regional dust storm, InSight's pressure sensor detected a sharp increase of the pressure slope with time, occurring every sol in early evening which then grew into pressure "bumps" in the storm's decaying phase. The pressure bumps reached a maximum of 4 Pa, occurring later and later every sol (for reasons not yet understood) before decreasing and disappearing at the end of the dust storm disturbance (Figure 4b). They were followed by 900-s-period fluctuations of pressure and air temperature as well as changes in wind speed and direction. For InSight, the density current causing the bore could be katabatic drainage flows coming from the slopes of Elysium Mons and/or the dichotomy boundary. Dust storm conditions on Mars reinforce the nighttime low-level jet[43]: this is known to be a near-surface trapping mechanism for wave energy conducive to bores[44]. Pressure jumps in the morning were also observed on at least one sol after the complete decay of the dust storm, suggesting bores might also occur in clear seasons.

Atmospheric oscillations at higher frequencies than gravity waves belong to the acoustic regime, never explored on Mars prior to InSight. Benefiting from unprecedented fine-sensitivity and high-frequency coverage, InSight's pressure sensor revealed coherent oscillations that are candidates for infrasound – acoustic waves at frequencies less than $\sim$20 Hz which may propagate over large distances[45]. The first type of candidate infrasound includes, embedded within a 300-500 s gravity wave signal, additional 80 s-period nighttime pressure oscillations (Figure 4c) slightly below the lower-limit gravity-wave period of $\sim$100 s in the observed conditions. The second type of candidate infrasound are pressure oscillations with a period of $\sim$0.8 s occasionally found within the pressure minimum of daytime convective vortices (Figure 4d).

3 Turbulence studies

Convective vortices are key phenomena during the daytime turbulent regime and termed dust devils if their dust content makes them visible. InSight is the most active site for convective vortices visited thus far by a spacecraft carrying a pressure sensor. About a thousand sudden pressure drop events deeper than 0.5 Pa corresponding to convective vortices were detected in InSight's first 220 sols (Figure 5a). InSight detected about twice as many vortices per sol as Pathfinder[46] and up to five times as many as Phoenix[47] and Curiosity[48], accounting for their respective temporal coverage (Figure 5b). This strong vortex activity caused ground deformations recorded in seismic measurements[49,50] and provided a natural seismic source to probe the first few meters below the surface[11] – magnetic signatures being ambiguous[51]. On sol 65, when a 9-Pa pressure drop passed over the lander (the strongest convective vortex measured to date on Mars), InSight recorded a sudden 1% increase in solar power (Figure 5c), putatively caused by dust being removed from the solar panels, and imaged clumps of particles that had moved on InSight's WTS. Orbital HiRISE imaging[52] of $\sim$100 km^2 around the InSight landing site has also revealed tens of newly-formed dust-devil tracks in a short 5-sol window after InSight's landing when intense vortex activity was detected by the pressure sensor. The inferred production rate for these tracks is $\sim$0.57 tracks/sol/km^2, an order of magnitude larger than pre-landing predictions[53]. Sol-to-sol linear or curvilinear changes in surface brightness have also occasionally been seen by taking ratios of InSight images at similar illumination[54].

Nevertheless, InSight shows that mobilization of dust particles from the surface is a subtle process. During the strongest wind gust recorded by InSight's wind sensors ($\sim$ 24 m/s on sol 26), no associated motion of dust particles could be robustly demonstrated. Furthermore, not a single dust devil has been imaged from the ground in the first 200 sols of the mission, despite hundreds of mid-day ICC and tens of IDC images (including periods with many vortex pressure drop detections) having been analyzed. If vortices lifted dust as often at InSight as at, e.g., the Spirit landing site[55], at least several dust devils (if not dozens) should have been imaged. The formation of dust devil tracks means that at least enough dust is being lifted by vortices to change the surface albedo. Yet it appears that either the amount of dust lifted is insufficient to produce dust devils visible to InSight's cameras, which would differ from other sites with similar (or even far less) vortex activity, or that InSight has simply missed seeing them due to the timing and number of observations made to date. On a more general note, InSight's potential to contribute to aeolian science will be fully expressed with a coverage over a full martian year of wind speeds, pressure drops, and surface change images[56].

The repeated continuous measurements by InSight, both atmospheric (Figure 2) and seismic[12,57], strongly suggest, in addition to the two aforementioned previously known daytime / nighttime turbulent regimes, the existence of a new, third “quiet” regime: both the ambient and turbulent wind speed are systematically extremely low about 2-4 hours after sunset (Figure 2b and Extended Data Figure 8), following the collapse of daytime turbulence. This has remained elusive in previous measurements lacking InSight’s resolution and continuity[4]. The transition from the daytime convective regime to the evening quiet regime is very abrupt, much more than what could be experienced on Earth, and results from the efficient radiative cooling of the surface and the near-surface martian atmosphere at sunset – interestingly, during the dusty sols 40-90, not only is daytime turbulence reduced (Figure 2b) but also the quiet regime is less clearly defined (Extended Data Figure 8). The later transition from the evening quiet regime to the nighttime shear-driven regime is more gradual: it corresponds to the onset of the nocturnal low-level jet[28,43]: as the nocturnal thermal inversion develops, the winds above become decoupled from the surface and the decrease in friction produces a net acceleration. Interestingly, a quiet regime akin to the evening regime is occasionally also observed a couple of hours before sunrise. The quiet regime identified by InSight has proven to be of paramount importance for seismic detection. The atmosphere is the major source of seismic noise on Mars[11] so strong ambient wind and/or strong turbulence significantly increases the detection threshold for Mars quakes[12]. As a result, the vast majority of seismic events are detected specifically during the quiet regime.

The InSight pressure measurements at high frequency yield novel results for turbulence compared to existing studies on Mars[30,58]. Nighttime high-frequency fluctuations of pressure, wind and air temperature, are found by InSight to be typically two to ten times smaller than in the daytime regime (Extended Data Figure 8a). Significant sol-to-sol variability in the intensity and peak timing of nighttime turbulence is experienced at InSight, the most remarkable phenomenon being the irregular occurrence of “pressure bursts” in the high-frequency 2-10 Hz range (Figure 6a), which show no correlation with any instrument artefacts or lander events. Such intermittent turbulence is also found on Earth in peculiar highly-stable and low-ambient-wind conditions[59], which are also met during the InSight pressure burst observations.

Mars is an interesting laboratory to study daytime turbulence on a purely theoretical basis: compared to Earth, the martian daytime turbulence is characterized by a stronger radiative control, a lack of latent heat forcing, and a reduced inertial range[60]. The high-frequency pressure measurements performed by InSight during numerous sols in this much different martian environment can be compared to turbulent pressure spectra measured on Earth[61,62], which contradict the inertial subrange predictions for pressure by the classical Kolmogorov theory. The power spectral density of pressure measured by InSight in daytime (Figure 6b) can be described consistently for frequencies f from 5×10^{-2} Hz to 2 Hz with a power law f^{α} such that α = -1.7. Despite the environmental differences between Mars and the Earth, this exponent slope retrieved by InSight is remarkably similar to exponent slopes α from -1.5 to -1.7 retrieved on Earth. Hence, both the terrestrial and martian measurements concur to show that the -7/3 ($\simeq$ -2.33) slope expected for pressure from the Kolmogorov theory[63] is not supported by *in-situ* observations. This strongly suggests that, contrary to wind and temperature, a combined influence of local turbulence and larger-scale variability is needed to account for high-frequency pressure fluctuations[62].

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Authors do not have any competing financial interest.

Author Contributions

D. B. and A. Sp., as equally-contributing lead authors, led the investigations described here within the InSight Atmospheres Science Theme Group, carried out the analysis reported in this paper on all topics, submitted event request proposals related to atmospheric science, and wrote the paper. C. N., F. F., D. V.-M., E. M., S. R. L. analyzed InSight meteorological data to support large-scale weather studies. M. L, R. L., J. N. M., A. Ma. analyzed InSight imaging and solar array data to support dust aerosol and cloud studies. N. Mur., J. P.-G., R. G., L. M., B. K., L. R., R. W. S., D. M., K. H. analyzed InSight meteorological data to support turbulence, gravity wave and infrasound studies. P. L., N. T., T. K., J. B. McC., A. St., T. W., W. T. P., E. B. analyzed InSight seismic data and submitted event request proposals to support atmospheric science, especially related to turbulence. O. K., B. V. H. analyzed InSight Entry, Descent and Landing data to retrieve the entry profile. J. C., S. C. S., S. C., D. G. routinely analyzed InSight seismic and pressure data within the Mars Quake Service to detect atmospheric events. C. P., S. R., I. D., A. J., A. Lu. analyzed HiRISE images to support dust devil tracks studies. N. Mue., T. P. analyzed InSight radiometer surface temperature measurements to support atmospheric science. C. C., M. G., M. B., V. A. analyzed InSight imaging and wind data to support aeolian science studies. C. L. J., A. Mi., C. T. R. analyzed InSight magnetometer data to support studies of atmosphere-induced magnetic signatures. L. M.-S., S. N., J. T., A. Le., A. Mo., M. M.-J., J. G.-E., V. P., J.-A. R.-M. produced the wind and temperature data from TWINS raw measurements and provide guidance on interpreting those measurements. B. T. C. and S. S. built the Mars Weather Service interface used by the team to explore the InSight meteorological data. W. B. B. and S. E. S. lead the InSight mission and helped to place this study in the broader context of the whole InSight mission. All listed co-authors contributed to the investigations, manipulated part of the InSight data reported in this paper, and provided comments in the writing process of this paper.

Methods

Mars calendars and times The Mars-Sun angle, named the solar longitude L_s in degrees (°), is used to indicate seasons on Mars: 0° corresponds to northern spring equinox, 90° to northern summer solstice (aphelion season), 180° to northern fall equinox, 270° to northern winter solstice (perihelion season). One solar day on Mars, named a sol, lasts 88775 seconds. A Mars solar year is about 1.9 Earth years, or 668.59 sols. InSight landing on November 26th, 2018 corresponds to InSight sol 0. Extended Data Figure 2 indicates the correspondence between InSight sols and solar longitude L_s. Mars Local Mean Solar Time (LMST) is measured by using a 24-hour "Mars clock", in which the timing of local noon undergoes a seasonal variation up to fifty minutes. Mars Local True Solar Time (LTST) indicates the sundial hours: noon always corresponds to a zenith position of the sun in the sky.

Atmospheric profiles during entry, descent and landing InSight's entry, descent and landing trajectory and associated atmospheric structure has been reconstructed using data from its accelerometers and gyroscopes, following a method similar to the one developed for Phoenix's entry, descent and landing trajectory[66]. Details of the method are provided in section 3.1 of the pre-landing paper[7].

Pressure measurements The pressure sensor on board InSight samples at 20 Hz with a noise level of 10 mPa $Hz^{-1/2}$ from 0.1-1 Hz rising to 50 mPa $Hz^{-1/2}$ at 0.01 Hz, respectively one order of magnitude higher frequency and two orders of magnitude finer resolution than previous instruments sent to Mars[4,6]. The pressure sensor communicates with the ambient atmosphere through an inlet tubing[6] specifically designed to minimize the effects of wind on the pressure measurements. Nevertheless, the variance of the pressure signal measured by InSight at frequencies above 2 Hz is sometimes correlated with wind speed, potentially pointing towards either a loss of effectiveness of the pressure inlet at such frequencies, or mechanical or electrical noise within the pressure sensor; as a result, although future work might extract useful information from the pressure measurements above 2 Hz, our discussions are based only on frequencies below this limit (see e.g. Figure 6b). A notable exception is the occurrence of nighttime high-frequency pressure bursts reported in Figure 6a which are not correlated with wind speed.

Wind and temperature measurements The Temperature and Wind for InSight (TWINS) sensor booms, based on the same principle as those on board the Curiosity rover[67], face outward over InSight's two solar panels at $\sim$ 1.2 m from the surface (respectively 121.5 cm and 111.5 cm from the surface for the west and east booms, due to InSight's tilt) to acquire wind and air temperature at a frequency of 1 Hz and an accuracy of $\sim$ 1 m s^{-1} for wind speed, 22.5° for wind direction, and 5 K for temperature. Wind speed and direction are reconstructed given the measurements of the two booms, the position of each boom compared to the prevailing wind, and corrections of the influence of lander elements on the retrieved wind, as obtained from computational fluid dynamics simulations. Details on wind measurements are provided in the pre-landing references[6,7]. Wind retrievals are not reliable for Reynolds numbers $Re \lesssim 50$, and sometimes questionable for $Re \lesssim 90$, corresponding to wind speeds respectively of 1.8 and 2.8 m s^{-1} at the pressure / temperature conditions experienced by InSight.

The air temperature measurements are perturbed from measuring a clean, true air temperature measurement due their close proximity to the lander itself (e.g., from ultra-cooled solar panels during the night) and their non-negligible radiative cross-section. When winds and convection are strong, the advective heat transfer to the sensor dominates, but when winds are low, radiative effects are more significant. Discrepancy from modeling suggests that these perturbations may reach as high as 10-15 K. The air temperature measurements by TWINS appear to be not perturbed equally at different local times: in daytime, differences between the two booms are very high, while at night, measurements by the two booms are close to one another but exhibit a spurious offset yielding air temperatures unphysically colder than the surface temperatures retrieved by InSight's radiometer. Further work is warranted to fully understand this issue.

Measurements by major InSight instruments of interest for atmospheric science The InSight instrument suite for atmospheric science also includes a radiometer within the Heat Flow and Physical Properties Package (HP^3) to measure surface brightness temperature[56 68]. For the first time on Mars, In-

Sight includes the ability to use the wind- and pressure-induced perturbations from seismic measurements by SEIS (Seismic Experiment for Interior Structure) for atmospheric science[7,11,12,57] with (since sol 66) the Wind and Thermal Shield (WTS) covering InSight's seismometer where it sits on the surface. The description of the methodology developed for seismic data is included in the SEIS companion papers[11,12].

Imaging *in situ* and from orbit The two cameras on board InSight[69] (the Instrument Deployment Camera, IDC, on the forearm with a 45° field-of-view and the Instrument Context Camera, ICC, just below the deck with a 180° field-of-view) can image the sky to perform regular dust opacity estimates (the method is detailed in the section 3.3.2 of the pre-landing reference[7]) and occasional surveys for dust devils and clouds. The reported HiRISE (High Resolution Imaging Science Experiment) images have the following references: ESP 057939 1845 (December 6th 2018), ESP 058005 1845 (December 11th 2018), ESP 060695 1845 (July 8th 2019). A simple ratio is performed between co-registered HiRISE images to bring out new surface changes such as dust devil tracks. Then, both manual mapping, and semi-automatic track detections using the radon transform technique, are performed to characterize the main track properties (e.g. azimuth, distance to lander, width, etc).

Noctilucent clouds The noctilucent clouds were found in a set of images taken after sun had set at the lander (around 18:30 local time), but the terminator still intercepted the atmosphere at an altitude of 50 km. The fact that the clouds were illuminated yields their height of at least 50 km. The images were map projected onto a spherical shell 50 km above the mean surface level and the motion of discrete features was measured in the projected image.

Airglow detection The airglow detection was made in a series of 4 IDC images taken from 22:06 to 22:47 local true solar time on sol 126, with the Sun roughly 60 degrees below the horizon. The images had 5 minute exposure times, and were dark corrected and co-added. The shadow of the scoop was clearly visible, demonstrating the existence of skylight as opposed to unmodeled dark current. The relative brightness of the excess light in the three broadband color channels of InSight's cameras was not diagnostic, but was consistent with a 577.8 nm emission, and not consistent with starlight or moonlight.

Dust devil imaging non-detection As of sol 200, 655 ICC images were taken with the Sun up; of these, 278 were taken with the Sun above 45 degrees, and 443 were taken over 11-17 LTST. At least 10 of the ICC images were taken within 5 minutes of a vortex with a recorded pressure drop >1 Pa. We examined ratios of these images to images that were nearby in a metric that combined time of day (for illumination) and sol (for dust on the optics). No features were seen at the percent level for high compression quality images (the large majority) or at the several percent level in low-quality images. In addition, 333 IDC images including the horizon were examined, of which 90% were taken from 11 to 17 LTST and half were taken with the Sun above 45 degrees elevation. These were primarily aimed to the SSE to SSW, with eastward directions rarely sampled. Similar processing, using an average of sky images for comparison, yielded no dust-devil-like features at sub-percent levels.

Atmospheric modeling The predictions by global climate modeling used for this study are referenced in section 2.2 of the pre-landing paper[7]. The method used to extrapolate the wind speed from the first model levels above the surface to the level of the TWINS measurements uses the formalism described in section 6.1 of the pre-landing paper[7]. The global climate model simulation with flattened topography mentioned in the text and presented in Extended Data Figure 4 was carried out in the exact same setting defined in the pre-landing paper[7], except for a flattening of the topographical slopes over a box 10° of latitude and longitude centered at the InSight landing site.

Signal processing To perform low-pass or high-pass filtering of the signal, time series of InSight measurements are smoothed using a one-dimensional convolution approach with a Hanning window, as is described in the cookbook of the `scipy` Python package `https://scipy-cookbook.readthedocs.io/items/SignalSmooth.html`. The spectral analysis carried out in this paper uses the wavelet approach adapted to atmospheric science described in the reference study on this topic[70] with details included in `http://paos.colorado.edu/research/wavelets` (the Python version adapted by Evgeniya Predybaylo is used in this study). Detailed information on the codes used for analysis in this paper are provided in the *Code availability* section.

Seasonal variations of pressure Carbon dioxide (CO_2) is the main component of the martian atmosphere and surface pressure on Mars varies on a seasonal basis up to 30% as a result of condensation / sublimation of the CO_2 in martian polar regions[2]. Over the timespan of about a quarter of a martian year covered by initial InSight measurements, the general pressure trend is a long-term decrease in northern winter caused by condensation of CO_2 in the northern seasonal polar cap, followed by an increase due to sublimation in northern spring. This evolution closely follows the Viking observations forty years ago, once corrected for topography and atmospheric dynamics[7 71].

Diurnal cycle of wind direction The InSight wind measurements indicate northwesterly wind in northern winter, slowly transitioning in northern spring to southeasterly wind only in daytime (Figure 2d), consistent with dust devil tracks and ripples in Elysium Planitia[53 72]. The measured wind behavior confirms the pre-landing predictions by global climate modeling[7] in the Elysium Planitia region, pointing to the combined influence of Hadley cells and western boundary currents, two key phenomena also controlling Earth's large-scale winds in the subtropics.

Gravity wave analysis Simultaneous detection of gravity-wave oscillations of pressure and wind by a surface weather station enables the horizontal wavelength of the putative gravity wave to be estimated[73]. The range of periods detected by InSight (less than half a martian hour) corresponds to high-to-mid-frequency gravity waves for which the Coriolis influence is negligible – an approximation also ensured by the equatorial position of InSight. In those conditions, according to the polarisation equations[33], the pressure perturbation p' is related to the wind speed perturbation V' by the "impedance relation"[73,74]

$$V' = \frac{p'}{\rho_0 \, (c - V)}$$

where ρ_0 and V are respectively the ambient density and wind speed, and $c = \omega/k = \lambda/T$ is the phase speed of the gravity wave with (ω, T) the frequency / period and (k, λ) the horizontal wavenumber / wavelength. Oscillations of pressure and wind are simultaneously detected only in rare cases (4 to 5 clear-cut cases) in the first 200 sols of InSight measurements; oscillations are more distinctively detected in wind direction than in wind speed. The wave packets identified in pressure and wind on sols 142 and 150 are included as representative examples in Extended Data Figures 5 and 6. The gravity-wave period is found to be similar both in the pressure and wind time series; zonal wind, meridional wind, and pressure are either in phase or 180° out of phase, which is compliant with polarisation equations in the case of high-to-mid-frequency gravity waves (conversely, wind components in low-frequency inertio-gravity waves would be 90° out of phase). Once the period T is determined, the knowledge from InSight measurements of p' and V', as well as the ambient wind V, leads to the horizontal wavelength λ through the impedance relation (ambient InSight measurements of pressure and temperature yields ρ_0 = 0.02 kg m^{-3}). Horizontal wavelengths of 25 km and 33 km and phase speeds 17 m/s and 22 m/s are respectively found for sol-142 and sol-150 nighttime wave packets. We checked that the non-linear version of the impedance relation[74] is not necessary since, in the cases studied here, the following linear approximation holds

$$\rho_0 \frac{V'^2}{2} \ll p'$$

Data Availability

The raw to calibrated data sets of InSight are available via the Planetary Data System (PDS). Data are delivered to the PDS according to the InSight Data Management Plan available in the InSight PDS archive. Data from the APSS pressure sensor and the temperature and wind (TWINS) sensor referenced in this paper is available from the PDS Atmospheres node. The direct link to the InSight data archive at the PDS Atmospheres node is: `https://atmos.nmsu.edu/data_and_services/atmospheres_data/INSIGHT/insight.html`. Other data used in this paper are available from the imaging node (ICC and IDC images) and the geosciences node (SEIS and HP3) of the PDS. SEIS data is also available from the Data center of Institut de Physique du Globe, Paris `http://dx.doi.org/10.18715/SEIS.INSIGHT.XB_2016`. Meteorology InSight data from the latest acquired sols can be found in the following user-friendly interface `https://mars.nasa.gov/insight/weather/`.

Code availability

The Python codes developed to produce the figures directly from the InSight files in the PDS Atmospheres node are available in the online repository `https://github.com/aymeric-spiga/insight-atmosphere-nature-geoscience`.

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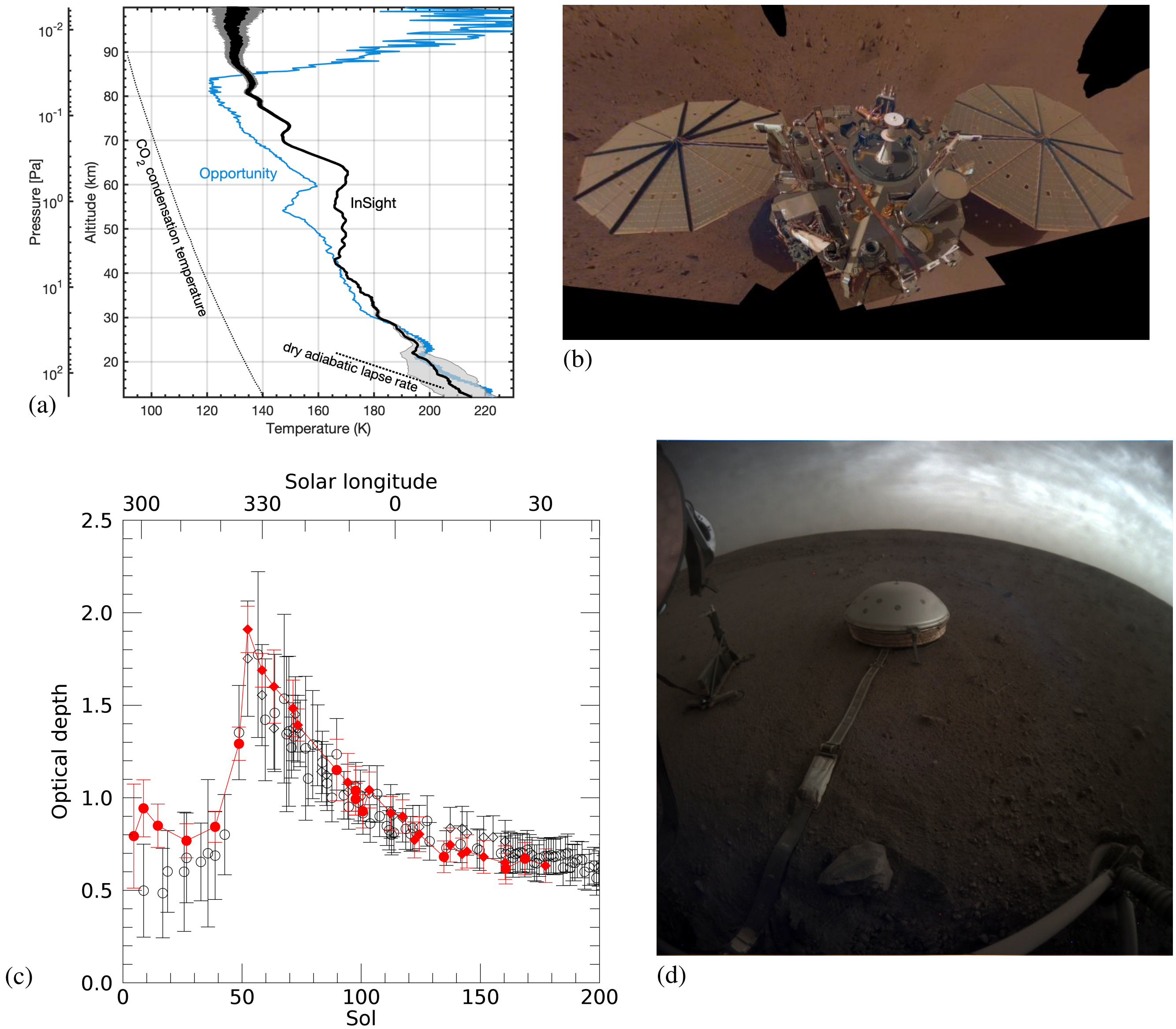


Figure 1: **After successful entry, descent and landing (EDL), InSight now provides continuous weather data for Mars.** (a) Reconstructed temperature profile (with 3-sigma error bars) from InSight's EDL the profile obtained for Opportunity at a similar location and season[64], the CO_2 condensation profile and a dry adiabatic lapse rate are included for reference. (b) Mosaic of InSight's deck imaged on sols 106 and 133 (L_s = 356 and 10°), featuring the two TWINS booms facing outward, overlooking the dusty solar panels, and the pressure sensor's inlet in the middle (PIA23203). (c) Atmospheric dust optical depth obtained from IDC (red) and ICC (black) imaging in the morning (diamonds) and evening (circles), 1-sigma error bars, dominated by systematic effects in the tau retrieval, are indicated on the plot. (d) ICC image on sol 145 (L_s = 16°) showing noctilucent clouds after sunset, with the HP^3 suite, and SEIS below the WTS, in the foreground (PIA23180).

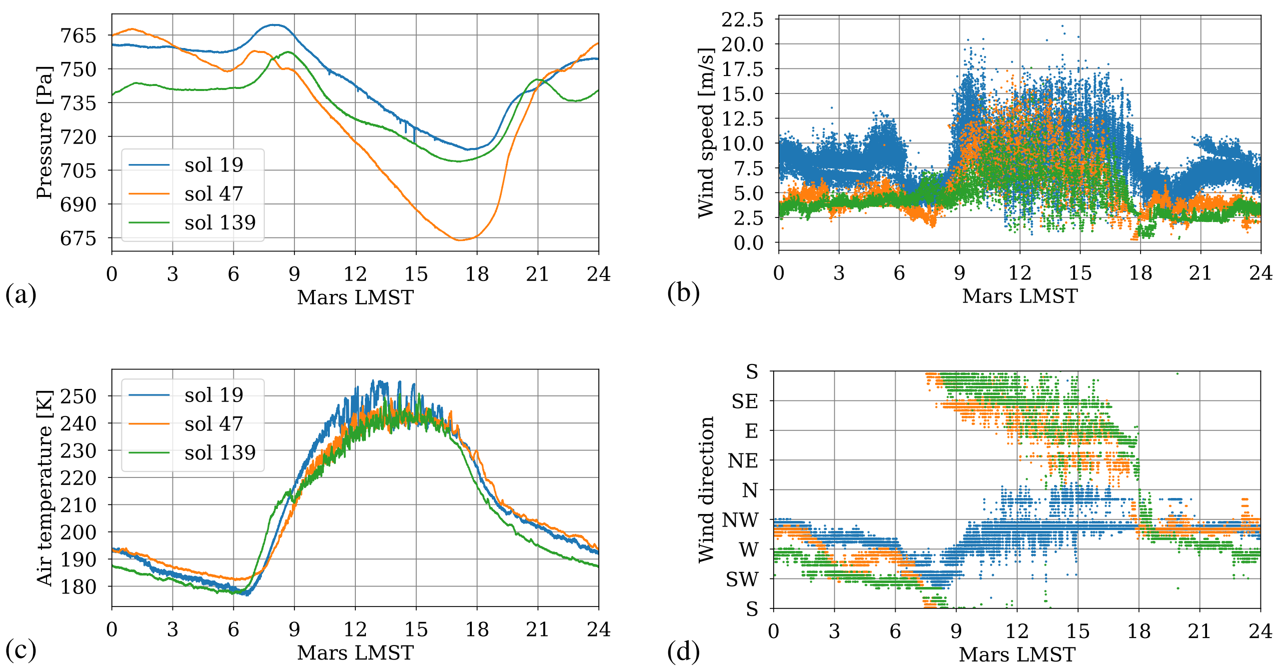


Figure 2: **The martian meteorology of three typical sols experienced by InSight shows a diversity of scales involved from the planetary scale to local turbulent scales.** Measurements of pressure (a), wind speed (b), atmospheric temperature (c), and wind direction (d) are shown. The blue lines correspond to sol 19, shortly after landing (L_s = 307°). The orange lines correspond to sol 47, during the regional dust storm which significantly perturbed the local weather at the InSight landing site (L_s = 324°). The green lines correspond to sol 139 (L_s = 13°), in northern spring after the decay of the regional dust storm. The direction indicated for winds are the direction from which the wind is blowing, following atmospheric science convention.

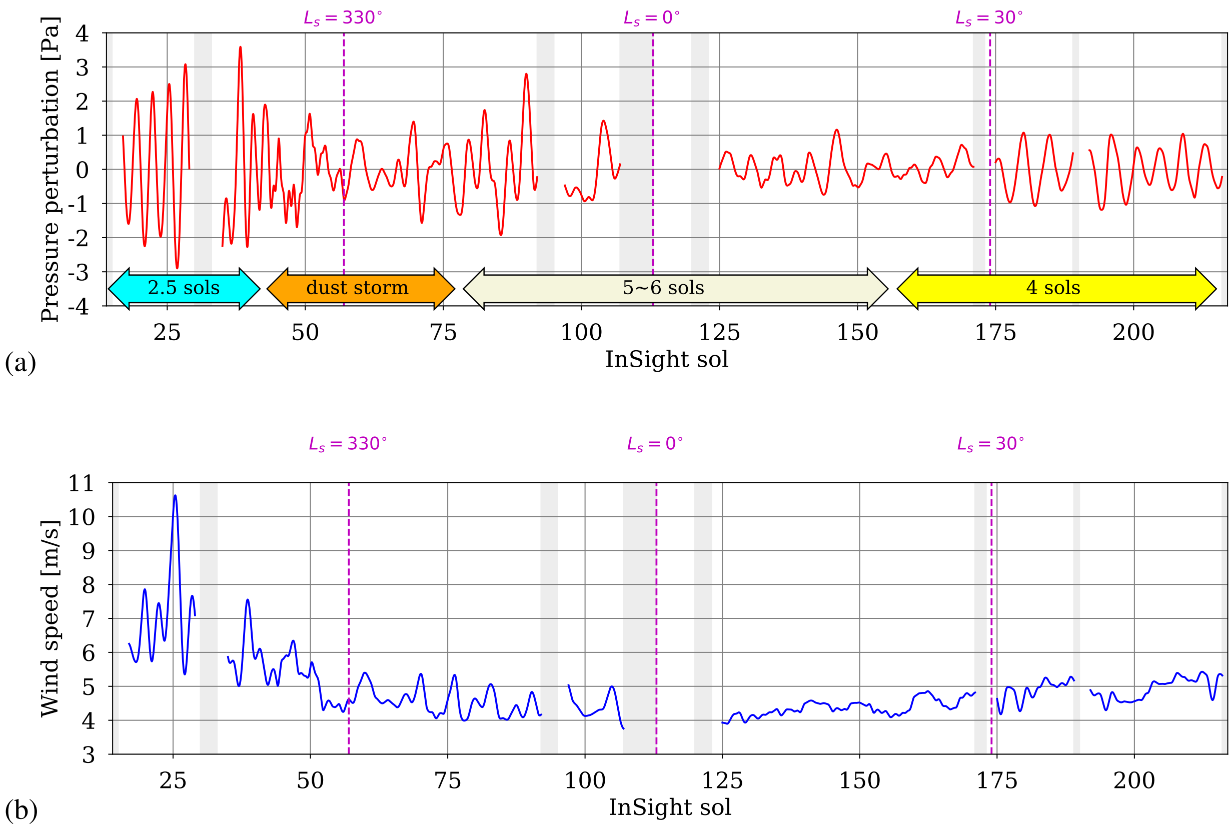


Figure 3: **Despite its equatorial location, InSight's pressure and wind daily variability are sensitive to weather in Mars' mid-latitudes, dominated by baroclinic instability**. Pressure (a) and wind (b) fluctuations obtained by low-pass filtering to remove thermal tides, mesoscale meteorology and local turbulence signals. Pressure is also detrended with a one-sol running mean, removing the seasonal impact of CO_2 condensation / sublimation. Grey areas correspond to sol intervals during which APSS experienced anomalies which prevented measurements from being carried out. Wavelet analysis of excerpts of the pressure signal in (a) are shown in Extended Data Figure 3.

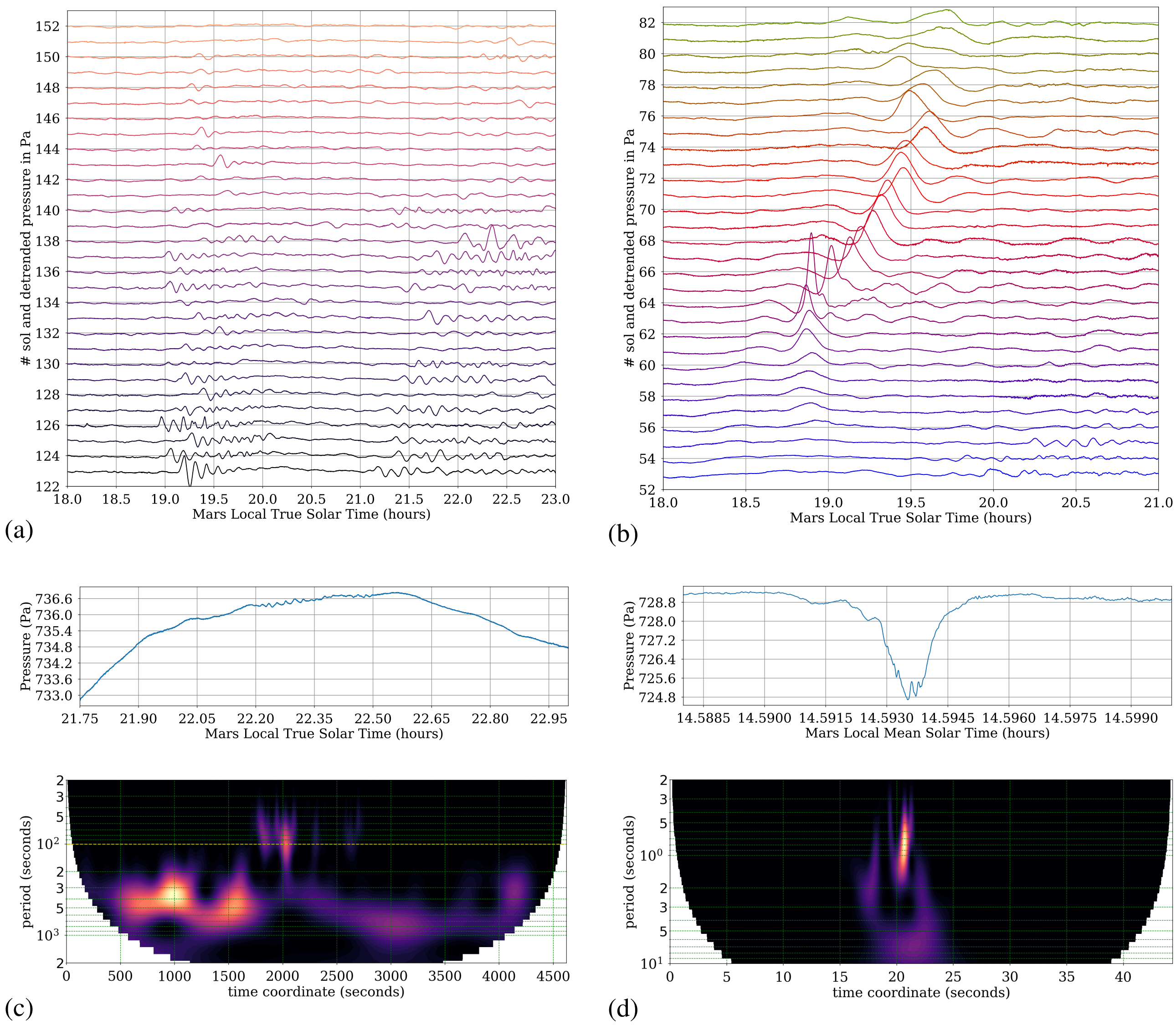


Figure 4: **InSight unveiled pressure fluctuations likely related to gravity waves (a), bores and solitary waves (b) and infrasound (c,d).** (a,b) Pressure detrended using a 2000 s smoothing window in evening conditions. The x-axis is the local true solar time in martian hours. The y-axis follows the pulsar plot by Craft[65] and used as the cover of Joy Division's *Unknown Pleasures* album: each line corresponds to a sol and the vertical scale is the detrended pressure in Pa offset by the sol number. (c) Pressure measurements during an evening gravity-wave event on sol 78 (L_s = 341°) above a wavelet power spectra of the signal detrended using a 500-s smoothing window. The yellow line shows the 100-s period below which oscillations are infrasound rather than gravity-waves. (d) Same as (c) during a daytime vortex-induced pressure drop on sol 26 (L_s = 311°) using a 2-s smoothing window to isolate the infrasound from the convective vortex.

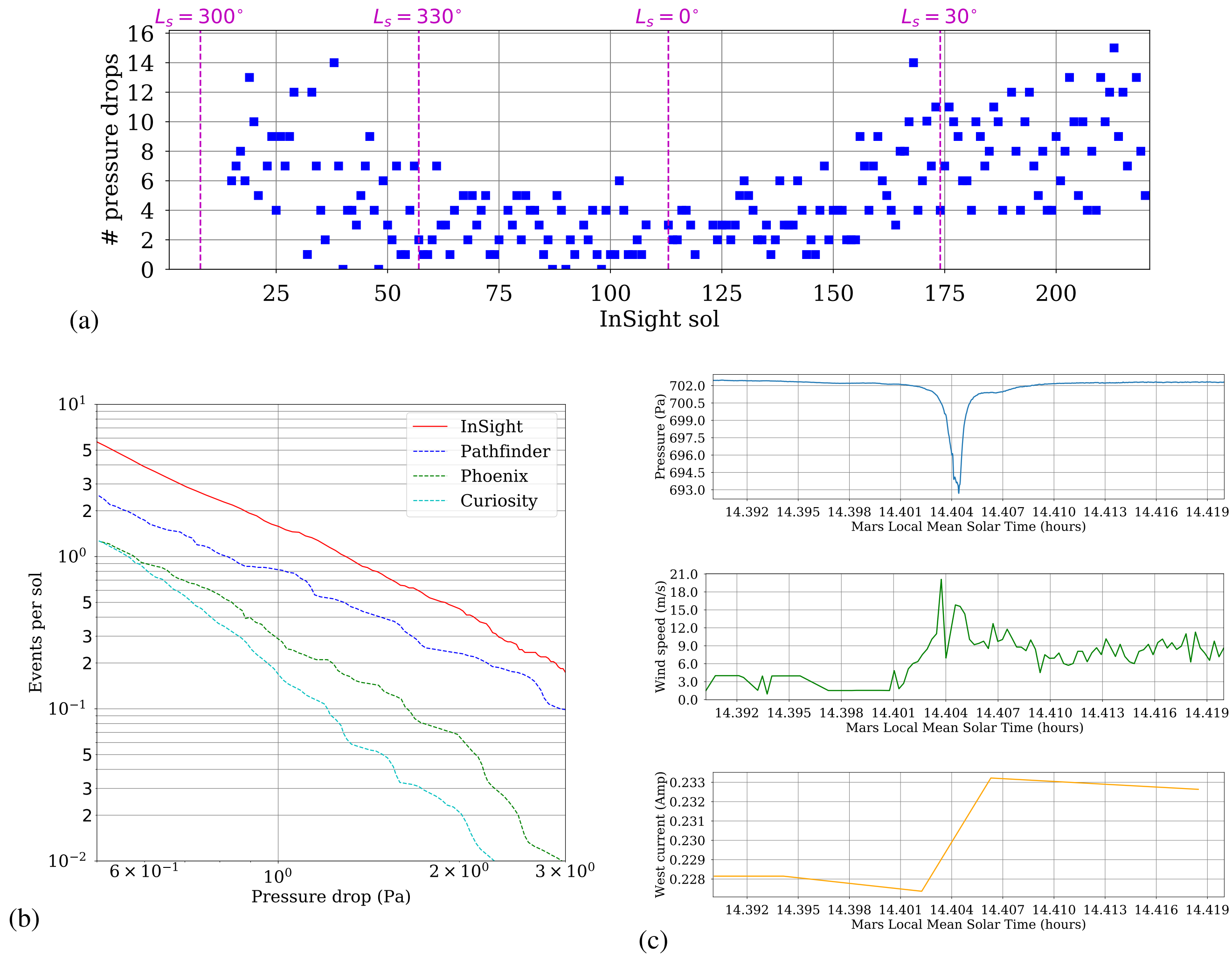
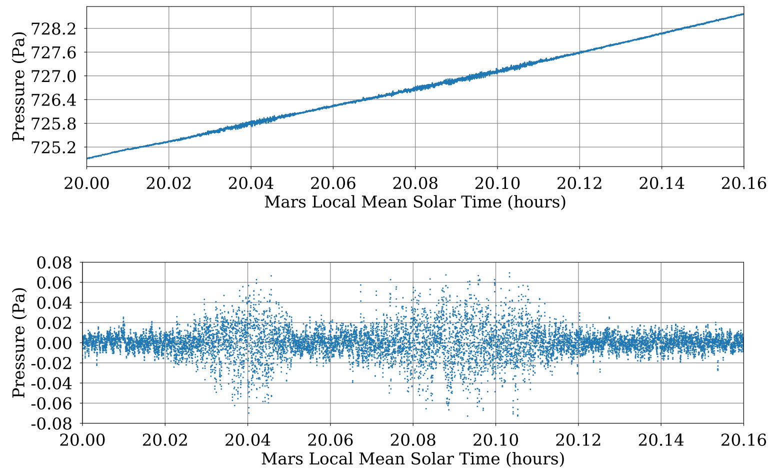
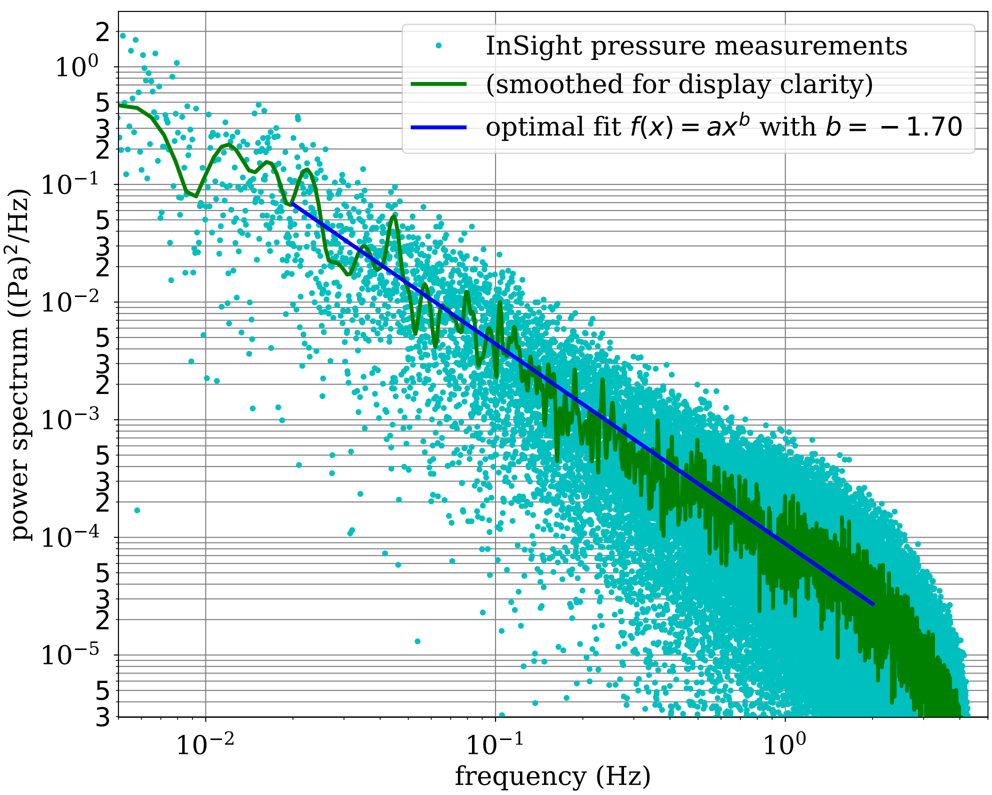


Figure 5: **Daytime dust-devil-like convective vortices are very active at the InSight landing site (a,b) and caused at least one solar-panel cleaning event witnessed by InSight (c).** (a) Number of pressure drops per sol exceeding 0.5 Pa (the list of the 15 strongest events is included as Extended Data Figure 7). (b) Distribution of pressure drops per sol, normalized by diurnal coverage and number of observed sols, including the statistics from other landers[46,47,48]. (c) Pressure, wind speed, and solar array current recorded during the deepest pressure drop observed at the surface of Mars thus far (InSight sol 65, $L_s = 334°$).

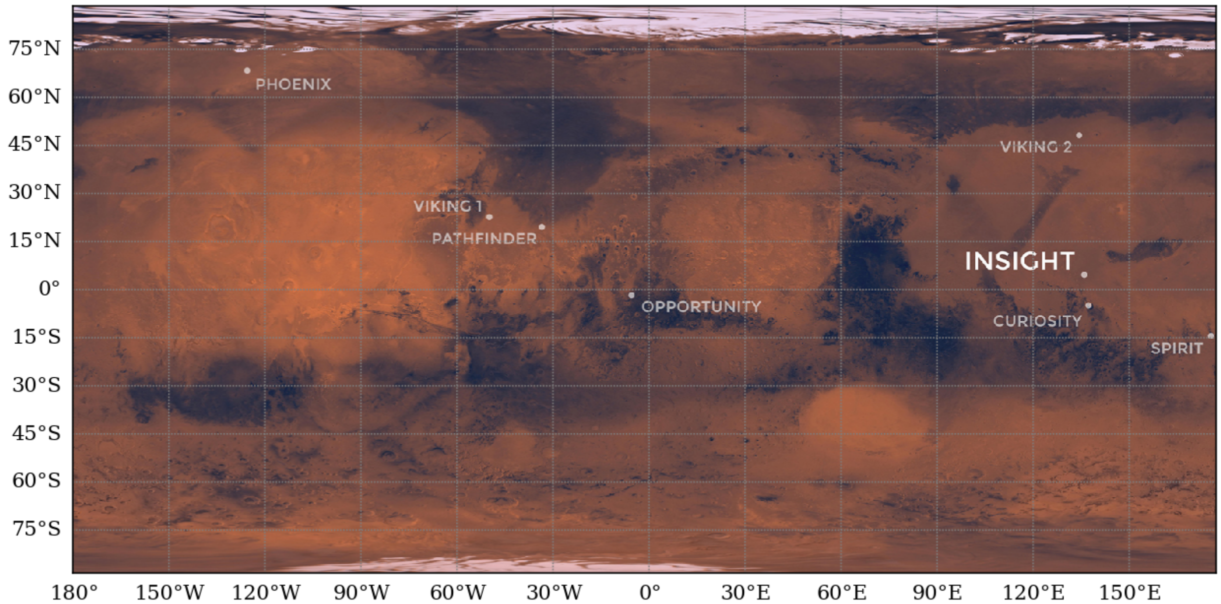


(a)



(b)

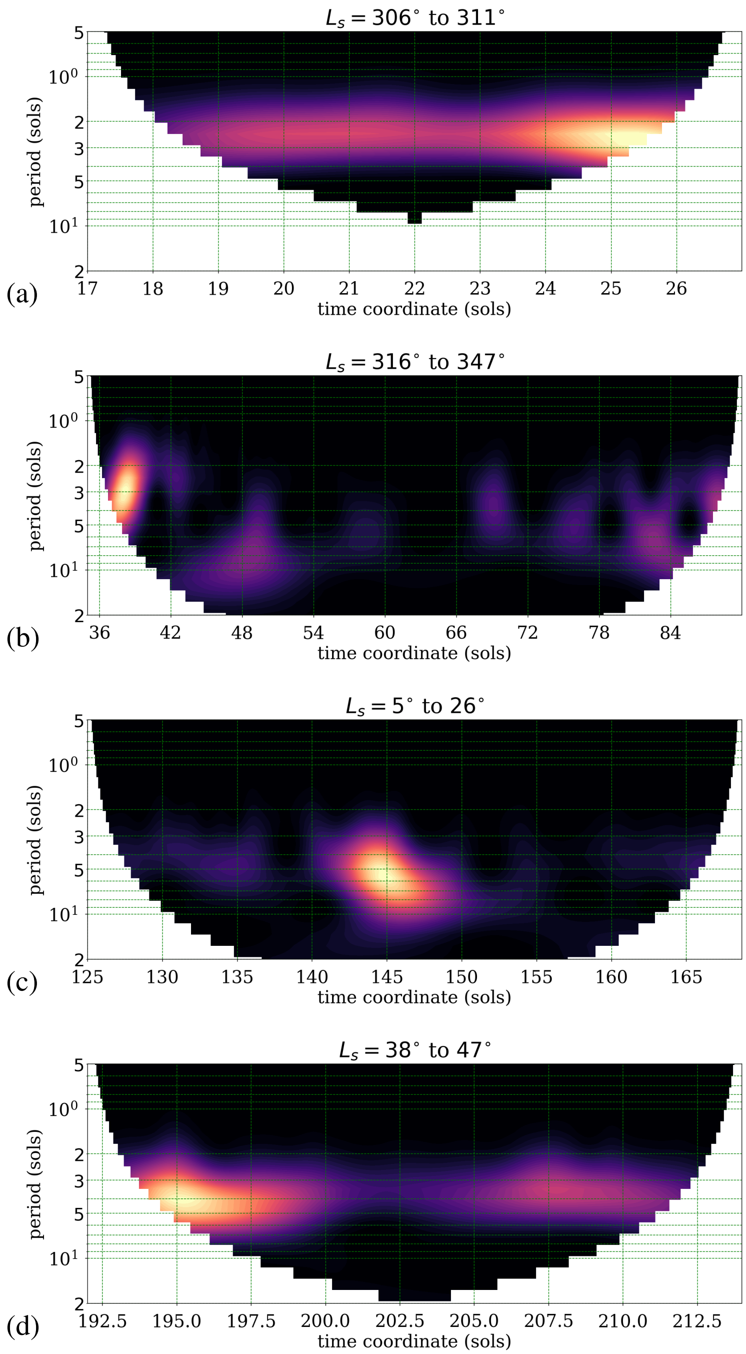
Figure 6: **The InSight pressure sensor explores a new territory of high-frequency turbulence on Mars.** (a) High-frequency "pressure bursts" detected on sol 114 (L_s = 0°): the raw pressure signal is shown on top of a detrended version using a smoothing window of 50 s. (b) Power spectrum produced from 40 sols of daytime pressure fluctuations from sols 168 to 208 (L_s = 27–45°) when pressure was continuously sampled at 10 Hz. Cyan points correspond to the spectra computed for InSight pressure measurements; the green curve is a smoothed version of the cyan points to display the average power spectrum of pressure more clearly. A power law fitting of the data points in cyan in the range 0.02-2 Hz is shown in the figure as a blue line.



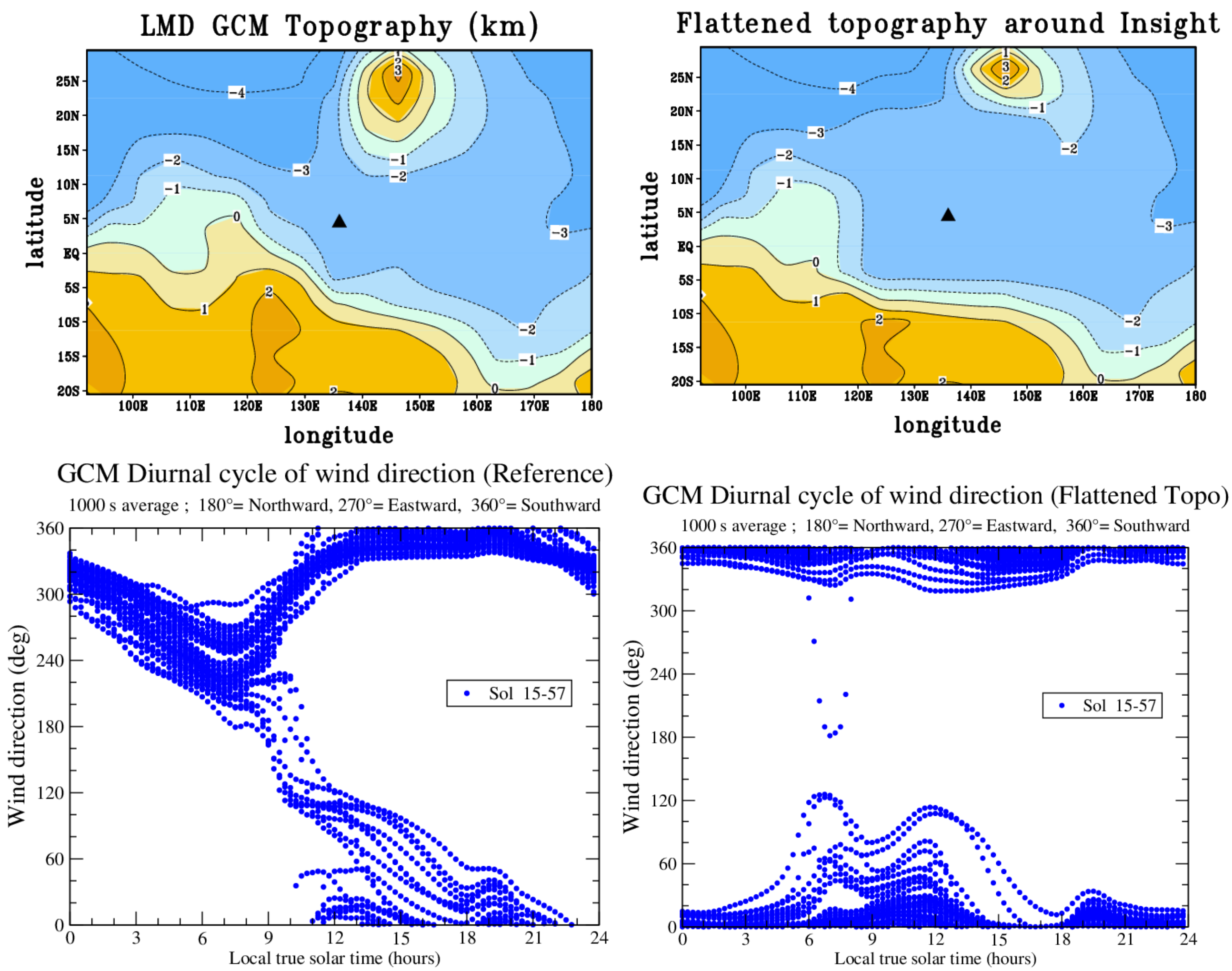
Extended Data Figure 1: Location of the InSight landing site on Mars, along with other landers and rovers having operated at the surface of Mars (PIA22232 with added longitude/latitude coordinates).

InSight sols	0	8	32	57	85	113	143	174	207
Solar longitude L_s (°)	295	300	315	330	345	0	15	30	45

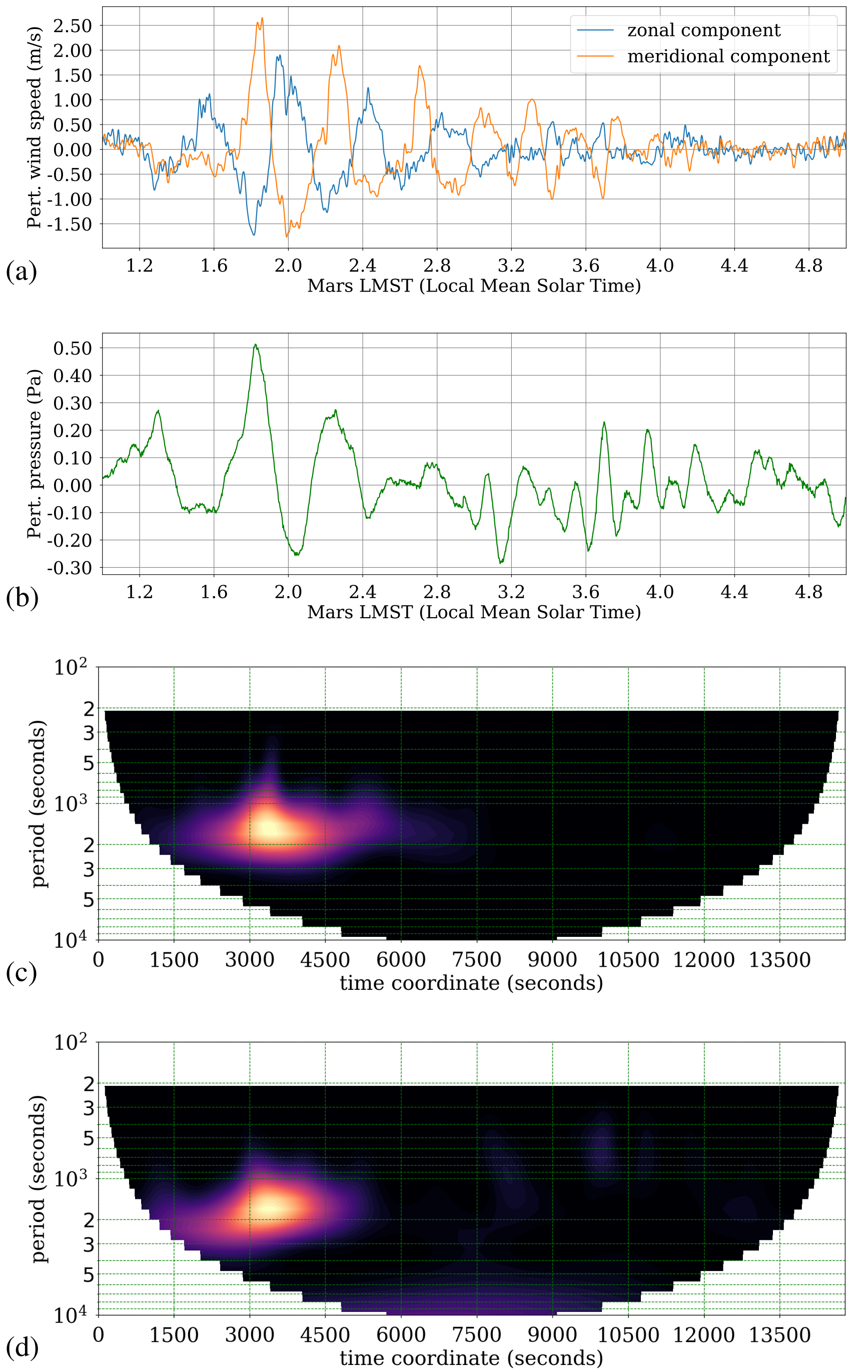
Extended Data Figure 2: Correspondence between InSight sols and solar longitude L_s for the first 200 sols of the InSight mission. Further details on solar longitude are provided in the *Methods* section.



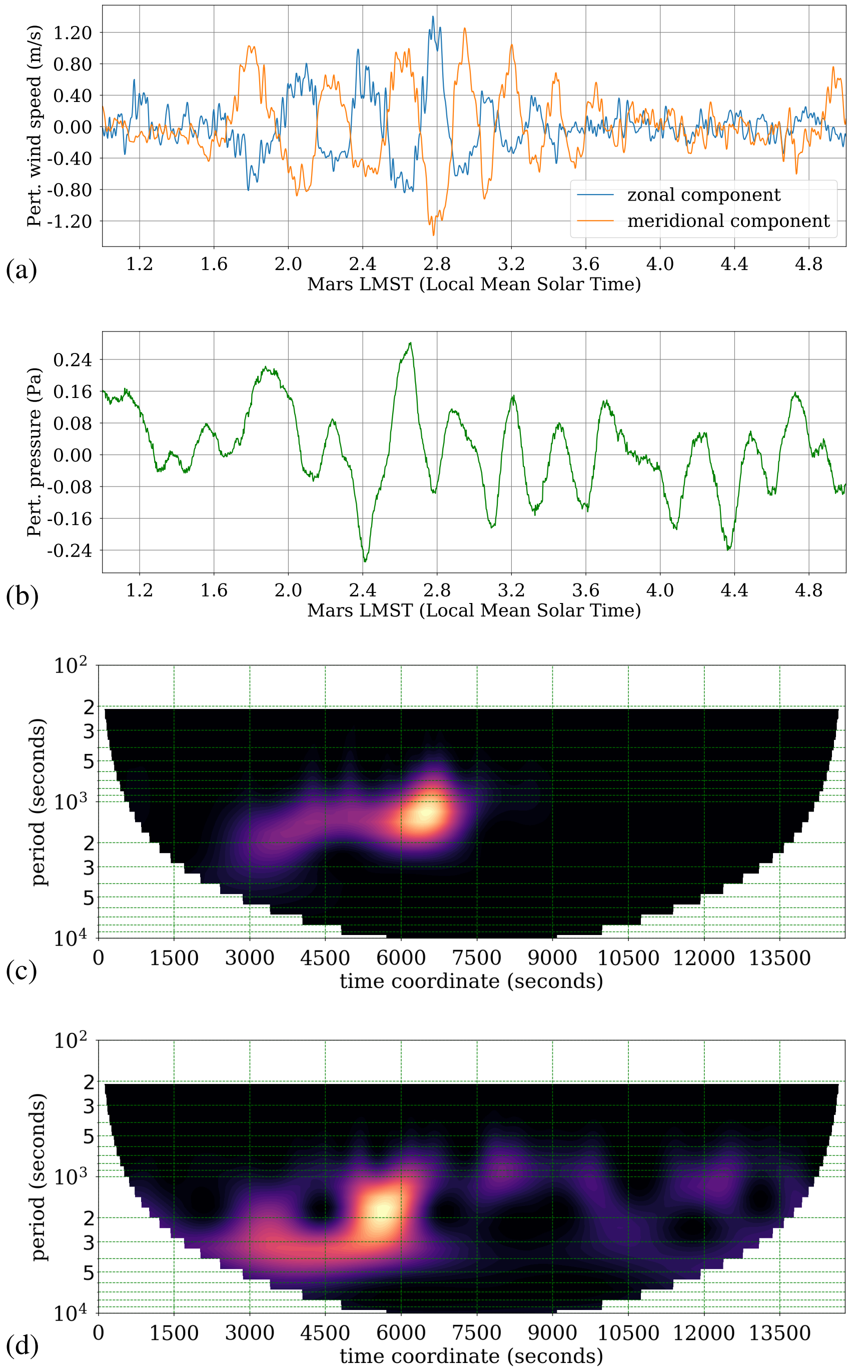
Extended Data Figure 3: Wavelet analysis of excerpts of the pressure signal in Figure 3a are shown here for northern winter (a), regional dust storm conditions (b), and northern spring (c,d). Colors show power spectra (brighter colors for higher power spectra, x-axes show the InSight sol, y-axes show detected periods. Power spectra are only shown inside the cone of influence.



Extended Data Figure 4: Atmospheric flows related to the moderate regional slope surrounding the InSight landing site account for the diurnal variability in wind direction. The left panels show the topography and the simulated diurnal cycle of wind direction in the global climate model referenced in the pre-landing study[7]. The right panels show the exact same simulation with flattened topography set as indicated in the top right plot. The thermal tide signal (e.g. in the diurnal cycle of atmospheric pressure) is similar in the two simulations.



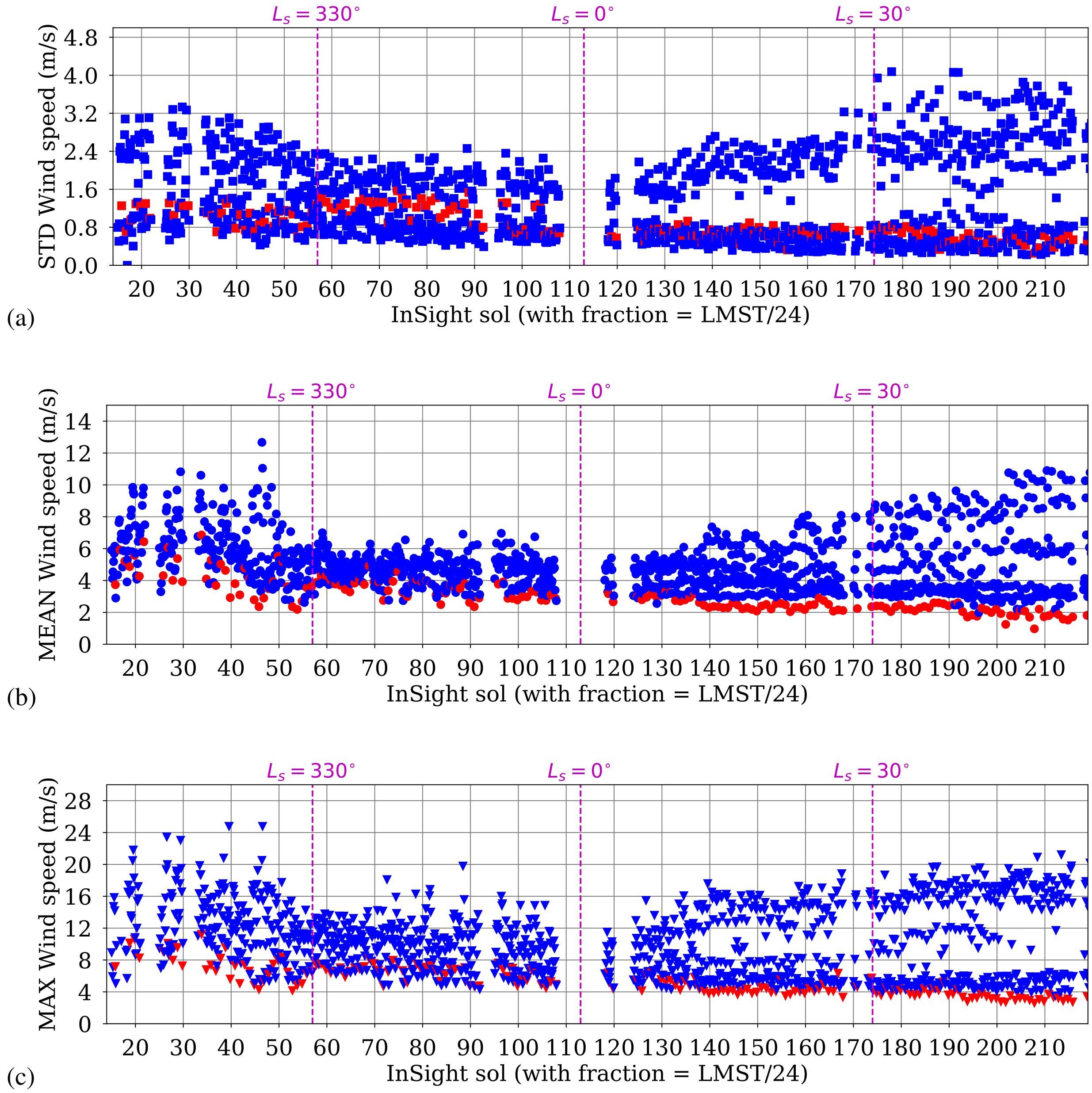
Extended Data Figure 5: Nighttime atmospheric measurements by InSight on sol 142, showing simultaneous gravity-wave oscillations of pressure and winds. (a) Perturbations of the zonal and meridional wind components, obtained by first removing high-frequency fluctuations from raw wind measurements using a 100-s smoothing window, then subtracting the long-term variations obtained by a 3700-s (one-martian-hour) smoothing window. (b) Perturbations of pressure obtained similarly as (a), except 100-s low-pass filtering is not performed. (c) Wavelet analysis of the perturbation zonal component shown in (a), with similar range on the x-axis as in (a). (d) Same as (c) for the perturbation pressure shown in (b).



Extended Data Figure 6: Same as Supplementary Figure 5 for sol 150.

DROP	LTST	SOL
-9.18	13.53	065
-5.76	14.13	019
-5.67	12.73	039
-5.18	14.16	170
-4.91	11.34	191
-4.82	13.71	019
-4.08	12.83	166
-4.05	11.99	065
-4.00	13.78	026
-3.84	12.74	026
-3.80	14.10	178
-3.76	14.21	211
-3.75	12.24	024
-3.71	9.40	170
-3.69	11.11	148

Extended Data Figure 7: The 15 strongest vortex-induced pressure drops detected by InSight in the first 220 sols of operations. The values of pressure drops in this table, as well as in Figures 5a and 5b, are obtained after removing from pressure measurements the low-frequency pressure variations obtained by applying a 1000-s smoothing window.



Extended Data Figure 8: InSight wind speed measurements shown for the first 220 sols of operations (only sols with complete wind measurements are included in this figure). In each 3-hour bin, (a) standard deviation, (b) average wind speed, and (c) maximum wind speed are displayed. The red dots denote the points corresponding to the bin in the interval 18-21 hours LMST, which is the evening “quiet” regime described in the main text.