THRESHOLDS FOR WIND-DRIVEN SEDIMENT TRANSPORT AT INSIGHT, MARS.

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Introduction: Aeolian activity, the movement of sand and dust by the wind, is common on Earth and has been observed on other planets [1]. Under the current climatic conditions on Mars, aeolian activity is the primary process of surface modification driven by winds, dust storms and wind vortices. Landed and orbiting cameras show that widespread aeolian activity occurs despite low measured and modelled winds, challenging Earth-based theories [2, 3]. Dust particles enter into long-term suspension forming global dust storms which drastically alter the Martian atmospheric dynamics and present hazards to robotic and human missions.

Several models have been proposed on the long-standing conundrum of sediment transport on Mars, however, none of these have been verified on the planet. The outstanding question of what wind shear velocities mobilize sediments on Mars has remained elusive despite multiple spacecrafts carrying wind sensors and studying aeolian activity on finer spatial and temporal scales than can be achieved in orbit. Quantitative examination of aeolian activity under natural Martian surface conditions is imperative in validating transport models.

Background and Methods: NASA's InSight mission has monitored simultaneous coverage of aeolian activity on Mars by combining, for the first time, imaging with atmospheric, seismic and magnetic measurements. Previous studies spanned over just half of the first Martian year and observed vortex-dominated aeolian activity limited to sporadic grain motion and dust devil tracks [4, 5]. Here we analyze the extensive multi-instrument dataset throughout the mission's lifetime over two Martian years. We exploit InSight's unique potential by directly correlating and quantifying aeolian activity with atmospheric conditions on the surface over various seasons and conditions, both of which are essential for arriving at a mechanistic understanding of wind-driven transport on Mars.

Two main issues have previously prohibited the systematic quantification of aeolian activity at InSight: 1) due to lander power constraints, the wind sensors were switched off after Sol ~784, permitting only intermittent meteorological measurements, and 2) the consistent saturation of the wind sensors from the vortical airflow during energetic vortex encounters results in data gaps. These gaps preclude us from probing the most energetic part of the vortex and the peak wind speeds, critical for inferring thresholds for motion [2, 4, 6].

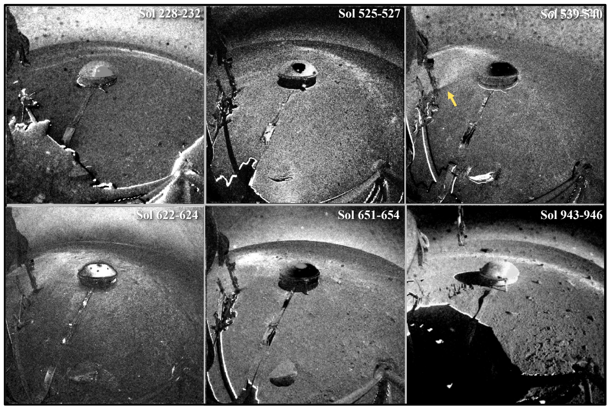

Figure 1 Selection of surface tracks identified from differencing Instrument Context Camera image pairs over different seasons at InSight. White pixels show surface albedo changes from dust-devil encounters associated with deep transient pressure drops.

In contrast to the above two issues, the seismometers have remained powered on continuously throughout the mission, capturing high-frequency variations of the wind forcing at 20 samples per second without saturation. We have derived estimates of wind speeds by using comodulation, which employs the strong correlation from the excitation of high-frequency lander resonances from wind forcing measured continuously by the seismometers [7]. This method has proven to be an effective atmospheric proxy of the wind magnitude. We also estimate the vortex-induced peak wind speeds from atmospheric parameters by assuming cyclostrophic balance and vortex advection by the ambient wind. The minimum estimate of the peak wind speed in the vortical system is therefore the vector sum of the background and local vortex-induced tangential wind velocity [8].

Each peak wind estimation is associated to the vortex encounter that caused surface changes. Aeolian activity is detected through differencing of image pairs with similar illumination conditions, allowing us to constrain the timing of the occurrence as outlined in [4].

Results. As shown in Fig. 2a, the high-frequency vibrations of lander resonances are excellent estimators of the mean ambient wind speed. Extending over two years these estimates bridge the data gaps when the wind sensor was off and confirm the seasonality of the wind regime at InSight. The occurrence of surface changes over the mission's lifetime is annotated in Fig. 2a and includes creep of granules up to 4 mm diameter; surface tracks; localized cleaning; sporadic saltation events with

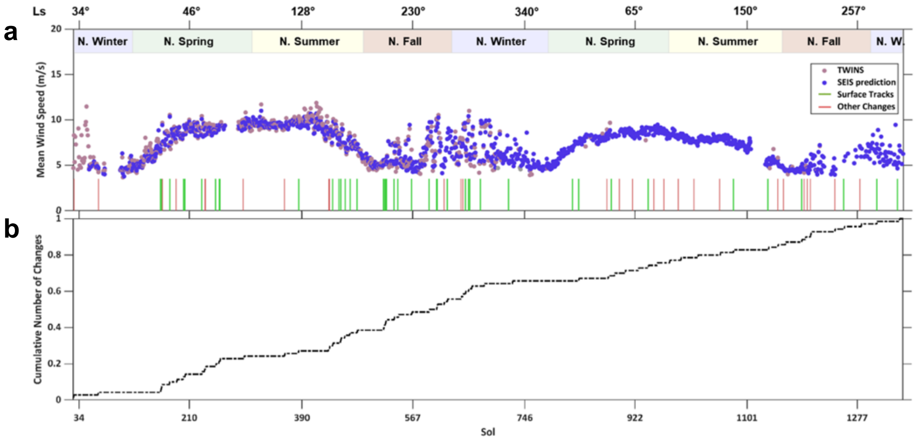

Figure 2 (a) Daytime (11 am – 3 pm) mean ambient wind speeds estimated using comodulation from seismic acceleration (blue) against actual wind speed measurements, when available (grey). The daytime window represents the period when nearly all detected changes occurred. Green vertical lines indicate surface tracks; red vertical lines indicate other surface changes. (b) Cumulative distribution of the number of changes over the two Martian years.

grain impacts removing dust areas many times the impactor's size, and others. Surface tracks appear as elongated dark linear to curvilinear albedo features, with few traces exhibiting irregular morphologies. Fig. 2b shows how the aeolian activity at InSight exhibits seasonality; changes occur predominantly during mid spring, and at the end of summer throughout fall, into early winter. We observe an overall cessation of surface changes during the northern winter into early spring.

This limited episodic aeolian activity is driven by the passage of turbulent vortices and is strongly suggestive of a stable surface around InSight under current conditions, in agreement with previous studies spanning just the first half year [4, 5]. The analysis of vortex encounters in Fig. 3 indicates a strong correlation between the *estimated* peak wind speeds and acceleration induced by passing vortices as measured from the excitation of high-frequency lander resonances. This correlation breaks down when considering instead the *measured* peak wind-speed measurements as the sensors saturate during energetic close encounters, but these can be recovered from our estimates. Overall, the high-frequency data from both the seismometer and pressure sensors are strongly indicative of sudden peak wind speeds unresolved by the wind sensors. Our preliminary results indicate that instantaneous peak wind speeds of 26 ± 2.5 m/s consistently cause surface changes from the passage of energetic convective vortices (Fig. 3b). This wind speed threshold maps to surface friction wind speeds of ~1.7 m/s for InSight's aerodynamic surface roughness length of $z_0 \sim 2$ mm, consistent with classic saltation theory for mobilization of 100-150 μm sand-sized grains [4, 9], the dominant size fraction at InSight [10, 16]. This finding suggests that sporadic saltation bursts are triggered at the skirts of passing vortices by instantaneous changes in wind speed exceeding this threshold. Despite initiation at this threshold, saltation is not sustained at the lower theoretical impact threshold required to keep it active downwind as hypothesized to occur on Mars [11], likely due to a limited number of saltators at reduced heights and cushioning by extended dust covers at InSight [12].

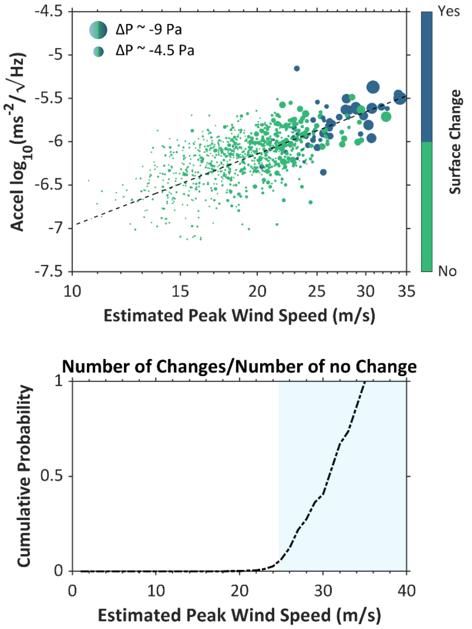

Figure 3 (a) Minimum estimate of the peak wind speed in the vortical system estimated from measured atmospheric variables against peak acceleration induced by the vortex and measured by the high-frequency lander resonances.

(b) Cumulative probability of the number of surface changes detected over the number of no changes caused by the peak wind speed from each vortex encounter at InSight.

The systematic exceedance of this threshold at which aeolian activity is observed suggests that surface track formation is likely caused by the sporadic mobilization and redistribution of sand grains at the skirt along the path of dust devils, which in turn impact and eject dust grains into suspension. The kinetic energy imparted by the saltating grains is enough to clean localized areas many times their intrinsic size and more effectively than on Earth [13], as observed by various cleaning events, including the semi-controlled solar array cleaning experiments [14, 15]. Our findings provide an insight into the long-standing paradox of aeolian transportation on Mars and strengthen the hypothesis that sand saltation is an effective means for setting dust into suspension.

References: [1] Hayes (2018) Science [2] Kok et al. (2012) RPP [3] Newman et al. (2022) Authorea [4] Charalambous et al. (2021) JGR 126(6) e2020JE006757 [5] Baker et al. (2021) JGR [6] Balme et al. (2003) GRL [7] Charalambous et al. (2021) JGR 126(4) [8] Lorenz (2016) Icarus [9] Shao & Lu (2000) JGR [10] Golombek et al. (2020) Nat. Comm. [11] Sullivan & Kok (2017) JGR [12] Golombek et al. (2017) SSR [13] Greeley (2002) PSS [14] Golombek et al. (2023) this issue [15] Golombek et al. (2023) SSR [16] Verdier et al. (2023) JGR