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Airplane pilots and parachutists have been killed by them; Mars rovers have been saved by them. Dust devils, whirlwinds that stalk the deserts of Earth and Mars—and perhaps Venus and Titan as well—are the producers of those unlikely results. They are convective vortices, driven by solar heating of the ground and made visible by lofted surface material.

Unlike tornados and hurricanes, dust devils are dry, powered by the sensible heat from the ground rather than by the latent heat of water. So they occur most frequently on hot summer afternoons. As air is drawn into a narrow column rising through surrounding cooler air, its rotation speed is boosted by the conservation of angular momentum. Unlike hurricanes, dust devils are too small for a planet's rotation to influence their circulation: Equal numbers of randomly cyclonic and anticyclonic devils generally exist, regardless of hemisphere.

Although dust devils cause occasional damage, injury, and even death—usually by light structures such as aircraft, barn doors, or sheds—they tend to be considered idle curiosities of terrestrial weather. But they are a prominent feature of Mars's meteorology, and their prevalence has stimulated study of their counterparts on Earth.

Pressure drops

A typical dust devil on Earth spans a few meters to tens of meters in diameter, with a height 5 to 20 times as large. Its height is capped by the top of the planetary boundary layer (PBL), usually between 0.2 km and 2 km thick, where air can mix in contact with the ground. Martian devils on average are about three times as large as their terrestrial counterparts, in part because the Martian PBL is deeper.

The word "typical" must be used cautiously, because dust-devil diameters and the core-pressure drops that define a whirlwind's intensity have highly skewed distributions. Much like in earthquakes, those properties follow power-law statistics. But while you might see a hundred times more 5 m dust devils than 50 m ones, the single largest (and usually longest-lived) devil in the set may lift more dust than the rest put together. Many vortices can exist on a landscape but be invisible as "dustless devils" if fine surface particulates are not abundant or too sticky.

Pressure data can easily detect vortices (see figure 1). A pronounced dip in the pressure record on Earth or Mars gives them away. Occasionally, the dip reaches 1–2% of ambient pressure; by comparison, the most violent terrestrial tornadoes and hurricanes experience pressure drops of 10–20%. Other signatures include infrasound emissions and electric fields caused by charged dust. The swirled dust and sand can produce atmospheric oxidants, such as ozone, either via catalysis on abraded surfaces or through electrical discharges. On Mars, the production of oxidants may be important in the destruction of methane and other organic compounds.

Prevalence and practicality

Like London buses, dust devils appear quasiperiodically. High-resolution numerical simulations show that in the con-

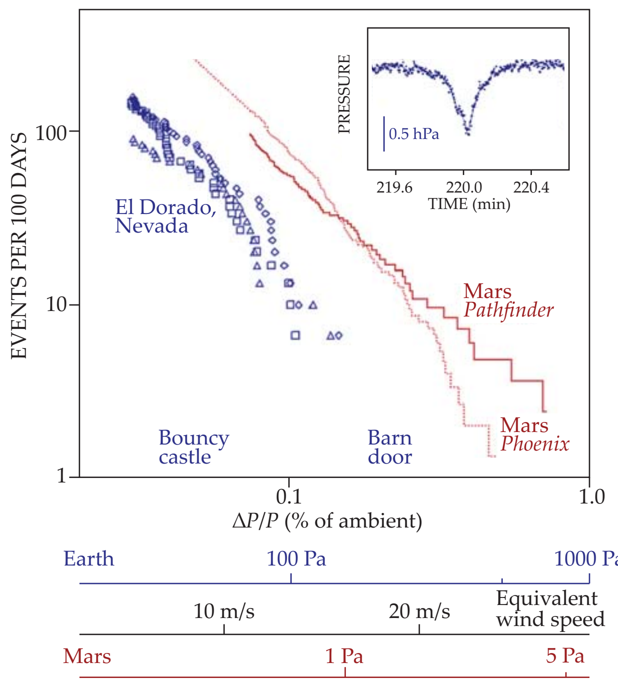

FIGURE 1. PRESSURE DATA. Vortices are most easily identified in pressure (P) records, in which a dust devil appears as a transient dip (inset). Deeper pressure drops, associated with stronger winds, occur less often, roughly according to a power-law distribution. On Earth, the pressure drops occasionally reach the weight per unit area of light structures, such as a barn door or an inflatable bouncy castle. The absolute pressure drops on Mars, where the ambient pressure is one-hundredth as large, are much smaller. Because the pressure drop provides the centripetal acceleration that moves the air in a circle, the fractional pressure drop relates to the wind speed on both planets. (Figure from Ralph Lorenz.)

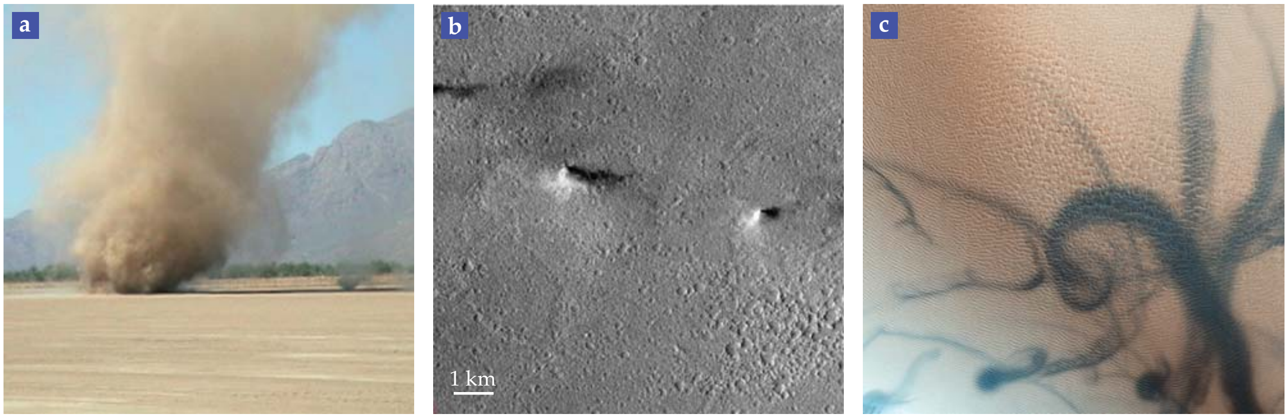

FIGURE 2. TRACKS IN THE WIND. (a) This desert dust devil is typical on Earth. It has a width of a few meters and sits next to a smaller devil at right. **(b)** Four Martian dust devils and their shadows are photographed from an orbiting spacecraft. Their regular spacing suggests a planetary boundary layer depth of 6 km. **(c)** In another orbital view of Mars, swirling cycloidal dark tracks appear from dust devils moving in light winds. The sand ripples are 1-4 m apart. (Images courtesy of NASA.)

vecting PBL, atmospheric cells circulate with broad, downwelling centers and upwelling sheets of warm air at their edges. Vortices form preferentially where those sheets join (at the corners of the cells), and the width of the cells, approximately equal to the PBL depth, can define a characteristic spacing of vortices (see figure 2b). Indeed, pressure records sometimes show periodic signatures as the cellular pattern drifts across a fixed meteorological station. Dust devils are sometimes abundant enough to mark out the regular spacing of the cell edges.

Dust-devil "whisperers" like me have learned how to remotely diagnose the wind conditions and composition of surface material from the shape and path of individual dust devils. When a mixture of sand and dust is present, a conical "sand skirt" may form, as sand too heavy to be lofted skips around the base of the devil. And over a deposit of uniform fine dust, a tall, perfect cylinder can appear with a clear center—the suspended dust centrifuged to the perimeter as it rises in the updraft.

A strong ambient wind can cause the dust column to tilt downwind and migrate in a nearly straight line. In light winds over a horizontal surface, a dust devil may wander randomly—sometimes curling like honey drizzled from a spoon—whereas on a slope, it tends to move uphill. Those migration patterns are frequently revealed on Mars in images from orbit, as shown in figure 2c, and they allow astronomers to remotely discern wind patterns and vortex activity over previous days to months.

Dust devils and the vortices that beget them are important for both climatological and practical reasons. On dry Mars, roughly 30% of the dust that hangs in the atmosphere is put there by dust devils. That dust, in turn, warms the atmosphere and regulates its ability to hold water vapor. It can thus influence the important exchange of volatiles between the atmosphere and polar caps. Furthermore, while the bright red dust settles, dust devils can scour it away to expose darker sands beneath. The effect of that change in albedo may be enough to modify the local climate.

The local removal of dust is a fortunate side effect for solar-powered Mars rovers and landers. In 1997 the *Sojourner* rover saw steady dust accumulation cut its power by 0.3% per day, an experience that conditioned NASA's expectations for the life span of later rovers *Spirit* and *Opportunity*. Although the power of those rovers similarly declined, it unexpectedly recovered from time to time. Some phenomenon had cleared dust from the panels and allowed the missions to persist for several thousand days—years beyond the rovers' expected 90-day lifetime.

The dust-clearing events occurred when solar heating of Mars's surface was greatest and with a frequency of once every few hundred days. Those conditions are consistent with the prevalence of dust devils, but direct attribution was impossible until this past year. In February 2019 the *InSight* mission's meteorological instruments recorded a direct hit with a strong vortex at the precise moment some of its solar panels increased their power output by 1–2%.

Dust devils at the *InSight* landing site are proving valuable in another respect. A vortex is a low-pressure system, and when one integrates the pressure field across the footprint of a typical devil, the weight can amount to that of a truck. Seismometers on the lander are sensitive enough at low frequencies to record the tiny tilt the ground makes as it deforms elastically under that (negative) load. Although atmospheric signals of all kinds influence seismometers, the localized and symmetrical nature of dust-devil loads makes them particularly convenient probes of the near-surface stiffness of Mars. Better the devil you know. . . .

Additional resources

▶ L. K. Fenton, R. Lorenz, "Dust devil height and spacing with relation to the Martian planetary boundary layer thickness," *Icarus* **260**, 246 (2015).

▶ R. D. Lorenz, *Exploring Planetary Climate: A History of Scientific Discovery on Earth, Mars, Venus and Titan*, Cambridge U. Press (2019).

▶ R. D. Lorenz et al., "History and applications of dust devil studies," *Space Sci. Rev.* **203**, 5 (2016).

▶ W. B. Banerdt et al., "Initial results from the InSight mission on Mars," *Nat. Geosci.* **13**, 183 (2020). PT