THE GEOLOGICAL SOCIETY
OF AMERICA®

RESEARCH **FOCUS**

Of kangaroo rats and gypsum gravel: Probing the extremes of aeolian transport in the present and the past

Nicholas G. Heavens
Department of Atmospheric and Planetary Sciences, Hampton University, Hampton, Virginia 23669, USA

A whirlwind is “a small-scale, rotating column of air” (American Meteorological Society, 2012a): a terse definition for some of the most intriguing and terrifying phenomena in the atmospheres of Earth and Mars. Whirlwinds fall into two classes: those that hang from cumulus clouds (tornadoes and waterspouts) and everything else (American Meteorological Society, 2013). The popular names for this latter class (e.g., shaitan, whirling dervish, dust devil, or willy-willy) (Reed, 1999; American Meteorological Society, 2012b, 2016) suggest that these vortices are manifestations of capricious intelligences. Meteorological science, however, has demonstrated that they instead are generated by the intense convection that forms over a strongly heated surface, particularly in dry atmospheric conditions (Kanak et al., 2000; Balme and Greeley, 2006). Therefore, Kurgansky (2005) named them “dry convective helical vortices” (DCHVs). And like the airy spirits they were once thought to be, DCHVs mostly remain unseen, only appearing to the naked eye when they are strong enough to mobilize sediment and entrain dust (generally clay and silt-sized particles).

DCHVs on Earth are thought to be weaker than the weakest tornadoes. Thermodynamic models treat them as heat engines powered directly by insolation, which implies horizontal winds of 11–16 m s^{-1} and vertical winds of 8–16 m s^{-1} for a typical case (Rennó et al., 1998). Thus, horizontal winds in DCHVs are below 29 m s^{-1}: the minimum velocity on the Enhanced Fujita (EF) Scale used to rate tornadoes (Wind Science and Engineering Center of Texas Tech University, 2006). Observations agree quite well with this thermodynamic theory (Sinclair, 1966; Kaimal and Businger, 1970; Schwiesow and Cupp, 1976; Bluestein et al., 2004). For instance, DCHVs can mobilize and entrain small mammals such as kangaroo rats and rabbits. By dropping kangaroo rats and jackrabbits from a tower, Ives (1947) found that their terminal velocity was 11–13 m s^{-1}, which should be the necessary updraft velocity for a DCHV to keep them aloft. The direct energy source for tornadoes is the release of latent heat from condensing water vapor, a means by which the atmosphere can store solar radiation on time scales of a few days and release it in a matter of minutes. However, the maximum wind speeds in tornadoes can exceed the predictions of thermodynamic models by a factor of two (a factor of four in kinetic energy) (Bluestein et al., 1993): an observation attributed to instability and breakdown of the tornadic vortex as its circulation adjusts to a pressure field that the circulation itself is rapidly modifying (Fiedler, 1994). So it is not entirely surprising that DCHVs of likely tornadic intensity are known anecdotally. Idso and Kimball (1974) cite reports of dust devils destroying a livery stable and a church under construction. In late October of 2013, a DCHV was observed on video detaching a side mirror from a motor vehicle in Hartford, Connecticut, USA (Parmenter, 2013).

Benison (2017, p. 423 in this issue of *Geology*) shifts the concept of tornadic-strength DCHVs from anecdote to actualism by describing the salar (saline pan) of Gorbea in Chile’s high Andes Mountains, whose sedimentary geological characteristics appear to record something unusual about the area’s meteorology. Salar Gorbea is covered by dozens of pools possibly excavated by wind erosion. Bladed-habit gypsum crystals, a few centimeters wide and up to 27 cm long, precipitate at the bottom of these pools. Once the pools dry out, these crystals are exposed at the surface. The flats and dunes of the salar are covered by massive deposits of gypsum crystals of similar size and internal microtexture to those in the pools. However, the surfaces of these crystals are abraded, frosted, and pitted: textures characteristic of sand and silt grains that have experienced aeolian transport in suspension. Benison also reports that Salar Gorbea is a site where large DCHVs occur. During the few days when this remote field site was studied, three DCHVs with diameters of up to 500 m were seen, as well several smaller ones. Based on the combined set of geological and meteorological observations, Benison proposes that the DCHVs are responsible for transporting the gravel-sized gypsum crystals.

This argument is not airtight, as Benison readily admits. Suspended gravel-sized gypsum crystals were not directly observed in the DCHVs. Moreover, aeolian deposits of millimeter-to-centimeter–sized particles formed by non-vortex winds of ~40 m s^{-1} have been described in Antarctica and Argentina (Bendixon and Isbell, 2007; Milana, 2009; Gillies et al., 2012; de Silva et al., 2013). Such non-vortex flows cannot be excluded at Salar Gorbea. Nevertheless, these isolated examples of aeolian gravel transport bolster the idea that the Salar Gorbea deposits represent the extreme end of the velocity distribution of aeolian transport. The question that remains is how strong would the wind need to be to transport the gypsum crystals of Salar Gorbea.

This question can be addressed theoretically by assuming that each gypsum crystals is large enough to be in turbulent flow relative to the wind, as implied by equation 11 of Gu et al. (2006), and is approximately cylindrical. In that case, the drag coefficient depends on the density and aspect ratio of the particle (Isaacs and Thodos, 1967). Applying equations 13 and 14 of Gabitto and Tsouris (2008), the estimated terminal velocity for a gypsum crystal of 27 cm length and 4 cm diameter being transported with its long side parallel to the ground in a 300 K atmosphere at 4000 m above sea level would be 79 m s^{-1}, and up to 230 m s^{-1} with its long side perpendicular to the ground (the former attitude and velocity is much more likely than the latter). Modeling of tornadic vortices that accounts for vortex breakdown effects (e.g., Fiedler and Rotunno, 1986; Rotunno et al., 2016) suggests that peak vertical velocities are approximately twice the tangential velocities. Thus, any vortex transporting the gypsum particles would contain horizontal velocities of ≈40–120 m s^{-1}, a range that spans the entire EF scale. The velocity of aeolian transport at Salar Gorbea is indeed extreme.

Therefore, in the context of meteorology, Benison has identified an unusual site with potentially frequent, intense DCHVs in a setting channelized by the local topography. This area could be studied by *in situ* measurements or radar (e.g., Bluestein et al., 2004), to understand why DCHVs become so intense here and also to study the dynamics of tornadic-strength vortices in a potentially advantageous field environment.

Moreover, as highlighted by Benison, Salar Gorbea is a geologically significant site as well. The stratigraphic record may contain any number of gravel-sized deposits of aeolian origin that record extreme wind events in Earth’s past, whether from tornadoes, DCHVs, or non-vortex winds. Most

GEOLOGY, May 2017; v. 45; no. 5; p. 479–480 | doi:10.1130/focus052017.1

immediately, these deposits would be an engaging illustration of actualism: that the processes that we observe in the present shaped the past. But given the role that extreme winds and potentially coincident phenomena (such as hail or fire) can play in disturbing the species composition and structure of terrestrial ecosystems (e.g., Glitzenstein and Harcombe, 1988; Hjelmfelt, 2010; Gower et al., 2015), Benison may expand the range of explanations for local-scale variability in paleontological and paleoecological characteristics just as much as it does for variability in sedimentology.

REFERENCES CITED

American Meteorological Society, 2012a, Whirlwind: Glossary of Meteorology: http://glossary.ametsoc.org/wiki/Whirlwind (accessed February 2017).

American Meteorological Society, 2012b, Dust whirl: Glossary of Meteorology: http://glossary.ametsoc.org/wiki/Dust_whirl (accessed February 2017).

American Meteorological Society, 2013, Tornado: Glossary of Meteorology: http://glossary.ametsoc.org/wiki/Tornado (accessed February 2017).

American Meteorological Society, 2016, Dust devil: Glossary of Meteorology: http://glossary.ametsoc.org/wiki/Dust_devil (accessed February 2017).

Balme, M., and Greeley, R., 2006, Dust devils on Earth and Mars: Reviews of Geophysics, v. 44, RG3003, doi:10.1029/2005RG000188.

Bendixon, Q.D., and Isbell, J.L., 2007, Gravel dunes formed by eolian processes in a cold dry environment, Allan Hills, Antarctica: A possible Mars analogue: Geological Society of America Abstracts with Programs, v. 39, no. 6, p. 143.

Benison, K.C., 2017, Gypsum gravel devils in Chile: Movement of largest natural grains by wind?: Geology, v. 45, p. 423–426, doi:10.1130/G38901.1.

Bluestein, H.B., Ladue, J.G., Stein, H., Speheger, D., and Unruh, W.F., 1993, Doppler radar wind spectra of supercell tornadoes: Monthly Weather Review, v. 121, p. 2200–2222, doi:10.1175/1520-0493(1993)121<2200:DRWSOS>2.0.CO;2.

Bluestein, H.B., Weiss, C.C., and Pazmany, A.L., 2004, Doppler radar observations of dust devils in Texas: Monthly Weather Review, v. 132, p. 209–224, doi:10.1175/1520-0493(2004)132<0209:DROODD>2.0.CO;2.

de Silva, S.L., Spagnuolo, M.G., Bridges, N.T., and Zimbelman, J.R., 2013, Gravel mantled megaripples of the Argentinean Puna: A model for their origin and growth with implications for Mars: Geological Society of America Bulletin, v. 125, p. 1912–1929, doi:10.1130/B30916.1.

Fiedler, B.H., 1994, The thermodynamic speed limit and its violation in axisymmetric numerical simulations of tornado-like vortices: Atmosphere-ocean, v. 32, p. 335–359, doi:10.1080/07055900.1994.9649501.

Fiedler, B.H., and Rotunno, R., 1986, A theory for the maximum windspeeds in tornado-like vortices: Journal of the Atmospheric Sciences, v. 43, p. 2328–2340, doi:10.1175/1520-0469(1986)043<2328:ATOTMW>2.0.CO;2.

Gabitto, J., and Tsouris, C., 2008, Drag coefficient and settling velocity for particles of cylindrical shape: Powder Technology, v. 183, p. 314–322, doi:10.1016/j.powtec.2007.07.031.

Gillies, J.A., Nickling, W.G., Tilson, M., and Furtak-Cole, E., 2012, Wind-formed gravel bed forms, Wright Valley, Antarctica: Journal of Geophysical Research, v. 117, F04017, doi:10.1029/2012JF002378.

Glitzenstein, J.S., and Harcombe, P.A., 1988, Effects of the December 1983 tornado on forest vegetation of the Big Thicket, southeast Texas, USA: Forest Ecology and Management, v. 25, p. 269–290, doi:10.1016/0378-1127(88)90092-8.

Gower, K., Fontaine, J.B., Birnbaum, C., and Enright, N.J., 2015, Sequential Disturbance Effects of Hailstorm and Fire on Vegetation in a Mediterranean-Type Ecosystem: Ecosystems (New York, N.Y.), v. 18, p. 1121–1134, doi:10.1007/s10021-015-9886-5.

Gu, Z., Zhao, Y., Li, Y., Yu, Y., and Feng, X., 2006, Numerical simulation of dust lifting within dust devils—Simulation of an intense vortex: Journal of the Atmospheric Sciences, v. 63, p. 2630–2641, doi:10.1175/JAS3748.1.

Hjelmfelt, M.R., 2010, Microbursts and macrobursts: Windstorms and blowdowns, *in* Johnson, E.A., and Miyanishi, K., eds., Plant Disturbance Ecology: The Process and the Response: Burlington, Massachusetts, Academic Press, p. 59–95.

Idso, S.B., and Kimball, B.A., 1974, Tornado or dust devil: The enigma of desert whirlwinds: American Scientist, v. 62, p. 530–541.

Isaacs, J.L., and Thodos, G., 1967, The free-settling of solid cylindrical particles in the turbulent regime: Canadian Journal of Chemical Engineering, v. 45, p. 150–155 .

Ives, R.L., 1947, Behavior of dust devils: Bulletin of the American Meteorological Society, v. 28, p. 121–125.

Kaimal, J.C., and Businger, J.A., 1970, Case studies of a convective plume and a dust devil: Journal of the Atmospheric Sciences, v. 9, p. 612–620.

Kanak, K.M., Lilly, D.K., and Snow, J.T., 2000, The formation of vertical vortices in the convective boundary layer: Quarterly Journal of the Royal Meteorological Society, v. 126, p. 2789–2810, doi:10.1002/qj.49712656910.

Kurgansky, M., 2005, A simple model of dry convective helical vortices (with applications to the atmospheric dust devil): Dynamics of Atmospheres and Oceans, v. 40, p. 151–162, doi:10.1016/j.dynatmoce.2005.03.001.

Milana, J.P., 2009, Largest wind ripples on Earth?: Geology, v. 37, p. 343–346, doi:10.1130/G25382A.1.

Parmenter, A., 2013, Ghostly Image Damages Officer's Car: http://www.nbcconnecticut.com/news/local/Strange-Weather-Vortex-Caught-on-Camera-230124431.html (accessed February 2017).

Reed, M., 1999, Weather Talk: Sometimes the weather gives you the willies: Weatherwise, v. 52, p. 43, doi:10.1080/00431679909604261.

Rennó, N.O., Burkett, M.L., and Larkin, M.P., 1998, A simple thermodynamical theory for dust devils: Journal of the Atmospheric Sciences, v. 55, p. 3244–3252, doi:10.1175/1520-0469(1998)055<3244:ASTTFD>2.0.CO;2.

Rotunno, R., Bryan, G.H., Nolan, D.S., and Dahl, N.A., 2016, Axisymmetric tornado simulations at high Reynolds number: Journal of the Atmospheric Sciences, v. 73, p. 3843–3854, doi:10.1175/JAS-D-16-0038.1.

Schwiesow, R.L., and Cupp, R.E., 1976, Remote Doppler velocity measurements of atmospheric dust devil vortices: Applied Optics, v. 15, p. 1–2, doi:10.1364/AO.15.000001.

Sinclair, P.C., 1966, A quantitative analysis of the dust devil [Ph.D. thesis]: Tucson, University of Arizona, 292 p.

Wind Science and Engineering Center of Texas Tech University, 2006, A Recommendation for an Enhanced Fujita Scale: Wind Science and Engineering Center of Texas Tech University Report (paper copy, 111 p.): Lubbock, Texas, Texas Tech University: http://www.depts.ttu.edu/nwi/Pubs/FScale/EFScale.pdf (accessed February 2017).

Printed in USA