DUSTY CONVECTION ON MARS: PROGRESS AND PROSPECTS N.G. Heavens, [1,2], [1]Department of Atmospheric and Planetary Sciences, Hampton University, 154 William R. Harvey Way, Hampton, VA, 23668, Nicholas.heavens@hamptonu.edu; [2]Space Science Institute, 4750 Walnut St. Suite 205, Boulder, CO, 80301, nheavens@spacescience.org

Introduction: The absorption of shortwave radiation by mineral dust in Mars's thin atmosphere long has been recognized as a potentially potent energy source for the atmospheric circulation at multiple scales [1]. At mass mixing ratios of 100s of ppm, atmospheric heating rates within a dusty airmass may be comparable to latent heating rates in deep convective clouds [2]. This possibility suggests an analogy between moist convection in Earth's atmosphere and convection driven by dust heating in Mars's atmosphere.

Here I review current progress in the understanding of dusty convection on Mars, particularly advances since the 8th International Conference on Mars in 2014, as well as identify key areas of uncertainty for future research to address.

Shallow and Deep Convection: The altitudes which Martian dust clouds reach are quite variable. One line of evidence for widespread shallow convection associated with dusty airmasses comes from analyzing the positive temperature response at ~ 25 km altitude to regional dust storm activity, which is interpreted to originate from a mixture of direct shortwave heating and indirect dynamical heating in the descending branch of the principal meridional overturning circulation. During a typical Mars Year, two to four regional dust storm events produce a significant planetary-scale temperature response at ~ 25 km [3]. But during Mars Year 30, these events were exceptionally weak [3]. Yet 11 regional dust storms were observed in visible imagery [4], suggesting that some proportion of regional dust storms do not mix significant dust above the boundary layer.

The importance of shallow dusty convection and its distinction from deep convection has been further underlined by close study of the "texture" or fine-scale morphology of Martian dust clouds in Mars Global Surveyor Mars Orbiter Camera (MGS-MOC) and Mars Reconnaissance Orbiter Mars Color Imager [5,6], which builds upon the systematic study of clouds in Viking imagery by [7] and occasional identification of cumuliform clouds in large-scale dust events [8,9]. Cumuliform or "puffy" texture is recognized by [6] as one of three dominant textural types along with "pebbly" and "plume-like." While texture within large-scale dust storm activity can be quite diverse, certain areas do seem to be hotspots of particular textures [6]. For instance, Noctis Labyrinthus in eastern Tharsis is a hotspot of puffy textures, while plume-like textures are commonly observed in N. Amazonis/S. Arcadia [6].

Interpretation of texture is somewhat contested. In the view of [6], plume-like texture arises from advection of dust from a putative, focused plume-head source by strong winds, and pebble-like texture is associated with strongly sheared, widespread boundary layer convection actively lifting dust. A study of dust storm activity focused in N. Amazonis/S. Arcadia [10] instead suggested that the plumes were actually shallow convective roll structures, that is three-dimensional boundary layer convection organized into two-dimensional convection by strong wind shear: a phenomenon with a well-known Earth analog [11]. If that view is correct, pebbly texture is probably associated with boundary layer convection in lower shear environments. But [5,6,10] all recognize or demonstrate that puffy texture indicates that a dust cloud extends significantly above the boundary layer: a deep convective cloud.

Energetics of Deep Convection: The perspective on heating rates in dust clouds in [2] is based on dust devils, whose extreme winds can generate high dust concentrations (> 1000 ppm) on the < 500 m (and usually <<500 m) horizontal scales of these systems. Mesoscale modeling of dust storms, however, has primarily considered the phase space where dust mass mixing ratios are below 100 ppm, with mixed results in simulating deep convection in dust storms [12,13].

Studies of deep convective structures, however, suggest dust mass mixing ratios >>100 ppm at 10 km scales are possible [14,15]. Dust cloud heating rates on the order of 10 W kg^{-1} seem plausible, placing the energetics of deep convective clouds on Mars within the phase space of severe tropical cyclone eyewalls and squall lines in the Earth's atmosphere. Nevertheless, outstanding questions remain about estimating effective dust cloud heating rates while taking account of multiple scattering, short length scales for extinction near the surface, water ice cloud formation, and non-local thermodynamic effects in the middle atmosphere [16].

Mesoscale Organization of Deep Convection:

Textural studies [5,6] as well as studies of individual dust storms [10,17] suggest the level/type of organization in dust storms varies widely. One outstanding question is whether dust storms are/contain convectively organized circulations analogous to mesoscale convective systems and/or severe tropical cyclones. One argument in favor of this idea is the observation of deep dusty convective structures on Arsia Mons and Olympus Mons (and nearby areas) during globally quiet weather conditions [14], which is hypothetically connected to daytime convergent upslope flow toward their summits [18,19]. That a strong mesoscale circulation, even in the absence of dust, develops on these mountains may help generate and focus deep convection-enabling, extremely dusty airmasses on these mountains that would otherwise rapidly diffuse and advect away from them. And so when deep convective structures appear in other areas during large-scale dust storm activity, it seems plausible that deep convective structures are likewise associated with strong mesoscale circulation. Yet directly measuring these circulations remains an outstanding problem.

Deep Convection and the Vertical Distribution of Dust: Dusty convective processes now appear essential to understanding inhomogeneous layering in the vertical dust distribution. A recent modeling study [20] was able to reproduce most aspects of the vertical dust distribution during the dustier second half of the Martian year by parameterizing convective plume injection by dust storms. Nevertheless, it remains unclear how to interpret and reproduce the layered dust distribution in the first half of the year as well as its high amplitude of diurnal variability [21, 22].

Dusty deep convection is rare/weak enough that dust above 50 km is unusual outside of global and regional dust events [14, 23-25]. The study in [25] is particularly valuable in detecting rare grain size changes in middle atmospheric dust that suggest deep convective plumes transport a continuous distribution of dust sizes up to 2 μm or more that sediments/size-segregates within a sol or so, so that only $O(100)$ nm-sized particles remain.

Deep Convection and the Vertical Distribution of Water: Dusty convective processes also may explain the episodic mixing/inhomogeneity in the vertical distribution of water vapor into the middle atmosphere first identified by [26, 27]. That is, vertically ascending airmasses containing dust lifted from the surface may carry boundary layer concentrations of water vapor along with it. Both direct and indirect remote sensing methods suggest that water concentrations an order of magnitude above climatology (up to 250 ppmv) reached the polar middle atmosphere within the first two weeks of the 2007 and 2018 global dust storms [15, 24, 28,29].

Vulnerable to photolysis from solar EUV, water transported to the middle atmosphere during dust storms is a large, potential source of atomic hydrogen to the upper atmosphere [30,31]. And thus, understanding dusty convective processes may be critical to reconstructing the history of water loss during the Amazonian. And indeed, taking account of the potentially high altitude that moist convection might reach under Mars's low gravity during Noachian and Hesperian time, this leak of water to the middle/upper atmosphere might be of general significance to the history of Martian escape.

Simulating the impact of dusty convection on the water cycle is still in its early stages. A recent study with a model that did not include mesoscale convection (but was advanced in its treatment of gravity waves/tides) seems to underestimate vertical mixing in the tropics and winter extratropics during the 2007 global dust event [cf. 32 and 24]. The author is currently leading an effort to develop explicit convective parameterizations of mixing [33] in parallel with efforts like [20].

Deep Convection As A Gravity Wave Source: Mesoscale modeling suggests that dusty deep convective structures generate gravity waves [13] just as deep convection on Earth does [35]. A survey of gravity wave activity at ~25 km altitude has found ambiguous evidence of dusty convective generation of gravity waves but underlines the difficulties of observing this phenomenon with currently available methods [36].

References: [1] P.J. Gierasch and R.M. Goody (1973), *JAS*, 30, 169-179. [2] S.D. Fuerstenau (2006), *GRL*, 33, L19S03. [3] D.M. Kass et al. (2016), GRL, 43, 6111-6118. [4] H. Wang and M.I. Richardson (2015), *Icarus*, 251, 112-127. [5] S.D. Guzewich et al. (2015), *Icarus*, 258, 1-13. [6] L. Kulowski et al. (2017), *Adv. Space. Res.*, 59., 715-721. [7] R. Kahn (1984), *JGR*, 89, 6671-6688. [8] S.C.R. Rafkin (2003), 1st International Workshop on the Mars Atmosphere. [9] M.J. Strausberg et al. (2005), *JGR*, 110, E02006. [10] N.G. Heavens (2017), *JAS*, 1011-1037. [11] G.S. Young et al. (2002), *Bull. Amer. Met. Soc.*, 83, 997-1001. [12] S.C. R. Rafkin (2009), *JGR,* 114, E01009. [13] A. Spiga et al. (2013), *JGR Planets*, 118, 746–767. [14] N.G. Heavens et al. (2015), *GRL*, 42, 3730-3738. [15] N.G. Heavens et al. (2018), AGU Fall Meeting, P43J-3859. [16] S.D. Eckermann et al. (2011), *Icarus*, 211, 429-442; [17] A. Määttänen et al. (2009), *Icarus*, 201, 504-516. [18] W.K. Hartmann (1978), *Icarus*, 33, 380-387. [19] S.C.R. Rafkin et al. (2002), *Nature*, 419, 697-699. [20] C. Wang et al. (2018), *JGR Planets*, 123, 982-1000. [21] S.D. Guzewich et al. (2013), *JGR Planets*, 118, 1177-1194. [22] N.G. Heavens et al. (2014), *JGR Planets*, 119, 1748-1774. [23] A. Kleinböhl et al. (2015), *Icarus*, 261, 118-121. [24] N.G. Heavens et al. (2018), *Nature Astron.* 2, 126-132. [25] R.T. Clancy et al. (2019), *Icarus*, 328, 246-273. [26] L. Maltagliati et al. (2011), *Science*, 333, 1868-1871. [27] L. Maltagliati et al. (2013), *Icarus*, 223, 942-962. [28] A. Fedorova et al. (2018), *Icarus*, 300, 440-457. [29] A.C. Vandaele et al. (2019), *Nature*, 568, 521-525. [30] M.S. Chaffin et al. (2014), *GRL*, 41, 314-320. [31] M.S. Chaffin et al. (2017), *Nature Geosci.*, 10, 174-178. [32] D.S. Shaposhnikov et al. (2019), *GRL*, in press, doi: 10.1029/2019GL082839. [34] M. Witek et al., this meeting. [35] J. Yue et al. (2013), *JGR Atmos.*, 118, 3178-3191. [36] N.G. Heavens (2017), AGU Fall Meeting, P23D-2766.