DEVILS, PLUMES, ROCKETS, JUMPS: THE "FUNKY" MARS.

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Introduction

Recent observational and modeling studies have shed light on the key role of mesoscale phenomena in driving the Martian climate and giving rise to remarkable signatures in the temperature, wind, pressure, and aerosol fields of the Martian atmosphere. At the mesoscale, Mars appears as an intense and exotic counterpart to the Earth (Figure 1), mainly as a result of pronounced diurnal and regional contrasts of surface temperature, and the much thinner atmosphere.

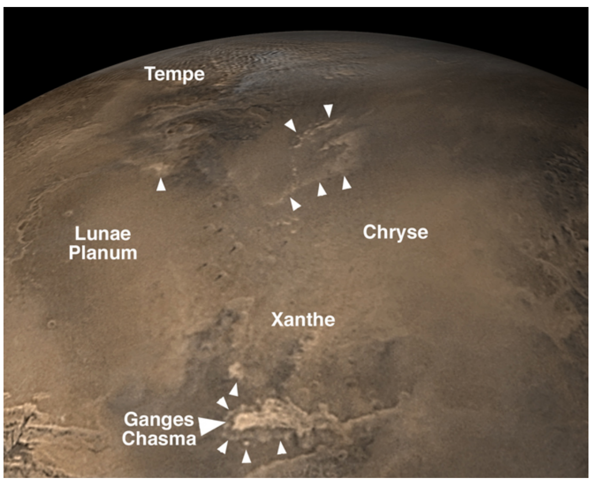

Figure 1: *The mesoscale zoo: a variety of phenomena at horizontal scales left unresolved by Global Climate Models. MGS/MOC imagery, Malin Space Science Systems, 02/2002.*

Mesoscale and microscale processes are left unresolved by Global Climate Models (GCMs), yet they are a particularly "funky" (e.g., energetic) side of the Martian meteorology (Figure 2), which implications extend much further than their dynamical interest for local meteorology and their potential qualification as atmospheric hazards for Martian robotic and human exploration. The variety and behavior of those phenomena are worthy of interest because of their impact on the Martian climate, dust, water, and CO_2 cycles, but also because key characteristics of the Martian atmosphere are unveiled and a comparative meteorology approach can be drawn with the terrestrial environment.

Here some of the most prominent and powerful mesoscale phenomena on Mars are described through a combination of dedicated high-resolution atmospheric modeling, and recent remote-sensing observations. We employ our Martian limited-area model (Spiga and Forget, 2009; Spiga et al., 2010) with the inclusion of the recent improvements in the LMD GCM (Madeleine et al., 2011, 2012). We use horizontal resolutions adapted to the dynamical phenomena we aim to resolve: from several tens of kilometers to compute regional winds (mesoscale simulations) to several tens of meters to compute atmospheric boundary-layer winds (microscale or turbulent-resolving simulations, also called Large-Eddy Simulations, LES). Apart from the meteorological analysis in itself, our modeling results draw perspectives for developing new subgrid-scale parameterizations to improve the predictions of Martian GCMs.

Figure 2: *A particularly funky metaphor for mesoscale and microscale meteorology on Mars. This band plays an apparent role as a catharsis by releasing the accumulation of energy through small-scale motions.*

Plumes and devils

The Planetary Boundary Layer (PBL) convection, also named shallow convection on Earth, is actually not so shallow on Mars: daytime turbulent plumes can reach about one atmospheric scale height. An accurate parameterization of the mixing of heat, momentum, tracers by PBL plumes is crucial to ensure the reliability of the predictions of GCMs and mesoscale models. To represent the effect of organized turbulent structures (updrafts and downdrafts) on the daytime PBL transport, we adapted a "thermal plume" model, recently developed for Earth climate modeling (Hourdin et al., 2002), to Martian GCMs, mesoscale models, and single-column models (Colaïtis et al., 2013). Results of LESs were used to constrain the parameterization. We find that the terrestrial thermal plume model needs to be modified to satisfyingly account for deep turbulent plumes found in the Martian convective PBL. Our Martian thermal plume model qualitatively and quantitatively reproduces the thermal structure of the daytime PBL on Mars: superadiabatic near-surface layer, mixing layer, and overshoot region at PBL top. Using a thermal plume model moreover enables a first-order estimation of key turbulent quantities (e.g., PBL height and convective plume velocity) in Martian GCMs and MMs without having to run costly LESs (Figure 3).

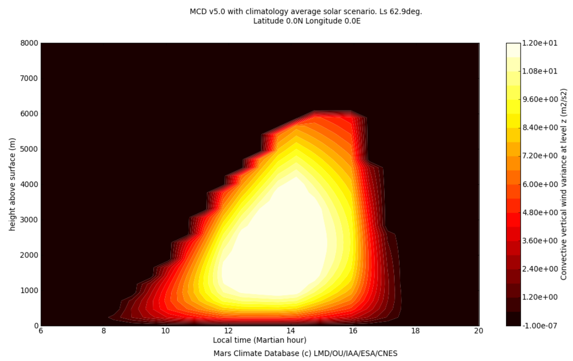

Figure 3: *PBL vertical wind variance computed using the thermal plume model of Colaïtis et al. (2013) and scaling laws in Spiga et al. (2010). This figure was obtained from the online Mars Climate Database version 5.0 based on recent GCM simulations including the new thermal plume model for PBL mixing.*

PBL is also important for dust lifting and transport by the widespread phenomena of dust devils, i.e. daytime convective vortices in the PBL being materialized as dusty whirlwinds by the dust particles lifted and transported in the vortex. In addition to many observational studies discussing the characteristics and variability of dust devils (e.g., Balme et al., 2012; Reiss et al., 2014), there is an ongoing debate about how much dust devils contribute to the maintenance of the background dust layer on Mars. Parameterizations of those effects in GCMs are based on heat engine arguments Renno et al. (1998); yet another possibility to parameterize those effects is to represent the overall statistical behavior of convective vortices in the PBL. This idea stems from recent studies discussing whether the distributions of dust devil sizes and pressure drops follow an exponential law (Pathare et al., 2010) or a power law (Lorenz, 2011). We use the fact that most turbulent motions responsible for boundary layer mixing in afternoon convective conditions – including convective vortices – are resolved through LES. We detect vortices (pressure drops) in a 10 m resolution LES and conduct a statistical analysis of the sizes of those vortices. Preliminary results tend to show that the sizes of convective vortices resolved through LES follow a power law of exponent 3 (i.e. a straight line in log-log histogram, see Figure 4). An in-depth sensitivity study will need to be carried out to be able to design a stochastic GCM parameterization of dust transport within dust devils.

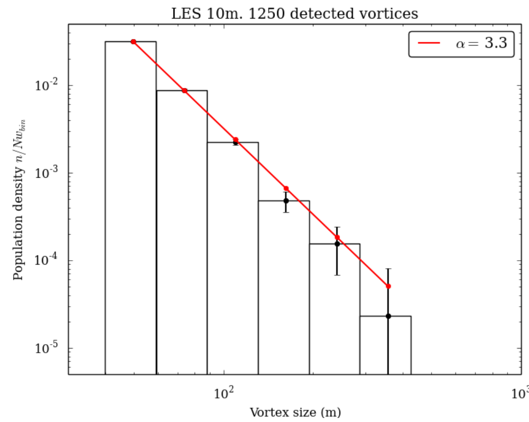

Figure 4: *Statistics of convective vortices' size obtained from a* 10*-m resolution LES in Phoenix-like environmental conditions. Logarithmic axis is used both for normalized populations and vortex sizes following the advice by Lorenz (2011).*

Rocket dust storms

Deep convective motions could occur in Martian local and regional dust storms. We name this phenomenon "rocket dust storm", or "conio-cumulonimbus", given the implied fast and powerful vertical transport (Spiga et al., 2013). The supply of convective energy is provided by the absorption of incoming sunlight by dust particles, rather than by latent heating as in moist convection on Earth and other environments (Figure 5). Dust-driven deep convection on Mars has potentially strong implications for the Martian atmospheric physics and dynamics, including the formation of high-altitude detached layers of aerosols (Heavens et al., 2011), or the emission of gravity waves.

Given their influence on the thermal structure at the global scale (Guzewich et al., 2013), detached layers of aerosol needs to be represented in GCMs. The global circulation is not able to maintain such layers alone, hence it is needed to parameterize the putative mesoscale processes that could lead to their formation, should those be rocket dust storms and/or orographic circulations (Rafkin et al., 2002). We will discuss our project to develop a physically-based parameterization for rocket dust storms in the LMD GCM. This aims not only to better constrain the influence of dust on the Martian thermal structure, but also to study how mesoscale deep

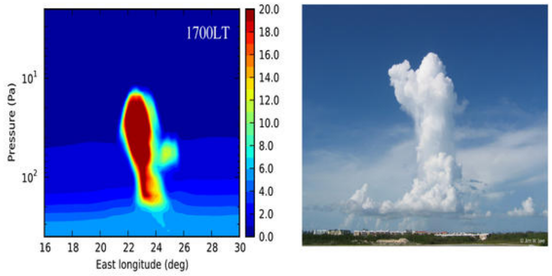

Figure 5: *Rocket dust storm (shown in the dust density-scaled opacity field) or conio-cumulonimbus (Spiga et al., 2013) (left) vs. terrestrial cumulonimbus (right, source: NOAA website).*

convective motions and the general circulation couple to transport dust from the Martian surface to the mesosphere.

Dust-driven convection also offers new perspectives to study the onset, variability, and dynamics of larger (and sometimes planet-encircling) regional storms that might behave like Mesoscale Convective Systems on the Earth. The case of the 2001 global dust storm is particularly interesting given the fast development and amplification of the initial regional dust storm in the northern Hellas region, suggesting that mesoscale processes are at play (Figure 6).

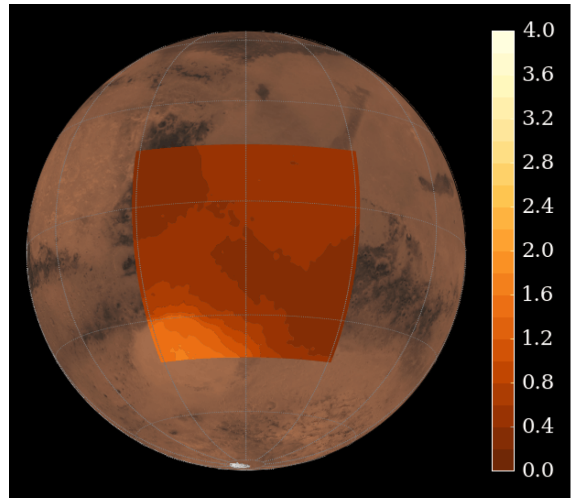

Figure 6: *Dust column opacity simulated during two sols around $L_s = 185°$ in the Hellas region where the 2001 planet-encircling dust storm originated. A mesoscale model with interactive dust scheme and dust lifting is used as in Spiga et al. (2013), except that lifting parameters are modified: threshold $u_{*t} = 0.8$ m s^{-1} and efficiency $\alpha = 2 \times 10^{-5}$ m^{-1}.*

Katabatic jumps

While observations of clear-cut katabatic events are difficult on Earth, except over vast ice sheets, those intense downslope circulations are widespread on Mars owing to near-surface radiative cooling and uneven topography. Their intensity and regularity can be witnessed through numerous aeolian signatures on the surface, and distinctive thermal signatures in the steepest craters and volcanoes (Spiga et al., 2011).

Katabatic winds also play an important role in the Martian polar regions, especially given the recent confirmation through radar observations of the plausible role of aeolian processes in shaping the water ice cap on geological timescales (Holt et al., 2010). Of peculiar interest are the long clouds appearing at the bottom of polar troughs (Figure 7) which suggest that ice migration might occur presently, as part of a "cyclic step" process (Smith et al., 2013). An analogy with the terrestrial "wall-of-snow" over e.g. Antarctica slopes or coastlines posits that those clouds are caused by local katabatic jumps, also named Loewe phenomena, which can be deemed similar to first order to hydraulic jumps in fluid mechanics.

Is this scenario supported by modeling? We show in Figure 7 the results from a nested simulation reaching a resolution of 250 m in the fifth nest located at one northern polar trough where clouds were observed by Smith et al. (2013). This demonstrates that our mesoscale model is capable to reproduce katabatic jumps at the location where trough clouds are observed, with strong ascending motions at the jump reaching 1 m s^{-1} – a significantly high value in a polar environment where the atmosphere is often stable and devoid of strong vertical motions. Future mesoscale modeling in continuation of this preliminary work seeks to explore the transport of water vapor, the formation of water ice clouds, and the stability and possible migration over geological timescales of water ice surface reservoirs.

Conclusion

Mesoscale modeling contributes to unveil how variable the Martian atmosphere is at small scales – below the ones usually resolved through GCMs. It allows for new interpretations of puzzling phenomena monitored from in-situ measurements or orbital remote sensing; and for getting a "big picture" of the Martian meteorological variability where the intimate link between the large-scale, the mesoscale, and the microscale is better characterized. Extending our knowledge of the Martian climate is the best way to characterize the present Martian environment, extrapolate to the past one, and prepare the next generation of missions to Mars.

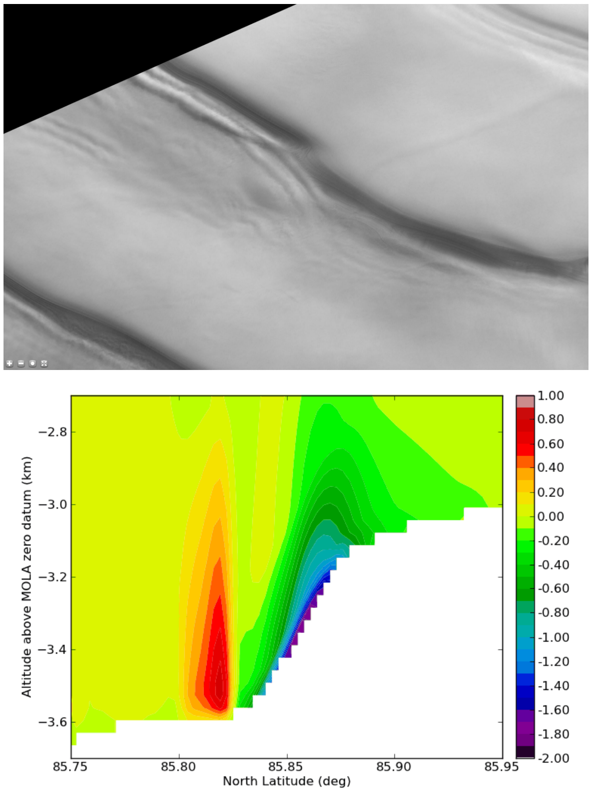

Figure 7: *Top plot displays an HRSC image from (Smith et al., 2013) showing a trough cloud over the Martian northern polar cap. Bottom plot shows the result of a nested 3D mesoscale simulations which can reproduce the katabatic jumps occurring in polar troughs, and putatively giving rise to trough clouds; vertical velocity field is shown at longitude -43°E in nest 5.*

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