Intense fine-scale meteorology on Mars described through simulations with a new mesoscale model based on WRF dynamical core and LMD Martian physics.

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1 Introduction

Recent missions to Mars yielded unprecedented views of the Red Planet. Since the 1990's, high-resolution measurements carried out by the instruments onboard Mars Global Surveyor, Mars Express and Mars Reconnaisance Orbiter revealed the diversity of the Martian meteorological phenomena at various horizontal scales below 100 kilometers: fronts, slope winds, gravity waves, dust storms, dust devils... Combining modeling to data analysis appears necessary to fully understand the atmospheric physics and dynamics underlying the results of in-situ or orbital Martian exploration. The need to complement Martian global circulation models (GCM) with numerical tools able to resolve atmospheric dynamics from the meso-scale (100-1 km) to the micro-scale (< 1 km, where larger turbulent eddies are computed by the model) is thus critical.

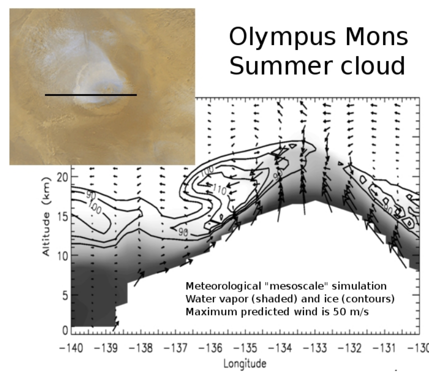

Figure 1: The ability of the model to transport tracers at regional scales is exemplified by model's prediction for the altitude of the Tharsis topographical water ice clouds in the afternoon. *Small plot* Mars Orbiter Camera image of Olympus Mons taken in 2002. *Main plot* Longitude-altitude cross-section of water mass mixing ratio in a 20 km Martian mesoscale simulation over the Olympus Mons volcano in summer; water vapor is shaded, water ice is contoured, wind vectors are superimposed.

2 Model description

Three-dimensional Martian mesoscale models were built by coupling state-of-the-art terrestrial regional climate models with physical parameterizations of the Martian environment initially developed for the Martian GCMs [7, 15]. This report details results of a novel Martian mesoscale model based on WRF and developed at the Laboratoire de Météorologie Dynamique (LMD). This is an independent effort compared to the PlanetWRF model [8], more focused on large-scale applications.

The model combines the NCEP-NCAR fully compressible nonhydrostatic ARW-WRF dynamical core [9], adapted to Mars (planetary constants, calendar, no ocean...), with the "state-of-the-art" physical parameterizations developed since the early 90s in the LMD Martian GCM by [2]: radiative transfer with CO2 and dust; turbulent diffusion; soil model; water and CO_2 ice clouds model; dust sedimentation and lifting; microphysics and chemistry. Surface static data (topography, thermal inertia, albedo) in the mesoscale domain are extracted from maps derived from recent spacecraft measurements (mostly Mars Global Surveyor datasets). LMD-GCM results are used every Martian hour to constrain the mesoscale model at the domain boundaries, in order to correctly account for strong impact of Martian thermal tides on near-surface meteorology. The use of the same Martian physical parameterizations both in the mesoscale model, and in the GCM that is providing initial and boundary conditions to the mesoscale model, ensures a high level of downscaling consistency. Invoking physical packages often with respect to the dynamical computations was found to be necessary to accurately account for near-surface friction effects where the wind acceleration is particularly high, typically in regions of strong Martian topographically-driven circulation. To define the initial state and the atmosphere at the domain boundaries, a specific "hybrid" vertical interpolation from the coarse-resolution GCM fields to the high-resolution mesoscale domain is used to ensure the stability and the physical relevancy of the simulations. A crude extrapolation of the near-surface GCM fields to the mesoscale levels, usually acceptable for terrestrial applications, cannot be used on Mars where, owing to the low density and heat capacity of the Martian atmosphere, terrain-following behavior is observed for near-surface temperature.

Characteristics and test simulations with the model are described in [11]. Used in synoptic-scale mode with cyclic domain wrapped around the planet, the LMD Mesoscale Model correctly replicates the main large-scale thermal structure and the zonally-propagating waves. The model diagnostics of near-surface pressure, wind and temperature daily cycles in Chryse Planitia are in accordance with the Viking and Pathfinder measurements. The ability of the model to transport tracers at regional scales is exemplified by model's prediction for the altitude of the Tharsis topographical water ice clouds in the afternoon (Figure 1).

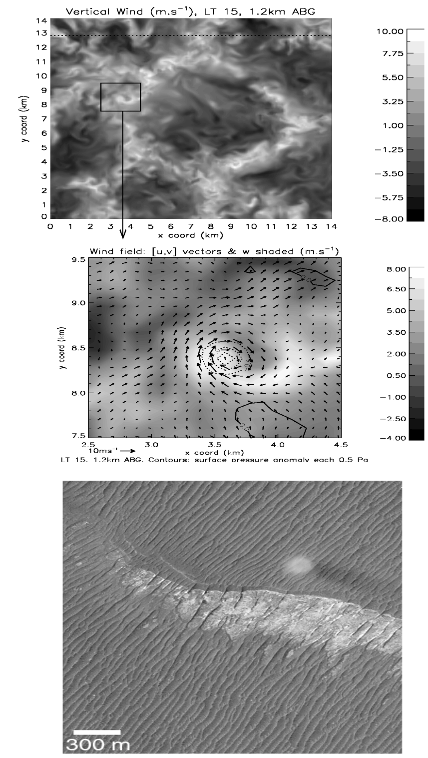

Figure 2: Large-Eddy Simulations are useful to describe the mixing layer growth during the afternoon and the associated dynamics: convective motions, overlying gravity waves and numerous dust devil-like vortices which appear at the intersection of simulated polygonal cells. *Top plots* Vertical velocity horizontal section 1.2 km above the surface at local time 15:00, showing the entire simulation domain (horizontal resolution is 100 m) and enhanced view of a particular vortical structure with superimposed horizontal wind vectors, as well as contours corresponding to the surface pressure (negative) perturbation. *Bottom plot* Mars Orbiter Camera image of a dust devil in the Mela Chasma region taken in 1999.

3 Regional variability in boundary layer convection

Our mesoscale model can be used at high resolution (¡ 100m grid spacing) in Large-Eddy Simulations. In idealized conditions simulating an infinite flat plain, turbulent motions responsible for boundary layer mixing in afternoon convective conditions are resolved. Those simulations are useful to describe the mixing layer growth during the afternoon and the associated dynamics [14, 5] : convective motions, overlying gravity waves and numerous dust devil-like vortices (Figure 2). Recently, mixing layer depths in various Martian regions were determined through Mars Express radio-occultations [3]. In low latitudes, the Martian convective boundary layer appeared to extend at higher altitudes over high plateaus than in lower plains despite similar surface temperatures. Through Large-Eddy Simulations (Figure 3), it is possible to relate such behaviour with the dominant radiative forcings of the Martian boundary layer [12]. Mars appears in striking contrast with terrestrial arid conditions where sensible heat flux dominates [10]. New scaling laws must be built for the Martian example to account for the turbulent heat flux not being maxi-mum near the surface but a few hundreds meters above it.

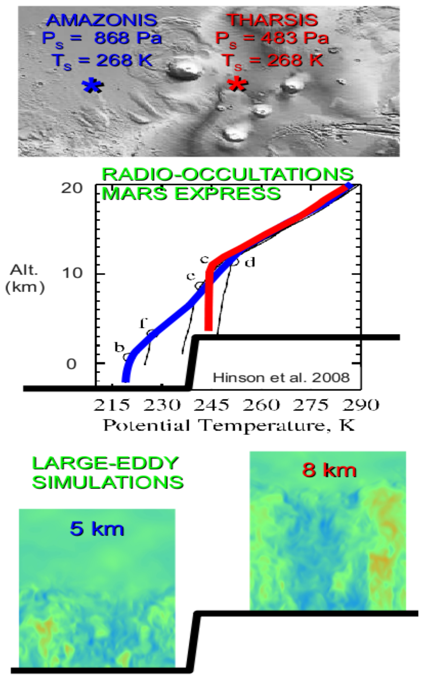

Figure 3: Recently, mixing layer depths in various Martian regions were determined through Mars Express radio-occultations. In low latitudes, the Martian convective boundary layer appeared to extend at higher altitudes over high plateaus than in lower plains despite similar surface temperatures, a behaviour which is reproduced by Large-Eddy Simulations including radiative transfer. *Top plots* Topographical map of the Amazonis/Tharsis region and vertical profiles of potential temperature obtained through radio-occultations on board Mars Express orbiter. *Bottom plots* Horizontal/vertical section of vertical velocity (arbitrary units) showing 50 m LES predictions of mixing layer heights.

4 Powerful slope winds and thermal impact

Our mesoscale model is a suitable tool to describe circulations in the vicinity of Martian topographical obstacles. Novel diagnostics can be derived, such that the fact that nighttime surface temperature over slopes is strongly influenced by mesoscale atmospheric dynamics. An alternate explanation can thus be proposed to account for the 15-20 K surface warmings over the slopes of Olympus Mons observed by Thermal Emission Spectrometer (hitherto believed to be mostly caused by contrasts of surface thermophysical properties, i.e. thermal inertia). Observed nighttime warmings around Olympus Mons are qualitatively and quantitatively reproduced in dedicated mesoscale simulations with uniform surface thermophysical properties (Figure 4). Strong katabatic winds blowing over Olympus slopes warm the atmosphere through compressional heating and enhance sensible heat flux (usually low on Mars) which in turn warms the surface [13]. This phenomenon have strong implications for meteorology and geology: 1. surface temperature measurements might be used to validate predicted slope winds; 2. retrievals of thermal inertia from orbit are impacted over Martian slopes (and not only over Olympus Mons, but also e.g. over low-inertia cratered terrains like Meridiani Terra); 3. slope winds on Mars have a thermal influence on the surface in addition to aeolian erosional effects.

5 The need to explore gravity wave activity

Our mesoscale model is useful to assess Martian dynamical effects unresolved by global circulation models, despite being crucial in controlling large-scale circulations. This is the case for gravity waves. Seldom observations are available, but observational clues are building up as new missions operate on Mars. For instance, new observations of fluctuations in the 1.27 microns O_2 dayglow emission obtained through Mars Express/OMEGA imaging spectrometry are reminiscent of gravity wave activity [1]. This provides important information to constrain gravity wave activity predicted through mesoscale modelling, which appears in reasonable agreement with those observations. Investigating gravity waves through fine-scale modelling is an important task to determine forcings caused in the higher atmosphere by their propagation and breaking (and to improve their parameterization in coarser-resolution models). In a different topic, gravity wave might be key to trigger the formation of high-altitude CO_2 clouds, some of which having a possible convective origin that remains to be found [4].

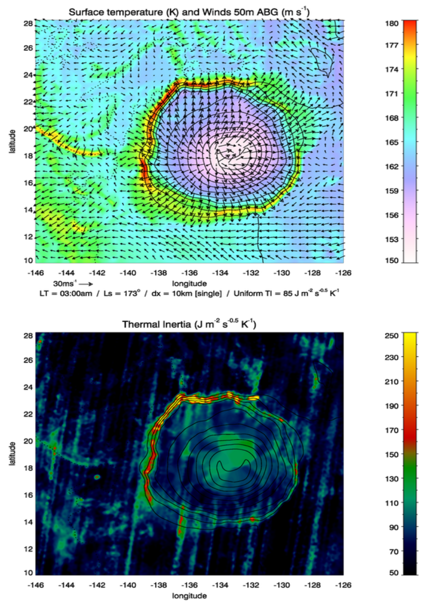

Figure 4: Mesoscale modeling show that 15-20 K nighttime surface warmings over the slopes of Olympus Mons observed by thermal infrared spectrometry, hitherto believed to be related to thermal inertia contrasts, are caused by powerful katabatic circulations. *Top plot* Mesoscale model predictions of horizontal wind and surface temperature over the Olympus Mons volcano in northern fall nighttime conditions (predictions for surface temperature are in close agreement with observations of thermal infrared spectrometry despite an assumed uniform thermal inertia in the simulations). *Bottom plot* Apparent thermal inertia retrievals based on surface temperature measurements obtained through infrared spectrometry (dataset described in [6]).

6 Perspectives

Not only the Martian experience would be helpful to prepare future robotic and human exploration of this environment, to yield further comparative planetology elements with the Earth, but it will path the way for studies of small scales processes on other planetary environments such as Titan, Venus, giant planets, ...

References

[1] F. Altieri, A. Spiga, L. Zasova, G. Bellucci, and J. P. Bibring. Gravity waves in mars polar regions: O_2 airglow maps and mesoscale modelling. Geophys. Res. Lett. (submitted), 2010.

[2] F. Forget, F. Hourdin, R. Fournier, C. Hourdin, O. Talagrand, M. Collins, S. R. Lewis, P. L. Read, and J-P. Huot. Improved general circulation models of the Martian atmosphere from the surface to above 80 km. *J. Geophys. Res.*, 104:24,155–24,176, 1999.

[3] D. P. Hinson, M. Pätzold, S. Tellmann, B. Häusler, and G. L. Tyler. The depth of the convective boundary layer on Mars. *Icarus*, 198:57–66, 2008.

[4] A. Määttänen, F. Montmessin, B. Gondet, F. Scholten, H. Hoffmann, E. Hauber, F. González-Galindo, A. Spiga, F. Forget, G. Neukum, J.-P. Bibring, and J.-L. Bertaux. Mapping the mesospheric co_2 clouds: Mex/omega and mex/hrsc observations and challenges for atmospheric models. Icarus (in press), 2010.

[5] T. I. Michaels and S. C. R. Rafkin. Large eddy simulation of atmospheric convection on Mars. *Q. J. R. Meteorol. Soc.*, 128, 2004.

[6] N. E. Putzig and M. T. Mellon. Apparent thermal inertia and the surface heterogeneity of Mars. *Icarus*, 191:68–94, 2007.

[7] S. C. R. Rafkin, R. M. Haberle, and T. I. Michaels. The Mars Regional Atmospheric Modeling System: Model Description and Selected Simulations. *Icarus*, 151:228–256, 2001.

[8] M. I. Richardson, A. D. Toigo, and C. E. Newman. PlanetWRF: A general purpose, local to global numerical model for planetary atmospheric and climate dynamics. *J. Geophys. Res.*, 112(E09001), 2007.

[9] W. C. Skamarock and J. B. Klemp. A time-split nonhydrostatic atmospheric model for weather research and forecasting applications. *Journal of Computational Physics*, 227:3465–3485, 2008.

[10] A. Spiga. Elements of comparison between martian and terrestrial mesoscale meteorological phenomena: Katabatic winds and boundary layer convection. Planetary and Space Science, in press, 2010.

[11] A. Spiga and F. Forget. A new model to simulate the Martian mesoscale and microscale atmospheric circulation: Validation and first results. *Journal of Geophysical Research (Planets)*, 114(E13):2009–+, 2009.

[12] A. Spiga, F. Forget, S. R. Lewis, and D. P. Hinson. Structure and dynamics of the convective boundary layer on mars as inferred from large-eddy simulations and remote-sensing measurements. *Quarterly Journal of the Royal Meteorological Society*, 136:414–428, 2010.

[13] A. Spiga, S. R. Lewis, F. Forget, E. Millour, L. Montabone, and J.-B. Madeleine. The Impact of Katabatic Winds on Martian Thermal Inertia Retrievals. In *Lunar and Planetary Institute Science Conference Abstracts*, volume 41 of *Lunar and Planetary Inst. Technical Report*, pages 1533–+, 2010.

[14] A. D. Toigo, M. I. Richardson, S. P. Ewald, and P. J. Gierasch. Numerical simulation of Martian dust devils. *Journal of Geophysical Research (Planets)*, 108:5047–+, 2003.

[15] D. Tyler, J. R. Barnes, and R. M. Haberle. Simulation of surface meteorology at the Pathfinder and VL1 sites using a Mars mesoscale model. *Journal of Geophysical Research (Planets)*, 107:5018–+, 2002.