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MARTIAN MESO-/MICRO-SCALE WINDS & SURFACE ENERGY BUDGET.

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Introduction and general discussion

Regional, diurnal and seasonal variations of surface temperature are particularly large on Mars. This is mostly due to the Martian surface remaining close to radiative equilibrium. Contrary to most terrestrial locations, contributions of sensible heat flux (i.e. conduction/convection exchanges between atmosphere and surface) to the surface energy budget [hereinafter SEB] are negligible on Mars owing to low atmospheric density and heat capacity (e.g. Figure 2 in Savijärvi and Kauhanen, 2008). This radiative control of surface temperature is a key characteristic of the Martian environment and has crucial consequences on the the Martian geology, meteorology, exobiology, etc.

In order to identify the impact of this Martian peculiarity to near-surface regional-to-local atmospheric circulations, we employ our recently-built Martian limited-area meteorological model (Spiga and Forget, 2009). 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).

Our discussions herein focus on the contribution to surface energy budget of sensible heat flux, which couples atmospheric temperature, surface temperature and near-surface winds. We show that, while daytime boundary layer convection indicates the prominence of radiative forcing over sensible flux over flat terrains (Spiga et al., 2010, and first section of this abstract), this is no longer true over slopes, as e.g. nighttime katabatic winds can cause sensible heat flux to become comparable to radiative flux (Spiga et al., 2011, and second section of this abstract). The contribution of sensible heat flux to the surface energy budget has been overlooked thus far: the Martian surface and atmosphere are more coupled than hitherto thought.

SEB drives wind: exotic boundary layer convection

In idealized conditions simulating an infinite flat plain, turbulent motions responsible for boundary layer mixing in afternoon convective conditions are resolved through Large-Eddy Simulations with grid spacing 50 m (Spiga et al., 2010). Mixing layer depths in various Martian

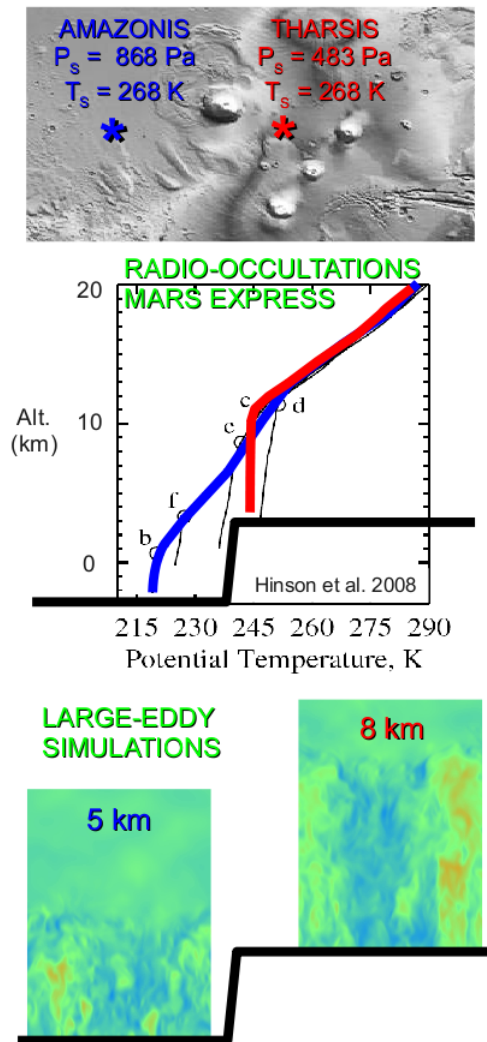


Figure 1: Mixing layer depths in various Martian regions have been determined through Mars Express radio-occultations. In low latitudes, the Martian convective boundary layer appears to extend at higher altitudes over high plateaus than in lower plains despite similar surface temperatures, a behaviour 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.

regions have been determined through Mars Express radio-occultations (Hinson et al., 2008), hence can be compared to model predictions to help to identify the underlying physical processes governing their behaviour. In low latitudes, both in observations and in simulations, the Martian convective boundary layer appears to extend at higher altitudes over high plateaus (e.g. Tharsis) than in lower plains (e.g. Amazonis) despite similar surface temperatures. Through Large-Eddy Simulations (Figure 1), it is possible to relate such behaviour to the dominant radiative forcing of the Martian boundary layer through a so-called “pressure effect” (equations and detailed explanations can be found in Spiga et al., 2010, note also that a similar effect is observed in very dusty boundary layer in the Saharian desert). Mars appears in striking contrast with terrestrial dry conditions where sensible heat flux dominates (Spiga, 2011). New scaling laws must be built for the Martian example to account for the turbulent heat flux not being maximum near the surface but a few hundreds meters above it.

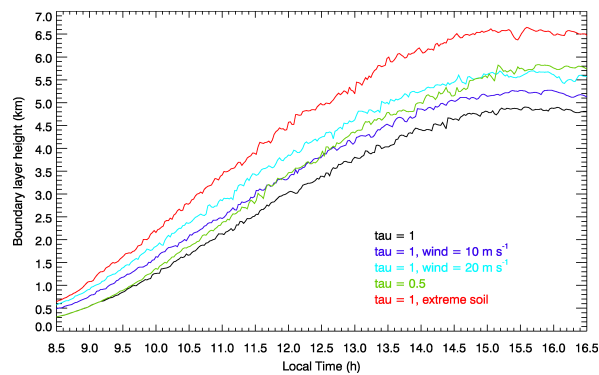


Figure 2: The evolution of daytime convective boundary layer height for a set of LES results in which various dust opacity or background wind were assumed. Simulations have been carried out all things being equal, in a “reference” Meridiani Terra site. Note that dust opacity is supposed to be uniform in the whole domain (well-mixed hypothesis).

Figure 2 shows that background wind and dust opacity can influence the mixing layer depths too, but more as second-order contributions. It is not possible to account for the nearly 3 km boundary layer depth difference between the Tharsis and Amazonis cases (cf. Figure 1) with even the most extreme combination of those two factors.

LES modeling also showed that maximum friction velocities in the boundary layer (caused by dust devils) follow the same tendency as the boundary layer depth: larger velocities are observed in regions where surface is higher and pressure is lower (Spiga and Lewis, 2010, and Lewis et al., this issue, Figure 2). This could explain e.g. why dust devils are found over Arsia Mons where density is very low (Reiss et al., 2009), hence lifting of dust from the surface much more difficult than in

lower-latitude Martian terrains. We found that enhanced friction velocity over the volcano would be large enough to compensate the decrease in density to yield a similar wind stress as in lower-altitude terrains.

SEB is driven by winds: slope thermal departures

To describe circulations in the vicinity of Martian topographical obstacles, mesoscale simulations are employed. We found that surface temperature can be impacted by mesoscale atmospheric circulations associated to the presence of topography. According to nighttime TES measurements in various non-dusty seasons, the Martian surface is up to 20 K warmer on slopes than on surrounding plains in the Olympus Mons/Lycus Sulci region.

Thus far, it has been thought that such behaviour was due to contrasts in soil thermophysical properties, especially thermal inertia (see e.g. Mellon et al., 2000, for a comprehensive description of this parameter and its retrieval from orbit through infrared spectrometry). We show through mesoscale modeling that those warm surface departures in the night, correlated with slope steepness, could just as well be accounted for by mesoscale atmospheric winds only, notably powerful katabatic winds which form over Martian sloping terrains all night long in various seasons. Observed nighttime warmings around Olympus Mons are indeed qualitatively and quantitatively reproduced in dedicated mesoscale simulations with uniform surface thermophysical properties (Figure 3). Katabatic winds are found to have a twofold impact on the Martian local atmosphere and surface: 1. their vertical component yields adiabatic compression of air, thereby atmospheric heating that could overwhelm infrared radiative cooling; 2. their along-slope horizontal component enhances sensible heat flux, thereby allowing for atmospheric heating described in point 1 to warm the surface, as sensible heat flux becomes comparable to radiative contributions [see Figure 4].

Despite the low density of the Martian atmosphere, sensible heat flux cannot be systematically neglected in surface energy budget: over Martian slopes in the night, it can become comparable to longwave radiative loss. Hence surface temperature can be far from radiative equilibrium over numerous sloping terrains on Mars, where the atmosphere adopts a more earth-like behaviour. Part of the surface temperature signal conveys information about slope winds.

One consequence is that warm signatures of surface temperature over slopes, observed through infrared spectrometry, cannot be systematically associated to contrasts of intrinsic soil thermal inertia. Apparent thermal inertia maps retrieved thus far possibly contain wind-induced structures. This also makes surface temperature maps in uneven terrains of great potential value to validate katabatic wind speeds predicted through mesoscale

Martian Meso-/Micro-Scale Winds & Surface Energy Budget

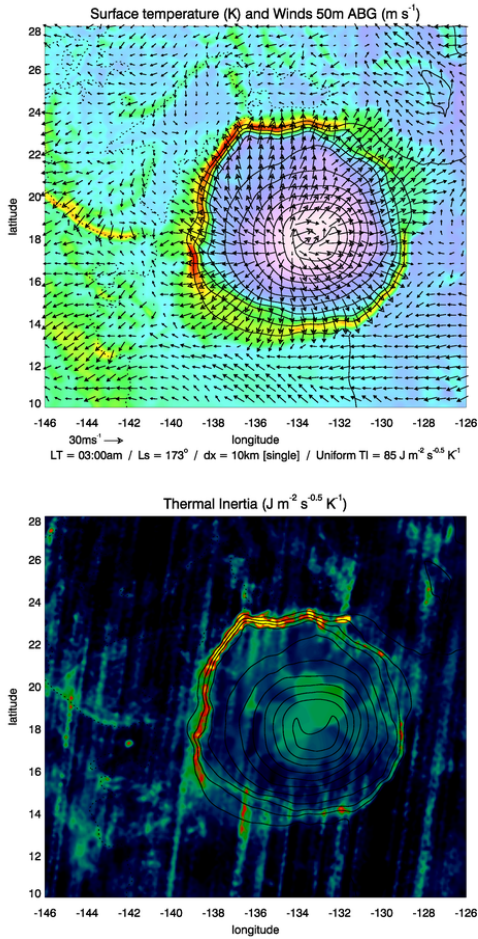


Figure 3: Mesoscale modeling show that 15-20 K nighttime surface warmings over the slopes of Olympus Mons observed by thermal infrared spectrometry, hitherto believed to be related to thermal inertia contrasts, are caused by powerful katabatic circulations. *Top plot* Mesoscale model predictions of horizontal 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 (Putzig and Mellon, 2007).

modeling, provided systematic intrinsic thermal inertia contrasts can be ruled out through geological analysis.

We showed that katabatic winds can have a strong thermal impact, in addition to their well-known aeolian influence. The impact of mesoscale winds on surface temperature (hence possibly on retrievals of apparent thermal inertia) is particularly prominent over steep slopes in low thermal inertia terrains. Olympus Mons is only an example amongst others: observations and mesoscale modeling indicate that e.g. Terra Meridiani cratered terrains are prone to the same phenomenon.

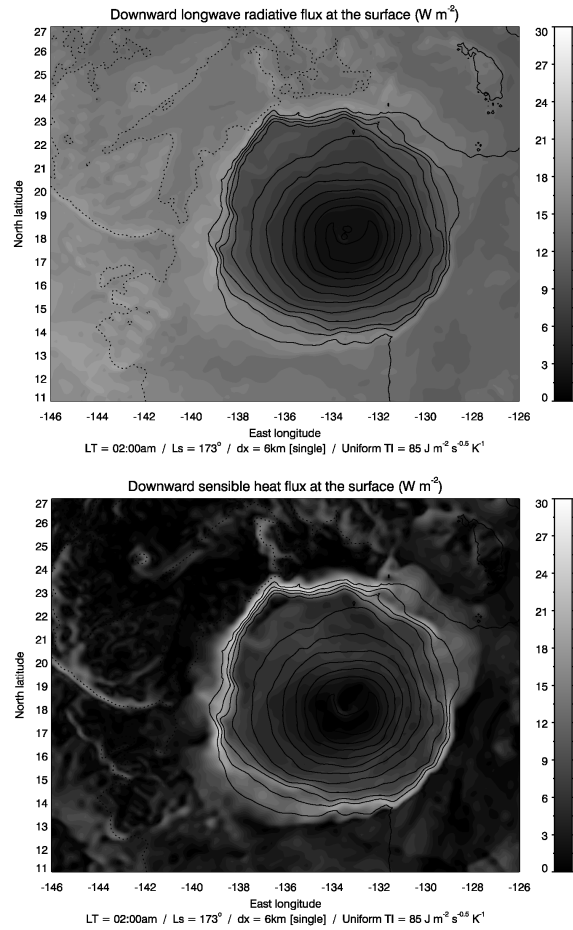


Figure 4: Despite the low density of the Martian atmosphere, sensible heat flux cannot be systematically neglected in surface energy budget: over Martian slopes in the night, it can become comparable to longwave radiative loss. Hence surface temperature can be far from radiative equilibrium over numerous sloping terrains on Mars. *Top* Downward longwave radiative flux (W m⁻²) and *bottom* downward sensible heat flux (W m⁻²) at the surface predicted in the Olympus Mons/Lycus Sulci area by the mesoscale simulation. Topography is contoured. Sensible heat exchanges warm the surface in white areas (bottom plot).

Our conclusions offer the possibility of improved future thermal inertia retrievals, unambiguously representing intrinsic characteristics of Martian soil, which would complement e.g. the recent efforts by Putzig and Mellon (2007) to take into account surface heterogeneities. The effect is even general enough to apply under daytime conditions, thereby providing a possible explanation for observed afternoon surface cooling, and to ice-covered terrains, thereby providing new insights on how winds could have shaped the present surface of Mars [Figure 5].

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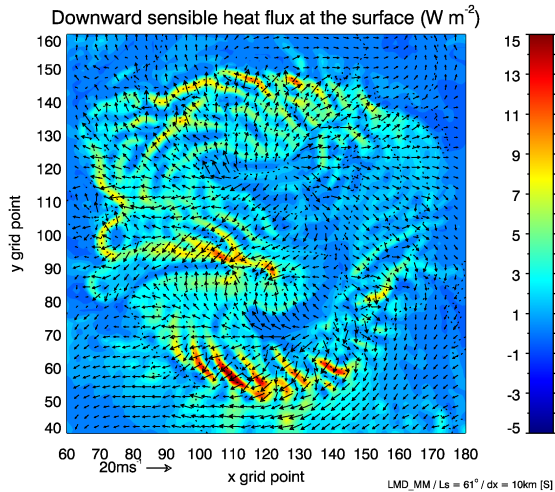


Figure 5: The effect is general enough to apply to ice-covered terrains, thereby providing new insights on how winds could have shaped the present surface of Mars. Downward sensible heat flux (W m^{-2}) and superimposed horizontal wind vectors 10 m above local surface (m s^{-1}) predicted in the northern polar region by a mesoscale simulation with 10 km horizontal resolution and polar stereographic projection. Season is northern spring, universal time 09:00. Topography is contoured. Vectors each 3 grid points. Sensible heat exchanges act to warm the surface in yellow/red areas of this figure.

Conclusion

This work exemplifies how studying the Martian meso- and micro-scale circulations through observations or modeling: 1. gives insights into key characteristics of the Martian environment, through phenomena usually left unresolved by general circulation models; 2. results in constraints not only on the meteorology but also on the geology of Mars; 3. represents a rich source for comparative planetology approach

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