Structure and dynamics of the Martian boundary layer: remote sensing, Large-Eddy Simulations and comparative meteorology

Aymeric SPIGA[1,2], François FORGET[1], Stephen R. LEWIS[2], David P. HINSON[3]

[1]*Laboratoire de Météorologie Dynamique, Université Pierre et Marie Curie, Paris, FR, spiga@lmd.jussieu.fr*
[2]*Dept of Physics and Astronomy, The Open University, Milton Keynes, UK*
[3]*Carl Sagan Centre, SETI Institute, Mountain View, USA*

ABSTRACT

We describe the structure of the Martian convective Boundary Layer (BL) by a novel approach combining modeling and data analysis. Mars Express radio-occultation (RO) temperature profiles by Hinson et al. [2008] are compared to Large-Eddy Simulations (LES) performed with the Martian Mesoscale Model by Spiga and Forget [2009]. The dramatic regional variations of the BL depth revealed by RO are quantitatively reproduced by the Martian LES. Intense BL dynamics is found to underlie the measured depths (up to 9 km): vertical speed up to 20 m s^{-1}, turbulent heat flux up to 2.7 K m s^{-1} and convective turbulent kinetic energy up to 26 m^2 s^{-2}. Under specific conditions, both the model and the measurements show a distinctive positive correlation between surface topography and BL depth. Our interpretation is that, in the tenuous CO2 Martian near-surface environment, the daytime BL is to first order controlled by the infrared radiative heating, fairly independent of elevation, which implies a simple correlation between the BL potential temperature and the inverse pressure ("pressure effect"). No prominent "pressure effect" is in action on Earth where sensible heat flux dominates the BL energy budget. The strong radiative control of the Martian convective BL implies a generalised formulation for the BL dimensionless quantities. Based on this formulation and the variety of simulated BL depths by the LES, new similarity relationships for the Martian convective BL in quasi-steady midday conditions are derived. Rigorous comparisons between the Martian and terrestrial BL are now made possible by such similarity laws.

1. INTRODUCTION

Spatial exploration of Mars showed the intensity of Martian boundary layer (BL) processes, driven by large diurnal surface temperature variations [1]: convective heat flux three times larger than in the terrestrial environment [2], wide dust devils with high altitude extent [3], strong daytime super-adiabatic near-surface gradients of temperature (5 to 10 K m^{-1}) [4] and large fluctuations of near-surface temperature over short timescales [5].

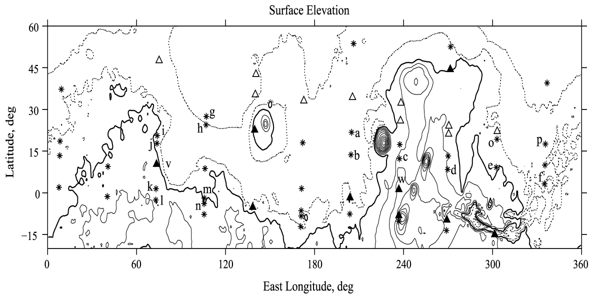

Figure 1. *Map of surface elevation derived from measurements by the Mars Global Surveyor laser altimeter. The elevation is 0 km along the heavy line. The dotted lines denote negative elevation. The contour interval is 2 km at elevations lower than +10 km, increasing to 2.5 km at higher elevations. In this report, we consider cases* b *in Amazonis Plains (- 3.6 km) and* c *in Tharsis plateaus (+ 2.5 km). From Hinson et al., 2008 [13].*

This context of observational achievements motivated studies based on numerical modeling. Parameterised single-column models were employed to interpret in-situ measurements and clarified the role of radiation in the Martian boundary layer energy budget [6, 7]. Since the beginning of the 2000's, the dynamics of the Martian convective boundary layer is analysed by means of Large Eddy Simulations (LES) [8, 9, 10, 11, 12], where grid spacing in Martian mesoscale models is lowered to a few tens of metres so as to resolve the larger turbulent eddies, responsible for most of the energy transport within the convective boundary layer. Through LES, the fine-scale structure of the Martian daytime BL, dominated by convective processes, can be analyzed: mixed-layer growth, polygonal cells, thermal updrafts and convective vortices.

To date LES studies have mostly centred on idealised numerical experiments, which have produced plausible results with respect to the limited observations available. The quantitative validation of LES diagnostics against existing data remains to be done. One of the main limiting factors is the paucity of data covering the entire vertical extent of the Martian BL. This limitation was recently addressed with the Mars Express RO experiment [13]. Temperature profiles were obtained with good vertical resolution and coverage at latitudes and local times where BL convection is occurring, permitting an unprecented estimation of convective BL depth. We report hereinafter the first quantitative comparison between LES predictions and actual measurements on Mars. We also show how this effort allows us to describe the structure and dynamics of the Martian convective BL and differences with its terrestrial counterpart. These results are published in Quarterly Journal of Royal Meteorological Society [14].

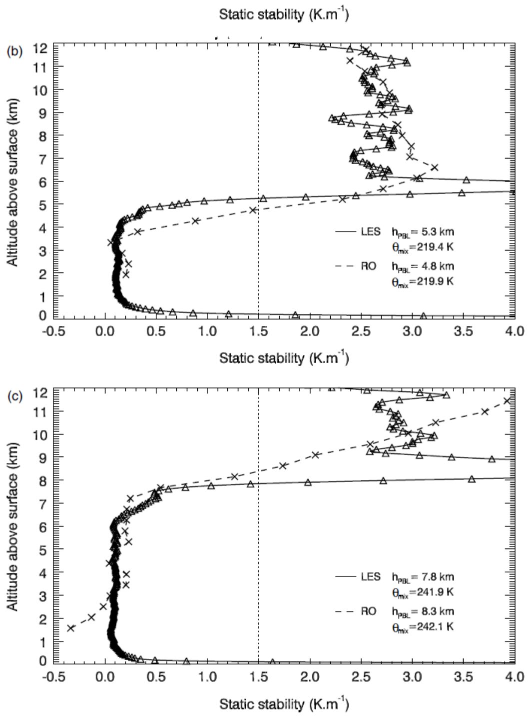

Figure 2. *Vertical profiles of static stability at local time 17:00 predicted by Large-Eddy Simulations (full lines and triangles) and obtained through radio-occultation measurements (dashed lines and crosses) for cases* b *and* c *(see Figure 1). Boundary-layer depths andmixed-layer potential temperatures are shown. Note that, for the sake of consistency, height above the surface is obtained by upward integration of the hydrostatic equation, using the (simulated and measured) temperature and pressure profiles. From Spiga et al., 2010 [14].*

2. MARTIAN LARGE-EDDY SIMULATIONS

LES presented in this study are performed a Martian Mesoscale/Microscale Model [12] combining the ARW-WRF fully compressible nonhydrostatic dynamical core [15] with the comprehensive set of physical parameterisations (in particular, radiative transfer) for Martian dust, CO2, water and photochemistry cycles in the LMD Global Climate Model (GCM) [16]. Details of simulations settings and sensitivity studies are not detailed here for the sake of brevity [cf. 14]. Note that, as far as integration of fluid dynamics equations and sub-grid scale parameterizations are concerned, the adopted strategy is closed to the approach usually adopted for terrestrial LES experiments with WRF [17].

Typical Martian LES experiments showed that [see 18 and references therein] Martian daytime BL turbulence is about one order of magnitude more vigorous than on Earth: vertical eddy heat flux and TKE are respectively of the order 1 K m s^{-1} and 10 m^2 s^{-2}, updrafts could easily reach 10 to 15 m s^{-1}. Daytime convective BL is significantly deeper on Mars than it is on Earth: typical Martian BL depths exceed extreme terrestrial values over desert regions (5 km), while maximum depths are over 10 km. Around local time 11:00, the growing Martian BL already extends higher than the fully-developed terrestrial BL over land in mid-latitudes (1 to 2 km).

3. STRUCTURE AND VARIABILITY OF THE MARTIAN CONVECTIVE BOUNDARY LAYER

The main conclusion of the RO measurements is the identification of dramatic regional contrasts of the depth of the convective BL on Mars [H08]. Notably, while the mixed layer is 5 km deep in Amazonis Planitia low plains, it reaches 8 km in Tharsis high plateaus, although surface temperatures are similar (owing to similar incoming sunlight and soil thermal properties). Figure 1 and 2 shows that these dramatic regional variations of convective BL depth are predicted by our LES. Surface altimetry strongly influences the regional variability of daytime BL growth when considering locations at constant latitude and local time.

Agreement between LES BL depth predictions and RO measurements is a step toward a better understanding of the Martian convective BL. High-resolution numerical modeling complements the RO observations acquired on a considerably larger area than the width of typical convective cells. The model offers a wealth of diagnostics not available in the data which enables us to get insights into the BL dynamics associated to regional differences in BL depth. Intense BL dynamics is found to underlie the measured depths (up to 9 km): vertical speed up to 20 m s^{-1}, turbulent heat flux up to 2.7 K m s^{-1} and convective turbulent kinetic energy up to 26 m^2 s^{-2}.

How could the variability of BL depth on Mars be accounted for? Consider a point at the bottom of the mixed-layer or, equivalently, at the top of the surface layer (typically a few tens of metres above ground). Values of pressure p and potential temperature θ are close to values of surface pressure (we assume that regional variations of pressure p only arise from contrasts in elevation) and mixed-layer potential temperature. Evolution of θ with time t is given by

$$c_p \frac{\partial \theta}{\partial t} = \left(\frac{p_0}{p}\right)^{R/c_p} \left(\mathcal{J}_{\rm LH} + \mathcal{J}_{\rm LW} + \mathcal{J}_{\rm SW}\right) - c_p \frac{\partial \langle w'\theta' \rangle}{\partial z}$$

with p_0 reference pressure value 610 Pa on Mars, c_p specific heat capacity, R ideal gas constant, w vertical velocity, z altitude above the surface. We define atmospheric heating rates in daytime conditions in K s^{-1}: J_{LH} condensation/evaporation energy transfers, J_{LW} divergence of net infrared radiative flux and J_{SW} divergence of net shortwave radiative flux. The righmost term in the equation is a combination of molecular transfer from heated surface in the microlayer and small-scale turbulent transport in the surface layer. At the bottom of the mixed layer, i.e. at a small distance dz above the surface layer top, it writes

$$\rho\, c_p\, \mathrm{d}\langle w'\theta' \rangle \approx \rho\, c_p\, \langle w'\theta' \rangle_z - H_{\rm s}$$

where ρ is the atmospheric density and H_s is the effective sensible heat flux.

On Earth, in daytime conditions, the influence of sensible flux H_s is overwhelmingly dominant and the latent component J_{LH} can be of importance outside arid regions. In contrast to these two terms, radiative contributions J_{LW} and J_{SW} are usually negligible. Thus, in terrestrial arid regions, total atmospheric heating rate is approximately zero; it follows from the equation describing the evolution of θ that atmospheric pressure plays no particular effect. Regional variations of daytime potential temperature on Earth are mostly caused by contrasts in sensible flux H_s: terrestrial conditions are not generally conducive to warmer potential temperatures in the daytime BL at higher elevations.

Owing to lower atmospheric density, thermal inertia and specific humidity on Mars, the two dominant contributions to the energy budget of terrestrial daytime near-surface atmosphere have less impact on Mars. Major contributors to the total heating rate are, in contrast to the terrestrial environment, the radiative terms J_{LW} and J_{SW}. This is a consequence of the predominance of CO_2 and dust in the tenuous Martian atmosphere. Upwelling thermal infrared radiation from the insolated soil is prone to strong net absorption by the colder atmospheric CO_2 and, to lesser extent, H_2O and dust [7]. Up to several 100s of metres above ground, from mid-morning to late afternoon, the infrared term J_{LW} dominates the BL energy budget [6], although the sensible contribution H_s cannot be totally neglected. Only in very dusty conditions, direct absorption of incoming solar radiation in the visible by airborne dust J_{SW} significantly contributes to the total heating rate.

Surface temperature controls the daytime BL potential temperature on Mars as it is the case on Earth, but for distinct reasons. In great contrast to terrestrial conditions, the Martian BL is strongly controlled by radiation. It follows from the equation describing the evolution of θ that the atmospheric pressure close to the surface layer (~ surface pressure) plays a particular role. BL potential temperature is even directly correlated to surface altimetry, if total heating rate does not vary much with pressure (or, equivalently, altimetry). This is exactly what occurs with the dominant infrared radiative heating J_{LW} of the Martian BL.

Consider indeed two locations with distinct altitudes but similar soil properties and insolation conditions -- e.g. cases *b* in Amazonis and *c* in Tharsis (see Figure 1). The Martian surface is close to radiative equilibrium, as influence of sensible and latent heat fluxes is negligible in the soil energy budget. Hence, regardless of the difference in altitude, values of surface temperature T_S are similar in low plains (Amazonis) and in high plateaus (Tharsis). Moreover, in the thin Martian near-surface CO_2 atmosphere, variations of the absorbed radiative energy in the infrared with pressure are negligible [19]. As a consequence, infrared heating rate J_{LW}, and to first order total atmospheric BL heating rate, are similar in the two locations. Thus, in contrast to the Earth, owing to the strong radiative control of the Martian BL, correlation between BL potential temperature and elevation is likely to originate on Mars, owing to the role played by inverse atmospheric pressure in the equation for the evolution of mixed-layer potential temperature θ ["pressure effect", as named in 14]. Convective plumes then rise higher in the free atmosphere so as to find a layer of equal potential temperature where their buoyancies reach zero: in other words, convective available potential energy of BL convective plumes is larger. Hence the "pressure effect" is likely to account for deeper modeled and observed BL in high plateaus compared to low plains.

4. DIMENSIONLESS ANALYSIS

Another notable consequence of the Martian radiative control is that the turbulent heat flux is not maximum near the surface, as is the case on Earth, but a few hundreds of metres above the surface [20, 10]. Decreasing (increasing) heat flux with altitude indicates warming (cooling) by BL convection. Martian radiative infrared heating is so strong in the lowest atmospheric levels that near-surface convective processes act to cool the atmosphere rather than warm it, which agrees with earlier diagnostics from single-column models [6].

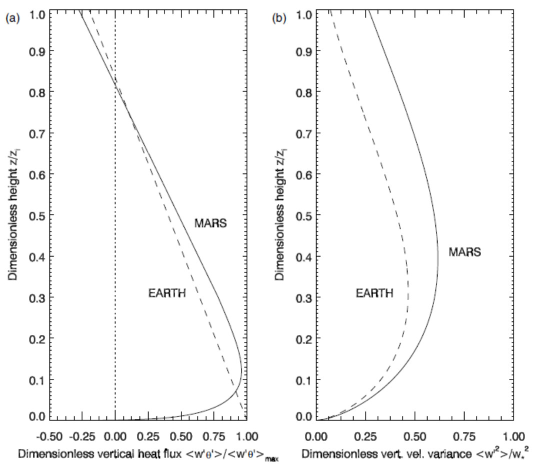

Figure 3. *Similarity empirical functions in quasi-steady midday conditions: average variation with dimensionless height of dimensionless (a) vertical eddy heat flux and (b) vertical velocity variance on Mars (solid line) and on the Earth (dashed line). From Spiga et al., 2010 [14].*

Mars confirms that BL has to be defined as the part of the atmosphere influenced by the *presence* of the surface, and not only by the surface itself. On Earth the afternoon BL warms "from below" by sensible heat flux incoming from the heated surface, whereas on Mars it warms "from inside and from below" respectively by infrared radiative heating (plus the visible absorption by the dust) and sensible heat flux.

In the Martian environment, the energy that fuels the thermals of mean typical velocity w^* does not originate only from the atmospheric levels immediately close to the surface. Thus, a version of mixing layer formulae valid both on Mars and on Earth should substitute the maximum heat flux $\langle w'\theta' \rangle_{max}$ for the surface heat flux $\langle w'\theta' \rangle_0$, which appears less relevant in the case of Mars (as well as, actually, in any radiatively-controlled convective boundary layer). Vertical wind scale w^*, which represents typical mean value for the BL convective motions, is usually defined by

$$w_* = \left[g\, z_{\mathrm{i}} \frac{\langle w'\theta' \rangle_0}{\langle \theta \rangle} \right]^{1/3}$$

with acceleration of gravity g, BL depth z_i, and BL potential temperature θ. This leads to underestimate the magnitude of typical Martian thermals resolved by LES. More consistent results are obtained if the following general formula (valid both on Earth and Mars) for vertical velocity scale W^* is used

$$W_* = \left[g\, z_{\mathrm{i}} \frac{\langle w'\theta' \rangle_{\mathrm{max}}}{\langle \theta \rangle} \right]^{1/3}$$

which yields W^* of 4 to 6.5 m s^{-1} on Mars accounting for the more vigorous convection compared to Earth ($w^* < 2$ m s^{-1}), in good agreement with similarity estimates based on observations [e.g. 2].

Using the same scaling strategy, similarity laws in quasi-steady mid-day conditions can be derived by taking advantage of both the temporal evolution of the BL convection and its regional variations. Figure 3 shows the vertical variations of vertical eddy heat flux and vertical velocity variance in the BL in dimensionless form (see 14 for more details, in Figure 3 only Martian empirical functions derived from averaging various profiles are shown, along with typical Earth relationships [21] for the sake of comparison).

While the terrestrial heat flux is maximum near the surface, the Martian heat flux is maximum around 0.1 z_i – 0.15 z_i. This is due to the prominent radiative contribution in the BL energy budget, as discussed previously: convective processes act to cool the atmosphere rather than warm it, hence the increase of turbulent heat flux between the surface and ~ 0.1 z_i. The heat flux at the Martian surface is only $\langle w'\theta' \rangle_0 \sim 0.15 \langle w'\theta' \rangle_{max}$. Above 0.3 z_i, vertical eddy heat flux decreases linearly with height and becomes negative around 0.8 z_i both on the Earth and on Mars.

Martian empirical similarity relationships provide a rigorous dimensionless frame for comparisons with the terrestrial convective BL. Other potential applications are numerous (e.g. new BL parameterisations). Only little information is necessary to compute the convective BL structure at a particular place. Two caveats must be eventually mentioned. Firstly, the generic mean profile remains an empirical approximation only valid in quasi-steady mid-day conditions. Secondly, an additional parameter is necessary in Martian similarity analysis to acccount for the influence of radiation [a difficulty mentioned in 22]. The scaling proposed in the present paper necessitates the estimation of maximum heat flux $\langle w'\theta' \rangle_{max}$ which is not given a priori.

5. FUTURE WORK

In spite of their idealised character, LES demonstrate good performance in reproducing measured BL depths. Future work will focus on the influence of variations of dust opacity, background wind, synoptic/mesoscale vertical motions so as to yield more realistic LES results. Although elements of comparison between Mars and the Earth can already be put into perspective, the Martian small-scale variability remains to be explored in greater detail, especially with additional measurements of wind and temperature, in order to validate diagnostics derived from numerical models and to expand the knowledge of small-scale phenomena by new studies in extreme environments.

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