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Planetary boundary layer and slope winds on Venus

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ABSTRACT

Few constraints are available to characterize the deep atmosphere of Venus, though this region is crucial to understand the interactions between surface and atmosphere on Venus. Based on simulations performed with the IPSL Venus Global Climate Model, the possible structure and characteristics of Venus' planetary boundary layer (PBL) are investigated. The vertical profile of the potential temperature in the deepest 10 km above the surface and its diurnal variations are controlled by radiative and dynamical processes. The model predicts a diurnal cycle for the PBL activity, with a stable nocturnal PBL while convective activity develops during daytime. The diurnal convective PBL is strongly correlated with surface solar flux and is maximum around noon and in low latitude regions. It typically reaches less than 2 km above the surface, but its vertical extension is much higher over high elevations, and more precisely over the western flanks of elevated terrains. This correlation is explained by the impact of surface winds, which undergo a diurnal cycle with downward katabatic winds at night and upward anabatic winds during the day along the slopes of high-elevation terrains. The convergence of these daytime anabatic winds induces upward vertical winds, that are responsible for the correlation between height of the convective boundary layer and topography.

1. Introduction

The interaction between the surface and the atmosphere is a key to understanding the processes driving the dynamics of both the atmosphere and the solid planet. The exchanges of heat and angular momentum drive the temperature and wind structure in the deepest layers of Venus's atmosphere, and affect Venus's atmospheric superrotation and the rotation of the planet itself. Yet, the deep atmosphere of Venus (below 10 km altitude above the surface) remains largely unexplored because of the difficulty in obtaining data below the dense and planet-wide cloud cover. Only a small number of probes have reached the surface: the Russian Venera series and VeGa missions, and the American Pioneer Venus mission. Among these probes, only one (VeGa-2) was able to measure a complete reliable temperature profile down to the surface (Linkin et al., 1986; Lebonnois and Schubert, 2017).

On Earth, the study of the planetary boundary layer (PBL) must take into account the variety of properties of the surface, and the water cycle and associated latent heat release. Its knowledge is important for a good understanding of the dispersion of trace atmospheric compounds, local circulations, clouds and water cycle or energy balance of the surface (e.g., Garratt, 1994). Arid areas are more relevant for comparative planetology since the water latent heat contribution can be neglected (e.g., Wang et al., 2016). The Martian PBL has also been studied extensively since the Viking landers (Hess et al., 1977), in particular with radio-occultation datasets and turbulence-resolving simulations (e.g., Hinson et al., 2008; Spiga et al., 2010). The surface temperature diurnal cycle is large on Mars, and the typical thickness of the diurnal convective PBL is much larger than on Earth. This PBL convective activity plays a crucial role in the dust cycle. The surface slope winds are also strong on Mars, both during daytime and nighttime. They were shown to have a significant impact on the near-surface temperature distributions (Spiga et al., 2011).

On Titan, the PBL may play a role in the near-surface methane cycle, but very few observational data are available to characterize it. The in-situ temperature profile obtained during the Huygens probe descent provided the best information to date to characterize the behavior of Titan's PBL. An interpretation of this profile and of the associated PBL characteristics was proposed by Charnay and Lebonnois (2012), based on simulations with a General Circulation Model: signatures are present of the height of the PBL at the time of the descent (300 m at 10:00 LT in the morning), of the remnant of the previous diurnal cycle, with a maximum vertical extent of the PBL of roughly 800 m, and of the height

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of the dominant surface circulation, with the seasonally-varying ascending branch (the equivalent of Earth's inter-tropical convergence zone) reaching 2 km altitude.

There have been a few attempts to investigate the surface temperatures, the PBL and the near surface winds on Venus. Surface temperatures were measured in-situ by several Venera landers (with an accuracy of ± 5 K) (Avduevskii et al., 1983) and the VeGa-2 lander (with an accuracy of ± 1 K) (Linkin et al., 1986). In addition, informations about the near-surface atmospheric temperatures can be inferred remotely from the analysis of near-infrared images in spectroscopic windows around 1.0, 1.10 and 1.18 microns. Such an analysis was done with the VIRTIS/Venus-Express datasets by Mueller et al. (2009). However, other unknown variables affect this analysis, such as the surface emissivity and the atmospheric opacities in the deep atmosphere. Disentangling all these variables is not easy, and assumptions are made that prevent a conclusive retrieval of the atmospheric lapse rate near the surface. Dobrovolskis (1983, 1993) modeled the atmospheric thermal tides induced by heating near the ground and determined wind magnitudes and directions in the PBL and the resulting surface stresses. These predictions are limited by simplifying assumptions, one of the most important being the neglect of the winds in the global circulation of the atmosphere. The PBL is affected by more than just the tidally driven winds at the surface. Several papers (Saunders et al., 1990; Greeley et al., 1991; 1994; 1995) have studied the patterns of wind streaks and aeolian transport of surface materials visible in the Magellan radar images in efforts to infer the nature of the circulation in the PBL. Greeley et al. (1994) analyzed thousands of wind streaks in the Magellan images associated with sand dunes and wind-sculpted hills. On the assumption that the streaks serve as local ”wind vanes” their orientations represent a global map of near-surface wind patterns on Venus. Equatorward streaks were most dominant, consistent with a Hadley circulation of the lower atmosphere.

While waiting for additional observations, the analysis of the PBL can be investigated with the help of models. Yamamoto (2011) used a microscale model to investigate the mixing induced by convective adjustment in idealized simulations of the PBL. However, the initial conditions assumed in these numerical experiments, i.e., the potential temperature profile and the surface thermal flux, are poorly constrained by observations. In addition, the effect of the background circulation was not taken into account. Therefore, these simulations may not reflect real Venus surface conditions. Here we take a different approach, and use the latest simulations from the Venus Global Climate Model (GCM) developed at the Institute Pierre-Simon Laplace (IPSL) to investigate the convective boundary layer, characterized by the depth of the surface convective activity, and the near-surface circulation. The GCM and the simulations used are described in Section 2. The vertical structure of the potential temperature is detailed in Section 3, the temporal and spatial variability of the convective activity is investigated in Section 4. Though there are no available observations of surface winds, our simulations suggest the presence of slope winds, so they are discussed together with their impact on the near-surface thermal structure in Section 5. Conclusions are given in Section 6.

2. Model and simulations

The IPSL Venus Global Climate Model has been developed for about a decade (Lebonnois et al., 2010; 2016). It includes a full description of the radiative transfer based on the latest modeling of the solar flux (Haus et al., 2015) and infrared net exchange rates (Eymet et al., 2009) taking into account the latest latitude-dependent cloud model (Haus et al., 2014), slightly tuned to get a vertical structure of the temperature close to the available observations. The latest simulations reproduce quite well the atmospheric structure, including the cold collar and the superrotation of the atmosphere (Garate-Lopez and Lebonnois, 2018). In the deep atmosphere, the planetary boundary layer scheme used is based on Mellor and Yamada (1982), a simple but useful scheme used, e.g., to study Titan's planetary boundary layer (Charnay and Lebonnois, 2012). This scheme is detailed in Appendix B of Hourdin et al. (2002) and based on level 2.5 model described by Mellor and Yamada (1982).

The GCM physics also includes a convective adjustment scheme. In the case of an unstable situation, both the PBL mixing scheme (based on Mellor and Yamada's formulation) and the convective adjustment can act to stabilize the unstable layer. In our GCM, the PBL scheme is applied before applying the convective adjustment and therefore this adjustment rarely occurs. The PBL scheme can compute a mixing coefficient in an unstable layer even away from the surface, so it acts to mix and stabilize the layer both in the PBL near the surface and in the highly convective cloud layer, with tendencies due to convective adjustment scarcely occurring. This adjustment mostly occurs in the first two layers just above the surface, when the PBL scheme does not completely remove the unstable gradient.

The reference simulation used in this work is described in detail by Garate-Lopez and Lebonnois (2018), in particular the tuning done in the radiative transfer. The horizontal resolution is 96 longitudes by 96 latitudes, on 50 vertical levels (hybrid coordinates, from surface to roughly 95 km altitude). In the deepest 10 km, the altitudes (above surface) of the layers are located around 10, 50, 150, 370, 750 m, 1.3, 2.1, 3.2, 4.7, 6.4 and 8.5 km. It was run for 300 Venus days from an already superrotating initial state.

As proposed by Lebonnois and Schubert (2017), it is possible that the deepest 7 km of the atmosphere may not be uniformly mixed, with a vertical gradient of nitrogen, from 3.5% at 7 km altitude to almost 0% at the surface. This would have an impact on the stability of the PBL since the mean molecular mass gradient reduces the buoyancy. A simulation was performed with this gradient of mean molecular mass taken into account in order to investigate its impact on the PBL structure. Since no physical process can yet be formalized in the model to have the N_2 abundance vary, the current implementation is simple: the profile of the mean molecular mass as a function of pressure obtained from VeGa-2 analysis is used at each grid point, and the potential temperature is modified accordingly (Lebonnois and Schubert, 2017). The initial state is the reference simulation, then the simulation is run for 50 Venus days with the modified mean molecular mass profile. The impact of this hypothesis on the PBL structure is discussed in Section 4.3.

To separate purely radiative effects from dynamical ones, 1-dimensional simulations (single vertical column) were also performed at selected locations. Starting from the temperature profile obtained at a given location by the GCM simulation, the 1-dimensional runs take into account only radiative heating and cooling and local vertical turbulent mixing. At the equator, this results in a temperature profile that tends to increase slowly, since energy is not redistributed to higher latitudes by the dynamics (mean meridional circulation and planetary-scale waves). The diurnal cycles of the 1-dimensional profile and of the convection are considered after a couple of Venus days.

A caution related to surface winds needs to be mentioned. Due to angular momentum conservation problems in the GCM (as discussed in Lebonnois et al., 2016), the zonal component of the zonally and temporally averaged surface winds could be biased, in particular in low-latitude regions. Caution should therefore be taken when discussing these winds. However, we find that the diurnal variations of the surface winds are significant, with amplitudes usually larger than the average values of the zonal component. Typically, at 10 m altitude, the temporally averaged zonal wind $\bar{u}$ ranges between ± 0.15 m/s, while the temporally averaged horizontal wind $\overline{U}$ ranges roughly from 0.2 to 0.6 m/s, often a factor of 3 to 5 larger than $|\bar{u}|$ (except in polar regions). Therefore, the slope winds effects discussed in this work should be rather independent of the bias due to angular momentum conservation problems.