Studying the Dynamics and Variability of the Upper Atmosphere of Venus using a General Circulation Model

Diogo Quirino(1), Gabriella Gilli(1,2), Vasco Silva(1), Sebastien Lebonnois(3)

1. Faculdade de Ciências da Universidade de Lisboa (FCUL), Lisbon, Portugal
2. Instituto de Astrofísica e Ciências do Espaço (IA), Lisbon, Portugal
3. Laboratoire de Météorologie Dynamique (LMD/IPSL), Paris, France

Introduction

Venus Global Circulation Models (VGCMs) are fundamental tools to help interpreting the observations and to further our understanding of physical and dynamical processes taking place at different layers of the Venusian Atmosphere. Models allow for the investigation of data retrieved by ground based telescopes and by past and present missions to Venus, such as the **Venus Express/ESA** (VEx) and **Akatsuki/JAXA** missions. The **Dynamical regime** on the Atmosphere of Venus is composed of **three** main regions. Below the cloud tops (~ 70 km), the regime is dominated by the *Retrograde Superrotation Zonal* (RSZ) circulation. On a second region (> 120 km), the circulation is dominated by the *Subsolar to Antisolar* (SS-AS) flow, a consequence of the strong day to night temperature gradient in the upper atmosphere. In between these two regions lays the so-called "*transition region*". Observational data measured by instruments on board VEx revealed the *high dynamical variability nature* of this region, whose behaviour is poorly understood by theoretical studies. Although above cloud tops no direct wind measurement is possible, the distribution and intensity of **dynamical tracers** such as O_2 nightglow, CO, and O, provide constraints on transport models in a region of the Venusian middle/upper difficult to probe with other in-situ or remote sensing methods (Bougher et al. 2006).
Current Objective: To study the dynamics of the "transition region" using the state-of-the-Art IPSL-VGCM following improvements in Gilli et al., 2017 and Garate-Lopez & Lebonnois, 2018.

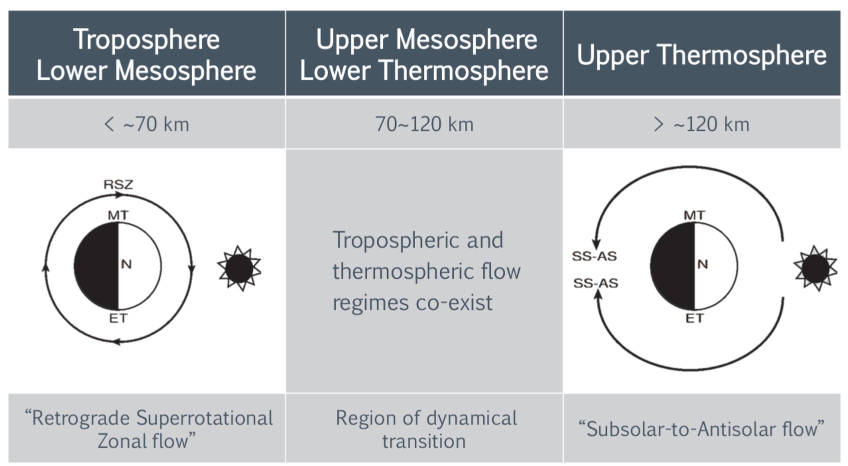
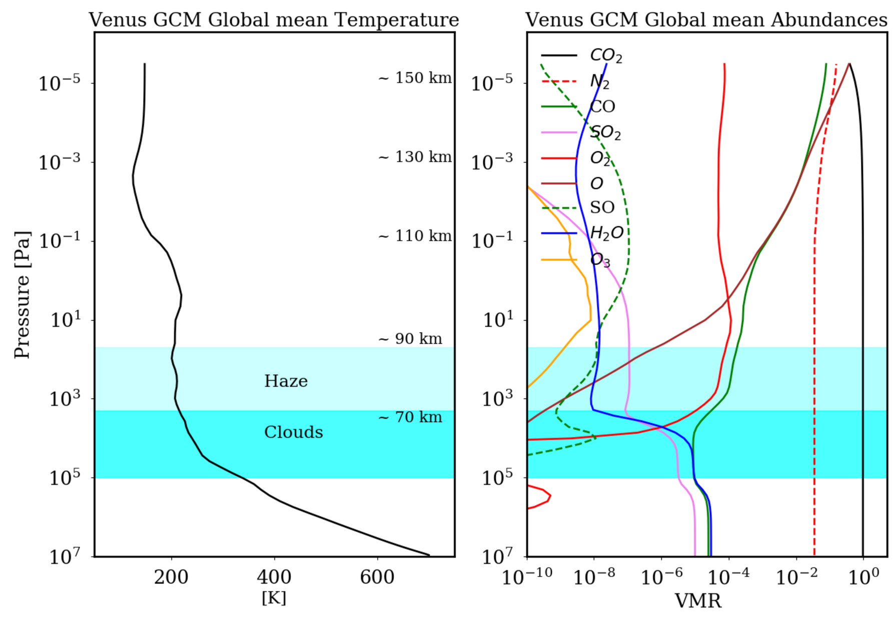


Figure 1. Sketch of the main dynamical flows in the atmosphere of Venus. MT is the Morning terminator, ET is the Evening terminator. Adapted from Brecht et al., 2011.

The LMD-IPSL Venus GCM:
A self-consistent ground-to-thermosphere model of the Venusian Atmosphere

Main Characteristics:

- ▷ Developed at *Laboratoire de Météorologie Dynamique* (LMD IPSL), Paris, France (Lebonnois et al., 2010);
- ▷ **Dynamical Part**: numerical solution of the general equations for atmospheric circulation (common to Earth and Martian Atmospheres);
- ▷ **Physical Part**: computes forced circulation and climate details at each point (specific to each planet);
- ▷ **Photochemical Model** coupled with a simplified cloud scheme that enables the study of the composition and the coupling with the Upper Atmosphere;
- ▷ **Recent improvements done at IA**: fine-tuning of the radiative tendencies combining LTE and non-LTE regimes to provide with a better description of the thermal structure between 90 - 140 km, according to VEx observational data (Gilli et al, 2020, in preparation).



A GCM for Venus:
- Ground-to-Thermosphere version of LMD-VGCM (Gilli et al., 2017);
- Horizontal Resolution: 48 long x 32 lat (7.5° x 5.625°);
- Vertical levels: 78 (approximately 0-150 km);
- 20 Venus days (Vd) runs (1 Vd = 117 Earth Days).

Figure 2. Atmospheric global zonal mean profiles from an improved version of the IPSL Venus GCM (Garate-Lopez & Lebonnois 2018) extended up to 150 km as in Gilli et al. 2017. Left panel: Pressure-Temperature profile. Approximate altitudes in km are indicated for reference. Cloud and haze location is approximately shown with shaded blue areas. Right panel: Gas mixing ratio profiles of the main molecular compounds in the Venus atmosphere.

Model Validation with Observational Data

Vertical Profiles

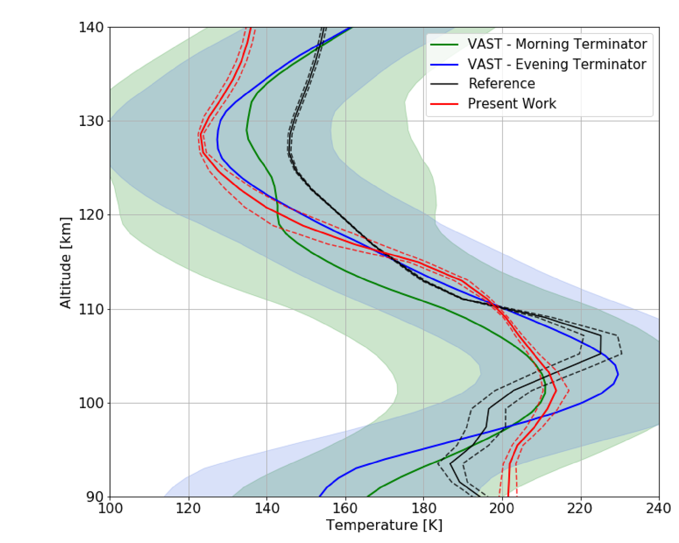
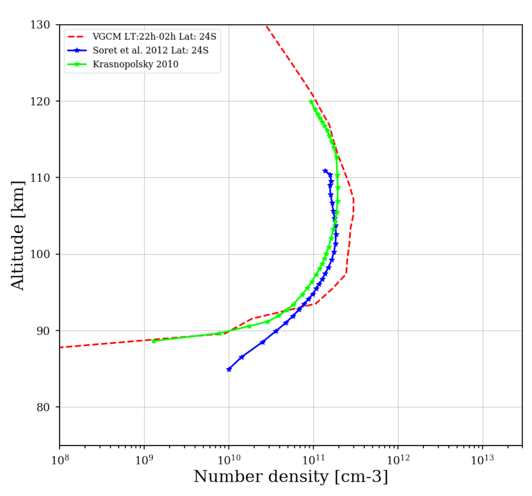


Figure 3. (Above) Averaged Temperature vertical profiles as function of altitude at the morning (LT:6h) and evening (LT:18h) terminators, predicted by the IPSL-VGCM in the latitudinal range of 30°N-50°N, before (solid black line, "Reference") and after (solid red line) improving the Non-LTE parameterization. Standard deviation of the mean for each simulation is represented by the dashed black and red line, respectively. VAST (Venus Atmosphere from SOIR/VEx measurements at the Terminator) temperature profiles for the same latitude range are shown in dark blue (evening terminator), and in green (morning terminator), together with retrieved standard deviations in shaded area (after Vandaele et al., 2016).



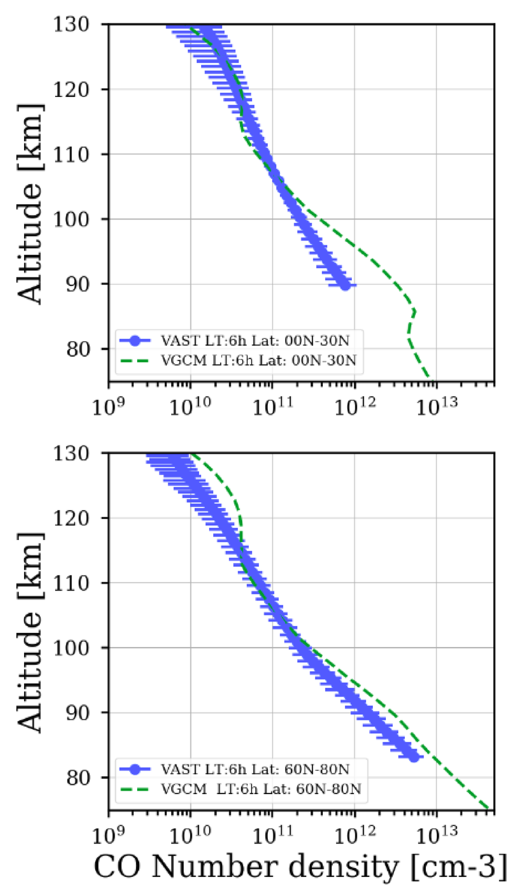


Figure 5. (Above) Examples of density profiles of CO as function of altitude at the morning terminator near equatorial latitudes (top panel), and at high latitudes (bottom panel). Model predictions are in green and retrieved density by SOIR/VEx with standard deviation, adapted from Vandaele et al. 2016, are in blue. As in Figure 4, the trend of the vertical profile is well described by our model, but in the regions 90-100 km the density seems to be overestimated. Those discrepancies are currently under investigation.

Figure 4. (On the left side) Example of density profiles of atomic Oxygen as function of altitude averaged around midnight (LT: 22h-2h) and near the equator (Lat = 24°S) predicted by the IPSL-VGCM (red line), together with retrieved densities from SPICAV/VEx stellar occultation (green line) as in Soret at al. 2012, and a semi-empirical photo-chemical model (blue line) by Krasnopolsky 2010, for comparison. The agreement is in general good, the peak of density is located around 100-110 km, as observed, but our model overestimate the maximum density by about a factor 2.

3D Maps

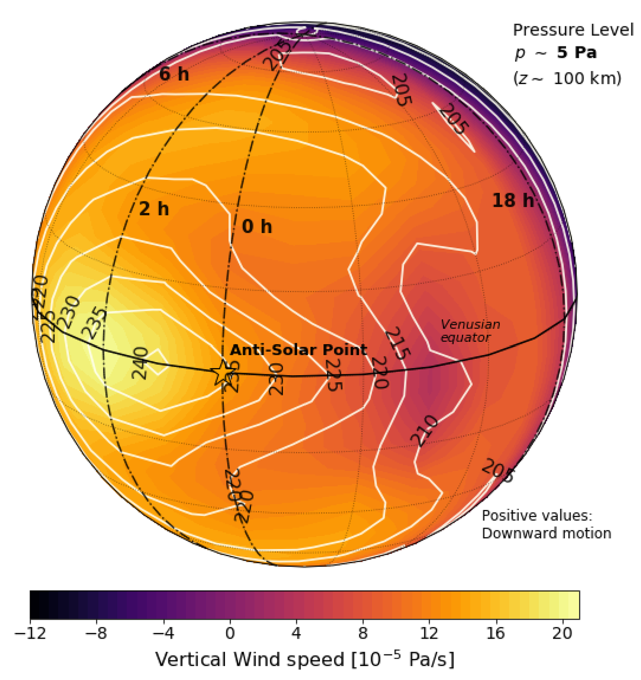
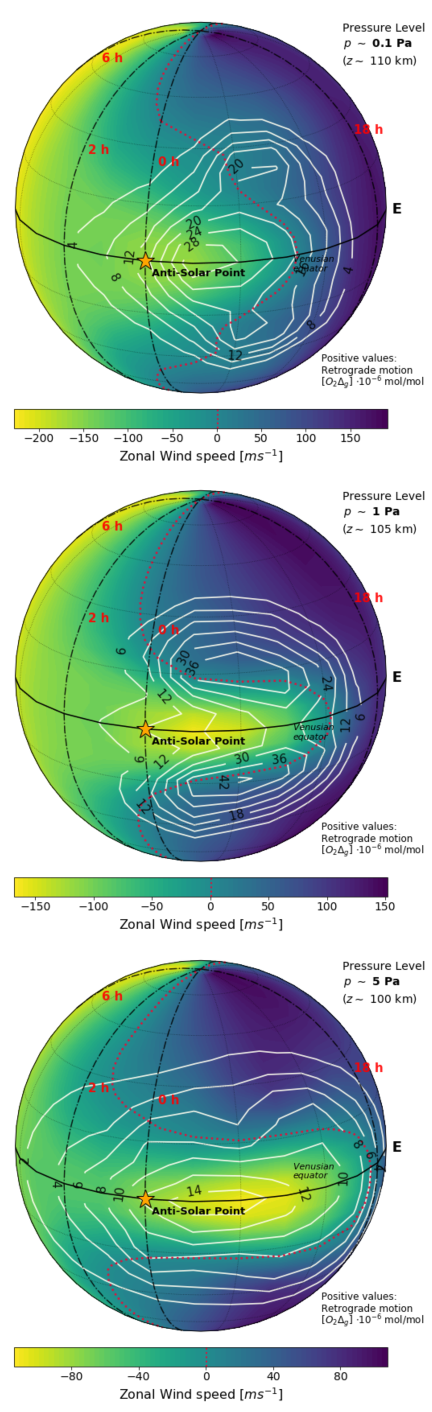


Figure 6. (Above) Example of 3D map obtained with IPSL-VGCM outputs. Temperature field (white contours) in K, and vertical field (color) in Pa/s. The local warm layer predicted at nighttime reaching about 240 K is produced by subsidence of day-to-night air around the AS-point. The selected pressure level is 5 Pa (around 100 km) where several observations from Venus Express confirmed the presence of a strong temperature inversion in the night side.

Figure 7. (On the right side) Example of 3D maps of zonal wind field (colour) and excited molecular oxygen volume mixing ratio (contour white lines) obtained using IPSL-VGCM outputs at three different pressure levels: 0.1 Pa ($\sim$110 km), 1 Pa ($\sim$105 km) and 5 Pa ($\sim$100 km). The O_2 IR fluorescence produced by the three-body recombination of oxygen is expected to be located around the AS-point. However, Venus Express observations revealed large variations of both the morphology and the intensity of those air-glows. This variation is difficult to predict by models and it is a topic still under investigation. However, our preliminary results also show a large variation of the distribution of the air-glow in the nighttime, and the presence of strong prograde ($u < 0$) jet around the equator.



Discussion & Future Work

Our results show the potential of IPSL-VGCM to understand the variability observed in the Upper Atmosphere of Venus, above cloud tops. Several processes could help explain the variability seen in the "transition region" (90-120 km), e.g. Large Scale Planetary Waves, Gravity Wave Propagation, and Thermal Tides. The relevance of those processes is currently under investigation. The improvement of the thermal structure, and the indirect observational evidence of the wind field provided by the Dynamical Tracers will help constrain the modelled wind fields simulated by the IPSL-VGCM in the those regions of the atmosphere of Venus, and to a further extent, support the study of the real impact of convectively-generated gravity waves. The impact of these Gravity Waves on Zonal Wind and Temperature Fields can be explored with the IPSL-VGCM thanks to a non-orographic gravity waves parameterization, which is included in the model. It is expected that the tools and the analysis produced during the current work could help the collectively effort for IPSL-VGCM to describe and enhance our actual knowledge of the "transition region's" dynamical behaviour. Ultimately, the success of VGCMs in describing the Venusian Atmosphere, can provide with an efficient tool to explore close-in orbit hot exoplanets whose atmospheres are believed to be similar to that of Venus.

References

Brecth AS et al. (2011). Tracing the dynamics in Venus'upper atmosphere. PhD thesis. Univ. of Mich., Ann Arbor; **Bougher** SW, Rafkin S, Drossart P. (2006). Dynamics of the Venus upper atmosphere: Outstanding problems and new constraints expected from Venus Express. *Planetary and Space Science.* 54.13-14: 1371-1380; **Garate-Lopez** I, Lebonnois S. (2018). Latitudinal variation of clouds' structure responsible for Venus' cold collar. *Icarus.* 314: 1-11.; **Gilli** G, et al. (2017). Thermal structure of the upper atmosphere of Venus simulated by a ground-to-thermosphere GCM. *Icarus.* 281: 55-72; **Lebonnois** S, et al. (2010). Superrotation of Venus' atmosphere analyzed with a full general circulation model. *Journal of Geophysical Research: Planets.* 115.E6.; **Soret** et al. (2012). Atomic oxygen on the Venus nightside: Global distribution deduced from airglow mapping. *Icarus.* 217.2: 849-855; **Krasnopolsky** (2010) Venus night airglow: Ground-based detection of OH, observations of O2 emissions and photo-chemical model. *Icarus.* 207.1: 17-27; **Vandaele** et al. (2016). Contribution from SOIR/VEx to the updated Venus International Reference Atmosphere (VIRA), *Adv. in Space Research* 57.1: 443-458.

Acknowledgments

This work received funding from the European Union's Horizon 2020 Research and Innovation Programme under Marie Sklodowska-Curie grant agreement No. 796923, and from Fundação para a Ciência e a Tecnologia (FCT/MCTES) through national funds bY "PTDC/FIS-AST/29942/2017"