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Wave analysis in the atmosphere of Venus below 100-km altitude, simulated by the LMD Venus GCM

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ABSTRACT

A new simulation of Venus atmospheric circulation obtained with the LMD Venus GCM is described and the simulated wave activity is analyzed. Agreement with observed features of the temperature structure, static stability and zonal wind field is good, such as the presence of a cold polar collar, diurnal and semi-diurnal tides. At the resolution used (96 longitudes × 96 latitudes), a fully developed superrotation is obtained both when the simulation is initialized from rest and from an atmosphere already in superrotation, though winds are still weak below the clouds (roughly half the observed values). The atmospheric waves play a crucial role in the angular momentum budget of the Venus's atmospheric circulation. In the upper cloud, the vertical angular momentum is transported by the diurnal and semi-diurnal tides. Above the cloud base (approximately 1 bar), equatorward transport of angular momentum is done by polar barotropic and mid- to high-latitude baroclinic waves present in the cloud region, with frequencies between 5 and 20 cycles per Venus day (periods between 6 and 23 Earth days). In the middle cloud, just above the convective layer, a Kelvin type wave (period around 7.3 Ed) is present at the equator, as well as a low-latitude Rossby-gravity type wave (period around 16 Ed). Below the clouds, large-scale mid- to high-latitude gravity waves develop and play a significant role in the angular momentum balance.

1. Introduction

The general circulation in Venus's atmosphere is dominated by the phenomenon called superrotation, with most of the atmosphere rotating in the same direction but about sixty times faster than the solid surface. The mechanism that controls this phenomenon combines transport of angular momentum by the mean meridional circulation with compensation done by planetary-scale waves. This idea was originally proposed by Gierasch (1975) and Rossow and Williams (1979), and has been demonstrated in recent years with the study of numerical simulations conducted by General Circulation Models (GCMs) of the Venus's atmosphere (e.g. Yamamoto and Takahashi, 2003; Lee et al., 2007). These tools are very useful to study the wave activity and its role in the angular momentum budget. In addition to the balance between transport by the mean meridional circulation and transport by the horizontal planetary waves, the role of thermal tides that transport angular momentum vertically in the low latitudes was confirmed by recent works (Lebonnois et al., 2010; Takagi and Matsuda, 2007). The most recent and realistic GCMs either use a full radiative transfer module to compute temperature self-consistently (Ikeda, 2011; Lebonnois et al., 2010; Lee and Richardson, 2011; Mendonca et al., 2015), or force the temperature structure with carefully prepared heating rate profile and Newtonian cooling (Sugimoto et al., 2014a; 2014b).

A variety of waves in Venus's atmosphere has been observed in the cloud region, in the middle cloud from infrared observations or at the cloud-top from reflected visible and ultraviolet sunlight (e.g. Belton et al., 1976; Rossow et al., 1980; Del Genio and Rossow, 1990; Peralta et al., 2008; Piccialli et al., 2014). These observed waves range from planetary-scale waves to small-scale gravity waves. Variability observed in the wind reveals periods from 4 to 5 Earth days to 1 Venus day, or even longer (Khatuntsev et al., 2013; Kouyama et al., 2013; Rossow et al., 1990). Small-scale gravity waves are observed in Venus-Express datasets, with VIRTIS images (Peralta et al., 2008), VMC images (Piccialli et al., 2014), or VeRa radio-occultations (Tellmann et al., 2012). The theoretical analysis of waves present in Venus's atmosphere is different from the Earth case, because of the cyclostrophic regime and the crucial role played by the mean zonal wind field. Most analytical works studying Venus's atmospheric waves use a realistic vertical wind

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Table 1
Values of the terms in the total angular momentum budget, averaged over the last 2 Vd (units are 10^{18} kg m^2 s^{-2}).

	$\overline{dM_r/dt}$	$\overline{T}$ ($\overline{T^+}$)	$\overline{F}$ ($\overline{F^+}$)	$\overline{D}$	$\overline{S}$	$\overline{\epsilon}$	$\overline{\epsilon^*}$	ξ
300 Vd (from rest)	1.5	−28.3 (42.5)	−7.6 (3.0)	1.6	−3.2	39.0	37.4	0.46
190 Vd (from superrotation)	6.8	−28.1 (41.6)	−7.0 (1.8)	1.9	−3.5	43.5	41.9	0.53

M_r = Relative part of the total atmospheric angular momentum, due to zonal wind u. T = Mountain torque on the atmosphere due to topography (T^+ is its positive (source) component). F = Surface torque on the atmosphere due to friction (F^+ is its positive (source) component). D = Residual torque due to conservation errors in the horizontal dissipation parameterization. S = Torque on the atmosphere due to upper boundary conditions (sponge layer). ϵ = Residual numerical rate of total angular momentum variation due to conservation errors in the dynamical core.$\epsilon^* = S + D + \epsilon$, should theoretically be zero. ξ= Ratio between $|\overline{\epsilon^*}|$ and $Max\left(\overline{T^+} + \overline{F^+}, |\overline{T^-} + \overline{F^-}|\right)$ (Lebonnois et al., 2012b).

profile, but with a solid-body rotation approximation for the latitudinal wind profile (e.g. Covey and Schubert, 1982; Schinder et al., 1990; Smith et al., 1993). A detailed theoretical analysis of waves in the context of a realistic zonal wind field for Venus has been recently undertaken by Peralta et al. (2014a); 2014b); 2015), exploring wave solutions and their classification.

Kouyama et al. (2015) explore the possibility of retroactive interactions between a low-latitude Kelvin type wave and mid-latitude Rossby type waves at the cloud top: the variations of the zonal wind induced by each wave favor the vertical propagation of the other one, that process yields long-term variability of the wind over periods of several Venus days.

Using a high-resolution Venus GCM starting from superrotation and forced by observed heating rate profile and Newtonian cooling, Sugimoto et al. (2014a, b) analyzed the wave activity produced in the cloud region. The large vertical zonal wind shear and latitudinal temperature gradient generate the basic state of baroclinic instability in the cloud region. Baroclinic waves develop, and at cloud-top, Rossby type waves are produced by this baroclinic activity. However, further studies of Venus waves using various GCMs are required to get a comprehensive understanding of Venus's atmospheric dynamics.

In this work, we present the recent evolutions of the LMD Venus GCM (Lebonnois et al., 2010), that simulates realistic temperature and zonal wind fields (Section 2), with a detailed analysis of the waves produced in this simulation (Section 3).

2. Simulations and validation against observations

2.1. The LMD Venus GCM

The model developed at LMD for the study of Venus's atmosphere has been described in details in Lebonnois et al. (2010). It is based on the LMDZ latitude–longitude grid finite-difference dynamical core (e.g. Hourdin et al., 2006), including a longitudinal polar filter.

Most of the features of this GCM are similar to those presented in Lebonnois et al. (2010). Among the physical parameterizations, the main difference is the use of a boundary layer scheme taken from Mellor and Yamada (1982) to compute the eddy diffusion coefficient and the time evolution of the mixed variables. The equations used are described in Appendix B of Hourdin et al. (2002). This boundary layer scheme is based on a more physical representation of the unstable regions. It was successfully used for other planetary applications of the LMD GCM (e.g. Lebonnois et al., 2012a, for Titan). At surface, the drag coefficient is similar to the one used in the previous parameterization: $C_d = (0.4/\ln(1 + z_1/z_0))^2$, where z_1 is the altitude of the center of the first layer of the model (roughly 10 m in our case) and z_0 is the roughness coefficient, taken equal to 1 cm. Otherwise, compared to Lebonnois et al. (2010) we use the same hybrid vertical coordinates with topography (50 vertical levels), the soil model is unchanged, the temperature dependence of the specific heat is taken into account, the radiative transfer includes solar heating rate profiles as a function of solar zenith angle taken from a look-up table based on Crisp (1986), and the infrared net-exchange rate (NER) matrix formulation discussed in Eymet et al. (2009). For the computation of the IR NER matrix, opacity sources (gas, clouds) are taken horizontally uniform and properties are the same as in Lebonnois et al. (2010).

The second main difference is the horizontal resolution. For the study that is presented here, the resolution was increased to 96 longitudes by 96 latitudes (3.75° × 1.875°). A few years ago, a simulation was performed with this model with a horizontal resolution of 48 longitudes by 32 latitudes and run for up to 190 Venus days (1 Venus day (Vd) = 117 Earth days (Ed)) starting from an atmosphere already in superrotation. Modeled temperature field was compared with VIRTIS/Venus-Express temperature retrievals to discuss thermal tides above the clouds (Migliorini et al., 2012). It must be noted that when starting from rest, the superrotation was not fully evolved in this version of the GCM, with weaker zonal wind in the deep atmosphere and a peak around 80 m/s at the cloud-top, after more than 1000 Vd. In the present work, the simulations were started either from rest (for 300 Vd) or from a zonal wind field already in superrotation (for 190 Vd). Both simulations converged toward very similar wind fields, meaning that the superrotation is fully evolved by the LMD VGCM from motionless state for the first time. The present work will focus on the analysis of the simulation started from superrotation.

Increasing the resolution had a drawback: it has induced a larger residual term in the angular momentum budget as indicated in Table 1 (that can be compared to simulations presented in Lebonnois et al., 2012b). As mentioned in Lebonnois et al. (2012b), the lack of angular momentum conservation is a problem for simulations of Venus's atmosphere, and Table 1 shows that in this configuration, our GCM has a bias in the angular momentum budget. This is currently investigated and needs to be improved in future simulations. This numerical inaccuracy alters the balance of angular momentum transport, the non-zero term due to dynamics in the angular momentum budget being compensated by a non-zero balance of the surface momentum exchanges. However, the convergence between simulations started from rest and started from superrotation gives confidence in the achieved wind distributions, except near the surface where the winds must be biased. This bias should be taken into account when comparing the resulting simulated circulation to the observations near the surface.