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Exploring the Venus global super-rotation using a comprehensive general circulation model

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ABSTRACT

The atmospheric circulation in Venus is well known to exhibit strong super-rotation. However, the atmospheric mechanisms responsible for the formation of this super-rotation are still not fully understood. In this work, we developed a new Venus general circulation model to study the most likely mechanisms driving the atmosphere to the current observed circulation. Our model includes a new radiative transfer, convection and suitably adapted boundary layer schemes and a dynamical core that takes into account the dependence of the heat capacity at constant pressure with temperature.

The new Venus model is able to simulate a super-rotation phenomenon in the cloud region quantitatively similar to the one observed. The mechanisms maintaining the strong winds in the cloud region were found in the model results to be a combination of zonal mean circulation, thermal tides and transient waves. In this process, the semi-diurnal tide excited in the upper clouds has a key contribution in transporting axial angular momentum mainly from the upper atmosphere towards the cloud region. The magnitude of the super-rotation in the cloud region is sensitive to various radiative parameters such as the amount of solar radiative energy absorbed by the surface, which controls the static stability near the surface. In this work, we also discuss the main difficulties in representing the flow below the cloud base in Venus atmospheric models.

Our new radiative scheme is more suitable for 3D Venus climate models than those used in previous work due to its easy adaptability to different atmospheric conditions. This flexibility of the model was crucial to explore the uncertainties in the lower atmospheric conditions and may also be used in the future to explore, for example, dynamical-radiative-microphysical feedbacks.

1. Introduction

The Venus atmospheric circulation has several characteristics which remain poorly understood, such as the mechanism of formation and maintenance of the atmospheric super-rotation below 100 km. The super-rotation is characterized by a much faster rotation of the atmosphere compared to the rotation rate of the solid planet. This phenomenon quantifies the excess of axial angular momentum that an atmosphere possesses when compared with an atmosphere co-rotating with the underlying planet. From Read (1986) this global phenomenon is quantified using the following equation:

$$S = \frac{M_t}{M_0} - 1, \tag{1}$$

where S is defined as the global super-rotation index, M_t is the total axial angular momentum of the atmosphere and M_0 is the axial angular momentum of the atmosphere with zero zonal wind velocities relative to its underlying planet. The total angular momentum of the atmosphere per unit mass (M_t) is defined by:

$$M_t = \int\int\int \frac{ma^2 \cos\phi}{g} d\phi d\lambda dp \tag{2}$$

where a is taken to be the radius of the planet, ϕ is the latitude, λ is the longitude, p is the pressure, g is the gravitational acceleration and m is the angular momentum per unit mass ($m = a\cos\phi(\Omega a\cos\phi + u)$), Ω is the rotation rate of the planet and u is the zonal component of the wind velocity). Using Eqs. (1) and (2) and the observational vertical profiles of zonal winds and their uncertainties from Kerzhanovich and Limaye (1985), we can estimate $S = 7.\ 7^{+4.2}_{-3.6}$ (S $\sim 1.5 \times 10^{-2}$ for the Earth, Read, 1986). The vertical profiles from Kerzhanovich and Limaye (1985) are associated with low latitudes. Three different profiles corresponding to the lowest, mean and highest wind values observed at each altitude were used to build three global wind fields to compute three different values of S (the mean value and its uncertainties). The three global

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wind fields were defined using the observational vertical wind profiles at the equator and were extrapolated to the pole region assuming that the atmospheric circulation follows a solid body rotation profile at each altitude. These three dimensional wind fields are axisymmetric. In general, the solid body rotation assumption slightly underestimates the values of the zonal winds at high latitudes, but is a very good approximation for the altitudes where the winds have the largest contribution to angular momentum density (at around 20 km, Schubert, 1983).

In general, dynamical motions in the atmosphere of Venus are driven by a differential insolation in latitude, which might be expected to induce atmospheric circulation in the form of cells with rising atmospheric flow at low latitudes and descending at high latitudes. The presence of middle or high latitude local super-rotation, which refers to the typically barotropically unstable jet, is a consequence of the existence of those cells that transport angular momentum from low toward high latitudes. The presence of a large equator-to-pole Hadley circulation in each hemisphere (e.g., Schubert et al., 1980) is due to the slow planetary rotation, which weakens the Coriolis acceleration, increasing the efficiency of the latitudinal heat transport of the atmosphere. The total axial angular momentum of the atmosphere is mainly controlled by the mechanical surface–atmosphere interaction. During the “spin-up” of the atmosphere this mechanical interaction pumps axial angular momentum into the atmosphere. More difficult to explain is the presence of the observed equatorial super-rotation. The strong winds in the equatorial region are not produced or maintained by the influence of zonal mean mechanisms (Hide, 1969). Such super-rotation requires the presence of non-axisymmetric eddy motions, unless super-rotation was its initial condition.

Using the equations of motion we can learn more about possible atmospheric mechanisms for generating and maintaining the strong winds in the equatorial region (Gierasch et al., 1997). The zonal momentum equation can be written as a conservation equation for axial angular momentum in the form:

$$\underbrace{\frac{\partial}{\partial t}(\rho m)}_{[A]} + \underbrace{\vec{\nabla}\cdot(\rho \mathbf{v} m)}_{[B]} + \underbrace{\frac{\partial p}{\partial \lambda}}_{[C]} = \underbrace{\vec{\nabla}\cdot(\tau\cdot\hat{\mathbf{z}}\times\mathbf{r})}_{[D]} \qquad (3)$$

where $\hat{\mathbf{z}}$ is the unit vector in the direction of the planetary angular velocity (Ω) and τ is the viscous stress tensor. m in this equation is the axial angular momentum per unit mass as mentioned previously. Zonally averaging this equation and assuming the friction is negligible, the terms [C] and [D] drop out. This simplification makes it easier to interpret the conservation of angular momentum in a circulating atmospheric cell. Unless there is convergence of the angular momentum flux, $\mathbf{F}_m = \rho \mathbf{v} m$, towards a location of maximum angular momentum per unit of mass, it is not possible to produce or sustain, for example, the observed strong prograde winds at low latitudes in the Venus atmosphere. Note that the term “prograde” in this work refers to winds in the direction of the planet's rotation. It was demonstrated in Hide (1969) that global or local super-rotation cannot be obtained in a purely inviscid, axisymmetric system that evolved from rest. This result is frequently called “Hide's first theorem” (Read, 1986), and implies that the excess of angular momentum, $S > 0$, can only be obtained from non-axisymmetric motions. This non-axisymmetric phenomenon can be represented by the known Reynolds' stress terms (associated with zonal pressure torques) that are defined by:

$$[F_m] = \rho a \cos\phi([u^\star v^\star], [u^\star w^\star]) \qquad (4)$$

where ρ is the atmospheric density, a is the planet radius, the square brackets denote a zonal average, v is the meridional component of the wind velocity and w is the wind speed in the vertical direction. The stars on each variable mean that they are disturbances in relation to their respective zonal average. The first and second terms are the meridional and vertical components of the eddy fluxes. From Eq. (4), the weight of each component of Reynold's stress (horizontal and vertical) is in general related to different possible mechanisms that contribute to the formation and/or maintenance of the super-rotation. To be able to complete the puzzle as to the real nature of the general super-rotation, there is a need to identify the atmospheric processes involved in these two terms and quantify their contribution to the phenomenon.

The Venus atmosphere has been explored by several space missions in the past: notably the Venera orbiters and entry probes, Pioneer Venus and Magellan, and more recently the European Venus Express mission. These missions made atmospheric data available which increased the interest in the development of global circulation models capable of interpreting these data and guiding their analysis. Numerical modeling of the global Venus atmospheric circulation started more than 40 years ago, with the complexity and accuracy improving along the years (e.g. Kalnay de Rivas, 1975; Yamamoto and Takahashi, 2003; Lee et al., 2007; Lebonnois et al., 2010a). Recently, typical Venus numerical models that use very simplified representations of radiation and boundary layer processes (e.g., Yamamoto and Takahashi, 2003; Lee et al., 2007; Lebonnois et al., 2013), have suggested that the global atmospheric super rotation is at least partially maintained by the equatorward momentum transport via synoptic eddies from high latitude barotropically unstable jets. This mechanism is commonly known as the GRW mechanism (Gierasch, 1975; Rossow and Williams, 1979). Further studies using simplified GCMs have also highlighted other possible mechanisms involving interactions between mid-latitude Rossby waves and equatorial Kelvin waves to form unstable modes that can lead to zonal acceleration in the tropics (Mitchell and Vallis, 2010; Potter and Vallis, 2014). Evolving towards more complex physically-based models we find the work by Ikeda et al. (2007) and Lebonnois et al. (2010a), who included for instance a self-consistent computation of temperature using a radiative transfer formulation. In these cases the diurnal cycle is not neglected, which revealed to be an important factor in the atmospheric dynamics produced. The diurnal cycle excites migrating thermal tides especially in the Venus cloud region due to the large extinction of solar energy there. The thermal tides play an important role maintaining the super rotation, since they transport prograde momentum vertically and predominantly at low latitudes, from above the cloud region towards the upper cloud deck (e.g., Newman and Leovy, 1992; Lebonnois et al., 2010a). These three momentum transport mechanisms: high latitude barotropic eddies, tropical Rossby–Kelvin instabilities or thermal tides, are thought to be the main possible mechanisms for the formation and maintenance of strong zonal winds at low latitudes: via the $[u^\star v^\star]$ and $[u^\star w^\star]$ terms respectively.

In this study we have developed a new Venus General Circulation Model called the Oxford Planetary Unified (Model) System for Venus (*OPUS-Vr*) that includes a new radiation scheme (Mendonça et al., 2015). We use it to simulate the Venus atmosphere in a physically consistent manner. The main advantage of our radiation code against previous works is the explicit calculation of the solar fluxes and the easy adaptability to different optical structures. The OPUS-Vr is aimed at studying the atmospheric mechanisms that transport momentum, and explore the range of atmospheric conditions favorable to the formation of an atmospheric circulation similar to the one observed.

In the next section we describe the numerical model used in this work. In Section 3 the results from the reference simulation are explored, and the main momentum transport mechanisms and waves are identified. In Section 3 we also compared the model results obtained with available observational data. In Section 4 a sensitivity test to the surface albedo is explored. Finally in Sections 5 and 6 a discussion on possible super-rotation mechanisms working within the lower Venus atmosphere is presented followed by the general conclusions.