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Dynamics of polar vortices at cloud top and base on Venus inferred from a general circulation model: Case of a strong diurnal thermal tide

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ABSTRACT

Polar vortices in the presence of a thermal tide are investigated using a Venusian middle atmosphere general circulation model. Around the cloud top, where the warm polar region is maintained by the thermal wind associated with a high latitude jet, the temperature contrast forms the polar vortex pattern. The cold collar and hot oval (monopole) near the pole are enhanced by the polar diurnal tide, and unstable vortices form the hot dipole and tripole. The centroid of the hot oval is displaced from the pole to around 80° by the diurnal tide. The hot dipole appears and breaks up into a tripole when transient vortical and divergent eddies with zonal wavenumbers 2 and higher are predominant within the polar hot oval region. Because the divergence and temperature are a quarter cycle out of phase with the eddy vorticity, the vortical eddies transport heat toward the cold region. Thus, the cloud-top polar vortices are mainly formed by a combination of the diurnal tide and transient baroclinic wave. At the cloud base, isotherms are almost zonally uniform and the eddy temperature structure is not apparent. In contrast, divergence and vorticity have large amplitudes within this region. The vortical eddies have a comma-shaped pattern, which is stably maintained and rotates with a period of about 5 days. The divergence and vorticity might be important in controlling cloud morphology at the cloud base via material transport.

1. Introduction

The Pioneer Venus (PV) orbiter radiometric temperature experiment (Taylor et al., 1979) found polar vortices at the cloud top, and identified features such as the polar hot dipole and cold collar. The polar dipole might result from the barotropic and baroclinic instabilities of the Venusian atmosphere (Elson, 1978; Young et al., 1984; Limaye et al., 2009). Subsequently, the Venus Express (VEX) mission observed complex and chaotic fine features of polar vortices (e.g., Piccioni et al., 2007; Titov et al., 2008; Limaye et al., 2009; Luz et al., 2011; Garate-Lopez et al., 2013).

Thermal tides with large amplitudes have been observed in the Venusian atmosphere. Diurnal and semidiurnal tides were seen above the cloud top in longitude–height cross sections of temperature (Schofield and Taylor, 1983) and detected by cloud tracking in the cloud-top on the dayside hemisphere (Smith and Gierasch, 1996). A polar diurnal tide of 3 K amplitude was observed at latitude 85° by the PV Orbiter Infrared Radiometer (OIR) experiment (Pechmann and Ingersoll, 1984). However, the VEX (Peralta et al., 2012) showed that the meridional wind of the diurnal tide had speed of 5 m s^{-1} at latitude 75°, and that the temperature amplitude was one-fifth of the PV OIR maximum ($\sim$5 K for Channel 5). The difference between the observations may be caused by vertical structure and/or interannual variation of thermal tides.

The dynamical structures have recently been updated following VEX observations. Cloud-tracking analysis has revealed zonal flow with velocities of 90 m s^{-1} at the cloud top (65–70 km) and 60 m s^{-1} around cloud base (e.g., Sánchez-Lavega et al., 2008; Moissl et al., 2009). The strong cyclostrophic jet has wind speeds of 140 m s^{-1} at mid-latitudes around the cloud top (Newman et al., 1984; Piccialli et al., 2012), corresponding to the upper limit of the cloud tracking by the Venus Monitoring Camera. Associated with the strong cyclostrophic jet, the atmosphere has a strong meridional gradient of zonal mean temperature and it is baroclinically unstable at high latitudes (Young et al., 1984).

General circulation models (GCMs) have been used to investigate the atmospheric dynamics of Venus (Lebonnois et al., 2013; Lewis et al., 2013). Yamamoto and Takahashi (2004) reproduced the polar diurnal tide for conditions of fully developed super-rotation. The simulated phase structure at 65 km was similar to the PV OIR experiment (Pechmann and Ingersoll, 1984) and the amplitudes were consistent with the VEX observations (Peralta

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et al., 2012). To understand polar atmospheric dynamics fully, we need to consider the large-amplitude polar tide.

Lee et al. (2010) showed the polar vortex and arm structures around the polar cloud deck in a GCM using a bulk cloud parameterization. In earlier work, we briefly reported the simulation of the cloud-top polar dipole using the Venus middle atmosphere GCM (VMAGCM; Yamamoto and Takahashi, 2012). However, the results simulated in the low-resolution VMAGCM could only be applied to the large-scale structure of the polar vortex, not to the finer internal structure (such as the S-shaped feature). Thus, here, we examine the dynamical processes of the planetary-scale polar vortices that were not discussed fully in previous works. In the present study, the planetary-scale dynamics and morphology of polar vortices are investigated in terms of various meteorological variables, and the analysis region is extended down to the cloud base.

2. Overview of VMAGCM results

The meteorological data used here were from the VMAGCM (Yamamoto and Takahashi, 2012), which is based on version 5.6 of the CCSR/NIES (Center for Climate System Research/National Institute for Environmental Study) AGCM (Numaguti et al., 1997). Horizontal spectra were truncated at wavenumber 21, and 72 layers were used to represent the model atmosphere from the surface to $\sim$90 km. The rotation vector of the planet was set to be positive along rotation axis of the spherical coordinate frame in the general circulation model. Thus, easterly wind of Venus has positive velocity. The negative (positive) latitudes in the model correspond to the northern (southern) hemisphere of Venus. The radiative processes were simplified to three-dimensional solar heating and Newtonian cooling. The model parameters were the same as in Yamamoto and Takahashi (2006), except for the solar heating and vertical layer configuration. A realistic solar heating rate at the subsolar point was used (Tamasko et al., 1985, the black solid line in Fig. 1a of Yamamoto and Takahashi, 2009), and the 3D distribution Q_S depends on $\cos^{1.4}\lambda$ (λ: zenith angle); Q_{00} is the global mean of Q_S. The reference temperature and the cooling rate were horizontally uniform, as shown by the solid line in Fig. 1b of Yamamoto and Takahashi (2006). The model was separated into two domains (upper and lower) at 30 km. Air temperature (T) and horizontal wind ($\boldsymbol{u}$) were integrated forward in time within the upper domain (>30 km), but not inside the lower domain (≤ 30 km), where a solid-body rotation of $30\cos\phi$ m s^{-1} (ϕ: latitude) was assumed. Equatorial Kelvin waves with zonal wavenumber 1 and 5.5-day period were forced by variations in the bottom geopotential height. The detailed model settings are described in Yamamoto and Takahashi (2012).

In the case of no Kelvin wave forcing (case A in Yamamoto and Takahashi, 2012), a 50 m s^{-1} equatorial wind and a 90 m s^{-1} mid-latitude jet develop near the cloud top. The cloud-top wind is driven by the thermal tide and meridional circulation (Newman and Leovy, 1992; Yamamoto and Takahashi, 2006). As Kelvin wave forcing increases, the superrotational wind is enhanced by the momentum convergence of the wave in the middle atmosphere. In particular, the acceleration due to the waves contributes to the development of the superrotation near the cloud base. As the angular momentum supplied by the forced wave near the cloud base is spread through the middle atmosphere by the meridional circulation, the superrotation is also enhanced at the cloud top. In the case of strong 5.5-day wave forcing (case D in Yamamoto and Takahashi, 2012), fully developed superrotation is produced at the cloud top and base (Fig. 1a). The greatest poleward flow, approximately 2 m s^{-1}, is seen at the 70–75 km level. Intriguingly, indirect circulations associated with the horizontal eddy heat flux are also formed near 80 km in the mid-latitudes. The simulated temperature (Fig. 1b) is similar to observations. The zonal mean temperature increases (decreases) with increasing latitude above (below) 70 km, associated with the vertical shear of the zonal flow according to the thermal wind relation. The temperature increase in the polar region is consistent with observations, although the observed temperature minimum (cold collar) is not seen around 60° latitude.

The simulation in case D reproduces both the cloud-top 4-day wave and cloud-base 5.5-day wave (Fig. 6a of Yamamoto and Takahashi, 2012), consistent with the results from Galileo (Belton et al., 1991) and related ground-based observations (Crisp et al., 1991). Signals of zonal phase velocities of $\sim$120 m s^{-1} are detected at the equator at 70.5 km, while the equatorial signal is $\sim$80 m s^{-1} at 50.5 km (Fig. 2). The horizontal structures of the cloud-top 4-day wave (Figure 8 of Yamamoto and Takahashi, 2012) are identified as equatorial Kelvin waves. The cloud-base 5.5-day wave corresponds to a forced Kelvin wave. The zonal mean field mentioned above satisfies the necessary condition for internal jet instability (Charney and Stern, 1962) in the equatorial and polar regions, where the sign of the meridional gradient of the zonal mean potential vorticity changes (Fig. 1a). Furthermore, the horizontally varying winds could lead to horizontal shear instability (Satomura, 1981; Iga and Matsuda, 2005). The equatorial 4-day waves at the critical latitude

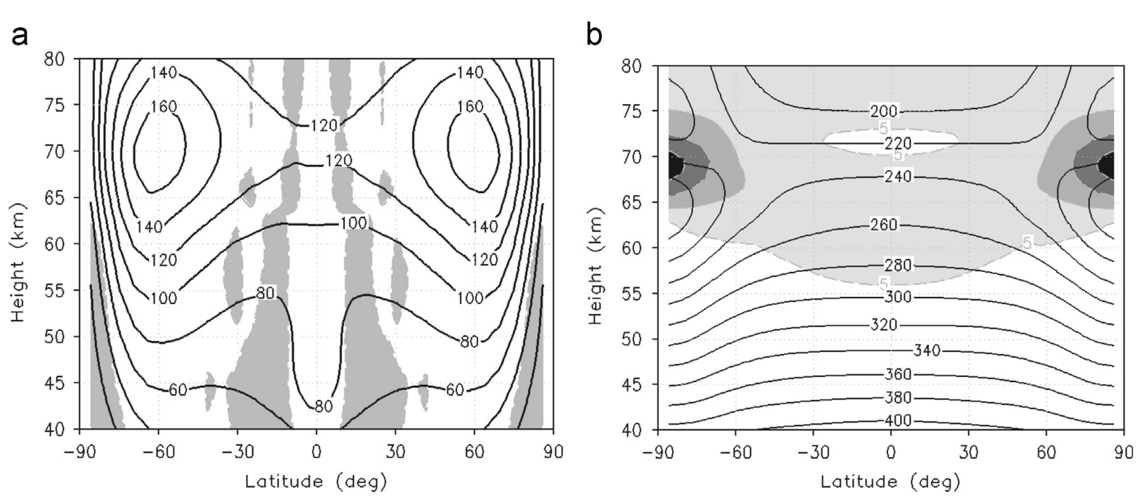

Fig. 1. Latitude–height distributions of zonally averaged (a) zonal flow (m s^{-1}) and (b) temperature (K) for case D of Yamamoto and Takahashi (2012) at 530 Venusian days (62,020 days). Grey shading in the left-hand panel shows areas of negative meridional gradient of zonal mean potential vorticity, and in the right-hand panel gray shading indicates static stability (K km^{-1}).