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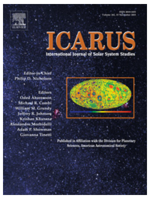

Dynamical relationship between wind speed magnitude and meridional temperature contrast: Application to an interannual oscillation in Venusian middle atmosphere GCM

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ABSTRACT

We derive simple dynamical relationships between wind speed magnitude and meridional temperature contrast. The relationship explains scatter plot distributions of time series of three variables (maximum zonal wind speed U_{MAX}, meridional wind speed V_{MAX}, and equator−pole temperature contrast dT_{MAX}), which are obtained from a Venus general circulation model with equatorial Kelvin-wave forcing. Along with V_{MAX} and dT_{MAX}, U_{MAX} likely increases with the phase velocity and amplitude of a forced wave. In the scatter diagram of U_{MAX} versus dT_{MAX}, points are plotted along a linear equation obtained from a thermal-wind relationship in the cloud layer. In the scatter diagram of V_{MAX} versus U_{MAX}, the apparent slope is somewhat steep in the high U_{MAX} regime, compared with the low U_{MAX} regime. The scatter plot distributions are qualitatively consistent with a quadratic equation obtained from a diagnostic equation of the stream function above the cloud top. The plotted points in the scatter diagrams form a linear cluster for weak wave forcing, whereas they form a small cluster for strong wave forcing.

An interannual oscillation of the general circulation forming the linear cluster in the scatter diagram is apparent in the experiment of weak 5.5-day wave forcing. Although a pair of equatorial Kelvin and high-latitude Rossby waves with a same period (Kelvin–Rossby wave) produces equatorward heat and momentum fluxes in the region below 60 km, the equatorial wave does not contribute to the long-period oscillation. The interannual fluctuation of the high-latitude jet core leading to the time variation of U_{MAX} is produced by growth and decay of a polar mixed Rossby-gravity wave with a 14-day period.

1. Introduction

Recently, extrasolar Earth-size planets have been detected by astronomical observations. Thus, we might expect a renewed effort toward a unified theory and mechanism driving the planetary general circulation, including the exoplanets. Golitsyn (1970) estimated horizontal wind speeds of planets based on his similarity theory of fluid dynamics. The superrotation strength (zonal wind speed) of Venus' atmosphere was theoretically estimated using idealized quasi-axisymmetric models in Gierasch (1975), Matsuda (1980), and Kashimura and Yoden (2015). Li et al. (2012) performed simulations of Titan and Earth under different scenarios of planetary rotation rate and investigated possible physical cause of rapid vertical change of the zonal wind on Titan. Yamamoto and Takahashi (2016) emphasized the importance of a dynamical process of a polar mixed Rossby gravity wave with meridional flows across the poles on a cloud-covered planet with the period of Venus' rotation. The polar wave transports heat poleward and weakens both high-latitude jets and the equator−pole temperature difference. Mitchell and Vallis (2010) and Dias Pinto and Mitchell (2014, 2016) also indicated that high-latitude Rossby-type waves are important in Earth-like planetary superrotation, along with Kelvin–Rossby waves (Yamamato and Takahashi, 2004; Iga and Matsuda, 2005; Wang and Mitchell, 2014). However, we lack full understanding of the influences of planetary-scale waves on zonal flow, meridional circulation, and equator−pole temperature contrast in the planetary middle atmosphere.

For the Venusian atmosphere, Newman and Leovy (1992) and Yamamoto and Tanaka (1997) discussed the dynamical roles of thermal tides and planetary-scale waves with the existence of a meridional circulation and superrotation. According to Yamamoto and Tanaka (1997), a forced 4-day wave (Covey and Schubert 1981,

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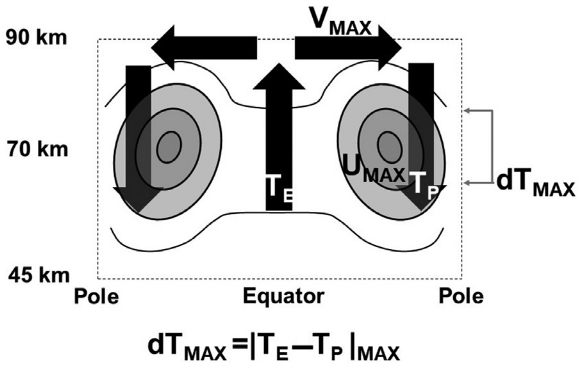

Fig. 1. Schematic of relationships among U_{MAX}, V_{MAX}, and dT_{MAX}. Contours represent zonal wind speed, and thick arrows represent meridional circulation. T_E is the equatorial temperature and T_P the polar temperature at the level where equator–pole temperature contrast is maximum. Thin gray arrows indicate the locations of dT_{MAX}. dT_{MAX} has almost the same magnitude as the equator–pole temperature contrast at ~60 km. The return flow (equatorward meridional wind) is not shown in the schematic figure, because it is unclear in the Venus lower atmosphere.

1982) enhances both equatorial superrotation and midlatitude jets. Such enhanced midlatitude jets induce baroclinic 5-day Rossby waves. Recently, Yamamoto and Takahashi (2012, 2015) extended these mechanistic models to the Venus Middle Atmosphere General Circulation Model (VMAGCM), in order to investigate the influences of planetary-scale waves and thermal tides on superrotation in the cloud layer. In their experiment with a 5.5-day Kelvin wave forced at the bottom boundary, superrotation is fully developed at the cloud top and base. Whereas the forced 5.5-day wave is dominant at cloud base, the 4-day wave is newly generated in the cloud layer. These two waves may correspond to the equatorial 5.5-day near-infrared (NIR) marking (Crisp et al., 1991) and 4-day ultraviolet (UV) dark band (Del Genio and Rossow, 1990), respectively. A Venus GCM (Yamamoto and Takahashi 2006) showed the generation of fast equatorial waves in the lower atmosphere and supported the assumption of Kelvin-wave forcing in our earlier studies (Yamamoto and Tanaka, 1997; Imamura, 2006; Yamamoto and Takahashi, 2012, 2015). These equatorial waves were recently simulated in several GCMs (Sugimoto et al., 2014; Lebonnois et al., 2016) and might influence the general circulation structure via wave mean-flow interaction. In the present work, the lower atmosphere condition of the VMAGCM was improved (Appendix A). In some simulations, long-period oscillations of the zonal wind are seen (Sections 3 and 4). According to long-term Pioneer Venus and Venus Express observations, zonal wind and planetary-scale waves varied with time (Del Genio and Rossow, 1990; Kouyama et al., 2015). These interannual variations may be associated with temporal wind change via wave mean-flow interaction seen in GCMs.

The purposes of the present study are to elucidate dynamical relationships between wind magnitude and equator−pole temperature contrast and dynamical process of the interannual oscillation of the general circulation. We derive simple equations (Section 2), that explain dynamical relationships among zonal wind, meridional wind, and equator−pole temperature contrast in a middle atmosphere model (Section 3). Dynamical processes during the long-term oscillation seen in the time series are investigated in Section 4. Finally, the results are summarized in Section 5.

2. Analytical estimation of wind magnitude and meridional temperature contrast

Fig. 1 illustrates the general circulation structure inferred from recent observations (e.g., Piccialli et al., 2012) and simulations in the Venus middle atmosphere (e.g., Yamamoto and Takahashi, 2012). In the middle atmosphere between 40 and 90 km, U_{MAX} and V_{MAX} are the maximum values of the zonal-mean zonal and meridional wind speeds, respectively. dT_{MAX} is the largest magnitude of the difference between zonal-mean polar temperature T_P and equator temperature T_E. U_{MAX} and V_{MAX} are located at ~70 km and ~90 km, respectively. Although dT_{MAX} (the largest magnitude of $|T_E - T_P|$) is located at ~60 km or ~75 km in our VMAGCM experiments, dT_{MAX} indicates the magnitude of the equator–pole temperature contrast at ~60 km, because $|T_E - T_P|$ below the jet core (~60 km) has approximately the same magnitude as that above the jet core (~75 km). Although the scatter plots of U_{MAX}, V_{MAX} and dT_{MAX} were applied to the seasonal variation of the superrotation (Yamamoto and Takahashi, 2007), the scatter plot distributions were not theoretically discussed in the previous work. The scatter plot distributions are investigated in the present work, based on simple analytical estimations under the condition that the seasonal variation is neglected.

2.1. Thermal wind relation in Venusian cloud layer

In a local superrotation frame of zonal-wind magnitude U_0 around a latitude φ^* in the cloud layer between 45 and 70 km, the thermal wind is described as

$$u_T \sim -\frac{R}{f^*}\ln\left(\frac{P_{45\,\mathrm{km}}}{P_{70\,\mathrm{km}}}\right)\frac{\partial T}{\partial y} \sim \frac{R}{f^*}\ln\left(\frac{P_{45\,\mathrm{km}}}{P_{70\,\mathrm{km}}}\right)\frac{dT_{MAX}}{a}, \qquad (1)$$

where R is the gas constant, P is pressure, T is temperature, and a is the planetary radius. Here, the magnitude of the meridional temperature gradient is estimated by dT_{MAX}. The effective Coriolis parameter f^* in the superrotational frame is set to

$$f^* = 2\Omega^* \sin\varphi^* \sim 2\frac{U_0}{a\cos\varphi^*}\sin\varphi^* \sim \frac{2U_0\tan\varphi^*}{a} \qquad (2)$$

where Ω^* ($=U_0/(a\cos\varphi^*)$) is the rotation rate of the superrotating frame, and U_0 is the zonal wind speed of the superrotation at a given latitude φ^* (Appendix B). For example, when the zonal wind speed at the 70-km level and latitude φ^* is approximately the same as U_{MAX},

$$U_{MAX} \sim U_{45\,\mathrm{km}} + \frac{R\ln(P_{45\,\mathrm{km}}/P_{70\,\mathrm{km}})}{2U_0\tan\varphi*}dT_{MAX}. \qquad (3)$$

Eq. (3) shows the linear relationship between U_{MAX} and dT_{MAX} for a simulation in which U_{MAX} is located at high latitudes. The altitude of ~45 km was used as the bottom boundary in the estimation of cyclostrophic winds from VeRa (Piccialli et al., 2012). Thus, we also used this height level as the bottom boundary in the present study.

2.2. Stream function equation above cloud layer

V_{MAX} is assumed to be located around 90 km (Fig. 1), where strong poleward flow is dominant, according to the result of the VMAGCM (Yamamoto and Takahashi, 2012). Here, we consider the domain above the cloud-top jet maximum. As seen in Figs. 10 and A1, although eddy heat flux and eddy-driven indirect circulation are limited to around the high-latitude jet cores in the domain between 70 and 90 km, they do not directly influence the poleward flow magnitude of the Hadley circulation around 90 km. Thus, eddy heat flux is not included for simplicity. On this assumption, the zonal-mean stream function equation is obtained from the temperature Eq. (B15), equation of continuity (B4) and meridional force balance (B8) in Appendix B. From the stream function, the zonal-mean meridional wind velocity $\bar{v}$ is described as,

$$\bar{v} = -\frac{1}{\rho\cos\varphi}\frac{\partial\bar{\chi}}{\partial z}, \qquad (4)$$

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