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Mean meridional circulation in the Venus atmosphere

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Abstract

Zonal-mean meridional circulation (MMC) in the Venus atmosphere is investigated by using a general circulation model. In the upper cloud layer (60–70 km), thermally direct and indirect cells appear in low- and mid-latitudes, respectively, as in the Earth troposphere. In the middle cloud layer (50–60 km), a strong direct cell appears in 0°–60° latitudes, which is tilted almost along the isentropic surfaces. Residual MMC suggests that an indirect cell in high-latitudes in 50–60 km is generated by baroclinic instability waves. The potential vorticity (PV) distribution suggests that the tilted MMC extending in low- and mid-latitudes may be generated by the symmetric instability, though its meridional structure remains unexplained. It is also suggested that the condition of symmetric instability is strongly influenced by the thermal tide.

1. Introduction

The zonal-mean meridional circulation (MMC) is considered as one of key processes for generation and maintenance of the Venus atmospheric superrotation [2, 6]. However, it has not been detected in observations so far, and its structures obtained in recent general circulation models have been diverged [e.g. 3, 5, 12]. The mechanism how the MMC is formed in the Venus atmosphere and its meridional/vertical structures have not been investigated so far. In the present study, we elucidate the Venus MMC and its formation mechanism by examining how its structure depends on static stability and/or the solar heating.

2. Model

A general circulation model (GCM) used in the present study is AFES-Venus, a full nonlinear GCM with simplified physical processes for the Venus atmosphere based on the primitive equations on the sphere [8]. This model enables us reproduce realistic structures of the Venus upper atmosphere at the cloud levels such as the baroclinic instability waves, the cold collar, the thermal tides, and the planetary-scale streak structure found by Akatsuki [1, 4, 9, 10]. The model atmosphere extends from the ground to about 120 km, and 120 levels are taken at a regular spacing of 1 km. The horizontal resolution is T63 (192×96 grid points in longitude and latitude). The vertical eddy viscosity with a constant coefficient of 0.015 $\mathrm{m^2\,s^{-1}}$ is used. The horizontal eddy viscosity is represented by the second-order hyper-viscosity, whose damping time for the maximum wavenumber is approximately 0.1 Earth days. The values of physical parameters are set adequately for the Venus atmosphere. The solar heating is based on the previous observation [11]; but it is neglected above 80 km in the present study. The temperature field is relaxed to a prescribed horizontally uniform field, which is taken from the Venus international reference atmosphere (VIRA). See our previous works [9, 10] for more details of the model. The initial condition is an idealized superrotating state, in which the zonal wind is assumed to be in the solid body rotation. The initial temperature distribution is cyclostrophically balanced with the initial zonal wind. We perform a nonlinear numerical integration for 10 Earth years. In the present study, we analyze the data obtained for the last 2 Earth years in the quasi-equilibrium state.

3. Results

The fast zonal flow (superrotation) of 130 m/s is maintained at the cloud top level (not shown) as in the previous works [9, 10]. Figure 1 shows zonal-mean mass stream function (MSF) of Eulerian and residual MMC averaged over 234 Earth days. The MMC in 60–70 km levels in 0°–60° consists of thermally direct and indirect cells in low- and mid-latitudes, respectively. It is suggested that the indirect cell is generated by the baroclinic instability waves because it does not appear in the residual MMC.

In the middle cloud layer (50–60 km), significant MMC cells exist, which are quite different from those

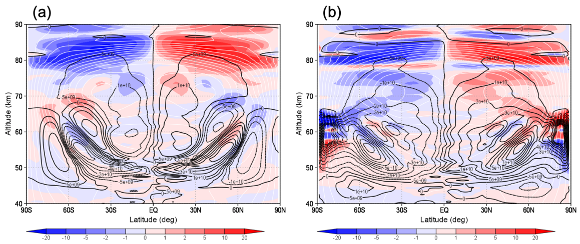

Figure 1: Zonal-mean distributions of mass stream function (MSF) of (a) Eulerian and (b) residual mean meridional circulation (MMC) averaged over 234 Earth days.

obtained in the previous GCM studies. It should be noted that the direct cell in these levels, which is tilted almost along the isentropic (equi-potential temperature) surfaces, is quite unsteady and not symmetric about the equator if observed at an certain moment. Momentum and heat transport associated with these MMC cells are comparable to those associated with waves and eddies including the thermal tides and the baroclinic instability waves. It is inferred that the superrotation could be affected by the MMC at 50–60 km. The indirect cell in high-latitudes also disappears in the residual MMC, suggesting that the baroclinic instability occurs not only in mid-latitudes at 60–70 km but also in high-latitudes at 50–60 km.

The potential vorticity (PV) distribution (not shown) indicates that the symmetric instability [7], whose most preferred mode is zonally uniform, may occur in mid-latitudes at 50–60 km, where the isentropic and angular momentum surfaces are parallel because of small static stability at these levels.

It is also interesting that large indirect cells extending from the equator to poles appear in the residual mean in the lower cloud layer (40–50 km).

4. Concluding remarks

The MMC in 60–70 km obtained in the present work is similar to that in the Earth troposphere. The MMC in 50–60 km has quit different structures, which change drastically in time and space. The preliminary analysis suggests that the tilted MMC found in mid-latitudes in the present work may be generated by the symmetric instability. It is noted, however, that its most preferred mode has zonal and meridional wave numbers of 0 and ∞, respectively. The meridional scale of tilted MMC might depend on the (effective) horizontal eddy viscosity.

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