Multiple Equilibrium States Appearing in a Venus-Like Atmospheric General Circulation Model

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Abstract

We investigated the existence of multiple equilibrium states in the Venusian atmospheric general circulation suggested by Matsuda (1980, 1982) using a Venus-like atmospheric general circulation model. We ran the model from two initial conditions: a state with large zonal wind increasing with height and a motionless state. For the large zonal wind initial state, a strong zonal wind with weak meridional circulation, i.e., super-rotation, appears. However for the motionless initial condition, slow zonal wind with strong meridional circulation relative to the farmer state appears. Each circulation reached a quasi-steady state. These results have the same features suggested by Matsuda. The presence of multiple equilibrium states was sensitive to the horizontal eddy viscosity parameter. For the strong zonal wind state, the acceleration of the zonal mean zonal wind results from the horizontal EP flux divergence from the wavenumber one component on the equator, which is mainly maintained by the Gierasch mechanism (1975). The presence of multiple equilibrium states suggests that an alternative slow zonal wind state could appear in the Venusian atmosphere if an appropriate initial condition or drastic fluctuation is assigned.

1. Introduction

Venus has a thick CO$_2$ atmosphere with surface pressure of $9.2 \times 10^9$ hPa. The surface temperature is about 730 K because of the greenhouse effect imparted by thick CO$_2$ gas. Sulfuric acid clouds blanket the entire planet at about 47−70 km. An important characteristic of Venus is its very slow rotation: its rotation period is 243 earth days. One Venus Solar day is 117 days considering both daily rotation and revolution. It might therefore be speculated that convection between dayside and nightside dominates the atmospheric circulation, and that the convection pattern moves slowly together with slowly migrating subsolar and antisolar points. However, such a convection has not been observed, and observations have confirmed that fast zonal winds, called super-rotation or four-day circulation, are predominant. The Venusian cloud pattern rotates in the same direction as the rotation of the solid Venus with about four days around Venus along the equator. The zonal wind speed increases with height; its velocity is about 100 m s$^{-1}$ at the cloud top level (about 70 km). The wind is 60 times faster than the solid planet. The reason why dayside-nightside circulation does not appear but super-rotation (four-day circulation) is dominant remains still unclear. Furthermore, the mechanism producing and maintaining such a fast zonal wind
remains unclear. A similar phenomenon was observed in the atmosphere of Titan (rotation period 16 days).

Some researchers have attempted to describe the super-rotation mechanisms. They have asserted that migrating dayside-nightside heating (Schubert and Whitehead 1969, Thompson 1970), vertically propagating thermal tide (Fels and Lindzen 1974), and meridional circulation (Gierasch 1975) are important for super-rotation formation and maintenance mechanisms.

For the Gierasch mechanism, infinite horizontal eddy diffusion was assumed. Matsuda (1980, 1982) investigated this mechanism for a finite horizontal eddy diffusion effect rather than an infinite value. Rossow and Williams (1979) and Iga and Matsuda (1999) suggested that two-dimensional barotropic eddies play the role of finite horizontal eddy diffusion. Matsuda (1980, 1982) made an interesting suggestion about the possibility of the presence of two different states for the same external parameters: multiple equilibrium states, which are strong zonal wind with weak meridional circulation, i.e., super-rotation, and a weak zonal wind with strong meridional circulation. Matsuda assumed axially symmetric two-dimensional solar heating. So he considered that the weak zonal wind with strong meridional circulation corresponds to dayside-nightside circulation in actual situation.

Recently, some researchers have reproduced super-rotation using a global numerical model. Del Genio et al. (1993) and Del Genio and Zhou (1996) reproduced super-rotation using AGCM for the earth by merely adopting the Venusian rotation rate and retaining other Earth parameters. Yamamoto and Takahashi (2003a (hereinafter, YT), 2003b) reproduced super-rotation by Venus-like AGCM that incorporates the Venus rotation rate, high surface pressure, high surface temperature, and zonally uniform solar heating; their results support the Gierasch mechanism. Yamamoto and Takahashi (2004) extend these works by adopting three-dimensional solar heating and reproduced super-rotation; their result also supports the Gierasch mechanism. Takagi and Matsuda (2007) reproduced super-rotation using a nonlinear dynamical model on a sphere that has Venusian parameters and the only tidal component for the sola heating; their results suggest that a vertically propagating thermal tide can reproduce super-rotation.

Del Genio and Zhou (1996) investigated sensitivity to initial conditions and present computations using two different initial states: a motionless state and one resembling super-rotation. However, they were unable to reproduce a multiple equilibrium state. Kido and Wakata (2007) (hereinafter, KW) investigated the possibility of multiple equilibrium states suggested by Matsuda (1980, 1982) using Venus-like AGCM. They also provided two initial values. For a motionless initial condition, slow zonal flow was reproduced. For a large zonal wind initial condition, quasi-steady super-rotation is reproduced. However, this state suddenly collapsed and settled to slow rotation with the precessional motion of the atmosphere. Eventually, they did not reproduce steady multiple equilibrium states.

To date, no studies have reproduced steady multiple equilibrium states using AGCM. For this study, we again target reproduction of steady multiple equilibrium states using Venus-like AGCM. We present a description of the model in Chapter 2, results of numerical simulation in Chapter 3, and a summary and discussion in Chapter 4.

2. Model

We use an atmospheric general circulation model (CCSR/NIES AGCM version 5.4; Numaguchi et al. 1995) that was developed for the earth atmosphere. Its horizontal resolution is T21, in which 64 grids are in the zonal direction and 32 grids are in the meridional direction. The vertical domain of 0–100 km is divided into 60 layers at even intervals.

The model is modified for application to a Venusian atmosphere, referring to YT. In particular, physical parameters are changed to Venus’ values as follows: the planetary rotation period is 243 days; the radius is 6050 km; the gravity acceleration is 8.87 m s⁻²; and the standard surface pressure is 9.2 × 10⁴ hPa. In addition, the specific heat is 8.2 × 10⁴ J kg⁻¹ K⁻¹ at constant pressure, and the gas constant is 191.4 J kg⁻¹ K⁻¹.

It is difficult to resolve radiation processes directly. Therefore, we use zonally uniform solar heating and Newtonian cooling for the reference temperature. Since our research is started from Matsuda (1980, 1982) in which he extended the Gierasch mechanism based on the meridional heating difference, we adopt only meridional heating as done by many researchers (Del Genio et al. 1993, 1996; Yamamoto and Takahashi 2003a, 2003b; Hollingthworth et al. 2007).

The heating rate \(Q(\lambda, \phi, z)\), which consists of
zonally uniform heating and the Newtonian cooling rate, is written as

\[
Q(\lambda, \phi, z) = \bar{Q}(\phi, z) - Q_0(z) + (T(\lambda, \phi, z) - T_0(z)) / \tau_N(z),
\]

which is discussed by YT in detail. In that equation, \(\lambda\) is the longitude, \(\phi\) is the latitude, \(z\) is the altitude, \(\bar{Q}(\phi, z)\) is a zonally uniform heating rate, but varied in meridional direction and altitude; \(Q_0(z)\) is a global mean of \(\bar{Q}\) at some altitude (Fig. 1). In the cloud layer, the global mean heating rate is provided as a maximum of 5.6 K day\(^{-1}\) at about 63 km. In addition, below 40 km, we set 0.079 K day\(^{-1}\). The heating rate is almost equal to that used in YT in the cloud layer, but the value is small about one-sixth below the cloud layer, because YT’s heating rate is too large for the real Venus near the ground. The real heating rate is estimated as about 3.0 \times 10^{-3} K day\(^{-1}\) at 0–10 km altitude, and the heating rate provided in this study is, nonetheless, too high for the real Venus near the ground (Tomasko et al. 1980). Figure 2 shows the reference temperature \(T_0(z)\), which is based on an observed value (Seiff et al. 1980). The model temperature is adjusted to this reference temperature. Figure 3 shows the time constant \(\tau_N(z)\) of Newtonian cooling (Hou and Farrel 1987).

For this study, we do not consider topographic effects, and the ground surface is assumed to be flat. Water processes, such as cumulus convection and large-scale condensation, are also excluded.

A fourth-order horizontal diffusion of the e-folding time of 24 hour at the maximum wavenumber is applied to prevent numerical instability. Vertical diffusion is calculated using the Mellor and Yamada level 2.0 closure model. We assume a large Rayleigh friction of 7.2 hour near the top layer to avoid artificial wave reflection from the top boundary.

In this study, model setting is almost the same as KW; the only difference from KW is the e-folding
time at the maximum wavenumber. In KW, the e-folding time was set as 480 hour; in contrast, 24 hour is provided in this study. These values differ greatly. However, the value of 24 hour is generally used in AGCM in horizontal resolution of T21 for the earth atmosphere.

3. Results of numerical simulations

In this study, we attempt to simulate multiple equilibrium states of the Venusian atmospheric general circulation. Therefore, we provide two initial conditions. One is a motionless state; hereinafter, we designate it as Case A. The other is zonal wind increasing linearly with height, which is 0 m s$^{-1}$ at the surface and 50 m s$^{-1}$ at the model top layer at the equator, and cos(θ) is multiplied in latitude. Hereinafter, we designate it as Case B. In each condition, meridional and vertical flows are 0 m s$^{-1}$; the initial temperature is the same as the reference temperature, with imperceptible turbulence.

3.1 Case A

Time evolutions of zonal-mean zonal winds are shown in Fig. 4. Two lines indicate the zonal mean zonal winds at 2.8°N latitude and at 70 km and 30 km altitudes, respectively. After about 150,000 days, the winds are almost in the steady state. The winds reach about 40 m s$^{-1}$ at an altitude of 70 km and about 10 m s$^{-1}$ at an altitude of 30 km. Figure 5a shows the latitude-height cross section of the zonal-mean zonal winds averaged 163,567–163,684 days (117 days). The maximum wind speed of 60 m s$^{-1}$ is apparent at about 63 km and 70° latitude in both hemispheres. The latitude-height cross section of zonal-mean meridional winds averaged for the same period as that shown in Fig. 5a. At greater than around 60 km altitude, winds are poleward, and the maximum wind speed is about 2 m s$^{-1}$. Equatorward winds are apparent at altitudes of 40–60 km, and poleward winds are apparent at 5–40 km altitude. Equatorward winds are also seen around the bottom layer. Two cell structures are apparent in the meridional circulation. The latitude-height cross section of zonal-mean vertical winds, which are averaged for the same time as that shown in Fig. 5a, is shown in Fig. 5c. The upward wind at the equatorial area and downward flow at the polar area are visible. The upward wind was cut off at around 40 km altitude in this period. However the upward wind is connected and seen in all ranges in another period; the cutting and connection are repeated with about a 200-day period. Figure 5d portrays the latitude-height cross section of temperature for the same period as that depicted in Fig. 5a.

3.2 Case B

Figure 6 portrays the time evolution of the zonal-mean zonal wind for case B, as depicted in Fig. 4 (Case A). Two lines indicate the zonal-mean zonal wind at 2.8°N latitude and at 70 km and 30 km altitudes, respectively. After about 40,000 days, the zonal-mean zonal winds are almost in the steady state at 70 km altitude. The zonal-mean zonal wind speed reaches about 100 m s$^{-1}$. Figure 7a shows that the latitude-height cross section of zonal-mean zonal wind averaged 163,567–163,683 days. The maximum wind speed of 120 m s$^{-1}$ is apparent at about 63 km and 55° latitude in both hemispheres. The zonal-mean meridional circulation for the same period as that depicted in Fig. 7a. At around 60 km altitude, there is a poleward wind of about 1.0 m s$^{-1}$. Figure 7c depicts the zonal-mean vertical wind for the same period as that depicted in Fig. 7a. The upward wind at the equatorial area and the downward wind at the polar area are shown there. The latitude-height cross section of temperature for the same period as that depicted in Fig. 7a is portrayed in Fig. 7d. At around altitude 40–70 km, the north-south temperature gradient is large; the centrifugal force attributable to the fast zonal-mean zonal winds balances with pressure gradient force because of the north-south temperature gradient related to the cyclostrophic wind balance.

In this study, we provide a strong Rayleigh friction near the top layer for avoiding the artificial wave reflection. This may supply virtual angler momentum, and enhance the super-rotation. However, since the zonal-mean zonal wind is positive at
the top layer, the Rayleigh friction decelerates the zonal-mean zonal wind near the top layer and does not supply angular momentum. The super-rotation is not enhanced by the Rayleigh friction. Furthermore, atmospheric density is so small near the top layer; therefore the effect of Rayleigh friction as the momentum supply is also quite small.

3.3 Comparison of Cases A and B

Comparing Fig. 5a with Fig. 7a, the maximum zonal-mean zonal wind is seen at high latitude in Case A, although the maximum zonal-mean zonal wind is seen in the middle latitude in Case B. The maximum zonal-mean zonal flow in Case B is twice that of Case A. Comparing Fig. 5b with Fig. 7b, the

Fig. 5. (a) Latitude-height cross section of zonal-mean zonal wind (m s$^{-1}$), averaged for days 163,567–163,683. The gray area indicates negative values. The contour interval is 10 (m s$^{-1}$).
(b) Same as (a), but for zonal-mean meridional wind. The contour interval is 0.5 (m s$^{-1}$).
(c) Same as (a), but for zonal-mean vertical wind. The contour interval is 0.1 (cm s$^{-1}$).
(d) Same as (a), but for zonal-mean temperature. The contour interval is 30 (K).

Fig. 6. Time evolution of zonal-mean zonal winds (m s$^{-1}$) at 70 km and 30 km altitudes at 2.8°N latitude.
maximum meridional flow in Case A is twice that of Case B at 60 km altitude. These features are summarized as Case A has a “weak zonal wind (half of Case B) and strong meridional circulation (twice of Case B)”; Case B has a “strong zonal wind and weak meridional circulation”. They are consistent with the results in Matsuda (1980, 1982).

Next, we investigate what makes a difference. Eliassen-Palm flux analysis is convenient to illustrate the wave effects. The residual mean meridional circulation \( \vec{u} \) and the Eliassen-Palm (EP) flux \( F \equiv (F^{(e)}, F^{(c)}) \) are defined as the following.

\[
\vec{u} = \vec{v} - \rho_0 \left( \frac{\rho v' \theta'/\theta_z}{\rho_z} \right) \\
\vec{v} = \vec{w} + (a \cos \phi)^{-1} (\cos \phi v' \theta'/\theta_z) \\
F^{(e)} = \rho_0 a \cos \phi \left( \frac{(f - (a \cos \phi)^{-1} (\vec{u} \cos \phi)' \theta')}{\theta_z - \vec{w}' u'} \right) \\
F^{(c)} = \rho_0 a \cos \phi \left\{ \left( f - (a \cos \phi)^{-1} (\vec{u} \cos \phi)' \theta' \right) / \theta_z - \vec{w}' u' \right\} 
\]

In addition, the divergence of a vector \( F \) is defined as shown below.

\[
\nabla \cdot F \equiv (a \cos \phi)^{-1} (F^{(e)} \cos \phi) + F^{(c)} 
\]

Transformed Eulerian-mean equation for zonal wind is shown below.
\[
\bar{u} + \bar{v} \left[ (a \cos \phi)^{-1} (\bar{u} \cos \phi) - f \right] + \bar{w} \bar{u} - \bar{X} = (\rho_0 a \cos \phi)^{-1} \nabla \cdot \mathbf{F}
\] (4)

In these equations, \( u \) is the zonal flow, \( v \) is the meridional flow, \( w \) is the vertical flow, \( \theta \) is the potential temperature, \( \rho_0 \) is the mean atmospheric density, \( a \) is the planetary radius, \( f \) is the Coriolis parameter, and \( \bar{X} \) is the unspecified zonal component of friction or the other nonconservative mechanical forcing (for details, see Andrews et al. 1987). The bar over the symbols indicates the zonal mean. The symbols with a prime indicate the anomaly component from the zonal mean. The EP flux indicates the angular momentum transport by eddies. The positive \( \nabla \cdot \mathbf{F} \) indicates zonal mean zonal wind acceleration attributable to the wave components; the residual mean circulation expresses the circulation caused by external heating. Figure 8 portrays vertical profiles of acceleration/deceleration at 2.8°N latitude averaged 163,099–163,683 days (5 Venus days) in Cases A and B. At 45–65 km altitude, the acceleration attributable to horizontal EP flux divergence (the first term of right-hand side of Eq. 3) is balanced against deceleration attributable to vertical advection in each case (Eq. 4). The contribution of vertical EP flux divergence (the second term of right-hand side of Eq. 3) is relatively small in each case. Zonal-mean zonal winds must be produced because of the Gierasch mechanism. Comparing Case A to Case B, the acceleration attributable to horizontal EP flux divergence in Case B is twice that of Case A at 58 km altitude. Fundamentally, the Gierasch mechanism works efficiently in Case B.

The horizontal EP flux divergence with respect to each wavenumber at latitude of 2.8°N and at altitude 58 km is calculated for the same period as that shown in Fig. 8 in each case (Fig. 9). Results indicate that the contribution from wavenumber one is dominant in each case. Figure 10 shows a Hovmöller diagram of geopotential height with wavenumber one at 2.8°N at the altitude of 58 km for 163,567–163,596 days to clarify the propagation property of wavenumber one. A remarkable difference between the two cases is the amplitude. In Case A (Fig. 10a), the amplitude is smaller than 20 m, but the amplitude is larger than 60 m in Case B (Fig. 10b). This difference yields the difference of horizontal EP flux divergence. In Case A, waves propagate in the same direction as the direction of Venusian rotation; its phase velocity is faster than the zonal-mean zonal wind velocity. In Fig. 10c, the phase velocity of wavenumber one component is estimated as about +49 m s\(^{-1}\); then the zonal-mean zonal
wind speed is about +27 m s$^{-1}$. In Case B, waves propagate in the same direction as the direction of Venusian rotation, and its phase velocity is slower than the zonal-mean zonal wind velocity. In Fig. 10d, the phase velocity of wavenumber one component is estimated as about +28 m s$^{-1}$; the zonal-mean zonal wind speed is about +75 m s$^{-1}$. The phase velocity of waves with the subtracted zonal-mean zonal wind speed is about −47 m s$^{-1}$. Figure 11 shows the longitude-latitude cross section of the wavenumber one component of geopotential height at 58 km altitude in Case B. The horizontal structure of waves has peaks at 70° latitude in both hemispheres; the phase of waves is connected between the equator and pole. Waves propagate in the same direction as the direction of Venusian rotation uniformly, and the phase velocity is slower than the zonal-mean zonal wind velocity at all latitudes. Therefore, the phase velocity of waves subtracted zonal-mean zonal wind speed is negative at all latitudes. In sum, the wavenumber one component in Case B has a similar character to that of Rossby waves. Figure 12 shows a time-height cross section of the wavenumber one component of geopotential height at 0°E and 2.8°N for 163,576-163,683 days in each case. In Case A (Fig. 12a), minute structures propagate upward and downward from about 60 km altitude, with characteristics resembling those of gravity waves. In Case B (Fig. 12b), the phase slope is vertical over about 50 km altitude; this character is barotropic waves. To seek the source of the disturbance, we investigate energy diagrams, in case B. The zonal kinetic energy is transferred to the eddy kinetic energy. This energy transformation denotes that barotropic instability is the source of the disturbance. This result is consistent with those of Rossow and Williams (1979), Iga and Matsuda (1999). Comparing Fig. 12a with Fig. 12b, the amplitude of disturbance in Case A is smaller than in Case B over about 50 km altitude.

4. Summary and discussion

We run the model from two initial conditions. In a case with motionless initial condition (Case A), slow zonal wind (half of Case B) with strong meridional circulation (twice of Case B) appears. For a large zonal wind initial condition (Case B), super-rotation with weak meridional circulation can be reproduced. In each case, the results attained a quasi-steady state. We can reproduce multiple equilibrium states, as suggested by Matsuda (1980, 1982), using Venus-like AGCM. The horizontal eddy viscosity parameter and lower heating are quite sensitive to obtain the multiple equilibrium states (KW; YT). The presence of multiple equilibrium states suggests that an alternative slow zonal wind state could appear in the Venusian atmosphere if an appropriate initial condition or drastic fluctuation is assigned.

In this work, a growing wavenumber one component like that which is apparent in KW with a precessional motion of the atmosphere does not exist. In KW, the collapse of super-rotation appeared before reaching a steady state at 30 km altitude; in this study, the zonal-mean zonal wind reaches a steady state at 30 km. Furthermore in this study, we run the model longer (163,683 days) than KW (129,168 days and collapse happens at about 75,000 day). For these reasons, we feel strongly that the collapse of super-rotation will not appear if we would carry on the time integration.
Fig. 10. Hovmöller diagram of the geopotential height with wavenumber one at 2.8°N latitude of 58 km: (a) is Case A during days 163,567–163,683 with contour interval of 20 (m); (b) is Case B for the same period of (a) with the contour interval of 20 (m); (c) is Case A during days 163,567–163,596 with the contour interval of 3 (m); and (d) is Case B for the same period of (c) and the contour interval is 20 (m). The solid line indicates the zonal-mean zonal wind and the dashed line indicates the peak of the wave phase.
In Case B, the Gierasch mechanism with barotropic eddies maintains super-rotation. In addition, the wavenumber one component plays an important role in acceleration. In this study, the zonal wind associated with the present super-rotation is almost the same as the observed value around 70 km altitude. However, below about 50 km, the zonal-mean zonal wind is less than the observed value (Fig. 7a). The reason remains unclear. We will investigate this issue.

It is noted that we obtained the multiple equilibrium solutions in the Venus-like GCM simula-
tion, but this results based on the assumption of the zonally homogeneous heating. The inclusion of dayside-nightside heating has the possibility to bring another processes. We are now investigating this topic.

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