Stationary and Slowly Propagating Waves in a Venus-Like AGCM: Roles of Topography in Venus’ Atmospheric Dynamics

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Topography and solar heating are incorporated in our Venus-like AGCM. Superrotation is fully developed at the cloud top. Stationary waves and slowly propagating waves with phase velocities of about 0 m/s are predominant because of the topographic and thermal forcings. The topography leads to the north-south asymmetries of the angular momentum and the vertical EP flux in the lower atmosphere. Since the winds near the surface are weak and the static stability is low, the vertical eddy momentum flux of stationary mountain wave with phase velocity of 0 m/s is not large near Maxwell Montes at high latitude. Rather than the stationary wave, slowly propagating waves produce large vertical EP flux. In the equatorial region where Aphrodite Terra is located, the vertical eddy momentum flux of stationary wave is locally predominant near the surface.

1. INTRODUCTION

Venus has almost the same size as Earth, but the surface is largely different from those on Earth. High temperature of 730 K and high pressure of 92 atm. are maintained at the surface. CO₂ is dominated in the Venus atmosphere and there are cloud layers of sulfuric acid aerosols globally covering the planet in the height range of 50–70 km. Short wave radiative heating by the cloud layer is one of driving forces of the atmospheric circulation of Venus.

The solid part of Venus slowly rotates with a period of 243 days (Earth days) in an inertial frame, while the atmosphere near the cloud top (65–70 km) rapidly rotates with the 4-day period 60-times shorter than 243 days. The cloud-top zonal flow has velocity of ~100 m/s. The atmospheric rotation with angular velocity faster than the planetary rotation is termed “superrotation”. In particular, the strong superrotation near the Venusian cloud top is known as “4-day circulation”. Some theories and scenarios of the formation and maintenance mechanism of the superrotation have been proposed¹⁻⁴. However, the validities of the theories and scenarios have not been fully discussed, since there is a very little observation of the circulation and waves. Furthermore, there remain many uncertainties in physical processes, and thus it is difficult to incorporate these physical processes in atmospheric general circulation model (AGCM). For the above-mentioned difficulties, the Venus superrotation remains one of unsolved problems in planetary meteorology and fluid dynamics.

Recently, we reproduce the superrotation in a Venus-like AGCM simplifying the physical processes, and propose the formation and maintenance mechanism on the basis of analyzing the atmospheric circulation and waves⁵⁻⁸. The superrotation is maintained by the Gierasch mechanism¹, in which the meridional circulation pumps up the angular momentum
required to maintain the superrotation with the help of waves with equatorward momentum fluxes. Thermal tides are forced by solar heating with a period of a Venusian day (117 Earth days) near the cloud top, and contribute to the Gierasch mechanism through the equatorial acceleration of mean zonal flow. Kelvin and Rossby waves are generated by shear instability in the lower atmosphere, and contribute to the Gierasch mechanism.

In addition to thermal forcing with the 117-day period, topographic forcing is also considered in the present study. We use the Venusian topography data\(^9\) as the lower boundary condition in our model, and examine the influences of mountains and highlands on the atmospheric circulation. In particular, we report stationary wave (the phase velocity \(c = 0\) m/s) and slowly propagating wave (\(c \sim 0\) m/s) simulated in the preliminary experiment.

![Fig. 1 Longitude-latitude distribution of elevation (m) of Magellan topography data\(^9\).](image)

2. MODEL

The model used is based on the version 5.6 of AGCM developed at the Center for Climate System Research / National Institute for Environmental Study\(^{10}\), and is similar to the model of Yamamoto and Takahashi\(^7,8\). The model description is summarized as follows. The horizontal spectra are truncated at wavenumber 21, and the vertical domain between 0 and 90 km has 52 layers. Thickness of layer is \(\sim 1\) km in the layer from 1 to 10 km altitude, and \(\sim 2\) km in the layer from 10 to 80 km. Below 1 km, three layers are located at 0.995, 0.980 and 0.953 on the sigma coordinate. The radiative processes are simplified by the 3D solar heating and the Newtonian cooling, whose rates are the same as those in Yamamoto and Takahashi\(^7,8\). The maximum solar heating rate given in this model is 30 K day\(^{-1}\) at the subsolar point and the 65-km altitude. The zenith-angle (\(\lambda\)) dependence of the solar heating is \(\cos^{1.4} \lambda\)\(^{11}\). The heating distribution is improved in Yamamoto and Takahashi\(^7,8\), however the rate is larger than that in the real atmosphere below 55 km (ref. Fig. 1 in Yamamoto and Takahashi\(^7,8\)). The radiative processes are not included on the surface and in the upper atmosphere. Horizontal flow is dissipated by Rayleigh friction of 30 days near the top of the model atmosphere. In addition, eddy components of horizontal flow are dissipated at the same time-constant as the Newtonian cooling in the model atmosphere. The 4th order horizontal diffusion of the e-folding time of 60 hours at the maximum wavenumber and the vertical diffusion coefficient of 0.15 m\(^2\) s\(^{-1}\) are introduced in the model.

The equator–pole contrast of the surface potential temperature is set at 10 K, though it is larger than the lower-atmospheric contrast (\(\leq 5\) K). The drag coefficient is set at \(4 \times 10^{-3}\) for temperature and horizontal flow\(^{12}\). Magellan topography data\(^7\) shown in Fig. 1 is given at the bottom boundary. The surface temperature on the topography is obtained from altitude,
adiabatic lapse rate, and the surface temperature at 0 km ($a = 6049.358$ km, where $a$ is the planetary radius).

3. RESULTS

Before discussing stationary and slowly propagating waves, the superrotation mechanism in a Venus-like GCM with topography is briefly summarized. The zonal mean and eddy fields were investigated using the data sampled over 3072 hours with 3-hour intervals on the equilibrium state, in order to detect waves with a wide range of phase velocities. The meridional circulation is driven by the differential heating and the dissipative waves in the same manner as our previous GCMs$^{5-8}$. A single cell, in which the vertical flow is upward (downward) at the equator (the poles) in the height range from 0 to 80 km, is predominant. The superrotation with wind speed of $> 100$ m/s is reproduced near the cloud top (65–70 km). In the lower atmosphere, equatorward momentum flux due to shear instability$^{13, 14}$ deposits the angular momentum into the upper branch of the meridional circulation, in which the upward flow efficiently pumps up the angular momentum. In the middle atmosphere, the horizontal and vertical angular momentum fluxes due to thermal tides maintain the equatorial superrotation, together with the advection due to meridional circulation$^{5, 6, 15}$. The development of the equatorial zonal flow due to equatorward eddy momentum fluxes enhances the upward angular momentum flux due to the meridional circulation, which balances with the downward momentum flux due to eddies. This corresponds to the Gierasch mechanism$^{13}$.

Fig. 2 shows a latitude-height distribution of the angular momentum of the zonal mean flow. The angular momentum has a maximum near 20 km and asymmetry between the north and south hemisphere below 10 km. Fig. 3 shows a latitude-height distribution of vertical EP flux. The vertical EP flux also has the north-south asymmetry. Large vertical EP flux is observed at 35 km in the latitudinal region where the highest mountain Mt. Maxwell is located. This asymmetry is caused by the topography, since the asymmetry is not large in our previous experiments without the topography.
Fig. 4 Longitude-height distributions of eddy zonal flows (m s\(^{-1}\)) averaged over a Venusian day at (a) 2.7° and (b) −69.2° latitude. Height is approximate height calculated from sigma on the assumption of the Venus standard atmosphere.

Fig. 5 Longitude-latitude distributions of eddy temperature (K) and horizontal flow (m s\(^{-1}\)) averaged over a Venusian day in the undermost layer of \(\sigma = 0.995\). \textit{XUNIT} and \textit{YUNIT} indicate longitudinal and latitudinal components of the unit vector at the lower right of the panel, respectively.

Fig. 4 shows longitude-height distributions of eddy zonal flows averaged over a Venusian day (117 days) at 2.7° and −69.2° latitude. The eddy zonal-flow component of \(\omega = 0\) for a sampling period of 117 days (where \(\omega\) is frequency) corresponds to that of stationary waves. The tilting phase structures are seen in the upper regions. This indicates that the stationary waves propagate vertically above the cloud top. The standing phase structures are seen below 70 km at the equator and below 50 km at high latitudes. Since the horizontal wind is weak and the stability is low near the surface of Venus, the vertical momentum flux \(\overline{u'w'}\) of the mountain waves is negligible in the large part of the lower atmosphere, except for near the surface at low latitudes. Fig. 5 shows longitude-latitude distributions of eddy temperature and horizontal flow averaged over a Venusian day at the undermost layer. The eddy temperature decreases with altitude, i.e., the lower eddy temperature indicates the higher elevation. Since the Newtonian cooling (which is a function of the pressure level) is stronger with height, the large cooling rate produces cool air parcel at top of high mountain. In this situation, the horizontal wind blows from top to foot of high mountain.
Fig. 6 Longitude-latitude distributions of eddy geopotential-height (m) and horizontal-flow (m s\(^{-1}\)) components of \(s = 1\) and \(c = 2.7\) m s\(^{-1}\) at the levels of (a) \(\sigma = 0.308\) (17 km approximate height) and (b) \(\sigma = 0.0514\) (37 km approximate height). XUNIT and YUNIT indicate longitudinal and latitudinal components of the unit vector at the lower right of the panel, respectively.

Large vertical EP flux near the latitude of Mt. Maxwell (Fig. 3) is caused by planetary-scale waves with phase velocity of 2.7 m/s, rather than stationary waves (such as mountain waves of \(c = 0\) m/s). Fig. 6 shows longitude-latitude distributions of geopotential height and horizontal flow of the planetary-scale wave of \(s = 1\) and \(c = 2.7\) m/s at the levels of \(\sigma = 0.308\) (~17 km, where a peak of the positive flux is seen at ~74.8° latitude) and \(\sigma = 0.0514\) (~37 km, a peak of the negative flux). The planetary-scale wave has vortical structures, such as Rossby wave. In the phase-velocity–height cross section of EP-flux spectrum (not shown), the sign of the vertical EP flux changes near 20 km altitude. The slowly propagating wave is not emitted from the bottom boundary, and thus is different from the mountain wave. The topography influences the structures of the planetary-scale waves generated in the atmosphere (e.g., shear instability) through the bottom boundary of geopotential, and leads to the north-south asymmetry of the vertical EP flux.

As mentioned above, stationary and slowly propagating waves forced or deformed by topography have significant amplitudes. Thus, the wave activity associated with topography may also result in the north-south asymmetry of the material exchanges between the middle and lower atmosphere (e.g., CO, H\(_2\)SO\(_4\), etc.). Effects of topography on material transport should be examined at the next step.

In the equatorial region where Aphrodite Terra is located, small-scale stationary eddies locally transport angular momentum upward near the surface. The EP fluxes are originated from vertical momentum flux \(\bar{u}'\bar{w}'\) in local areas of 50° and 170° longitudes. The above-mentioned characteristics of the small-scale stationary waves near the equatorial surface are different from those of large-scale stationary waves at high latitudes, of which \(\bar{u}'\bar{w}'\) is negligible.
4. SUMMARY

The superrotation is maintained by the Gierasch mechanism under the condition that thermal and topographic forcings are given in a Venus-like GCM. Horizontal and vertical angular momentum fluxes due to thermal tides contribute to the equatorial superrotation in the middle atmosphere, while shear instability raises the efficiency of pumping up the angular momentum from the lower to the middle atmosphere.

Venus topography forces stationary wave, such as mountain wave. The planetary-scale stationary waves are forced by Mt. Maxwell near −69.2° latitude, and the phase is standing vertically in the lower atmosphere. Thus the vertical momentum flux of the stationary wave (c = 0 m/s) is negligible at high latitudes. In this region, slowly propagating planetary waves (c = 2.7 m/s at −74.8° latitude) generated near 20 km produce large vertical eddy angular momentum flux. The topography influences the structures of slowly propagating planetary-scale waves generated in the atmosphere (e.g., shear instability) through the bottom boundary of geopotential, and leads to the north-south asymmetry of the eddy angular momentum flux. In a different manner from large-scale stationary waves, small-scale stationary eddies locally produce upward angular momentum fluxes near the surface in the equatorial region.

At the next step, further analysis of stationary waves, slowly propagating waves and local convection is required in order to elucidate the wave generation mechanism and the momentum transport process. In addition, the effects of Venus topography on material transport (CO, H₂SO₄, etc.) should be examined using AGCM coupled with chemical transport model.

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http://pds-geosciences.wustl.edu/geodata/mgn-v-rss-5-gravity-l2-v1/mg_5201/topo/

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