

# A transposable planetary general circulation model (PGCM) and its preliminary application to Titan

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## Abstract

We present in this work an application to Titan, Saturn's satellite of the transposable planetary general circulation model (PGCM), which was developed based on the second version of the Community Atmosphere Model (CAM2) of NCAR. The PGCM is a spectral model with the sigma coordinate (where  $\sigma$  is the pressure normalized to its surface value, commonly used as a vertical coordinate in general circulation models) and is integrated in time using the semi-implicit leapfrog scheme. The horizontal resolutions of the model are based on 128 points in longitude and 64 points in latitude, and the vertical discretization is of 26  $\sigma$ -levels. In Titan's conditions we apply the PGCM to simulate Titan's general circulation in this study. Some interesting phenomena such as equatorial superrotation, vertical meridional circulations, vertical structure, etc. are well replicated. This demonstrates the good performance and applicability to Titan of our model and provides a foundation for further studies on simulating and understanding Titan's general circulation and its variability by coupling the physical processes. The features of Titan's circulation under the condition of the Earth's rotation rate are also investigated. The results suggest that different rotation rates can significantly affect the dynamical structure of Titan's circulation.

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## 1. Introduction

General circulation models (GCMs) are important tools in understanding different planetary atmospheric structures, their evolution and related processes. GCMs have already been widely used to simulate the general circulation on Earth. For Mars, one of the first attempts was made by Leovy and Mintz (1969). Since then, Martian GCMs have been mainly developed at the NASA Ames Research Center (e.g., Pollack et al., 1981, 1990, 1993; Haberle et al., 1993, 1999, 2003; Barnes et al., 1993, 1996; Murphy et al., 1995; Hollingsworth and Barnes, 1996). After the mid-

1990s, several Martian GCMs were developed mainly at the Geophysical Fluid Dynamics Laboratory (GFDL) (e.g., Wilson and Hamilton, 1996, Wilson et al., 1997), Oxford University and Laboratoire de Météorologie Dynamique (LMD) (e.g., Forget et al., 1999; Lewis et al., 1999). More similar studies were conducted at the Hokkaido University (Takahashi et al., 2003, 2004) and the Center for Climate System Research (CCSR, Univ. of Tokyo)/National Institute for Environmental Studies (NIES) in Japan (Kuroda et al., 2005), the York University in Canada (e.g., Moulden and McConnell, 2005), and the Max Planck Institute for Solar System Research in Germany (e.g., Hartogh et al., 2005, 2007). Same as for the Martian atmosphere, the atmosphere of Venus has also been simulated using GCM. Before the mid-1990s many scenarios of the Venus atmosphere have been proposed by some GCMs (e.g., Young and Pollack, 1977; Rossow, 1983; Del Genio et al., 1993; Del Genio and Zhou, 1996).

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Thereafter, the GCM of the CCSR/NIES (e.g. Yamamoto and Takahashi, 2003, 2004) and the United Kingdom Meteorological Office Unified Model (e.g., Lee et al., 2005, 2007) have also been applied to the Venus atmosphere.

In this research, we studied Titan's atmosphere, the target of several other numerical simulations by GCMs. Titan's GCMs are mainly developed at the LMD (e.g., Hourdin et al., 1995; Lebonnois et al., 2003; Rannou et al., 2004; Luz et al., 2003) and Cologne University (e.g., Tokano et al., 1999; Tokano and Lorenz, 2006). Recently, a new planetary atmospheric numerical model—called Planet WRF (the Planetary Weather Research and Forecasting model)—has been developed. It has been applied to Mars, Venus, and Titan (Richardson et al., 2007). In addition, Dowling et al. (1998) developed the explicit planetary isentropic-coordinate (EPIC) atmospheric model to simulate the atmosphere of the four gas giant planets and the middle atmospheres of all planets in 1998. Recently, this model has also been applied to terrestrial atmospheres (Dowling et al., 2006).

All the GCMs mentioned above are used to simulate the planetary atmospheres from extensive aspects. The major concerns of simulating the Martian atmosphere by the GCM are dust cycle simulation (e.g., Basu et al., 2004), the general circulation of Martian atmosphere (temperature, pressure, wind velocity, etc.) (e.g., Pollack et al., 1990, 1993; Haberle et al., 1993; Forget et al., 1999; Hartogh et al., 2007), the tracer (dust and water ice cloud) distribution and its influences on the thermal and dynamical structure of Martian atmosphere (e.g., Wilson et al., 1997; Montmessin et al., 2004), and the global dust storm (e.g. Basu et al., 2006). The simulation of Venus' atmosphere was mainly focused on reproducing the super-rotation (e.g., Yamamoto and Takahashi, 2003, 2004; Lee et al., 2007). On the other hand, the Titan studies mainly focus on the vertical circulation (e.g., Hourdin et al., 1995; Grieger et al., 2004; Tokano and Lorenz, 2006), the superrotation in the stratosphere (Hourdin et al., 1995; Grieger et al., 2004), the feedback due to haze distribution on circulation (e.g., Rannou et al., 2004), the hemispheric asymmetry of temperature and haze (e.g., Tokano et al., 1999; Lebonnois et al., 2003; Luz et al., 2003), etc. All of these previous studies have improved our understanding of the physical processes occurring on different planets. However, some drawbacks and limitations of these models should be noted. First of all, these models are grid-point models except for the GCMs of the Hokkaido University (Takahashi et al., 2004) and the CCSR NIES of Japan (Kuroda et al., 2005). The GCMs are divided into grid-point models and spectral models according to different discretization and numerical methods used to resolving partial differential equations of the GCMs. Compared with grid-point models, spectral models (the horizontal aspects in the GCM are treated by the spectral-transform method) have advantages in at least three aspects. Firstly, spectral models have better computational precision and stability than that of the grid-point models. Secondly, spectral

models can automatically and completely filter the high-frequency noises caused by converging meridians in spherical coordinates at high latitudes. The high-frequency noises are usually removed by the use of polar filtering in grid-point models, but the polar filters have side effects. Moreover, spectral models can provide uniform spatial resolution over the entire surface of the sphere more easily than grid-point models which employ reduced or other special grids (e.g., Randall et al., 1998). Thirdly, the spectral models can choose a longer time step-size and as a result save computational time. Furthermore, some of the current models could not be easily transplanted to different platforms of operating systems.

In addition to these advantages of the spectral models over the grid-point models, a three-dimensional (3D) model that can be run in parallel approach on the multiprocessor computer system is needed to simulate 3D structures of general circulations and understand their long-term evolution (which requires long-term integration, especially for Titan). Taking all these factors into account, the NCAR'S Community Atmosphere Model (CAM2) (Collins et al., 2003) is adapted to different planetary environments for the first time in this study. We call it "planetary general circulation model" or PGCM. The PGCM is a spectral model that can be adapted to different planetary atmospheres and can be run in parallel on different platforms of operating systems. We expect that the PGCM could be used to further study some characteristics and physical processes of various planetary atmospheres.

We present in this work the performances of the PGCM when applied to Titan. The paper is organized as follows. The model is described in Section 2. Section 3 presents the experimental design for a preliminary simulation of Titan's atmosphere (LMD Titan's GCM (Rannou et al., 2005) is also introduced briefly in this section). Section 4 discusses the results from this preliminary simulation of Titan's atmosphere by the PGCM, and Section 5 provides a general summary and conclusions.

## 2. Model description

The PGCM is a spectral model in which the horizontal representation of an arbitrary variable consists of a truncated series of spherical harmonic functions, while its basic framework is based on the CAM2. Moreover, the PGCM adopts the sigma coordinate (in the sigma coordinate,  $\sigma$  is the pressure normalized to its surface value, is commonly used as a vertical coordinate in GCMs) and is integrated in time using the semi-implicit leapfrog scheme. The detailed features of the CAM2 are presented in Collins et al. (2003). To apply it to other planetary atmospheres, some modifications were made on the CAM2 as follows.

Firstly, since different planets have specific environments, changes were made to the model to adjust to these environments (e.g., Mars, Titan and Venus): radius of the

planet, acceleration of gravity, solar constant, components of the atmosphere, orbital elements (eccentricity and angle of equator inclination) and calendar (generalized planetary timing: longitude of the Sun is used here). These parameters are placed in a single file except for the calendar (the corresponding model codes are compiled in another file). In this way these parameters can be easily modified for different planets. The stability and time of integration has a close relation with the modifications of these parameters. Secondly, there is a small amount of water vapor on the other planets compared to the Earth. Furthermore, although there are ‘hydrological’ cycles of various substances (Schaller et al., 2007), their understanding in the different planetary atmospheres remains limited. Were we to adopt a coarse convective parameterization, we would not bring further insights to the problem. Therefore, dry convective adjustments are applied while the moisture process in the model is temporarily ignored. Thirdly, due to different vertical structures of the pressure field on different planets, the model’s vertical levels had to be adjusted. With Titan as our main objective, Table 1 gives the adjusted sigma (pressure/surface pressure) and approximate pressure levels (mbar) in the PGCM. Obviously, this modification is adequate for the vertical structure of pressure on Titan. At present, considering the stability and time of integration required by the model, we temporarily do not adjust the number of model levels but the level values.

Table 1  
Sigma (pressure/surface pressure) and approximate pressure levels (mbar) in the PGCM

Number of levels	$\sigma$ levels	Pressure levels
1	6.567e-4	6.498e-2
2	3.280e-3	1.905
3	1.062e-2	7.935
4	2.262e-2	23.935
5	3.696e-2	43.935
6	5.311e-2	66.935
7	7.006e-2	92.409
8	8.543e-2	117.769
9	1.005e-1	138.549
10	1.183e-1	162.995
11	1.391e-1	191.756
12	1.637e-1	225.591
13	1.925e-1	265.396
14	2.265e-1	312.224
15	2.665e-1	367.316
16	3.135e-1	432.128
17	3.688e-1	508.376
18	4.339e-1	598.078
19	5.105e-1	703.608
20	6.005e-1	827.758
21	6.968e-1	973.815
22	7.877e-1	1116.574
23	8.672e-1	1246.532
24	9.296e-1	1394.473
25	9.706e-1	1455.832
26	9.926e-1	1488.834

Due to a relatively even topography on Titan (Radebaugh et al., 2007) the ground morphology does not change the global surface wind pattern except for a significant impact on the wind pattern near the surface locally (such as Xanadu or Tsegihi) (Tokano, 2008). Therefore, the topography is temporarily not considered in the model and in this case the vertical coordinate is changed from a hybrid coordinate to a sigma coordinate. However, topography could be taken into account in the model in the future. Furthermore, to avoid instabilities due to changes of radius of the planet and vertical resolution the time step size is modified to 10 min from 20 min according to the Courant–Friedrichs–Lewy (CFL) stability criterion (that is the maximum velocity multiplied by time step size should less than the space time step size). In short, the model grids are based on 64 latitude Gaussian points and 128 longitude points (2.8125° intervals) in the horizontal plane, and the vertical resolution is 26 layers with  $\sigma$ -levels. The dynamical equations are integrated with a time step of 10 min.

From a practical point of view, the PGCM is fully capable to operate on different sorts of computers such as IBM-SP, SGI-Origin, Solaris, Compaq-alpha-cluster and Linux-PC. As noted, the PGCM differs from the CAM2 mainly as concerns the orbital constants, the adoption of generalized planetary timing, the vertical levels, the vertical coordinates, the time step size and some constants and parameterizations of physical processes.

### 3. Experimental design

Titan is the largest moon of Saturn. A thick reddish-brown photochemical smog hides the surface in the optical range. It is an Earth-size moon. Many investigations have been focused on Titan’s atmosphere (for those related to this work see for instance Bézard et al., 1995; Coustenis and Bézard, 1995; Hourdin et al., 1995; Tokano et al., 1999; Tokano and Lorenz, 2006; Grieger et al., 2004; Rannou et al., 2004; Zhu and Strobel, 2005; Coustenis et al., 2007; Lavvas et al., 2007a, b; Richardson et al., 2007). These studies mainly focus on the vertical circulation, the superrotation in the stratosphere, the feedback due to haze distribution on circulation, the hemispheric asymmetry of temperature and haze, etc. The PGCM is also employed to simulate Titan’s atmospheric circulation and investigate the effects of different Titan rotation rates on Titan’s atmospheric circulation.

To test the dynamical core of the model and to simplify the problem, the detailed radiative, turbulence and moist convective parameterizations are replaced with very simple forcing and dissipation (Held and Suarez, 1994; Williamson et al., 1998). The upper boundary condition is not confined. The only specified dissipation is a simple linear damping of the velocities. This damping is non-zero only in layers near the surface ( $\sigma > 0.9$ ). Along the same line of thought in the work by Herrnstein and Dowling (2007) and Lee et al. (2007), temperatures are relaxed to a prescribed

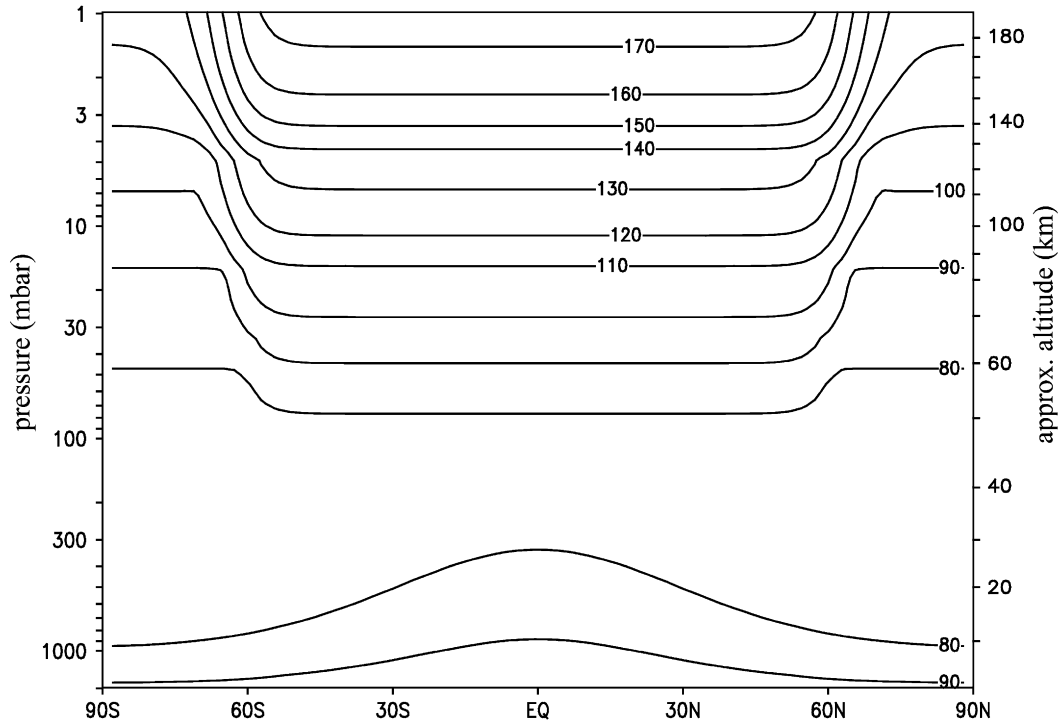


Fig. 1. Latitude–pressure cross-section of the prescribed temperature field used in the PGCM experiments. Unit: K.

temperature field (Fig. 1). The radiative relaxation coefficients ( $K_T$ ) and the Rayleigh friction coefficients ( $K_V$ ) are given by  $K_T = K_a + (K_s - K_a) \max(\sigma - \sigma_b / 1 - \sigma_b) \cos^4 \phi$  and  $K_V = K_f \max(0, \sigma - \sigma_b / 1 - \sigma_b)$ , respectively, where  $\sigma_b = 0.9$ ,  $K_f = 1 \text{ titan day}^{-1}$ ,  $K_a = 1/40 \text{ titan day}^{-1}$  and  $K_s = 1/4 \text{ titan day}^{-1}$ . The PGCM starts out with an ideal gas atmosphere over a rotation spherical surface. There is no topography, in the sense that the surface is at constant geopotential height. Besides testing the dynamical core of the PGCM, the behavior of Titan's circulation under the conditions of the Earth's rotation rate (angular velocity) is the other emphasis in this study. In this case we could understand some effects of different Titan rotation rates on the structure of Titan's circulation. Therefore, two experiments are carried out in this study. One is a control run which is performed under Titan-like conditions. The other is a sensitivity run which is performed under the same conditions as the control run but for the Earth's rotation rate.

To shorten the spin-up time, the initial atmospheric state is provided by the Titan GCM of LMD (Rannou et al., 2005). Fig. 2 provides the model's spin-up phase. Fig. 2a shows the time evolution of the planetary averaged dimensionless angular momentum of the four atmospheric layers (surface–200, 200–100, 100–10 and 10–1 mbar which correspond to troposphere, near tropopause, lower stratosphere and upper stratosphere, respectively). The planetary averaged dimensionless angular momentum is an index of atmospheric rotation which is defined as the ratio of the specific angular momentum  $a \cos \phi (u + a\Omega \cos \phi)$  to the mean specific angular momentum of the atmosphere at

rest  $2a^2\Omega/3$  (Hourdin et al., 1995). The atmospheric conditions of these four layers all reach steady-state regimes after 4 Titan years. At the end of the simulation, this rotation index is of the order of 10 in the upper stratosphere, which means that at this level the atmosphere rotates 10 times faster than the solid planet in terms of mean angular momentum. The vertical integration of the atmospheric kinetic energy per unit mass reaches the steady-state regime after 4 Titan years (Fig. 2b). Although there is a different spin-up phase in the first two Titan years between zonal-mean wind at 40 and 140 km above the equator (Fig. 2c and d), they both reach steady-state regimes after 4 Titan years. Therefore, to achieve a steadier result, we run the PGCM for 6 Titan years. Furthermore, the results of the sixth Titan year are used to analyze the Titan-like atmospheric climatological circulation.

The diurnal cycle and gravitational tide effects are not included since the LMD's Titan GCM is a two-dimensional circulation model. It is a grid-point model. The model grid is based on 49 latitude points ( $3.75^\circ$  intervals), with 55 vertical layers. The dynamical equations are integrated with a time step of 3 min (Rannou et al., 2005). This model includes the interaction between dynamics, haze, chemistry and radiative transfer. Gaseous infrared cooling rates are computed from prescribed uniform descriptions of  $\text{CH}_4$ ,  $\text{H}_2$ ,  $\text{C}_2\text{H}_2$  and  $\text{C}_2\text{H}_6$  (Hourdin et al., 2004). Haze production parameterization is not taken into account. The LMD's Titan GCM could simulate some observed features of the zonal-mean circulation on Titan such as the zonal-mean atmosphere state (wind, temperature, etc.), the zonal-mean haze structure and the zonal-mean chemical

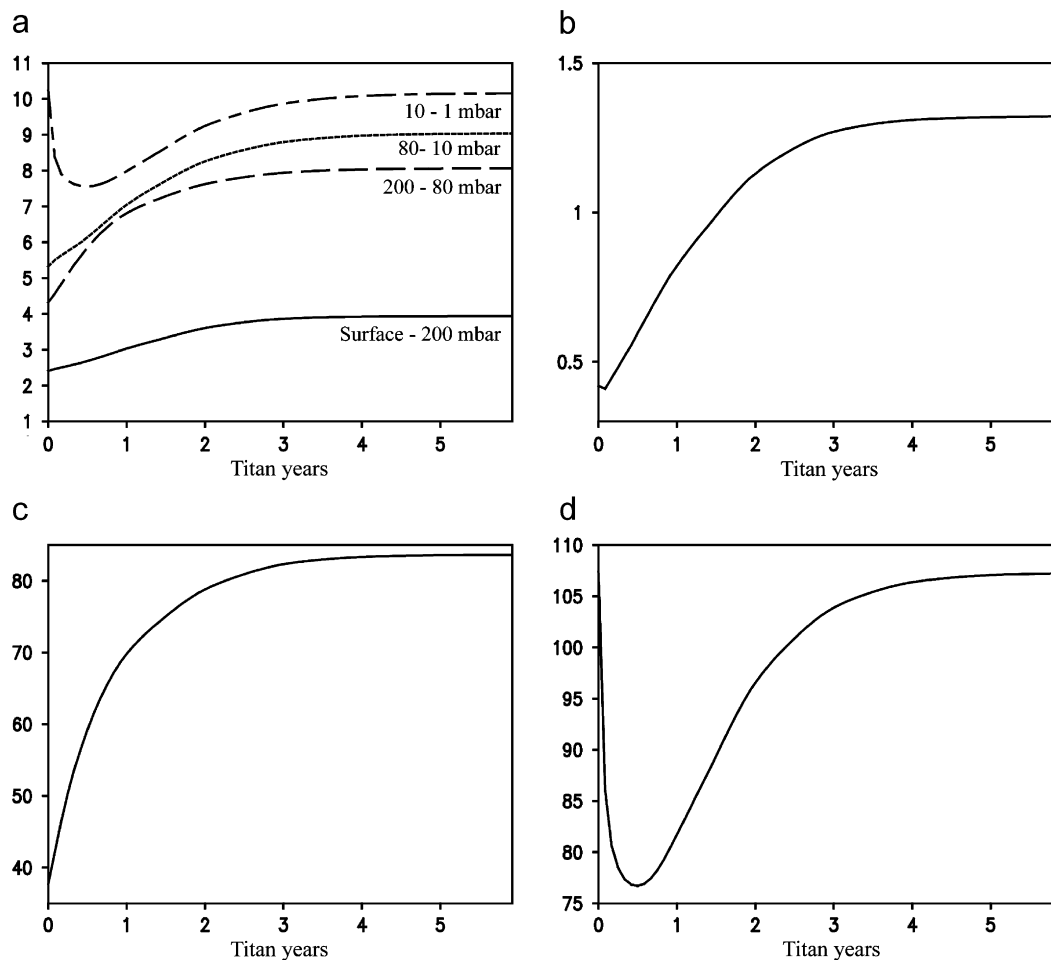


Fig. 2. (a) Time evolution of the planetary average of the dimensionless angular momentum; (b) same as (a) but for a planetary average of the vertical integration of atmospheric kinetic energy per unit mass. Unit:  $108 \text{ m}^2 \text{ s}^{-2}$ ; (c) same as (a) but for zonal-mean zonal winds at 40 km above the equator. Unit:  $\text{m s}^{-1}$ ; (d) same as (a) but for zonal-mean zonal winds at 140 km above the equator. Unit:  $\text{m s}^{-1}$ .

species distributions (Rannou et al., 2005). The results of the PGCM can be compared with those of the LMD's Titan GCM at the same level. Meanwhile, this comparison also provides some information on differences between the results of a spectral model and those of a grid-point model. Note that the seasonal change cannot be included in this study because the temperatures of the PGCM are relaxed to a prescribed temperature field step by step (Fig. 1), although previous studies have given a lot of attention to the meridional circulation at solstice and equinox (e.g., Tokano et al., 1999; Richardson et al., 2007). In this paper, we retrieve results only on the annual mean atmospheric circulation.

#### 4. Preliminary simulation of Titan's atmosphere

Fig. 3 illustrates the annual zonal-mean meridional circulation of the PGCM control run (Fig. 3a), LMD model (Fig. 3b) and PGCM sensitivity run (Fig. 3c). Fig. 3a shows that in each hemisphere there is a Hadley circulation cell over low latitudes (over approximately  $45\text{--}0^\circ\text{S}$  or  $0\text{--}45^\circ\text{N}$ ) and a high-latitude circulation (over

approximately  $90\text{--}45^\circ\text{S}$  in the Southern Hemisphere or  $45\text{--}90^\circ\text{N}$  in Northern Hemisphere) in the troposphere. Similar results are also shown by the LMD model (Fig. 3b), whereas the circulation pattern in the PGCM control run (Fig. 3a) are significantly more regular than those in the LMD model (Fig. 3b). The results from the PGCM control run in the troposphere agree with the results of Hourdin et al. (1995) and Rannou et al. (2004). If we assume that the Titan's rotation rate takes the Earth's rotation rate (Fig. 3c), the vertical structure of meridional circulation in the troposphere is distinct from that in the PGCM control run (Fig. 3a); that is, there are three cells in each hemisphere in the PGCM sensitivity run, which is similar to that in the Earth's case. Obviously, the weak polar cells could be found over the two polar caps in the PGCM sensitivity run. Furthermore, there are a series of cells in the planetary boundary layer below 1000 mbar (Fig. 3a and b), which is also quite different from the case of the condition of the Earth's rotation rate (Fig. 3c). However, the series of cells simulated by the LMD's Titan GCM and the PGCM in the planetary boundary layer, as mentioned above, need to be further validated. The results imply that



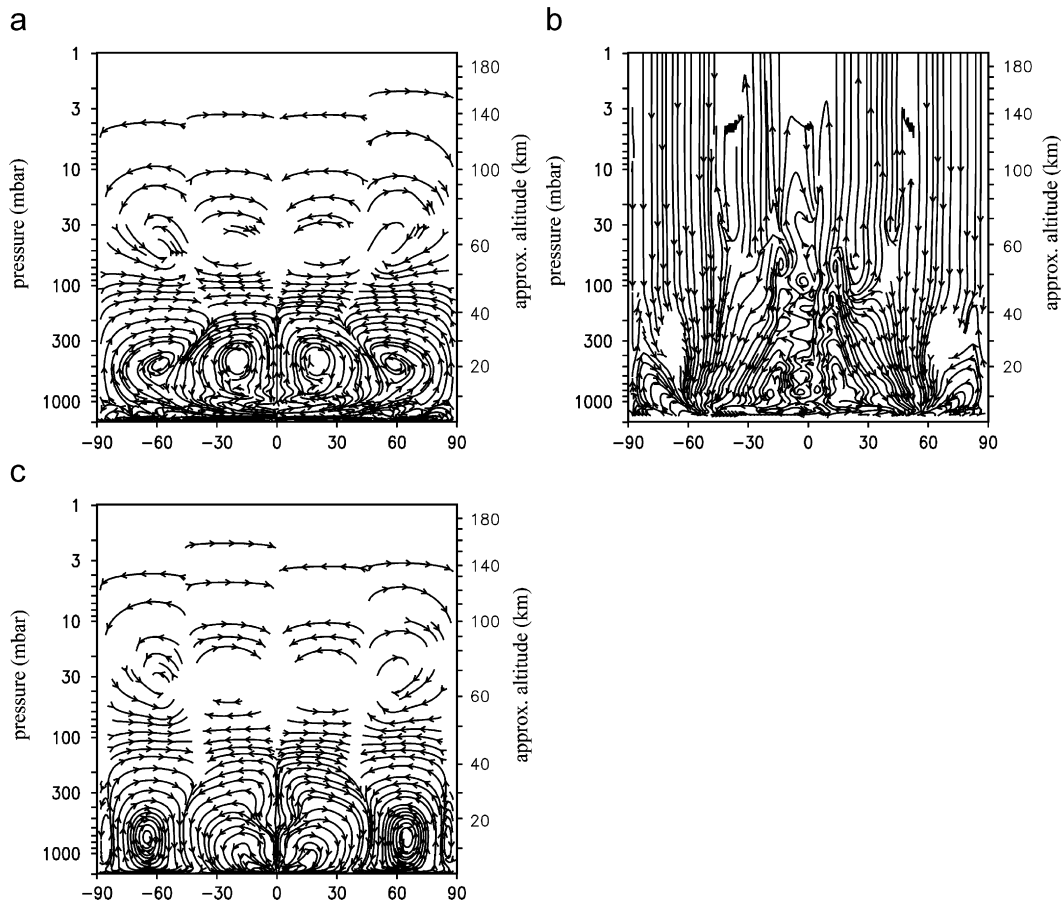


Fig. 3. The simulated annually zonal-mean meridional circulation (streamline) of Titan in both latitude–pressure and latitude–height coordinates: (a) the PGCM control run; (b) the LMD Titan’s GCM; (c) same as (a) but for the case of the Earth’s rotation rate.

the meridional vertical circulation in the troposphere could be significantly changed by the magnitudes of the different Titan rotation rates. In the stratosphere, both the PGCM control run (Fig. 3a) and the LMD model (Fig. 3b) show that two ascending branches approximately lie over mid-latitudes in two hemispheres and three descending branches are located over Titan’s equator and over the two polar regions. There is no significant difference in meridional vertical circulations in the stratosphere between the PGCM control run (Fig. 3a) and the PGCM sensitivity run (Fig. 3c), implying that the effect of different Titan rotation rates on the meridional circulation in the stratosphere may not be very important. However, this hypothesis needs to be further confirmed by more numerical experiments.

Fig. 4 presents the annual zonal-mean temperature fields of the PGCM control run, LMD model and PGCM sensitivity run. The difference in the zonal-mean temperature field between the PGCM control run (Fig. 4a) and the PGCM sensitivity run (Fig. 4c) is not obvious because both their temperature fields are relaxed to the same temperature field (Fig. 1), a similar case can also be found in the annual zonal-mean vertical profile of temperature over Titan’s equator (Fig. 5a and b). By comparing Fig. 4a with Fig. 4b, we observe that the meridional temperature

gradient of PGCM in the troposphere is larger than that of the LMD’s Titan GCM, whereas the situation is contrary to the stratosphere. Moreover, temperatures of the PGCM are higher (around 10 K) than those of the LMD model from the surface up to 20 mbar, whereas the contrary applies over  $50^{\circ}\text{S}$ – $50^{\circ}\text{N}$  from 20 to 2 mbar. The atmosphere over the high latitudes and polar caps in the PGCM is found to be warmer than that in the LMD model. The annual zonal-mean temperature field of the LMD model (Fig. 4b) does not exhibit significant hemispheric contrast in the stratospheric temperature although much attention has been given to the pronounced hemispheric asymmetry of Titan’s stratospheric temperatures at solstice and equinox (e.g., Flasar and Conrath, 1990; Bézard et al., 1995; Tokano et al., 1999). The hemispheric asymmetry of the stratospheric temperature on Titan cannot be simulated by the PGCM either (Fig. 4a) because of the hemispheric symmetry of the prescribed temperature field. Undoubtedly, simulating the pronounced hemispheric asymmetry of the Titan’s stratospheric temperature in the model is an extremely important issue in the future study. At closer inspection, a remarkable difference in the simulation of the vertical profile of the annual zonal-mean temperature over Titan’s equator (Fig. 5a) can be found that the altitude of the tropopause simulated over tropics

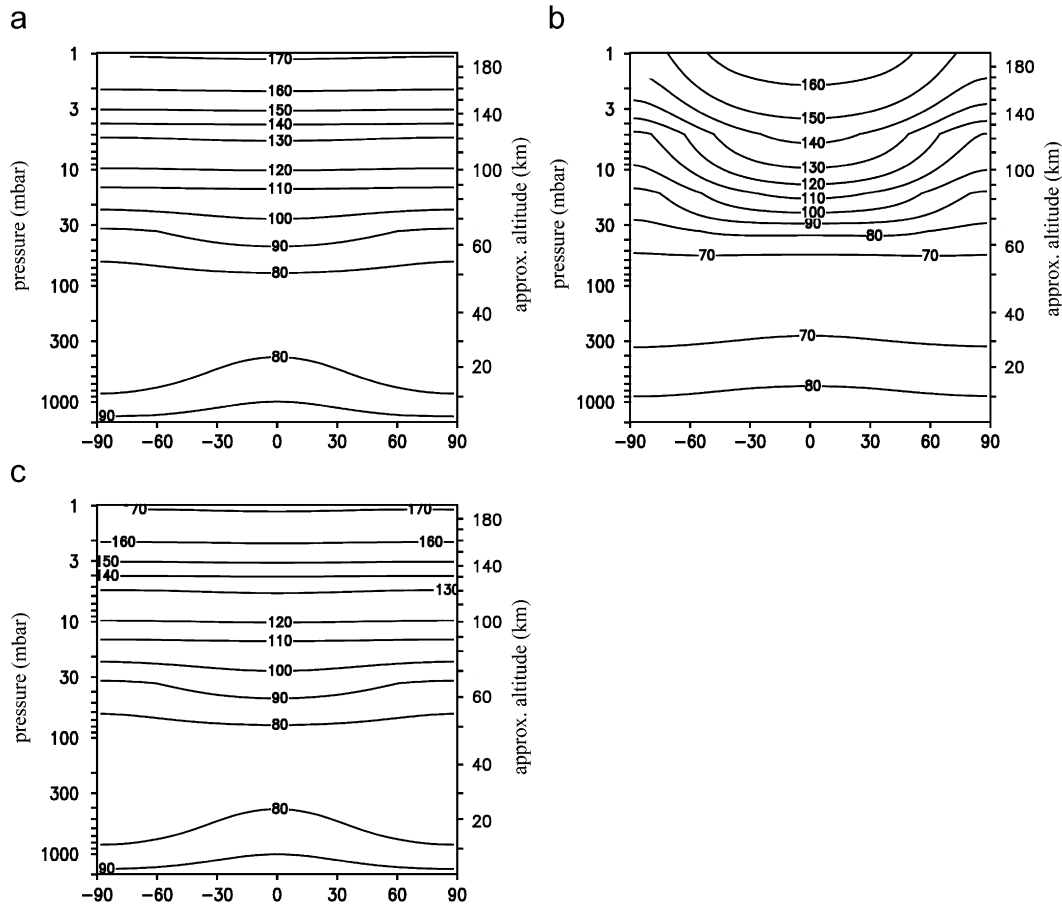


Fig. 4. The simulated annually zonal-mean temperature field in both latitude–pressure and latitude–height coordinates: (a) the PGCM control run; (b) the LMD Titan’s GCM; (c) same as (a) but for the case of the Earth’s rotation rate. Unit: K.

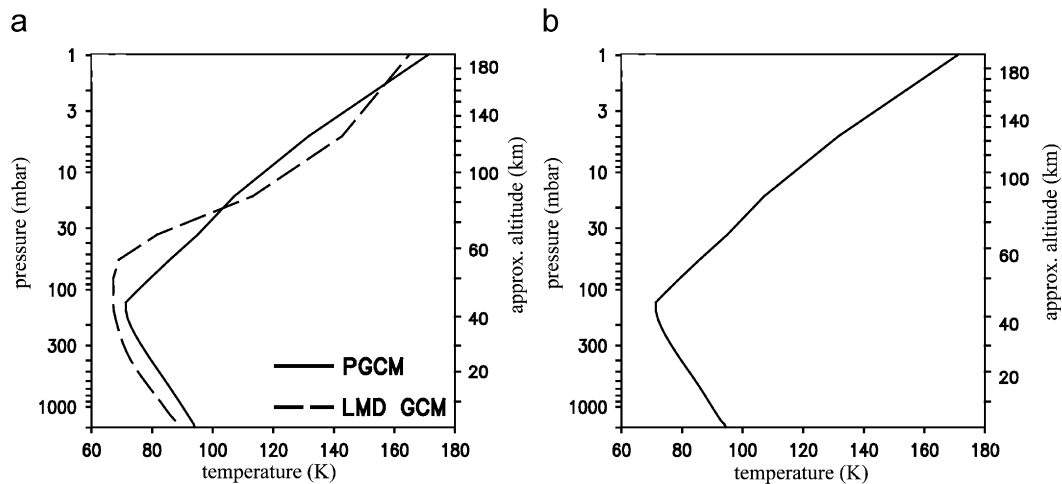


Fig. 5. The simulated vertical profiles of annually zonal-mean temperature at Titan’s equator: (a) the PGCM control run (solid line) and the LMD Titan’s GCM (dashed line); (b) same as (a) but for the PGCM sensitivity run. Unit: K.

by the PGCM (approximately at 130mbar) is lower than that by the LMD model (at about 70 mbar). Meanwhile, the simulated temperature lapse rates in the two models are almost equal although there is about 10 K difference between them in the troposphere, as mentioned above.

The result of the PGCM simulation for the temperatures may be strongly associated with the prescribed temperature field used here and could be improved probably by adopting a more rational prescribed temperature field (e.g., the observed climatological temperature field).

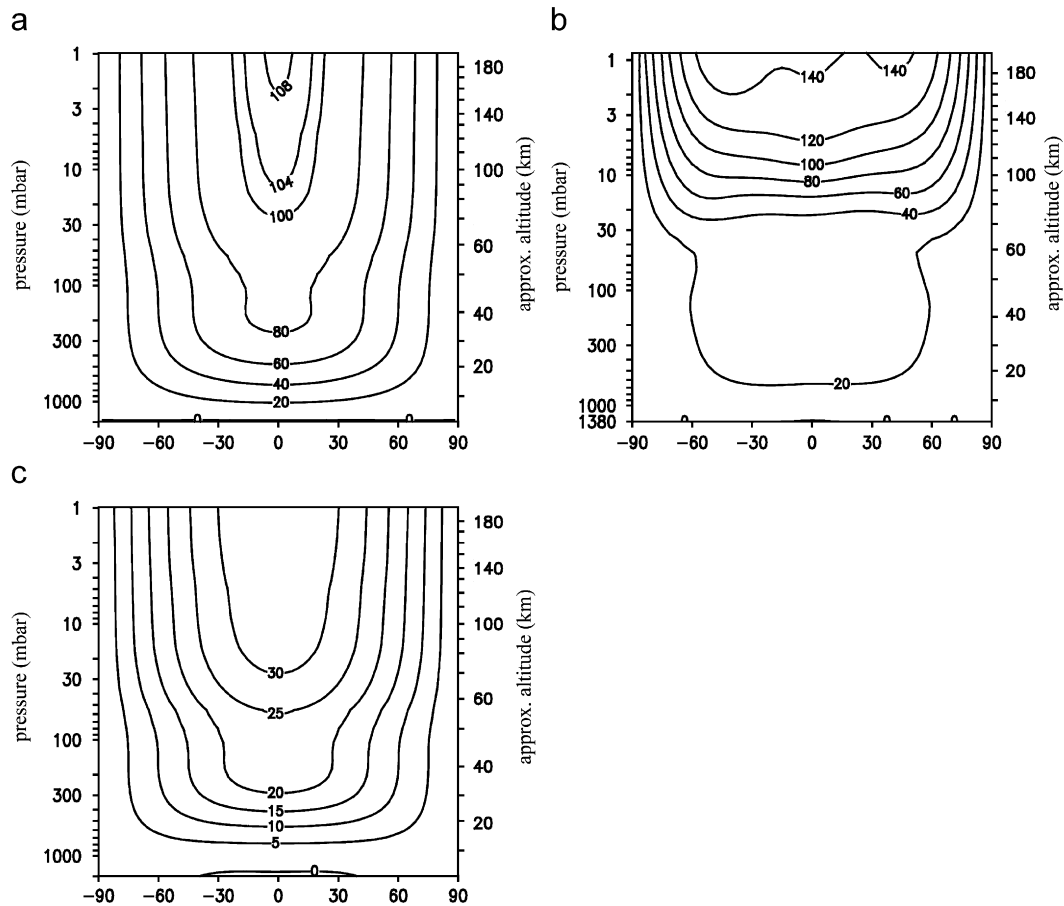


Fig. 6. The simulated annually zonal-mean zonal wind field in latitude–pressure and latitude–height coordinates: (a) the PGCM control run; (b) the LMD Titan's GCM; (c) same as (a) but for the case of the Earth's rotation rate. Unit:  $\text{m s}^{-1}$ .

A notable feature of the upper stratosphere of Titan is the superrotation phenomenon over the tropics which has been observed (e.g., Hubbard et al., 1993; Bird et al., 2005) and investigated (e.g., Zhu and Strobel, 2005). Our PGCM was able to simulate the superrotation with a magnitude approximately of  $108 \text{ m s}^{-1}$  in the upper stratosphere (Fig. 6a), which is very close to the observations (Bird et al., 2005). However, this magnitude is weaker than that ( $\sim 140 \text{ m s}^{-1}$ ) shown by the LMD's Titan GCM (Fig. 6b). The zonal winds in the troposphere and lower stratosphere in the PGCM control run are evidently stronger than those in the LMD model. At the surface the winds are very weak easterlies in both models (Fig. 6a and b). This is consistent with the observed Titan surface winds (Bird et al., 2005). A difference in the zonal wind structure in the upper stratosphere between the two models is that the PGCM control run shows a hemispheric symmetric zonal wind field, whereas the LMD model displays a hemispheric asymmetric structure. The Titan's rotation rate may be an important factor which causes the superrotation in Titan's stratosphere because the zonal winds ( $\sim 30 \text{ m s}^{-1}$ ) to become very weak assuming the Earth's rotation rate

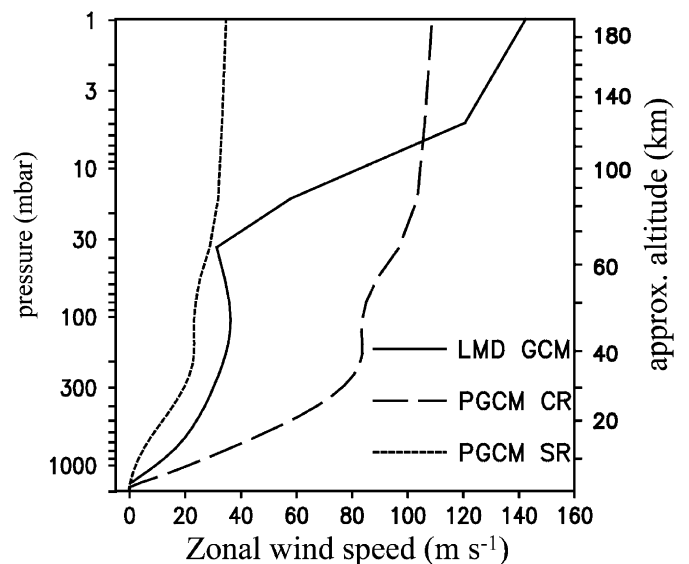


Fig. 7. The simulated vertical profiles of annually zonal-mean zonal wind at the Titan's equator. LMD GCM, PGCM CR and PGCM SR stand for the LMD Titan's GCM (solid line), the PGCM control run (long dashed line) and the PGCM sensitivity run (short dashed line). Unit:  $\text{m s}^{-1}$ .



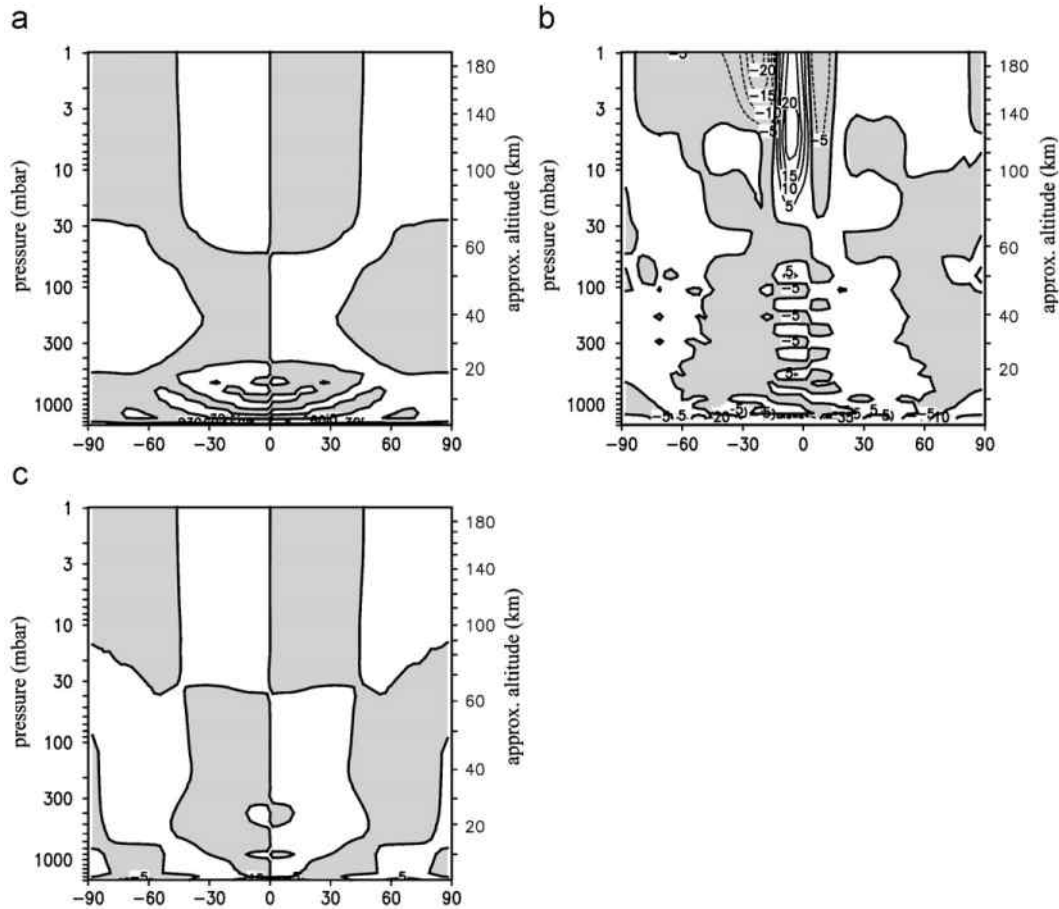


Fig. 8. The simulated annually zonal-mean meridional wind field in both latitude–pressure and latitude–altitude coordinates: (a) PGCM control run; (b) LMD Titan’s GCM; (c) same as (a) but for the case of the Earth’s rotation rate. The shaded areas indicate the northerly winds. Unit:  $10^{-3} \text{ m s}^{-1}$ .

(Figs. 6c and 7). In addition, compared to Fig. 6a, strengthened easterly wind can be seen under the condition of the Earth’s rotation rate (Fig. 6c) over the equator near the surface.

Fig. 7 shows the simulated vertical wind profile at the equator in the PGCM and the LMD models. A minimum zonal wind was found around the tropopause, where the strong vertical wind shear is also detected. Indeed, the observational analysis of the vertical profile of winds on Titan (Bird et al., 2005) shows that there is a layer with slow wind ( $< 3 \text{ m s}^{-1}$ ) at altitudes between 60 and 100 km. This feature is not simulated well by our PGCM, which could be due to an insufficient number of vertical layers in the stratosphere in the model (just with five layers over 60 mbar, see Table 1). This needs to be tested in the future. In addition, it could be associated with the prescribed temperature field in the model.

The simulated annual zonal-mean meridional wind fields are shown in Fig. 8. In the lower level of the troposphere ( $\sim 1000$  mbar) convergence regions of airflow are located over the tropics and two polar regions and divergence regions of airflow are situated in mid-latitudes, respectively (Fig. 8a and b). The opposite situations are presented at the tropopause. There are besides irregular structures of the

meridional wind field corresponding to a series of cells below 1000 mbar in Fig. 3a and b. The situation in the troposphere under the condition of the Earth’s rotation rate (Fig. 8c) is distinct from that in the PGCM control run. As shown in Fig. 8c, in the lower level of the troposphere ( $\sim 1000$  mbar), the divergence regions of airflow are located over the two polar regions and the regions around  $45^\circ\text{S}$  and  $45^\circ\text{N}$ , and the convergence regions of airflow are situated over the equator and the regions around  $80^\circ\text{S}$  and  $80^\circ\text{N}$ , respectively. The opposite situations are presented in the upper troposphere. However, there is no evident difference in the meridional winds in the stratosphere between the PGCM control run (Fig. 8a) and the PGCM sensitivity run (Fig. 8c).

Fig. 9 presents the simulated departure from the zonal-mean geopotential height fields which are the departures from the average of the whole layer. The basic structures of geopotential height field from the PGCM control run (Fig. 9a) and the LMD Titan’s GCM (Fig. 9b) are similar to each other but their magnitudes. The geopotential height over the tropics is stronger than that over high latitudes. The departures from the geopotential height in the PGCM control run are larger than those in the LMD’s Titan GCM below 30 mbar, while the situation is opposite above

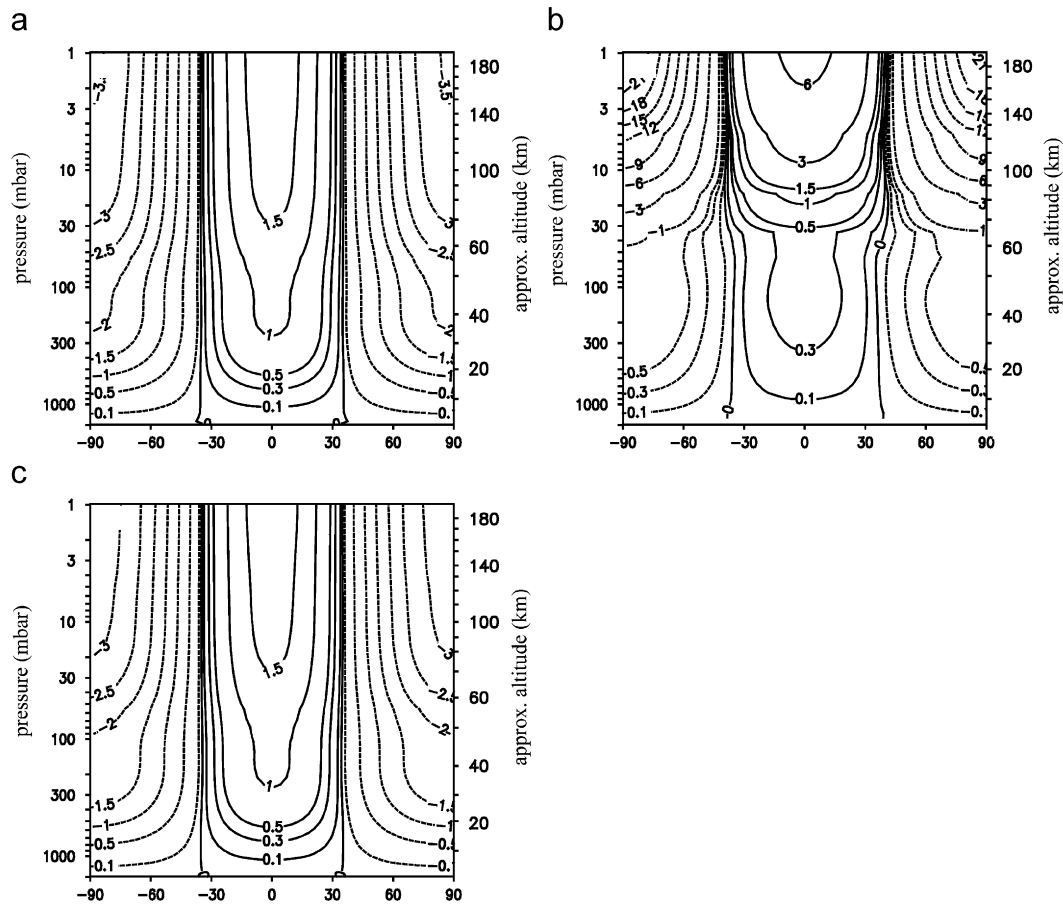


Fig. 9. The simulated annually zonal-mean geopotential height field in both latitude–pressure and latitude–altitude coordinates: (a) PGCM control run; (b) LMD Titan's GCM; (c) same as (a) but for the case of the Earth's rotation rate. Departures from the average of the whole layer are shown. Unit:  $10^3$  gpm.

30 mbar. There is no significant difference between Fig. 9a and c except for the areas approximately from 300 to 100 mbar and above 3 mbar over two polar caps. It seems that the different Titan rotation rates may not cause larger differences in the geopotential height field.

## 5. Conclusions and discussion

The transplantable PGCM based on the earth-representative CAM2 is developed to simulate other planetary atmospheres. In this research we test the basic performance of the PGCM by simulating Titan's atmospheric circulation. The results of the PGCM model are compared with those of the LMD model. Moreover, the features of Titan's circulation when assuming the Earth's rotation rate are investigated to search for possible influences of the rotation rate on Titan's circulation. The PGCM is able to adequately simulate basic circulation structures of Titan, e.g., the equatorial superrotation ( $\sim 108$  m/s) in the Titan's stratosphere, vertical meridional circulations, some vertical profiles, easterly wind near the surface, etc. The magnitude of the Titan's rotation rate can significantly affect the dynamical structure of the Titan's circulation. The westerly winds of a whole layer are weakened, but the easterly winds

are strengthened near the surface, when the rotation rate of Titan is changed to that of the Earth. The effects of the different Titan rotation rates on the meridional circulation mainly pertain to the troposphere. Furthermore, when the Earth's rotation rate is assumed, three cells are present in the troposphere in the two hemispheres, whereas only two cells occur for the Titan's rotation rate.

This preliminary work demonstrates the good performance of the PGCM and provides a foundation for further work in simulating and understanding Titan's general circulation and its variability through coupling the physical–chemical processes.

In this paper the detailed radiative, turbulence and moist convective parameterizations are replaced with very simple forcing and dissipation, thus seasonal variation and hemispheric asymmetry of the stratospheric temperature cannot be properly simulated. Major attention is devoted to the dynamic core of the model. However, our PGCM should include a more complex physical framework in the future. Further numerical experiments should be conducted to assess the sensitivity of the simulations to arbitrary parameters in the future. It is within our future aims to couple and investigate physical and chemical processes in the model in order to better simulate and understand

Titan's circulation, its variations and relevant phenomena by the model.

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