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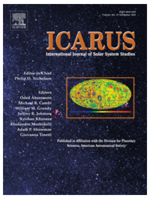

The circulation pattern and day-night heat transport in the atmosphere of a synchronously rotating aquaplanet: Dependence on planetary rotation rate

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ABSTRACT

In order to investigate a possible variety of atmospheric states realized on a synchronously rotating aquaplanet, an experiment studying the impact of planetary rotation rate is performed using an atmospheric general circulation model (GCM) with simplified hydrological and radiative processes. The entire planetary surface is covered with a swamp ocean. The value of planetary rotation rate is varied from zero to the Earth's, while other parameters such as planetary radius, mean molecular weight and total mass of atmospheric dry components, and solar constant are set to the present Earth's values. The integration results show that the atmosphere reaches statistically equilibrium states for all runs; none of the calculated cases exemplifies the runaway greenhouse state. The circulation patterns obtained are classified into four types: Type-I characterized by the dominance of a day-night thermally direct circulation, Type-II characterized by a zonal wave number one resonant Rossby wave over a meridionally broad westerly jet on the equator, Type-III characterized by a long time scale north-south asymmetric variation, and Type-IV characterized by a pair of mid-latitude westerly jets. With the increase of planetary rotation rate, the circulation evolves from Type-I to Type-II and then to Type-III gradually and smoothly, whereas the change from Type-III to Type-IV is abrupt and discontinuous. Over a finite range of planetary rotation rate, both Types-III and -IV emerge as statistically steady states, constituting multiple equilibria. In spite of the substantial changes in circulation, the net energy transport from the day side to the night side remains almost insensitive to planetary rotation rate, although the partition into dry static energy and latent heat energy transports changes. The reason for this notable insensitivity is that the outgoing longwave radiation over the broad area of the day side is constrained by the radiation limit of a moist atmosphere, so that the transport to the night side, which is determined as the difference between the incoming solar radiation and the radiation limit, cannot change greatly.

1. Introduction

A number of recent systematic surveys have discovered many earth-sized exoplanets (e.g., Torres et al., 2015). Many of those planets exist inside the tidal lock radius of their central stars, and are thought to be synchronously rotating (e.g., Von Bloh et al., 2007). Even when the global mean incoming heat flux from the central star is comparable to that of the present Earth's, the incident flux on the perpetual day side of a synchronously rotating planet can easily exceed the radiation limit of a moist atmosphere, which is the upper limit of outgoing longwave (infrared) radiation at the top of the atmosphere (OLR) defined by a one-dimensional radiative–convective equilibrium model of an atmosphere with a sufficient amount of liquid water on its bottom surface (Nakajima et al., 1992). So, a synchronously rotating planet may

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easily enter the runaway greenhouse state if the day side to night side (hereafter, day-night) energy transport is insufficient.

However, in previous studies on atmospheres of synchronously rotating planets using general circulation models (GCMs), the runaway greenhouse state does not emerge for several different values of planetary rotation rate with the present value of the Earth's solar constant (e.g., Joshi, 2003; Merlis and Schneider, 2010; Edson et al., 2011). Even with the a solar constant 1.9 times that of the Earth, Yang et al. (2013) obtains statistically equilibrium states in an aquaplanet GCM experiment, in which high cloud albedo in the regions around the subsolar point presumably prevents a runaway greenhouse state. These results suggest that the mechanism that determines the amount of day-night energy transport still remains to be understood and its dependence on planetary rotation rate to be revealed. These issues may be crucial in considering the habitability of synchronously rotating exoplanets.

The atmospheric circulation structure, which should be related to day-night energy transport, has been shown to depend on the planetary rotation rate (e.g., Showman et al., 2013), which is, in this paper, represented by Ω^*, the value divided by that of the present Earth: 7.272×10^{-5} s^{-1}. Using a GCM with a slab ocean, Merlis and Schneider (2010) obtains a day-night thermally direct circulation in the case with $\Omega^* = 1/365$, whereas high-latitude westerlies emerge in the case with $\Omega^* = 1$. The latter circulation pattern is similar to that obtained earlier by Joshi (2003) with $\Omega^* = 1$. Merlis and Schneider (2010) names the two circulation regimes the "slowly rotating regime" and the "rapidly rotating regime", respectively. However, there is little information on the transition between these two regimes. Edson et al. (2011) explores the Ω^* dependence of the atmospheric circulation structures of both dry and moist planets, and shows that, in addition to the two regimes similar to those identified by Merlis and Schneider (2010), a regime with a strong westerly zonal wind in low latitudes appears with intermediate values of Ω^*. It is also shown that, for the dry planet condition, an abrupt change of zonal wind velocity occurs and multiple equilibria with hysteretic behavior exist between $\Omega^* = 0.109$ and $\Omega^* = 0.25$. However, corresponding multiple equilibria for the aquaplanet have not been described clearly.

As for day-night energy transport, Merlis and Schneider (2010) shows that the amounts of moist static energy transport are almost the same for the two cases with $\Omega^* = 1/365$ and $\Omega^* = 1$, but there is no information about energy transport for intermediate values of Ω^*. Edson et al. (2011) describes Ω^* dependences of minimum, maximum, and globally averaged mean surface temperature, but does not present that of energy transport. The dependence of day-night energy transport on Ω^*, together with possible constraints on it, remain to be explored.

Recently, GCM experiments have also been performed in order to examine possible climates on synchronously rotating terrestrial exoplanets with particular parameter setups estimated from observations (e.g., Heng and Vogt, 2011; Wordsworth et al., 2011). Naturally, detailed parameter dependence is not examined in these works, since they focus on exploration of climates for the parameters of particular exoplanets.

In this paper, a series of GCM runs with Ω^* incremented by small steps is performed under a simple setup considering a moist planet that rotates synchronously. We will attempt to confirm that, for the same value of incoming solar flux as that of the present Earth's, statistically equilibrium states are obtained and the runaway greenhouse state does not occur for various values of Ω^* including those that are not closely examined in the previous studies. We also examine how Ω^* affects the atmospheric circulation structure and day-night energy transport, and consider what determines the amount of day-night energy transport. The same simple model configuration as used in Ishiwatari et al. (2002) and Ishiwatari et al. (2007) is adopted, namely cloud-free conditions, gray radiation, swamp ocean and so on. This choice allows us to compare the results of the experiment directly with our previous studies showing that the three-dimensional moist atmosphere evolves into the runaway greenhouse state when the global mean insolation exceeds the radiation limit. Using the swamp condition allows the system to reach a statistically equilibrium state in a shorter time than with a slab ocean, and is convenient for execution of a large number of runs with various Ω^* and initial conditions. Varying these initial conditions is necessary to search for possible multiple equilibrium solutions.

The specification of the GCM and the experimental setups are described in Section 2. The realization of statistically equilibrium states is confirmed, and an overview of the dependence of the structure of the atmospheric circulation on Ω^* are given in Section 3. Four typical cases with different values of Ω^* are chosen and their associated structures of atmospheric circulation are described in Section 4. The dependence of day-night energy transport on Ω^* is analyzed, and it is argued that day-night energy transport is constrained by the radiation limit of a moist atmosphere in Section 5. Discussions and conclusions are given in Section 6.

2. Model and experimental setup

The GCM utilized in this study is DCPAM5 (the Dennou-Club Planetary Atmospheric Model, http://www.gfd-dennou.org/library/dcpam/index.htm.en), which is reconstructed from GFD-Dennou-Club AGCM5 used in Ishiwatari et al. (2002) and Ishiwatari et al. (2007) with a design convenient for numerical experiments on various planetary atmospheres. With DCPAM5, it is confirmed that the runaway greenhouse state emerges under the same conditions as those of Ishiwatari et al. (2002). Here we use the same model configuration as that of Ishiwatari et al. (2002). The governing equations for dynamical processes are the primitive equations. Simple parameterization schemes are adopted for physical processes. The atmosphere consists of water vapor and dry air. Both dry air and water vapor are transparent to shortwave radiation, and only water vapor absorbs longwave radiation with constant absorption coefficient (0.01 m^2 kg^{-1}). The moist convective adjustment scheme (Manabe et al., 1965) is used as a cumulus parameterization. Condensed water is immediately removed from the atmosphere as rain. There is no cloud; absorption and scattering of radiation by clouds are not incorporated. The surface of the planet is entirely covered with the swamp ocean, an ocean with zero heat capacity. It is assumed that the ocean does not transport heat horizontally and does not freeze. The surface albedo is set to zero. A bulk formula (Louis et al., 1982) is used for surface flux calculation.

In order to draw on existing knowledge of the present Earth's atmosphere, the values of parameters used in our experiment are basically those of the Earth except for planetary rotation rate and obliquity. The values of molecular weight and specific heat of dry air are set to 28.964×10^{-3} kg mol^{-1} and 1004.6 J K^{-1} kg^{-1}, respectively. The values of molecular weight and specific heat of water vapor are set to 18.0×10^{-3} kg mol^{-1} and 1810.0 J K^{-1} kg^{-1}, respectively. The planetary radius R_p is set to 6.371×10^3 km. The acceleration of gravity is 9.80665 m s^{-2}, and global mean surface pressure is 10^5 Pa. The synchronously rotating planet is configured with the obliquity set to zero, and the distribution of solar incident flux fixed to the planetary surface (Fig. 1) according to

$$S_{\mathrm{solar}} = S_0 \max[0, \cos\phi\cos(\lambda - \lambda_0)], \tag{1}$$

where ϕ is latitude and λ is longitude, with subsolar longitude $\lambda_0 = 90^\circ$ and solar constant $S_0 = 1380$ W m^{-2}, which is about 88% of the threshold value ($S_0 = 1570$ W m^{-2}) to enter the runaway greenhouse state obtained by the non-synchronously rotating aquaplanet experiment by Ishiwatari et al. (2002). We use 16 values of Ω^*: $\Omega^* = 0$, 0.05, 0.1, 0.15, 0.2, 0.25, 0.33, 0.5, 0.6,

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