Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

PPS020-29 Room:103 Time:May 24 18:00-18:15

Numerical experiments of synchronously rotating planets with increasing solar constant

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Many exoplanets orbit nearby central stars and are thought as synchronously rotating planets because of the strong tidal force of the star. In the vicinity of small and low luminous stars such as M dwarfs, there may exist synchronously rotating terrestrial planets with liquid water on their surface.

In order to investigate the climate of synchronously rotating planets, we have performed numerical experiments with various rotation rate and solar constant fixed at Earth's value. These experiments showed that, according to rotation rate, there existed several climate regimes: equilibrium states in which a direct circulation from day side to night side dominate, equilibrium states in which disturbances with precipitation and equatorial waves dominate, and so on.

However, for increased solar constant, the atmosphere cannot reach equilibrium states and the runaway greenhouse state appears. In these cases, liquid water cannot exist on the planetary surface. In this study, for the purpose of examining the dependence of threshold values of solar constant at which the runaway greenhouse occurs (hereafter, "runaway limit") on planetary rotation rate, we perform numerical experiments with varying the values of solar constant and planetary rotation rate.

The model utilized here is atmospheric general circulation model, dcpam5 (http://www.gfd-dennou.org/library/dcpam/index.htm.en). The atmosphere consists of the dry air (noncondensable component) and vapor (condensable component).

The radiative processes are quite crude. Shortwave radiation is not absorbed by the atmosphere, while longwave radiation is absorbed only by vapor. We assume no scattering by cloud. Moist convective adjustment (Manabe et al., 1965) is used to include effects of cumulus convection.

The surface is assumed to be covered with swamp (zero heat capacity wet surface) and surface albedo is zero. The values of radius and surface pressure are the same as those of the Earth.

We use two types of the insolation pattern. One is the synchronously rotating condition (SR) in which the subsolar point is fixed to a point on the equator. Another is the annual and diurnal mean insolation pattern of the Earth (nonSR). The values of rotation rate we examine are zero and same value of the Earth. In the experiment with these two rotation rates

and solar constant of Earth's values, we have obtained different equilibrium states. In this study, five values of solar constant are used:

from the Earth's value to increased values. All experiments consist of 18 cases (see table).

The resolution used in this study is 5.6 degrees longitude-latitude grid with 48 vertical layers. The model is integrated for 2000 Earth days from isothermal atmosphere at rest.

Results of experiments show that equilibrium state is not reached in all cases with solar constant of 1600 W/m2. In these cases, global mean outgoing longwave radiation flux decreases monotonically with time, while global mean surface temperature increases monotonically. It is considered that the runaway greenhouse state occurs in these cases.

The value of the runaway limit tends to increase with decreasing the rotation rate of the planet. On the other hand, for same values of rotation rate, the runaway limit in nonSR case is larger than that in SR case.

Run summaries in each insolation pattern('Pattern', 'SR' represents synchronously rotating condition, and 'nonSR' represents the Earth like condition), rotation rate(Ω, normalized by the Earth's value), solar constant(S, W/m2). Circles represent the atmosphere reaches equilibrium state, while crosses represent the atmosphere does not reach equilibrium state. blank is not calculated.

Pattern	SR		nonSR	
$S \setminus \Omega$	0	1	0	1
1600	×	×	×	×
1550	×	×	○	×
1500	○	×	○	○
1450	○	○		
1380	○	○	○	○

Keywords: synchronously rotating planet, general circulation model, exoplanet, runaway greenhouse state, solar constant