A numerical study on atmospheric general circulations of synchronously rotating aqua-planets -Dependence on planetary rotation rate and solar constant- S. Noda[1], M. Ishiwatari[2], K. Nakajima[3], Y.O. Takahashi[1,4], S. Takehiro[5], M. Onishi[1], S. Nishizawa[6], Y.-Y. Hayashi[1,4]; [1]Kobe University,Kobe, Japan: [2]Hokkaido University, Sapporo, Japan; [3]Kyushu University, Fukuoka, Japan; [4]Ceneter of Planetary Science, Kobe, Japan; [5]Kyoto University, Kyoto, Japan; [6]RIKEN AICS, Kobe, Japan

Introduction: Numerical experiments on climate states of synchronously rotating terrestrial planets are performed. Previous studies (Joshi, 2003[1]; Merlis and Schneider, 2010[2]; Edson et al., 2011[3]) performed GCM experiments for fixed day-side and night-side condition, and examined atmospheric structures with some values of planetary rotation rate Ω and present Earth's solar constant. The aim of this study is to clarify the parameter dependence of climates of synchronously rotating terrestrial planets with GCM experiment for various values of planetary rotation rate and solar constant.

Model and experimental setup: The GCM utilized in this study is dcpam5 (Dennou-Club Planetary Atmospheric Model, http://www.gfd-dennou.org/library/dcpam/index.htm.en}). Simplified hydrologic and radiative processes are used such as gray radiation scheme and the moist convective adjustment scheme. The surface of planet is entirely covered with ocean with zero heat capacity (swamp ocean). The value of planetary rotation rate Ω is varied from zero to the Earth's value Ω_E (7.272×10^{-5} sec^{-1}). Solar constant is varied from 1380 W/m^2 to 1700 W/m^2. The values of planetary radius and global mean surface pressure are set to the Earth's values.

The solar insolation pattern is fixed to the planetary surface with the subsolar point on 90 degrees of longitude at the equator. The region of 0-180 degrees of longitude and the region of 180-360 degrees of longitude correspond to day-side and night-side, respectively.

For horizontal direction, the triangular truncation of the spectral transform method is used up to the total wave number 21 (T21; 64 grid-points for the longitudinal axis and 32 grid-points for the latitudinal axis). The number of vertical levels is set to be 16 or 32.

Dependence of atmospheric structure on planetary rotation rate: IN this section, results of Ω dependence experiment with present Earth's solar constant are shown.

Atmospheric circulation pattern are changed according to Ω as follows. For cases that Ω is nearly zero, dayside-nightside direct circulation dominates (Fig.1a). As Ω increases, super rotation becomes stronger (Fig.1b). When Ω increases to Ω_E, jets in sub-tropical and high-latitudinal regions dominate (Fig. 1c). In the range of $0.2\Omega_E < \Omega < 0.85\Omega_E$, oscillation of meridionally asymmetric patterns appear (Fig.1b shows meridionally symmetric pattern, since this is a long-term averaged field). This phenomenon has not been reported in previous studies, while states shown in Fig. 1 (a) and (c) are similar to results of previous studies.

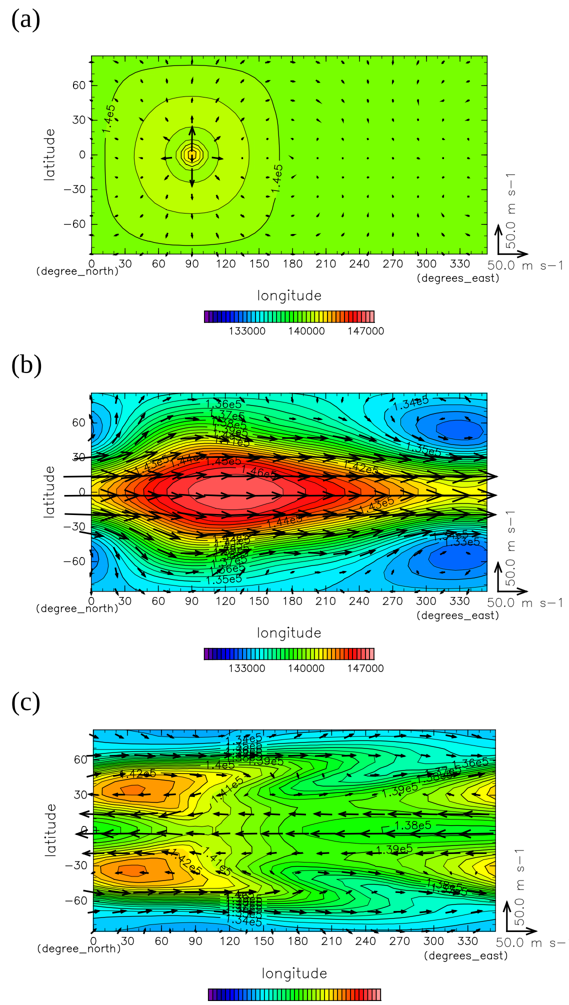

Figure 1. Wind vector [m/s] and geopotential [J/kg] at pressure level of 0.2 p_s (p_s is surface pressure). Time mean fields between 1000 to 2000 days are shown. (a) $\Omega = 0$, (b) $\Omega = 0.5\Omega_E$, (c) $\Omega = \Omega_E$. The vectors beside figures indicate 50 m/s. Contour interval of geopotential is 500 J/kg.

In addition, it is shown that multiple equilibrium appears in the range of $0.75\Omega_E < \Omega < 0.85\Omega_E$ with performing ensemble experiment using slightly different initial conditions. In this range of Ω, both of states shown as Fig. 1(b) and states shown as Fig. 1(c) are obtained as multiple solutions.

Although circulation pattern and temperature field change according to Ω, total energy transport (summation of sensible and latent heat transports) from the dayside to the nightside almost remains unchanged (Fig. 2). This is caused by the fact that outgoing longwave radiation (OLR) in dayside is suppressed to radiation limit (the maximum value of OLR of moist atmospheres; Nakajima et al., 1992[4]). Actually, OLR in broad area of dayside almost correspond to the radiation limit obtained by one-dimensional radiative-convective equilibrium model.

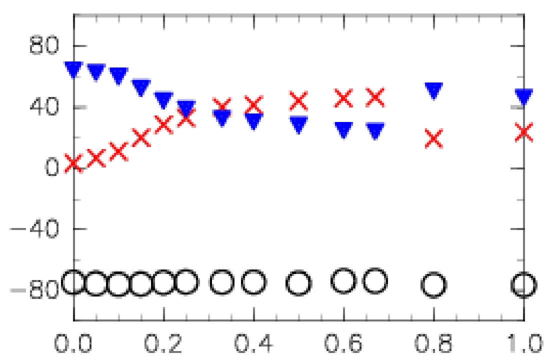

Figure 2. Heat budget of night-side. Blue triangle, red cross, and black circle indicate sensible heat transport from dayside to night-side, condensation heating integrated over night-side, and OLR integrated over night-side, respectively. Unit is 10^{15}W. Night-side OLR corresponds to total heat transport from dayside to night-side.

Appearance condition for the runaway greenhouse state: In this section, results of experiment with various values of Ω and solar constant are discussed.

For all Ω, with increasing solar constant, atmospheres cannot reach any equilibrium states and the global mean surface temperature keeps increasing. These states are considered to correspond to the runaway greenhouse states (Nakajima et al., 1998). Table 1 shows the maximum values of solar constant with which statistically equilibrium states are obtained. These maximum values are almost unchanged against the change of Ω, and they almost correspond to the radiation limit obtained by a one-dimensional radiative-convective equilibrium model. In these experiments, the condition for the occurrence of the runaway greenhouse state is that the global mean value of incident flux exceeds the radiation limit.

Ω	Maximum values of solar constant
0	1640(410.0)
$0.15\Omega_E$	1560(390.0)
$0.5\Omega_E$	1550(387.5)
Ω_E	1550(387.5)

Table 1. The maximum values of solar constant with which statistically equilibrium states are obtained. The values in parenthesis indicate global mean values of incident solar radiation flux. Unit is W/m^2.

Conclusion: Climate states of synchronously rotating moist planets are examined for various planetary rotation rate and solar constant. With Ω dependence experiment, total energy transport from day-side to night-side does not depend on Ω. With experiment with increased solar constant, it is shown that the maximum values of solar constant with which statistically equilibrium states are obtained are almost unchanged against the change of Ω. For both of above results, it is important that OLR in dayside are almost suppressed to radiation limit obtained by one-dimensional radiative-convective equilibrium model.

References: [1] Joshi M. (2003) Astrobiol., 3, 415-427. [2] Merlis T. M. and Schneider T.(2010) J. Adv. Model. Earth Syst., 2, Art. \#13, 17 pp., doi:10.1029\/JAMES.2010.2.13. [3] Edson A. et al.(2011) Icarus, 212, 1-13. [4] Nakajima S. et al. (1992) J. Atmos. Sci., 49, 2256-2266.