Numerical explorations of climates of terrestrial exoplanets

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More than thousand exoplanets have been discovered by Kepler space telescope. Some exoplanets are called as Super Earths which is defined as planets with mass several times of Earth mass. Investigations for exoplanets similar to Earth are a base of discussion on the possibility of existence of extrasolar life, and a lesson for understandings of climate stability and the existence condition of mild climate like Earth's. From the circumstances of increasing the number of objects of climate research, we are aiming to explore the varieties of planetary climate numerically.

Our objectives are to grasp the variety of planetary climate, and to understand the existence condition of the ocean. Occurrence conditions of the snowball state and the runaway greenhouse state are important for examining the existence of the ocean. As an investigation on the snowball state, Budyko (1969)'s climate regime diagram is well known, which shows appearances of the snowball state, partially frozen state, no-ice state according to the value of solar constant. The runaway greenhouse state is defined as a state in which incident flux given to the atmosphere exceeds the radiation limit: the upper limit of outgoing longwave radiation (OLR) emitted from the top of the moist atmosphere on a planet with ocean (Nakajima et al., 1992). In the runaway greenhouse state, thermal equilibrium cannot be realized and entire ocean evaporates. We have performed some experiments on the snowball state and the runaway greenhouse state with an atmospheric general circulation model.

The model we have utilized is a atmospheric general circulation model, DCPAM (http://www.gfd-dennou.org/library/dcpam). Subgrid physical processes are parameterized with standard methods used in terrestrial Meteorology. The amount of cloud water is calculated with integrating a time dependent equation including generation, advection, turbulent diffusion, and extinction of cloud water. Extinction rate of cloud water is simply assumed to be proportional to the amount of cloud water, and extinction time is given as an external parameter. Since we focus on parameter sweep experiment, our style of numerical experiment is to perform many numbers of small scale computation. Contrary to the meridionally one-dimensional model of Budyko (1969), three-dimensional GCM needs a large amount of computational resources. Computational resources which we need are small scale ones suitable for parameter sweep, in addition to large scale computational resources used for high resolution experiment.

With DCAPM, we have examined the occurrence condition of the runaway greenhouse state for synchronously rotating planets, aqua planets, and land planets. Our results seem to suggest that, regardless the existence of clouds and solar flux distribution, the runaway greenhouse state appears with the increased value of solar constant for which global mean absorbed solar radiation flux exceeds the maximum values of OLR.

Our experiments so far are based on present Earth configuration: radiation scheme for present Earth (Chou et al., 1996; Chou et al., 2001) is used, and the values of extinction time of cloud water is tuned with observational data of present Earth. Surface process is also simply represented in our model. The entire surface is assumed to be a ``swamp ocean'' with zero heat capacity. At present, in order to expand model applicability, we are developing a radiation scheme of H_2O-CO_2 atmosphere and a dynamical ocean model. We are planning to draw climate regime diagrams including the snowball state and the runaway greenhouse state for various exoplanet configurations concurrently with model development.

Keywords: atmospheric general circulation model, exoplanet, habitability, runaway greenhouse state, snowball state