DEVELOPMENT OF AN ATMOSPHERIC GENERAL CIRCULAION MODEL AND SEQUENTIAL EXPERIMENTS FROM AN EARTH-LIKE PLANET TO A MARS-LIKE PLANET.

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Introduction

We have been developing an atmospheric general circulation model (GCM) aiming at investigating general circulation of atmospheres not only of Mars, but also of the Earth, the Venus, and ideal planets which may have some characteristics of exoplanets. Purposes of the model development are to enable us to investigate, with a common dynamical framework, possible varieties of general circulations of planetary atmospheres including Mars', and to understand underlying mechanisms that realize the varieties of circulations to extend our knowledge on planetary atmospheres.

Although the model development has not been completed, some preliminary experiments have been performed in parallel with the development. Those calculations include experiments of Mars' atmosphere, Earth's atmosphere, Venus-like atmosphere, and an atmosphere on an ideal synchronously rotating planet. In the followings, the model which is being developed is described, and some preliminary results of experiments for Mars' atmosphere and the Earth- and Mars-like planetary atmospheres are presented.

Model description

An atmospheric GCM, dcpam (http:// www.gfd-dennou.org/library/dcpam/index.htm.en), is developed with the basis of the Geophysical Fluid Dynamics (GFD) Dennou Club atmospheric GCM (http://www.gfd-dennou.org/ library/agcm5/index.htm.en). Dynamical core of dcpam solves the primitive equation system by using spectral transform method with the finite difference method of *Arakawa and Suarez* (1983) in vertical direction. The included physical processes are the radiative, the turbulent mixing, and the surface processes. In addition, the simple forcing for the dynamical core test of *Held and Suarez* (1994) and for an experiment of Venus-like atmosphere following *Yamamoto and Takahashi* (2003) are also implemented.

The radiation models currently implemented in the model are those for experiments of Mars' and the Earth's atmospheres. The radiation model for grey atmosphere is also prepared for experiments of ideal planets. Radiation model for Mars' atmosphere is almost the same as those used by *Takahashi et al.* (2003, 2004, 2006), except for the neglect of scattering in infrared. Radiation model for the Earth's atmosphere is newly constructed by combining several band models and k-distribution method with very simple consideration of cloud effects. The turbulent mixing is evaluated by using the *Mellor and Yamada* (1982) level 2 scheme with the surface flux evaluated by method of *Louis et al.* (1982). In addition, the dry and moist convective adjustments are included. The surface processes include a model for thermal diffusion in the soil and a bucket model (*Manabe*, 1969).

In addition to those physical processes, simple condensation scheme of CO_2 is included for Mars experiment. This scheme considers thermal effect of CO_2 condensation and temperature is fixed to condensation temperature when the temperature decreases below it. However, this condensation scheme does not consider effect of atmospheric mass change due to condensation.

Below, some preliminary results of a Mars experiment and experiments for ideal Mars- and Earth-like planets are presented.

Mars experiment

The Mars experiment is performed with the resolution of T21L40. The horizontal resolution of T21 is equivalent to about 5.6 degrees longitude-latitude grid and the model has 40 vertical layers. In this study, the dust distribution is prescribed, and is uniform horizontally and follows vertical distribution by *Conrath* (1975). The dust optical depth is assumed to be 0.2 in the present experiment. The model has been integrated for 2 Mars years from an initial condition of isothermal atmosphere at rest. The result in second Mars year is analyzed.

Figure 1 shows the zonal mean temperature distribution at northern spring, summer, fall, and winter by the Mars experiment. The gross structure of zonal mean temperature distribution obtained by the model is qualitatively similar to those shown by previous studies (e.g., *Takahashi et al.*, 2003, 2006). At equinox seasons, the temperature distribution is almost symmetric with respect to the equator, and baroclinic zones appear in both hemispheres. On the other hand, at solstitial seasons, the temperature distribution is significantly asymmetric with respect to the equator. Temperature decreases monotonically from high latitude in summer hemisphere to high latitude in winter hemisphere below about 1 hPa

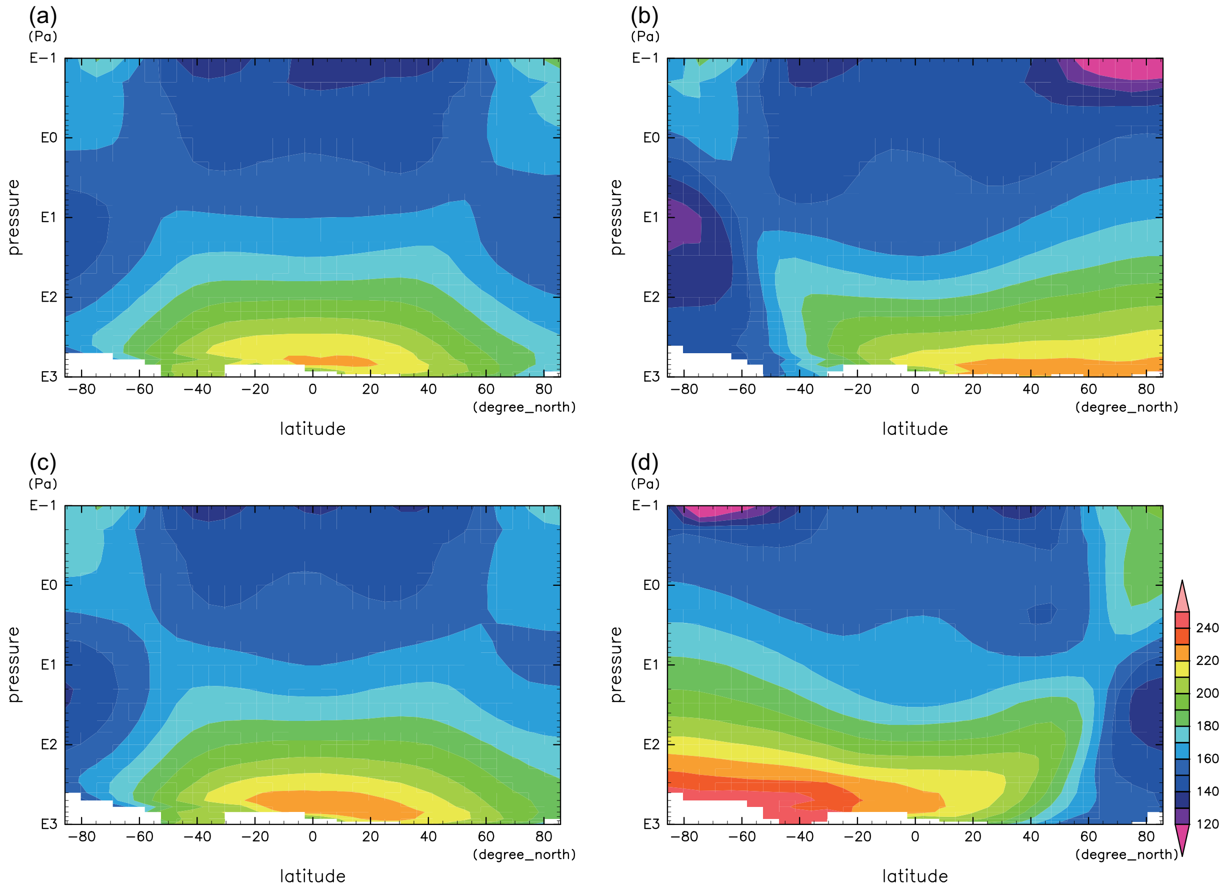

Figure 1: Distribution of zonal mean temperature at (a) northern spring (L_s = 351°–19°), (b) summer (71°–96°), (c) fall (150°–181°), and (d) winter (250°–286°) by a Mars experiment.

pressure level. Above the pressure level, the temperature at middle latitude in winter hemisphere is higher than that on the equator due to strong meridional circulation in these seasons. Further model development and analysis of results are ongoing to validate the model.

Experiments of Earth- and Mars-like planets

Experiments of Earth- and Mars-like planets are performed to investigate the physical mechanisms that cause difference in general circulation of the Earth's and Mars' atmospheres. Those experiments are performed with the resolution of T42L16. The horizontal resolution of T42 is equivalent to about 2.8 degrees longitude-latitude grid and the model has 16 vertical layers. With the use of this resolution, 6 experiments have been performed, (I) the Earth experiment, in which Earth's topography and land-ocean contrast are used and planetary radius and length of day in a year are Earth's values, (II) the same as (I) but without orographic variation, (III) the same as (II) but without ozone heating, (IV) the same as (III) but without water/moist processes in the system, (V) the same as (IV) but with planetary radius of Mars' value, and (VI) the same as (V) but with length of days in a year of Mars' value (669 days). In the experiments (I)-(III), the Earth's land-ocean distribution is used and the climatological sea surface temperature is prescribed on the ocean grid point. In all experiments, the values of the planetary rotation rate, the solar declination angle, the gravitational acceleration, and the atmospheric constituents are the same as those of the Earth and the Earth's atmosphere, respectively. The series from (I) to (VI) represents a gradual change of the setups from the Earth's to the Mars'. However, it should be noticed that the end of the series still is not Mars. Under these conditions, the model is integrated for 20 years from an initial condition of isothermal atmosphere at rest. The result during last 10 years is analyzed.

In this study, we focus on the structure of Hadley circulation, especially at solstitial seasons when the structure is asymmetric with respect to the equator. Figure 2 shows the meridional circulation at northern summer, "August", obtained by series of experiments from (I) to

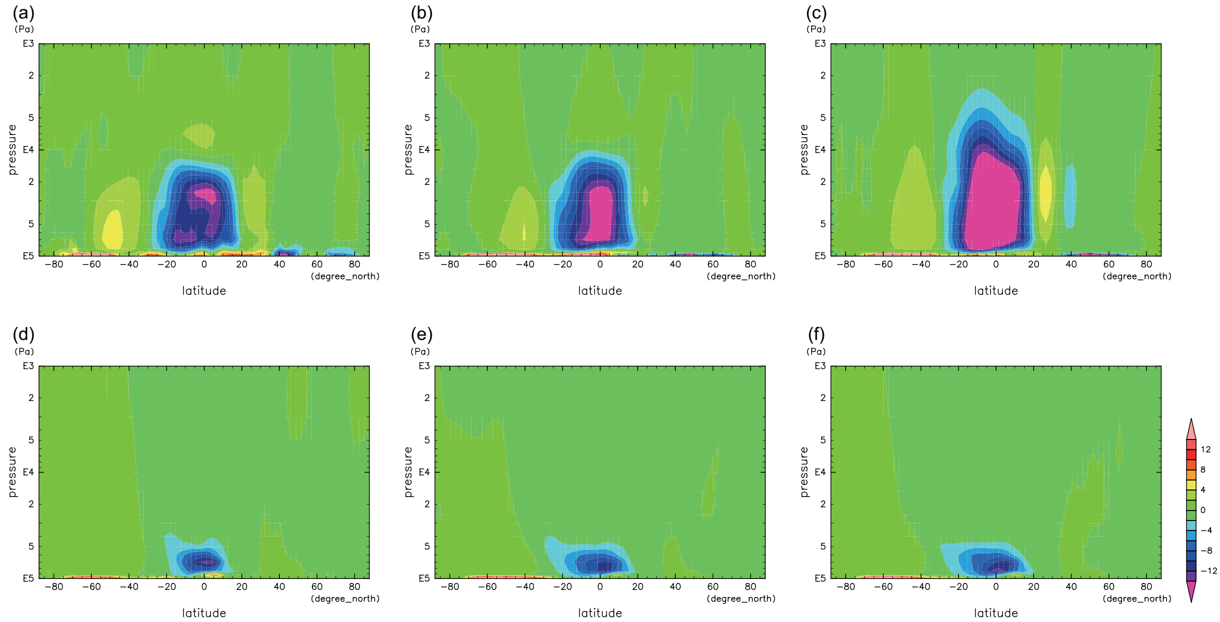

Figure 2: Mass stream functions at northern summer "August" by experiments (I) to (VI). Unit of mass stream function is 10^{-10} kg s^{-1}, but the value of Earth's radius is used to calculate mass stream function in all experiments for clarity.

(VI).

In the experiment (I), which is performed with almost the Earth's condition, the Hadley circulation shows equatorially asymmetric structure. The cross-equatorial Hadley circulation extends from ∼25°S to ∼20°N and up to about 150 hPa pressure level in vertical direction. In the experiment (II), in which no orographic variation is specified but with land-ocean distribution, the Hadley circulation is slightly stronger than that in experiment (I). However, the latitudinal width of Hadley circulation is almost the same as that in experiment (I). In the experiment (III), in which ozone heating is neglected, the Hadley circulation is stronger than those in experiments (I) and (II). In addition, the circulation extends up to higher altitude than that in experiments (I) and (II). In the experiment (IV), in which water is removed from the system and moist convection does not occur, the Hadley circulation becomes weak compared to those in experiments (I)-(III). Further, the vertical extent of Hadley circulation becomes small and circulation extends up to about 400-500 hPa pressure level. In the experiment (V), in which the Mars radius is used, the latitudinal width is slightly larger than that in the experiment (IV). In the experiment (VI), in which the length of year is set to Mars' value (669 days), the latitudinal width is almost the same as that in experiment (V).

One of the most important differences in Hadley circulation in each experiment is caused by existence or absence of water in the system, as expected (e.g., *Miyoshi and Morita*, 1993). The results in this study show that it affects intensity and vertical extent of Hadley circulation significantly. This is qualitatively interpreted by the difference in moist and dry adiabatic lapse rate, if the surface temperature does not change significantly. In addition, the difference in planetary radius appears to have some influence on the latitudinal width of Hadley circulation. An experiment with quarter of Earth's radius shows that the latitudinal width of Hadley circulation is larger than that in the experiment with Mars' radius (figure is not shown). The change of latitudinal width of Hadley circulation with changing planetary radius may be interpreted by considering the change of equatorial Rossby deformation radius. However, these are still preliminary results, and further experiments and analyses are required to understand physical mechanisms of change of Hadley circulation observed in this study.

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