B-5.1 Study on the Development and Improvement of a Climate Model

Contact Person Itsushi Uno
Head, Atmospheric Environment Division,
National Institute for Environmental Studies, Environmental Agency.
Onogawa 1, Tsukuba, Ibaraki, 305 Japan
Phone:+81-298-51-6111 (Ext.439) Fax:+81-298-51-4732
Email:iuno@nies.go.jp

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Abstract An atmospheric and oceanic general circulation model has been developed. This model is intended for a community-use research on climate change of the time-scale ranging from several years to several hundreds of years. Physical parameterizations of atmospheric radiation process and hydrological processes were developed. We also developed a high-accuracy and high-efficiency global ocean GCM. Then preliminary experiments were performed with realistic boundary conditions. It was found that the GCM is compatible with the most advanced models in the world by comparing with observed climate data. In addition, a land-surface model and sea-ice model were developed and their characteristics were investigated.

Key Words Climate model, Atmospheric General Circulation, Ocean General Circulation, Land-surface process, Parameterization

1 Introduction

A quantitative evaluation of climate change such as the global warming is impossible without a high-quality numerical model which describes the dynamics of the climate system and the circulations of the energy and material. The purpose of this research is to develop a community climate model which enables research into mechanism of the climate change with the time scales ranging from several years to hundreds of years.

At the present time, there are about five comprehensive atmosphere-ocean combined climate models in the world. Also, the atmospheric general circulation models are developed at about ten organizations and are used for the experiment of carbon dioxide doubling. These models give qualitatively similar results for the global warming prediction, but do not coincide quantitatively with one another. For example, the global average of the temperature rise at CO_2 doubling varies from 2°C to 5°C depending on the models. In addition, the ability of each model in reproducing the current climate is not satisfactory. For example, the ocean-atmosphere coupled models cannot yield realistic climate maps without making an artificial adjustment of the flux between atmosphere and ocean. These problems are attributed to the incomplete representation of physical processes and limited spatial resolution.

Considering such a situation, we developed atmospheric and oceanic GCMs which would be capable of the quantitative prediction of the climate change. The basic standpoint in the development is to make the model based on obvious physics and possibly less dependent on empirical parameters. Effective model code was employed to make the long-term run possible with high resolution. In addition, considerable attention was paid to the readability and module compatibility of the code to enable a community use of the model.

2 Development of accurate radiative transfer scheme

Development of efficient radiation code: We must evaluate radiative fluxes corresponding to more than seven hundred thousand absorption lines, whose wave lengths distribute between 0.2μm and 200μm. It can be estimated by solving the radiative transfer equations including the scattering, the absorption, and clouds. In order to solve the transfer equation efficiently, the Discrete Ordinate/Adding method is adopted in our scheme. However, the number of channels of absorption that the model computes is extremely limited even with the scheme. We have overcome this difficulty by adopting k-distribution method and by applying a nonlinear optimization scheme for the selecting the channels. As the result, we can reduce the number up to 48 from 242 keeping the error of the heating rate to be smaller than 0.5 $^\circ$ K/day below 40 km altitude.

Estimation of the cloud single scattering albedo: In order to compute the scattering and absorption in the cloudy atmosphere, an appropriate evaluation of the band-averaged single scattering albedo is important in our scheme. On can estimate the averaged single scattering albedo from the ratio of the averaged absorption cross section and the averaged extinction coefficient (cross section average method). Another choice of the averaging is the average of the square root of single scattering albedo (square-root average method). By comparing these two methods, It is found that the heating rate is correctly evaluated with both method for long wave radiation. For short wave radiation, however, the cross section average method provides overestimation of heating rate within the cloud layer, while the square-root averaging method results almost correctly except the underestimation in the cloud top.

3 Development of parameterizations of atmospheric physical processes

Cloud liquid water content prediction: In order to express the feedback process concerning the cloud optical thickness appropriately, an scheme for the prediction of cloud liquid water content is developed. In this scheme, the predicting variable is the total water content. The liquid water is diagnosed assuming the variability of the total water within the grid. The precipitation and evaporation of rain is estimated by simplified Kessler type formula.

Modified Arakawa-Schubert cumulus parameterization: An Arakawa-Schubert type cumulus parameterization is developed. The mass flux is prognostically estimated using cloud work function. The effect of downdraft is incorporated in a rather simple manner.

Improved treatment of boundary layer processes: The effect of cloud is incorporated in the vertical diffusion process by use of moist Richardson number. In the surface flux parameterization, the effect of free convective motion is incorporated to improve the evaporation field over the tropical ocean. The effect of non-local diffusion in the boundary layer is also incorporated.

Gravity wave drag: A parameterization scheme of orographic gravity-wave drag is developed following McFarlane(1987). The zonal wind field in the upper troposphere and stratosphere is improved by the introduction of this scheme.

4 Climate simulation by atmospheric GCM

Simulation of climatology: Introducing physical parameterizations reported above, the model was run under realistic boundary conditions and the results were compared with observed climatology fields. The adopted horizontal resolutions is T21(equivalent grid size 5.5°) or T42(3°) and vertical resolution is 20 levels.

The zonally averaged distribution of temperature and its deviation from observed climatology is shown in Fig.1 for three month average from June to August. The deviation is less than two degrees in most part of the troposphere. However, there is large cold bias near the tropopause region, especially near the pole.

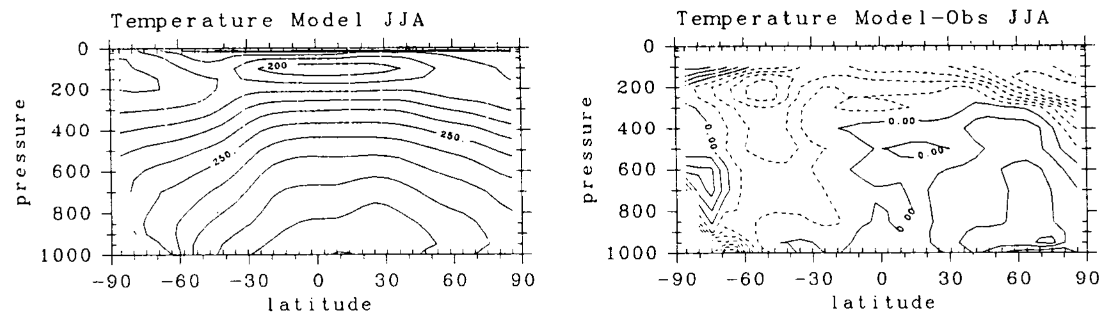

Figure 1: Distribution of zonal mean temperature (left) and its deviation from observed climatology (right). Three month average from June to August is shown. Contour interval is 10K(left) and 2K(right).

The distribution of precipitation is shown in Fig.2. The location and strength of the large-scale precipitation area is well simulated.

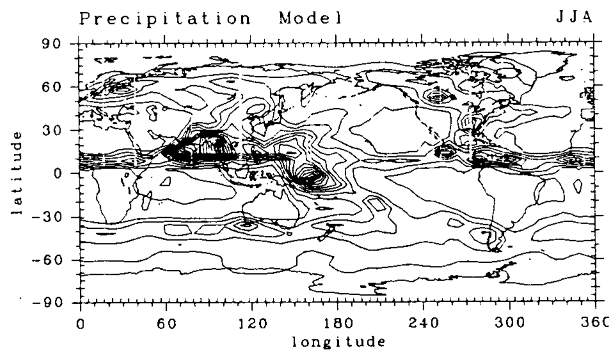

Figure 2: Distribution of precipitation. Three month average from June to August is shown. Contour interval is 50mm/month.

By examining the model result, it is found that the model reproduces fairly realistic climate except for some problems, for example, too dry tropical middle troposphere and too moist upper troposphere and deformed circulation pattern in the stratosphere.

Simulation of QBO: Using our atmospheric GCM, we have succeeded in a simulation of the quasi-biennial oscillation in the tropical troposphere. This is the first success in the world by using three-dimensional GCM. In this simulation, we have employed very high resolution model (equivalent grid size $\sim$ 1.1°) and moist adiabatic adjustment scheme in order to get high gravity wave activity. The results clearly indicate the importance of gravity wave in the formation of quasi-biennial oscillation.

5 Study on the land surface model

Sensitivity study with soil model: Aiming to the development of comprehensive land surface model in use of climate model, a simple sensitivity study are done using an one-dimensional model of land surface. A one-dimensional soil model with explicit treatment of ground water table was developed. The model is based on thermal diffusion equation and Richards' equation for soil water. The model was coupled with a simple model of atmospheric boundary layer and was run for long time with various conditions of precipitation and radiation as external forcing. The result indicates the importance of appropriate treatment of the deep water and runoff in the long-term behavior of the land surface.

Incorporation of vegetation effect: An attempt in incorporating the effect of vegetation into the land surface model is done basically following the SiB model by Sellers *et al.*(1986). Results of one dimensional simulation with and without the effect of transpiration and interception show significant difference in the seasonal pattern of evaporation.

6 Development of oceanic general circulation model and sea ice model

Development of oceanic general circulation model: We have developed a highly efficient oceanic general circulation model including simple physical processes. The model with 2 degree grid size and realistic topography reproduces fairly realistic distribution of temperature, salinity and velocity. It was ascertained that these models are compatible to the most advanced models of the world. However, our model shares some common defects appeared in other oceanic models.

Development of sea ice model: A sea ice model as a part of climate model is developed. The model incorporates not only the thermodynamic process but also the dynamical process of ice. The results of the experiments with coupled ocean-ice model show the importance of the ice dynamics for the simulation of the sea ice extent.

7 Conclusion

In this study, we have developed the main parts of comprehensive climate model, an atmospheric general circulation model, an oceanic general circulation model, and models of land-surface and sea ice. The models are successful in simulating realistic climate distributions, and the performances are comparable to the other state-of-the-art general circulation models.

The outline of the atmospheric model is summarized as the followings.

Basic Equations: 3-dimensional hydrostatic primitive equations on sphere.

Prognostic Variables: horizontal velocity, temperature, surface pressure, total water content, soil temperature, soil moisture, snow depth.

Horizontal Discretezation: spectral transformation method with Gaussian grid.

Vertical Discretezation: grid differentiation in normalized pressure (σ)

Physical Processes: 2 stream DOM/adding method for radiative transfer .
estimation of cloud liquid water by prognostics of the total water content.

Arakawa-Schubert type cumulus parameterization with prognostic closure.
Mellor-Yamada level 2 closure for turbulent diffusion with moist effect.
non-local diffusion in planetary boundary layer.
bulk scheme for surface fluxes with the effect of free convective motion.
orographic gravity-wave drag scheme.
multi-layer treatment of land-surface energy budget and hydrology.

Although the development of the first versions of the atmospheric and oceanic models are successfully completed, further study should be necessary to make these models to be useful tools for the quantitative estimation of the climate change. Further improvement of the parameterization schemes and their evaluation by the numerical experiments and observational studies are required. Moreover, the coupling of the atmospheric and oceanic model is one of the most important subject in the future study.

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