B-1 Study on Modeling of Aerosol, Water Cycle, and Vegetation for Improving Future Projection of Climate Change (Abstract of the Final Report)

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1. Introduction

It is required to reduce uncertainties in the future projection (or prediction) of the global scale climate change associated with global warming for contributing to evaluation of the impact of the global warming on society and human beings. It is also required to develop a climate model incorporating material circulation and ecosystems. These subjects remain as issues to be overcome, and classified as important issues by the IPCC (Intergovernmental Panel on Climate Change).

2. Research Objective

The main objectives of the project are to clarify the effect of tropospheric aerosol and ozone on climate, to clarify the effect of water cycle on climate variability, and to establish the basis of a climate model incorporating interaction of material circulation and ecosystems with climate. Moreover, the project aims at developing a numerical, global three-dimensional climate model on the basis of the above results of process studies, and to apply it to global warming issues.

3. Methods and Results

This project carries out modeling of processes affecting the evaluation of the impact of climate change, such as aerosol, ozone, water cycle, and ecosystems, as an attempt to develop a climate model of the CCSR/NIES coupled atmosphere-ocean general circulation model (AOGCM), which is developed through joint research of NIES (National Institute for Environmental Studies) with CCSR (Center for Climate System Research, University of Tokyo). Some analyses of observational data from satellite observation, forest site observation, etc., are done as validation of the modeling. Developing model of the processes means naturally understanding the processes. We keep in mind applying the climate model to future projection of climate change associated with emission scenarios of greenhouse gases and aerosols. The project consisted of the following three sub-themes.

1) Study on the effect of tropospheric aerosol and ozone on climate

The ultimate aim of this study is to gain the knowledge on uncertainties in the projection of climate change, attributed to the insufficient modeling of tropospheric aerosols and ozone. The concrete purpose is to obtain spatial and temporal distributions of aerosol and ozone in response to emissions of sulfur dioxide, carbon, etc. with use of global climate models incorporating transport and chemical reaction processes, and to evaluate climate variability considering uncertainties in the effects of aerosol and ozone with use of a global climate model at the stage of increased greenhouse gases.

The main results are as follows, detailed in the papers[1-18]: (i) The direct effect of aerosols (whereby aerosols scatter and absorb mainly solar radiation, thereby perturbing the energy budget of the earth-atmosphere system) and the indirect effect of aerosol (whereby aerosols serve as cloud condensation and ice nuclei, thereby modifying the radiative properties and microphysics of clouds) in radiative forcing were studied on the basis of a global three-dimensional aerosol transport-radiation model experiment analysis and satellite data analysis. The aerosol types considered were the major four types: soil dust, carbonaceous, sulfate, and sea salt aerosols. As for the direct effect, model experiments showed that the net cooling effect of aerosols is smaller than the estimate by IPCC (2001) even though within the range of uncertainty. Model experiments showed that the indirect effect is larger than the direct effect in net negative radiative forcing although the uncertainty in the indirect effect is still large. (ii) The global three-dimensional aerosol transport-radiation model was validated against observation especially for East Asia. The future projection of aerosol distribution was calculated under the condition of future scenarios of anthropogenic emissions, and the radiative forcing became almost 2 times as the present after 50 years from the present for a scenario. (iii) A global three-dimensional chemistry climate model capable of evaluating the effects of troposperic ozone and sulfate aerosols was developed, and validated against observations. Using the model, the radiative forcing of tropospheric ozone was estimated to have almost the same value as methane. An experiment on factors determining tropospheric ozone chemistry showed that in the tropics, the main factors of an observed interannual variability of ozone were the east-west circulation, convection pattern, water vapor associated with El Nino phenomena. (iv) As a result of future projection of tropospheric ozone and aerosol concentration using the chemistry climate model, ozone concentrations increase almost linearly with concentrations of the ozone precursors increase. (v) Aerosol-type detection from satellite remote sensing, an important challenge for improving the estimation of aerosol radiative forcing, was done. We have classified aerosols into four major aerosol types, that is, soil dust, carbonaceous, sulfate, and sea salt aerosols using SeaWiFS four-channel data. (vi) To investigate long-term variation in optical properties of tropospheric aerosols during the past 20 years with use of satellite data, NOAA/AVHRR sensor calibrations were done. The method of relative calibration was developed. The determination of absolute values of calibration is still to be overcome, but the issues and its solutions were concretely investigated.

2) Study on the effect of water cycle on climate variability

The aim of this study is to gain the knowledge on uncertainties in the projection of climate change, attributed to the insufficient modeling of hydrological processes. In order to accomplish it, we analyze characteristics of cloud and precipitation processes in observed data as well as in data simulated by the climate model, and improve the climate model related to those processes. We set three concrete tasks to clarify the relationship between the cloud-precipitation processes and the climate change: (a) To make projection of hydrological cycle change associated with the global warming, and examine its sensitivities, with use of the state-of-the-art climate model; (b) To improve schemes related to the hydrological processes in the climate model; (c) To describe the details of cloud-precipitation phenomena, which will contribute to the development of the next generation climate models, with use of the state-of-the-art satellite observation data as well as accumulated long-term meteorological data.

The primary achievements are as follows, detailed in the papers[19-22)]: (i) With observation data, it was inferred that there are regional variations of long-term trend in snow amounts. Utilizing the CCSR/NIES climate model, we simulated the regional variation of snow amount change associated with the global warming and analyzed its mechanism. (ii) With the climate model, changes of the Baiu activities associated with the global warming were simulated, and its relation to large-scale circulation change was examined. (iii) Improvements of the moisture transport scheme in the climate model were achieved. (iv) A new version of the climate model was developed, excluding 'the flux adjustments', which artificially adjusts the atmosphere-ocean coupling. (v) Utilizing new observation data with instruments on Tropical Rainfall Measuring Mission (TRMM) satellite, statistical description of precipitation characteristics were achieved, to obtain what is the realistic precipitation we should be able to simulate in the next generation climate model. (vi) Mechanism of the interannual variation of the South Asian Monsoon rainfall was analyzed with observational data. It was shown that the activity of transient disturbances, which determines the rain amount, is affected by the large-scale circulation variations, such as El Nino. (vii) We observationally clarified the effects of large-scale atmospheric stratification on organized tropical precipitation systems. It was strongly suggested the necessity of reproducing realistic atmospheric stratification which may partly attribute to subtle cloud microphysics, in order to simulate realistic precipitation systems.

3) Study on the feedback of terrestrial ecosystems on the global warming process

Aiming at elucidating the feedback mechanism between the climate system and terrestrial ecosystems, observational and modeling studies have been conducted on (a) the biosphere-atmosphere interactions at a vegetation-stand scale, (b) the flux aggregation processes toward mesoscale fluxes, and (c) validation of land-surface models at continental scales.

The followings are the summary of major results details of which are described in the papers[23-33)]: (i) The boreal forest is characterized by a simple vertical forest structure as compared with the complex structure of tropical forests. The boreal forest is usually comprised of two layers, namely, canopy tree layer and understory layer in the forest floor. Utilizing this simple structure, we investigated how understory plants (Sasa dwarf bamboo) affect the growth and competition of canopy trees (Betula ermanii) by establishing two types of experimental plots in Moshiri Forest, Hokkaido, i.e., control plots with Sasa in the forest floor and plots where Sasa was artificially removed. The presence of Sasa alleviated intra-specific competition between Betula ermanii trees by absorbing much water in the soil. Consequently, the growth of leaf area and biomass of trees at the stand level was enhanced in the plots with Sasa in the forest floor. Therefore, the interaction between canopy trees and understory plants must be taken into consideration when we study the dynamics of boreal forests, although it has been generally neglected. (ii) In order to clarify the feedback mechanism between the climate system and terrestrial ecosystems, it is necessary to use a land surface model that can represent temporal change in composition and spatial distribution of terrestrial ecosystems. We therefore developed a prototype of land surface model that include forest ecosystem dynamics, by coupling a multilayer canopy model for vegetation microclimate and a model for dynamics of plant size distribution. The model was validated against field data of vegetation dynamics in an evergreen coniferous and a deciduous coniferous plantation (mono-specific forest). After some improvements of parameterizations, the model produced fairly good predictions for the 5-year development of plant size distribution in these forests. Annual growth rate of each size-class plant was also well reproduced by the model. Then the model was further developed to describe the interspecific competition in a mixed forest, making it possible to apply the model to natural forest ecosystems under various climate conditions. Additionally, we developed a scheme of representing the surface energy partitioning at rice paddy fields, which play an important role in the land-atmosphere interaction in Southeast Asia. (iii) Since energy, water vapor, and other chemical substances such as CO_2 are transported with turbulence affected by the surface topography, we analyzed turbulent flow over a two-dimensional steep hill by large eddy simulations (LES). First, four LES computations were carried out using different sub-grid scale (SGS) models. The accuracy of these computations was assessed by comparing the results with data from a wind-tunnel experiment. The results of the dynamic SGS model gave very poor agreement with the experiment, mainly owing to its poor prediction accuracy near the ground surface. In order to improve the prediction accuracy of the dynamic SGS model, we introduced a hybrid SGS model, i.e., a combination of the standard Smagorinsky model and the dynamic SGS model. The hybrid model provided very accurate predictions and produced the best results of the four SGS models compared here. Then the LES model was applied to the turbulent transportation of CO_2 around a two-dimensional hill, showing that CO_2 transportation around the hill was strongly affected by mechanically induced turbulence rather than thermally induced one, and cavity flow in the lee side of the hill caused significant variations in CO_2 concentration near the hill surface. (iv) A preliminary study was conducted to develop a scheme for validating land surface models at a continental scale using river discharge data. For the comparison with discharge data, a long-term simulation of global hydrology must be carried out. However, long-term atmospheric data for driving land surface models are basically lacking in the past and must be estimated from monthly mean data (only available for temperature and precipitation) or climatological data (other variables). Therefore we tested the sensitivity of simulated hydrology on these variables to clarify which variable should be specified accurately and which requires less accuracy. The results showed that the time series of precipitation exerts very large influences on the simulated hydrology while the other variables are less important. We then developed a statistical scheme to prescribe precipitation data, and confirmed that the estimated precipitation data were accurate enough for hydrological simulations. Finally, global precipitation data for the last 100 years were prescribed by this scheme, and discharge data for world major rivers were tabulated.

4. Concluding Remarks

The research project treated not only sulfate aerosols but also other aerosols such as carbonaceous aerosols. It developed a scheme to incorporate not only the direct effect but also the indirect effects of aerosols in radiative forcing into the CCSR/NIES climate model, and a scheme to incorporate the effect of tropospheric ozone into the climate model. It also developed a scheme of incorporating the effect of terrestrial ecosystems into the climate model. The project required computer resources, and utilized the computer system of NIES including the supercomputer (NEC SX-4 and SX-6).

Part of the project consequently aims at contributing to IPCC, especially IPCC 4AR (Fourth Assessment Report) scheduled in 2007, by applying the developed model to future projection of climate change. The project is related to the following international research projects of WCRP (World Climate Research Programme): GEWEX (Global Energy and Water Cycle Experiment); GEWEX/ISLSCP (International Satellite Land Surface Climatology Project); CLIVAR (Climate Variability and Predictability Programme); AMIP (Atmospheric Model Intercomparison Project under WCRP/WGNE (Working Group on Numerical Experimentation)); CMIP (Coupled Model Intercomparison Project under WCRP/CLIVAR/WGCM (Working Group on Coupled Models)). It is also related to the following projects of IGBP (International Geosphere-Biosphere Programme): GAIM (Global Analysis, Interpretation, and Modelling); BAHC (Biospheric Aspects of the Hydrological Cycle).

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