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DEVELOPMENT OF CLIMATE CHANGE SCENARIOS FOR IMPACT ASSESSMENT USING RESULTS OF GENERAL CIRCULATION MODEL SIMULATIONS

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Abstract

In order to develop climate change scenarios for impact assessments using the results of General Circulation Models (GCMs), it is important to examine which characteristics of the results can be taken into account. For this purpose, we listed some important characteristics of GCMs to be used in creating climate change scenarios for impact assessment, and evaluated the ability of each GCM to reproduce the characteristics by comparing the results of the GCMs with the observed climate data. Four characteristics were examined; regionally aggregated 30-year-normal annual mean surface temperature/precipitation, spatial distribution of 30-year-normal annual mean suface temperature, regionally aggregated 30-year-normal monthly surface temperature/precipitation (intra-annual variability) and inter-annual variability of annual mean surface temperature. Some GCMs were found to have less ability to reproduce the observed climate data than others. Regionally aggregated 30-year-normal annual mean surface temperature can be reproduced well, whereas spatial distribution cannot be predicted well enough to be directly used for creating climate change scenarios for impact assessment. Monthly temperature is also reproduced well except for some models and regions. In general, precipitation is reproduced less accurately than surface temperature.

KEYWORDS: *General Circulation Model, climate change impact, climate scenario*

1. Introduction

In quantitative climate change impact assessment studies targeted at the global level, the most frequently used method is as follows; (1) development of a model for estimating the impact on the object of assessment, (2) construction of future climate scenarios as the input data for the model, (3) application of impact assessments. In early climate change studies, future climate scenarios were constructed as inputs for impact assessment models by sensitivity analysis-like methods such as

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adding a uniform temperature increase to present observed surface temperature data, or assuming that precipitation would increase at a uniform rate globally (synthetic scenarios).

In the early 1990s, with the development of General Circulation Models (GCMs), equilibrium simulation results for a doubling of greenhouse gas (GHG) concentrations in the atmosphere were used as climate scenarios for impact models. Because of the too coarse spatial resolution and unreliability of GCM results, future climate scenarios were sometimes established by superposing the difference between simulated results under current GHG concentration and a doubling of GHG concentrations on the presently observed climate data. In the latter half of the 1990s, as both GCMs and computer technology improved rapidly, two types of the simulations have been conducted. One is baseline type experiments (control-run) which assume that present GHG concentrations will continue in the future, and the other is gradual increase type climate change experiments (transient-run) which provide changes in future GHG concentrations as scenarios.

From the standpoint of global climate change impact assessment, more practical impact assessments taking into account the rate of adaptation of the impacted system are possible by the information obtained from these transient-run. Although the accuracy is not sufficient, information on future changes in variability such as inter-annual fluctuations, and intra-annual fluctuations on a seasonal scale, can also be obtained. This is effective to propose measures which takes into account the assessment of impacts due to extreme climatic conditions and the inter-annual fluctuation range.

Many climate change impact studies have been carried out, where individual researchers constructed their own climate scenarios to use as inputs for their impact assessment model. Therefore, it was not possible to distinguish the differences arising from each impact assessment model with different climate scenarios, so that comparisons between studies were difficult. Due to these circumstances, the Intergovernmental Panel on Climate Change (IPCC) has established the Task Group on Scenarios for Climate Impact Assessment (TGCIA) to facilitate mutual comparisons between impact assessment studies toward the Third Assessment Report scheduled for release in 2001, and to propose standard methods for constructing climate scenarios using coupled climate models. In addition, TGCIA has established the IPCC Data Distribution Centre (IPCC-DDC, http://ipcc-ddc.cru.uea.ac.uk/ipcc-ddc.html) to gather the results of transient-run employing the latest coupled climate models which should be used for climate scenarios development, and to release them to the public via the Internet. IPCC-DDC has already commenced operation.

In adopting the method for constructing scenarios proposed by TGCIA, the following are important; (1) to examine the characteristics and accuracy of each coupled atmosphere and ocean model provided by IPCC-DDC, to clarify the errors generated by the differences in climate models, and to select the climate model(s) suitable for the intended impact assessment, (2) to quantitatively estimate the degrees and trends of errors that may occur due to the choice of method for constructing the scenarios. Concerning the latter point, we have been studying the necessity of using normals having a duration of about 15 to 30 years in order to develop mean scenarios in which inter-annual fluctuations are negated for global-scale impact assessments. However, we will report on this work separately. In the present paper, the results of a study on the former point are summarized.

For the assessment of climate change impact at the global scale on agriculture, river flow rates, forests, etc., the major climate change factors governing the estimation results are surface temperature and precipitation. In order to express the global warming trend, the expression that "the global annual mean surface temperature can be predicted to rise by 2.0° C at the year 2100" is often used. However, in impact estimation, regional biases in climate change, monthly fluctuations, inter-annual fluctuations, unexpected weather conditions, and other factors are also important in addition to the trend in mean climate change. With regard to the two climate factors of surface temperature and precipitation, the extent to which each model can reproduce the climate characteristics required for global-scale impact assessment is summarized in this study from several viewpoints in comparisons with climate data sets prepared by the observed data. The objective of this study is to provide guidelines for climate model selection for construction of climate scenarios for impact assessment.

The background and objectives of the study have been summarized in this section. The next section outlines the information that is expected to be provided by the climate models for climate scenario development, and the criteria used for comparison of climate model in section 3. In section 3, the assessment results from each model are outlined and examined. Lastly, the information obtained by this study is summarized and points requiring further study in the future are outlined with respect to climate model selection for scenario construction.

2. Climate model comparison criteria for constructing climate scenarios

Using the results of transient-run by coupled climate models as the inputs for a climate change impact assessment model has many advantages, which enables us to examine more realistic impact assessment with adaptations. This is therefore expected to become the standard method for impact assessment of future climate change. At the present time, however, its accuracy is insufficient for direct use in impact assessment, and further improvements are required such as regional climate models with spatially higher resolution, enhanced prediction capability, etc. Even so, the calculation results of the coupled climate models distributed by IPCC-DDC can be used for the construction of future climate scenarios; they should be actively employed in areas that the present coupled climate models can simulate relatively well.

Table 1 summarizes coupled climate model experiments conducted by seven institutions distributed by IPCC-DDC at the end of the year 1998. They are distributed for the purpose of the application to the impact studies contributing IPCC third assessment report. At the current point (Jan. 2001), more improved experiments have been executed in some institutions and distributed by IPCC-DDC, however the version of results distributed in the end of the year 1998 is treated in this study in order to evaluate the characteristics of GCMs for the IPCC third assessment report. The simulation results for mean surface temperature, maximum surface temperature, minimum surface temperature, precipitation, solar radiation, dew point, wind velocity, and atmospheric pressure are provided for each model. However, focusing on mean temperature and precipitation, which have been treated as important climate factors in many impact assessment models, this study defines several assessment criteria based on the required characteristics for construction of climate scenarios for an impact assessment model (Takahashi et al., 1998), and analyzes the simulation results of each climate model. This section describes the establishment of these assessment criteria.

The target area of the impact assessment model developed by the authors is the whole world.

Table 1 GCM experiments distributed by IPCC-DDC
(IPCC-TGCIA, 1999; Some information are appended by the authors)

	CCSR	CCCma	CSIRO	GFDL	HADCM2	ECHAM4	NCAR
Institution, country	Tokyo University and National Institute for Environmental Studies, Japan	Canadian Center for Climate Modelling and Analysis	Australia's Commonwealth Scientific and Industrial Research Organisation	Geophysical Fluid Dynamics Laboratory, USA	Hadley Centre for Climate Prediction and Research, UK	Deutsches Klimarechenzentrum, Germany	National Centre for Atmospheric Research, USA
Resolution (A-GCM)	5.6° ×5.6° 20layer	3.7° ×3.7° 10layer	3.2° ×5.6° 9layer	4.5° ×7.5° 9layer	2.5° ×3.75° 19layer	2.8° ×2.8° 19layer	4.5° ×7.5° 9layer
Resolution (O-GCM)	2.8° ×2.8° 17layer	1.8° ×1.8° 29layer	3.2° ×5.6° 21layer	4.5° ×3.75° 12layer	2.5° ×3.75° 20layer	2.8° ×2.8° 11layer	1° ×1° 20layer
CO2 concentration (Control run)	345ppmv	295ppmv	330ppmv	300ppmv	323ppmv	354ppmv	330ppmv
CO2 concentration (Transient run)	1%/yr	1%/yr	0.9%/yr	1%/yr	1%/yr	1%/yr	1%/yr
Simulated period (Control run)	1890-2099 210yr	1900-2100 200yr	1881-2100 219yr	1958-2057 100yr	1860-2099 240yr	1860-2099 240yr	1901-2036 136yr
Climate sensitivity	3.5°C	3.5°C	4.3°C	3.7°C	2.5°C	2.6°C	4.5°C
Reference	Emori et al., 1999	Reader and Boer, 1998	Hirst et al.	Manabe and Stouffer, 1996	Johns et al., 1997	Roeckner et al., 1996	Meehl, 2000

Four types of impact are examined; (1) impact on agricultural productivity, (2) impact on river flow rate, (3) impact on forest vegetation and (4) impact on potential malaria propagation. This impact assessment model requires climate data with a 0.5° mesh spatial resolution and monthly mean time resolution as input data. In order to use the results of coupled climate models having a 1 to 5° spatial resolution for impact assessments with a 0.5° spatial resolution, original coarse results are interpolated with a simple mathematical method such as spline interpolation. Therefore, analyses are also made in this paper utilizing the same process (Takahashi et al., 1998).

2.1 Analysis 1: Annual mean

First, in order to roughly grasp the reproducibility of the present climate by each model, the 30-year normals (1961 to 1990) of annual mean surface temperature/annual precipitation from baseline experiments on each model and observed data for verification were aggregated and compared for 12 world regions (Africa, Australia/New Zealand, Middle East/arid Asia, islands region, temperate Asia, tropical Asia, former Soviet Union, Europe, U.S.A., Canada, Central America, and South America). LINK (New et al., 1998) was used for the observed data for verification. These regional classifications were made based on those in the regional assessment report issued by Working Group II of IPCC (IPCC, 1998). If the area of one region is too wide, it is further subdivided.

2.2 Analysis 2: 0.5° x 0.5° spatial distribution

Next, in order to investigate GCMs' reproducibility of spatial distribution of climate (with a 0.5° mesh resolution), difference between the normals of annual mean surface temperature/annual precipitation by baseline experiments on each model and the normals of observed data were calculated for each grid, and their absolute values were aggregated for each regional classification.

2.3 Analysis 3: Intra-annual fluctuations/monthly mean values

As well as the accurate reproduction of annual mean surface temperature shown in Analysis 1, the reproduction of intra-annual fluctuations is also important. Taking agriculture as an example, even when the annual mean is the same, if the climate during the cultivation period differs, crop growth will also change. Since monthly input data are used for the impact assessment model, the monthly mean temperature normals/monthly precipitation normals of the baseline experiments for each model and the observed data were aggregated and compared for each month and each region. At the same time, as one of the criteria indicating intra-annual variability, the deviation of monthly mean temperature/monthly precipitation from the annual mean values of each climate model were calculated and compared with the observed values.

2.4 Analysis 4: Inter-annual fluctuations

Lastly, in order to propose actual measures from the results of climate change impact assessment, it is important to take inter-annual variability into consideration. In the case of agriculture, for example, preparations must be made so as to enable both bumper harvest years and poor harvest years to be handled, and with regard to river flow rates, it is necessary to study measures for water shortages occurring once every several years, etc. As the assessment criteria for inter-annual variability, the deviations of annual mean temperature/precipitation of each year from the normal annual mean temperature/annual precipitation of each climate model were calculated and compared with the observed values.

3. Evaluation of climate models

3.1 Analysis 1: Annual mean

Figure 1 shows a regional aggregation of the 30-year-normal annual mean surface temperatures of the seven coupled climate models and the observed data of LINK. The results of NCAR and GFDL models deviate on both the higher and lower sides by 3 to 5 ° C from the observed values in all regions. Taking into consideration that the climate change issue deals with a temperature increase of around 2 ° C over a period of 100 years, it can be said that the accuracy of these two models is insufficient. In most of the regions, the median of calculated values of the seven climate models agree with the observed values of LINK closely, which confirms the validity of constructing scenarios using not only one specific model but multiple models.

Figure 2 shows the results of aggregation for precipitation carried out in the same way as Fig. 1. In the case of precipitation also, the accuracy of the NCAR model is low, whereas the accuracy of the ECHAM4 and HADCM2 models is comparatively high. Unlike the case of temperature, the observed values are often positioned at the limits of the range of the seven climate models. The method of using the median of calculated values of the seven climate models is not so effective. However, in terms of the point that qualitative variations in precipitation among regions can be expressed, it may be possible to use this method in the construction of climate scenarios.

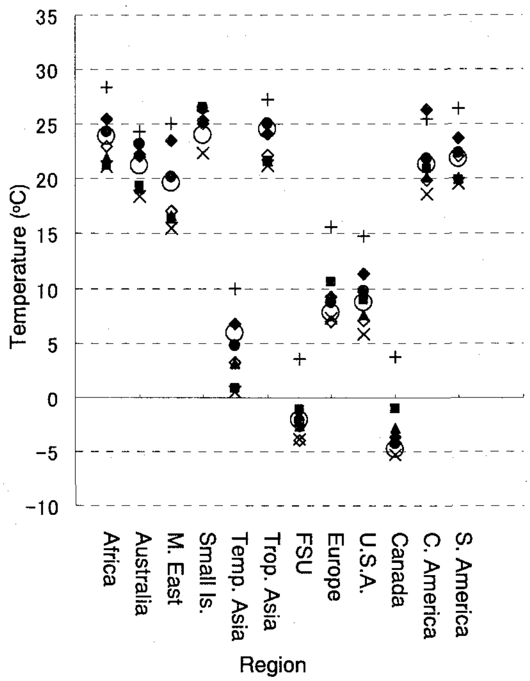


Fig. 1 30-year-normal annual mean temperature

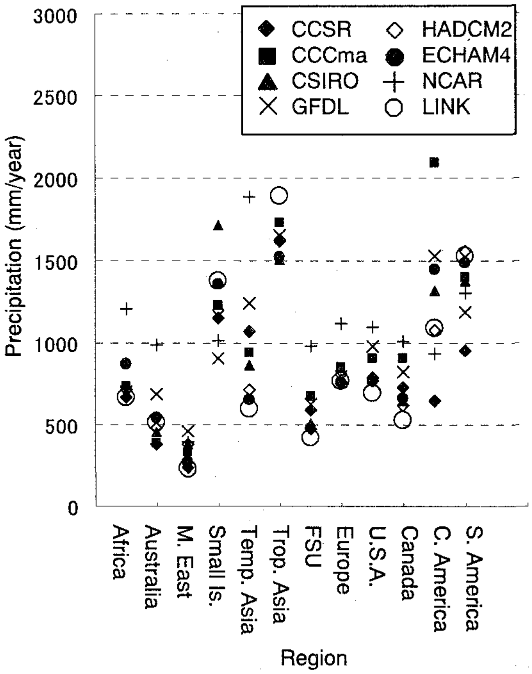


Fig. 2 30-year-normal annual mean precipitation

3.2 Analysis 2: 0.5° x 0.5° spatial distribution

Figure 3 shows the results obtained when the differences between the model values and LINK observed values for 30-year-normal annual mean temperature were calculated for each grid and their absolute values were aggregated. The reproducibility of spatial distribution is demonstrated at a resolution of 0.5° x 0.5°. However, even ECHAM4 and HADCM2, which have comparatively good accuracy, have errors of 1 to 3° C, indicating that coupled climate model output cannot be used as a directly input climate scenario for an impact assessment model requiring high spatial resolution. It is necessary to employ a method such as scaling (IPCC, 1994) using observed data for normals, etc.

3.3 Analysis 3: Intra-annual fluctuations/monthly mean values

Figure 4 shows the deviation of 30-year-normal monthly mean surface temperatures from 30-year-normal annual mean surface temperatures calculated in the following equation.

$$DEV = \frac{\sqrt{\sum_{m=1}^{12}(Temp_m - Atemp)}}{12}$$

DEV: Deviation
Temp$_m$: 30-year-normal monthly mean surface temperature
Atemp: 30-year-normal annual mean surface temperature

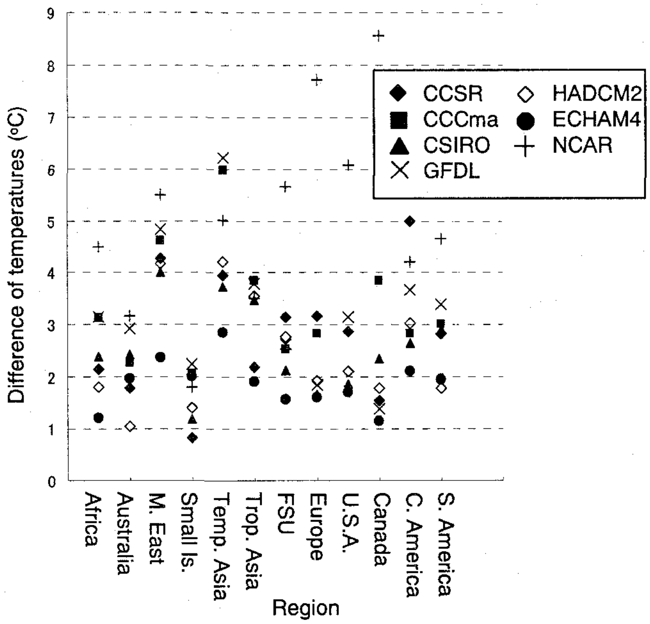


Fig. 3 Difference between the model values and LINK observed values for 30-year-normal annual mean temperature (Regional aggregation of values calculated for each grid)

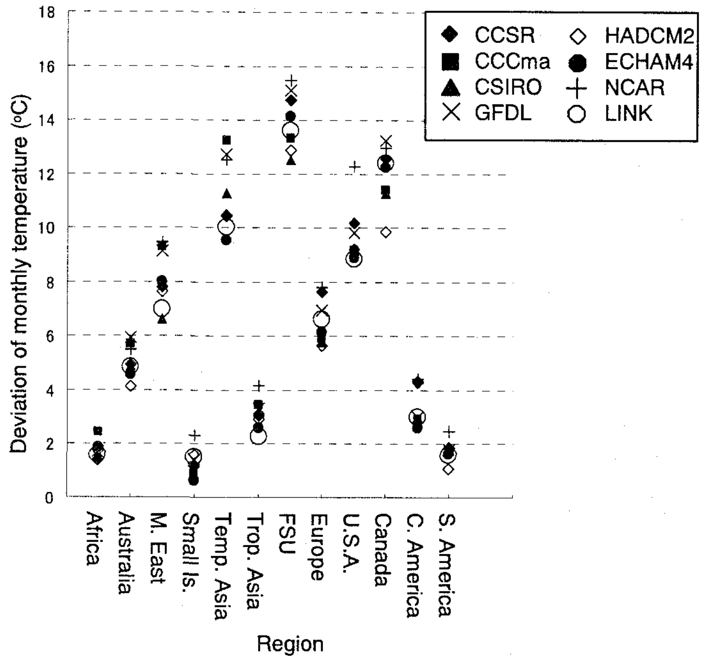
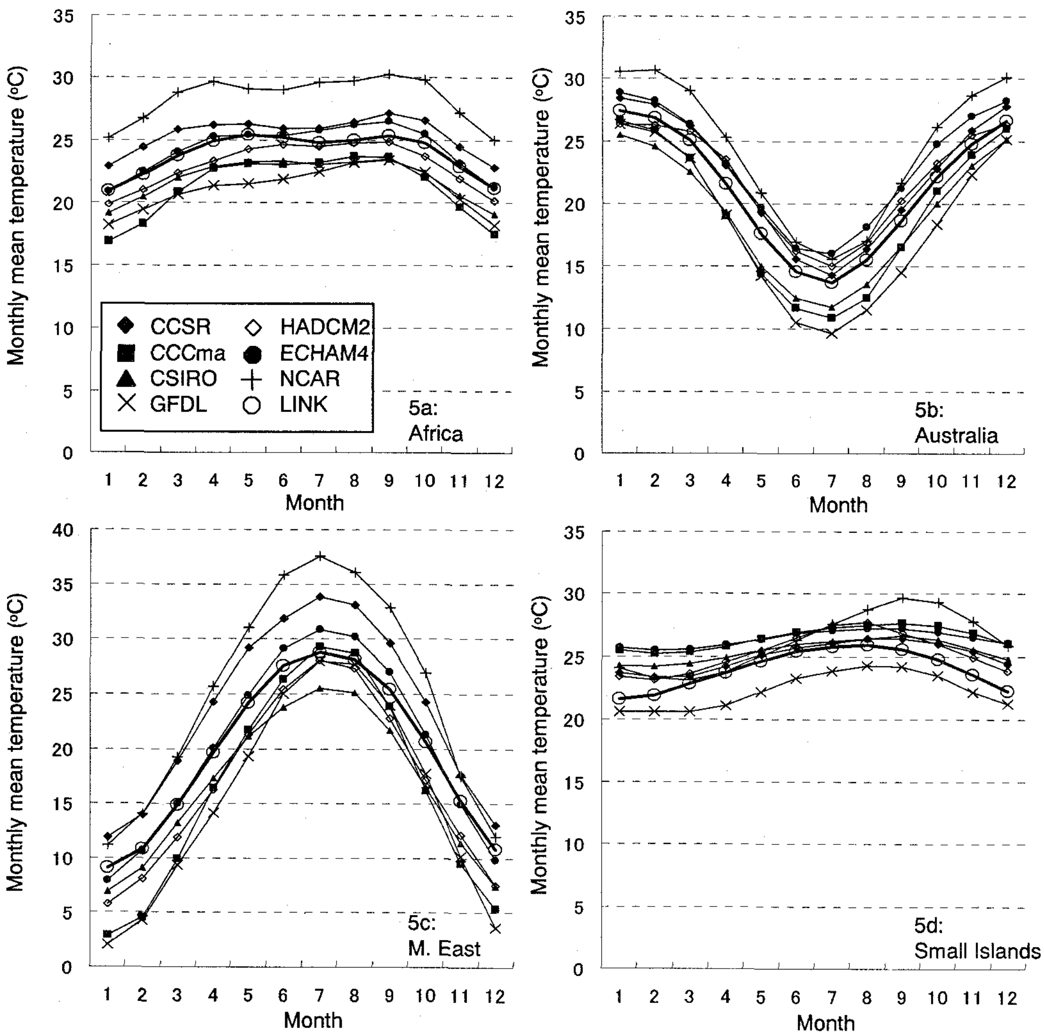


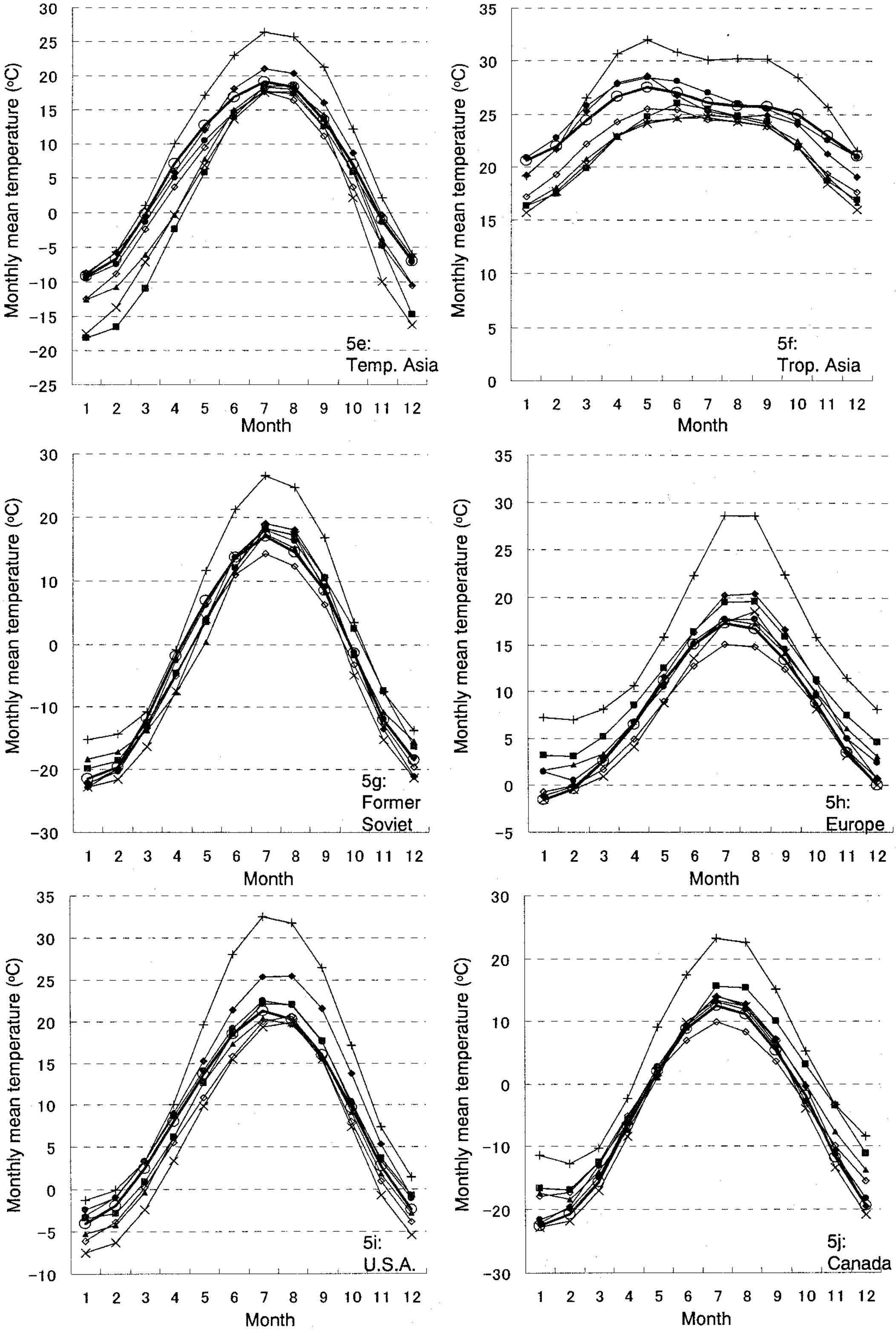
Fig.4 Deviation of 30-year-normal monthly mean temperatures against 30-year-normal annual mean temperatures

This was used as a criterion for the reproducibility of seasonal temperature distribution. Although bias (deviations of GCMs are larger than that of LINK) is found in some region (Middle East, Temperate Asia, Tropical Asia, U.S.A), it can be seen that the models reproduce the dispersion of intra-annual temperatures for many regions well and the difference among regions is reproduced well. This indicates that information on future seasonal distribution variations obtained by transient-run is sufficiently reliable to construct future climate scenarios.

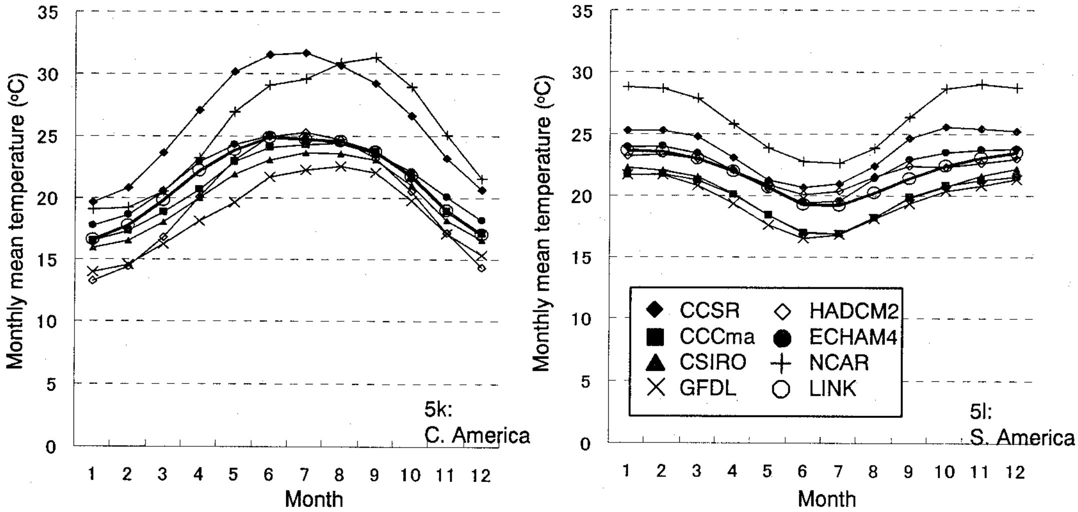
When the 30-year-normal monthly mean surface temperatures of each region are compared with the observed data (Figures. 5a-5l), it is found that seasonal distributions can be reproduced accurately in many regions, except with the results predicted by NCAR model. However, the calculation results for Central America obtained by the CCSR model have a conspicuously large error. At temperate and tropical Asia, monthly temperature is well reproduced in summer, whereas most models estimate temperature lower than observed data in winter. On the other hand, warmer winter is estimated by most climate models for Europe.



Figs. 5a-5d 30-year-normal monthly mean temperature in each region



Figs. 5e-5j 30-year-normal monthly mean temperature in each region



Figs. 5k-5l 30-year-normal monthly mean temperature in each region

Figure 6 shows the results of aggregation carried out for precipitation in the same way as Fig. 4. The regions with large deviations tend to have a wider estimation range, indicating the difficulty of estimating the seasonal distribution of precipitation in regions with large intra-annual fluctuations.

Figures 7a-7l show the regional aggregation of monthly fluctuations in precipitation. In comparison with surface temperature, the seasonal distribution is not reproduced well. Here again, NCAR model reproduces less accurately monthly fluctuations than other models. Precipitation is estimated to be more than the observed data in Former Soviet Union, U.S.A. and Canada, while it is less than the observed data for South America.

3.4 Analysis 4: Inter-annual fluctuations

Figure 8 shows the deviation of the annual mean surface temperatures (1961 to 1990) from the 30-year-normal annual mean surface temperatures, revealing the extent of inter-annual fluctuations of the annual mean surface temperature. Although a wide range is seen between the calculated results of the models, it is found that by using the median of calculated results of seven climate models in many regions, the range of inter-annual fluctuations obtained by the observed values can be reproduced with fairly good accuracy. This indicates the possibility that the information on future changes in inter-annual fluctuations estimated by gradual increase type climate model experiments can be used to construct climate scenarios.

4. Conclusions

In the present study, the reproducibility of observed values by coupled climate models was evaluated based on several criteria. From the results obtained, it was found that the NCAR and GFDL

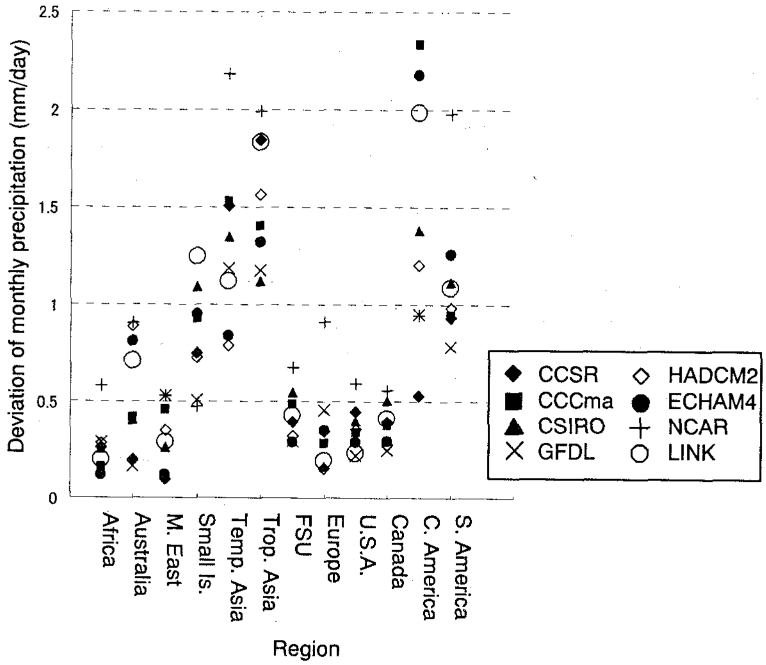
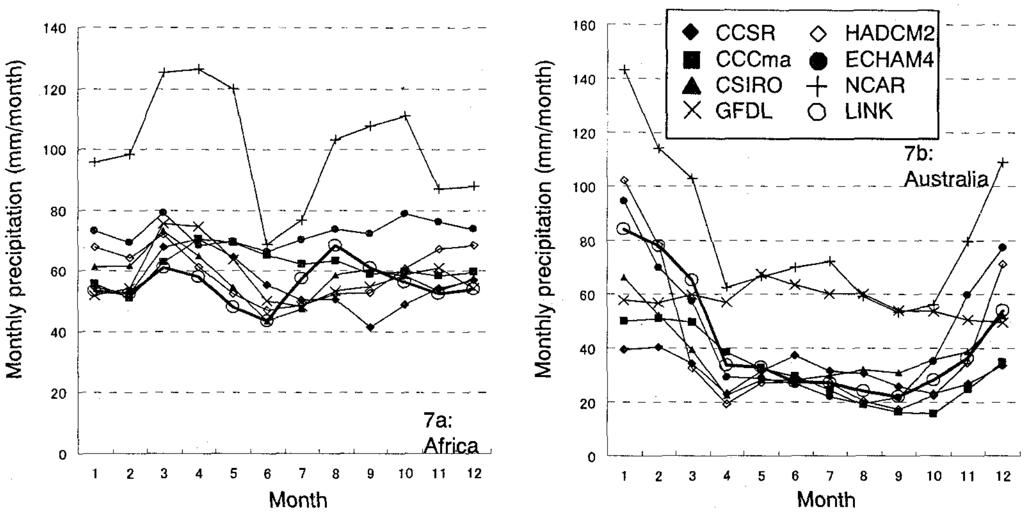
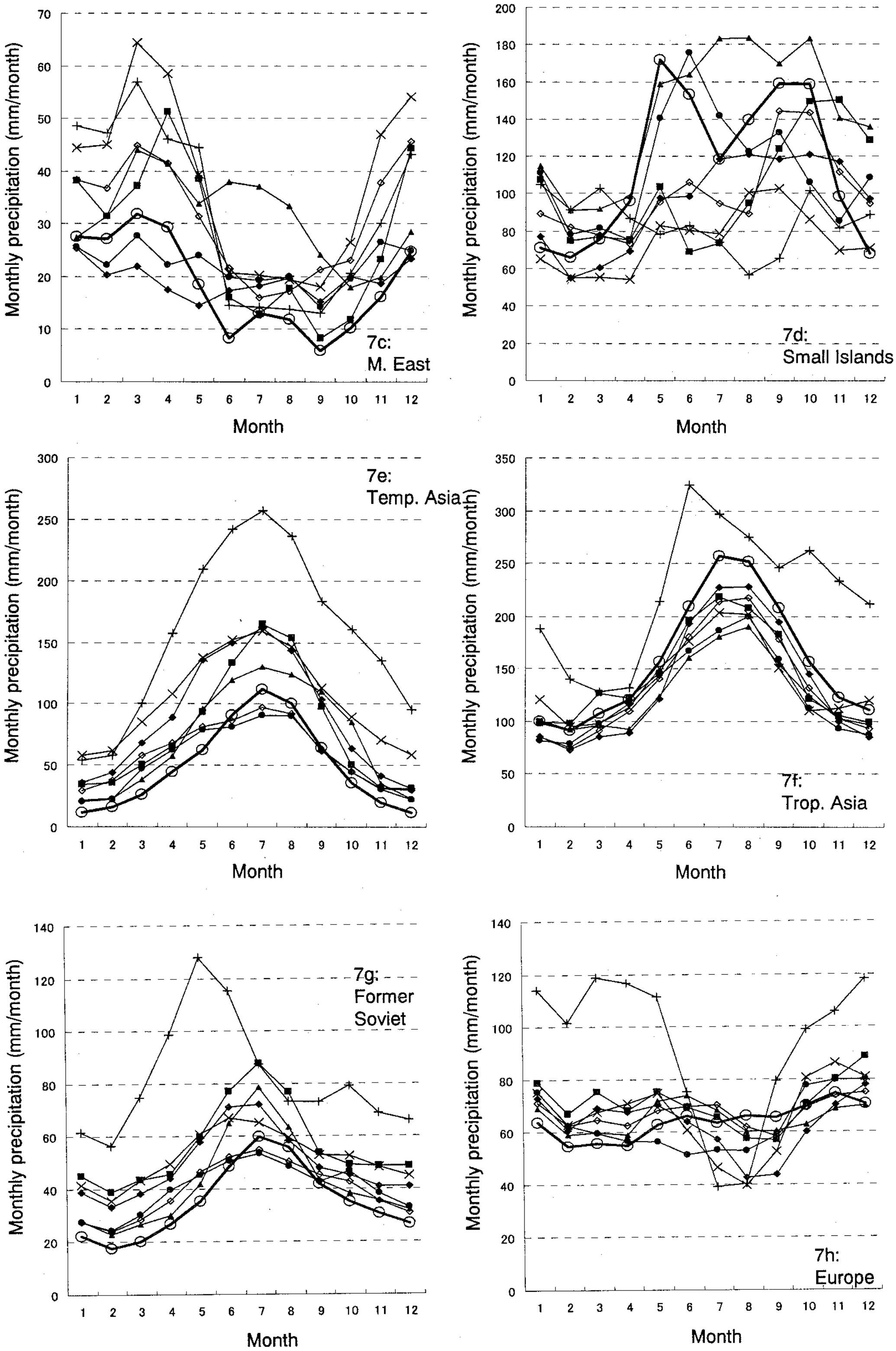


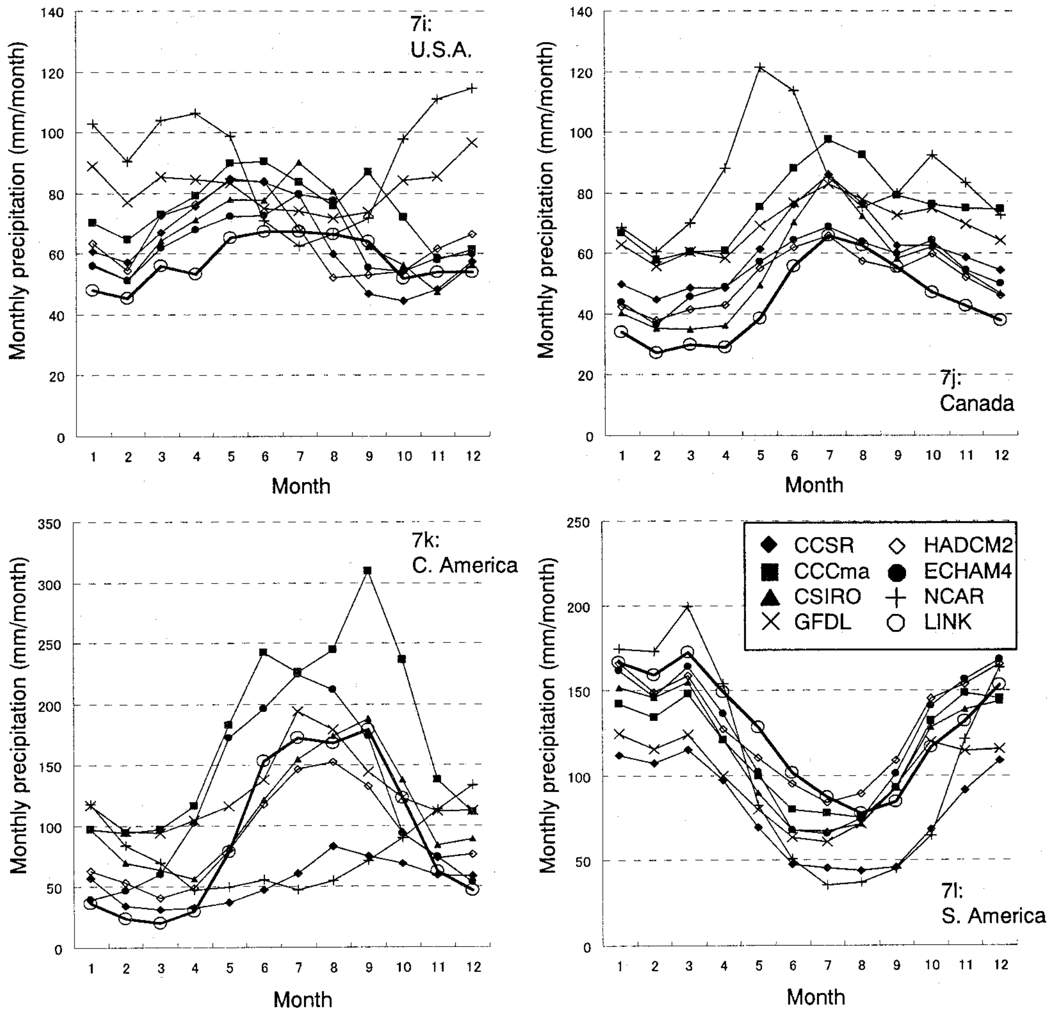
Fig. 6 Deviation of 30-year-normal monthly precipitation against 30-year-normal annual precipitation



Figs. 7a-7b 30-year-normal monthly precipitation in each region



Figs. 7c-7h 30-year-normal monthly precipitation in each region



Figs. 7i-7l 30-year-normal monthly precipitation in each region

reproduced the observed values comparatively worse than the other models. It was confirmed in many cases that using the median of the calculation results of many climate models is effective in constructing scenarios. Intra-annual fluctuations at a monthly level can be estimated well for surface temperature, whereas many of the regions or models are insufficient with regard to precipitation. It was also found that the results of control-run provide information on future changes in inter-annual fluctuations that can be trusted to a certain extent.

Surface temperature and precipitation were set as the targets for assessment in this study, and the models were evaluated by focusing on several criteria. In order to evaluate the suitability for the use of impact study more precisely, reproducibility of other parameters such as dew-point temperature and wind speed also should be investigated in future.

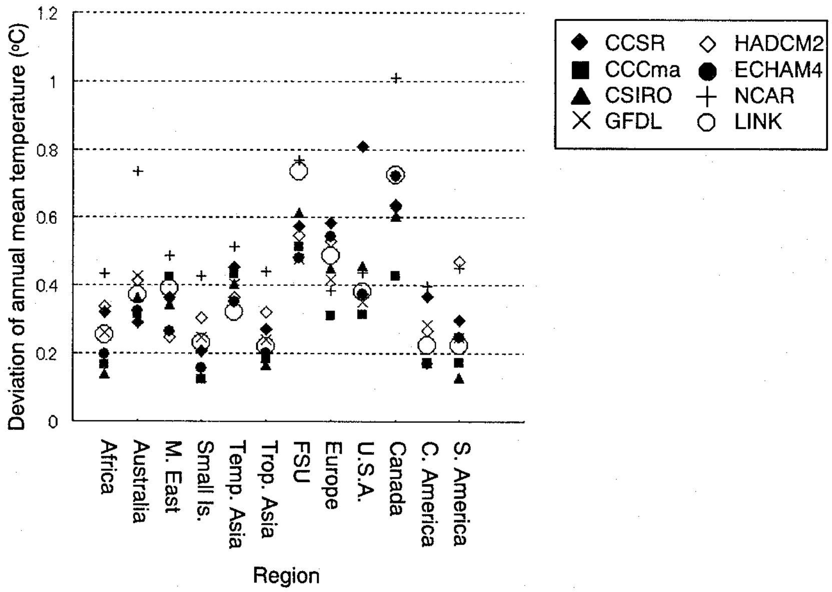


Fig. 8 Deviation of the annual mean temperatures (1961 to 1990) against the 30-year-normal annual mean temperature

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