Mesh Climate Change Data for Evaluating Climate Change Impacts in Japan under Gradually Increasing Atmospheric CO₂ Concentration

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Abstract

General circulation models (GCMs) that can simulate global climate are used to predict climate changes caused by an increase in atmospheric CO₂ concentration. However, the spatial resolutions of currently running models are rough with a resolution of about 3° to 6° in latitude/longitude. Thus, reducing the relatively large-scale climatic states that the GCM provides to smaller-scale ones is required to evaluate impacts of climate changes on agriculture and natural ecosystems at local and regional scales. We constructed a dataset, namely the mesh climate change data of Japan, using the inverse distance weighted interpolation against coupled atmosphere-ocean GCMs' (A-O GCMs) experiment results under gradually increasing atmospheric CO₂ concentration. The A-O GCMs used in this article are ECHAM4/OPYC3 (Germany), CGCM1 (Canada), CSIRO-Mk2 (Australia), and CCSR/NIES (Japan). The dataset gives the average climate change scenarios in Japan for every 10-year period over the next 100 years with a resolution of 7.5' in longitude and 5' in latitude (approximately 10 by 10 km). This article describes the construction method and contents of the dataset. In order to demonstrate the characteristics of the dataset, we examined the transient changes in spatial distribution of accumulated surface air temperature, accumulated precipitation, and mean short wave radiation during the months of May through September, corresponding with the major crop cultivation period in Japan.

Key words: Downscaling, Global warming, Mesh climate change data, Transient climate change scenario.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has reported that global agricultural production could be maintained relative to baseline production in the face of climate changes likely to occur over the 21st century but that regional impacts would vary widely (IPCC, 1996; 1998). Since the reports were released, the significance of regional impact assessments has increased and many studies have been done (e.g. Matthews *et al.*, 1997; Luo and Lin, 1999). We should take stock of the current state

of knowledge regarding potential climate change and consider actions and policies for adapting to the changes.

While there is scientific consensus that increased atmospheric concentrations of greenhouse gases will likely raise global temperatures, with increasing global precipitation and rising sea levels, there is no consensus on how quickly and how much the climate may change, on how different regions may experience the change, or on how the variability (as well as the mean values) of climatic conditions may change. To cope with the uncertainties, different types of climate change scenarios have been used for the assessment of the direction and magnitude of potential responses of agriculture at global and regional scales (Rosenzweig and Parry, 1994; Bachelet *et al.*,

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1995; Seino, 1995; Horie *et al.*, 1995). Climate change scenarios are defined as plausible combinations of future climatic conditions. The climate change scenarios are often derived from coupled atmosphere-ocean general circulation model (A-O GCM) experiments with specified forcing mechanisms (e.g. increasing concentrations of greenhouse gases and/or sulfate aerosols). Most climate change impacts studies, however, have been conducted by A-O GCM experiments under a doubled CO₂ equilibrium condition. These are based on simulation outputs that assume a step change in greenhouse gas content and a corresponding abrupt change to a new equilibrium climate. In reality, however, climate change is evidently being forced by a gradual increase in greenhouse gas concentrations. Therefore, a transient A-O GCM experiment is considered to be a more realistic representation than the equilibrium experiment. A transient A-O GCM experiment is one in which climate change occurs gradually over time and is used to simulate the response of the climate system to a continual rise of greenhouse gas concentrations (IPCC, 1996; 1998). Considering the fact that there are large uncertainties among climate change scenarios, we should compare and evaluate different types of climate change scenarios over space and time for a full risk assessment of climate change impacts (Lal and Harasawa, 2001).

Recently, the IPCC Task Group on Scenarios for Climate Impacts Assessments archived results of various A-O GCM experiments at the IPCC Data Distribution Center (IPCC-DDC) to form the basis for assessing climate change impacts (IPCC-DDC, 1999). The data are available through the Internet (<http://ipcc-ddc.cru.uea.ac.uk> and <http://www.dkrz.de>). We retrieved four results of seven different transient A-O GCM experiments out of the IPCC-DDC Web site and constructed the mesh dataset, which we called mesh climate change data of Japan. This dataset describes the regional climate change in Japan for every 10-year period over the next 100 years using a linear interpolation method. In this article, we describe the construction and characteristics of the mesh climate change data of Japan.

2. Data and Method

2.1 GCM scenarios

The IPCC Task Group on Scenarios for Climate Impacts Assessments defined a set of specific criteria

that have been used to identify A-O GCM experiments of climate change whose results could be archived at the IPCC-DDC (1999). The set of criteria includes the following:

- IPCC IS92a-type emission scenario (IPCC, 1996): greenhouse gas forcing increasing 1% per year from 1990
- Well-documented models: easily accessible to references about model's structure and performance
- Models that have participated in AMIP/CMIP (standard experimental protocol for atmospheric general circulation models)
- Integrations without/with aerosols and that go up to 2100 for greenhouse gas only
- Historically-forced integrations: the increase in greenhouse gases is based on the historical records until 1990
- Integrations with results available now and with data located in the public domain

The IPCC-DDC currently archives the results of seven A-O GCM experiments. Accounting for the climate sensitivity of each model, we here used four different results of A-O GCM experiments. The climate sensitivity of a model refers to the long-term change in global mean temperature under doubling of atmospheric CO₂ concentration. The institutions in which each model was developed are as follows:

- Deutsches Klimarechenzentrum (DKRZ), Germany: ECHAM4/OPYC3

The ECHAM4 is an atmospheric general circulation model developed at the European Centre for Medium-Range Weather Forecasts (ECMWF) (Roeckner *et al.*, 1992). The OPYC3 is an ocean general circulation model developed at the Max Planck Institute for Meteorology (Oberhuber *et al.*, 1998). The climate sensitivity of ECHAM4/OPYC3 is about 2.6°C, which is at the low end of the range of sensitivities among models archived in the IPCC-DDC.

- Canadian Centre for Climate Modelling and Analysis (CCCma), Canada: CGCM1

The Canadian Global Coupled Model (CGCM1) is the first version of the coupled model developed at the Canadian Centre for Climate Modelling and Analysis. Its control climate is described by Flato *et al.* (2000). The climate sensitivity of CGCM1 is about 3.5°C.

- Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia:

CSIRO-Mk2

The model CSIRO-Mk2 was developed at the CSIRO Atmospheric Research Institute (Hirst *et al.*, 1996). The climate sensitivity of CSIRO-Mk2 is about 4.3°C (Watterson *et al.*, 1997), which is at the high end of the range of model sensitivities.

- Center for Climate System Research (CCSR) and National Institute of Environmental Studies (NIES), Japan: CCSR/NIES

This is a coupled ocean-atmosphere model consisting of the CCSR/NIES atmospheric GCM, the CCSR ocean GCM, a thermodynamic sea-ice model, and a river routing model (Emori *et al.*, 1999). Climate sensitivity of the CCSR/NIES model derived by equilibrium runs is estimated to be 3.5°C.

The characteristics of the models are also summarized in Table 1. More details on the models and references on the simulation results can be found at the Web sites given above. The full sets of results from the transient experiments as well as their control runs are available from the archive. The data is bundled in files holding the monthly mean values of one climatic element averaged for 10 years. We sampled only a single future forcing scenario, i.e. 1% per year growth in equivalent CO₂ concentration. The use of increases in CO₂ as a surrogate for the effect of other greenhouse gases is referred to as equivalent CO₂. The configurations of grid points used in the atmospheric GCMs around Japan islands are shown in Fig. 1. We used these grid point data for the interpolation to construct the dataset.

2.2 Interpolation method

Although computing power has substantially increased during the last few years, the horizontal

resolution of present-day A-O GCMs is still too coarse to provide information suitable for climate change impacts assessment studies at local and regional scales. So-called downscaling techniques have subsequently emerged as a means of bridging the gap between what A-O GCMs can currently provide and what impact assessment studies require (for review, Wilby and Wigley, 1997). An example used for an agricultural study is Wilks (1989), who developed a regression formula to predict regional distributions of climatic elements in the Great Plains of the United States from a time series of large-scale averages.

We here adopted the inverse distance weighted interpolation of deviation as a linear downscaling method together with a baseline climate data. The method is similar to that for estimating meteorological elements of arbitrary points from observed ones (Seino, 1993). As the baseline climate data, we used the second order mesh climatic data with a resolution of 7.5' in longitude and 5' in latitude (approximately 10 by 10 km). The data includes the monthly values for five climatic elements: mean, maximum, and minimum surface air temperatures (°C), precipitation (mm), and short wave radiation (MJ/m²). These data were constructed by re-sampling the third order mesh climatic data of Japan with approximately 1 by 1 km resolution (Okamura, 1987; Masatsuka *et al.*, 1988). We made interpolation of each GCM experiment results using the baseline mesh climatic data.

The procedure is as follows:

- For a target grid point of the baseline climate data, find the four nearest neighboring grid points among the A-O GCM's grid points (Fig. 1).

Table 1. Characteristics of coupled GCM experiments.

Model name	Resolution of AGCM	Resolution of OGCM	CO ₂ concentration for control run	Forcing scenario	Climate sensitivity at doubled CO ₂
ECHAM4/OPYC3	2.8° × 2.8°	2.8° × 2.8°	354 ppmv	Historical ^{a)} + 1% yr ⁻¹ compounded	2.6°C
CGCM1	3.7° × 3.7°	1.8° × 1.8°	295 ppmv	Historical ^{b)} + 1% yr ⁻¹ compounded	3.5°C
CSIRO-Mk2	3.2° × 5.6°	3.2° × 5.6°	330 ppmv	Historical ^{c)} + 1% yr ⁻¹ compounded	4.3°C
CCSR/NIES	5.6° × 5.6°	2.8° × 2.8°	345 ppmv	Historical ^{d)} + 1% yr ⁻¹ compounded	3.5°C

^{a)} Historical greenhouse gas forcing from 1860 to 1990.

^{b)} Historical greenhouse gas forcing from 1850 to 1990.

^{c)} Historical greenhouse gas forcing from 1880 to 1990.

^{d)} Historical greenhouse gas forcing from 1890 to 1990.

- Make deviation of a climatic element Δd_j at the j -th grid point between the A-O GCM's control run and CO₂-increase run at the same time slice, e.g. the decade, 2060s. The deviation is defined as the difference, $\Delta d_j = X_{\text{increase}}^j - X_{\text{control}}^j$ for temperature, and the ratio, $\Delta d_j = X_{\text{increase}}^j / X_{\text{control}}^j$ for precipitation and short wave radiation, where X 's represent the values of climatic element.
- Interpolate the deviation of a climatic element using the inverse distance weighted method:

$$d = \frac{\sum_{j=1}^4 (\Delta d_j / R_j)}{\sum_{j=1}^4 (1/R_j)},$$

where R_j is the distance along a geodetic line from the A-O GCM's j -th grid point to the target grid point of the baseline climate data.

- Superimpose the interpolated deviation of climatic element, d , onto the climatic element of target grid point, x_{baseline} , to get the climate-changed value of

the climatic element, x_{changed} , i.e. $x_{\text{changed}} = x_{\text{baseline}} + d$ for temperature, $x_{\text{changed}} = x_{\text{baseline}} \times d$ for precipitation and short wave radiation.

The use of deviations for the interpolation, i.e. differences and ratios of results between control run and CO₂-increase run, may be appropriate for adjusting baseline climate (representing the current climate condition) with that by control runs of different A-O GCMs, and eliminating the intrinsic differences of each model, e.g. the simulated long-term climate changes irrelevant to greenhouse effects. However, it should be noted that the deviation defined as ratio depends on time scale. By repeating the above procedure over all the grid points of the second order mesh climatic data, we are able to get data describing regional climate change with the same resolution as the second order mesh climatic data. We named the resulting data the 'mesh climate change data of

Fig. 1. Configuration of grid points used in each of A-O GCMs.

Japan'. The mesh climate change data of Japan developed here describes average climate change in Japan for every 10-year period over the next 100 years for each of the A-O GCM scenarios.

3. Transient Changes in Agro-Climatic Resources

In order to demonstrate the characteristics of the mesh climate change data of Japan, we examined geographical distribution of changes in accumulated surface air temperature, accumulated precipitation, and mean short wave radiation during the months of May through September, which correspond to the cultivation periods for major crops in Japan. Values were plotted only for meshes including more than 100 ha of paddy fields, which are the main type of cropland in Japan. Meshes filled with black color represent the other land covers, e.g. forests, and grasslands. We also examined area-averaged monthly mean projected values, surface air temperature, precipitation, and short wave radiation, for the decade 2060s. Japan islands have been divided into eight areas depicted in Fig. 2. The monthly values were averaged over each area.

3.1 Surface air temperature

Figure 3 shows geographical distributions of changes in accumulated surface air temperature during the months of May through September under the climate change derived from four A-O GCMs. The maps depict the ratio of the value under the climate change to that of baseline climate data for

three decades 2020s, 2040s, and 2060s. In general, the projected accumulated surface air temperature monotonically increases over Japan. The rise in surface air temperature is likely to be most pronounced in the northern area. The ECHAM4/OPYC3 model projected an increase in accumulated air temperature of more than 20% in Hokkaido and Tohoku for the decade 2060s compared to baseline climate. Under current climate, the northern limit areas of rice cultivation extend the west and east parts of Hokkaido, in which the accumulated surface air temperature is about 2,500°C days (Uchijima, 1962). Approximately, 3,500°C days corresponds to the northern limit areas of double cropping of rice plants, which extend from the southern coast of Kinki and Shikoku to the eastern coast and southern part of Kyushu (Uchijima, 1962). The mesh climate change data projected that the accumulated surface air temperature would be more than 4,000°C days in the southern part of Kanto, Tokai, and Kyushu for the decade 2060s. From Fig. 4, it is projected that the area-averaged monthly mean surface air temperature would be more than 28°C during the summer in Kyushu and Shikoku areas for the decade 2060s. This would raise up the high temperature injury risks for crop cultivation with current cultivars (Hayashi *et al.*, 2001).

3.2 Precipitation

The geographical distributions of changes in accumulated precipitation during the months of May through September are shown in Fig. 5. The time and spatial changes are quite different among climate change scenarios. The CCSR/NIES model projected an increase in accumulated precipitation of more than 20 to 50%, especially in the western areas for the decade 2060s. The accumulated precipitation in the southern parts of Shikoku and Kyushu is predicted to be more than 3,000 mm by the 2060s. Furthermore, area-averaged monthly precipitation is predicted to be over 700 mm in June or July in Kyushu area, suggesting an increase in the risk of flood occurrence (Fig. 6). On the other hand, in the northern part of Japan, the projected increases in precipitation are not so high. The CSIRO-Mk2 and ECHAM4/OPYC3 models projected a decrease in precipitation in the Hokkaido area for the decades 2040s and 2060s.

3.3 Short wave radiation

The projected changes in mean short wave radia-

Fig. 2. Eight areas in Japan islands.

tion during the months of May through September are given in Fig. 7. The decreases in short wave radiation were pronounced under climate change except for the CSIRO-Mk2 projection. This partly reflects the negative correlation between precipitation and incoming radiation (Fig. 8). The change in precipitation intensity, from low to high, due to climate change also leads to such a decrease. Three models projected 5 to 10% decrease of mean short wave radiation for the decades. Specifically, the ECHAM4/OPYC3 model projected a large decrease in area-averaged monthly precipitation in September (Fig. 8).

4. Concluding Remarks

We constructed mesh climate change data of Japan for the evaluation of regional impacts of climate change on agricultural activities in Japan. Based on four A-O GCMs' transient experiment results under gradually increasing atmospheric CO₂, we conducted the inverse distance weighted interpolation for monthly climate elements, i.e. mean, maximum, minimum temperatures, precipitation, and short wave radiation, with second order mesh resolution. We also examined spatial and temporal changes of agro-climatic resources and differences in regional response of the resources to climate change.

The mesh climate change data of Japan includes only monthly climatic elements averaged for 10 years. We did not provide estimates of changes in inter-daily and inter-annual climate variability, which potentially can have a large influence on climate change impact studies, especially on agriculture (e.g. Mearns *et al.*, 1997). The expansion of the data in time scale could be done by use of such a weather generator (e.g. Richardson, 1981).

This dataset is now being used for evaluation of changes in rice crop productivity (Hayashi *et al.*, 2001), prevalence of plant disease (Yamamura and Yokozawa, 2002), water resources, vegetation pattern and other climate-influenced phenomena in Japan. Their research results will be reported elsewhere. This dataset is available from the authors upon request. It can be provided as text format files in CD-ROM or Magneto-optical disk (MO).

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Fig. 3. Geographical distributions of changes in accumulated temperature during the months of May through September; the ratio of the value under climate change to that of baseline climate for the decades 2020s, 2040s, and 2060s. Meshes are plotted only for ones including more than 100 ha of paddy fields. Meshes filled with black color represent other land covers.

Fig. 4. Area-averaged monthly mean air temperature for the decade 2060s.

Fig. 5. As in Fig. 3. Accumulated precipitation.

Fig. 6. As in Fig. 4. Monthly precipitation.

Fig. 7. As in Fig. 3. Mean short wave radiation.

Fig. 8. As in Fig. 4. Monthly mean short wave radiation.

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大気 CO₂ 濃度漸増時の気候変化が日本へ及ぼす影響評価のための 気候変化メッシュデータ

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要 約

大気中の CO₂ 濃度上昇に伴う気候変化の予測には、地球の気候をシミュレートする大気・海洋循環結合モデル (A-O GCM) が用いられている。しかしながら、現在稼働しているモデルの空間分解能は緯度・経度方向ともに 3° から 6° 程度と粗く、温暖化が農業および自然生態系へ及ぼす影響の評価には、A-O GCM が出力する大スケールの気候状態を小スケールの気候状態へ還元したデータが必要である。我々は、距離の逆数で重み付けした線形内挿法を、最新の A-O GCM による温暖化シナリオに適用して、日本付近の気候変化を表すメッシュデータ (気候変化メッシュデータ) を作成した。使用した温暖化シナリオは、ECHAM4/OPYC3 (ドイツ),

CGCM1 (カナダ), CSIRO-Mk2 (オーストラリア), CCSR/NIES (日本) の A-O GCM によるものである。気候変化メッシュデータは、経度方向 7.5°, 緯度方向 5° (約 10 km 四方) の空間分解能で、将来 100 年間における 10 年ごとの平均的な気候変化を表している。本文では、気候変化メッシュデータの作成方法とその内容について述べ、その特徴を示すために、主要作物の栽培期間に相当する 5 月から 9 月までの積算気温、積算降水量、および平均日射量の空間分布の過渡的变化を図示した。

キーワード: 温暖化、過渡的気候変化シナリオ、気候変化メッシュデータ、ダウンスケーリング