Influence on Rice Production in Japan from Cool and Hot Summers after Global Warming

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Abstract

A cool summer seriously damages rice production in Japan under the present climate. On the other hand, an extremely hot summer may reduce production because of heat stress during the flowering period in a post-global warming climate. Reliable impact projections are required to grasp the hazards of production variability. However, accuracy limitations of the General Circulation Model (GCM) products obstruct impact projections in a particularly extreme year. A new dynamic downscaling method is suggested by the current study, which contributes to estimating a higher-resolution climate from GCM products while reducing the GCM bias. The bias means the difference between the simulated value and observations, and is the most serious factor in decreasing the reliability of impact projections. This study aims to show the difference in (1) the region-scale climate change and (2) the influence on rice production between a cool summer year and a hot summer year after global warming. A Regional Climate Model (RCM) downscales the change in climate over Japan based on GCM products under the Special Report for Emission Scenario-A2 scenario. Simulated changes in daily maximum/minimum temperatures, daily total solar radiation and monthly total precipitation vary depending on the target month and the area. Crop model simulations show that climate changes reduce the damage caused by a cool summer throughout Japan. On the other hand, climate changes enhance the damage caused by heat stress in central to southwestern Japan, but the damage is not found in northern Japan even in a hot summer year. As the result of global warming, the damage to yield from a cool summer is mitigated; however, damage from heat stress is enlarged in a post-global warming climate.

Key words: Dynamical downscaling, Global warming impact, Japan, Regional climate model, Rice model

1. Introduction

Rice production may change as a result of global warming. Rice is a staple crop in eastern and south-eastern Asia, the most populous areas in the world. Impact projections on rice production are important in relation to food security for these areas. Reliable projections work as an early warning and contribute to the investigation of mitigation and adaptation techniques. In particular, Japan is one of the suitable countries for which to establish impact projection methods for paddy rice because of the reliable accumulation of data, i.e.,

phenological data, socio-economic data related to production infrastructure and dense observational weather data. The established projection methods may be applied to other Asian countries as well to Japan.

Most impact projections on rice growth and production in Japan are based on the IS92A scenario. The scenario is presented in the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (AR2; IPCC, 1996). Several early studies use other simple climate projections instead of the IS92A scenario, such as Seino (1993) and Yonemura *et al.* (1998).

Toritani *et al.* (1999) shows that the rice growth period shortens in the current major source area and

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that the cultivable rice area shifts northward until the year 2100. These results are based on climate projections of the Meteorological Research Institute-Coupled General Circulation Model (MRI-CGCM; Tokioka *et al.*, 1995). Horie *et al.* (1995a) and Nakagawa *et al.* (2003) show that the mean rice yield during the 2090s increases in northern Japan and decreases in southwestern Japan. Nakagawa *et al.* (2003) also shows that the inter-annual variability of rice yield during the 2090s changes significantly compared with that under the present climate condition. Their results are based on four CGCMs products; i.e., the Center for Climate System Research and the National Institute of Environmental Studies, Japan (CCSR/NIES; Emori *et al.*, 1999); the Canadian Center for Climate Modeling and Analysis, Canada (CGCM1; Flato *et al.*, 2000); Australia's Commonwealth Scientific and Industrial Research Organisation, Australia (CSIRO-Mk2; Watterson *et al.*, 1997); the European Center for Medium-Range Weather Forecasts and the Max Plank Institute for Meteorology, Germany (ECHAM/OPY3; Roeckner *et al.*, 1992; Oberhuber *et al.*, 1998). The above four General Circulation Model (GCM) products are downscaled by the interpolation technique in Yokozawa *et al.* (2003). Simply, these downscaled climate projections express climate changes by the addition or multiplication of climatological mean differences between the CO₂ increase run and the control run of the GCMs to the observational climate datasets. Thus, the climate projections are limited in analyzing extreme years and inter-annual variability. Therefore, impact projections are still under development when subject to inter-annual variability and extreme years after global warming; i.e., the hot summer year and the cool summer year.

Antecedent impact projection studies only use the climatological mean condition in the future and present due to reliability limitations of GCMs. However, new dynamical downscaling methods are suggested to increase the reliability of GCM products, such as in Sato *et al.* (2006) and Misra and Kanamitsu (2004). They also use the GCM anomalies between the future and the present to reduce the GCM bias. Additionally, they estimate the regional-scale climate change by using a Regional Climate Model (RCM). In particular, the method suggested by Sato *et al.* (2006) allows us to estimate the regional-scale climate change in respective years. A new dynamic downscaling method has several limitations according to the use of clima-

tological anomalies in the GCM and the capability of RCMs. For example, the method does not account for changes in inter-annual variability of future climates. Nevertheless, the method provides useful information for impact projection studies, such as changes in the spatial pattern of climate elements.

This study aims to show the difference in (1) the regional-scale climate change and (2) the influence on rice production between the cool summer year and the hot summer year after global warming.

2. Models and Numerical Experiments

2.1. Regional climate model and climate simulations

We adapted a RCM (TERC-RAMS); the TERC-RAMS is a version of the Regional Atmospheric Modeling System (RAMS) modified by the Terrestrial Environmental Research Center, University of Tsukuba (Yoshikane and Kimura, 2003; Sato and Kimura, 2005; Sato *et al.*, 2006). The original version of the RAMS was developed at Colorado State University (Pielke *et al.*, 1992). The RCM includes the physical schemes and parameterizations summarized in Table 1 and has a two-way nested grid system as shown in Fig. 1. The coarse grid system entirely covers eastern Asia with 120 km grid intervals; otherwise, the fine grid system entirely covers Japan, except for the southeastern islands, with 30 km grid intervals. Both grid systems include 30 vertical layers in the terrain following coordinate system. The lowest layer is located 110 m up from the screen height.

The role of the RCM is to reproduce the present climate and to project the regional-scale climate in the 2070s based on the GCM products under the Special Report on Emission Scenario (SRES; IPCC, 2000) -A2 scenario. Additionally, the RCM projects a regional-scale climate change as a result of the simulated future climate and the present climate. The MRI-CGCM2 (Yukimoto *et al.*, 2001) products were adapted in this study. The GCM products are referred to as climate projections by the IPCC Third Assessment Report (IPCC, 2001).

We conform to a new dynamical downscaling method suggested by Sato *et al.* (2006). The method was developed to estimate the regional-scale climate change while preventing a GCM bias. The GCM bias is the most serious issue for projection of regional-scale climate based on the GCM products (Sato *et al.*, 2006; Misra and Kanamitsu 2004). And, the GCM bias also

Table 1. The calculation condition of the RCM

Horizontal grid system:
Coarse grid system: 50×50, 120 km grid interval, centered on 137.0°E, 38.5°N
Fine grid system: 62×62, 30 km grid interval, centered on same with above
Vertical layer: 30 layers, 110 m thickness in lowest layer
Soil layer: 11 layers
Vegetation type: Short grass
Sea surface temperature: Monthly mean SST (Reynolds <i>et al.</i> , 2002)
Start time: 24 hour before the 1st day each month for every integrations
Dynamical process:
Nonhydrostatic equations
Terrian following coordinate system
Physical process:
Radiation: (Nakajima <i>et al.</i> , 2000)
Cumulus convection: (Arakawa and Schubert, 1974)
Cloud microphysics: (Walko <i>et al.</i> , 1995)
Surface process: (Louis, 1979)
Soil model: (Tremback and Kessler, 1985)

influences the reliability of impact projections through the response model.

The RCM boundary condition is given as the following process when the RCM projects a climate condition in the 2070s. The warming components of GCM are given as the monthly mean 10-year mean difference of climate variables between the control run (1991 to 2000) and the SRES-A2 scenario run (2071 to 2080) simulated by MRI-CGCM2. The warming components of the GCM include wind speed and temperature, geopotential height, specific humidity, and sea surface temperature (SST). The warming components of GCM are loaded on the time series of reanalysis data and the SST data, time independently. The reanalysis data is produced by the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR). The numerical experiment is named as the "Clim.warming-run". By using the composite of reanalysis data and the warming component of GCM in the Clim.warming-run, the synoptic condition of the simulated future year is very similar to that of the specific present year. Therefore, the simulated future year is called "pseudo-year", and means a year after global warming that has very similar synoptic conditions to the present year.

The RCM uses the reanalysis data and monthly mean SST (Reynolds *et al.*, 2002) as the boundary conditions when the RCM reproduces the present climate. The reanalysis data is six-hourly NCEP/NCAR reanalysis. The numerical experiment corresponds to the "hind-

Fig. 1. The domains of grid systems in the RCM. The shade shows the topography in the RCM with contour for each 100 m.

cast" and is named the "Clim.present-run".

The hindcast and the projection were carried out for the two extreme years (i.e., 1993 and 1994), respectively. The two years represent a typical cool summer year and a typical hot summer year in eastern Asia (Suh and Lee, 2004) in the 1990s.

RCMs have the climate-model bias as well as GCMs. The RCM bias is also a serious issue when the global warming impact is projected using the RCM products. Thus, we prepare the warming component of RCM as the differences between Clim.warming-run and Clim.present-run. The warming component of RCM

includes temperature, downward short wave radiation, and precipitation. The warming components of RCM are added to the grid point value of observational datasets. The observational datasets are given by the Automated Meteorological Data Acquisition System (AMeDAS) as provided by the Japan Meteorological Agency. And, the value of AMeDAS is interpolated to the grid points of the second coordinate of the Digital Numerical Land Information (DNLI) with temperature adjustments reflecting altitude. The Ministry of Land, Infrastructure and Transportation of Japan provides the DNLI. The grid interval of the DNLI is 5.0 minutes in latitude and 7.5 minutes in longitude (approximately 10 km×10 km). We assumed the processed datasets as the future climate datasets. The datasets are named the “adjusted climate projection”.

2.2. Rice model and potential rice yield simulations

A crop model for rice (SIMRIW) was adapted. The SIMRIW (SIMulation Model for RICE and Weather-relationship; Horie *et al.*, 1995a, Nakagawa *et al.*, 2003) estimates potential rice growth and yield under the assumption of an irrigated paddy field and good management of nutrients, pests and diseases. The SIMRIW has adequate capability to reproduce the inter-annual variability and the spatial distribution of rice yield in Japan (Horie 1995a, Nakagawa *et al.*, 2003).

The SIMRIW detail is amplified by Horie *et al.* (1995b). Here, we overview the parameterization regarding yield formation suggested by above mentioned work of Horie *et al.* The constituent elements of parameterization will be shown as a result of the rice model simulations for diagnosing the rice response to climate change.

The potential yield (PY) means the potential dry weight of brown rice in this study. The potential dry weight of brown rice is a function of the total dry weight including roots at maturity day (W_t) and the harvest index (h), as follows:

$$PY = hW_t \quad (1)$$

The harvest index takes account of two types of spikelet sterility; i.e., that due to a cool temperature (h_c) and that due to a high temperature (h_h) during the flowering period. The more influential value is adapted as the h in the model.

The harvest index (h_c) is given as the following function when the harvest index corresponds to stress from cool temperatures:

$$h_c = h_m (1 - \gamma_c) \left\{ 1 - \exp \left[-K_h (DVI - 1.22) \right] \right\} \quad (2)$$

where h_m is the maximum harvest index of the given cultivar and K_h is an empirical constant. The maximum harvest index of the given cultivar is obtained under optimum conditions for air temperature, solar radiation, nutrients, pests and diseases. The DeVelopment Index (DVI) represents the alternation of the crop stage in the range of 0 to 2. The DVI means the heading day, approximately same as the flowering day, when its value reaches 1. The DVI means the maturity day when its value reaches 2. The ratio of sterile spikelets as a result of the damaged caused by a cool summer (γ_c) is approximated as follows:

$$\gamma_c = \gamma_0 - K_q Q_t^a \quad (3)$$

where γ_0 , K_q and a are empirical constants. The cooling degree-days Q_t is given as a function of daily mean temperature (T_i) during the period when rice panicles are most sensitive to cool stress. The time period is defined by the DVI and ranges from 0.75 to 1.20. Thus Q_t is given as follows:

$$Q_t = \sum (22 - T_i) \quad (0.75 \leq DVI \leq 1.20) \quad (4)$$

Rice yield is also damaged by high temperature during the flowering period. The harvest index (h_h) is given by the following function when the harvest index corresponds to heat stress. The parameterization is suggested by Nakagawa *et al.* (2003).

$$h_h = h_m (1.00 - 0.95\gamma_h) \quad (5)$$

$$\gamma_h = \begin{cases} \left[\left(\frac{\overline{T_{\max}} - T_b}{T_o - T_b} \right) \left(\frac{T_c - \overline{T_{\max}}}{T_c - T_o} \right)^{\frac{T_c - T_o}{T_o - T_b}} \right]^\alpha, & \text{for } T_{\max} > T_o \\ \gamma_h = 0, & \text{for } T_{\max} \leq T_o \end{cases} \quad (6)$$

where γ_h is the ratio of sterile spikelets as a result of heat damage to unity. $\overline{T_{\max}}$ is the daily maximum temperature averaged over the flowering period. T_b is the lower critical temperature for rice growth. T_o is the optimum daily maximum temperature during the flowering period. T_c is the upper critical temperature. α is the curvature factor. We conform to Nakagawa *et al.* (2003), and we adapted the same values for the

above parameters; i.e., 10 and 43°C for T_b and T_c . α is also fixed at 4.77 and 12.78 for CO₂ concentrations below and above 550 ppm, respectively.

We also conformed to Nakagawa *et al.* (2003) with respect to the cultivars setting in each prefecture. Additionally, the initial values of leaf area index, DVI, initial dry weight and technical coefficient were regulated to fit the actual yield record, provided by the Ministry of Agriculture, Forestry and Fisheries of Japan. The rice model simulates at each grid point of DNLI, respectively, based on the given climate datasets. The climate datasets include the daily maximum/minimum temperatures and the daily total solar radiation. Precipitation is eliminated from the input elements because the accuracy of precipitation in the RCM products is quite low. However, a slight change in precipitation is not the critical factor in the irrigated paddy rice. Thus, not using precipitation does not spoil the reliability of our simulation results.

The rice model hindcasts the present yield when the model is based on a 330 ppm CO₂ concentration and observational climate datasets. The numerical experiment is named the “Yield.present-run”. The rice model projects the future yield when the model is based on a 550 ppm CO₂ concentration and the adjusted climate projection and this experiment is named the “Yield.warming-run”.

Despite its good capability, the SIMRIW has limited capability in climate acclimatization. The partial effect of climate acclimatization is included in the parameters regarding the phenology sub-model of the current model through the parameter optimization process. The current model implicitly considers the effect of climate acclimatization rather than explicitly. Thus, our simulation results have an uncertainty regarding the effect of climate acclimatization.

3. Results

3.1. Region-scale climate change over Japan as a result of global warming

Figure 2 shows the change in climate variables between the future and the present in the hot summer year, while Fig. 3 shows the same changes but for the cool summer year. These changes are derived from the results of the Clim.warming-run and the Clim.present-run. The following four changes in climate variables are shown as the warming components of the RCM: (a) the monthly mean daily minimum temperature (ΔT_{min}); (b) the monthly mean daily maximum

temperature (ΔT_{max}); (c) the monthly mean daily total solar radiation (ΔSR); and, (d) the monthly total precipitation ($\Delta Prec$).

In the cool summer year after global warming (pseudo-year 1993), the monthly mean daily minimum temperature increases by 0.0 to 4.5 K throughout Japan from May to October. The increase is remarkable in northern Japan.

The spatial patterns of the maximum temperature increase practically agree with those of the minimum temperature. And, the increase in the maximum temperature is smaller than that of the minimum temperature.

The change in the monthly mean daily total solar radiation varies depending on the month and the area. Radiation decreases in northern Japan and increases in southwestern Japan from June to July. However, radiation increases in all of Japan in August and decreases in May. For September and October, the changes in radiation depend on area.

The change in monthly total precipitation also varies depending on the month and the area. Precipitation increases slightly in part of northern Japan in June and July. Precipitation tends to decrease in western Japan in September and October and increases in most of Japan in May.

In the hot summer year after global warming (pseudo-year 1994), the monthly mean daily minimum temperature increases by 0.0 to 3.5 K throughout Japan in May. The minimum temperature increases 1.5 to 3.0 K from June to September, except for a greater increase in northern Japan. The minimum temperature increases by 2.0 to 4.0 K in October.

The monthly mean daily maximum temperature shows the same spatial pattern as that of the minimum temperature. However, the increase in the maximum temperature is less than that of the minimum temperature from May through October.

The monthly mean daily total solar radiation increases slightly in southwestern Japan and decreases in northern Japan from May to June. The radiation increases slightly over all of Japan from July to October, whereas the increase is less than 400 KJ/m².

The change in monthly total precipitation varies depending on the month. Precipitation increases by 0 to 150 mm/month throughout most of Japan in May, July, August and October. Precipitation decreases slightly throughout Japan in June except for the Sea-of-Japan area. Precipitation tends to decrease in northern Japan

Fig. 2. The warming components of the RCM (see in the Chapter 3.1) in the year with a hot summer.

Fig. 3. Same as Fig. 2 but the year with a cool summer.

Year with a cool summer

Year with a hot summer

Fig. 4. The percentage of change in the yield formation factors (see in the Chapter 2.2) in the year with a cool summer (left) and that with a hot summer (right).

and increases in southwestern Japan in September.

The temperature increase in the hot summer year is slightly greater than that for the cool summer year. However, the increase in temperature in the cool summer year is greater than that for the hot summer year in most target months in northern Japan. The minimum temperature increases are greater than the maximum temperature increases in both years. The changes in radiation are similar each year; i.e., radiation decreases in northern Japan from May to June but increases throughout Japan from July to October. Precipitation changes are different each year. Precipitation increases in southwestern Japan in May in the hot summer year and decreases in the cool summer year. Precipitation increases in most of Japan in May for both years. Precipitation changes show different spatial patterns

from June to October. Precipitation tends to increase in southwestern Japan in the hot summer year, and decreases in this area in the cool summer year.

3.2. Global warming impact on rice growth and yield in Japan

Figure 4 shows the percentage of simulated change in yield formation elements, such as (a) the potential yield (PY); (b) the averaged daily maximum temperature during the flowering period ($\overline{T_{\max}}$); (c) the spikelet sterility (γ_c in the cool summer year and γ_h in the hot summer year); (d) the harvest index (h); and, (e) the total dry weight at maturity (W_t). These yield formation elements are shown for the two years, respectively.

In the cool summer year after global warming (pseudo-year 1993), the potential rice yield increases 5 to 50 percent throughout Japan as a result of global

Fig. 5. The simulated changes in the total rice production in the year with a cool summer (a) and that with a hot summer (b). Figures 5c and 5d are same with 5a and 5b but area mean of potential rice yield in agricultural area.

warming. However, the potential yield remains the same as that under the present climate condition in northern Japan. The area mean average daily maximum temperature during the flowering period increases by 1.82 K, caused by an increase in the maximum temperature shown in Fig. 2. Spikelet sterility decreases by 50 percent in northern Japan and in the high altitude area of southwestern Japan as a result of a reduction in the damage from a cool summer. The change in the harvest index corresponds to the change in spikelet sterility. The harvest index increases in accordance with the decrease in spikelet sterility. The total dry weight of rice including roots increases throughout all of Japan.

In the hot summer year (pseudo-year 1994), the potential yield decreases by 5 to 20 percent in southwestern Japan. However, yield under the future climate

condition continues to increase 5 to 50 percent in northern Japan, compared to the increase under the present climate condition. The area mean average daily maximum temperature during the flowering period increases by 2.89 K, as a result of the increase in the daily maximum temperature from July to August. Spikelet sterility increases by 40 percent throughout Japan except for northern Japan and in the high altitude area of southwestern Japan, as a result of heat stress. The harvest index decreases by 5 to 20 percent, caused by an increase in spikelet sterility and an increase in the average maximum temperature during the flowering period. However, the harvest index shows either an increase in the northern Japan. The total dry weight of rice including roots remains the same under the present climate condition in most of Japan. However, the total dry weight continues to

increase in northern Japan.

Figures 5a and 5b show changes in total rice production in each agricultural area in the cool summer year and in the hot summer year. Figs. 5c and 5d are the same as Figs. 5a and 5b, but show mean rice yield. Total production is calculated assuming the same paddy acreage distribution as today. The land-use information is given by the DNLI.

In the cool summer year, the mean yield averaged over agricultural areas increases from 3.809 t/ha to 5.343 t/ha. The tendency for a yield increase is consistent across all areas, but the yield increase is significant in Hokkaido and Tohoku. Thus, the total production increases from 7.1×10^6 t to 12.3×10^6 t. On the other hand, in the hot summer year, the mean yield averaged over agricultural areas decreases from 4.990 t/ha in the present to 4.451 t/ha in a post-warming. Yield increases in Hokkaido, Tohoku, Kanto/Tozan, and Kyushu and decreases in Tokai, Kinki, Chugoku, and Shikoku. The yield in Kyushu, as well as the other areas in southwestern Japan (Fig. 4), is affected by the increase in spikelet sterility caused by heat stress. However, the summation of a slight yield increase in the mountainous area is greater than the summation of the decrease in the lowland area. As the result of the change in yield, total production decreases from 11.9×10^6 t in the present to 10.5×10^6 t in a post-warming.

4. Discussion

The regional-scale climate change is projected by the dynamical downscaling method. This method allows us to obtain climate data under global warming conditions in respective years; i.e., the hot summer year and the cool summer year.

The projected regional-scale climate condition shows that the daily maximum and minimum temperatures increase by 0.0 to 4.5 K throughout Japan. In our simulations, the temperature increase in the hot summer year is slightly greater than the increase in the cool summer year. The cool summer year and the hot summer year changes to one with a moderate or slightly hot summer under present climate conditions and to one with an extremely hot summer under future climate conditions, respectively. Additionally, the climate change projection is also obtained for solar radiation and precipitation. The projected climate variables maintain their inter-variable relationships under physical laws within the limits of the climate model. Thus, our climate data progresses in the above point

compared with the climate data obtained by variable-independent interpolation.

In the cool summer year, the monthly mean daily total solar radiation tends to increase slightly in most of Japan from July to August. These changes in climate conditions positively affect rice yield. The temperature increase obediently leads to an increase in the average maximum temperature during the flowering period. However, the daily maximum temperature increase remains moderate throughout Japan. Thus, the temperature increase causes a significant decrease in spikelet sterility in northern Japan, which has been suffering from damage caused by a cool summer in the present climate. Spikelet sterility decreases cause a direct increase in the harvest index. The total dry weight of rice including roots increases throughout Japan. As the result, the rice yield increases significantly in most of northern Japan as a result of a decrease in spikelet sterility. However, the yield increase is quite small in northern Tohoku and Hokkaido despite the decrease in spikelet sterility. In such areas, the damage due to a cool summer is found even in the year after global warming.

In the hot summer year after global warming, changes in climate conditions affect the rice yield both positively and negatively depending on the area. The average maximum temperature increase obediently causes an increase in the maximum temperature during the flowering period. The daily maximum temperature increase causes a significant increase in spikelet sterility in central to southwestern Japan, as a result of heat stress. The increase in spikelet sterility causes a direct decrease in the harvest index. The total dry weight of rice including roots remains the same as under the present climate. As the result, the rice yield decreases in central to southwestern Japan because of the increase in spikelet sterility due to heat stress. However, the maximum temperature increase does not reach a critical level. The temperature increase and a slight solar radiation increase lead to a yield increase in northern Japan even in the hot summer year after global warming.

Damage from a cool summer is the most serious damage factor for rice production in northern Japan. The hazard is expected to lighten as a result of the temperature increase due to global warming. However, we notice the possibility of cool summer damage even after global warming by considering the inter-annual climate variability with paddy rice acclimatized to

high temperatures. Additionally, the yield damage from heat stress is not found in southwestern Japan during the cool summer year after global warming. Yield damage by heat stress during the flowering period is expected to swell during the hot summer year after global warming. However, yield damage from heat stress is not found in northern Japan even in the hot summer year after global warming. These changes indicated that the hazard related to yield variability by climate condition shifts southward as a result of global warming.

5. Conclusion

This study updates the impact projection on rice production in Japan based on the dynamical down-scaled MRI-CGCM2 products under the SRES-A2 scenario. The newly suggested dynamical downscaling method makes it possible to project the regional-scale climate change over Japan, and also allows us to extend the discussion to rice production hazards in the cool summer year and in the hot summer year after global warming.

The projected regional-scale climate changes are summarized as follows:

- (1) The different changes in climate are found between the cool summer year and the hot summer year, although the boundary condition of the RCM in both years includes a common warming component of the GCM;
- (2) In the cool summer year after global warming, the monthly mean daily maximum/minimum temperatures increase by 1.0 to 4.5 K throughout Japan. Additionally, the monthly mean daily total solar radiation slightly increases in the summertime over Japan, whereas radiation decreases in northern Japan in June and July;
- (3) In the hot summer year after global warming, the monthly mean daily maximum/minimum temperatures increase by 0.0 to 4.0 K. The monthly mean daily total solar radiation shows an increase from July to October throughout Japan and a decrease in northern Japan from May to June.

The impact of region-scale climate changes on rice production is summarized as follows:

- (4) The impact of global warming on rice production is different between the hot summer year and the cool summer year, and also varies by area.
- (5) In the cool summer year after global warming, the temperature increase during the flowering period

causes a spikelet sterility reduction derived from the damaged caused by a cool summer in northern Japan. Spikelet sterility reduction reflects the increase in the harvest index and leads to an increase in yield. The yield damage caused by heat stress is not found because the temperature increase remains at a moderate level in southwestern Japan;

- (6) In the hot summer year after global warming, the temperature increase directly reflects the increase in the averaged daily maximum temperature over the flowering period. The temperature increase leads to a significant increase in spikelet sterility as well as a decrease in the harvest index. As the result, yield decreases in central and southwestern Japan while yield continues to increase in northern Japan;
- (7) The hazard for yield variability by climate condition shifts southward as a result of global warming. The major hazard in the present climate, i.e. damage caused by a cool summer, is reduced in northern Japan. On the other hand, heat stress is enhanced, and becomes a new serious hazard in central to southwestern Japan in the hot summer year.

Further study is required regarding estimating the change in frequency in the cool summer year and in the hot summer year after global warming based on GCM simulations. Another study is needed for impact projections based on the inter-annual variability simulated by the GCMs, as this study considers only the change in the mean climate and assumes that the inter-annual variability in the future climate is same as that in the present climate. Since our impact projection is based on one GCM, an ensemble of GCM products is required to improve the reliability of impact projection in future studies.

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温暖化後の冷夏と暑夏による日本の水稻生産への影響

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要 約

温暖化予測に用いられる大循環モデル(GCM: General Circulation Model)の出力値は、信頼性の限界から、既存の温暖化影響評価では気候値と比較せざるをえなかった。そのため、温暖化後の気候の極端年や年々変動による生産リスクの変化を把握することは重要であるにもかかわらず、その評価は困難であった。最近の研究で新たな力学的ダウンスケーリング手法が提案され、信頼性の低い影響評価を導く最大の要因の一つであるGCMバイアスを軽減しつつ、粗い空間解像度のGCM出力値から高い空間解像度の気候データを得ることが可能になった。本研究では、新たに提案された力学的ダウンスケーリング手法を用いて、温暖化による領域気候変化が、暑夏年と冷夏年で異なること、日本の水稻生産に対する温暖化影響がそれぞれの年で異なることを示す。領

域気候モデル(RCM: Regional Climate Model)によるシミュレーションの結果から、RCMの境界条件に加重したGCMの温暖化トレンドが同じであるにもかかわらず、日本付近の日最高・最低気温の上昇幅や日積算日射量の増減は暑夏年と冷夏年で異なることが示された。推定した領域気候変化に基づいた、水稻生育モデルによる数値実験結果は、温暖化後の冷夏年では現在気候下の冷夏年と比較して、日本全域で冷害による被害が軽減されることを示している。また、暑夏年では、日本の中央部から西日本の広い地域で高温障害による被害が増大するが、北日本では高温障害の被害が起きていないことが示された。

キーワード: 力学的ダウンスケーリング, 温暖化影響, 日本, 領域気候モデル, 水稻モデル