Climate Change Impact on Rice Insurance Payouts in Japan

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ABSTRACT
The authors constructed the framework for a preliminary assessment of climate change impact on the rice insurance payout in Japan. The framework consisted of various models ranging from climate projection downscaling, rice yield estimation, yield loss assessment, and rice insurance payout estimation. In this study, a simulation was conducted based on the dynamically downscaled regional climate projection with a lateral boundary condition given by the global climate projection of the Meteorological Research Institute Coupled General Circulation Model, version 2 (MRI CGCM2), under the A2 scenario of the Special Report on Emission Scenarios (SRES). Results indicated that rice yield in the 2070s will decrease slightly in central and western Japan and increase in northern Japan. The increase in yield was derived from a significant reduction in yield loss caused by cool-summer damage; on the other hand, the decrease in yield was caused by the increase in yield loss caused by heat stress and the shortening of the growth period induced by the temperature rise. The increase in the atmospheric CO2 concentration resulted in an increase in paddy rice biomass because of the fertilization effect; however, the increase in biomass was not enhanced much as a result of shortening of the growth period if early planting was not considered as an adaptation practice. Reflecting such changes in yield, the rice insurance payout significantly decreased in northern Japan but only slightly increased in the areas of central and western Japan. In total, the 9-yr mean payout in Japan in the 2070s decreased to 120.2 billion yen; the value corresponded to 87% of the payout averaged over 9 yr in the 1990s (1991–99).

1. Introduction

The rice yield may change as a result of changes in climate and the atmospheric carbon dioxide (CO2) concentration under climate change conditions induced by increasing anthropogenic greenhouse gas emissions (e.g., Baker et al. 1990; Horie et al. 1995; Ziska et al. 1997). Since rice is a staple crop in Southeast Asia and eastern Asia, including Japan, a reliable assessment of the impact of climate change on the rice yield is required to determine what countermeasures are available to mitigate the impacts and secure food security. From such a background, the impact of climate change on the rice yield in Japan has been assessed and updated in accordance with improvements in climate models, methods for climate projection downscaling, and crop models.

Early studies demonstrate the following impacts of climate change on rice growth and yield in Japan under the IS92a scenario performed for the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (Watson et al. 1996): the rice yield will decrease in southwestern Japan and increase in northern Japan (Horie et al. 1995; Nakagawa et al. 2003) based on four projections of general circulation models (GCMs), that is, the Canadian Centre for Climate Modelling and Analysis GCM, version 1 (CGCM1) (Flato et
al. 2000), Australian Commonwealth Scientific and Industrial Research Organisation Mark 2 GCM (CSIRO-Mk2) (Hirst et al. 1996), Japanese Center for Climate System Research and National Institute for Environmental Studies GCM (CCSR/NIES) (Emori et al. 1999), and German Max Planck Institute for Meteorology GCM (ECHAM4/OPYC3) (Roeckner et al. 1992; Oberhuber et al. 1998); the rice growth period will be shortened in current major source areas, and cultivable lands for rice will shift to the north (Toritani et al. 1999) according to the projection of the Meteorological Research Institute (MRI) CGCM (Tokioka et al. 1995).

In a current study, Iizumi et al. (2006) support these results on the basis of five projections under the A1B scenario of the Special Report on Emission Scenarios (SRES; Nakicenovic and Swart 2000), performed for the IPCC Fourth Assessment Report (Solomon et al. 2007).

As a result of the indication in the IPCC Third Assessment Report (TAR; Houghton et al. 2001) that the rising socioeconomic costs related to weather damage and to regional variations in climate suggest increasing vulnerability to climate change, it is important for policymakers to assess the impact of climate change on the economy as well as on rice growth and yield. Crop insurance payouts are especially vulnerable to climate change because of the potential for yield loss from weather disasters, diseases, and pests. The Japanese government provides crop insurance based on the agricultural loss compensation law (e.g., paddy rice insurance); such insurance contributes to farmer income stability in Japan (Yamauchi 1986). The Japanese government subsidizes more than 50% of the premium and bears a substantial part of the administrative costs of the insurance (Tsujii 1986). In addition, paddy rice farmers expect the insurance to protect them against climate risk now and in the future. Therefore, information regarding the possible impact of climate change on the rice insurance payout is of great interest to policymakers in Japan for determining future reform of the insurance system. Considering such circumstances, our objectives are to develop an appropriate framework for the impact assessment and to provide a preliminary assessment of climate change impact on the rice insurance payout in Japan on the basis of the climate projection in the 2070s under the SRES-A2.

2. Data and method

The constructed framework consisted of four parts (hereinafter referred to as “module”), shown in Fig. 1: 1) a module for climate projection downscaling that included a regional climate model (RCM) and dynamically downscaled a projection of GCM to provide a high-resolution regional climate projection. For this study, we used the global climate projection of the MRI CGCM2 (Yukimoto et al. 2001) submitted to the IPCC TAR (Houghton et al. 2001); 2) a module for rice yield estimation that included a simple process-based crop model for paddy rice. The module mechanically esti-
mated the phenological development and potential yield of paddy rice on the basis of a time series of daily climate datasets. In addition, this module also assessed the yield losses caused by cool-summer damage and heat stress in a process-based manner; 3) a module for yield loss assessment that consisted of empirical equations and statistically assessed yield losses caused by storms, diseases, and pests. The module was used to revise the estimated potential yield downward, since such yield losses were not simulated by the crop model included in the module for the rice yield estimation; and 4) a module for the estimation of rice insurance payout that simulated the insurance payout according to the aggregated yield loss and yield trend in an area.

The framework above was constructed for 46 local governmental areas in Japan (called prefectures) with the exception of the Okinawa Prefecture, which is located in the southwestern islands. The exclusion was due to the small size of the paddy field area in Okinawa Prefecture. In addition, we had fewer computational resources for the inclusion of the southwestern islands in the domain of the module for climate projection downscaling. The simulation result was aggregated for nine agricultural areas in Japan (Fig. 2) defined by the Ministry of Agriculture, Forestry, and Fisheries of Japan (MAFF), although simulations were conducted for each prefecture.

a. Module for climate projection downscaling

We used a version of the Regional Atmospheric Modeling System (RAMS; Pielke et al. 1992) modified by the Terrestrial Environmental Research Center, University of Tsukuba (TERC-RAMS) (Yoshikane and Kimura 2003; Sato et al. 2007) for this module. The RCM consists of nonhydrostatic equations and is available for a terrain-following coordinate system. For this study, we used the following physical processes: a radiation scheme by Nakajima et al. (2000), cumulus convection parameterization by Arakawa and Schubert (1974), cloud microphysics by Walko et al. (1995), surface processes by Louis (1979), and a soil scheme by Tremback and Kessler (1985). The coarse grid system covered most of East Asia with a 120-km grid interval, whereas the fine one covered Japan with the exception of the southeastern islands with a 30-km grid interval (Fig. 3). The 30 layers were set vertically, and the lowest one was 110 m above the screen.

We used the pseudowarming method suggested by Kimura (2005) as a dynamical downscaling method. The method was developed to estimate the regional climate change while preventing a GCM bias, which is a serious problem in regional climate projection (Sato et al. 2007; Misra and Kanamitsu 2004); such a system has already been implemented in Mongolia (Sato et al. 2007), Japan (Iizumi et al. 2007), and Turkey (Tanaka et al. 2006). In this method, the RCM used 6-hourly National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) and monthly mean sea surface temperature (SST) data (Reynolds et al. 2002) as lateral boundary conditions when it downscaled the current climate (so-called hindcast). On the other hand, when the RCM downscaled future climate projections, it used the linear composite of reanalysis data and the warming component between the 1990s and the 2070s in the global climate projection of the MRI CGCM2 as the lateral boundary conditions. The warming components for wind speed, temperature, geopotential height, specific humidity, and SST were given by the following four steps: first, the monthly mean data were calculated from the global climate projection of the GCM; second, the 10-yr mean data were provided by averaging the monthly mean data for both the 1990s and the 2070s; third, the warming component

FIG. 2. Agricultural areas in Japan.

FIG. 3. Domains of the regional climate model. Shading indicates topography contoured each 100 m.
was given as the difference in the monthly 10-yr mean data between the above two periods; fourth, the warming component was loaded on the time series of the reanalysis and SST time independently. Because of the above-mentioned steps, the lateral boundary conditions at which the RCM downscaled a future climate had a similar synoptic condition to that of a specific current year (thus, a year in the future is called a pseudoyear) although they included the 10-yr mean change in climate simulated by the GCM. Hindcast and climate projection downscaling were conducted for two 9-yr periods from 1991 to 1999 and the corresponding pseudoyears in the 2070s.

Regional climate models have a model bias, as do GCMs (e.g., Solomon et al. 2007; Mearns et al. 2003; Iizumi et al. 2007); thus, we used a composite of observational datasets and simulated change between the hindcast and downscaled projections to obtain the climate datasets for downriver modules. The observational datasets were provided by interpolating the data of the Automated Meteorological Data Acquisition System (AMeDAS) provided by the Japan Meteorological Agency (JMA) into the grid points with a 10-km grid interval (Table 1). The RCM-simulated changes were also interpolated in a similar manner. The interpolated RCM-simulated changes were added (multiplied) to the gridpoint values of the observational data for temperatures and wind speed (precipitation and insolation). Correction of the climate data was performed for the daily maximum and minimum temperatures, daily total insolation, and atmospheric CO₂ concentration. The original version considers a fertilization effect on biomass under an enriched atmospheric CO₂ condition assuming that the radiation conversion efficiency is given as a function of the atmospheric CO₂ concentration (Horie et al. 1995). Furthermore, the period from emergence to heading is shortened under doubled CO₂ concentration (Nakagawa et al. 1993); thus, the minimum number of days required for heading day is also given as a function of the atmospheric CO₂ concentration. Unfortunately, there is no direct comparison in a model performance between the original version of the SIMRIW and other major crop models [e.g., the Crop Estimation through Resource and Environment Synthesis (CERES) model (Hanks and Ritchie 1991)]. Seino (1995) reports that the CERES rice model (Godwin et al. 1990) accurately simulates the 13-yr average yield (1975–87) in Japan but fails to simulate the yield in specific years during the period. On the other hand, the original version of the SIMRIW shows good capability to simulate the historical variance in yield and their regional differences in Japan (Horie et al. 1995; Nakagawa et al. 2003); therefore, we believe that the SIMRIW has enough capability to simulate the growth and yield of irrigated paddy rice in Japan in comparison with other major crop models.

Conventional crop models, including the original version, assume a farm-field scale that is roughly several dozen meters, whereas the grid sizes of climate models are several dozen kilometers. Even though the climate projection was downscaled by the upriver module, the grid size of the regional climate projection was 10 km. Therefore, use of the large-scale crop model was required to reduce the errors relating to such a disagree-
ment in the spatial scale. Considering such circum-
stances, a modified version of the model was developed
for the prefectural scale while considering the funda-
mental processes of the original version (M. Yokozawa
et al. 2006, personal communication). The prefectural-
specific parameters were optimized for the modified
version using the datasets of the heading day and yield
and the daily time series of the area-mean climate on
paddy fields in a prefecture. The observational heading
day and yield were obtained from the governmental
crop statistics provided by the MAFF. As Table 1
shows, the observational climate datasets were given by
gathering and averaging the 1-km grid size data inter-
polated from the AMeDAS data (they have a different
spatial resolution but are from the same source as those
shown in section 2a) provided by Seino (1993).

In addition to the enlargement of the spatial scale,
the modified version improved the parameterization rel-
ting to the spikelet sterility response to the combina-
tion of high air temperature during the flowering period
and high atmospheric CO2 concentration. The im-
proved parameterization suggested by Nakagawa et al.
(2003) was implemented for the modified version.

c. Module for yield loss assessment caused by
storms, diseases, and pests

1) YIELD LOSS CAUSED BY STORMS

It is not necessarily clear what physiological process
in plants dominates yield loss caused by storms as op-
posed to that caused by cool-summer damage or heat
stress; however, storms are a major factor for yield loss
in southwestern Japan. In particular, yield loss caused
by storms includes complex factors, such as salt injury,
insufficient oxygen caused by overhead flooding, flash-
ing caused by floods, and wind injury on stems, leaves,
and spikes. Tani (1966) indicates the following results
obtained from field experiments: yield loss relating to a
storm is caused by high winds, heavy precipitation, and
their interaction; a linear relationship can be observed
between the daily maximum hourly wind speed and the
total amount of loss in paddy rice.

We assumed that the linear relationship suggested by
Tani (1966) can be seen on a prefectural as well as on a
farm-field scale and defined the yield loss caused by
storms as the function of climate indices regarding the
daily maximums of hourly precipitation and hourly
wind speed as follows:

\[ L_{\text{storm},ij} = \beta_{0,i} + \beta_{1,i} PI_{i,j} + \beta_{2,i} WI_{i,j} \]  

(1)

where \( L_{\text{storm},ij} \) is the \( i \)th prefectural yield loss caused by
storms in the \( j \)th year, \( PI_{i,j} \) and \( WI_{i,j} \) are the climate
indices relating to precipitation and wind speed, respec-
tively, and \( \beta_{0,i}, \beta_{1,i}, \) and \( \beta_{2,i} \) are the parameters in the \( i \)th
 prefecture. The climate indices were given as follows:

\[ PI_{i,j} = \sum_{m=D_{\text{maturity}}}^{D_{\text{maturity}}} P_m, \]

(2)

\[ P_m = P_{\text{max},i,m} - P_{0,i} \text{ (} P_{\text{max},i,m} > P_{0,i} \text{), and} \]

\[ P_m = 0 \text{ (} P_{\text{max},i,m} \leq P_{0,i} \text{)} \]

and

\[ WI_{i,j} = \sum_{m=D_{\text{maturity}}}^{D_{\text{maturity}}} W_m, \]

(4)

\[ W_m = W_{\max,i,m} - W_{0,i} \text{ (} W_{\max,i,m} > W_{0,i} \text{), and} \]

\[ W_m = 0 \text{ (} W_{\max,i,m} \leq W_{0,i} \text{)} \]

The concept of these indices was similar to that of cool-
ing-degree days. We took precipitation as an example;
the climate index relating to precipitation, \( PI_{i,j} \), was
calculated by the summation of the values of daily
maximum hourly precipitation above the thresholds
\( P_{\text{max},i,m} - P_{0,i} \) during the influential period ranging
from the first day of the period, \( D_{\psi} \), to maturity day,
\( D_{\text{maturity}} \). The maturity day was mechanically estimated
by the submodel for phenological development (Horie
et al. 1995) in the module for rice yield estimation. On
the other hand, the first day of the influence period was
the empirical constant and was optimized by the best-
subset selection procedure using the datasets of yield
loss obtained from the governmental crop statistics
(Table 1) and observational climate described in sec-
tion 2b. The climate index relating to wind speed, \( WI_{i,j} \),
was calculated in the same manner as for \( PI_{i,j} \).

2) YIELD LOSS CAUSED BY DISEASES AND PESTS

Regarding the yield losses caused by diseases and
pests, the module for yield loss assessment dealt with
two diseases (i.e., rice blast and sheath blight) and two
pests (i.e., the small brown planthopper and the rice
stem borer). These are major diseases and pests for
paddy rice in Japan. The patterns of diseases and pests
are the result of climate conditions in general. For ex-
ample, the rice blast often occurs in a year with a cool
summer; thus, the amount of yield loss caused by a
disease highly correlates with that caused by cool-
summer damage. Furthermore, the occurrence of sheath blight is correlated with heat stress and/or
storms because the disease often occurs under condi-
tions of high air temperature and high humidity. Similar
relationships are found in pests. The increase in the
population density of the rice stem borer over several
successive years is related to low temperatures in July
(Yamamura et al. 2006). As a result, the yield loss caused by the pest tends to correlate with that caused by cool-summer damage.

After we confirmed the empirical relationship reported above using the dataset of damaging-factor-segmented yield loss that was available from the governmental crop statistics, we constructed a set of linear regression formulas for the part of the module used for yield assessment. In particular, the yield loss caused by the $k$th damaging factor (one of two diseases and two pests), $L_{i,k}$, was a linear function of the yield loss caused by the $m$th meteorological disaster in the $i$th prefecture in the $j$th year, $L_{i,j,m}$, as follows:

$$L_{i,k} = \alpha_{i,k} + \beta_{i,k}L_{i,j,m}$$  \hspace{1cm} (6)

The most influential meteorological disaster that was the explanatory variable in the linear regression formula was chosen by referring to the table of the coefficient of determination ($R^2$), which consisted of four rows for diseases and pests and three columns for meteorological disasters (i.e., cool-summer damage, heat stress, and storms). The values of $R^2$ in the table were calculated from the dataset of damaging-factor-segmented yield loss in odd years and varied with the prefecture (Table 1). However, the following tendencies were consistent in most prefectures: the rice blast highly correlated with cool-summer damage; the sheath blight correlated with heat stress or storms; the small brown planthopper showed comparatively higher correlation with cool-summer damage; and the most influential meteorological disaster for the rice stem borer varied widely depending on the prefecture.

### d. Module for rice insurance payout estimation

Equations frequently used as a simple insurance scheme (Ray 1967; Hazell et al. 1986; Abbaspour 1994) were used for the module for the rice insurance payout estimation to simulate the rice insurance payout in a prefecture. The insurance payout in the $i$th prefecture in the $j$th year, $\text{Payout}_{i,j}$, is given by the functions of the insured yield loss, $\Delta Y_{i,j}$, insured acreage of paddy rice, $\text{Area}_{i,j}$, and price of rice, $P_{\text{rice}}$, as follows:

$$\text{Payout}_{i,j} = \Delta Y_{i,j} \times \text{Area}_{i,j} \times P_{\text{rice}}.$$ \hspace{1cm} (7)

The rice insurance program provided by the Japanese government is designed with the assumption that all rice farmers must participate. An objective of the program is to establish full participation by farmers (Yamauchi 1986). With this consideration, we used the total planted acreage as the insured acreage. On the other hand, the insured yield loss, $\Delta Y_{i,j}$, is given by

$$\Delta Y_{i,j} = \phi \bar{Y}_i - Y_{i,j}, \quad \text{if } Y_{i,j} < \phi \bar{Y}_i,$$

$$\Delta Y_{i,j} = 0, \quad \text{if } Y_{i,j} \geq \phi \bar{Y}_i,$$

where $Y_{i,j}$ is the yield in a given year, $\bar{Y}_i$ is the standard yield, and $\phi$ is the insurance coverage. The insurance coverage varies depending on the prefecture and ranges from 0.7 to 1.0 in the National Agricultural Insurance Association (NAIA) insurance program (NAIA 2004). For simplification herein, we took the value of 1.0 for all prefectures.

There were three difficult issues for simulating the rice insurance payout: (i) the standard yield, (ii) the insured acreage of paddy rice, and (iii) the price of rice. In the insurance program provided by the Japanese government, the standard yield is defined as the yield trend curve assuming normal climate conditions. The standard yield for a prefecture is calculated by the non-parametric regression method that uses the climate indices and the number of years as the explanatory variables (MAFF 1998). The calculated standard yield of a prefecture is broken into the municipalities with due consideration of their yield histories. However, because the future climate dataset for this study was not a sequential time series but a sliced time series, we used a simple method for calculating the standard yield instead of the existing method. In the simple method, we eliminated both high-order 20% samples and low-order 20% samples from the time series of yield during the intended period and calculated the linear time series regression curve as the trend line. The second issue is the insured acreage of paddy rice. We were compelled to use the current values of planted acreage for the future period, although we believe that the planted acreage changes year by year as a result of the change in price under future conditions of demand and supply. The third issue is the price of rice. Price is affected by economic factors, that is, demand and supply, including exports and imports; thus, the price in the future is perhaps unequal to the current one. However, we were compelled to use the mean price of rice during the 1990s (257,000 yen per metric ton). Our future projection of the rice insurance payout had the limitations mentioned above for the treatments of future economic factors (i.e., planted acreage and price). In future studies, the inclusion of applied general equilibrium models will help us develop our framework and achieve a more realistic simulation.

### 3. Results and discussion

**a. Validation of modules**

We optimized the model parameters in modules for rice yield estimation and yield loss assessment using the
datasets in odd years and validated their performance using the datasets in even years. Figure 4 shows the comparisons of the 21-yr mean yield losses between the estimations and observations from 1979 to 1999 in nine areas of Japan. The yield losses caused by cool-summer damage and heat stress were mechanically estimated by the module for rice yield estimation, whereas the other yield losses were statistically estimated by the module for yield loss assessment. To assess the performance of modules, we checked the statistics calculated from estimations and observations. The coefficients of determination ($R^2$) ranged from 0.576 to 0.897 with the exception of 0.219 for the storm; the root-mean-square errors (RMSEs) ranged from 0.001 to 0.138 t ha$^{-1}$; the mean percentage error (MPE) varied depending on the damaging factors and ranged from $-1.5\%$ to 28.2%. The largest RMSE and MPE were found in cool-summer damage as a reflection of comparatively large variance. Therefore, the modules showed fairly good performance to reproduce the long-term averaged yield losses.

Figure 5 indicates the comparison of the rice yield

![Fig. 5. Scatterplots of the estimated and observed yield loss due to the factors listed in each panel. The values indicate the 21-yr average yield loss in nine agricultural areas.](image)

![Fig. 5. Comparisons of the estimations and observations in (a), (c) yield and (b), (d) rice insurance payout in the areas of (left) Hokkaido and (right) Kyushu.](image)
and rice insurance payout between estimations and observations from 1979 to 1999, for example, in the areas of Hokkaido and Kyushu. The estimated yield obtained as a combined output of the modules for rice yield estimation and yield loss assessment reproduced the historical variance in yield quite well, although it was slightly underestimated in the area of Hokkaido and slightly overestimated in the area of Kyushu (Figs. 5a,c). The statistics in the areas of Hokkaido and Kyushu were 0.679 and 0.574 in $R^2$ but 0.578 and 0.309 t ha$^{-1}$ in RMSE, respectively.

As a result of the good performance in yield estimation, the module for rice insurance payout could simulate a comparable value of the standard yield (Figs. 5a,c). However, a slight underestimation in the standard yield was found in some areas (e.g., Kyushu). The variance in the estimated payout agreed with that in the observation, although the amount of the estimated payout was overestimated (Figs. 5b,d). The statistics for the insurance payout in the areas of Hokkaido and Kyushu were 0.850 and 0.676 in $R^2$ but 15.7 billion yen and 14.8 billion yen in RMSE, respectively. The main reason for the overestimation in payout was the higher value of insurance coverage ($\phi$) in comparison with the actual one. In the area of Hokkaido, the slight underestimation in the yield in a given year was also a factor for the overestimation in payout. The underestimation in the standard yield was one factor in overestimating payout in some areas (e.g., Kyushu); however, the effect of the error in the standard yield on the payout was small in comparison with that of other factors.

b. Phenological response of paddy rice to climate change

Figure 6 indicates the simulated phenological responses of paddy rice to the projected regional climate change. The indicated values were the 9-yr mean differences between two 9-yr periods in the 1990s and the 2070s. Since the module for climate change downscaling projected that the air surface temperature around Japan will increase by 2°C, the cooling-degree days (the base temperature was 21°C) during the growth period decreased in the areas of Tohoku and Hokkaido (Fig. 6a). The decrease in the cooling-degree days induced a reduction in the potential threat of cool-summer damage. On the other hand, the daily maximum temperature averaged over the flowering period is projected to rise by 0.5°C–2.5°C throughout Japan (Fig. 6b). Since rice spikelets are also sensitive to high temperature at flowering (approximately 35°C; Satake and Yoshida 1978; Matsui et al. 1997), the rise in the daily maximum temperature indicated the increase of the potential threat relating to high temperature.

The module for climate change downscaling also projected that downward shortwave radiation will slightly increase by approximately 1 MJ m$^{-2}$ day$^{-1}$ during July and August in most of Japan (no figure). The climate projection of the MRI CGCM2 that was a boundary condition of the regional climate model indicates a decrease in the days of rainfall and a delay in the northern movement of the Baiu front from June to July (Kitoh et al. 2004). The decrease in the days of rainfall and the delay can cause an increase in the radiation in the summer in Japan; therefore, our regional climate projection included the characteristics. As far as radiation change around Japan goes, a current study supports the idea of a radiation increase in the summer season in Japan on the basis of the projection downscaled by a statistical method (Iizumi et al. 2008). An increase in radiation causes an increase in paddy rice biomass in general. However, the simulated period from planting day to heading day was shortened by more than 14 days in northern Japan and by 3–9 days in western Japan (Fig. 6d). A similar result was found in the growth period, that is, the period from planting day to maturity day (Fig. 6e). The shortening of the growth period was caused by the acceleration of the phenology development derived from the rise in the daily mean temperature. Such a simulated result in the growth period agreed with the field experimental result reported by Nakagawa et al. (1993). As a result of their combined effects, the increase in biomass caused by the fertilizing effect and the slight increase in radiation were not significantly enhanced by the shortening of the growth period if we did not assume early planting as an adaptation practice. Therefore, the response of dry weight including roots (which is approximately equal to the biomass) to the projected regional climate change varied depending on the prefecture (Fig. 6c).

c. Yield loss response to climate change

Figure 7 indicates the simulated changes in yield losses caused by meteorological disasters, diseases, and pests in the 2070s relative to the 1990s. The indicated values were the 9-yr mean differences, as in the case of the phenological responses reported above. The yield loss caused by cool-summer damage decreased remarkably in the areas of Hokkaido and Tohoku as a result of the reduction in cooling-degree days in these areas (Fig. 7a). On the other hand, the yield loss caused by heat stress increased in central to southwestern Japan, especially, in the areas of Kanto–Tozan and Kinki (Fig. 7b), as a result of the rise in the daily maximum temperature during the flowering period. In comparison with such clear changes, the yield loss caused by storms showed various changes depending on the prefecture (Fig. 7c).
Using the area of Tohoku as an example, the yield loss decreased in prefectures on the Pacific side but increased on the Sea of Japan side. The yield loss caused by diseases (the aggregation of the rice blast and sheath blight) accompanied changes in storm or cool-summer damage (Fig. 7d). The aggregated yield loss caused by pests showed various responses, as did that caused by storms. The cause of various responses was the combi-
Fig. 7. Spatial changes in yield losses: (a) cool-summer damage, (b) heat stress, (c) storms, (d) diseases, and (e) pests.
nation of a decrease in the yield loss caused by the brown planthopper and various responses of the yield loss caused by rice stem accompanying heat stress and storms (Fig. 7e).

d. Climate change impact on rice yield

Our result obtained as the combined output of the modules for rice yield estimation and yield loss assessment indicated that the rice yield in Japan will decrease slightly from 4.36 to 4.26 t ha$^{-1}$ (Table 2). Regionally, a 10% increase in yield was found in the area of Hokkaido; it was the result of the significant reduction in cool-summer damage. On the other hand, a 3%–8% decrease was observed in the eight other areas, with the exception of the area of Tokai; this decrease was caused by the combination of the increase in heat stress and the reduction in biomass as a result of the shortening of the growth period (see section 3b). These responses in yield were reasonable compared to those in previous studies, with the exception of the area of Tohoku.

The results in the area of Tohoku were contrary to those from previous studies, such as those by Toritani et al. (1999) and Nakagawa et al. (2003). A remarkable increase in yield was certainly noted in the year with a cool summer (pseudoyear 1993). However, the increase was cancelled by the accumulation of slight decreases in yield during the other eight pseudoyears, which was caused by the shortening of the growth period. This opposite result was mainly due to the fact that, in previous studies, 14-day-earlier planting is assumed in the yield estimation under future climate conditions (Toritani et al. 1999), whereas we assumed no change in the planting time. In addition, the difference in the climate dataset was another factor; we used a year-to-year climate projection for 9 yr, whereas the previous studies used only the climatological mean of the projection.

e. Climate change impact on rice insurance payouts

Table 3 indicates the change in rice insurance payouts that were simulated by the module for rice insurance payout estimation. Figure 8 indicates detailed changes in yield, standard yield, and insurance payouts, as examples, in the areas of Hokkaido and Kyushu. The module computed the standard yield in the 2070s using the simple method mentioned in section 2d. The simulated standard yield increased in the areas of Hokkaido and Tokai as the reflection of the increase in yield but decreased in other areas (e.g., Kyushu; Figs. 8a,c). The simulated payouts in Japan decreased from 120.2 to 104.4 billion yen; the payouts in the 2070s corresponded to 87% of the payouts in the 1990s. The decrease in payouts was mainly found in the areas of Hokkaido and Tohoku. The significant reduction in cool-summer damage was the cause of the significant decrease in the payouts (Figs. 8a,b). On the other hand, the payout in the areas of Kanto–Tozan, Hokuriku, and Kinki increased by 18%, 19%, and 11%, respectively, relative to the payouts in the 1990s. These increases in payouts were caused by the combination of increases in yield loss caused by heat stress.

4. Conclusions

An analysis framework, that is, the combination of various models ranging from climate projection downscaling, yield estimation, yield loss assessment, and insurance payout estimation, was constructed to provide a preliminary assessment of climate change impact on the rice insurance payout provided by the Japanese government. The simulated results under the SRES-A2 showed that the rice yield in the 2070s will decrease slightly in most areas of Japan, with the exception of Hokkaido in northern Japan, if we did not adopt early
planting as an adaptation practice. The increase in yield in Hokkaido was caused by a significant reduction in yield loss caused by cool-summer damage. The decrease in yield in most areas in central and western Japan was derived from the increase in yield loss caused by heat stress. In addition, the shortening of the growth period induced by the temperature rise was another factor in decreasing the yield; the reduction in the paddy rice biomass caused by the shortening of the growth period was often greater than the increase in biomass derived from the increase in the atmospheric CO$_2$ concentration. The simulated change in yield was also reflected in the standard yield, and, as a result, the rice insurance payouts are expected to decrease in most of Japan. In our simulation, the 9-yr mean payout in Japan in the 2070s was 120.2 billion yen; the value corresponded to 87% of the payouts averaged over 9 yr in the 1990s (1991–99).

There are areas in which further study is needed to obtain a more realistic and reliable assessment of climate change impact on the rice yield and rice insurance payouts in Japan. The consideration of adaptation in cultivation practices, for example, the adoption of early planting and new cultivars, may result in the development of a realistic simulation. Using multiclimate projections of GCMs and emission scenarios also contributes to an increase in the reliability of the simulations. These, among other issues, are to be addressed in future studies.

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