S. Peng K.T. Ingram
H.-U. Neue L.H. Ziska (Eds.)

Climate Change and Rice

With a Foreword by Klaus J. Lampe

With 102 Figures and 67 Tables

Effect of Anticipated Change in Global Environment on Rice Yields in Japan
T. Horie, M.J. Kropff, H.G. Centeno, H. Nakagawa, J. Nakano, H.Y. Kim, and M. Ohnishi .

Springer

IRRI
International Rice Research Institute

Effect of Anticipated Change in Global Environment on Rice Yields in Japan

T. Horie, M.J. Kropff,[2] H.G. Centeno,[2] H. Nakagawa,[1]
J. Nakano,[3] H.Y. Kim,[1] and M. Ohnishi[1]

Almost all rice in Japan is produced in rice fields flooded with water supplied through well-developed waterways. Therefore, unlike most other countries in the world, water plays a negligible role as a yield-reducing factor in Japanese rice production. The major climatic factors that influence rice production in Japan are temperature, solar radiation, and strong winds and heavy rainfalls associated with typhoons. Although Japan as a whole loses a certain amount of rice every year because of typhoons, the location and timing of typhoon damages are unpredictable. Except for typhoons, temperature and solar radiation are the main factors that produce spatial and yearly variations of rice yield in Japan. Cool summer temperatures in northern Japan (Hokkaido and Tohoku districts) can cause severe yield reductions and may significantly impact on national rice production (as occurred in 1993). Horie (1987) and Horie et al. (1992) quantitatively explained that yield variation in Japan was based on temperature and solar radiation using the simulation model SIMRIW (SImulation Model for Rice-Weather relationships).

Models of the dynamics of the atmosphere of the earth, known as general circulation models or GCMs, predict that with increasing levels of greenhouse gases in the atmosphere, global climate change is likely (Hansen et al. 1984). Because predicted climate change may have enormous effects on Japanese rice production, it is vitally important to assess the impacts on regional rice yield to provide a basis for counter measures (e.g., cultivar improvements, alterations of cropping seasons, and cultivation technologies). For this purpose, Horie (1993) modified SIMRIW to include processes describing: direct effects of atmospheric CO_2 on growth, and high temperature-induced spikelet sterility of rice. The modified model was then used to assess impacts of doubled CO_2 and climate change on rice yield in three representative rice-producing prefectures in Japan. Preliminary analysis indicated that doubled CO_2 and the associated climate change had different effects on rice yield in different locations, but the study was not sufficiently detailed to clarify the overall effect on rice production in the whole country. The objectives of this study are to validate the simulation model SIMRIW using rice growth and yield data obtained under widely different

[1] Faculty of Agriculture, Kyoto University, Kyoto 606, Japan
[2] International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines
[3] Faculty of Agriculture, Tottori University, Tottori, Japan

S. Peng et al. (Eds.) Climate Change and Rice
© Springer-Verlag Berlin Heidelberg 1995

environmental conditions and to assess, by use of SIMRIW, the effects of elevated CO_2 and climate change on rice yields in the major rice-producing areas of Japan.

The Model

The details of SIMRIW have already been reported (Horie 1987; Horie et al. 1992). This brief description emphasizes the derivation of components that govern the direct effects of atmospheric CO_2 on growth and temperature-induced spikelet sterility of rice.

Basic Structure

SIMRIW consists of three major parts that describe the processes of ontogenetic crop development, biomass accumulation, and yield formation. Ontogenetic development of rice from emergence to heading is represented by a continuous variable, the developmental index (DVI). The value of DVI is defined to be zero at emergence, 1.0 at heading, and 2.0 at maturity. The value of DVI is computed daily by integrating the developmental rate (DVR) with respect to time. The DVR is a nonlinear function of daily mean temperature and day length (Horie and Nakagawa 1990).

Dry-matter accumulation is simulated based on the principle that dry weight of the crop at any moment is proportional to the absorbed solar radiation accumulated up to that moment (Monteith 1977). This process of biomass accumulation is characterized by one crop parameter, the solar radiation conversion efficiency (Cs). The Cs is assumed to be constant up to heading (DVI=1), and thereafter to decrease as a function of DVI to simulate maturation and senescence processes. Leaf-area growth rate, which governs radiation interception, is modeled as a unique function of temperature. This approach contrasts with traditional models that simulate leaf dry-weight accumulation and then calculate leaf area by multiplying leaf dry-weight by specific leaf area. The SIMRIW models leaf-area growth independent of leaf dry weight, thereby accounting for their largely independent natures (Horie et al. 1979).

Grain yield is simulated in SIMRIW from calculated total biomass by multiplying by harvest index. Harvest index is a function of DVI and spikelet sterility. The harvest index-DVI relationship makes the yield formation process dynamic, and simulates premature cessation of growth when crops encounter autumn coolness. Spikelet sterility is a function of cooling degree-days (Uchijima 1976) during the period when spikelets are sensitive to cool temperature ($0.75<DVI<1.2$).

The SIMRIW estimates the climatic potential yield of a given cultivar of irrigated rice under optimal cultivation technologies. Horie (1987) showed a close linear relationship between the simulated potential yield (Yp) and actual yield (Ya) across respective locations in Japan and in the United States. The relationship can be represented by:

$$Ya = KYp, \quad (1)$$

where K is an index of overall technology level of rice culture.

Modeling Effects of Carbon Dioxide and High Temperature on Rice

To determine the parameters for elevated CO_2 and high-temperature effects on rice for SIMRIW, temperature × CO_2 experiments were conducted at Kyoto University for three cropping seasons (1990, 1991, and 1992) using temperature-gradient tunnels (TGTs) with and without elevated CO_2. The TGT is a newly developed experimental system that can impose long-term temperature × CO_2 treatments on crops under seminatural environmental conditions (Horie et al. 1991).

Long-term temperature × CO_2 treatment revealed that nearly doubled day-time CO_2 concentration has negligible effects on nitrogen uptake and leaf-area development, but enhances dry-matter production. The observed insensitivity of leaf area to CO_2 is consistent with observations of Imai et al. (1985) and Baker et al. (1992b). The experimental results with TGT and those of previous workers (Imai et al. 1985; Baker et al. 1992b) indicate that doubled CO_2 concentration increases the dry weight of rice by 24% mainly through the enhancement of radiation conversion efficiency, not through enhanced light interception. These experimental data also showed that temperature did not consistently affect growth enhancement by elevated CO_2. From these findings and from an analysis of the rice canopy photosynthesis versus atmospheric CO_2 relationship by Baker et al. (1990a), Horie (1993) obtained an equation to describe the effects of CO_2 concentration (C_a) on radiation-conversion efficiency (Cs) of rice:

$$Cs = Co\left\{Rm(Ca-330)/\left[(Ca-330)+Kc\right]+1\right\}, \quad (2)$$

where Co is the conversion efficiency at 330 μl/l CO_2, Rm+1 is the asymptotic limit of the relative response to CO_2, and Kc is the Michaelis-Menton constant (estimated values are Rm=0.54 and Kc=370 μl/l). Equation (2) is identical to the one obtained by Allen et al. (1987) for the response of soybean seed and biomass yield to CO_2.

Elevated CO_2 enhanced panicle dry weight to a similar level as crop dry weight under temperature conditions near ambient in Kyoto (about 27 °C), but this effect of CO_2 decreased sharply with increase in temperature. The decline of panicle dry weight with temperature resulted from an increase in numbers of unfertile grains. Rice spikelets have the highest sensitivity to high temperature at anthesis, and are liable to be sterile because of a failure in pollination when temperatures exceed 35 °C during flowering (Satake and Yoshida 1978; Matsui and Horie 1992). Because rice spikelets usually flower during the day, daily maximum temperature is considered to be more closely related to high temperature-induced spikelet sterility of rice than the average temperature. When spikelet fertility is plotted against average daily maximum temperature over a 10-day period close to heading for 'Akihikari' rice grown under elevated and ambient CO_2 conditions in TGTs (Fig. 1), we see that CO_2 concentration has no effect on the relationship between temperature and spikelet fertility. The relation shown in Fig. 1 may be approximated by (Horie 1993):

$$\delta = 100/\{1 + \exp[0.853(\mathrm{Tm} - 36.6)]\}, \tag{3}$$

where δ is fertility percentage, and Tm is average daily maximum temperature during flowering. Equations (2) and (3) were incorporated into SIMRIW to simulate rice growth and yield under elevated CO_2 concentration and global warming conditions.

Sensitivity Analysis

A sensitivity analysis of SIMRIW to conditions in the aerial environment was made by examining responses of simulated yield to daily mean temperature, solar radiation, and CO_2 concentration, under constant conditions of those environments over the entire growth season (Fig. 2). In this analysis, the cultivar Nipponbare was used and the diurnal range of temperature was set at 8 °C. Under constant environmental conditions, the optimum mean temperature for simulated yield was 22–23 °C. Below 22 °C, yield decreased sharply because of the increase of sterile spikelets from cold temperature damage. As temperature increased above the optimum, yield declined more or less linearly up to about

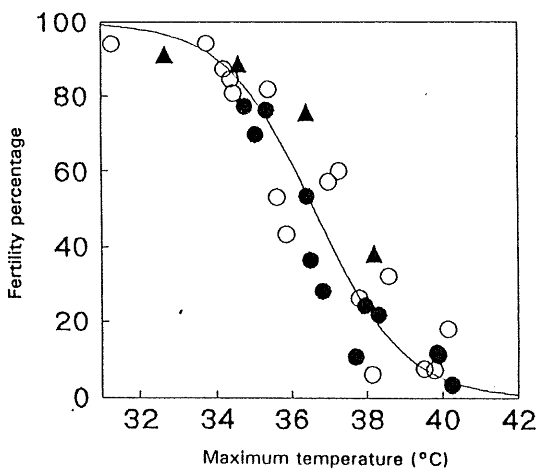


Fig. 1. Relationship between average daily maximum temperature during flowering period and fertility percentage of spikelets for Akihikari rice acclimated to different CO_2 concentrations. (Horie 1993). ○ 350 μl/l; ▲ 690 μl/l; ● 840 μl/l

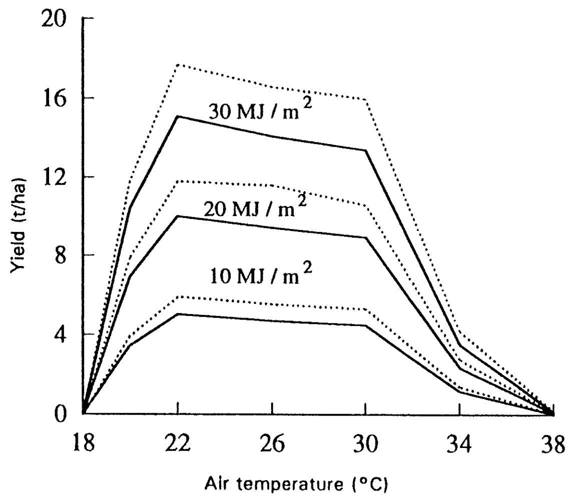


Fig. 2. Simulated yield responses of Nipponbare rice to daily mean temperature, solar radiation, and CO_2 concentration under constant environmental conditions. Day length was set at 12 h in all cases. — 350 μl/l; ··· 700 μl/l

30 °C, above which it declined sharply. The linear decline of yield with increasing temperature from 22 to 30 °C results from shortened total crop duration because of acceleration of phenological development. Sharp decline of yield above 30 °C results from spikelet sterility caused by high-temperature damage.

The overall response pattern of simulated yields to temperature is similar to the results of Munakata (1976) in which the effect of temperature on yields was statistically analyzed using data from long-term field experiments from various regions in Japan. The linear decline of simulated yield over a temperature range between 22 and 30 °C is similar to the results of Yoshida and Parao (1976) in which a mathematical analysis was made of the effect of climate on rice using experimental data from IRRI.

Simulated rice yields were proportional to solar radiation over the entire temperature range, reflecting the axiom that biomass production, and therefore potential yield, is proportional to absorbed solar radiation. This response agrees with the results presented by Yoshida and Parao (1976). The model predicts that doubled CO_2 in the atmosphere alone increases rice yield by 24% under each temperature and radiation condition.

Validation

Prior to application of SIMRIW for the impact assessment of global environment change on Japanese rice production, the validity of the model was examined by using past weather and measured yield data in different rice-producing areas of Japan. For this validation, we used reported yield data for 1979–1990 from five prefectures: Hokkaido, Miyagi, Gunma, Aichi, and Miyazaki. We used daily weather data for 1979–1990 from one weather station for each prefecture:

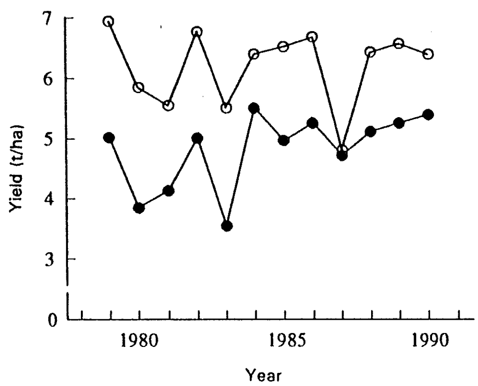


Fig. 3. Yearly changes in reported rice yields at Sapporo, Hokkaido, and those simulated by SIMRIW. ● actual; ○ simulated

Sapporo, Hokkaido; Sendai, Miyagi; Maebashi, Gunma; Nagoya,Aichi; and Miyazaki, Miyazaki. To simulate past rice yields, we used the leading cultivars for each prefecture: Ishikari for Hokkaido, Sasanishiki for Miyagi, Koshihikari for Gunma, Nipponbare for Aichi, and Mizuho for Miyazaki.

Figure 3 shows actual and simulated yearly variation of rice yield in Hokkaido for 1979–1990. Because the model gives climatic potential yield, simulated yields were much higher than the actual yields. The difference between simulated and actual yields decreased with time, indicating an advancement of rice-production technology. Therefore, the technological coefficient (K) that converts simulated yields to actual yields obtained by farmers is a function of year. By assuming a linear increase in rice-production technology by year, the simulated yield (Yp) may be converted to the yield obtained by farmers (Ya) by:

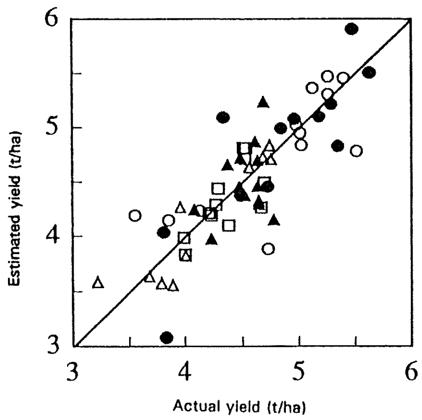
$$Ya = [b_0 + b_1(i-1)]\, Yp, \tag{4}$$

where i represents year since 1979, and b_0 and b_1 are the coefficients of the linear regression between K and time.

A multiple regression analysis was performed between the actual yield (Ya) and simulated yield (Yp) using Eq. (4) for each prefecture. Positive values of b_1 were found, with the highest value in Gunma (b_1=0.026) and the lowest in Aichi (b_1=0.005). This suggests that the increase in rice yield because of technological advancement is 2.6%/year in Gunma and 0.5%/year in Aichi.

Using Eq. (4) with coefficients for each prefecture, simulated yields were converted to yields predicted from weather conditions and cultivation technology level for a given year. The converted yields that were obtained, were plotted against actual yields obtained by farmers for each year for each prefecture (Fig. 4). SIMRIW explained 69% of the year-to-year variation of the rice yields in the five prefectures. Considering that rice yields vary not only in response to temperature and solar radiation, but in response to typhoon, pest, and disease damages, SIMRIW explained satisfactorily the regional yield variations in Japan from weather conditions.

Fig. 4. Comparison between reported rice yields and those simulated by SIMRIW for five representative prefectures in 1979–1990. O Hokkaido; ● Miyagi; Δ Gunma; ▲ Aichi; □ Miyazaki



Likely Effects of Doubled Carbon Dioxide on Rice Production in Japan

Scenarios for Doubled Carbon Dioxide Climate

To assess the impacts of doubled CO_2 climates on regional rice yields in Japan, we used the agroecological zones (AEZ) proposed by Ozawa (1962), which classified the Japanese islands into 14 zones based on climate and land use. Daily weather data during 12 years from 1979 to 1990 from nine representative weather stations were used as base climates. Besides this base climate, five climate scenarios were adopted for future environments: 450 μl/l CO_2 with no change in temperature or radiation; 450 μl/l CO_2 with a 2°C temperature rise; 700 μl/l CO_2 with the climate predicted by the GISS model; 700 μl/l CO_2 with GFDL-predicted climate; and 700 μl/l CO_2 with UKMO-predicted climate. These GCM climate scenarios were supplied by the data support section within the Scientific Computing Division of the National Center for Atmosphere Research (NCAR).

Among climate scenarios predicted by the three GCMs under a doubled CO_2 concentration, temperature rise is greatest in UKMO, moderate in GFDL, and smallest in GISS. Although the GFDL model predicts reductions of solar radiation under doubled CO_2 in most parts of Japan in most seasons, GISS and UKMO predict increases (particularly in the latter).

Future climate conditions were created by adding those monthly temperature changes in each scenario to current daily maximum and minimum temperatures of the same month, and by multiplying relative changes in monthly solar radiation by current daily solar radiations.

Effects of Carbon Dioxide Concentration and Climate Change

Average climate for each location was used as the baseline against which to evaluate the effects of climate change on rice yields. Average climate was synthesized by averaging daily weather values over the 12 years for each location.

Table 1 shows the predicted change in rice yield under each climate scenario from that of base (current) climate for the nine locations investigated. The SIMRIW predicts that a 100 μl/l increase in CO_2 concentration under current climate would increase rice yield by 7–8% in all locations. A comparison of these results with long-term CO_2 experimental data on rice (Imai et al. 1985; Baker et al. 1992b; Kim et al. 1994) suggests that this prediction is reasonable.

Figure 5 gives SIMRIW predictions of the effects of GFDL, GISS and UKMO climates on rice yields in Japan (as a relative yield change from the present). In AEZ X and XIII, where we did not have actual weather data, relative yield changes under the respective scenarios were interpolated from those in adjacent AEZs. Although the predicted effects of doubled CO_2 climate on Japanese rice yield differed quantitatively among climate scenarios, the directions of the effects were similar. Under all scenarios, SIMRIW predicted that climate change would have moderately positive effects on rice yield in northern and north-central Japan, and negative effects in south-central and southwestern Japan. The greatest negative effect would be in AEZ XI (Tokai district).

The positive effects of doubled CO_2 and global warming on rice yield in northern Japan are predicted because the temperatures suggested by the GCMs are not high enough to cause drastic yield reduction. The beneficial direct effects of doubling CO_2 more than offset the negative effects of warming. Negative effects of doubled CO_2 and global warming on simulated rice yields in south-central and southwestern Japan result because the temperatures predicted by GCMs are high enough to shorten rice-growth duration and to cause extensive spikelet sterility. Because temperatures above 35 °C during flowering cause spikelet sterility (Satake and Yoshida 1978; Matsui and Horie 1992), the results shown in Fig. 6 indicate that daily maximum temperatures under doubled CO_2 climates frequently exceeded 35 °C during flowering in south-central (AEZ XI) and southwestern Japan (AEZ XII, XIII, and XIV). Indeed, the SIMRIW predicts more than 30% yield reduction in AEZ XI under the GFDL and UKMO climate scenarios.

Probability Analysis on Effects of Doubled Carbon Dioxide Climate

Probability analyses were made of the effects of doubled CO_2 and climate change on rice yield for representative locations, using daily weather data from 1979 to 1990 at Sapporo (AEZ III), Sendai (AEZ V), Nagoya (AEZ XI), and Miyazaki (AEZ XIV) as base climates, and the described climate-change scenarios. Figure 6 gives the results of the probability analysis by SIMRIW. The simulated rice

Table 1. Predicted changes (%) in current rice yields at various locations under different CO_2 and climate conditions (predicted by SIMRIW model)

CO_2 (μl/l)	Temperature	Sapporo	Akita	Sendai	Maebashi	Toyama	Nagoya	Hiroshima	Kohchi	Miyazaki
450	+0 °C	+6.7	+8.0	+7.8	+7.7	+7.7	+7.7	+7.7	+7.7	+7.8
450	+2 °C	+0.7	+6.2	+3.8	+5.2	+2.4	–6.8	+1.9	+3.1	+7.3
700	GFDL	+0.0	+15.8	+10.3	+10.2	–8.0	–32.0	–18.7	–12.8	+6.7
700	GISS	+16.6	+29.8	+23.4	+25.7	+21.6	+0.5	–15.0	–26.9	+4.0
700	UKMO	+11.5	+27.6	+21.1	+16.7	+16.9	–39.2	–45.4	–34.8	–7.0

The prediction was based on experimental data on 'Akihikari' for high temperature effect on spikelet sterility.

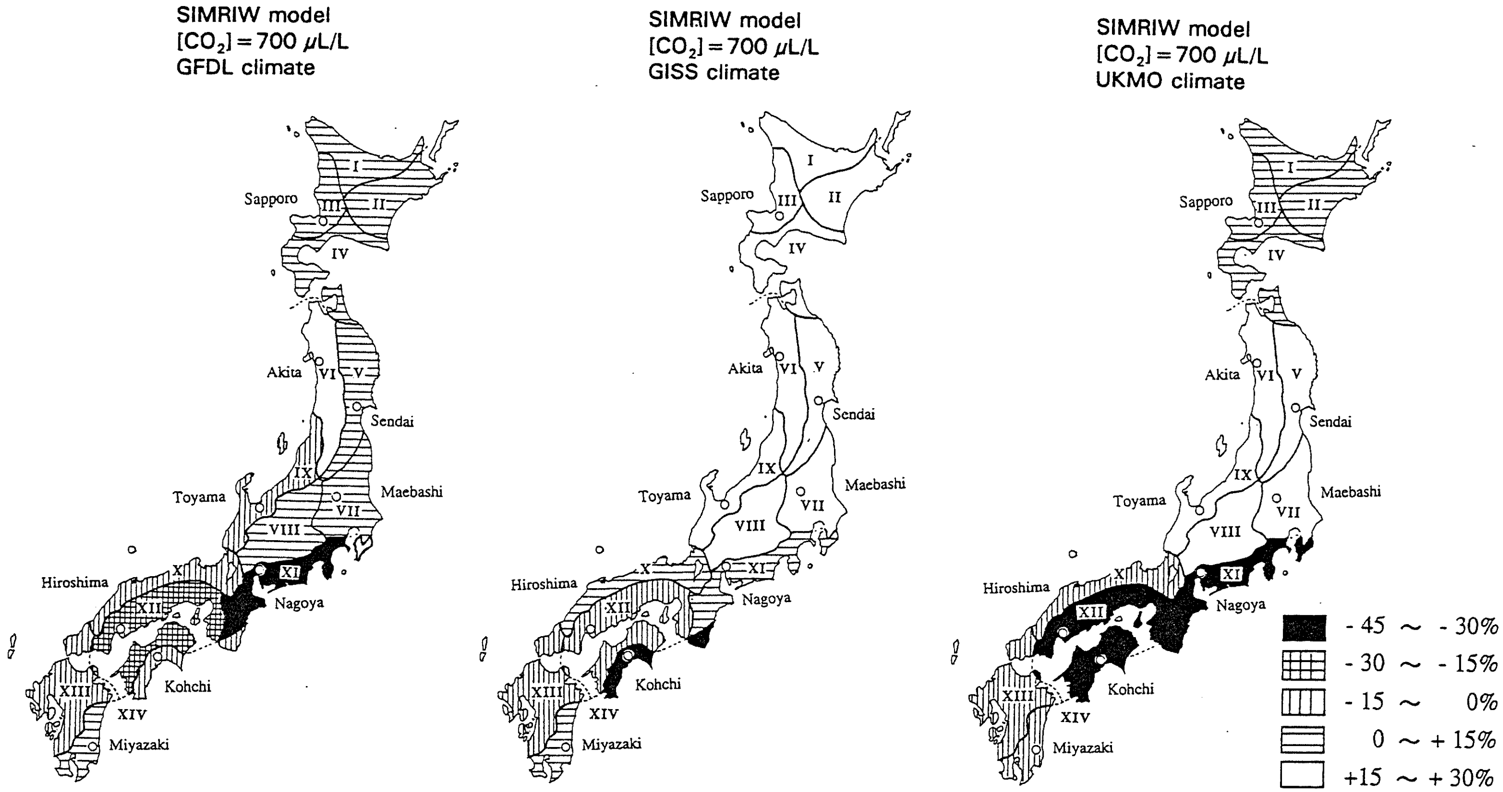


Fig. 5. Likely effects of doubled CO_2 and climate change predicted by three GCMs on regional rice yield in Japan (prediction by SIMRIW). The prediction was based on experimental data on 'Akihikari' rice for high temperature effect on spikelet sterility.

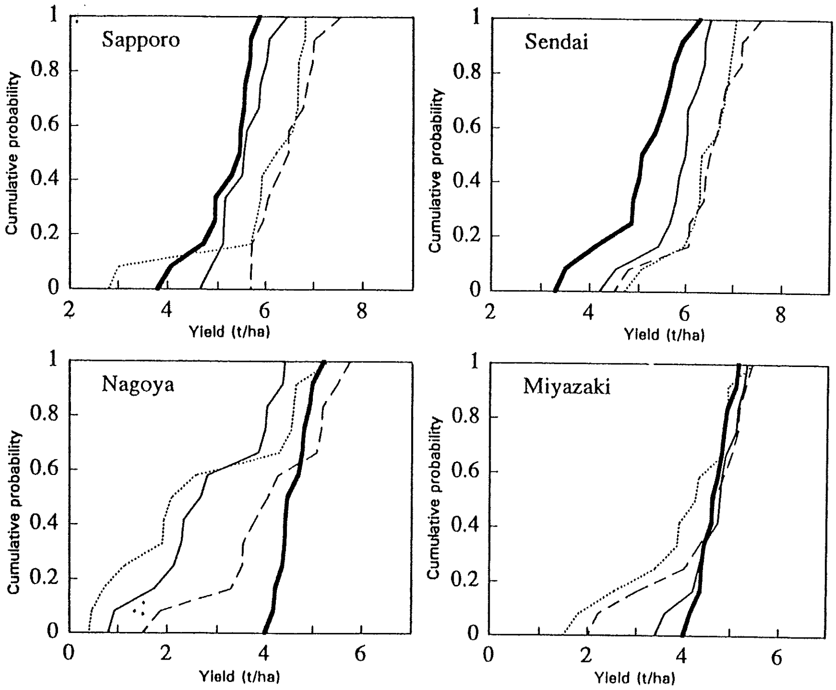


Fig. 6. Cumulative distribution functions for rice yield at four representative locations in Japan under three scenarios of global climate change (prediction by SIMRIW). — present; — GFDL; ---Giss; ··· UKMO

yields for 12 years under the three different climate scenarios were plotted as cumulative probability distributions.

At Sapporo in Hokkaido (AEZ I to IV), the average yield and its coefficient of variation (CV) under the current climate are 5.27 t/ha and 9.7%, respectively. The relative increases in average yield under doubled CO_2 climates of the GFDL, GISS, and UKMO were predicted to be 6, 23, and 15%, respectively. The GISS scenario gave the largest yields of the three GCMs because it predicts the smallest temperature rise and increased solar radiation levels. Because cool-summer damage is rare under the doubled CO_2 scenarios of GFDL and GISS, yield variability was also reduced. The temperature rise predicted by the UKMO scenario is so large that it causes heat-induced spikelet sterility, even in Hokkaido during some years. In general, a doubled CO_2 climate will substantially increase the average yield and reduce the yield variability in Hokkaido.

The largest positive effect of doubled CO_2 climates are expected in Tohoku district (AEZ V and VI). At Sendai, the predicted yield increase is 14–26%, depending on climate scenarios. Doubled CO_2 climates will reduce the yield variability in Tohoku by reducing the CV from the present 15% to less than 10%.

The most catastrophic effect of a doubled CO_2 climate was predicted at Nagoya, Aichi prefecture (AEZ XI), where average yield reductions of 8 and 38%

were predicted with the three scenarios. Yield variability was also predicted to significantly increase from the current coefficient of variation of 7% to between 27 and 61%. These catastrophic effects are because Nagoya has the highest daily maximum temperatures of all the locations investigated under current summer conditions. Any further warming increases the probability of heat-induced spikelet sterility. Similarly, at Miyazaki prefecture (AEZ XIV), 0–13% yield reduction is predicted under a doubled CO_2 climate, depending on the scenario. Yield variability was also predicted to increase from the current 4.7% to 11–26% under a doubled CO_2 climate.

Simulations indicate that a doubled CO_2 climate will substantially increase rice yields and yield stability in northern and north-central Japan, but in the south-central and southwestern Japan a doubled CO_2 climate will markedly decrease yields and yield stability. By aggregating regional effects over the whole country, it appears that the average rice production of Japan will not change significantly from the current levels under a doubled CO_2 climate. However, yield variability is likely to increase, reflecting increased heat-induced spikelet sterility in south-central and southwestern Japan.

This analysis assumes the use of current cultivars and cropping seasons. It may be possible to reduce the predicted instability by adjusting planting dates to avoid heat-induced spikelet sterility by allowing the flowering period to escape the hottest period. This strategy, however, may reduce average yields, because the hottest season in Japan is also associated with the highest solar radiation. Grain formation and grain filling in rice has been found to be strongly influenced by solar radiation levels during the reproductive period. Further studies are needed to quantitatively assess to what extent the predicted effects of a doubled CO_2 climate on rice yield can be mitigated by using different cropping seasons and cultivars.