Nationwide assessment of the impact of climate change on agricultural water resources in Japan using multiple emission scenarios in CMIP5

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Abstract:

The present study generated nationwide assessment maps for the impact of climate change on agricultural water resources throughout Japan, using climate scenarios derived from global climate models and DWCM-AgWU, a hydrological model that incorporated irrigation water management. In addition, we analyzed the uncertainty of the assessment maps, investigating the ranges of the assessment indices in 11 climate scenarios used. For the assessment of drought discharge, we generated the assessment maps for two rice growth stages (puddling and heading) that are highly vulnerable to water shortages. The maps generated in this study provide a framework for assessing the impact of climate change on agricultural water resources in Japan and reveal the vulnerable regions to climate change. The uncertainty analysis suggested that the assessment uncertainty depended on the hydrological processes used to calculate assessment indices and on the magnitude of their natural annual variability. For a deeper understanding of the uncertainty in hydrological assessments it is necessary to investigate the impact on the assessment uncertainty of the natural variability of hydrological processes especially relating to extreme events.

KEYWORDS climate change; nationwide map; agricultural water resources; rice growth stage; uncertainty analysis; CMIP5

INTRODUCTION

Water is one of the principal resources for agriculture, and securing sufficient water and adequately managing it are important roles of irrigation engineering. Recently, assessment of the impacts of climate change on water resources has become a critical issue facing irrigation engineering or hydrology, because the changes in temperature and precipitation patterns that will result from global climate change will alter hydrological cycles at both global and regional scales.

Since the Japanese archipelago extends a large distance from north to south and contains subarctic, temperate, and subtropical climate zones, the impacts of climate change will show pronounced regionality in their magnitude, in the vulnerability to climate change, and in the most significant hydrological processes that will be affected. The assessment of the regional features on climate change impact is therefore required to plan climate adaptation strategies.

In Japan, although many studies have carried out nationwide assessments of the impacts of climate change on hydrology, most have focused on flood risk (e.g., Kazama et al., 2009; Tachikawa et al., 2010). A few studies have dealt with water resources assessments (Wada et al., 2005; Tachikawa et al., 2011; Kotsuki et al., 2013). However, these analyses were based on only one climate scenario; they did not consider uncertainty arising in the impact assessments. In general, assessments of climate change impacts are known to involve large uncertainty (Falloon et al., 2014), and the uncertainty must be quantified to provide the level of confidence in the assessments (Katz et al., 2013).

To assess agricultural water resources in developed river basins, hydrological modeling must account for both anthropogenic and natural hydrological processes, because river flows in such basins are strongly regulated by water use facilities such as reservoirs, diversion weirs, and irrigation canals. Moreover, the agricultural assessment should account for the growth stages of plants, because the impacts of water shortage depend on these stages.

In this study, to assess impacts of climate change on agricultural water resources and their uncertainties throughout Japan, nationwide assessment maps were generated using climate change scenarios produced by global climate models (GCMs) and a hydrological model that accounted for anthropogenic hydrological processes relating to irrigation. We also accounted for differences in the impacts between rice growth stages and for the uncertainty caused by GCMs. In our previous study (Kudo et al., 2016), we generated assessment maps using a single emission scenario (RCP4.5, see next section) in the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012). Here, we expanded our assessment maps based on two additional emission scenarios (RCP2.6 and RCP8.5) and investigated the differences in their impacts.

METHODS

Generation of regional climate scenarios

Figure 1 summarizes the procedure to assess the impact of climate change. The procedure consists of three steps: generation of regional climate scenarios, modeling of hydrological
cycle, and impact assessment. For climate change scenarios, the present study employed the outputs from the GCMs in CMIP5. The emission scenarios used in this study were three Representative Concentration Pathways (RCPs), namely RCP2.6, RCP4.5, and RCP8.5 for the period of 2081 to 2100 (van Vuuren et al., 2011). The numbers in each RCP denote the magnitude of the radiative forcing, with larger values indicating a stronger effect of global warming. The baseline for the assessment was the historical period of 1981 to 2000.

From CMIP5, we selected five GCMs that have a horizontal resolution of less than 1.8° in longitude and latitude and collected 11 climate scenarios (hereafter, “projections”) that included up to three ensemble members from each GCM (Table I). These projections were used to quantify the assessment uncertainty. Ensemble members are projections that are produced by a single GCM with the same boundary conditions (e.g., emission scenarios and ground surface conditions) but with different initial conditions (Taylor et al., 2012). In addition to uncertainty due to the GCMs, the ensemble members allow us to investigate uncertainty arising from natural climate variability (Chen et al., 2011; Dobler et al., 2012). According to these projections, the increases in the annual mean temperature under each RCP compared with the historical experiment throughout Japan were 1.9°C in RCP2.6 (ranging from 1.1 to 2.6°C), 2.9°C in RCP4.5 (ranging from 2.0 to 3.4°C), and 4.9°C in RCP8.5 (ranging from 3.4 to 5.7°C). The changes in annual precipitation were 6% in RCP2.6 (ranging from –2% to 12%), 7% in RCP4.5 (ranging from 2% to 14%), and 11% in RCP8.5 (ranging from 4% to 17%). More detailed features of regional climate change are shown in Figure S1.

GCM outputs with horizontal resolutions of 100 to 200 km are insufficient to account for local climate conditions. To generate regional-scale climate scenarios, we spatially interpolated the 11 projections to 5-km grids throughout Japan by means of simple linear interpolation using the inverse distance weighted method; daily outputs at the four nearest GCM grids from a 5-km grid to be interpolated were averaged using a weighting based on the inverse values of distances between the 5-km grid and GCM grids. Then, bias correction was carried out to bridge statistical gaps of climate variables between observations and GCM simulations by the CDF mapping method (Ines and Hansen, 2006; Li et al., 2010). A gamma distribution was used for daily precipitation and daily-mean wind velocity, while a normal distribution was used for daily maximum, minimum, and mean temperatures, daily-mean relative humidity and daily shortwave radiation. The observations were interpolated to a 5-km grid by means of the inverse distance weighted method using daily meteorological data recorded at Japan Meteorological Agency observation stations.

Assessments of the impacts of climate change on hydrological cycles in developed river basins require a model that accounts for anthropogenic hydrological processes. We used the DWCM-AgWU developed by the Institute for Rural Engineering, a grid-based hydrological model that incorporates irrigation water management (Kudo et al., 2015; Vongphet et al., 2016). In addition to natural hydrological processes (e.g., snow processes, rainfall-runoff processes, and river flow routing), this model accounts for water management processes by irrigation facilities: flow regulation by reservoirs, water withdrawal by diversion weirs, artificial water flow in canals, water depth management in paddy plots, and the return flow to natural river systems (Figure S2). This model was applied throughout Japan with a 5-km horizontal resolution. To obtain the information on irrigation facilities required by the model, such as their location, maximum water use amounts, irrigation period, and rice growing stages, we used GIS data from the Japanese Institute of Irrigation and Drainage (2016) and statistical data on rice cultivation from Ministry of Agriculture, Forestry and Fisheries (2016). Consequently, 1310 irrigation areas (each larger than 100 ha) and 1084 reservoirs (each with effective storage volumes greater than 10^6 m^3) were modeled for the nationwide hydrological simulation. For details of the
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We input the 11 bias-corrected projections for each emission scenario into the DWCM-AgWU. For drought assessment, the present study investigated the impact during two rice growth stages (puddling and heading, Figure S4) that are particularly vulnerable to water shortages. In addition to the drought assessment, the assessment maps of flood discharge were generated, because changes in flood discharge will have a large impact on the operation of water use facilities.

The assessment indices used were the ratios of the RCP values to the historical (from 1981 to 2000) values for the 10-year drought discharge during the puddling stage, 10-year drought discharge during the heading stage, and 10-year flood discharge from June to October. 10-year discharges are design levels to be usually used for irrigation and drainage planning. To map the impacts, these indices were calculated at the cells that contained one or more diversion weirs (Figure S2) and then were averaged in each basin (a total 336 basins in this study).

Based on a plotting position formula (here, we employed the Weibull plot), we approximated the 10-year drought discharges using the second-smallest value during 20 years in the annual-minimum 5-day moving averages for daily discharge in each growth stage. The 10-year flood discharge was approximated by the second-largest value during 20 years in the annual-maximum daily discharges from June to October. This study defined the assessment uncertainty as the projection ranges of the change ratios for these indices between the 11 projections.

To clarify regional features on the climate change impacts and their uncertainty, Japanese archipelago was classified into nine regions: Hokkaido, Tohoku, Hokuriku, Kanto, Chubu, Kinki, Chugoku, Shikoku, and Kyushu (Figure 2). In the assessments, we often refer to Hokkaido, Tohoku, and Hokuriku regions collectively as northern Japan and to Kinki, Chugoku, Shikoku, and Kyushu regions collectively as western Japan.

In the assessments, we did not consider the changes in land use and rice growth stages between the historical and future periods because their future conditions have high uncertainty.

RESULTS AND DISCUSSION

Ten-year drought discharge during the puddling stage

Figure 3a illustrates the changes in drought discharge during the puddling stage based on the ensemble mean of the 11 projections. In northern Japan, since the puddling stages are mainly during snowmelt seasons (specifically, in early May), the drought discharge decreased greatly with radiative forcing being higher, except in Hokkaido. Particularly, Hokuriku and Tohoku regions were vulnerable to temperature changes because they showed decreasing trends even under RCP2.6, which expects the smallest temperature changes of RCPs. Under RCP8.5, drought discharge was projected to decrease even in areas of western Japan such as Kinki and Chugoku as well as in Hokkaido where the climate condition is very cold and the slight changes in temperature such as RCP2.6 and RCP4.5 had little effect on snow processes.

Figure 3b shows that the uncertainty of the assessment results exhibited clear regionality, with consistent decreasing trends in northern Japan (Tohoku and Hokuriku) under all of the emission scenarios. In contrast, western Japan (especially Kyushu) showed an inconsistent trend with the distributions of the change ratios crossing the line for change ratio of 1.0. In general, the puddling stage in western Japan is mainly in June, when river flows are dominated by rainfall. This implies that the uncertainty tends to be large in western Japan, because precipitation changes projected by GCMs have larger uncertainty (i.e., the discrepancy in projected changes between GCMs) than temperature changes, which are the main source of changes in snow processes. These results suggest that differences in the hydrological processes that dominate river flow (e.g., snow-dominant or rainfall-dominant basins) are key factors that control the magnitude of the uncertainty.

Ten-year drought discharge during the heading stage

The assessment maps for the heading stage (Figure 4a) show that the drought discharge decreased in northern Japan, Kinki, and part of Chugoku under RCP8.5, while no significant changes were projected throughout Japan under RCP2.6 and RCP4.5. The increase in evapotranspiration due to higher temperature under RCP8.5 was superior to the changes in rainfall in these regions, which was probably the cause of decreased drought discharge.

Figure 4b demonstrates that the discrepancies in the change ratios between the projections were larger than during the puddling stage, and that the projection ranges in western Japan (particularly Chugoku, Shikoku, and Kyushu) were wider than those in northern Japan. In western Japan, the change ratios differed substantially even between ensemble members within each GCM (Figure S5). The differences between ensemble members are attributed to natural variability in the climate system (Chen et al., 2011). The implication is that uncertainty of the assessments in the heading stages is dominated by both the GCM modeling and natural variability in drought discharge (more broadly, natural vari-
Figure 3. Results of the nationwide assessments of the 10-year drought discharge during the puddling stage in the three RCP scenarios. (a) Nationwide maps of climate change impact (medians of the change ratios between the 11 projections), (b) Projection ranges of change ratios between the 11 projections. H, Hokkaido; T, Tohoku; K, Kanto; H, Hokuriku; C, Chubu; K, Kinki; C, Chugoku; S, Shikoku; K, Kyushu

Figure 4. Same as Figure 3 but for the heading stage
ability in low flow). The main heading stage in northern Japan is at the end of the Baiu (rainy) season (end of July) when the soils in river basins remain stably wet. On the other hand, the main heading stage in western Japan is after mid-August; soil water conditions can vary significantly from year to year according to the annual weather conditions. These differences in weather or soil water conditions would produce differences in the annual variability of the low flow during the heading stage and can lead to the differences in the magnitude of the uncertainty between these regions. To analyze the uncertainty arising in this stage, it will be necessary to investigate the regional characteristics of the annual variation of low flows.

Ten-year flood discharge from June to October

In general, higher temperature changes in humid regions such as Japan will lead to an increase in the potential for heavy rainfall. Indeed, the assessment maps show that the magnitude of the change in flood discharge increases with radiative forcing (Figure 5a).

The ranges of the change ratios (Figure 5b) were much larger than the ranges for drought discharge (Figures 3b and 4b). Nonetheless, almost all of the members showed consistent increasing trends in all regions. The explanation of this is that large annual variability in flood discharge brought about large quantitative differences in the change ratios between the 11 projections, whereas the simple mechanism of increasing the potential for heavy rainfall led to a qualitatively consistent trend. That is, the assessments of changes in flood discharge have a large uncertainty in terms of the quantitative changes but a small uncertainty in terms of the qualitative changes.

CONCLUSIONS

The present study generated nationwide maps to assess the impact of climate change on agricultural water resources throughout Japan, by using climate scenarios derived from GCMs and a hydrological model that incorporated irrigation water management (DWCM-AgWU). In addition, we analyzed the uncertainty of the assessment maps, investigating the ranges of projected hydrological indices.

These maps provide a framework for assessing the impacts of climate change on agricultural water resources in Japan and reveal the vulnerable regions to climate change. In these vulnerable regions, we can perform more detailed assessments on irrigation water management by modeling specific operating rules for irrigation facilities in target river basins (Kudo et al., 2012). In addition, our results can be applied to other kinds of impact studies. For example, the results of this study have supported economic assessments of the climate impacts on rice productivity in Japan (Kunimitsu et al., 2016).

The uncertainty analysis suggested that the assessment uncertainty depended on the hydrological processes used to calculate assessment indices and on the magnitude of their natural annual variability. For a deeper understanding of the uncertainty in hydrological assessments, it is necessary to investigate the impact on the assessment uncertainty of the natural variability of hydrological processes especially relating to extreme events.
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SUPPLEMENTS

Text S1. Application of DWCM-AgWU to river basins throughout Japan (Kudo et al., 2016).
Figure S1. Regional features of climate change
Figure S2. Modeling of the water use facilities for irrigation
Figure S3. Example of simulation results of monthly discharges in nine river basins by DWCM-AgWU
Figure S4. Periods of puddling and heading stages set in this study
Figure S5. Projection ranges of change ratios for 10-year drought discharges in heading stage

REFERENCES


