Introduction of daily minimum and maximum temperature change signals in the Shikoku region using the statistical downscaling method by GCMs

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Abstract:

Impacts of climate change may depend more on changes in mean daily minimum temperature ($T_{\min}$) or maximum temperature ($T_{\max}$) than on average temperature (T_{avg}). In this study, we apply a statistical downscaling model (SDSM) for estimating the average length of spells with temperature values greater than $T_{\max} = 30^{\circ}\text{C}$ (ALS30), $T_{\max}$, and diurnal temperature range (DTR) for the present period (1961–1990) and the future period (2071–2099) climate conditions. The outputs of two GCMs (HadCM3 and CGCM3) are used to show the potential applicability of SDSM. Scenarios A2, A1B and B2 are used by the SDSM to construct climate scenario information over the Shikoku region. The results showed that: (1) The SDSM model is able to capture the major part of the temperature change signals, with a plausible climatic regime for higher warming; (2) From June to August, the average DTR changes in northern Shikoku would be positive; but in southern Shikoku, the changes would be negative under A2, A1B, and B2 scenarios using HadCM3 and CGCM3. The most important finding is that the DTR trend will be different at the local scale and these results highlight the importance of separately considering projections for $T_{\min}$ and $T_{\max}$, when evaluating climate change impact for hydrological and agricultural applications.

KEYWORDS climate change; maximum temperature; diurnal temperature range; statistical downscaling model; Shikoku

INTRODUCTION

It has been pointed out by the IPCC (2007) that the global surface temperature has increased by $0.74^{\circ}\text{C} \pm 0.18^{\circ}\text{C}$ in the last century (1906–2005), and the frequency of heavy rain has increased in many land areas, even when total precipitation has decreased. These climate changes tend to most severely affect the mid- and high-latitudes of the Northern Hemisphere, which in turn can be expected to affect ecological, social and economical systems, industrial and agricultural water supplies, human health, and other factors. Global warming has the potential to cause higher evaporation rates and transport larger amounts of water vapor into the atmosphere, possibly resulting in the acceleration of global hydrological and agricultural cycles. Thus, the impacts of global warming on the agricultural cycle have

become the focus of large-scale investigations (Masutomi *et al.*, 2009; Tan and Shibasaki, 2003; Tatsumi *et al.*, 2011). In addition, global warming may have a large effect on the land productivity of individual crops and overall crop production. In southern Japan, there are many correlations between the higher temperature in the period between June to August, and an outbreak of cracked, broken, dead, and immature rice grains (Nagata *et al.*, 2004).

Studies on changes in extreme temperature events such as frost days or heat waves have been previously carried out by several researchers (Hegerl *et al.*, 2004; Tebaldi *et al.*, 2006; Lobell *et al.*, 2007). Their focus primarily reflects the importance of both average daily temperatures and extreme events in determining climate change impacts (Easterling *et al.*, 2000). Thus, the agricultural impacts are more directly related to changes in $T_{\min}$ or $T_{\max}$ rather than T_{avg} or extreme events. For example, quantities such as accumulated temperatures and growing degree days, which are widely used in the crop models, are influenced differently by $T_{\min}$ and $T_{\max}$ (Wilkins and Singh, 2001; Tatsumi *et al.*, 2012). In addition, changes in evapotranspiration and photosynthetic rates are likely to be more affected by $T_{\max}$ than $T_{\min}$ (Dhakhwa and Campbell, 1998). Deterioration and low yield of rice are often caused by high temperatures ($> 30^{\circ}\text{C}$) (Kondo *et al.*, 2005). Moreover, their results using the GCM (General Circulation Models) outputs are useful in understanding climate change uncertainty and the impacts of global warming on hydrology and agriculture.

Downscaling methods can be broadly divided into two classes: dynamical downscaling (DD) and statistical downscaling (SD). In dynamical downscaling, the GCM outputs are used as boundary and initial conditions used to drive a Regional Climate Model (RCM), such as the Japan-Meteorological-Agency Non-Hydrostatic Model (JMA-NHM) (Saito *et al.*, 2006), or the Weather Research Forecasting (WRF) model (Skamarock *et al.*, 2005). This method responds in physically consistent ways to different external forcing. DD has a higher computational cost, and the results depend strongly on the boundary conditions provided by the GCM. In comparison, SD produces local- or station-scale meteorological time series by calculating the appropriate statistical or empirical relationships with predictor variables. This method does not require high levels of computational resources, and it has been widely used in climate change studies and uncertainty assessments. However, SD requires historical observational data of sufficient length, typically 30 years (Wilby *et al.*, 2002). Studies on statistical downscaling methods have been carried

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out by many researchers (Chen *et al.*, 2006; Hashmi *et al.*, 2011; He *et al.*, 2011; Huang *et al.*, 2011; Iizumi *et al.*, 2012). However, few attempts have been made to reproduce the $T_{\max}$ and DTR using SDSM in a sub-grid scale (around 1 km). The SDSM method may be able to contribute to further improvement of the hydrological and agricultural model. For these reasons our study addresses the Shikoku region of Japan.

In this study, the ability of a SDSM to downscale temperature is investigated with the aim of evaluating simulations of $T_{\max}$, DTR and ALS30 magnitude, and frequency in order to facilitate agricultural and hydrological resource assessment. Here, we evaluate using SDSM the differences between statistical properties of the present and the future $T_{\max}$, $T_{\min}$ and DTR using the Hadley Centre Coupled Model, version 3 (HadCM3), and the third version of the Canadian Centre for Climate Modelling and Analysis Coupled Global Climate Model (CGCM3).

DATA AND METHODS

Study site

The study focuses on the Shikoku region, which is located in the southwestern part of Japan, between about 32.7N and 34.6N, and 132.0E and 134.8E. The island has a typical sea island climate. Shikoku has notably different characteristics to the north and south of the Shikoku Mountains. The Seto Inland Sea side, to the north, has a warm climate and scanty rainfall. Conversely, the side facing the Pacific Ocean has relatively high temperatures and high precipitation. In this study, the region is divided into two parts separated by the Shikoku Mountains: (a) the northern Shikoku region (red points in Figure 1); and (b) the southern Shikoku region (blue points in Figure 1).

Figure 1. The location of climate gauging stations and HadCM3 and CGCM3 grid boxes in the Shikoku region

Data

The daily observed $T_{\min}$ and $T_{\max}$ data for the period 1961–2000 were collected at a total of nine stations over the Shikoku region (Figure 1), from the Surface Daily observation Point (SDP) data. Large-scale observed atmospheric predictor variables were obtained from the National Centers for Environmental Prediction (NCEP) for reanalysis. This dataset is a daily series for the period 1961–2000 at a special scale of 2.5° (lat) $\times$ 2.5° (lon), including 26 atmospheric variables including geopotential height at 500 and 850 hPa, sea level pressure, near-surface relative humidity, near-surface specific humidity, and 2 m air temperature, amongst others (Supplement Table SI). The time series data of the atmospheric predictor variables of a grid box closest to the study area were used as predictor variables to develop and test the SDSM model with observed temperature data (1961–2000). At this time, HadCM3 and CGCM3 (DAI CGCM3 Predictors, 2008) multi-models have been officially published and are available as statistical downscaling input by SDSM. The GCMs adopted in this study are the HadCM3 and CGCM3. HadCM3 is a coupled atmosphere–ocean GCM developed at the Hadley Centre, UK (Gordon *et al.*, 2000; Pope *et al.*, 2000). HadCM3 is a grid point model over land with a horizontal resolution of $2.5^\circ \times 3.75^\circ$ lat–long and 19 levels in the vertical, while the ocean model has a resolution of $1.25^\circ \times 1.25^\circ$ lat–long. The CGCM3 surface and near-surface variables were defined at a daily scale on a global Gaussian grid of $3.75^\circ \times 3.75^\circ$ lat–long (DAI CGCM3 Predictors, 2008). NCEP data was interpolated in order to adjust its resolution to be the same as both models. Therefore, predictor variables are interpolated from a native regular Gaussian grid to the HadCM3 and CGCM3 regular grid, respectively. The transformed data can be directly downloaded from the internet site: <http://www.ccsn.ec.gc.ca/index.php?page=dst-sdi>. The HadCM3 and CGCM3 grid boxes selected in the Shikoku region are shown in Figure 1 and Supplement Table SII. Supplement Table SII shows that the coordinates of each station and value in each grid box corresponds to the value over the center of the cell defined over an area. To simulate different climate change scenarios, HadCM3 data under A2 (high greenhouse gas emission scenarios, H3_A2, including the present climate) and B2 (low greenhouse gas emission scenarios, H3_B2, including the present climate), and CGCM3 data under 20th Century Climate in Coupled Models (C3_20C3M), A2 (C3_A2) and A1B scenarios (balanced across energy sources, C3_A1B) established by SRES (IPCC, 2001; 2007), were used with a calibrated model, weather generator and scenario generator. The scenario generator operation produces ensembles of synthetic daily weather series for the potential atmospheric predictor variables supplied by GCMs for the present or future climate experiments.

Statistical downscaling model

In this study, SDSM version 4.2, which is a decision support tool for the assessment of regional climate change impacts (Wilby *et al.*, 2007), was used to downscale daily $T_{\min}$ and $T_{\max}$ for the simulated $T_{\max}$ and DTR indices in the Shikoku region. SDSM is a multivariate regression method for generating future climate scenarios to assess the

impact of climate change. It is designed to simulate, through a combination of regressions and weather generators, sequences of daily climatic data for the present and future periods by extracting statistical parameters from observed data series (Supplement Figure S1). The daily data from NCEP and GCMs are used in the construction of current and future daily weather series (Wilby *et al.*, 2002; Wilby and Dawson, 2007). Using the explanatory and objective variables detailed above, present and future daily weather data was developed. The procedure of downscaling is based on the availability of tools and data follows nine discrete processes: (1) Quality control of data and transformation; (2) Selection of appropriate predictor variables for model calibration; (3) Development of a nonlinear regression model by means of a statistical transfer function, using NCEP reanalysis data and the observed values; (4) Calibration of the model using predictors from NCEP and current reproduction; (5) Synthesis of observed data and generation of daily data; (6) Verification of the simulation precision of the model by comparing its results with the observed values (Validation of the model); (7) Development of a daily weather dataset for 1961–2099 for CGCM3 and HadCM3 using the regression model, weather generator, and scenario generator; (8) Analysis of the outputs; and (9) Diagnostic testing and statistical analyses. In order to evaluate the robustness method, statistical tests were carried out on the monthly $T_{\max}$ and DTR indices. The first 30 years (1961–1990) are considered for calibrating the regression models. The validation period was 10 years (1991–2000). Some of the SDSM setup parameters for variance inflation and bias correction are adjusted during calibration to obtain a good statistical agreement between the observed and simulated climate variables. The detailed technical information of SDSM can be found in Wilby *et al.* (2002).

Finally, the daily, monthly, seasonal and annual temperature series under the northern and southern Shikoku region can be constructed by the average value of all stations. The future long-term change in $T_{\max}$, DTR and ALS30 indices were analyzed for the Shikoku region.

RESULTS

Calibration and validation of SDSM

Supplement Figure S2 shows that the overall Coefficients of Determination (R^2) and Standard Errors (SE) of each month during the calibration period have seasonal variation. The visualization interpreted for generated daily data showed that SDSM methods were on the whole doing well. However, the simulation results were better for $T_{\max}$ than DTR. R^2 (0.60) of $T_{\max}$ in the south is relatively low in summer. In contrast, SE is larger in winter than in summer (July–September). Gridded data such as reanalysis and GCM that present a large-scale meteorological field is not suited to reproduce the local events, although the data for $T_{\max}$ and DTR indices is of statistical significance (t-test, $p < 0.01$). Supplement Figure S3 shows a comparison between the observed and SDSM-estimated $T_{\max}$ and $T_{\min}$ in north and south regions of Shikoku during the validation period (1991–2000). For NCEP, H3_A2 and H3_B2, the maximum and minimum temperatures in autumn tended to be lesser than the observed data, but the reproducibility was very high.

Similarly, for H3_A2, H3_B2 and C3_20C3M, ALS30 was lower than for the observed data, except for winter, and the statistical reproducibility of ALS30 using the explanatory variables from NCEP and GCMs was high (Supplement Figure S4). Likewise, the data obtained by statistical downscaling for the minimum and maximum daily temperature were generally in agreement with the observed data, and the reproducibility was favorable overall (Supplement Figure S5 and Supplement Figure S6).

Downscaling temperature corresponding to future climate change scenario

The downscaling models have been setup and validated. The next step is to use these models to downscale the future climate change scenario simulated by HadCM3 and CGCM3. The large-scale predictor variables to be used as an input to the downscaling model are derived from GCM simulation outputs. The SDSM tool allows us to generate ensembles of current weather data using observed predictor variables (Wilby *et al.*, 2002). In order to analyze extreme temperature events, we fitted the distribution to more than 50 continuous and discrete distributions (for example, Gaussian, Weibull, Gamma, Pearson, etc.) and calculated the best fitted test statistics for each of the fitted distributions. As a result, the log-normal (three-parameter) distribution was found to be the best fitted. Figure 2 shows the ALS30 of twenty ensemble members for the present and the future using the calibrated regression models. Under the A2 scenario by HadCM3 and CGCM3, ALS30 for the future period increased significantly compared to the present period (t-test, $p < 0.01$). The modes of ALS30 pdf are about 2 and 6–8 days for the present and the future under the A2 scenario for both regions. Under the B2 scenario, the modes of ALS30 are 2 and 6 days for the present and the future in the north;

Figure 2. Log-normal (three-parameter) distribution of average length of spells with amounts more than $T_{\max}$ 30°C between the present and future projections. (a) northern Shikoku region, (b) southern Shikoku region

Figure 3. Extreme values by Log-normal (three-parameter) fit to observed and downscaled maximum daily temperature for the present and the future. (a) northern Shikoku region, (b) southern Shikoku region

while in the south, the modes are 2 and 4 days. Under the A1B scenario, modes in the future would be between the A2 and B2 scenarios. Compared to the northern region, the average changes in ALS30 were smaller in the south. In addition, average changes in ALS30 under the B2 scenario were small as compared to the A2 scenario for both GCM models.

$T_{\max}$ frequency analysis based on the downscaled data in the Shikoku region is shown in Figure 3. In this figure, the log-normal (3P) distribution-estimated $T_{\max}$ are plotted for the studied return periods obtained using the observed and the future data (1961–1990, 2071–2099), and the SDSM-downscaled data. As shown in Figure 3, downscaled data for the future clearly show a significant increase in both the frequency and intensity of future extreme temperature events under both scenarios (t-test, $p < 0.01$). In the northern region, the extreme $T_{\max}$ having 100-year return period will be 40.0°C under the B2 scenario, while it will be 43.7°C for the case of the A1B scenario. Under the A2 scenario, the extreme $T_{\max}$ for the HadCM3 and CGCM3 will be 41.5°C and 44.6°C, respectively. In the southern region, the extreme $T_{\max}$ will be 37.5°C under the B2 scenario, while it will be 40.6°C in the case of A1B scenario. Under the A2 scenario, the extreme $T_{\max}$ for the HadCM3 and CGCM3 will be 38.7°C and 41.6°C, respectively. The log-normal (3P) estimated on the basis of SDSM-downscaled data suggests a 40°C or a greater increase in the magnitude of a low-return period $T_{\max}$ event under the A1B and A2 scenario for CGCM3 (Figure 3a).

Figure 4. Diurnal temperature range comparison between the present and future projections. (a) northern Shikoku region, (b) southern Shikoku region

Figure 4 shows the mean projected change in DTR for each month. In the northern Shikoku region, the average changes of DTR increased since average changes in $T_{\max}$ were larger than associated changes in $T_{\min}$ for every month under both scenarios by HadCM3, except for CGCM3. In addition, from June to August, which is an important period for rice because this period includes the flowering and maturity dates, DTR changes using HadCM3 were positive from 0.44°C in A2, and 0.32°C in B2. Also, DTR changes using CGCM3 were positive from 0.13 in A2, and 0.15 in A1B. From June to August in the southern Shikoku region, DTR changes using HadCM3 were negative from 0.48°C in A2, and 0.33°C in B2. Also, the changes using CGCM3 were negative from 0.52 in A2, and 0.69 in A1B.

DISCUSSION

Future temperature signals

The distribution-estimated magnitudes of temperature for studied return periods suggest that there is a possibility of serious damage to crop productivity due to increasing ALS30 and $T_{\max}$ in the future, due to reduced rice quality caused by high temperatures ($> 30^{\circ}\text{C}$) (Kondo *et al.*, 2005). The disparities between the two GCM models were generally not statistically significant (t-test, $p < 0.01$). This result suggests that part of the difference between model uncertainties in extreme values may be related to handling solar forcing and radiation fluxes, and there is a need to clearly understand these phenomena through a further study.

On a global scale, previous modeling results suggest a

trend towards a reduction in DTR, except for the United States and Western Europe from June to August (Dai *et al.*, 2001; Stone and Weaver, 2003; Lobell *et al.*, 2007), while IPCC indicated that projected changes in DTR over Asia are negative in summer, using AOGCM simulations with increasing concentrations of greenhouse gases and sulfate aerosols in the atmosphere. As mentioned in the introduction, the agricultural and hydrological impacts are cases where $T_{\max}$ and DTR changes may be very important, because changes in DTR have multiple possible causes (cloud cover, urban heat, land use change, aerosols, water vapor, and greenhouse gases) and biological and hydrological processes are differentially sensitive to daytime and nighttime conditions. In our study using a statistical downscaling model, it was found that future $T_{\max}$ and DTR have the different tendency in northern and southern Shikoku region.

Limitations and uncertainties related to the study

Some potential errors and differences of the future warming from SDSM remain, as the regression-method is inherently conservative in the presence of non-stationarity of the cross-scale relationships in the climate system. These errors and differences could be mainly due to the chosen predictors. The relationship between the predictor and predictand is achieved by only considering the data statistical condition. The SDSM model does not take into consideration the physical process. In addition, the model is highly sensitive to the choice of predictor variables and empirical transfer scheme. Moreover, the location of regional grid points strongly influences the temperature simulated by GCMs. Therefore, strong biases are present in the temperature regime simulated by GCMs for the current climate over the Shikoku region. There is considerable variability and uncertainty in results on a regional scale, and climate change signals strongly vary between different GCMs (IPCC, 2001). The significant difference between NCEP and GCM predictors indicate that, even if the SDSM is calibrated well with the NCEP including predictors, it does not guarantee a comparable downscaling performance when we use the corresponding GCM predictors. However, a reasonable spatial projection of local climate change is produced for some interest areas for impact studies.

GCM models do not sample a wide range of uncertainty and are not distributed around the truth. Therefore, combining multi-model ensembles can help quantify uncertainties in future climate projections, through exploring and comparing structural characteristics of the models. This study points to the potential for empirical methods by demonstrating the convergence of different climate change projections at the local scale from different GCMs used as inputs to the SDSM process. Given that a model provides one possible climate behavior under the designed climate change scenario, it is desirable that several GCM or SDSM simulation outputs are produced and compared to achieve greater confidence in extreme event analysis for temperature. Taking the uncertainty in the impact of future climate impact into consideration, the effects of future climate on agriculture need to be further studied.

CONCLUSIONS

The objective of this study was to downscale large-scale atmospheric variables from GCM outputs to produce climate variables at a regional- and local-scale, to apply SDSM method to GCM data over the Shikoku region. According to the results, the main conclusions are as follows:

1. The average length of spells with amounts greater than $T_{\max}$ 30°C for the present and the future increased significantly for CGCM3 and HadCM3. The ratio of ALS30 increase is the largest for the A2 scenario. Additionally, the increasing rate in the northern Shikoku region is larger than in the southern Shikoku region.
2. The distribution of $T_{\max}$ for the 100-year return period was obtained. The downscaled data for the future clearly showed a significant increase in both the frequency and intensity for future extreme events of temperature under both scenarios. In particular, a future 100-year return period event will be around 2 (H3_B2, southern) to 7°C (C3_A2, northern) higher than that of the present-day 100-year return period event.
3. Downscaling is able to capture the systematically higher climate warming corresponding to the A2 scenario as compared to the B2 emission scenario. From June to August, the average DTR changes using HadCM3 and CGCM3 were negative in the southern Shikoku region and were positive in the northern Shikoku region under A2, A1B, and B2 scenarios.

Future works to evaluate the performance of the statistical and dynamical downscaling models in simulating past changes, $T_{\max}$ and DTR would be useful for further constraining uncertainty in future projections.

SUPPLEMENTS

Supplement Figure S1. The SDSM downscaling process and the generation of the daily synthetic weather time series based on two GCM models

Supplement Figure S2. R^2 and SE between the observed and simulated results for the calibration period (1961–1990)

Supplement Figure S3. Comparison of the observed and SDSM-estimated maximum and minimum temperature for the validation periods (1991–2000) ((a) $T_{\max}$, north, (b) $T_{\min}$, north, (c) $T_{\max}$, south, (d) $T_{\min}$, south)

Supplement Figure S4. Comparison of the observed and SDSM-estimated ALS30 for the validation periods (1991–2000) ((a) north, (b) south)

Supplement Figure S5. Time series of observed (SDP) and simulated (NCEP) daily maximum and minimum temperature for 1961–1971 ((a) $T_{\max}$, north, (b) $T_{\min}$, north, (c) $T_{\max}$, south, (d) $T_{\min}$, south)

Supplement Figure S6. Time series of simulated (HadCM3 and CGCM3) daily maximum and minimum temperature for 1961–1971 and 2071–2081 ((a) $T_{\max}$, HadCM3, north (b) $T_{\max}$, CGCM3, north, (c) $T_{\min}$, HadCM3, north, (d) $T_{\min}$, CGCM3, north, (e) $T_{\max}$, HadCM3, south (f) $T_{\max}$, CGCM3, south, (g) $T_{\min}$, HadCM3, south, (h) $T_{\min}$, CGCM3, south)

Supplement Table SI. Summary of predictors in NCEP reanalysis (the one in bold text was selected for model calibration)

Supplement Table SII. The coordinates of each station and value in each grid box correspond to the value over the center of the cell defined over an area (CGCM3: 3.75° longitude and 3.75° latitude, HadCM3: 3.75° longitude and 2.5° latitude)

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