Improvements to Statistical Climate Downscaling Simulations by Incorporating the APHRO_JP Advanced Gridded Daily Precipitation Dataset

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Abstract

In this study, we compared the daily precipitation indices derived from two types of statistical downscaling simulations in Japan. One simulation was conducted by applying a cumulative distribution function-based downscaling method (CDFDM) to a state-of-the-art gridded daily precipitation dataset for Japan, APHRO_JP (Kamiguchi *et al.*, 2010). The other simulation was conducted by applying the same downscaling method to a simple dataset, namely a set of linearly interpolated rain gauge data. We then highlighted the added values for the coarse-resolution general circulation model (GCM) outputs achieved by the incorporation of the APHRO_JP dataset into the statistical downscaling simulations, relative to the simulations using the simple dataset. The evaluated indices were mean precipitation, number of wet days, 90th percentile of daily precipitation, and maximum number of consecutive dry days. A comparison of the two approaches shows that the relative improvements achieved using the APHRO_JP dataset vs. the simple dataset are most pronounced for mean precipitation in mountainous areas, precipitation frequency on the leeward side of mountains, and intensity and frequency of heavy precipitation. These relative improvements over the regional climate change scenarios derived from the CDFDM demonstrate a significant benefit from combining advanced gridded observation datasets with statistical downscaling methods. On a regional scale, the bias of the daily precipitation indices for the simple dataset, relative to the APHRO_JP dataset, is occasionally comparable in amplitude to the projected change. This finding suggests the importance of higher-quality gridded observation datasets in assessing climate impacts in various fields, particularly, hydrological regimes, irrigation planning, and risk assessments of water-related disasters.

Key words: climate change scenario, gridded dataset, precipitation extremes, statistical downscaling method

1. Introduction

High-resolution climate change scenarios are essential to project possible impacts of future climate change on various sectors and in examining potential adaptation practices on a regional scale. Statistical downscaling methods (SDMs) are frequently used to generate spatially-fine and less biased climate data from coarse-resolution general circulation model (GCM) outputs and/or regional climate model (RCM) outputs (*e.g.*, Mearns *et al.*, 2003; Semenov *et al.*, 2010; Iizumi *et al.*, 2011; Sharma *et al.*, 2011).

Statistical downscaling methods are techniques for estimating the local conditions of climate elements at a station from the large-scale conditions of the atmosphere, as represented by GCM outputs using empirical relationships established from long-term historical data (Wilby *et al.*, 1998). A few decades of quality-controlled

observations are required for using SDMs to calibrate statistical models. The quality of climate data derived from SDMs, especially precipitation extremes, is sensitive to the observed data used for statistical model calibration. An additional well-known limitation of SDMs is that the spatial resolution and the coverage of climate data derived from these methods depend on the density of observation networks, as SDMs typically generate climate data station by station (Wilby *et al.*, 2004).

For these reasons, high-quality and high-resolution gridded daily precipitation datasets are called for. Such datasets can be obtained by applying advanced spatial interpolation methods to accurate long-term observation data. Recently, a gridded daily precipitation dataset with a grid interval of 0.05° has been released for Japan (APHRO_JP; Kamiguchi *et al.*, 2010). This dataset is based on gauge data collected at over 1300 Automated

Meteorological Data Acquisition System (AMeDAS) stations. The data are further refined using a combination of spatial interpolation methods to reduce the estimation error in mountainous areas and in frequency of heavy precipitation.

In this study, we compared the daily precipitation indices in the present-day and future climate conditions derived from the two types of statistical downscaling simulations in Japan: one simulation was achieved by applying the cumulative distribution function-based downscaling method (CDFDM; Iizumi *et al*., 2010; 2011) to the state-of-the-art gridded dataset APHRO_JP, and the other simulation was conducted by applying the same downscaling method to the 'simple' gridded daily precipitation dataset, that is, the linearly interpolated AMeDAS data. We then highlighted the added values for the coarse-resolution GCM outputs achieved by the incorporation of the APHRO_JP dataset into the statistical downscaling simulations, through a comparison between the simulations using the two types of observation datasets.

2. Data and Methods

2.1 Observed daily precipitation datasets

The AMeDAS used for this study include a dense gauge observation network, of which the average distance between the stations was 17 km. For the statistical model calibration, we used two types of gridded daily precipitation datasets over Japan, the linearly interpolated AMeDAS (simple) dataset and the APHRO_JP dataset. The simple dataset, with a grid interval of 0.2°, was provided by applying the inverse distance weighted average method to the daily precipitation data collected from 742 AMeDAS stations. These stations are less densely arrayed in the mountainous areas of Japan (Fig. 1). Stations to be used were selected from over 1,300 AMeDAS stations for which less than 20% of the data were missing for every month during the 20-year study period (1985-2004) to avoid errors in estimating the daily precipitation indices. The average horizontal distance between selected stations was over 25 km. The precipitation value at a grid point was calculated from the precipitation values at eight neighboring stations (and not from the ratio of the precipitation value to the climatological mean). Orographic effects on precipitation were not considered in the spatial interpolation, and very small amounts of interpolated precipitation were not truncated. For these reasons, the AMeDAS dataset is referred to as the 'simple' dataset.

The APHRO_JP dataset is a quality-controlled, high-resolution gridded daily precipitation dataset for Japan that covers the more than 100-year period since 1900 (Kamiguchi *et al*., 2010). The APHRO_JP dataset was obtained by applying a combination of spatial interpolation methods, *i.e*., the Spheremap and mountain mapper methods (Willmott *et al*., 1985; Schaake *et al*., 2004), to the gauge data of a dense network of observation stations while considering the effects of orography
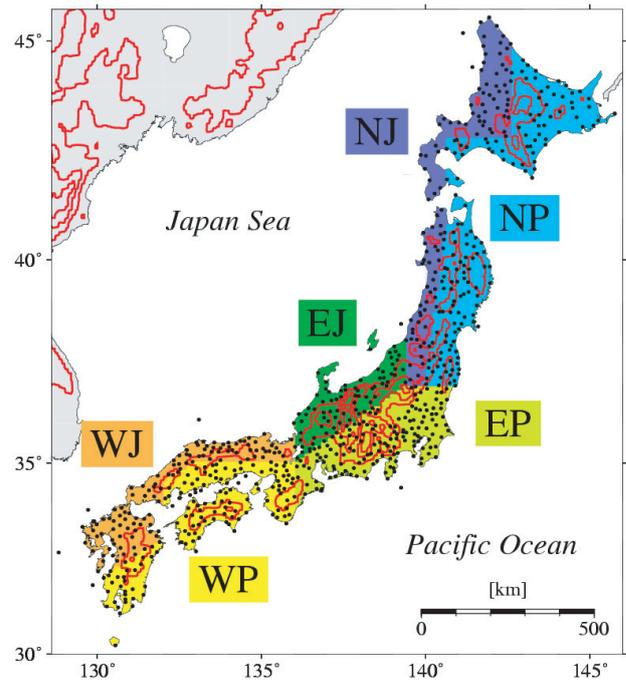

Fig. 1 AMeDAS stations used for providing the simple dataset (see Section 2.1; black dots). Areas are indicated by different colors: North Japan/Japan Sea side (NJ); North Japan/Pacific side (NP); East Japan/Japan Sea side (EJ); East Japan/Pacific side (EP); West Japan/Japan Sea side (WJ); and West Japan/Pacific side (WP). Altitudes are indicated by red lines spaced every 500 meters.

and network bias on precipitation in mountainous areas. For the time period analyzed in this study (1985-2004), the APHRO_JP dataset includes gauge data from surface observation stations of the Japan Meteorological Agency (JMA) (the number of stations varied by year up to a maximum of 158) as well as from over 1,300 AMeDAS stations. Thus, the APHRO_JP dataset utilized a substantially larger amount of data than the simple dataset. The quality of daily precipitation data was substantially controlled, based on the system developed in the APHRODITE project (Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources; available at http://www.chikyu.ac.jp/precip/). In this study, the APHRO_JP data were spatially aggregated to a grid interval of 0.2° from the original interval of 0.05° for consistent comparison with data from the simple dataset.

2.2 Statistical downscaling method

For this study, we used the CDFDM (Iizumi *et al*., 2010; 2011), which is a bias correction-type statistical downscaling method. Bias correction-type SDMs estimate the condition of a climate element at a station through a statistical bias correction of the same climate element derived from a GCM. These methods are generally simpler than 'sophisticated' statistical downscaling methods (*e.g*., weather typing methods, regression-type methods, and weather generator techniques; Wilby *et al*., 2004). Due to this simplicity, there is some controversy as to whether bias correction-type SDMs fall into the

category of statistical downscaling methods (see Schmidli *et al.*, 2006; Iizumi *et al.*, 2011). However, these methods certainly bridge the coarse-resolution GCM outputs and climate inputs required for impact models. Therefore, in this study, we consider bias correction-type methods to be statistical downscaling methods in a broader sense.

The CDFDM uses daily precipitation data from a GCM (or reanalysis data) as the predictor of local precipitation. In the CDFDM algorithm, the GCM error is defined for each position of cumulative distribution, F, on the basis of the empirical cumulative distribution functions (CDFs) of daily GCM outputs and observed data for the long-term calibration period. The defined GCM error (referred to as the F-e relationship) is then removed from the empirical CDF of daily GCM outputs for a downscaling period, with the assumption that the F-e relationship does not change with time. This assumption is similar to the stationarity assumption used in other SDMs. Compared to quantile-quantile mapping (Wood *et al.*, 2004), which is a CDF-based statistical bias correction method, the CDFDM method can incorporate changes in maximum precipitation values on the basis of GCM projections. In contrast, the maximum precipitation values derived from quantile-quantile mapping are constrained to be equal to those of the existing observations, even in altered climate conditions.

In this study, the F-e relationship was provided for warm (May-October) and cold (November-April) seasons, respectively, after confirming the results in which the 6-month periods produced a slightly better representation of daily precipitation indices than other time periods (monthly and yearly). We applied the CDFDM to each grid point of the re-gridded APHRO_JP dataset and simple one, respectively. The statistical downscaling simulations of daily precipitation were performed using the high-resolution version of the Model for Interdisciplinary Research On Climate version 3.2 (K-1 model developers, 2004; referred to as MIROCHI) outputs under the 20th Century Climate in Coupled Model (20C3M) experiment and the Special Report on Emissions Scenarios (SRES: Nakicenovic & Swart, 2000) A1B experiment. The downscaling period corresponded to two 20-year periods, *i.e.*, 1981-2000 and 2081-2100 for the 20C3M and A1B downscaling simulation, respectively. The calibration period was commonly set for 1985-2004 for the two simulations, although there was a slight discrepancy between the calibration and downscaling periods for the 20C3M experiment. We believe the error associated with this discrepancy to be small.

2.3 Daily precipitation indices

Four types of diagnostics of daily precipitation (called daily precipitation indices) listed in Table 1 were evaluated. Namely, (1) mean precipitation, MEA; (2) number of wet days, FRE; (3) 90th percentile of daily precipitation, Q90; and (4) maximum number of consecutive dry days, CDD. A wet day was defined as a day with

Table 1 Diagnostics of daily precipitation (daily precipitation indices) used in this study.

Index	Description	Unit
MEA	Mean precipitation	mm/day
FRE	Number of wet days (≥1 mm/day)	fraction
Q90	90th percentile of daily precipitation	mm/day
CDD	Maximum number of consecutive dry days (< 1 mm/day)	days

precipitation ≥1 mm/day. All indices except for Q90 were calculated for each month and the index values for three months were averaged to obtain a seasonal value. The calculated seasonal value was averaged for the 20 years and used in the analysis. We used a simple approach to calculate Q90. In practice, Q90 was calculated for each month from the empirical CDF of daily precipitation, consisting of 28-31 days x 20 years. No fitting of a parametric probability distribution was conducted to avoid any fitting errors. Seasonal mean Q90 values were calculated by averaging monthly Q90 values for the corresponding months.

3. Results

3.1 Bias of the simple dataset

Figure 2 shows the geographical pattern of mean winter (December, January, and February; DJF) and summer (June, July, and August; JJA) precipitation (MEA) calculated from the two types of observation datasets and of the GCM outputs downscaled by the CDFDM using each of the observation datasets. The two types of observation datasets have comparable geographic patterns (Fig. 2a-b). However, compared to the APHRO_JP dataset, the simple dataset underestimated the mean winter precipitation by over 10% on the northwest (windward) side of the mountains facing the Sea of Japan and overestimated it by over 10% on the southeast (leeward) side of the mountains (Fig. 2c). The simple dataset also underestimated the mean summer precipitation in the mountains and overestimated it in the basins and on the plains (Fig. 2i). On the other hand, compared to the APHRO_JP dataset, the simple dataset overestimated the number of wet days (FRE) on the southeast (leeward) side of the mountains facing the Pacific Ocean in winter (Fig. 3c). A similar geographical pattern of bias for the simple dataset was found for Q90 and CDD (figures not shown).

These differences between the two observation datasets were attributed to the following factors. In the simple dataset, the maximum value of daily precipitation in the mountains is constrained by the observed values at nearby stations that are often located in the plains: the result is a lower value of daily precipitation on the windward side of the mountains for the simple dataset. In addition, the simple dataset spatially interpolated precipitation events in the plains to the leeward side of the mountains without accounting for the mountains' rain shadows: this causes more frequent precipitation events to be reported in such areas. We therefore emphasize that

the APHRO_JP dataset is more realistic than the simple one from the viewpoint of the orographic effects on precipitation.

The CDFDM accurately estimated the geographical pattern of the mean precipitation data from MIROCHI-20C3M output. The mean precipitation bias of the GCM output downscaled using the simple dataset, relative to the GCM output downscaled using the APHRO_JP dataset, varied little regardless of the season (Fig. 2c, f, i, and l). This indicates that the downscaled GCM output has statistical characteristics similar to the observation dataset used for the statistical model calibration. This finding is also applicable to the other daily precipitation indices, such as the number of wet days FRE (Fig. 3c, f, i,

and l).

The area-mean bias of the daily precipitation indices for the simple dataset, relative to the APHRO_JP dataset, was calculated for six areas in Japan and summarized in Fig. 4 (see Fig. 1 for the areas). Compared to the APHRO_JP dataset, the simple dataset frequently underestimated the mean precipitation (MEA) and 90th percentile of daily precipitation (Q90) in most areas, whereas the simple dataset showed more frequent wet days (FEA) and shorter consecutive dry days (CDD) in all areas for both winter and summer. For all daily precipitation indices, the downscaled GCM output under the present-day climate condition (20C3M) took over the bias of the simple dataset. Similar results were found for
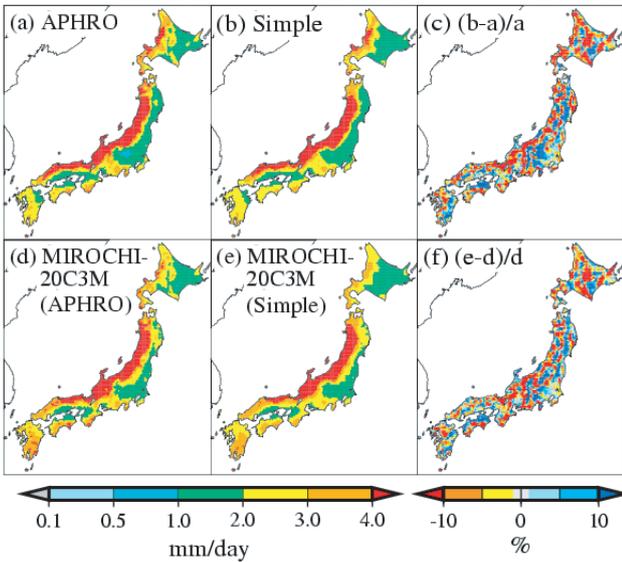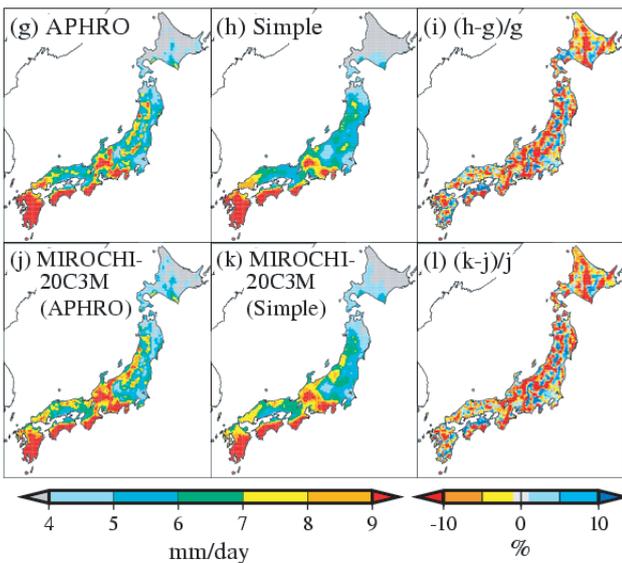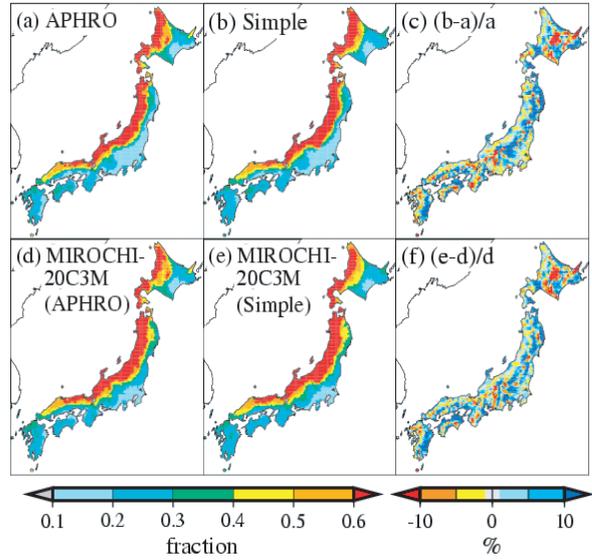

Fig. 2 Geographical pattern of mean winter (DJF) and summer (JJA) precipitation (MEA) for (a and g) the APHRO_JP dataset, (b and h) the simple dataset, MIROCHI-20C3M outputs downscaled using (d and j) the APHRO_JP or (e and k) simple dataset, and (c, f, i, and l) the bias of the MEA for the simple dataset, relative to the APHRO_JP dataset (presented in percentages).
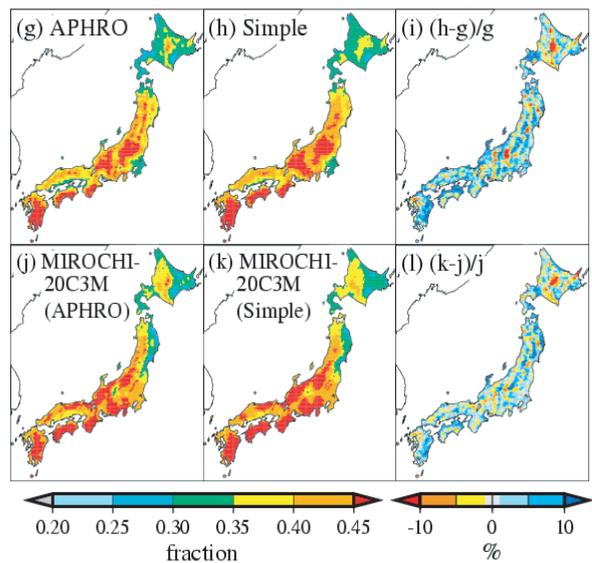
Fig. 3 Geographical pattern of mean winter (DJF) and summer (JJA) number of wet days (FRE) for (a and g) the APHRO_JP dataset, (b and h) the simple dataset, MIROCHI-20C3M outputs downscaled using (d and j) the APHRO_JP or (e and k) simple dataset, and (c, f, i, and l) the bias of the FRE for the simple dataset, relative to the APHRO_JP dataset (presented in percentages).
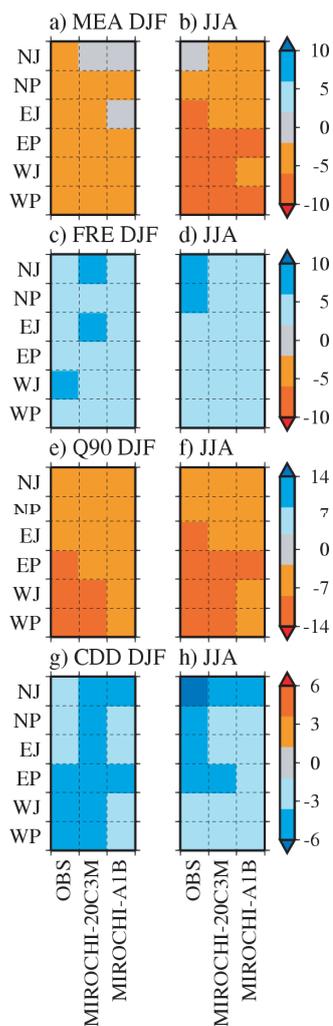
Fig. 4 Bias of the simple dataset, relative to the APHRO_JP dataset, for mean winter (DJF) and summer (JJA) daily precipitation indices for six areas in Japan. The bias of the simple dataset (simple minus APHRO_JP) was calculated from the observation datasets (OBS), MIROCHI-20C3M and -A1B outputs, downscaled using each of the observed datasets. (a and b) Mean precipitation, MEA; (c and d) number of wet days, FRE; (e and f) 90th percentile of daily precipitation, Q90; and (g and h) maximum number of consecutive dry days, CDD. The unit is a percentage relative to the 20-year mean value of daily precipitation indices calculated from the APHRO_JP dataset or the GCM outputs downscaled using the APHRO_JP dataset.

the downscaled GCM output under the future emission scenario (A1B).

3.2 Probability density function of daily precipitation

Figure 5 shows the probability density functions (PDFs) of summer daily precipitation (≥1 mm/day) provided from the two types of observation datasets and from the MIROCHI-20C3M output downscaled using each of the observation datasets. The PDFs were provided from the daily data for the period 1985-2004. The frequency was calculated for every 1 mm/day bin. The PDF was provided for each grid and then averaged across the grids along the bins.

The provided PDF was similar to that of Kamiguchi *et al.* (2010), but the PDF presented here showed a smaller amount of daily precipitation because of the spatial aggregation through re-gridding. The simple dataset showed a shorter tail on the heavy precipitation side as compared to the APHRO_JP dataset. In addition, the simple dataset produced a higher frequency of low precipitation (around 1 mm/day). The downscaled MIROCHI-20C3M outputs obviously took over the statistical characteristics of the observation dataset used for the statistical model calibration in terms of PDF. The daily precipitation characteristics for the simple dataset reported here were consistent with the other results. For instance, the simple dataset had more frequent wet days (FRE) and lower 90th percentile values of daily precipitation (Q90) (Fig. 4c, d, e, and f).

3.3 Projected future changes and bias

Figure 6 shows the projected change in daily precipitation indices for the 2081-2100 period, relative to 1981-2000 (referred to as the 2090s and 1990s, respectively), as calculated from the MIROCHI-A1B and -20C3M outputs, downscaled using the APHRO_JP dataset. In the downscaled GCM projection, the mean winter (DJF) precipitation will decrease by up to 13% in the western areas and on the Japan Sea side of the eastern area (WJ, WP, and EJ). The number of wet days (FRE) will decrease in most areas except for the Pacific side of the northern area (NP) in winter. Heavy precipitation (represented by Q90) will increase over Japan in winter.
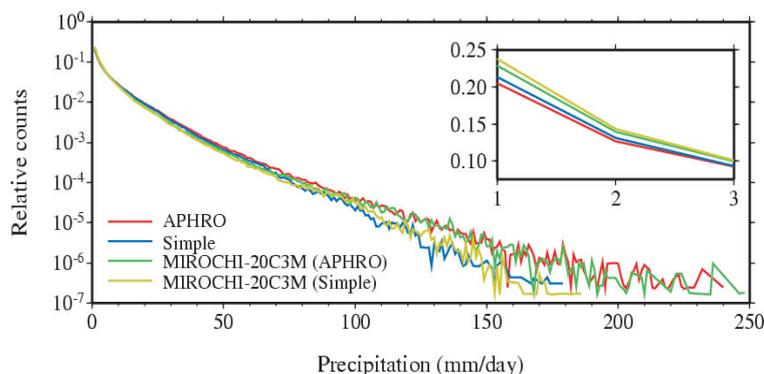

Fig. 5 Mean probability density function of summer (JJA) daily precipitation (≥1 mm/day) averaged over the grids for the two types of observation datasets (the APHRO_JP and simple datasets) and MIROCHI-20C3M outputs downscaled using each of the observation datasets.

The maximum number of consecutive dry days (CDD) in winter will be increased in all areas except for the Pacific side of the northern area (NP) as a result of the decrease in the number of wet days.

For summer (JJA), the mean precipitation (MEA) and heavy precipitation (Q90) will increase by over 19% and by up to 23% in all areas, respectively. The number of wet days will increase mainly in the northern areas (NJ and NP) in summer. The change in the maximum number

of consecutive dry days (CDD) in summer is not remarkable, but it will decrease by 10% on the Pacific side of the eastern area (EP). For both winter and summer, the downscaled projected change in mean precipitation is consistent with the results of the original GCM outputs (Kimoto *et al*., 2005) in terms of the geographical pattern, amplitude, and tendency of change.

Figure 7 summarizes the projected changes in the daily precipitation indices and bias of the simple dataset,
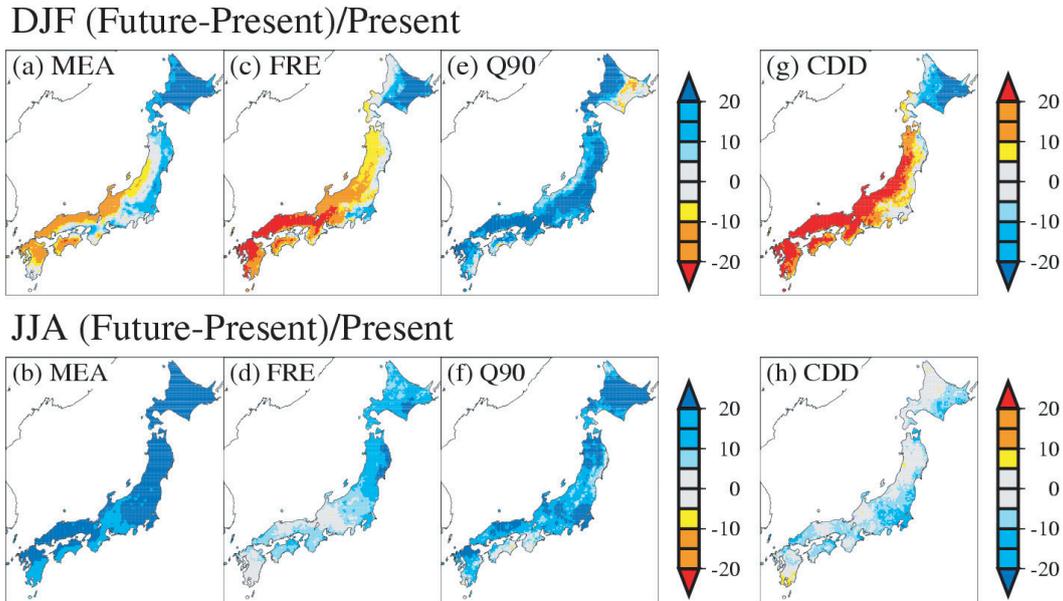

Fig. 6   Geographical pattern of the projected change in daily precipitation indices in the 2090s, relative to the 1990s, calculated from the MIROCHI-20C3M and -A1B outputs downscaled using the APHRO_JP dataset. (a and b) Mean precipitation, MEA; (c and d) number of wet days, FRE; (e and f) 90th percentile of daily precipitation, Q90; and (g and h) maximum number of consecutive dry days, CDD. Bluer colors indicate wetter conditions in future, relative to the present-day, whereas redder colors correspond to drier conditions.
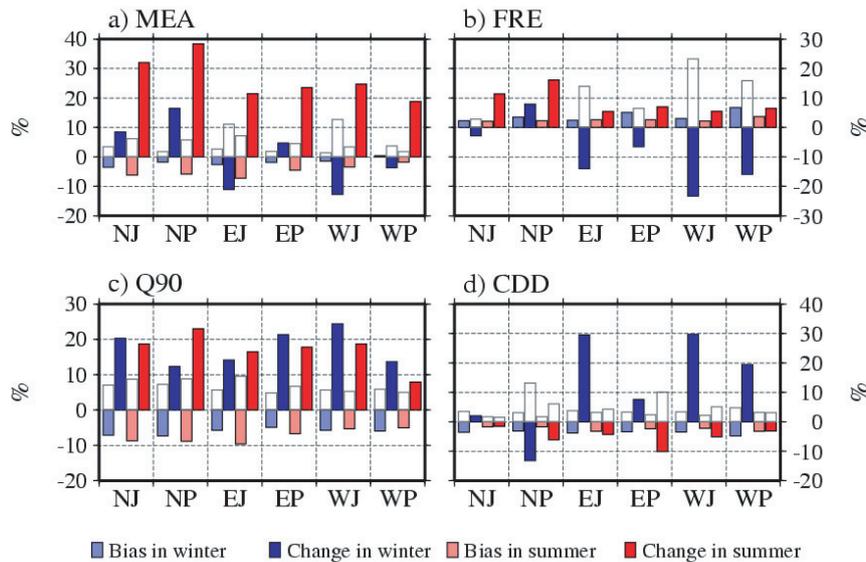

Fig. 7   Bias of the simple dataset, relative to the APHRO_JP dataset, and projected change in mean winter (DJF) and summer (JJA) daily precipitation indices for six areas in Japan. The bias of the simple dataset was calculated from the MIROCHI-20C3M outputs downscaled using each of the observation datasets (simple minus APHRO_JP). The projected change was calculated from the MIROCHI-20C3M and -A1B outputs downscaled using the APHRO_JP dataset. The unit is a percentage relative to the 20-year mean value of MIROCHI-20C3M outputs downscaled using the APHRO_JP dataset. Open bars are used when the bias or projected change is negative in order to facilitate a comparison of the absolute values of these data.

relative to the APHRO_JP dataset, for the six areas in Japan. The projected change was calculated from the MIROCHI-20C3M and -A1B outputs downscaled using the APHRO_JP dataset, whereas the bias of the simple dataset was calculated from the MIROCHI-20C3M outputs downscaled using each of the observation datasets. Both change and bias are presented in percentages relative to the same reference, *i.e.*, the 20-year mean value of the daily precipitation indices calculated from the MIROCHI-20C3M output downscaled using the APHRO_JP dataset. From Fig. 7, the amplitude of the bias was found to be smaller in many cases, but it was occasionally close to half of the projected change, indicating the possibility that the bias could be comparable in amplitude to the projected change. This possibility seems be higher for FRE and CDD than MEA and Q90.

4. Discussion

As shown in Section 3, the GCM outputs downscaled by the CDFDM take on the statistical characteristics of the observation dataset, demonstrating the sensitivity of climate data derived from SDMs to the calibration data. The bias of the daily precipitation indices for the simple dataset, relative to the APHRO_JP dataset, is occasionally non-negligible in amplitude compared to the projected change; though this conclusion was derived from a single GCM analysis. However, Okada *et al.* (2009) provided climate change scenarios over Japan for the agricultural sector using the six GCM outputs under the SRES-A1B and -A2 emission scenarios, and they showed that some GCMs projected smaller changes in mean winter and summer precipitation compared to the MIROCHI-A1B. If we consider this result, the bias of the simple dataset, relative to the APHRO_JP dataset, could be comparable to, or larger than, that of the projected change for some GCMs other than MIROCHI-A1B.

For precipitation characteristics in mountainous areas, the APHRO_JP dataset showed relative improvements in data quality compared to the simple dataset. The relative improvements in the APHRO_JP dataset are pronounced for mean precipitation values in mountainous areas, for precipitation frequency on the leeward side of mountains, and for the intensity and frequency of heavy precipitation. These relative improvements are taken over the climate change scenario derived from the SDMs. The incorporation of the APHRO_JP dataset into statistical downscaling simulations thereby offers a better representation of daily precipitation indices under the present-day climate condition as well as a possibility to produce climate change scenarios based on more realistic estimates of historical precipitation. The incorporation of the APHRO_JP dataset can significantly improve the findings of impact and adaptation studies in the field where precipitation in mountainous areas plays a central role: for instance, in studies of hydrological regimes, irrigation planning, and risk assessments of water-related disasters (floods, droughts and land slides).

As demonstrated in this study, the quality-controlled, high-resolution gridded daily dataset represented by the series of precipitation products developed in the APHRODITE project (Yatagai *et al.*, 2008) is a highly beneficial data source for statistical downscaling simulations, and enables modelers to overcome many of the known limitations of SDMs. Gridded datasets for climate elements other than precipitation over Japan and other regions could support achievement of more realistic statistical downscaling simulations and be beneficial in conducting climate impact and adaptation studies on a regional scale. To examine the stationarity assumption of the F-e relationship across various climate zones and at various time scales may be a further study.

5. Conclusions

In this study, we highlight the improvements to the statistical downscaling simulations of coarse-resolution GCM outputs by incorporating the APHRO_JP advanced gridded daily precipitation dataset. These improvements are significant relative to the results achieved by simulations using a simple dataset. Specifically, the APHRO_JP dataset produced improved data quality in terms of the statistical characteristics of daily precipitation data compared to the results obtained using the simple dataset: the improvements are most pronounced for mean precipitation in mountainous areas, precipitation frequency on the leeward sides of mountains, and the intensity and frequency of heavy precipitation.

These improvements, resulting from the incorporation of the APHRO_JP dataset, yield better results for climate change scenarios derived from SDMs (CDFDM). On a regional scale, the bias of the daily precipitation indices for the simple dataset, relative to the APHRO_JP dataset, is occasionally comparable in amplitude with the projected change. The bias associated with the choice of observation datasets potentially affects the results of impact and adaptation studies on hydrological regimes, irrigation planning, and risk assessments of water-related disasters. It is therefore recommended that statistical downscaling simulations of coarse-resolution GCM outputs incorporate gridded observation datasets created using advanced quality control algorithms and spatial interpolation methods. Such gridded observation datasets will help reduce errors in simulating climate impacts and adaptation practices, particularly errors associated with unrealistic precipitation data derived from SDMs calibrated using biased observation datasets.

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