Assessment for the 30-Year Daily Precipitation Change due to Global Warming Using Regional Frequency Analysis

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Abstract:
This study assessed the future change of the 30-year return level of daily precipitation due to global warming for Kagoshima Prefecture, (except for the Amami Islands) in southern Kyushu, Japan, using regional frequency analysis. The 20km-mesh regional climate model (MRI-RCM20) was used for this analysis. The present climate data was reproduced for the years 1981 through 2000, and the future climate data was projected for the years 2081 through 2100 under the greenhouse gas emission scenario SRES A2. Over Kagoshima Prefecture, the future change of the regional average of annual maximum daily precipitation was projected to increase by only 3.3%. However, the quantile that corresponds to the non-exceedance probability of the 30-year return level was projected to increase by 14.5%. As a result, in Kagoshima Prefecture, the 30-year return level of daily precipitation was projected as likely to increase by 18.3% in about one hundred years.

KEYWORDS global warming; 30-year daily precipitation; regional climate model; regional frequency analysis

INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007), it is very likely that heavy precipitation events will continue to become more frequent due to global warming. As an adaptation to climate change, the accurate assessment of the possible future change in extreme precipitation is an important issue for river projects, infrastructure improvements, and similar activities.

Both the 20km-mesh global climate model (MRI-GCM20) and the 20km-mesh regional climate model (MRI-RCM20) were recently developed by the Meteorological Research Institute (MRI) to project future climate change. These models were able to reproduce the present local climate that is characterized by the complicated mountainous geography of Japan (Kurihara et al., 2005; Mizuta et al., 2006). The projection results of these climate models have been used to assess the potential future change of hydrological risk (e.g. Sayama et al., 2008; Wada et al., 2008).

However, the detailed integration periods of these climate models are usually only 20 years for both the present climate and the future climate under a greenhouse gas emission scenario, and a reliable assessment of the future change in rainfall with a long-term return period at each grid site is difficult, due to the limited number of samples (Takara and Takasao, 1988). Moreover, in general, the smallest scale of weather events which are able to be represented by a climate model is only a few times the size of the horizontal resolution of the model. In view of these circumstances, the regional assessment of the future change in rainfall with a given return value might be more appropriate than an “at-site” analysis using data of each single point.

The regional frequency analysis introduced by Hosking and Wallis (1997) is one of the most useful regional assessment methods, and Toyama and Mizuno (2002) applied this method to all available Automated Meteorological Data Acquisition System (AMeDAS) data for the estimation of up to 1000-yr daily and hourly precipitation at each site. Fowler and Kilshy (2003) also applied this method to produce generalized extreme value growth curves for long return-period rainfall events for each of nine regions in the UK. Recently, Ishihara (2010) applied a regional frequency analysis to each prefecture in Japan, and demonstrated that it can estimate a more idealistic 30-yr daily precipitation than those estimated individually by site.

Thus, regional frequency analysis has achieved steady results as an extreme value analysis, and is one of the most appropriate methods for the assessing the future change of rainfall within a given return period due to global warming. To confirm the applicability, this study assessed the future change of the 30-yr return level of daily precipitation for Kagoshima Prefecture (except for the Amami Islands), in southern Kyushu, Japan.

DATA

This study used results obtained by the MRI-RCM20 (Kurihara et al., 2005). A historical experiment run was executed to reproduce the actual climate over Japan from 1981 to 2000 by using initial and boundary conditions from the coupled atmosphere-ocean general circulation model (MRI-CGCM2; Yukimoto et al., 2000) which was also developed by MRI. An experiment run was also executed to project the future climate over Japan from 2081 to 2100 by using initial and boundary conditions from MRI-CGCM2 under the greenhouse gas emission scenario SRES A2.

To check the reproducibility of MRI-RCM20, 18 AMeDAS stations, which had annual maximum daily precipitation data for more than 20 years, starting from the beginning of the observation through 2008, were used for Kagoshima Prefecture (except for the Amami Islands). Here, it should be noted that observation began in the late 1970’s
at most AMeDAS stations but the starting year varies with
the site. Based on MRI-RCM20 results, the nearest grid
points from those AMeDAS stations in Kagoshima
Prefecture were selected for both the present and future
climes (Figure 1).

As a result, three kinds of annual maximum daily
precipitation data at 18 sites were used in this study:

“AMeDAS data” since the beginning to 2008, “present
climate” derived from MRI-RCM20 for 1981 to 2000 and
“future climate” derived from MRI-RCM20 for 2081 to
2100 under the SRES A2 scenario.

REPRODUCIBILITY AND FUTURE CHANGE
OF PRECIPITATION

Figure 2 shows the relations between the present climate
and both the AMeDAS data (blue squares) and the future
climate (red circles) for (a) annual precipitation, and (b)
annual maximum daily precipitation.

Both graphs indicate that the present climate has the
same general tendency as the AMeDAS data. Though the
present climate overestimates the annual maximum daily
precipitation, the differences were within 20% at most sites
for both elements. The correlation coefficient between them
for the annual precipitation was 0.87, and the annual
maximum daily precipitation was 0.68. These results indicate
that MRI-RCM20 adequately reproduces the detailed
precipitation characteristics around Kagoshima Prefecture.

Both graphs also indicate that the future climate was
projected to have the same tendency as the present climate
and to be slightly wetter as a whole. The correlation
coefficient between the present and future climates for
annual precipitation was close to 1.00, and that for the annual
maximum daily precipitation was 0.81. These high
correlations indicate that the ratios of future change to
present precipitation did not vary between sites in this area.
On average, over Kagoshima region, both the future change
of the regional average of annual precipitation and the annual
maximum daily precipitation were projected to increase by
only 3.3%.

Figure 1. Geographical map of 18 sites in Kagoshima
Prefecture (except for the Amami Islands) used in this study.
A star denotes an AMeDAS station, and a circle denotes
the grid point of MRI-RCM20. A star and a circle of the
same color indicate corresponding sites.

Figure 2. Scatter plots between the present climate and both the AMeDAS data (blue squares) and the future climate (red circles) for (a) annual precipitation and (b) annual maximum daily precipitation. A square or a circle denotes an averaged value for the entire period at the site.
METHODOLOGY AND APPLICATION RESULTS

Calculation of sample L-moments and sample L-moment ratios

In general, the r-th L-moment is defined as

\[ \lambda_r = r^{-1} \sum_{j=0}^{r-1} (-1)^j \binom{r-1}{j} \mathbb{E}(X_{r-j}), \]  

(1)

where \( X_{k:n} \) denotes the k-th smallest value from a sample of size \( n \). The first L-moment is a measure of the average, the second one is a measure of the scale, the third one is a measure of skewness, and the fourth one is a measure of kurtosis.

The r-th L-moment ratio is defined as

\[ \tau_r = \lambda_r / \lambda_2, \]  

(2)

where the third L-moment ratio is known as L-skewness and the fourth one is known as L-kurtosis.

Furthermore, L-CV is defined as Equation (3).

\[ \tau = \lambda_2 / \lambda_1. \]  

(3)

L-moments \( \lambda_r \), L-CV \( \tau \) and L-moment ratios \( \tau_r \) are estimated from a finite sample in practice, and these values are nothing but estimators called “sample L-moments”, “sample L-CV” and “sample L-moment ratios”. However, according to Hosking and Wallis (1997), the biases are negligible in samples of size 20 or more and these values are regarded as unbiased estimators. In this study, estimated sample L-moments \( \lambda_r \), sample L-CV \( \tau \), and sample L-moment ratios \( \tau_r \) were used as unbiased L-moments, L-CV, and L-moment ratios, respectively.

The sample L-moments and sample L-moment ratios at 18 sites were first calculated for both the present and future climates. Table I presents sample L-CV, sample L-skewness and sample L-kurtosis, averaged over Kagoshima Prefecture. The potential future change of sample L-CV was the largest, indicating that the future change of variability was projected to be larger than that of average.

Identification of homogeneous regions

Second, the degree of heterogeneity in a region is estimated to assess whether the sites might be treated as a homogeneous region. For this estimation, first, the weighted standard deviation of the at-site sample L-CV at site \( i \) (total number \( N \)), respectively, and \( \bar{R} \) denotes regional average sample L-CV which are weighted proportionally to the sites’ sample record length \( n_i \) and expressed in equation (4),

\[ V = \left[ \sum_{i=1}^{N} n_i (R_i - \bar{R})^2 / \sum_{i=1}^{N} n_i \right]^{1/2}, \]  

(4)

where \( n_i \) and \( R_i \) denote record length and sample L-CV at site \( i \), and \( \bar{R} \) denotes regional average sample L-CV which are weighted proportionally to the sites’ sample record length \( n_i \).

Next, by fitting a Kappa distribution to sample L-moment ratios of the region, a large number \( N_{\text{sim}} \) of realizations of a region with \( N \) sites are simulated. \( V \) is calculated for each simulated region, and the mean \( \mu_V \) and standard deviation \( \sigma_V \) of the \( N_{\text{sim}} \) values of \( V \) are determined. Consequently, the heterogeneity measure \( H \) is expressed in equation (6),

\[ H = (V - \mu_V) / \sigma_V. \]  

(6)

Hosking and Wallis (1997) suggests that the region is regarded as “acceptably homogeneous” if \( H < 1 \), “possibly heterogeneous” if \( 1 \leq H < 2 \), and “definitely heterogeneous” if \( 2 \leq H \).

In this study, \( N_{\text{sim}} \) was 1000, and \( H \) was 0.83 for the present climate and 0.30 for the future climate; homogeneousities were confirmed for both data.

Choice of a frequency distribution

Third, the best frequency distribution is selected from the generalized logistic distribution (GLO), generalized extreme-value distribution (GEV), lognormal distribution (LN3), Pearson type III distribution (PE3), and generalized Pareto distribution (GPA). These distributions have three parameters given by sample L-moments and sample L-moment ratios. The goodness of fit \( Z^{\text{DIST}} \) is defined as the distance between L-kurtosis \( t_4^{\text{DIST}} \) fitted to each frequency distribution and the regional average sample L-kurtosis \( t_4^{\text{R}} \), and is expressed in equation (7),

\[ Z^{\text{DIST}} = (t_4^{\text{DIST}} - t_4^{\text{R}} + B_4) / \sigma_4. \]  

(7)

Here, \( B_4 \) denotes the bias of \( t_4^{\text{R}} \) similarly simulated with the Kappa distribution for a large number \( N_{\text{sim}} \) and is defined as

\[ B_4 = N_{\text{sim}}^{-1} \sum_{m=1}^{N_{\text{sim}}} (t_4^{[m]} - t_4^{\text{R}}), \]  

(8)

where \( t_4^{[m]} \) denotes the regional average sample L-kurtosis for the m-th simulated region. \( \sigma_4 \) denotes the standard deviation of \( t_4^{\text{R}} \), and is defined as equation (9),

\[ \sigma_4 = \left( N_{\text{sim}} - 1 \right)^{-1} \left[ \sum_{m=1}^{N_{\text{sim}}} (t_4^{[m]} - t_4^{\text{R}})^2 - N_{\text{sim}} B_4^2 \right]^{1/2}. \]  

(9)

Hosking and Wallis (1997) suggests that a reasonable criterion is indicated to satisfy \( |Z^{\text{DIST}}| \leq 1.64 \), and the best distribution is the one that has the minimum \( |Z^{\text{DIST}}| \) value.

| Table I. Regional average sample L-CV, sample L-skewness and sample L-kurtosis for the present and future climates. These regional average values were weighted proportionally to the sites’ record length. |
|-----------------|--------|--------|--------|
|                 | sample L-CV | sample L-skewness | sample L-kurtosis |
| Present climate | 0.224   | 0.220  | 0.144  |
| Future climate  | 0.280   | 0.253  | 0.165  |
In this study, \( N_{\text{sim}} \) was similarly 1000, and the same distribution was selected for both the present and future climates to exclude influence by the choice of different distributions, even though the distribution was not the best one for both data. As a result, LN3 was selected as the best common distribution. \( Z_{\text{DIST}} \) was 0.63 for the present climate and 0.08 for the future climate. Figure 3 depicts the L-moment ratio diagram for LN3, the present climate, and the future climate. This figure illustrates how well the regional averages of these data fit in LN3.

**Estimation of future change of the 30-yr daily precipitation**

Once the best frequency distribution is selected and parameters are calculated, the regional quantile function \( q(F) \) with the non-exceedance probability \( F \) is estimated. Therefore, the 30-yr return levels \( Q_i(F=0.967) \) at site \( i \) are obtained by

\[
Q_i(0.967) = l_1^{(i)} q(0.967),
\]

where \( l_1^{(i)} \) is the first sample L-moment at the site.

Consequently, the 30-yr return level of daily precipitation at each site is estimated. However, in this study, since the regional assessment for the future change of rainfall with a given return period was thought to be more appropriate, and only the regional quantile functions \( q_p(F) \) for the present climate and \( q_f(F) \) for the future climate with the non-exceedance probability \( F \) were estimated (Figure 4).

As a result, the regional quantile with the non-exceedance probability \( F = 0.967 \) for the present climate \( q_p \) (\( F = 0.967 \)) was 1.956, and that for the future climate \( q_f \) (\( F = 0.967 \)) was 2.239. Thus, the regional quantile with the 30-yr return level in Kagoshima Prefecture was projected to increase by 14.5%.

Consequently, since the annual maximum daily precipitation averaged over Kagoshima Prefecture was projected to increase by 3.3%, according to Equation (10), the regional 30-yr return level of daily precipitation in Kagoshima Prefecture was projected to increase by 18.3% (multiplication of 1.145 and 1.033) in about one hundred years.

**DISCUSSION AND CONCLUSIONS**

This study assessed the future change of the 30-yr return level of daily precipitation due to global warming for Kagoshima Prefecture (except for the Amami Islands) using regional frequency analysis. Over Kagoshima Prefecture, the future change of the regional average of annual maximum daily precipitation was projected to increase by only 3.3% on average, but the quantile that corresponds to the non-exceedance probability of the 30-yr return level was projected to increase by 14.5%. As a result, it was discovered that the 30-yr return level of daily precipitation in Kagoshima Prefecture was likely to increase by 18.3% in about one hundred years.

However, since rainfall within a given return period is a theoretical value rather than an actual measured value, it is uncertain whether the reliability of the estimated rainfall is related to the reproducibility of the climate model. To confirm this, regional frequency analysis was applied to the AMeDAS data in a similar way, and the 30-yr daily precipitation for both the AMeDAS data and the present climate was estimated at every site.

Figure 5 presents the relation between the reproducibility of the 30-yr daily precipitation and that of both the first and the second sample L-moment at every site. The
reproducibility of the 30-yr daily precipitation was highly correlated with that of the first sample L-moment. This result is natural because rainfall with a given return period at each site, estimated with regional frequency analysis, is proportional to the first sample L-moment at the site and the regional quantile value (see Equation (10)). Moreover, it was also found that the 30-yr daily precipitation was overestimated at most sites where the variability was also overestimated. This result indicates that the reproducibility of the 30-yr daily precipitation depends on that of both the average and the variability of annual maximum daily precipitation. More reliable assessments require not only appropriate extreme value analysis but also improving the climate model as well as providing well-established ways to assess the reproducibility of the model.

In this study, regional frequency analysis was applied only to Kagoshima Prefecture. Naturally, it is possible to apply this analysis to each river basin and this application to other regions will be an issue in the future.

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