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Extreme Rainfall Projection for Hong Kong in the 21st Century using CMIP5 Models

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利用 CMIP5 模式推算香港 21 世紀極端降水

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摘要

本文利用政府間氣候變化專門委員會第五份評估報告中的 CMIP5 模式逐日數據進行降尺度統計分析以推算 21 世紀香港極端降水的變化。綜觀各溫室氣體濃度情景的推算結果，可見在高溫室氣體濃度情景下，香港平均降雨強度會增加，極端降雨（日雨量≥100 毫米）日數會由 1986-2005 年平均每年 4.2 日增加至本世紀末(2091-2100 年)的 5.1 日。每年最高單日、連續三日雨量也會上升。然而，每年最長連續乾旱日數亦同時增加。

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Abstract

CMIP5 model daily data used in the IPCC Fifth Assessment Report were statistically downscaled to project the extreme rainfall in Hong Kong in the 21st century. Looking at the projection results for different greenhouse gas concentration scenarios, it could be seen that daily rainfall intensity would increase under the high greenhouse gas concentration scenario, with the annual number of extreme rainfall days (daily rainfall ≥ 100 mm) increasing from 4.2 during 1986-2005 to 5.1 by the end of this century (2091-2100). The annual maximum daily and 3-day rainfall would also increase. Nevertheless, the annual maximum number of consecutive dry days would increase at the same time as well.

1. Introduction

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change(IPCC, [1]) projected that extreme rainfall was expected to increase over most land areas with increasing global temperature. These projections were based on a set of global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) which had a typical resolution of 200 x 200 km, meaning that downscaling would be required to generate local-scale climate projections for impact assessment.

In 2005, the Hong Kong Observatory carried out a statistical downscaling study on rainfall projections for Hong Kong [2] based on projections made in the Third Assessment Report of IPCC. The rainfall projections were subsequently re-assessed in 2008 [3] and 2011 [4] using data of improved climate models and advanced statistical downscaling methods.

In this study, CMIP5 model daily data under the four greenhouse gas concentration scenarios, i.e. RCP2.6 (low), RCP4.5 (medium-low), RCP6.0 (medium-high), RCP8.5 (high), are statistically downscaled to project the changes in extreme rainfall in Hong Kong for the 21st century. Section 2 presents the data used in this study including observations, re-analysis data and CMIP5 model data; Section 3 describes the statistical downscaling methodology; results are presented in Section 4, followed by concluding remarks in Section 5.

2. Data

2.1 Observation and re-analysis

Historical daily rainfall data recorded at the Hong Kong Observatory (HKO) during 1966-2005 are used for training and verification purposes in the statistical downscaling process. Surface and upper-air parameters of the NCEP 20thCentury Re-analysis Version 2 (20CR, [5]) averaged over southern China and the northern part of the South China Sea (108-120^{o}E, 16-30^{o}N) are examined as large-scale predictors in constructing the statistical downscaling models. The NCEP 20CR data have a horizontal resolution of 2 x 2 degrees.

2.2 CMIP5 model data

Daily data of a number of CMIP5 models (Table 1) with different horizontal resolution are acquired from the Program for Climate Model Diagnosis and Intercomparison website (http://pcmdi9.llnl.gov). There are 23 models offering projections (2006-2100) under the RCP4.5 and RCP 8.5 scenarios but only 13 and 11 models for the RCP2.6 and RCP6.0 scenarios respectively. Historical simulations of the CMIP5 models during the period 1966-2005 are used to evaluate the statistical downscaling models while future simulations under the four scenarios are used to generate projections for Hong Kong. To match the horizontal resolution of NCEP 20CR data, CMIP5 model data are re-gridded using bi-linear interpolation to a resolution of 2 x 2 degrees.

3. Methodology

3.1 Statistical downscaling

Global climate models used for climate studies and climate projections are usually run at a coarse spatial resolution, which are inadequate to represent sub-grid scale features. There are two downscaling approaches: dynamical downscaling and statistical downscaling. Dynamical downscaling involves the use of a regional climate model and is computationally demanding. Here, we adopt the statistically downscaling approach because of its computation economy and its comparable skill against dynamical downscaling.

3.2 Predictor selection

Six predictor sets are used for the statistical models (Sections 3.4, 3.5) in this study to ensure that the climate projections cover and reflect the uncertainties of models as well as the choice of predictors. These six predictor sets have increasing complexity while maintaining a balance between the number of thermo-dynamical and atmospheric circulation parameters contributing to the statistical downscaling process.

Set 1: Rainfall
Set 2: Rainfall, mean sea level pressure
Set 3: Rainfall, mean sea level pressure, 850-hPa relative humidity
Set 4: Rainfall, mean sea level pressure, 850-hPa relative humidity, 850-hPa wind (zonal and meridional)
Set 5: Rainfall, mean sea level pressure, 850-hPa relative humidity, 850-hPa wind (zonal and meridional), 500-hPa wind (zonal and meridional)
Set 6: Stepwise regression of Set 5

3.3 Cubic root transformation and standardization

To make daily rainfall data conform to the normal distribution, cubic root transformation is performed in the first place (only for rainfall amount model in Section 3.5). To reduce systematic biases, it is a common practice to standardize the predictors and predictands in building and applying the statistical downscaling model. Here, 1966-2005 is taken as the reference period for standardization. The standardized predictors and predictands (standardization of HKO daily rainfall only for the rainfall amount model in Section 3.5) are then used to construct the statistical model. Outcomes of the rainfall amount model in Section 3.5 will be adjusted for variance while preserving the long-term trend, de-standardized and then inversely transformed (i.e. cubed).

3.4 Rainfall occurrence model

Rainfall occurrence is a binary predictand and is commonly modelled by logistic regression [6]. The logistic model is given by:

$$p = \exp(a_o + a_1 * x_1 + \ldots a_i * x_i + \ldots a_n * x_n) / \exp(1 + (a_o + a_1 * x_1 + \ldots a_i * x_i + \ldots a_n * x_n))$$

where *p* is the probability of rainfall occurrence and x_i are the standardized predictors.

The workflow of the rainfall occurrence model is shown in Figure 1. Actual daily rainfall data at HKO are first binarized with 1 representing rain days with daily rainfall of at least 1 mm and 0 representing other situations. A regression relationship between the binary predictand and the standardized predictors is then established for each month using the historical data during 1966-2005. To determine the rainfall occurrence, a probability threshold is identified by matching the simulated probability of rainfall occurrence to the corresponding climatological rainfall occurrence. For example, if the observed ratio between rain days and dry days is 6:4, then the 40th percentile of the simulated probability of occurrence will be set as the threshold. Days with probability of occurrence greater than or equal to the threshold are counted as rain days.

3.5 Rainfall amount model

Multiple linear regression is then invoked with the daily rainfall at HKO as the predictand. The workflow of the rainfall amount model is illustrated in Figure 2. Normally, the variance of regression outcomes is smaller than that of the observations and variance adjustment is needed. Here we adopt the variance inflation method in which the regression outcomes will be multiplied by the factor:

$$\frac{\text{standard deviation of observations}}{\text{standard deviation of regression outcomes}}$$

where the standard deviations are computed over the same reference period (1966-2005). To preserve the long-term trend of the regression results, the following procedures are conducted:

(a) the regression outcomes are first de-trended by simple linear regression;
(b) variance inflation is applied to the de-trended outcomes from (a); and
(c) the linear trend obtained in (a) is then added back to the inflated outcomes from (b).

4. Results

4.1 Validation of the statistical models

Validation and projection results are based on the grand ensemble mean of projections using the six predictor sets (Section 3.2). Uncertainties of the projections are assessed through the spread of the ensemble, viz the 5th and 95th percentile of the grand ensemble. This spread is considered as the "likely range" of the projections, following the convention used in IPCC AR5.

The cross validation approach is employed to evaluate the statistical models. A block of observed daily rainfall data of five years is omitted in turn, i.e. 1966-1970, 1971-1975, 1976-1980, 1981-1985, 1986-1990, 1991-1995, 1996-2000, 2001-2005. Regression equations of the rainfall occurrence and rainfall amount models are constructed using the remaining data. The equations are then used to generate predictions for the omitted days, using NCEP 20CR data as predictors.

For the rainfall occurrence model, the total percentage of correct rainfall occurrence prediction is 78%. Figure 3 shows the predicted and observed monthly number of rain days. The correlation between the predictions and observations is 0.83 ($R^2 \sim 0.69$). The predicted daily rainfall amounts are summed up to monthly and yearly rainfall. The annual cycle of the predicted monthly rainfall shows close resemblance to the observed cycle (Figure 4). The predicted average annual rainfall during 1966-2005 is 2271 mm, 3.8% less than the observed value of 2361 mm (Table 2).

4.2 Performance in simulating the past climate

It is also essential to evaluate the performance of the statistical models using CMIP5 model data rather than re-analysis data as predictors. The downscaling results and the corresponding observed values for mean annual rainfall, daily rainfall intensity (average daily rainfall on rain days), annual number of extreme rainfall days (daily rainfall ≥ 100 mm) and annual number of rain days during 1966-2005 are summarized in Table 3. The performance in simulating annual rainfall and daily rainfall intensity is satisfactory with only a small discrepancy (less than 2%) when compared to the observations. The simulated annual number of extreme rainfall days and annual number of rain days are also close to the observed values.

4.3 Projection for the 21st century

The projected annual numbers of rain days under the RCP2.6 and RCP4.5 scenarios show slight fluctuation in the 21st century (Figures 5a-5b). However, for the RCP6.0 and RCP8.5 scenarios, the numbers are expected to be persistently below the 1986-2005 average of 102.4 days (Figures 5c-5d). For the RCP8.5 scenario, the number will drop to 96.5 days in 2091-2100, a 5.4% decrease relative to the 1986-2005 average. These results compare well with those of Sun *et al.* [7] reporting on the changes of rain days in China using direct output of CMIP5 models without any downscaling: the number of rain days would decrease over southern China under the RCP8.5 scenario but there would be little trend under the RCP2.6 and RCP4.5 scenarios (the RCP6.0 scenario not included in their study). On the other hand, the annual maximum number of consecutive dry days is expected to increase in future in all RCP scenarios compared to the 1986-2005 average (Figure 6). The increase in consecutive dry days is most prominent in the RCP8.5 scenario (Figure 6d).

The simple daily rainfall intensity index (SDII), defined as annual rainfall divided by annual number of rain days, is also examined. The index is projected to stay generally above the 1986-2005 average in this century in all RCP scenarios (Figure 7). A more prominent increasing trend in the index is shown in the RCP8.5 scenario (Figure 7d).

Figure 8 shows that there would be generally more extreme rainfall days compared to the 1986-2005 average of 4.2 days under all the scenarios, although the difference appears to be small. The increase is more prominent in the late 21st century under the RCP8.5 scenario. In addition, 76% (RCP6.0) and 73% (RCP8.5) of the models suggest an increase despite the large uncertainties reflected by the likely range of the projections. The annual maximum daily rainfall and annual maximum 3-day rainfall are expected to increase compared to the 1986-2005 average in all of the scenarios (Figure 9 and 10).

5. Concluding remarks

Daily data of CMIP5 models with different greenhouse gas concentration scenarios are statistically downscaled to examine the projected changes in different aspects of extreme rainfall in Hong Kong for the 21st century. To a certain extent, the likely ranges in the projections reflect the uncertainties of the global climate models as well as the downscaling method in simulating climate changes in the real world. However, it is also an indication that the year-to-year and decade-to-decade rainfall variabilities are likely to remain large for the rest of this century. Examination of the ensemble means of the multi-model multi-predictor-set projections reveals increasing trends for the following parameters in the 21st century: average rainfall intensity, annual extreme rainfall (both in terms of frequency and amount) and the annual maximum length of consecutive dry days. However, the annual number of rain days is expected to decrease.

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Table 1 Global climate models used in this study

Model	Center	RCP4.5	RCP8.5	RCP2.6	RCP6.0
ACCESS1-0	CSIRO	✓	✓		
BCC-CSM1-1	BCC	✓	✓	✓	✓
BNU-ESM	BNU	✓	✓	✓	
CanESM2	CCCma	✓	✓	✓	
CNRM-CM5	CNRM	✓	✓	✓	
CSIRO-Mk3-6-0	CSIRO	✓	✓	✓	✓
GFDL-ESM2G	NOAA GFDL	✓	✓		✓
GFDL-ESM2M	NOAA GFDL	✓	✓		✓
HadGEM2-CC	UKMO Had	✓	✓		
IPSL-CM5A-LR	IPSL	✓	✓	✓	✓
IPSL-CM5A-MR	IPSL	✓	✓	✓	✓
IPSL-CM5B-LR	IPSL	✓	✓		
MIROC5	MIROC	✓	✓	✓	✓
MIROC-ESM	MIROC	✓	✓		
MIROC-ESM-CHEM	MIROC	✓	✓	✓	✓
MPI-ESM-LR	MPI	✓	✓	✓	
MRI-CGCM	MRI	✓	✓		✓
Nor-ESM1-M	NCC	✓	✓	✓	✓
MPI-ESM-MR	MPI	✓	✓	✓	
ACCESS1-3	CSIRO	✓	✓		
BCC-CSM1-1-m	BCC	✓	✓	✓	✓
CMCC-CMS	CMCC	✓	✓		
CMCC-CM	CMCC	✓	✓		

Table 2 The predicted (using the cross-validation approach) and observed average yearly rainfall during 1966-2005.

Predicted (mm)	**Observed (mm)**	**Difference (mm)**	**% Difference**
2271	2361	-90	-3.8%

Table 3 Statistical downscaling results for mean annual rainfall, daily rainfall intensity, annual number of extreme rainfall days (daily rainfall ≥ 100 mm) and annual number of rain days (daily rainfall ≥ 1 mm) during 1966-2005.

	Mean annual rainfall (mm)	**Daily rainfall intensity (mm/day)**	**Annual number of extreme rainfall days**	**Annual number of rain days**
Downscaling result	2324	22.7	3.7	102.3
Observation	2361	23.0	3.9	102.4
Standard deviation of observation	493	3.4	2.0	12.6

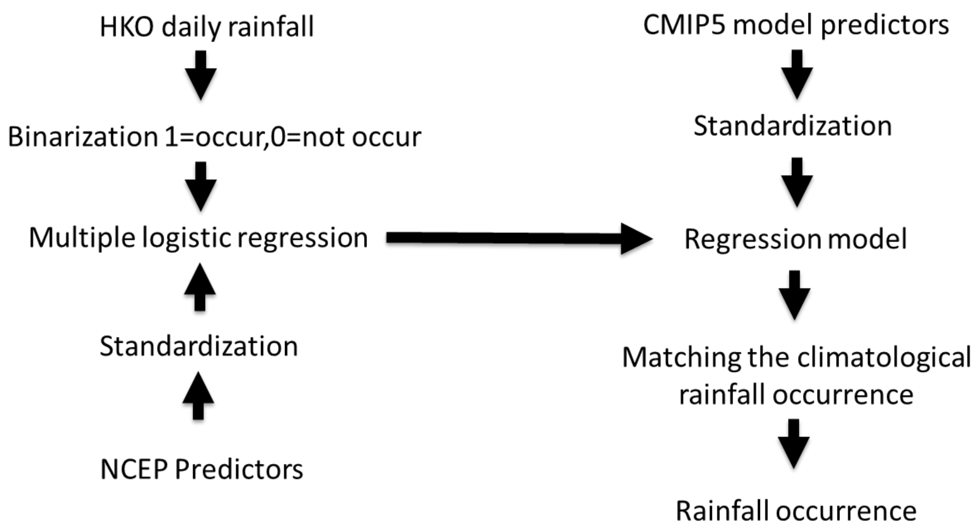

Figure 1 Workflow of the rainfall occurrence model

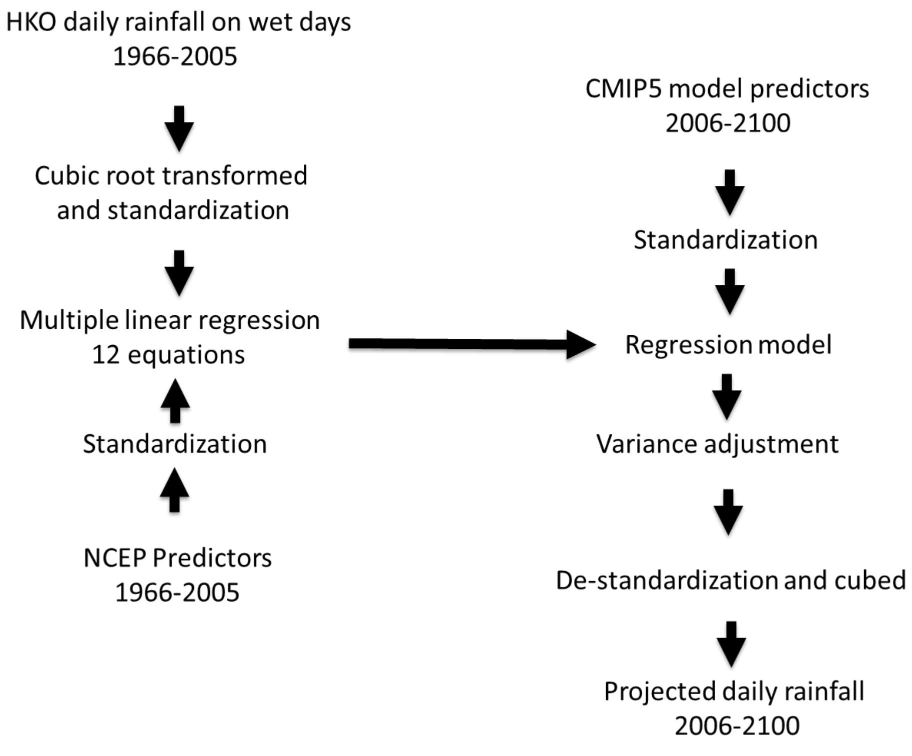

Figure 2 Work flow of the rainfall amount model.

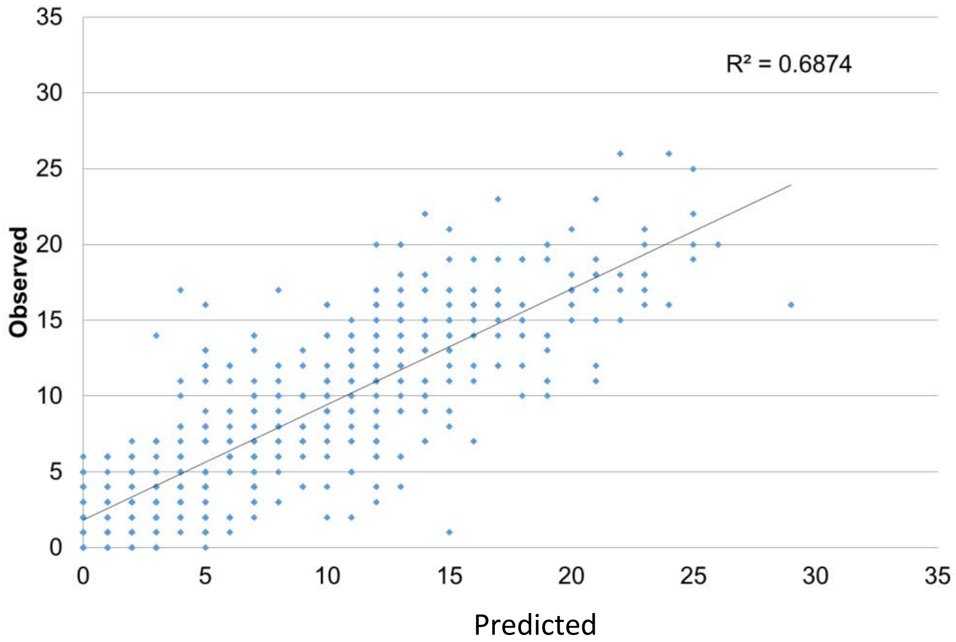

Figure 3 Predicted (using the cross-validation approach) and observed monthly number of rain days during 1966-2005.

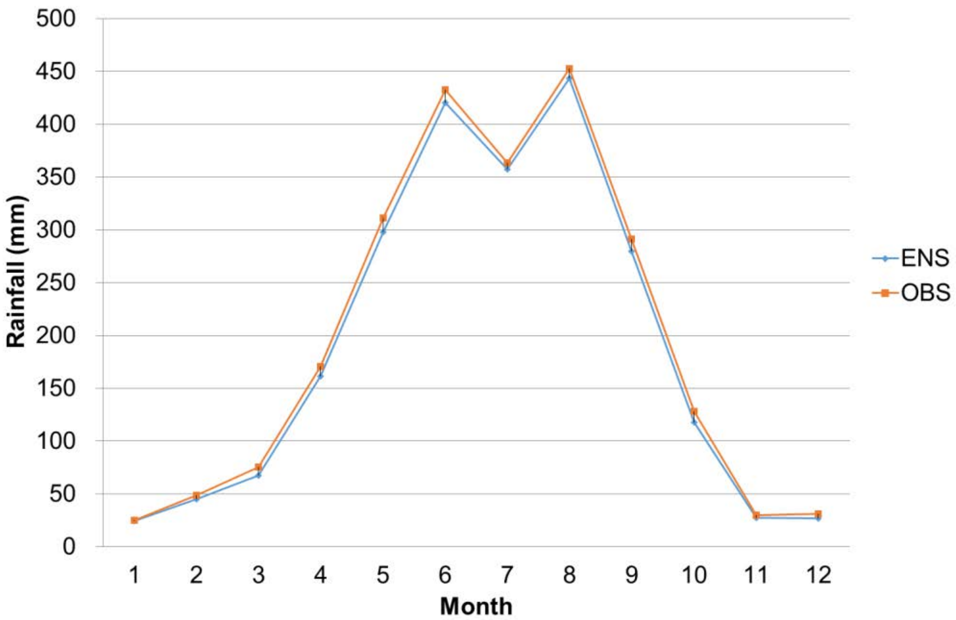

Figure 4 Predicted (blue line, using the cross-validation approach) and observed (orange line) annual cycle of monthly rainfall during 1966-2005.

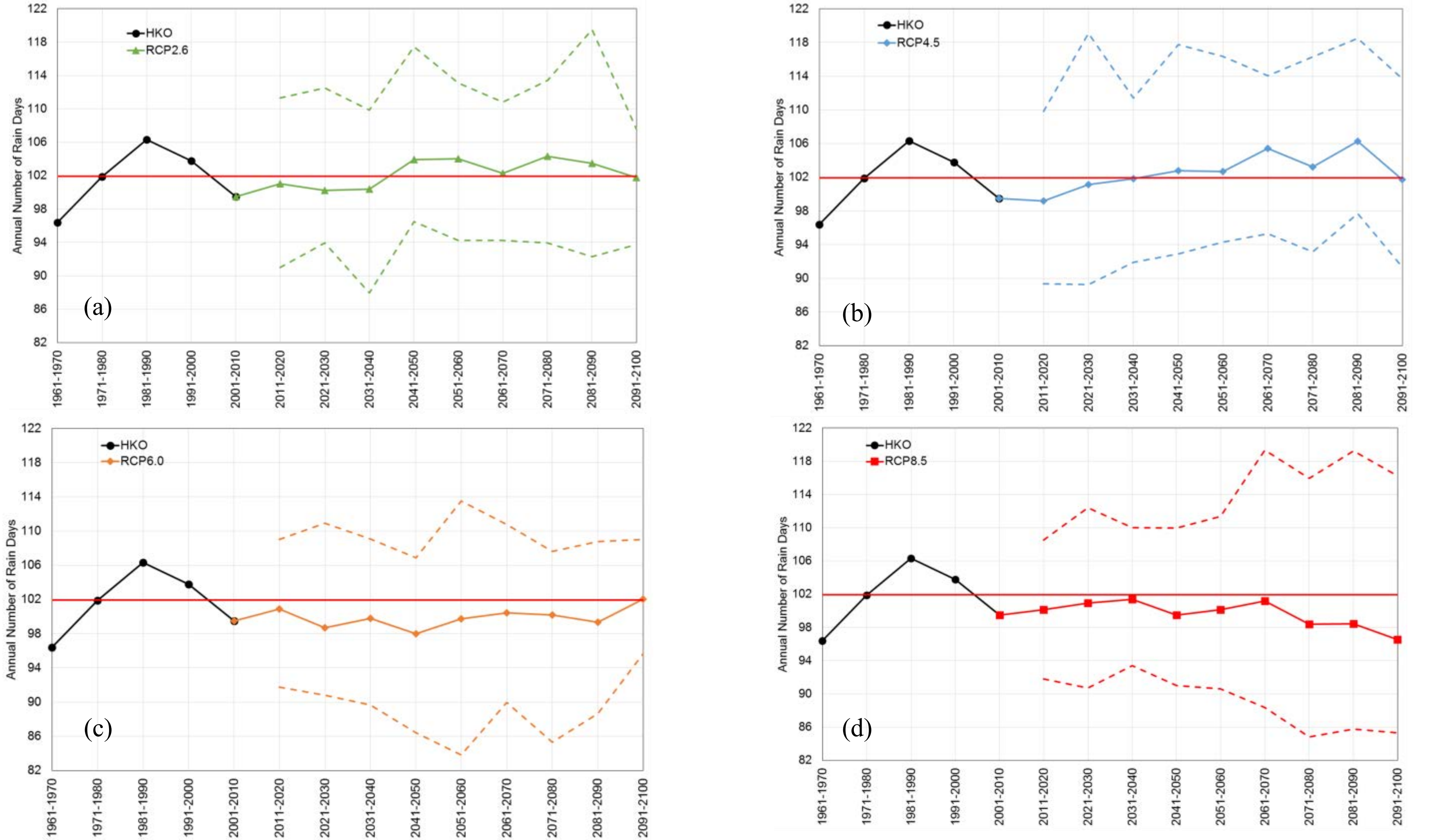

Figure 5 Projected decadal average annual number of rain days under (a) RCP2.6, (b) RCP4.5, (c) RCP6.0 and (d) RCP8.5 scenarios (solid line plots the mean value while dashed lines show the likely range of projections results). Historical observations are shown in black. The red flat line shows the 1986-2005 average of 102.4 days.

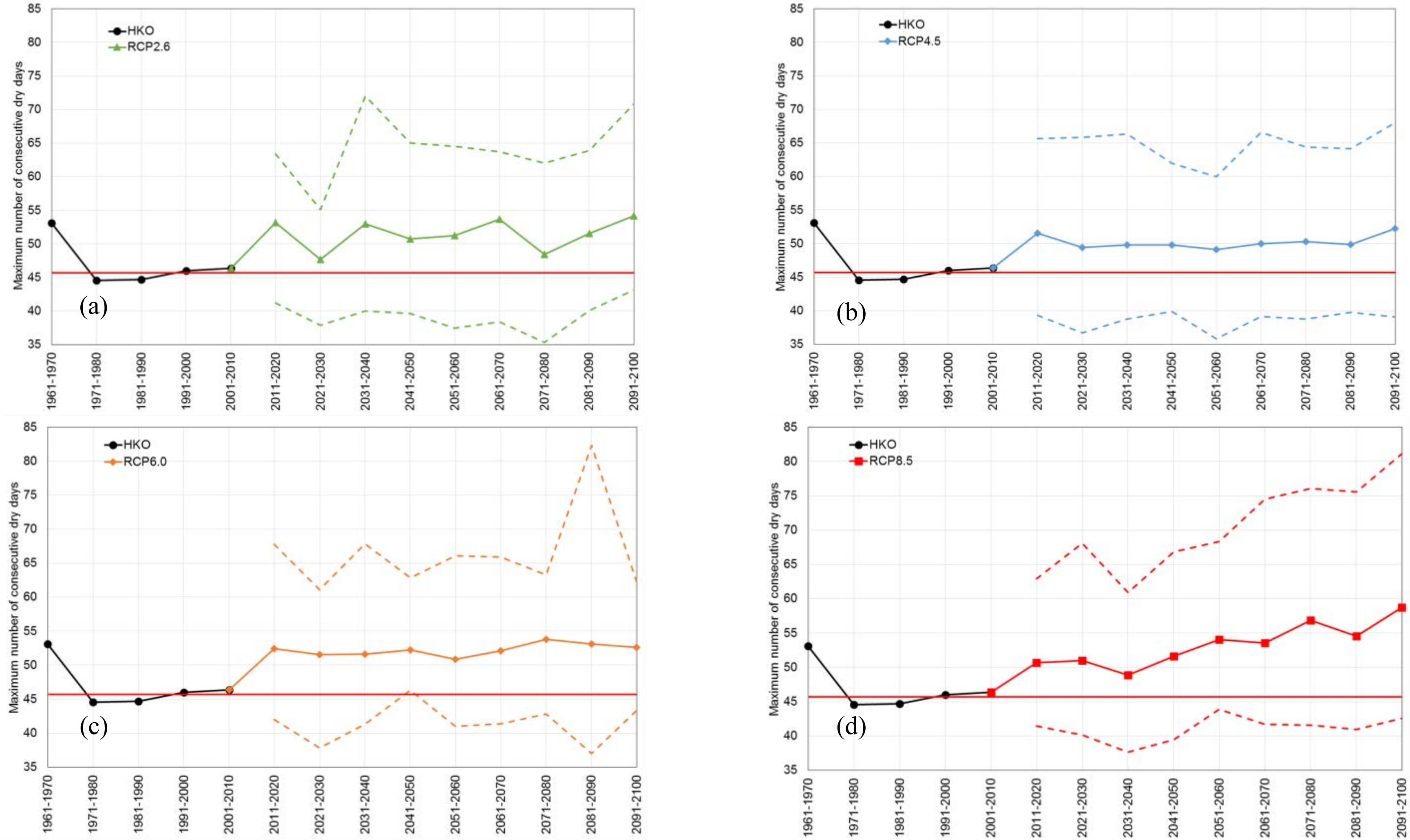

Figure 6 Projected decadal average annual maximum number of consecutive dry days under (a) RCP2.6, (b) RCP4.5, (c) RCP6.0 and (d) RCP8.5 scenarios (solid line plots the mean value while dashed lines show the likely range of projections results). Historical observations are shown in black. The red flat line shows the 1986-2005 average of 45.7 days.

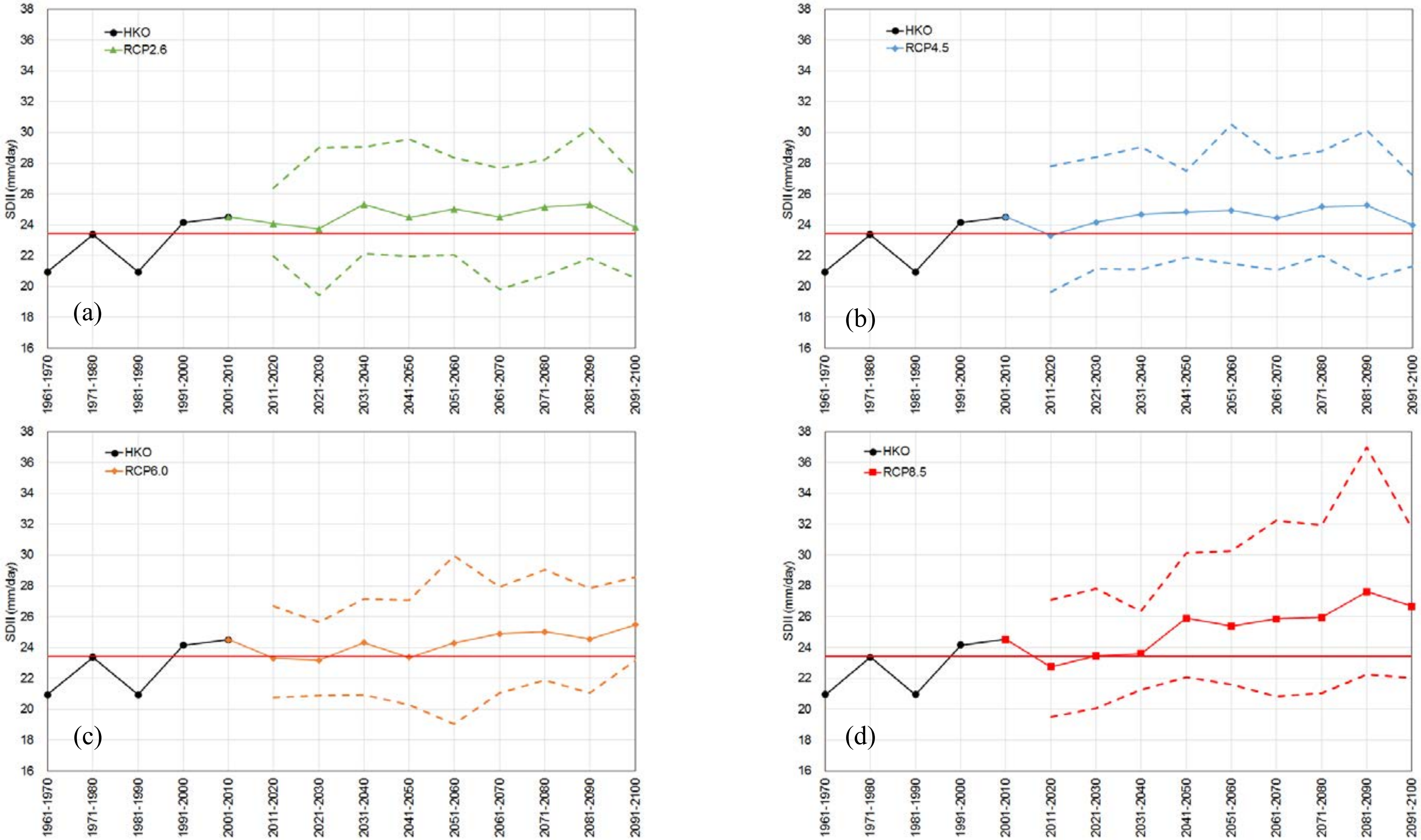

Figure 7 Projected decadal average rainfall intensity under (a) RCP2.6, (b) RCP4.5, (c) RCP6.0 and (d) RCP8.5 scenarios (solid line plots the mean value while dashed lines show the likely range of projections results). Historical observations are shown in black. The red flat line shows the 1986-2005 average of 23.4 mm/day.

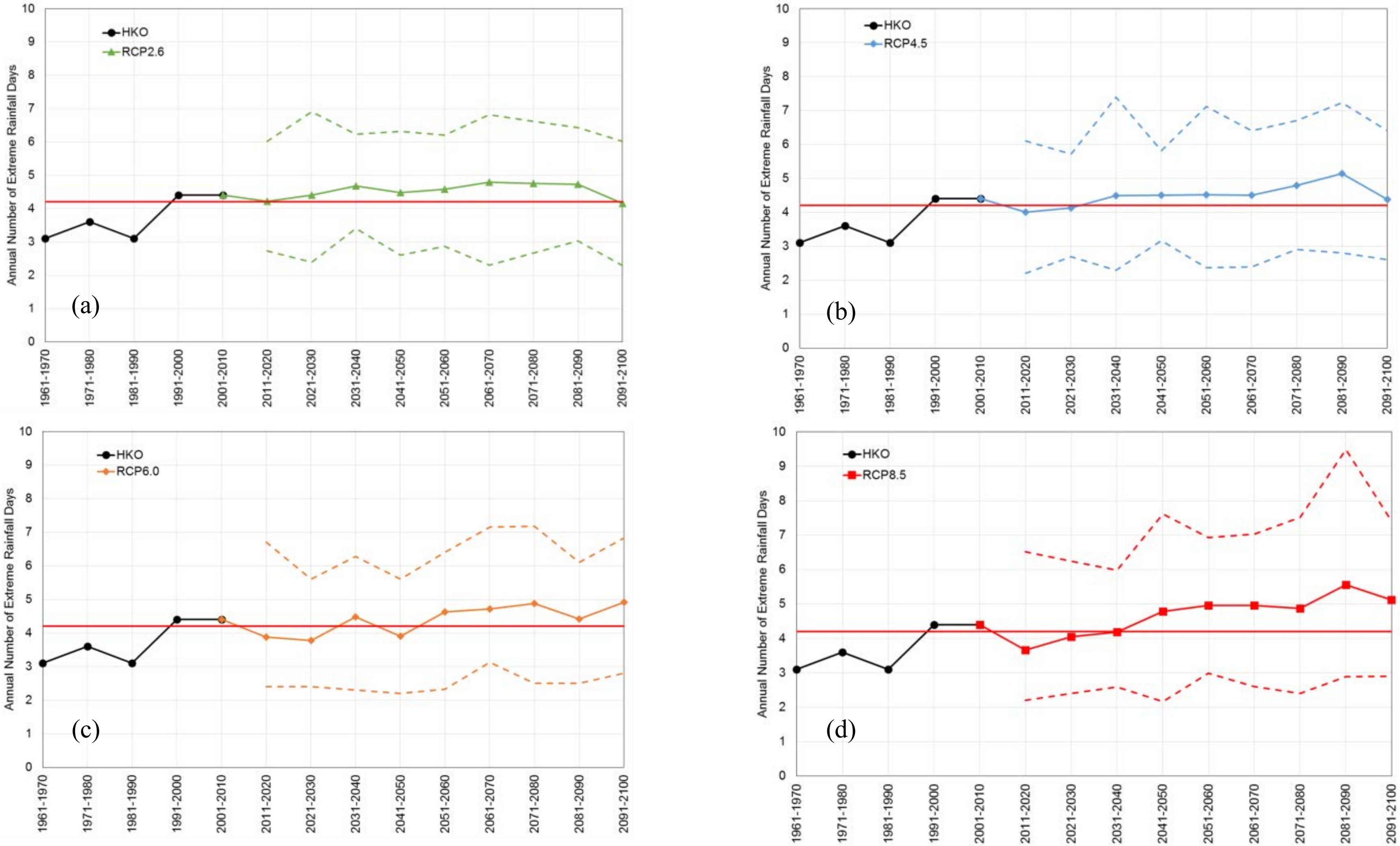

Figure 8 Projected decadal average number of extreme rainfall days under (a) RCP2.6, (b) RCP4.5, (c) RCP6.0 and (d) RCP8.5 scenarios (solid line plots the mean value while dashed lines show the likely range of projections results). Historical observations are shown in black. The red flat line shows the 1986-2005 average of 4.2 days.

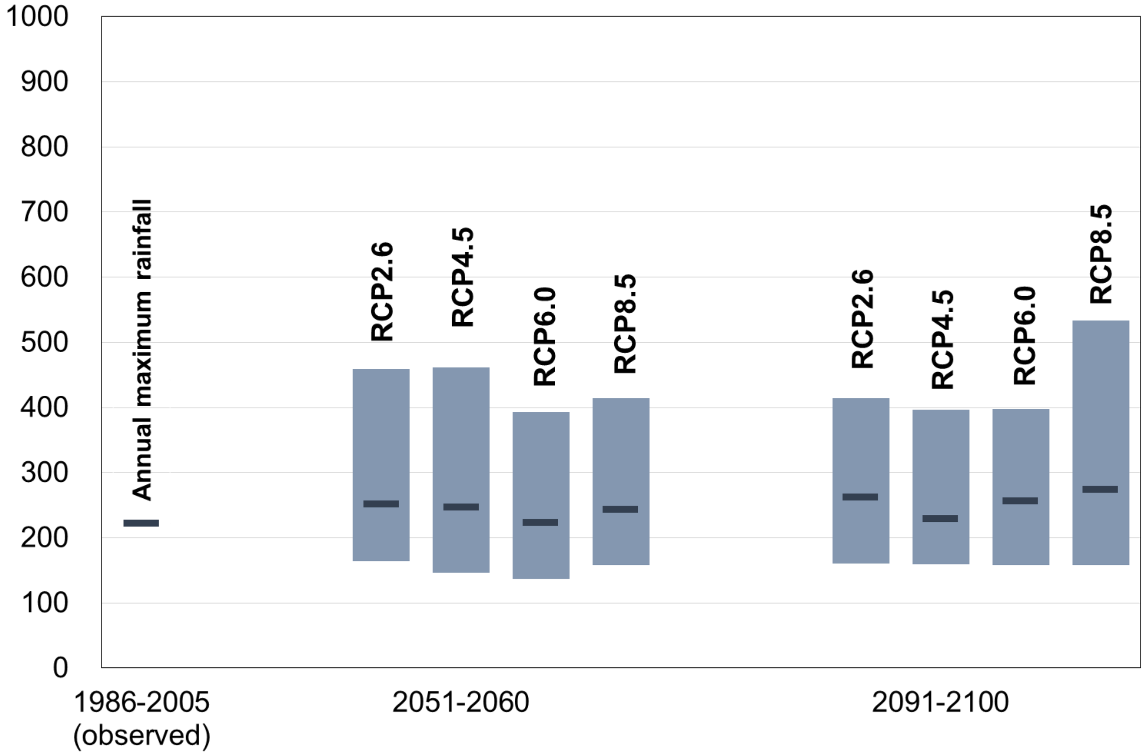

Figure 9 Projected annual maximum daily rainfall (mm) under RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios (thick line indicates the ensemble mean while shaded region shows the likely range of projections).

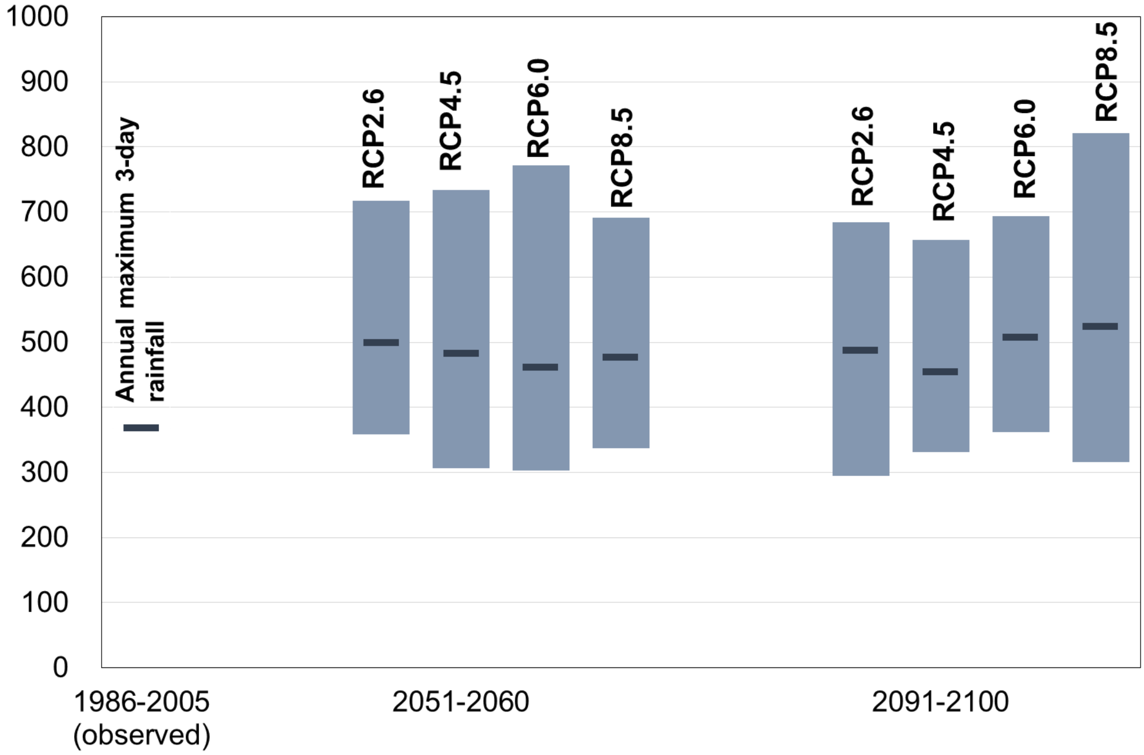

Figure 10 Projected annual maximum 3-day rainfall (mm) under RCP2.6, RCP4.5, RCP6.0, RCP8.5 scenarios (thick line indicates the ensemble mean while shaded region shows the likely range of projections).