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Rainfall Projection for Southern China in the 21st Century using CMIP5 Models

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Rainfall Projection for Southern China in the 21st Century using CMIP5 Models

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Abstract

The Working Group I contribution to the IPCC Fifth Assessment Report (AR5) was released in September 2013. In this study, rainfall projections for Hong Kong as well as other stations in southern China were undertaken to obtain an overall picture of the potential climate change impact in the region. Monthly data of a number of AR5 global climate models were statistically downscaled for projecting the rainfall trends in Hong Kong, Macao, Guangzhou, Heyuan, Shantou and Shanwei in the 21st century.

Results show that by 2081-2100, the annual rainfall for all six stations are likely to increase when compared to the average of 1986-2005 under the high greenhouse gas concentration scenario (RCP8.5). Such increasing trends, though of lesser magnitudes, are still expected for most of the stations under the medium-high (RCP6.0) and medium-low (RCP4.5) scenarios; while the signs of the rainfall trends tend to vary among the six locations under the low greenhouse concentration scenario (RCP2.6). The occurrences of extremely wet and extremely dry years are examined, and comparison is also made between these projections and the results derived from dynamical downscaling using RegCM4 with BCC_CSM1.1 as boundary conditions.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Working Group I released the Fifth Assessment Report (AR5) in September 2013, reaffirming that the warming of the climate system was unequivocal and it was extremely likely that human influence had been the dominant cause of the observed warming since the mid-20th century [1]. IPCC AR5 used a new set of global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and four new greenhouse gas (GHG) concentration scenarios, namely RCP2.6, RCP4.5, RCP6.0 and RCP8.5 to project precipitation changes in the 21st century. These scenarios were developed based on the approximate total radiative forcing in year 2100 relative to year 1750: 2.6 Wm^{-2} for RCP2.6, 4.5 Wm^{-2} for RCP4.5, 6.0 Wm^{-2} for RCP6.0 and 8.5 Wm^{-2} for RCP8.5. Under the high GHG concentration scenario of RCP8.5, the annual rainfall over East Asia was projected to increase. However, as these global climate models have a typical horizontal resolution of 200 x 200 km, too coarse for impact assessments for cities such as Hong Kong, downscaling of the projection is therefore needed.

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 view of the new set of CMIP5 models and GHG concentration scenarios, a study was initiated to update the rainfall projections for Hong Kong. Five other stations in southern China, namely Macao, Guangzhou, Heyuan, Shantou and Shanwei, were also included in the study to obtain a broader picture of the potential climate change impact in the region. Section 2 presents the data used in this study including observations, re-analysis data and CMIP5 model data, and Section 3 describes the statistical downscaling methodology. Results are presented in Section 4, followed by conclusion and discussion in Section 5.

2. Data

2.1 Observational data

Monthly rainfall of Hong Kong and the five southern China stations are the predictands of the statistical downscaling model in this study. The locations of the stations are shown in Figure 1. Historical rainfall data during the period 1961-2005 are partitioned into two groups (1961-1990 and 1991-2005) to support the construction and validation of the statistical model.

2.2 Re-analysis data

Surface and upper-air parameters of the NCEP 20th Century Reanalysis (20CR; [5]) over southern China (108-120^{o}E, 16-30^{o}N; Figure 1) are examined as large-scale predictors in constructing and validating the statistical downscaling model. The NCEP 20CR has a horizontal resolution of 2 x 2 degrees.

2.3 Global climate model data

Monthly data of a number of CMIP5 models with different horizontal resolutions are obtained from the Program for Climate Model Diagnosis and Intercomparison website (http://pcmdi9.llnl.gov). There are 25 models available for projections (2006-2100) under the RCP4.5 and RCP8.5 scenarios and seventeen for the RCP2.6 and RCP6.0 scenarios. Surface and upper-air parameters of these model runs are used to project future rainfall of the six stations using the statistical downscaling model. To match with 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 Cubic root transformation and standardization

To make monthly rainfall data conform to the normal distribution, cubic root transformation is performed in the first place. To reduce systematic biases, it is a common practice to standardize the predictors and predictands in building and applying the statistical downscaling model [4] [6] [7] [8]. Here, 1961-1990 is taken as the reference period for standardization. The standardized predictors and predictands are then used to construct the statistical model. Outcomes of the statistical downscaling model will be adjusted for variance while preserving the long-term trend (details in 3.3), de-standardized and then inversely transformed (i.e. cubed). Figure 2 shows a schematic diagram of the workflow.

3.2 Predictor selection

Potential predictors for this study are first-guessed based on literature review [9] [10] [11] and expert judgment drawing from operational experience. To sample the uncertainties associated with the choice of predictors, a number of combinations of thermodynamical parameters and low-level to mid-level circulation parameters are considered. Five predictor sets are examined:

Set 1: surface precipitation
Set 2: surface precipitation and mean sea level pressure
Set 3: surface precipitation, mean sea level pressure and 850-hPa relative humidity
Set 4: surface precipitation, mean sea level pressure, 850-hPa relative humidity, 850- hPa zonal and meridional winds
Set 5: surface precipitation, mean sea level pressure, 850-hPa relative humidity, 850-hPa zonal and meridional winds, 500-hPa zonal and meridional winds

These five predictor sets have increasing complexity while maintaining a balance between the number of thermodynamical and circulation parameters contributing to the statistical downscaling process.

3.3 Multiple linear regression

For the multiple linear regression approached adopted in this study, monthly data of the training period 1961-1990 are aggregated into four seasons (January-March, April-June, July-September and October-December) to establish four regression models for each station.

Rainfall simulated by the statistical downscaling model using predictors from the NCEP 20CR data of 1991-2005 is used for model validation purpose. Predictors from CMIP5 model data of 2006-2100 are used to project future rainfall of the six stations using the statistical downscaling model.

Normally, the variance of regression outcomes is smaller than that of the observations [12] [13] 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 (1961-1990 in this study). 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).

Simulated and projected rainfall using the five predictor sets are pooled together to form a grand ensemble. Validation and projection results in subsequent sessions are based on the grand ensemble mean and uncertainties are assessed by means of the spread of the ensemble, viz 5^{th} and 95^{th} percentile of the grand ensemble.

4. Results

4.1 Validation of the statistical downscaling model

Figure 3 shows the scatter plots of simulated annual rainfall using predictors from the NCEP 20CR day against observations during the training period (blue dots) and validation period (orange dots). The statistical model shows acceptable skill in simulating the observed annual rainfall. Table 2 and 3 summarize the means of observed and simulated annual rainfall, the correlation coefficients between the two quantities, and the root-mean-squared-error (RMSE) of the simulated rainfall for the six stations during the training and validation periods respectively. The statistical model demonstrates reasonable skill in simulating the present climate, with differences between the observed and simulated rainfall ranging between -1 to -2% and -8 to +5% during the training and validation periods respectively. The correlation coefficients between the simulated and observed annual rainfall vary from 0.41 to 0.63 in the training period. For the validation period, the correlation coefficients exceed 0.50 for all stations except Shanwei (0.23). The correlation coefficients obtained in this study are in general comparable to those obtained in previous studies [2] [3] [4]. The RMSEs range between 370 and 550 mm during the training period and between 330 and 530 mm during the validation period. The annual cycles of observed and simulated rainfall for the six stations are shown in Figure 4. The simulated rainfall follows the observed annual cycle reasonably well.

4.2 Projections for the 21st century

Figure 5 presents the projected percentage annual rainfall changes of the six stations under the four GHG concentration scenarios with respect to the average of observed rainfall in 1986-2005. Under the RCP4.5, RCP6.0 and RCP8.5 scenarios, the projected annual rainfall show generally rising trends throughout the 21^{st} century for all stations, although there may be some periods with negative changes in the interim. Figure 6 shows the absolute rainfall changes as well as the spread of the ensemble in 2081-2100 relative to the average of 1986-2005. Under the RCP8.5 scenario, the ensemble means of the projected rainfall in 2081-2100 show increases of around 170, 360, 100, 350, 140 and 250 mm for Hong Kong, Macao, Guangzhou, Heyuan, Shantou and Shanwei respectively. Similar increases, though of lesser magnitudes, can also be seen in the RCP4.5 and RCP6.0 scenarios for all stations. However, the signs of rainfall trends become more varied among the six stations under RCP2.6.

It should be noted that the inter-model differences can be quite large, judging from the spread of the ensemble, most noticeable for the RCP8.5 scenario. The 5^{th} percentiles are even below zero, indicating disagreements among climate models on the trend towards the end of this century. This, to some extent, reflects the uncertainty in both the global climate models and the statistical downscaling method. Knutti and Sedlacek [14] reported that model spread at the local scale has not changed much despite the improvements in CMIP5 models.

4.3 Extreme rainfall years

Extremely wet (dry) year is defined as a year with rainfall more than two standard deviations above (below) the mean rainfall in the reference period. The period 1885-2005 (1961-2005) is taken as reference for Hong Kong (other southern China stations). The rainfall thresholds are listed in Table 4.

The number of extremely wet and dry years during the reference period and the projection period (2006-2100) under the four GHG concentration scenarios are shown in Table 5. It can be seen that the numbers of dry years as well as wet years would both tend to increase regardless of the GHG concentration scenarios. Noting that, unlike Hong Kong, the other five southern China stations have shorter reference period (45 years) compared to the projection period (95 years), we also assess the risk of extremely wet/dry years by estimating the probability of occurrence X_{prob}, defined as:

$$X_{prob} = X * 100/T$$

where X is the number of extremely wet/dry years in the reference/projection periods; and T is the number of years covered by the reference/projection periods. As reflected by the results summarized in Table 6:

(a) under RCP4.5, RCP6.0 and RCP8.5, the probability of occurrence of extremely wet years would increase for all six stations;
(b) under RCP2.6, the probability of occurrence of extremely wet year would slightly increase for Hong Kong, Macao and Heyuan but remain about the same for Guangzhou, Shantou and Shanwei; and
(c) in all GHG scenarios, the chance of occurrence of extremely dry years would remain about the same (Hong Kong, Macao, Heyuan and Shanwei) or slightly increase (Guangzhou and Shantou).

4.4 Comparison with dynamical downscaling results

For comparison between statistical and dynamical downscaling, downscaling results from BCC_CSM1.1_RegCM4.0 (hereafter RegCM4 [15]), bi-linearly interpolated to the six stations for the periods 1980-1999 and 2006-2100 under the RCP4.5 and RCP8.5 scenarios, are obtained from the Guangdong Meteorological Bureau. RegCM4 is a regional climate model driven by the boundary conditions from the global climate model BCC_CSM1.1. The reference period of the statistical downscaling results discussed in previous sections is adjusted from 1986-2005 to 1980-1999 in this section to facilitate comparison.

In simulating the annual rainfall during the reference period of 1980-1999, RegCM4 shows dry bias for Hong Kong, Macao and Heyuan but wet bias for Guangzhou, Shantou and Shanwei (Table 7). Given that some of the biases are quite large, the projected annual rainfall is therefore compared against model climatology (average RegCM4-simulated annual rainfall during 1980-1999) instead of average observed annual rainfall.

For the RCP4.5 scenario (Figure 7), the overall projected changes of annual rainfall over the six stations between the two downscaling methods are comparable. For the RCP8.5 scenario (Figure 8), RegCM4 generally projects more precipitation increase towards the end of this century (2081-2100). The average percentage increase of annual rainfall over the six stations projected by statistical downscaling is 10.1% against 14.1% by dynamical downscaling. Nevertheless, the projected changes by RegCM4 are well within the ensemble spread derived from statistical downscaling. As such, it can be concluded that the projected changes in annual rainfall by RegCM4 are generally consistent with those generated by statistical downscaling.

5. Conclusion

In this study, selected CMIP5 models are statistically downscaled to Hong Kong and five other stations in southern China to project the annual rainfall changes in the 21st century. Results show that the annual rainfall would generally increase under the RCP4.5, RCP6.0 and RCP8.5 scenarios for all the stations, but the sign of the trends may vary among the stations for the RCP2.6 scenario. The chance of occurrence of extremely wet years would increase for all stations under the RCP4.5, RCP6.0 and RCP8.5 scenarios. Under the RCP2.6 scenario, the chance of extremely wet year would either increase or remain about the same. On the other hand, the chance of occurrence of extremely dry years would either remain about the same or slightly increases regardless of the GHG concentration scenario.

Results from the statistical downscaling method are compared with those projected by dynamical downscaling using RegCM4. It is found that results from RegCM4 are generally comparable and consistent, falling within the ensemble spreads derived from statistical downscaling. However, it should be noted that the comparison is somewhat limited as RegCM4 is driven by only one global climate model and has only one simulation for each RCP scenario. A more comprehensive inter-comparison study would require outputs from more regional climate models driven by different global climate models.

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Table 1 CMIP5 models and projections used in this study.

Model	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
ACCESS10	×	✓	×	✓
BCC-CSM1-1	✓	✓	✓	✓
BNU-ESM	✓	✓	×	✓
CanESM2	✓	✓	×	✓
CCSM4	✓	✓	✓	✓
CNRM-CM5	×	✓	×	✓
CSIRO-Mk36	×	✓	✓	✓
GFDL-ESM2G	✓	✓	✓	✓
GFDL-ESM2M	×	✓	✓	✓
FGOAL_Sg2	✓	✓	×	✓
GISS-E2-H	✓	✓	✓	✓
GISS-E2-R	×	✓	✓	✓
HadGEM2-AO	✓	✓	✓	✓
HadGEM2-CC	×	✓	×	✓
HadGEM2-ES	✓	✓	✓	✓
INM-CM4	×	✓	×	✓
IPAL-CM5A-LR	✓	✓	✓	✓
IPSL-CM5A-MR	✓	✓	✓	✓
IPSL-CM5B-LR	×	✓	×	✓
MIROC5	✓	✓	✓	✓
MIROC-ESM	✓	✓	✓	✓
MIROC-ESM-CHEM	✓	✓	✓	✓
MRI-CGCM3	✓	✓	✓	✓
Nor-ESM-1M	✓	✓	✓	✓
Nor-ESM1-ME	✓	✓	✓	✓
Total	17	25	17	25

"✓" - model simulation is used

"×" - data not available or incomplete

Table 2 Mean of the observed and simulated (using predictors from the NCEP 20th CR data) annual rainfall, correlation coefficient between the observed and simulated annual rainfall, and RMSE of the simulated annual rainfall for the training period (1961-1990).

Stations	Mean			Correlation coefficient	RMSE
	Observed	Simulated	% difference		
Hong Kong	2214	2185	-1.3	0.53	548
Macao	2031	1997	-1.7	0.55	543
Guangzhou	1682	1674	-0.5	0.46	402
Heyuan	1936	1926	-0.5	0.63	367
Shantou	1531	1517	-1.0	0.41	439
Shanwei	1869	1843	-1.4	0.52	494

Table 3 Same as Table 2 but for the validation period (1991-2005).

Stations	Mean			Correlation coefficient	RMSE
	Observed	Simulated	% difference		
Hong Kong	2510	2323	-7.5	0.65	477
Macao	2046	2082	1.7	0.60	438
Guangzhou	1823	1736	-4.8	0.50	360
Heyuan	1943	2039	5.0	0.55	460
Shantou	1600	1628	1.7	0.52	335
Shanwei	1989	1963	-1.3	0.23	527

Table 4 Criteria of extremely dry and extremely wet years.

Stations	Extremely dry year	Extremely wet year
	Rainfall less than (mm)	Rainfall more than (mm)
Hong Kong	1289	3168
Macao	1038	3035
Guangzhou	1055	2403
Heyuan	1122	2754
Shantou	900	2208
Shanwei	1009	2809

Table 5 Number of dry and wet years during the reference period (1885-2005 for Hong Kong, 1961-2005 for other stations) and the projection period (2006-2100) under the four GHG concentration scenarios.

	Hong Kong		Macao		Guangzhou		Heyuan		Shantou		Shanwei	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Observed	2	3	1	1	0	2	1	1	0	3	1	2
RCP2.6	3	7	1	6	3	5	2	8	3	7	2	5
RCP4.5	2	9	1	7	2	7	2	10	3	9	2	7
RCP6.0	3	8	1	7	3	6	3	9	3	8	2	7
RCP8.5	2	12	1	10	3	9	2	13	3	12	2	10

Table 6 Probability of occurrence (%) of dry and wet years during the reference period (1885-2005 for Hong Kong, 1961-2005 for other stations) and the projection period (2006-2100) under the four GHG concentration scenarios.

	Hong Kong		Macao		Guangzhou		Heyuan		Shantou		Shanwei	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Observed	1.7	2.5	2.2	2.2	0	4.4	2.2	2.2	0	6.7	2.2	4.4
RCP2.6	2.7	7.2	1.5	5.8	2.9	4.9	2.3	8.2	3.1	7.0	2.0	5.3
RCP4.5	1.8	9.2	1.3	7.7	2.5	6.9	2.3	10.9	2.7	9.7	1.7	7.6
RCP6.0	2.9	8.8	1.6	6.9	3.4	6.0	2.9	9.3	3.7	8.1	2.3	6.9
RCP8.5	2.4	12.2	1.5	10.3	3.1	9.2	2.3	13.7	3.0	12.4	2.0	10.2

Table 7 Average annual rainfall during 1980-1999 as observed and as simulated by RegCM4 .

Stations	Observation (mm)	RegCM4 (mm)
Hong Kong	2267	1753
Macao	2073	1507
Guangzhou	1740	1803
Heyuan	2042	1958
Shantou	1624	1981
Shanwei	1919	2091

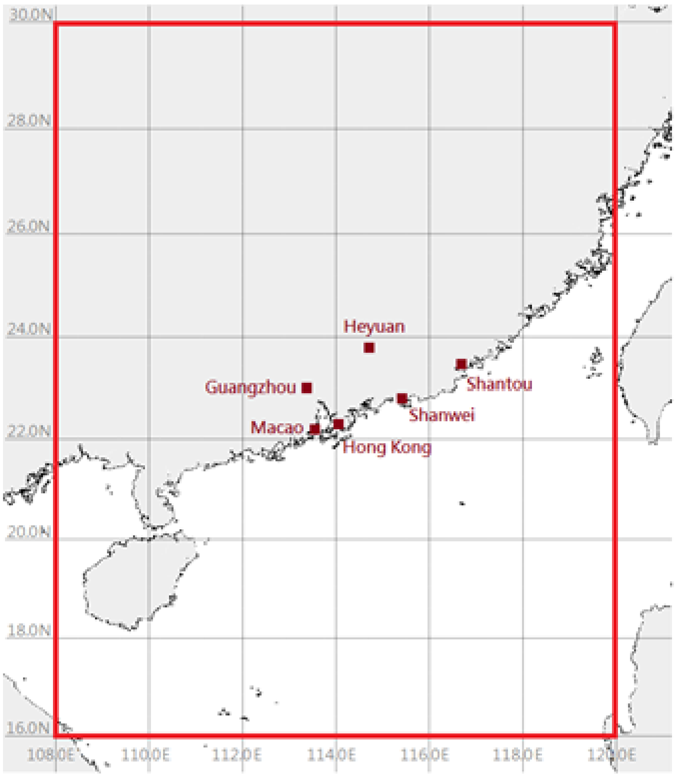

Figure 1 Locations of the stations and the area of large-scale predictors used in this study (bounded by the red rectangle).

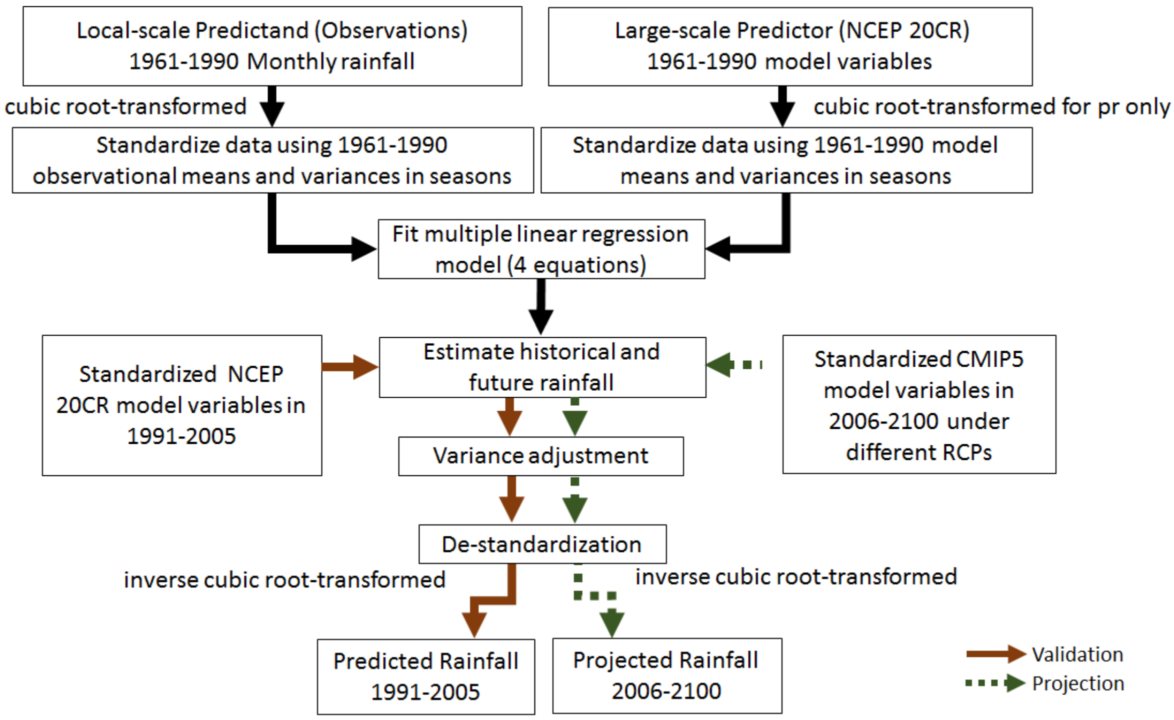

Figure 2 Schematic diagram of the workflow adopted in this study.

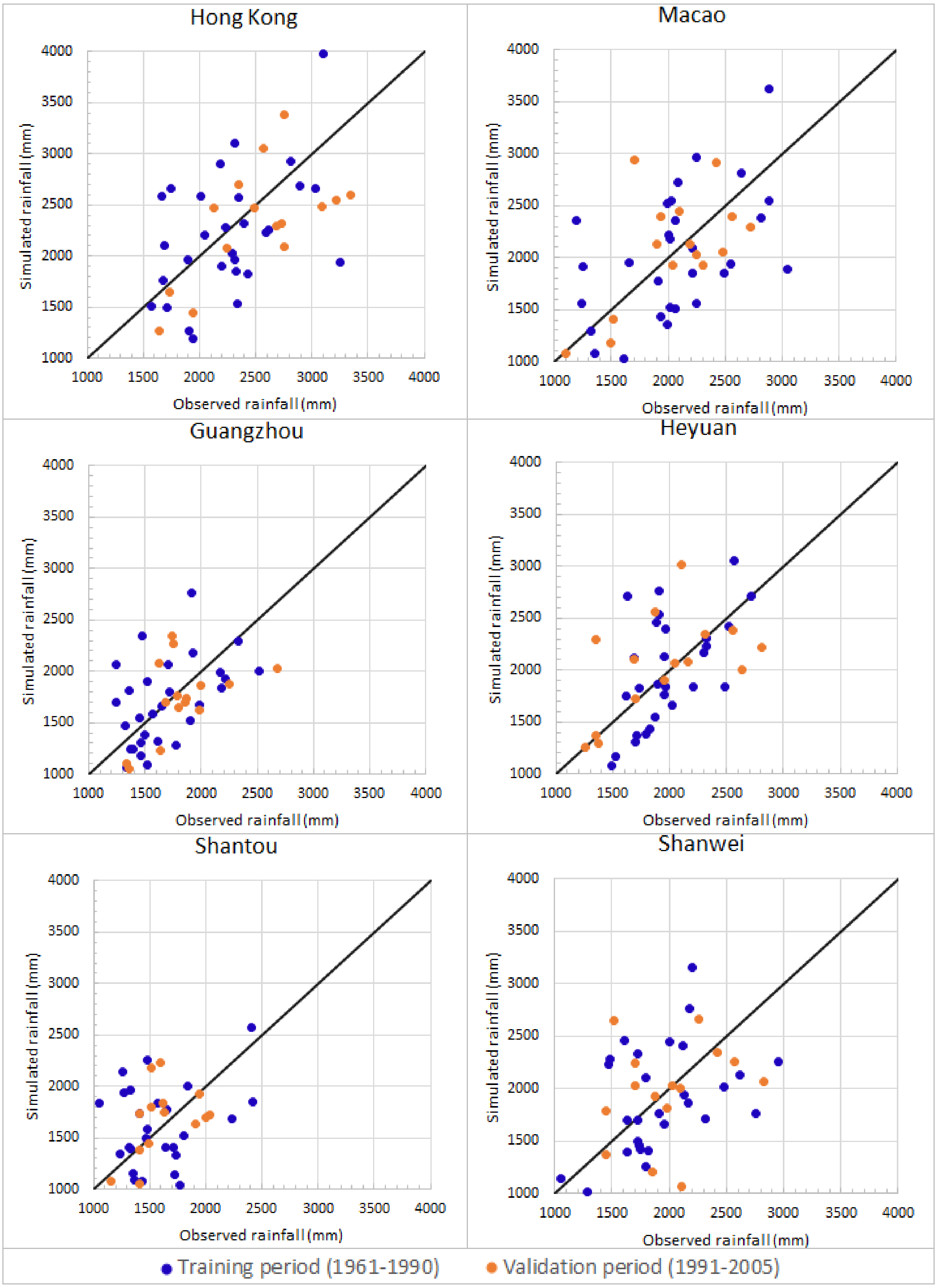

Figure 3 Scatter plots of simulated annual rainfall using predictors from the NCEP 20CR data against observations. Blue (orange) dots indicate data in the training (validation) period.

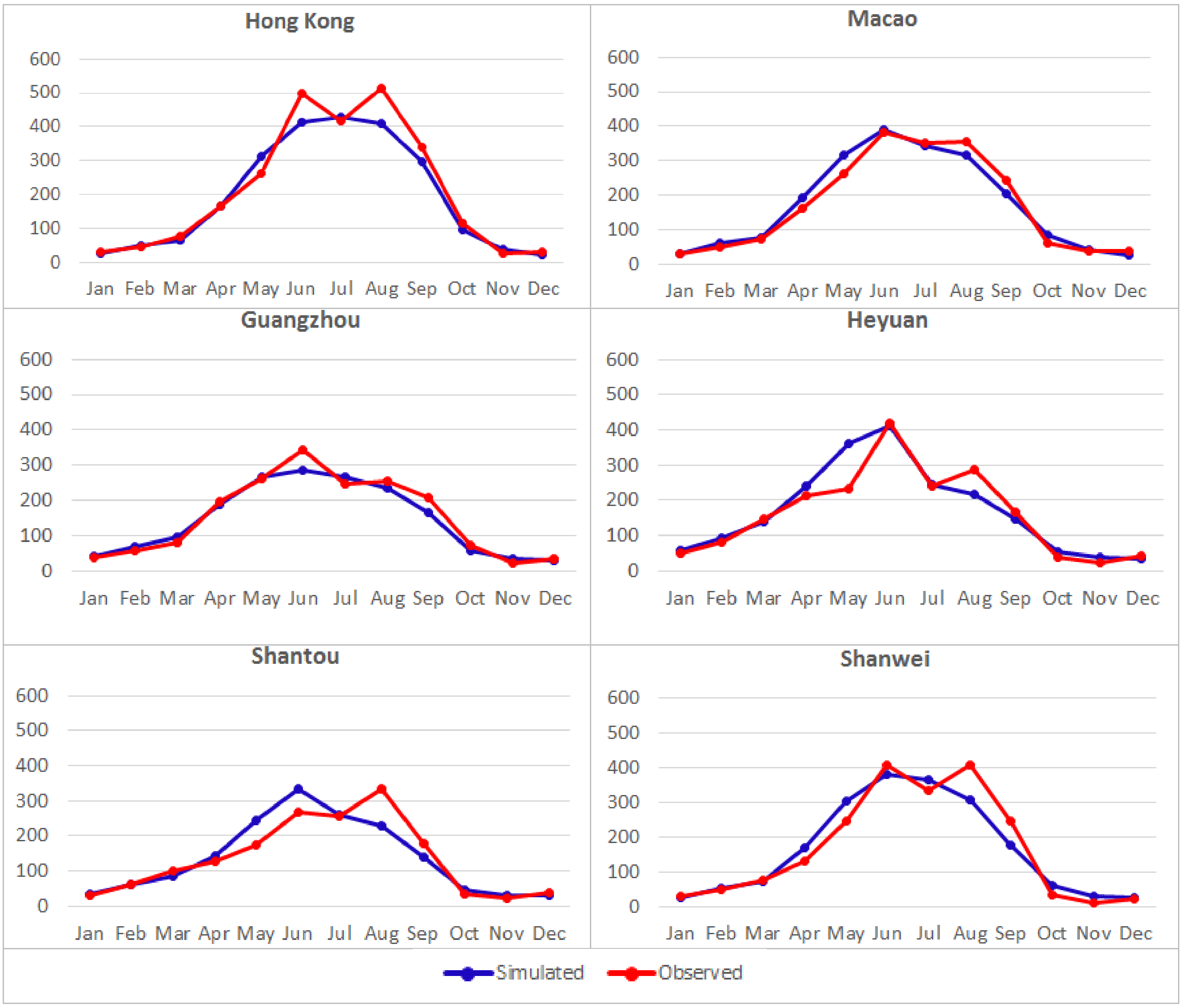

Figure 4 Annual cycle of observed/simulated rainfall (mm) of the six stations during the period 1991-2005. Red lines indicate observations and blue lines indicate the simulated rainfall using predictors from the NCEP 20CR data.

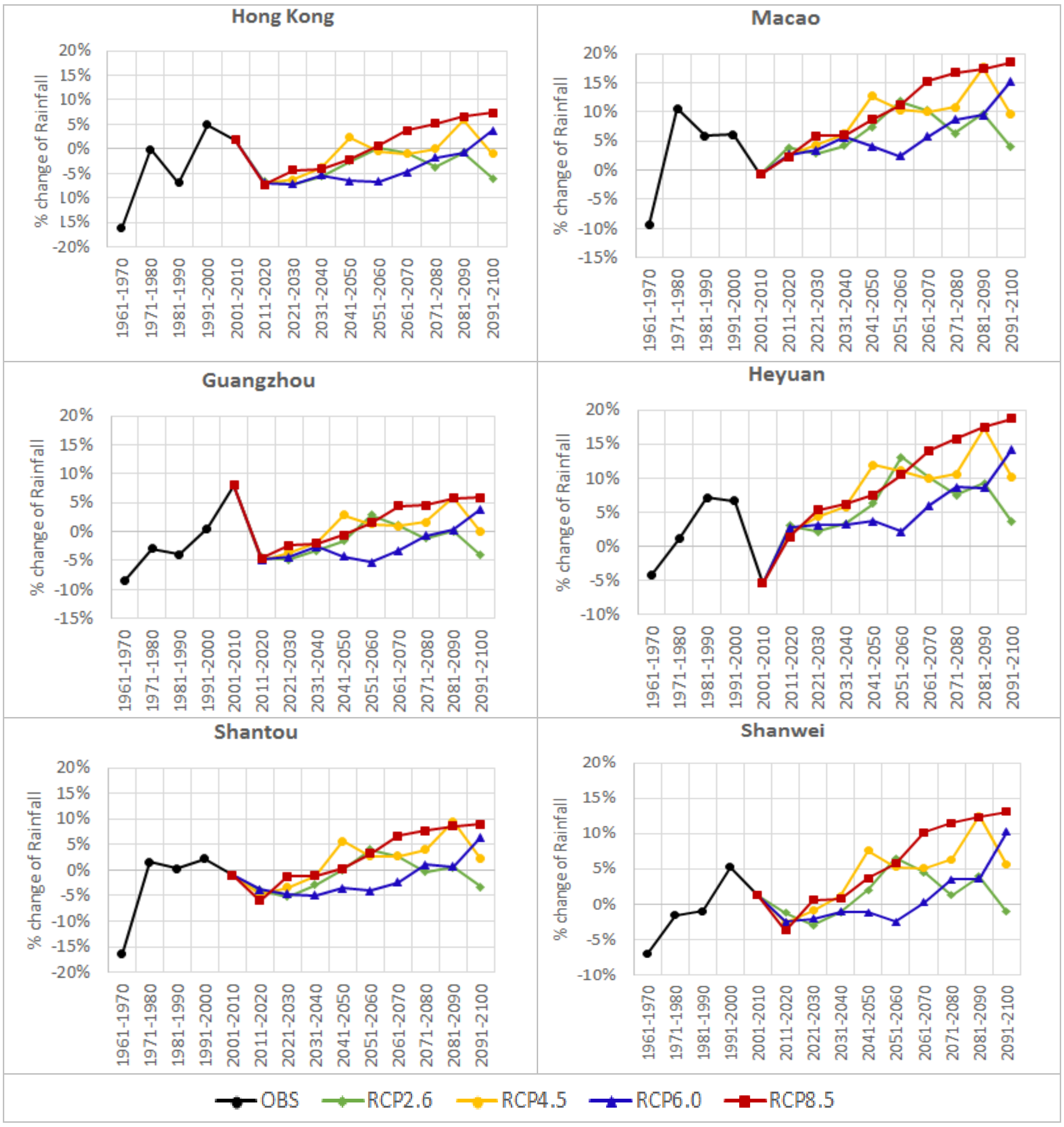

Figure 5 Projected percentage changes of annual rainfall of the six stations for the 21st century (with reference to the average of 1986-2005). Black lines indicate historical observations. Projections under the RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios are indicated by green, yellow, blue and red lines respectively.

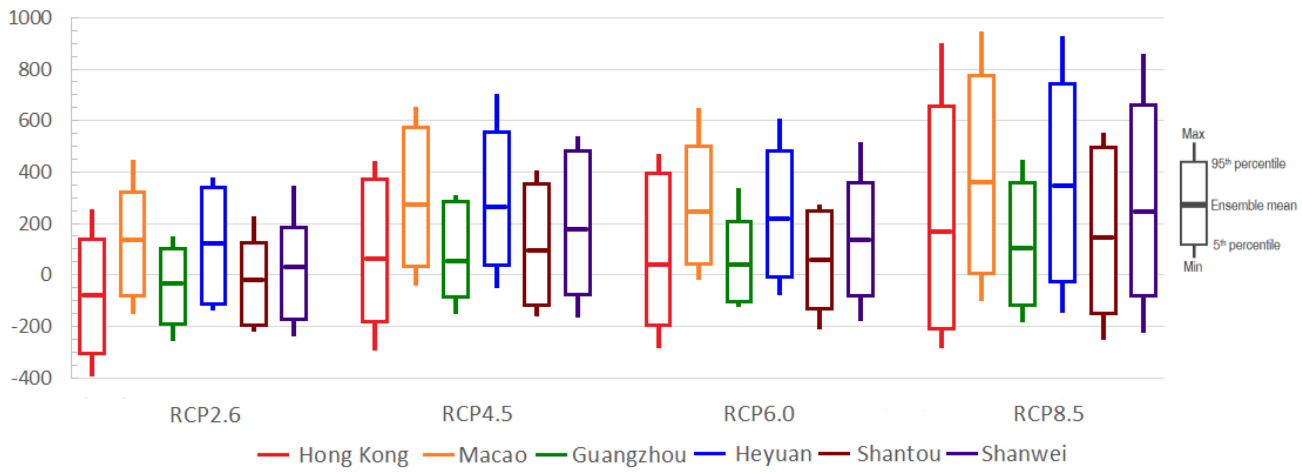

Figure 6 Box-plots of projected changes of annual rainfall (mm) in 2081-2100 with respect to the average of 1986-2005 under the four RCP scenarios.

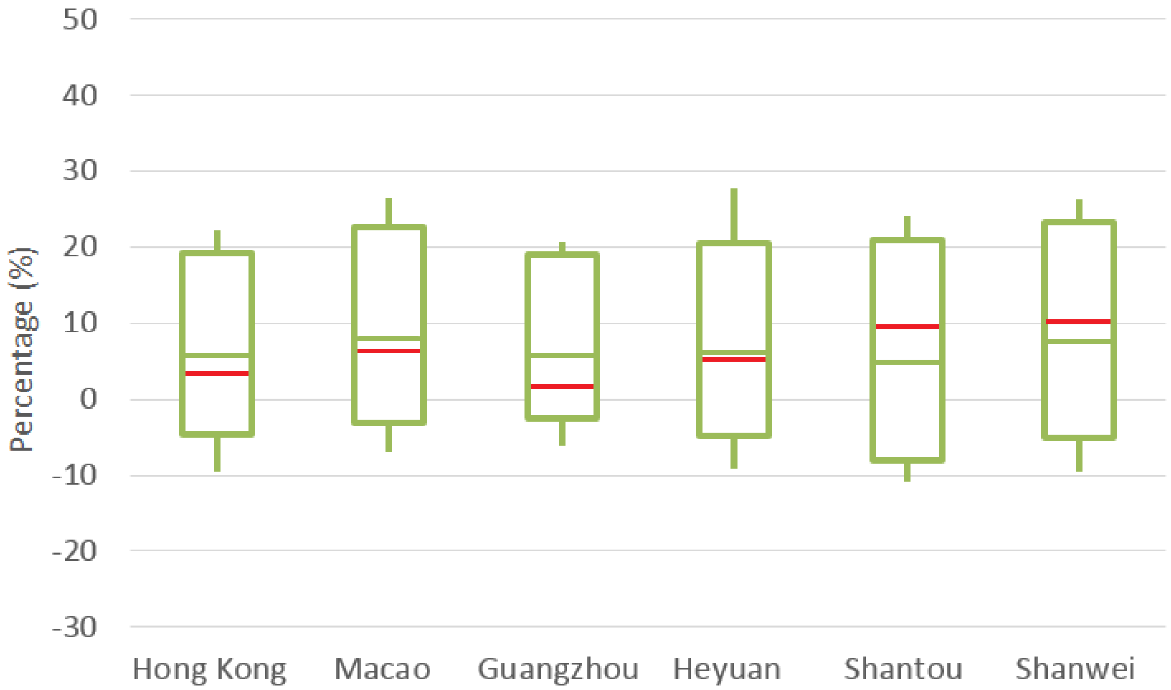

Figure 7 Projected percentage changes (%) of annual rainfall in 2081-2100 with respect to 1980-1999 by RegCM4 (red lines) and statistical downscaling (green boxes) for the six stations under the RCP4.5 scenario. The green lines in the middle of the boxes indicate the grand ensemble mean. The top (bottom) of the boxes represent the 95th (5th) percentile of the grand ensemble, while the extents of the spikes at both ends indicate the minimum (bottom) and maximum (top) value of the ensemble.

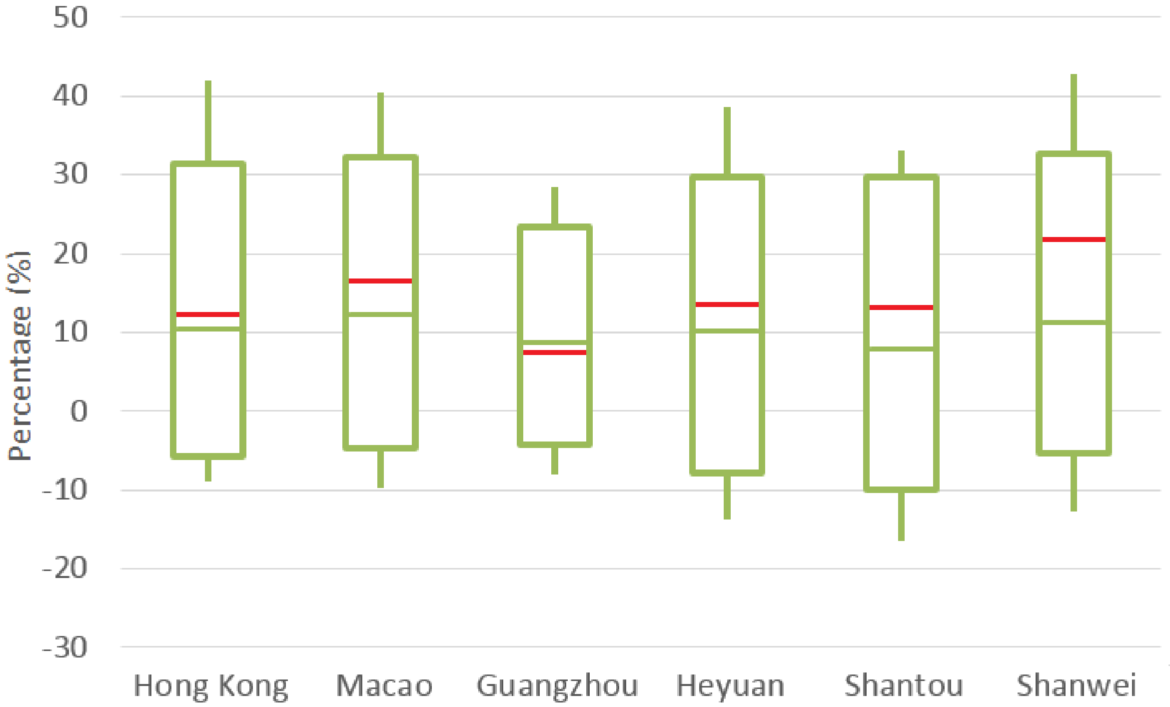

Figure 8 Same as Figure 7, but for the RCP8.5 scenario.