Projections of Extreme Rainfall in Hong Kong in the 21st Century

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ABSTRACT

The possible changes in the frequency of extreme rainfall events in Hong Kong in the 21st century were investigated by statistically downscaling 30 sets of the daily global climate model projections (involving a combination of 12 models and 3 greenhouse gas emission scenarios, namely, A2, A1B, and B1) of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. To cater for the intermittent and skewed character of the daily rainfall, multiple stepwise logistic regression and multiple stepwise linear regression were employed to develop the downscaling models for predicting rainfall occurrence and rainfall amount, respectively. Verification of the simulation of the 1971–2000 climate reveals that the models in general have an acceptable skill in reproducing past statistics of extreme rainfall events in Hong Kong. The projection results suggest that, in the 21st century, the annual number of rain days in Hong Kong is expected to decrease while the daily rainfall intensity will increase, concurrent with the expected increase in annual rainfall. Based on the multi-model scenario ensemble mean, the annual number of rain day is expected to drop from 104 days in 1980–1999 to about 77 days in 2090–2099. For extreme rainfall events, about 90% of the model-scenario combinations indicate an increase in the annual number of days with daily rainfall $\geqslant$ 100 mm (R100) towards the end of the 21st century. The mean number of R100 is expected to increase from 3.5 days in 1980–1999 to about 5.3 days in 2090–2099. The projected changes in other extreme rainfall indices also suggest that the rainfall in Hong Kong in the 21st century may also become more extreme with more uneven distributions of wet and dry periods. While most of the model-emission scenarios in general project consistent trends in the change of rainfall extremes in the 21st century, there is a large divergence in the projections among different model/emission scenarios. This reflects that there are still large uncertainties in model simulations of future extreme rainfall events.

Key words: extreme rainfall projections, statistical downscaling, climate projections, climate change, Hong Kong

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1. Introduction

Climate change has become a hot topic of discussion in the past few years. Based on multiple lines of scientific evidence and many research findings, the United Nations Intergovernmental Panel on Climate Change (IPCC) clearly indicated in its Fourth Assessment Report (AR4) in 2007 that the warming in the climate system is unequivocal. It also stated that the increase in the atmospheric greenhouse gas (GHG) concentration due to human activities is very likely responsible for most of the observed global warming since the middle of the 20th century (IPCC, 2007a). The warming could also have an effect on precipitation as warmer air can in principle hold more moisture. According to the Clausius-Clapeyron relation, the moisture holding capacity of the atmosphere increases with temperature at a rate of about 7% per degree of temperature rise. This would result in changes not only in mean precipitation but also in the frequency and intensity of extreme precipitation events (Semenov and Bengtsson, 2002; Trenberth et al., 2003; Watterson and Dix, 2003; Kharin et al., 2007; O'Gorman and Schneider, 2009; Lenderink and Meijgaard, 2010).

Over the years, various studies have reported changes in the mean precipitation and frequency of occurrence of extreme precipitation events around the world in the 20th century (Easterling et al., 2000; Manton et al., 2001, Frich et al., 2002; Groisman et al., 2005; Alexander et al., 2006; IPCC, 2007a;

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Choi et al., 2009). Many studies also detected regional changes in extreme precipitation frequency and intensity in China and East Asia (Zhai et al., 1999, 2005; Gong and Wang, 2000; Wang and Zhou, 2005; Qian et al., 2007a; Zhang et al., 2008; Ning and Qian, 2009; Wang and Qian, 2009; Wang and Zhai, 2009; Lu et al., 2010; Zhao et al., 2010). For Guangdong and Hong Kong, recent studies revealed that both the frequency of occurrence and intensity of heavy rain events exhibited a long term increasing trend in the past century (Guangdong Provincial Meteorological Bureau, 2007; Wong and Mok, 2009; Zhang et al., 2009; Ginn et al., 2010; Wong et al., 2010). From the hydrological perspective, such changes in the frequency and intensity of extreme precipitation events may have considerable impacts on society, including agriculture, industry, slope safety, transportation, flood control, drainage design, etc. (Frich et al., 2002; IPCC, 2007b; WMO, 2009). As such, results of projections of future changes in regional and local precipitation extremes are important information for policy decisions regarding climate change adaptation and mitigation.

In 2005, the Hong Kong Observatory (HKO) conducted studies on rainfall projections for Hong Kong utilizing the data of global climate model projections included in the IPCC's Third Assessment Report (Wu et al., 2005). The projections were later updated in 2008 based on model data of IPCC AR4 (Lee et al., 2008). In these two studies, projections of the rainfall trends in Hong Kong in the 21st century were made using the monthly mean data of simulations of the global climate models together with observed rainfall in Hong Kong and southern China through statistical downscaling techniques. The projection results of the 2008 study suggested that the average annual rainfall in Hong Kong will increase during the latter half of the 21st century and the year-to-year variability in rainfall will also increase. Since only monthly mean model data were used in the 2008 study, the estimation of the annual number of heavy rain days (days with hourly rainfall $\geqslant$ 30 mm) could only rely on additional correlation relationships between past annual rainfall and the number of heavy rain days. The results suggest that there will be an increase in the number of heavy rain days in Hong Kong towards the end of the 21st century.

This study is undertaken to extend the previous study on extreme rainfall projections using daily global climate model data for IPCC AR4 and a more direct and comprehensive statistical downscaling technique. The daily projections with higher temporal resolution eliminated the need for additional correlation relationships between annual rainfall and the number of extreme events and should thus better depict the plausible changes in extreme rainfall events than using the monthly mean projections.

The data and extreme rainfall indices used in this study are described in Section 2. The statistical downscaling method and extreme analysis approach are depicted in Section 3. Results of the projection are presented in Section 4. Section 5 contains a summary of the study and discussion of the results.

2. Data and extreme indices

2.1 Observations

The performance of the statistical downscaling technique (see Section 3) depends strongly on the availability and quality of large scale (predictors) and local scale (predictands) observational data for developing the downscaling model. In this study, daily rainfall data recorded at the Hong Kong Observatory Headquarters (HKOHq) from 1971 to 2000 were used as the local scale observational data (predictands). For large scale predictors, 6-h (0000, 0600, 1200, and 1800 UTC) surface and upper air (at 850-, 500-, and 200-hPa levels) reanalysis grid-point data (resolutions $1.9°\times1.9°$ for precipitation and $2.5°\times2.5°$ for the others) over southern China (20°–30°N, 105°–120°E) from 1971 to 2000 were retrieved from the US National Centers for Environmental Protection (NCEP) for the study. NCEP reanalysis data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website (http://www.esrl.noaa.gov/psd/) (Kalnay et al., 1996). NCEP data before 1971 were not used to establish the regression equations in the downscaling model as a previous study by Yang et al. (2002) indicated that the quality of NCEP reanalysis data for Asia prior to 1968 may be low. Unless otherwise stated, the observed rainfall in Hong Kong, the observed rainfall anomaly, the projected rainfall in Hong Kong, and the projected rainfall anomaly, refer to the corresponding values at HKOHq in this study.

2.2 Global climate model data

2.2.1 Time-slice data

Time slices of gridded daily projection data for the periods 2046–2065 and 2081–2100 by 22 AR4 global climate models under different emission scenarios are available from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) website (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php) (Meehl and Hibbard, 2007). Among the 6 GHG emission scenarios used by IPCC AR4 in global climate simulations (from low to high GHG emissions: B1, A1T, B2, A1B, A2, and A1FI), model data for 3 out of the 6 emission scenarios, namely A2, A1B, and B1, are available from the PCMDI website. Further details of the GHG emission scenarios employed by IPCC AR4 are documented in the IPCC Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000).

In this study, models satisfying the following criteria on spatial resolution and data availability are used:

(1) Models with both daily surface and upper air data available;

(2) Models with spatial resolution better than 4°×4°;

(3) For climate models with more than one version, the latest model version or the version with higher spatial resolution will be used.

After a selection based on the above criteria and noting that not all three of the emission scenarios (A2, A1B, and B1) are available for each model, a total of 30 sets of model emission scenario combinations (12 models) are available for this study (Table 1).

Table 1. Emission scenarios and model simulations used in this study

Model	A2	A1B	B1
CCCMA_CGCM3_1_T63	×	√	√
CNRM_CM3	√	√	√
CSIRO_MK3_5	√	√	√
GFDL_CM2_1	√	√	√
GISS_AOM	×	√	√
IAP_FGOALS1_0_G	×	√	√
INGV_ECHAM4	√	√	×
IPSL_CM4	√	√	×
MIROC3_2_HIRES	×	√	√
MIUB_ECHO_G	√	√	√
MPI_ECHAM5	√	√	√
MRI_CGCM2_3_2A	√	√	√
TOTAL		30 model-scenario combinations	

"√" denotes that model simulation is used, and "×" means that the data are not available or incomplete.

The simulation data of the past climate for 1971–2000 based on the historical GHG concentrations (20C3M scenario) of the 12 models used in this study were also retrieved from the PCMDI website and compared with the past climate for assessing the performance of the models (Section 4.2).

2.2.2 Whole 21st century model data

In addition to the time-slice data from PCMDI, daily projection data of the GFDL_CM2_1 model (A2 and B1 scenarios) and MIROC3_2_HIRES model (A1B scenario) for the whole 21st century were respectively acquired from the Geophysical Fluid Dynamics Laboratory (GFDL) and Center for Climate System Research (The University of Tokyo)/National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC) with a view to examining the decadal variation of extreme rainfall events and possible changes in the frequency of the extreme events in the 21st century.

2.3 Extreme rainfall indices

A suite of 9 extreme rainfall indices to indicate the trend and significance of extreme rainfall events were used in this study. They were adopted from the list of extreme indices proposed by the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) working under the joint WMO Commission for Climatology (CCl)/World Climate Research Programme (WCRP) Climate Variability and Predictability (CLIVAR) project (Peterson et al., 2001; Peterson, 2005) (http://cccma.seos.uvic.ca/ETCCDI/indices.shtml) with appropriate modifications to suit the subtropical climate of Hong Kong. The nine extreme rainfall indices are briefly described below.

R100 is the annual number of days with daily rainfall $\geqslant$ 100 mm.

R1d is the annual maximum daily rainfall. R3d, R5d, and R7d respectively represent annual maximum consecutive 3-, 5-, and 7-day rainfall. These indices are modified from the indices proposed by ETCCDMI for use with reference to Hong Kong.

The Simple Daily Precipitation Intensity Index (SDII) is the annual total rainfall divided by the number of rain days (daily rainfall $\geqslant$ 1 mm) in a year.

The consecutive dry days (CDD) and consecutive wet days (CWD) indices are the annual maximum length of dry and wet spells respectively, counting the maximum number of consecutive days with at least 6 consecutive days with daily rainfall $<$ 1 mm for CDD and $\geqslant$ 1 mm for CWD between April and September, which is the rainy season in Hong Kong (Lee et al., 2006).

R95p is the fraction of annual total rainfall due to events exceeding the daily 95th percentile of the climatological normal (with reference to the period 1971–2000). This is a measure of the contribution of extreme rainfall events to the total rainfall in a year.

A list of the nine rainfall related extreme indices, details of their definitions and deviations from those proposed by ETCCDMI, if any, are summarized in Appendix I for ease of reference.

3. Methods

3.1 Statistical downscaling

Statistical downscaling is used to generate local scale climate projections from global climate model forecasts which are usually made at a relatively coarse spatial resolution, typically 300 km × 300 km (e.g., Kilsby et al., 1998). It is a popular approach because of its computational economy compared with the alternative method of dynamical downscaling (Fan et al., 2005), and has a level of skill on a par with the dynamical approach (Murphy, 1999). Regression is often employed in statistical downscaling and this is also the technique used by HKO in the previous rainfall projection studies in 2005 and 2008 (Wu et al., 2005; Lee et al., 2008), and this study as well.

To handle the intermittent and skewed character of the daily rainfall, a two-stage approach to simulate daily rainfall occurrence (rainfall occurrence model) and daily rainfall amount (rainfall amount model) associated with rain days for the four seasons are adopted (Beckmann and Buishand, 2002; Gangopadhyay et al., 2004; Frost, 2007). Here, spring refers to the period from March to May, summer from June to August, autumn from September to November, and winter from December to February. A rain day is defined as the day with daily rainfall $\geqslant$ 1 mm. For the occurrence model, a multiple stepwise logistic regression (Wilks, 2006; Fealy and Sweeney, 2007; Crawley, 2008) is used with the rainfall occurrence as the predictand. For the rainfall amount model, a multiple stepwise linear regression is used with the rainfall amount in Hong Kong on a rain day as predictand. For both models, the spatial average of the NCEP reanalysis grid point daily data (surface and upper air) bounded by 20°–30°N, 105°–120°E is used as the large scale predictors. As local rainfall is likely to be affected by the rainfall in its vicinity, a smaller domain (21.25°–26.25°N, 111.25°–116.25°E) is used for the spatial average of the rainfall predictor. Furthermore, to handle the skewed nature of daily rainfall, a fourth root transformation is applied to the rainfall predictor (Dubrovsky et al., 2004; Wilby and Dawson, 2007) before feeding into the regression equations. The choice of the predictors is limited by the availability of data fields from the PCMDI. Table 2 lists the predictors and predictands used in this study. Besides surface variables, upper air predictors at 850-, 500-, and 200-hPa levels were also used in both occurrence and rainfall amount models.

The global climate model projection data for southern China are then inputted into the regression

Table 2. Predictands and predictors used in this study

Predictands	Predictors
Daily rainfall amount at HKOHq	Precipitation (Pr)
Daily rainfall occurrence at HKOHq	Surface mean temperature (T)
	Sea level pressure (Slp)
	850-hPa temperature (T850)
	850-hPa specific humidity (Sh850)
	850-hPa vorticity (Vort850)
	500-hPa temperature (T500)
	500-hPa specific humidity (Sh500)
	200-hPa divergence (Div200)

relationships to obtain the projections of rainfall occurrence and rainfall amount for Hong Kong. To reduce systematic biases in the mean and variance of global climate model predictors, all data are standardized for each season by subtracting the mean and then dividing by the standard deviation for a reference period prior to performing the statistical downscaling (Schubert, 1998; Wilby et al., 2004; Cheng et al., 2008). In this study, the period 1980–1999 (the period chosen by IPCC AR4 as the reference period for the evaluation of projections into the 21st century) is taken as the reference period for preparing the standardized anomalies. Mathematically, the standardized anomaly for a variable x is

$$x_{\rm std} = (x - \langle x \rangle)/\sigma, \quad (1)$$

where $\langle x \rangle$ is the mean and σ is the standard deviation of x over the reference period (1980–1999).

Figures 1 and 2 show the schematic diagrams of the workflow for the two statistical downscaling models used in this study. Further descriptions on the key steps are described in Sections 3.1.1 and 3.1.2.

3.1.1 Rain occurrence model

For a binary predictand such as rainfall occurrence, linear regression is not a suitable technique as

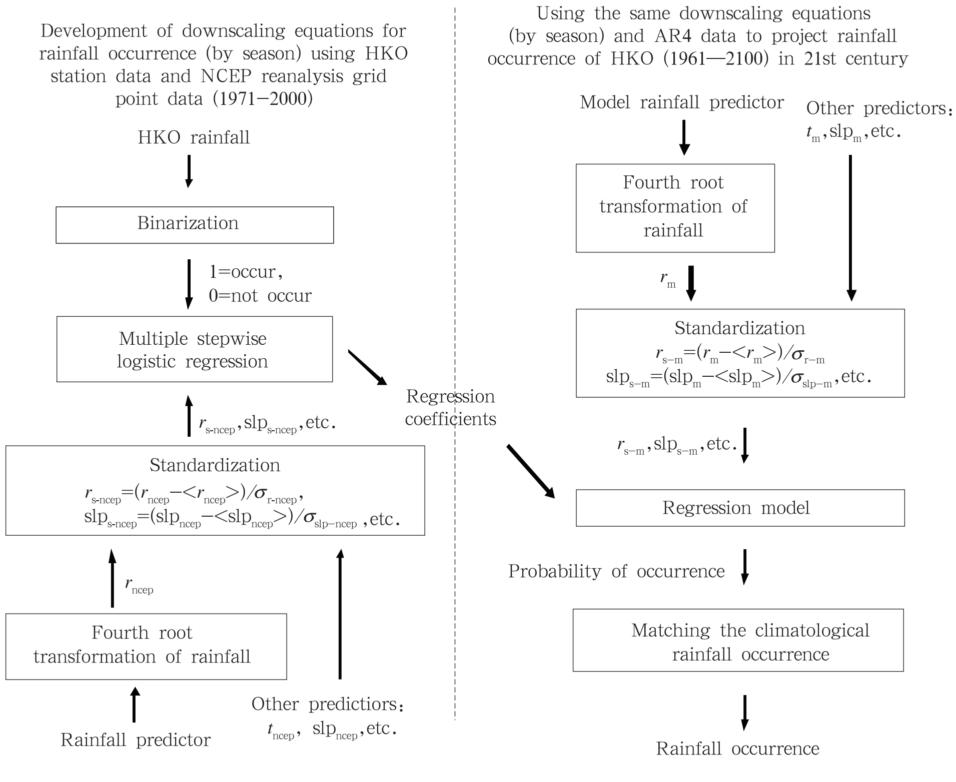

Fig. 1. Schematic diagram of the workflow for the rainfall occurrence model.

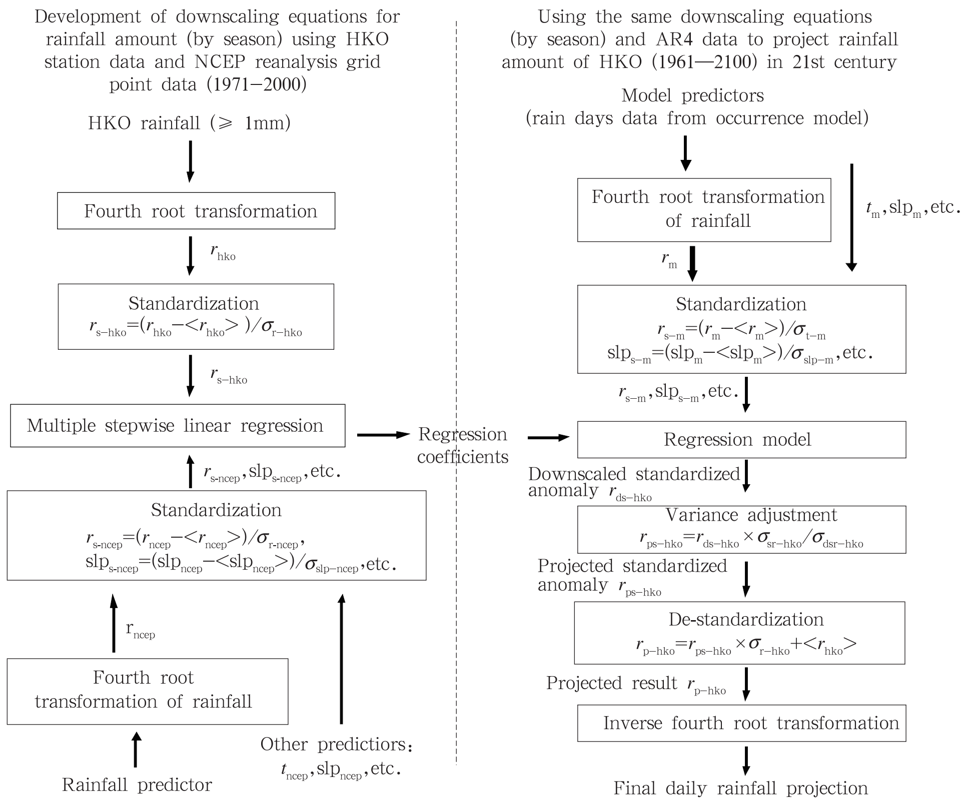

Fig. 2. Schematic diagram of the workflow for the rainfall amount model.

the predicted values of binary predictands are strictly bounded, the residuals are clearly not Guassian, and their variances are not constant. Under such circumstances, logistic regression is a widely-used technique for making predictions (Wilks, 2006). Multiple stepwise logistic regression is employed in this study to develop the statistical downscaling equations for rainfall occurrence. The logistic model is given by

$$p = \exp(a_0 + a_1 \times x_1 + \ldots + a_i \times x_i + \ldots a_n \times x_n)/ (1 + \exp(a_0 + a_1 \times x_1 + \ldots + a_i \times x_i + \ldots + a_n \times x_n)), \quad (2)$$

where p is the probability of rainfall occurrence and x_i are the standardized predictors. The model output is strictly bounded by 0 and 1. By accommodating the Bernoulli distribution for the regression residuals, the unknown coefficients (a_i) are estimated by maximum likelihood method (Wilks, 2006; Crawley, 2008).

Actual rainfall data at HKOHq are first binarized with 1 representing days with daily rainfall $\geqslant$ 1 mm and 0 representing days with daily rainfall $<$ 1 mm. A regression relationship between the binary predictand and the standardized predictors is then established for each of the four seasons using historical data from 1971 to 2000. Table B1 in Appendix II summarizes the predictors and coefficients of the four logistic regression equations of rainfall occurrence model used in this study.

Standardized anomalies of global climate model data over southern China are used as predictors in the corresponding seasonal dependent logistic regression equations to produce the probability of rainfall occurrence. In order to determine the rainfall occurrence, a probability threshold is identified for each model for each season by matching the projected rainfall occurrence (depending on the probability threshold) in the season to the corresponding climatological rainfall occurrence in the period 1971–2000. Lastly, days with probability of occurrence greater than or equal to the threshold for the corresponding model are counted as rain days.

3.1.2 Rainfall amount model

Multiple stepwise linear regression (Wilks, 2006; Crawley, 2008) is employed in this study to develop the statistical downscaling equations for rainfall amount on rain days. A regression relationship between the standardized predictand (fourth-rooted rainfall at HKOHq) and standardized predictors from NCEP re-analysed variables on rain days is established for each season using historical data from 1971 to 2000. The predictors and coefficients of the four regression equations used in this study for rainfall amount are listed in Table B2 in Appendix II.

Standardized anomalies of global climate model data over southern China on rain days (determined from the occurrence model) are input as predictors into the corresponding linear regression equations to produce the downscaled standardized fourth-rooted rainfall anomaly for Hong Kong. In order to adjust for the difference of variance between the observed and downscaled data (e.g., Karl et al., 1990; Huth, 1999), the downscaled standardized fourth-rooted rainfall anomaly for Hong Kong ($r_{\mathrm{ds-hko}}$) is multiplied by a factor ($\sigma_{\mathrm{sr-hko}}/\sigma_{\mathrm{dsr-hko}}$) to give the projected standardized fourth-rooted rainfall anomaly for Hong Kong ($r_{\mathrm{ps-hko}}$), where $\sigma_{\mathrm{sr-hko}}$ and $\sigma_{\mathrm{dsr-hko}}$ are the standard deviation of the standardized fourth-rooted rainfall anomaly in 1980–1999 and the standard deviation of the downscaled standardized fourth-rooted rainfall anomaly in 1980–1999, respectively (see Eq. (3)).

$$r_{\mathrm{ps-hko}} = r_{\mathrm{ds-hko}} \times \sigma_{\mathrm{sr-hko}}/\sigma_{\mathrm{dsr-hko}}. \quad (3)$$

The projected standardized fourth-rooted rainfall anomaly is then de-standardized (see Eq. (4)) to give the projected fourth-rooted rainfall in Hong Kong ($r_{\mathrm{p-hko}}$).

$$r_{\mathrm{p-hko}} = r_{\mathrm{ps-hko}} \times \sigma_{\mathrm{r-hko}} + \langle r_{\mathrm{hko}} \rangle, \quad (4)$$

where $\langle r_{\mathrm{hko}} \rangle$ and $\sigma_{\mathrm{r-hko}}$ are the mean and standard deviation of fourth-rooted HKO rainfall in 1980–1999, respectively.

Finally, daily rainfall amount projection in Hong Kong on rain day ($r_{\mathrm{p-hko}}$) is given by the fourth power of the projected fourth-rooted rainfall.

3.2 Return period analysis

The long term trend of the variation of the return period of extreme rainfall in Hong Kong in the 21st century is studied by applying the time-dependent Generalized Extreme Value (GEV) distribution technique (Coles, 2001) to the projected daily rainfall in Hong Kong. The rainfall projection data are downscaled from GFDL_M2_1 model (A2 and B1 scenarios) and MIROC3_2_HIRES model (A1B scenario) where daily data for the whole 21st century are available. As the principles and analysis method of the time-dependent GEV distribution technique have been well documented in other reference publications (Kharin and Zwiers, 2005; Wong and Mok, 2009; Wong et al., 2010), they are not repeated here.

4. Results

4.1 Validation of the downscaling models

The correlation coefficients (R) for the 4 downscaling equations for the rainfall amount model based on the method described in Section 3.1.2 range from 0.4 to 0.5. Due to the large variability in the daily rainfall in Hong Kong, it is not surprising to see that the R values of the downscaling model for rainfall are significantly lower than those for downscaling daily temperature (ranging between 0.67 and 0.95) obtained in the extreme temperature projection study (Lee et al., 2011). The R values of this study are in general comparable to the correlation levels reported in similar rainfall downscaling studies for other places, including the Dongjiang River region near Hong Kong (Beckmann and Buishand, 2002; Fealy and Sweeney, 2007; Huang et al., 2010; Wang et al., 2011).

A cross validation method is employed to evaluate the goodness of the downscaling equations in predicting the average rainfall. The cross validation consists of omitting 1 yr of daily data in turn when setting up the regression equations. The regression equations developed based on the remaining dataset are applied to predicting the omitted data (Wilks, 2006; Crawley, 2008). The process is repeated for all 30 years from 1971 to 2000.

For the rain occurrence model, the total percentage of correct forecast of occurrence of rain (daily rainfall ⩾ 1 mm) and no-rain day (daily rainfall < 1 mm) in the four seasons ranged from 72% to 84%. As regard the rainfall amount model, the root mean square (RMS) errors of the cross validation for the 5-yr mean annual rainfall are shown in Table 3. Except for winter which is usually the driest season with less rainfall, the errors are all below 25% of the long term average rainfall in the corresponding seasons.

Table 3. Root mean square (RMS) errors of the cross validation for 5-yr mean rainfall in the four seasons (1971–2000)

	Spring	Summer	Autumn	Winter
RMS error (mm)	89	165	115	34
Average total rainfall in 1971–2000 (mm)	589	1207	475	112

4.2 Evaluating model performance in simulating the past climate

For evaluating the performance of the global climate models in simulating the past extreme rainfall events, the multi-model means of the number of rain day, number of days with rainfall exceeding different thresholds and annual rainfall estimated from the downscaled model data for 1971–2000 (under 20C3M scenario) are compared with the actual observations in Hong Kong. As shown in Table 4, the differences in the simulated mean annual rainfall, number of rain days and extreme rainfall days (R100) compared with the actuals are respectively –62.9 mm, –6.9 days, and –0.5 days, which are well within the corresponding one standard deviations of the actual observations during 1971–2000 (i.e. 482.9 mm, 12.0 days, and 2.1 days, respectively). Figure 3 shows the comparison between the simulation and observation for the mean number of days with daily rainfall exceeding different thresholds during 1971–2000. The discrepancies for different rainfall ranges are again well within the corresponding one standard deviations. For the extreme rainfall days (daily rainfall ⩾ 100 mm), comparison of the variation in 5-yr intervals (Fig. 4) shows that the multi-model average of the climate model simulations in general has an acceptable skill in reproducing the changes in the evaluation period from 1971–2000, with errors less than 1 day for most of the 5-yr periods.

Table 4. Mean annual rainfall, annual number of rain days, and number of days with daily rainfall ⩾ 100 mm (R100) observed in Hong Kong during 1971–2000 and the corresponding estimations obtained from the downscaled data under the 20C3M scenario

Model/actual (1971–2000)	Annual rainfall (mm)	Number of days with daily rainfall ⩾ 1 mm (day)	Number of days with daily rainfall ⩾ 100 mm (day)
Simulation using 20C3M scenario	2319.8	97.1	3.2
Actual observation	2382.7	104.0	3.7
Difference of simulation from actual data	–62.9	–6.9	–0.5
Standard deviation of the actual observation during 1971–2000	482.9	12.0	2.1

The comparison for the monthly rainfall variation is shown in Fig. 5. The multi-model ensemble mean values are in general comparable to the actual observations with the wet and dry months reasonably simulated.

4.3 Projection results

4.3.1 Annual rainfall

Table 5 summarizes the changes in the annual rainfall in Hong Kong (relative to the 1980–1999 average of 2324 mm) projected by different models under the three available emission scenarios (B1, A1B, and

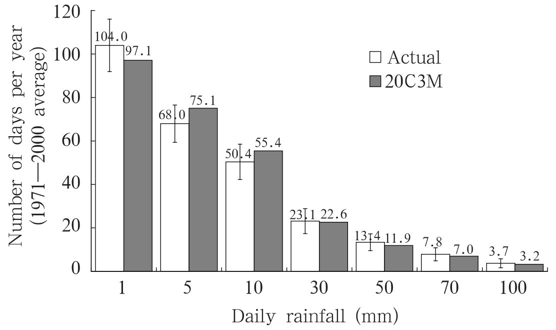

Fig. 3. Mean annual number of days with daily rainfall exceeding different thresholds during 1971–2000 and the corresponding multi-model ensemble mean estimations obtained from the downscaled data of 12 models under the 20C3M scenario. The error bar represents the corresponding standard deviation of the actual observations during 1971–2000.

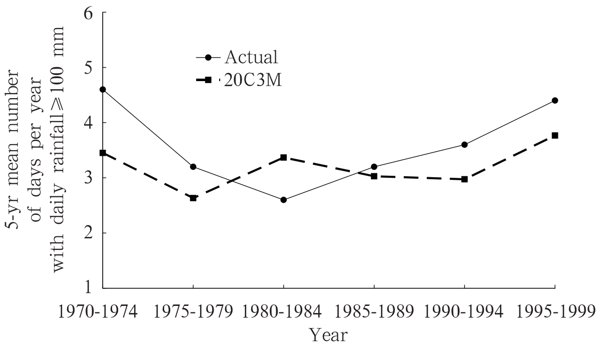

Fig. 4. 5-yr mean number of extreme rainfall days (daily rainfall ⩾ 100 mm) in Hong Kong in 1970–1999 and the corresponding multi-model ensemble mean estimations obtained from the downscaled data of 12 models under the 20C3M scenario.

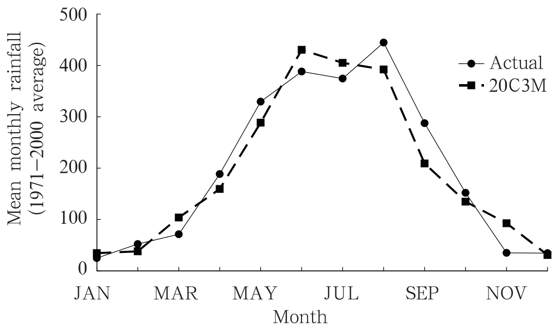

Fig. 5. Variation of mean monthly rainfall in 1971–2000 observed in Hong Kong (solid line) and the corresponding multi-model ensemble mean estimations obtained from the downscaled data of 12 models under the 20C3M scenario (dashed line).

A2) for the decades of 2050–2059 and 2090–2099. Figure 6 also shows the projected annual rainfall anomaly in Hong Kong for the whole 21st century period given by GFDL_CM2_1 model (A2 and B1 scenarios) and MIROC3_2_HIRES model (A1B scenario) together with the spread of the projections of all the models-scenario combinations for the decades 2050–2059 and 2090–2099. The multi-model scenario average of the projected annual rainfall anomaly for the decade 2090–2099 is +234 mm. About 63% of the model-scenario combinations suggest a positive rainfall anomaly towards the end of this century.

4.3.2 Number of rain days (daily rainfall ⩾ 1 mm)

The projected annual number of rain days in Hong Kong for different models and emission scenarios for the decades of 2050–2059 and 2090–2099 are given in Table 6. Figure 7 also shows the projected mean annual number of rain days in Hong Kong for the whole 21st century period given by GFDL_CM2_1 model (A2 and B1 scenarios) and MIROC3_2_HIRES model (A1B scenario) together with the spread of the projections of all model-scenario combinations for the decades 2050–2059 and 2090–2099. All model-scenario combinations suggest that the decreasing trend of the annual number of rain days as observed in the 20th century will continue in the 21st century. The annual number of rain days is expected to drop from 104 days in 1980–1999 to about 77 days by the decade 2090–2099 (multi-model scenario ensemble mean).

4.3.3 Extreme rainfall days (days with daily rainfall ⩾ 100 mm)

The projections for the annual number of days with daily rainfall ⩾ 100 mm (R100) in Hong Kong for different models and emission scenarios for the decades of 2050–2059 and 2090–2099 are tabulated in Table 7. Figure 8 also shows the projected R100 in Hong Kong for the whole 21st century period given by GFDL_CM2_1 model (A2 and B1 scenarios) and MIROC3_2_HIRES model (A1B scenario) together with the spread of the projections of all the models-scenario combinations for the decades 2050–2059 and 2090–2099. Relative to the 1980–1999 average, about 90% of the model-scenario combinations suggest an increase in R100 towards the end of the 21st century.

Table 5. Projected changes in the annual rainfall in Hong Kong (relative to the 1980–1999 average of 2324 mm) of different models and emission scenarios for the decades 2050–2059 and 2090–2099

Parameter	2050–2059	2090–2099
Model ensemble mean for B1 (M_{B1})	16.8	50.8
Model ensemble mean for A1B (M_{A1B})	260.1	346.6
Model ensemble mean for A2 (M_{A2})	–65.8	305.7
Ensemble upper limit	1905.1	1939.7
Ensemble mean for 3 scenarios (mean of M_{B1}, M_{A1B}, and M_{A2})	70.4	234.4
Ensemble lower limit	–602.7	–590.0

Table 6. Projected annual numbers of rain days in Hong Kong for different models and emission scenarios. The mean annual number of rain days in 1980–1999 is 104.4 days

Parameter	2050–2059	2090–2099
Model ensemble mean for B1 (M_{B1})	83.9	82.5
Model ensemble mean for A1B (M_{A1B})	85.2	76.2
Model ensemble mean for A2 (M_{A2})	78.1	72.9
Ensemble upper limit	95.3	95.5
Ensemble mean for 3 scenarios (mean of M_{B1}, M_{A1B}, and M_{A2})	82.4	77.2
Ensemble lower limit	64.2	61.4

The multi-model scenario ensemble mean of R100 is expected to reach about 5.3 days in the decade 2090–2099. The corresponding average annual number of extreme rainfall days in 1980–1999 is 3.5 days.

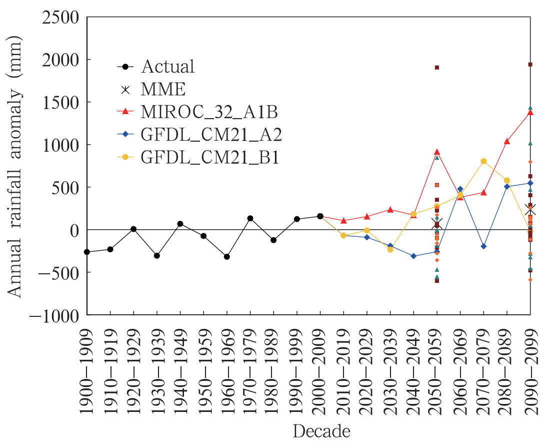

Fig. 6. Projected mean annual rainfall anomaly (relative to the 1980–1999 average of 2324 mm) in Hong Kong for the whole 21st century period given by GFDL_CM2_1 model (A2 and B1 scenarios) and MIROC3_2_HIRES model (A1B scenario) together with the spread of the projections of all the model-scenario combinations for the decades 2050–2059 and 2090–2099. The mean annual rainfall in Hong Kong is expected to increase from 2324 mm in 1980–1999 to 2559 mm (black cross) in 2090–2099.

Figure 9 also shows the projected changes in the multi-model scenario ensemble mean annual number of days with daily rainfall exceeding various thresholds in the decades 2050–2059 and 2090–2099 (relative to the 1980–1999 average). It can be seen that the mean

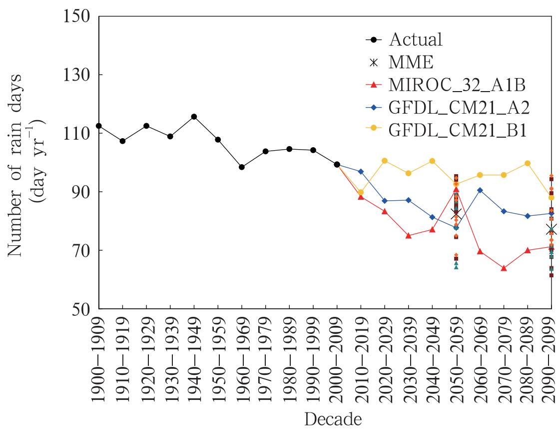

Fig. 7. Projected mean annual number of rain days (daily rainfall ⩾ 1 mm) in Hong Kong for the whole 21st century period given by GFDL_CM2_1 model (A2 and B1 scenarios) and MIROC3_2_HIRES model (A1B scenario) together with the spread of the projections of all the model-scenario combinations for the decades 2050–2059 and 2090–2099. The mean annual number of rain days is expected to decrease from 104 days in 1980–1999 to 77 days (black cross) in 2090–2099.

Table 7. Projected annual number of days with daily rainfall ⩾ 100 mm (R100) in Hong Kong for different models and emission scenarios. The mean R100 in 1980–1999 is 3.5 days

Parameter	2050–2059	2090–2099
Model ensemble mean for B1 (M_{B1})	4.0	4.6
Model ensemble mean for A1B (M_{A1B})	4.9	5.9
Model ensemble mean for A2 (M_{A2})	4.1	5.5
Ensemble upper limit	12.4	12.1
Ensemble mean for 3 scenarios (mean of M_{B1}, M_{A1B}, and M_{A2})	4.3	5.3
Ensemble lower limit	1.9	2.7

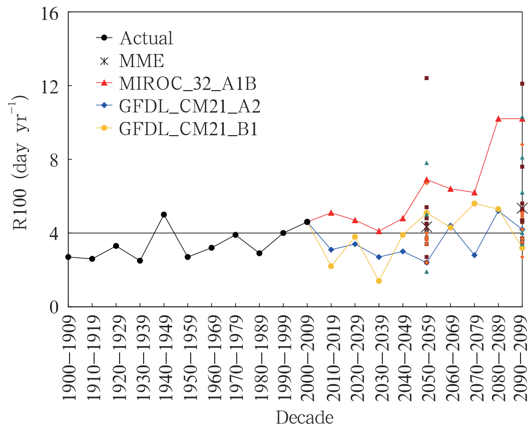

Fig. 8. Projected mean annual number of days with daily rainfall ⩾ 100 mm (R100) in Hong Kong for the whole 21st century given by GFDL_CM2_1 model (A2 and B1 scenarios) and MIROC3_2_HIRES model (A1B scenario) together with the spread of the projections of all the model-scenario combinations for the decades 2050–2059 and 2090–2099. The mean R100 is expected to increase from 3.5 days in 1980–1999 to 5.3 days (black cross) in 2090–2099.

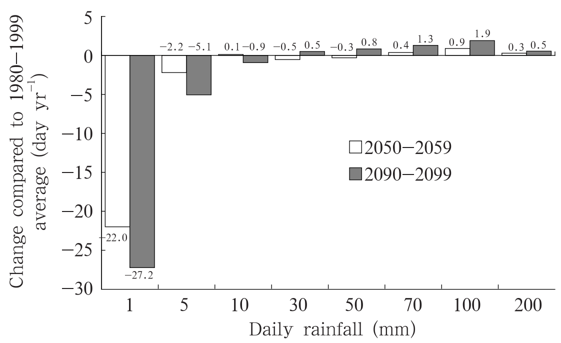

Fig. 9. The projected changes in the multi-model scenario ensemble mean number of days with daily rainfall exceeding various thresholds in Hong Kong in the decades 2050–2059 and 2090–2099 (relative to the 1980–1999 average).

annual number of days with daily rainfall ⩽ 5 mm is expected to decrease, while that for daily rainfall ⩾ 70 mm increases.

4.3.4 Other extreme rainfall indices

Table 8 summarizes the projections (multi-model scenario ensemble mean) of the other 8 extreme indices (SDII, R1d, R3d, R5d, R7d, CDD, CWD, and R95p) for the decades 2050–2059 and 2090–2099 as well as the average of the observed values in 1980–1999. Concurrent with the projected increase in annual rainfall and decrease in the number of rain days, SDII is expected to increase significantly in the 21st century. Similar to the results in Section 4.3.3, R1d, R3d, R5d, and R7d will also increase. Moreover, the projected increase in R95p suggests that the contribution of rainfall events exceeding the daily 95th percentile of the climatological normal to the annual rainfall will increase in the 21st century. The projected CDD and CWD in rain season (April to September) are expected to increase too, suggesting the distribution of rain days may become more uneven in the future.

4.3.5 Return period analysis

Using the actual observations for 2000–2009 and the projected annual maximum daily rainfall for the rest of the 21st century downscaled from the data of GFDL_CM2_1 model (A2 and B1 scenarios) and MIROC3_2_HIRES model (A1B scenario), the time dependent GEV technique is applied to analyze the return periods for daily rainfall ⩾ 300 mm and ⩾ 500 mm in Hong Kong by 2050. The numbers of 300 and 500 mm are used as references since daily rainfall of about 300 mm occurred on average once in a decade in the past century, and the highest daily (calendar day) rainfall recorded at HKOHq up to 2009 since record began in 1885 is 534 mm. The results together with those obtained using the observed data over the period

Table 8. Projections (multi-model scenario ensemble mean and ensemble limits) of the 8 extreme indices (SDII, R1d, R3d, R5d, R7d, CDD, CWD, and R95p) in Hong Kong for the decades 2050–2059 and 2090–2099 as well as the mean of the observed values in 1980–1999. Figures in brackets are the deviation from the 1980–1999 mean

Extreme indices	1980–1999 mean (actual)	2050–2059		2090–2099	
		Ensemble mean	Lower and upper limits	Ensemble mean	Lower and upper limits
SDII (mm day^{-1})	22.0	29.0(+7.0)	22.0–51.0	33.6(+11.6)	23.6–60.2
R1d (mm)	232.8	245.1(+12.3)	130.5–517.6	277.0 (+44.1)	156.4–562.0
R3d(mm)	347.3	469.7(+122.4)	254.1–1017.7	539.6(+192.3)	317.7–994.0
R5d (mm)	384.5	566.1(+181.6)	320.2–1275.8	653.6(+269.1)	395.7–1248.1
R7d (mm)	404.8	630.1(+225.3)	376.9–1441.9	723.5(+318.7)	435.1–1436.9
CDD (days)	14.1	27.1(+13.1)	19.3–37.8	28.9(+14.9)	20.3–47.8
CWD (days)	8.9	13.8(+4.9)	9.4–21.0	13.4(+4.6)	10.1–20.1
R95p (%)	28.8	33.8(+5.1)	19.4–61.3	39.3(+10.5)	23.0–66.0

1885–2009 are summarized in Table 9. It can be seen that the return period for daily rainfall ⩾ 300 mm will decrease from 9 yr in 2000 to around 2–5 yr in 2050. Moreover, for daily rainfall ⩾ 500 mm, the return period will significantly shorten from 117 yr in 2000 to around 14–25 yr in 2050 for GFDL_CM2_1 model (B1 scenario) and MIROC3_2_HIRES model (A1B scenario). For the GFDL_CM2_1 model (A2 scenario), which has a relatively larger projection in R100, this less than once-in-a-century event in 2000 will occur once in every 5 yr after 2050. On average, the return periods for daily rainfall ⩾ 300 mm and ⩾ 500 mm are 4 and 15 yr respectively in 2050. This suggests that, based on the three model-scenario combinations with daily projection data available for the whole 21st century, extreme rainfall events would become more frequent in the 21st century. However, it should be cautioned that there are large uncertainties in these projected return period values as only three sets of simulation with whole 21st century data available are used in this analysis.

Table 9. Projected return periods for daily rainfall ⩾ 300 mm and daily rainfall ⩾ 500 mm in Hong Kong in 2050 for GFDL_CM2_1 model (A2 and B1 scenarios) and MIROC3_2_HIRES model (A1B scenario) using time dependent GEV approach with actual observations for 2000–2009 and model projections for 2010–2099. The return periods for daily rainfall ⩾ 300 mm and daily rainfall ⩾ 500 mm in 2000 as computed based on the observations from 1885 to 2009 are 9 and 117 yr, respectively (shown in brackets)

Model/actual	Return period for daily rainfall ⩾ 300 mm in 2050 (yr)	Return period for daily rainfall ⩾ 500 mm in 2050 (yr)
GFDL_CM2_1 (A2 scenario)	2	5
GFDL_CM2_1 (B1 scenario)	5	14
MIROC3_2_HIRES (A1B scenario)	4	25
Average of the 3 available model-scenario combinations	4(9)	15(117)

4.4 Uncertainties

Although the projected changes in extreme events reported by IPCC AR4 in general match with the observed changes in the 20th century, there are still large uncertainties and gaps in our knowledge of climate change and extremes (WMO, 2009). It should be noted that the skills of global climate models in predicting rainfall vary widely and some of the physical processes associated with extreme precipitation may not be well represented in the models. Furthermore, confidence in model estimates is usually low at the regional level (IPCC, 2007a; Kharin et al., 2007). In this study, although a majority of the projections suggest that the observed changes in rainfall extremes during the 20th century will continue into the 21st century, the intermodel disagreements are still large with a divergence in the projections for the number of extreme precipitation events. This, to a certain extent, reflects that there are still large uncertainties in the model simulation of the future climate, depending very much on the future forcing emission scenarios, the choice of models, model skills, the downscaling methodology, the stability of the statistical relationships between predictors and predictands in the future as well as the response of models to different emission scenarios and aerosol effects (STARDEX, 2005; Stainforth et al., 2007; Tebaldi and Knutti, 2007; Knutti, 2008; Hundecha and Bárdossy, 2008; Reichler and Kim, 2008).

Moreover, as pointed out by Reifen and Toumi (2009), a model which performs better in the verification period may not outperform other models and the multi-model ensemble mean in future projections. This is because the climate feedback strength and forcing is not stationary during the projection period and each model may respond differently to the feedback strength, favoring no particular model consistently. Therefore, a generally accepted approach is to adopt the multi model-scenario ensemble to depict plausible changes in extreme rainfall events (STARDEX, 2005; Kiktev et al., 2007; IPCC, 2007a; Knutti, 2008; Fowler and Ekström, 2009; Weigel et al., 2010). This is the approach employed in this study of extreme rainfall events in Hong Kong in the 21st century.

5. Conclusion

Although it may not be possible to attribute each extreme event to climate change alone, a relatively small shift in the mean state of climate can result in substantial changes in the frequency of extreme weather events. In a warmer climate, one can expect that the water content of the atmosphere will increase, providing a more favorable condition for intense precipitation events (Meehl et al., 2000, 2005; Meehl and Tebaldi, 2004; Emori and Brown, 2005; Kharin and Zwiers, 2005, Benestad, 2006; Mitchell et al., 2006, Min et al., 2011). Previous studies reported that there was an increasing trend in the frequency and intensity of extreme precipitation events in Guangdong and Hong Kong in the last century (Guangdong Meteorological Bureau, 2007; Wong and Mok, 2009; Zhang et al., 2009; Ginn et al., 2010; Wong et al., 2010).

Projections of extreme rainfall in Hong Kong for the 21st century were made by statistically downscaling 30 sets of the daily global climate model projections (12 models) of the IPCC AR4 for the three available greenhouse gas emission scenarios, i.e., A2, A1B, and B1. Multiple stepwise logistic and linear regressions were employed to develop the statistical downscaling models for predicting rainfall occurrence and rainfall amount respectively using global climate model data over southern China as predictors. The downscaling method has been validated using cross validation method. By using the 20C3M simulation data, the multi-model ensemble mean of the downscaled global climate model outputs has also been verified to have an acceptable skill in reproducing past extreme rainfall events during 1971–2000.

The projections suggest that the number of rain days is expected to decrease in the 21st century while the daily rainfall intensity will increase, concurrent with the expected increase in annual rainfall. The multi-model scenario ensemble mean of the annual number of rain days is expected to drop from 104 days in 1980–1999 to about 77 days in the decade 2090–2099. For extreme rainfall events, about 90% of the model-scenario combinations suggest an increase in the annual number of days with daily rainfall $\geqslant$ 100 mm (R100) towards the end of the 21st century. The mean R100 is expected to increase from 3.5 days per year in 1980–1999 to about 5.3 days in the decade 2090–2099. The frequency of occurrence of extreme rainfall events is also expected to increase in the 21st century. Return period analysis of the projections of the three model-scenarios with daily data for the whole 21st century (i.e., GFDL_CM2_1 model (A2 and B1 scenarios) and MIROC3_2_HIRES model (A1B scenario)) suggests that, on average, the return periods of daily rainfall $\geqslant$ 300 mm and $\geqslant$ 500 mm are expected to decrease from 9 and 117 yr in 2000 to about 4 and 15 yr in 2050, respectively. The projected changes in other extreme rainfall indices also suggest that the rainfall in Hong Kong in the 21st century may become more extreme with more uneven distributions of wet and dry periods.

When compared with the observed changes in the 20th century, the projections of a decrease in the number of rain days and increase in the number of days with extreme rainfall in the 21st century are generally consistent with the past trends of extreme rainfall events in the last century. According to the study of Wong et al. (2010), SDII, R95p, and CDD in Hong Kong had significant increasing trends from 1885 to 2008 (at the 5% level). R1d, R3d, and R5d also had rising trends though not statistically significant due to large interannual variations. For the number of rain days, a recent analysis reveals that the number of rain day decreased by 1.1 day per decade from 1885 to 2009. The trend is significant at the 5% level (figure omitted).

The projection results of this study are also generally in line with the findings reported in other studies for extreme weather projections in China and East Asia (Kitoh et al., 2005; Zhang et al., 2006; Jiang et al., 2007, 2009; Kharin et al., 2007; Sun et al., 2007; Feng et al., 2011). The study by Jiang et al. (2009) using grid point data of 7 IPCC AR4 models indicated that the SDII, R5d, R95p, and CDD in southern China will increase in the 21st century. The simulations for East Asia conducted by Kitoh et al. (2005) using 3-member ensemble global ocean-atmospheric coupled general circulation model (GCM) and Sun et al. (2007) using 17 coupled GCMs also suggested that, in the 21st century, southern China is a region where summer rain day frequency decreases and rainfall intensity increases.

Studies on greenhouse gas forcing suggested that the increase in atmospheric greenhouse gas concentration may play a role in the changes in extreme precipitation events in China (Gong and Wang, 2000; Gao et al., 2001, 2002; Li et al., 2011). Furthermore, the study conducted by Sun and Ding (2010) on the changes in the East Asian monsoon precipitation in the 21st century indicated that the increase in precipitation in China may be attributed to the combined effect of the increase in the atmospheric moisture content and strengthening of the East Asian monsoon circulation. Kitoh et al. (2005) suggested that the projected decrease in rain day and increase in rainfall intensity could be related to the increased atmospheric moisture content due to global warming and an intensified and more westward extended North Pacific subtropical anticyclone. This circulation change may be associated with El Niño-like mean SST changes while other possibilities remain. The study by Qian et al. (2007b) also suggested that the decrease in lighter precipitation may be attributed to the increasing temperature, which makes it harder for air to reach dewpoint temperature. Besides the warming and the associated circulation changes, another study using observation and simulation data pointed out that the increase in the human-induced aerosol concentrations could also be partly responsible for the decrease in light rain events observed in China over the past 50 years (Qian et al., 2009).

In this study, although a majority of the projections suggest that the observed changes in rainfall extremes during the 20th century will continue into the 21st century, there is a large divergence in the projections for the number of extreme rainfall events simulated by different model-emission scenario combinations. This, to a certain extent, reflects that there are still large uncertainties in the model simulation of the future climate, depending very much on the future forcing emission scenarios and the models' characteristics/performance.

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Appendix I

Definitions of the extreme rainfall indices used in this study

Extreme indices	Definition	Modifications to the ETCCDMI (if any)	Unit
R100	Annual number of days with daily rainfall ⩾ 100 mm	Change the threshold to 100 mm	Day
R1d	Annual maximum daily rainfall	Change the threshold to 1 day	mm
R3d	Annual maximum consecutive 3-day rainfall	Change the threshold to 3 days	mm
R5d	Annual maximum consecutive 5-day rainfall		mm
R7d	Annual maximum consecutive 7-day rainfall	Change the threshold to 7 days	mm
SDII (Simple daily precipitation intensity index)	Simple daily precipitation intensity index: Total annual rainfall divided by the annual number of wet days (daily rainfall ⩾ 1 mm)		mm day^{-1}
CDD (Maximum consecutive dry days)	Maximum length of dry spell, maximum number of consecutive days with daily rainfall< 1 mm. Let RR_{ij} be the daily rainfall amount on day i in period j. Count the largest number of consecutive days where: $RR_{ij} < 1$ mm	Changed from whole year to the period from April to September	Day
CWD (Maximum consecutive wet days)	Maximum length of wet spell, maximum number of consecutive days with daily rainfall ⩾ 1 mm: Let RR_{ij} be the daily rainfall amount on day i in period j. Count the largest number of consecutive days where: $RR_{ij} \geqslant 1$ mm	Changed from whole year to the period from April to September	Day
R95p	The fraction of annual rainfall amount due to extreme rainfall days (>95th percentile). Let RR_j be the sum of daily rainfall amount in period j. Let RR_{wj} be the daily rainfall amount on a wet day w (rainfall ⩾ 1 mm) in period j and let $RR_{wn}95$ be the 95th percentile of precipitation on wet days in the 1971–2000 base period. Then $R95_{pj}$ is determined as the sum of R_{wj} at days with $RR_{wj} > RR_{wn}95$ divided by the total annual rainfall.	Reference period changed from 1961–1990 to 1971–2000	%

Appendix II

Table B1. Predictors and standardized coefficients of the regression equations of rainfall occurrence model for each of the four seasons

Predictors	Spring	Summer	Autumn	Winter
Precipitation (Pr)	1.29	1.31	1.64	0.77
Surface mean temperature (T)	×	×	×	–0.96
Sea level pressure (Slp)	–0.76	×	×	–0.20
850-hPa temperature (T850)	–1.37	–0.39	–0.83	×
850-hPa specific humidity (Sh850)	×	×	0.30	0.49
850-hPa vorticity (Vort850)	0.24	–0.30	×	0.29
500-hPa temperature (T500)	–0.34	0.09	×	–0.43
500-hPa specific humidity (Sh500)	0.74	0.39	0.36	0.25
200-hPa divergence (Div200)	–0.30	0.10	0.13	–0.12

Table B2. Predictors and standardized coefficients of the regression equations of rainfall amount model for each of the four seasons

Predictors	Spring	Summer	Autumn	Winter
Precipitation (Pr)	0.25	0.35	0.40	0.19
Surface mean temperature (T)	0.66	0.18	×	×
Sea level pressure (Slp)	–0.20	×	×	×
850-hPa temperature (T850)	–0.71	–0.15	×	0.11
850-hPa specific humidity (Sh850)	×	–0.11	–0.20	×
850-hPa vorticity (Vort850)	0.10	0.14	×	0.12
500-hPa temperature (T500)	–0.08	×	×	–0.17
500-hPa specific humidity (Sh500)	×	0.10	0.23	0.09
200-hPa divergence (Div200)	×	×	×	0.18

×–not included as predictors in the regression equations.

Note: for precipitation, standardized fourth-rooted anomaly is used as predictor.

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