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Abstract

By downscaling rainfall forecasts made by global climate models, it was found that due to global warming, the annual rainfall in Hong Kong would increase at a rate of about 1% per decade in the 21st century, about the same as in the previous 120 years. In the last 10 years of this century, that is, in the years 2090-2099, the annual rainfall at the Hong Kong Observatory (HKO) Headquarters is expected to be about 2430 mm, or 216 mm above the 1961-1990 average of 2214.3 mm.

In addition, the year-to-year variability in rainfall would also increase. In the 21st century, it is expected that there will be 6 years with annual rainfall exceeding 3343 mm, the highest rainfall recorded at HKO Headquarters in the past 120 year, and 3 years with annual rainfall less than the lowest of 901 mm. Also, from the 30-year period 1961-1990 to the last 30 years of this century, that is, 2070-2099, the number of days in a year with hourly rainfall exceeding 30 mm will increase from about 5.6 to 6.5.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) concluded in its Third Assessment Report that the global mean surface temperature has increased by 0.6 ± 0.2°C in the 20th century, and might increase by a further 1.4°C to 5.8°C before the end of 2100 depending on the emission scenario (IPCC 2001). The report also pointed out that in association with this global warming, the global average precipitation would increase and larger year to year variations in precipitation are very likely over most areas where an increase in mean precipitation is projected. Enhancement in the water cycle associated with global warming is a likely reason for the projected increase in global precipitation.

For Hong Kong, using the statistical downscaling method, Leung *et al*. (2005) showed that under the influence of global warming, in the last decade of this century the annual mean temperature in Hong Kong could rise by 1.7°C to 5.6°C above the 1961-1990 normal. The present study is an attempt to project the change in rainfall in Hong Kong up to the end of the century using this statistical downscaling method. The parameters examined are annual rainfall, the number of rain days, viz., days with more than 0.1 mm of rainfall, and the number of heavy rain days, viz., days with hourly rainfall greater than 30 mm which is one of the criteria for issuing the Amber Rainstorm Warning.

2. Data

Historical rainfall data and rainfall forecasts made by global climate models are used in this study. The historical rainfall data used are the monthly rainfall recorded between 1951 and 2000 at the HKO Headquarters, 41 stations in southern China (area bounded by 20-30°N, 105-120°E) indicated by white dots in Figure 1, and 40 in central China (area bounded by 30-40°N, 105-120°E) indicated by black dots in Figure 1. The data were sourced from HKO and the National Climate Centre (NCC) of the China Meteorological Administration (CMA).

The rainfall forecasts used here are the gridded monthly forecasts made by the seven global climate models CSIRO-Mk2, ECHAM4/OPYC3, HadCM3, NCAR DOE-PCM, GFDL (consisting of the low resolution GFDL-R15 and the high resolution GFDL-R30), CCCma (consisting of CGCM1 & CGCM2) and CCSR/NIES. These forecasts are available from IPCC's Data Distribution Centre website http://ipcc-ddc.cru.uea.ac.uk/. A summary of the parent organizations and resolutions of these models can be found in Leung *et al*. (2005). The emission scenarios under which rainfall projections are available from the Data Distribution Centre are listed in Table 1. Details of the emission scenarios can be found in Houghton *et al*. (1994) and Nakicenovic *et al*. (2000).

3. Methodology

(a) Annual rainfall

(i) *Statistical downscaling*

The statistical downscaling technique is one of two techniques used to generate local and regional scale climate projections from global climate model forecasts which are usually made at relatively low spatial resolution, typically 300 km x 300 km (e.g., Kilsby *et al*. 1998). It has become popular because of its computational economy compared with the alternative approach which is dynamical downscaling (see for example Benestad 2001, Fan *et al.* 2005), and has a level of skill on par with the dynamical approach (Murphy 1999). Rainfall and temperature are two of the variables most frequently downscaled statistically (e.g., Hanssen-Bauer *et al.* 2005). Regression is often employed in statistical downscaling (see for example Wigley *et al*. 1990, Wilby *et al.* 2005).

Statistical downscaling usually involves two main steps (e.g., Mullan *et al*. 2001). Firstly, an empirical relationship between a local or regional predictand, such as rainfall or temperature, and some large-scale predictors which may be sea level pressure, air temperature, geopotential height (von Storch *et al.* 1993, Kidson and Thompson 1998, Wilby and Wigley 2000) or rainfall (Widmann *et al*. 2003) is established using historical data. Secondly, global model forecasts of the selected large-scale predictors are fed into the regression equation to give projected values of the local or regional predictand.

As in the temperature projection study for Hong Kong undertaken by Leung *et al.* (2005), this study uses regression–based downscaling of the rainfall forecasts of global climate models to project the change in Hong Kong's annual rainfall to the end of the century.

A multiple linear regression relationship between annual rainfall anomaly at HKO as the predictand and two large-scale predictors, viz., the spatially averaged annual rainfall anomaly in southern China and the spatially averaged annual rainfall anomaly over central China (see Section 3(ii)) is established using historical data. The average annual rainfall anomaly over southern China is calculated from the monthly rainfall recorded at the 41 stations, and the average annual rainfall anomaly over central China from the 40 stations. The average annual rainfall anomaly over each of these two regions in the future are computed from the model grid point values and then fed into the regression equation to give the projected annual rainfall anomaly for Hong Kong.

(ii) *Selection of predictors*

That two large-scale predictors - spatially averaged rainfall over southern China and over central China - are needed is because of the very clear out-of-phase relationship in the annual rainfall anomalies in these two regions. When southern China has more than normal annual rainfall, central China would usually have lower than normal annual rainfall and vice versa (e.g., Dai *et al*. 1997).

(iii) *The multiple linear regression equation for annual rainfall*

The multiple regression equation for annual rainfall anomaly at HKO Headquarters y is

$$y = 2.05x_1 - 1.79x_2 + 19.14 \qquad (1)$$

where x_1 is the spatial average of rainfall anomalies in southern China, and x_2 the spatial average of rainfall anomalies in central China (Figure 2). The coefficient of determination R^2 is 0.42. That is, the proportion of variation in the annual rainfall anomaly at HKO Headquarters accounted for by the regression is 42% (Wilks 1995).

(b) <u>Extreme annual rainfall</u>

The usual way of classifying extreme values is to use two standard deviations as boundary (e.g., Palmer and Räisänen 2002, Wang and Xu 1997). Adopting this classification and using the mean and standard deviation in the period 1961-1990 lead to an annual rainfall greater than 3239 mm as extremely high annual rainfall, and an annual rainfall less than 1189 mm as extremely low annual rainfall. Furthermore, the absolute maximum and minimum annual rainfall for the 120 years of record were 3343 mm and 901 mm respectively. The annual rainfall for each model and for each scenario is first found as in (a) and the number of years with annual rainfall outside the above thresholds is counted.

(c) Number of rain days and number of heavy rain days

The projected number of rain days per year N_r is derived from the projected annual rainfall y. The linear regression equation, constructed from the number of rain days and annual rainfall observed at HKO Headquarters, is

$$N_r = 0.019\ y + 95.6 \tag{2}$$

The coefficient of determination R^2 is 0.35, or 35% of the variation in the number of rain days N_r is accounted for by the regression.

Projection of the number of heavy rain days N_h, viz., the number of days with hourly rainfall exceeding 30 mm is similarly made. The regression equation is

$$N_h = 0.0035\ y - 2.04 \tag{3}$$

The corresponding coefficient of determination R^2 is 0.44. Thus some 44% of the variation in N_h is accounted for by equation (3).

4. Results and Discussion

4.1 Past rainfall trend

Rainfall record at HKO Headquarters dated back 120 years to 1885. As shown in Figure 3, the annual rainfall at the HKO Headquarters has a rising trend of 20 mm (that is about 1%) per decade between 1885 and 2004, though this trend is not statistically significant at 5% level. Between 1947 and 2004, the trend is higher at 43 mm per decade, but it is again not statistically significant at 5% level. In the past 120 years, the annual rainfall lies between 901 mm and 3343 mm. The 1961-1990 normal of annual rainfall is 2214.3 mm.

4.2 Projected changes in rainfall

(a) Annual rainfall

Table 2 and Figure 4 give the projected annual rainfall in Hong Kong, which varies with the scenario and the model.

For the scenario IS92a GG, Figure 5 shows little change in the multi-model ensemble mean annual rainfall anomaly in the 21st century. The multi-model ensemble mean annual rainfall anomaly is generally negative in the emission scenario IS92a GS but positive in the SRES. Lai and Harasawa (2001) noted that if sulphate aerosols are added in the climate model simulation experiments, the rainfall in Asia will decrease. It was also mentioned in IPCC (1998) that when both the increase in greenhouse gases and sulphate aerosols are considered, the temperature difference between land and sea in the Asian monsoon region would decrease. Hence the monsoon would weaken and its associated rainfall would become less. For all scenarios, the multi-model ensemble mean annual rainfall anomaly is positive and also has a rising trend (Figure 5d).

In the 30-year period 2070-2099, 20 out of 24 (i.e. 83%) different scenarios and models combinations forecast the annual rainfall anomaly to be positive, despite all forecasting positive annual mean temperature anomalies (Figure 6).

Focusing on the models, the difference in simulation results between CCSR/NIES and CCCma is the largest (Table 3). Projected annual rainfall anomalies from CCSR/NIES in the eight emission scenarios are all positive, and also higher than those of other models in the same scenarios. The forecasts by CCCma are negative in most of the scenarios in contrast to the positive values from other models. This difference in model forecasts is possibly related to the limited skill of CCCma in simulating the present Asian climate (Lai and Harasawa 2001).

Except IS92a GS, the multi-model ensemble mean annual rainfall anomalies are positive for different emission scenarios (see Table 3). This reflects that the increase in annual rainfall of Hong Kong is in line with the increase in the concentration of carbon dioxide. Past model simulation studies have already revealed that the rainfall in East Asia and China would increase under the scenario of doubled carbon dioxide concentration (Zhao *et al*. 2005).

Using the multi-model ensemble mean, the rainfall in Hong Kong would increase at a rate of about 1% per decade in the 21st century, and the trend is statistically significant at the 5% level. This result is similar to that obtained by NCC of CMA for Guangdong (http://www.ipcc.cma.gov.cn/cn/MapSys/) (Figure 7). Table 4 compares the projected change in annual rainfall for Hong Kong from 1961-1990 to 2070-2099 obtained in the present study with that obtained by the Climate Research Unit (CRU) of the University of East Anglia of the United Kingdom (http://www.cru.uea.ac.uk/%7Etimm/climate/ateam/TYN_CY_3_0.htm). It can be seen that the projected changes from the two studies are of the same sign for each scenario though differing in magnitude. This difference in magnitude is probably related to the difference in the downscaling method adopted. CRU has used the weighted average of projections at 0.5° resolution (Mitchell *et al*., 2002).

In the last 10 years (2090-2099) of this century the ensemble mean annual rainfall is 2430 mm, or 216 mm above the 1961-1990 average of 2214.3 mm (Figure 4).

(b) Extreme annual rainfall

The multi-model ensemble mean number of years in which extremely high annual rainfall and extremely low annual rainfall would occur in 30-year periods in the 21st century are shown in Figure 8. It can be seen that the ensemble mean number of years with extremely high annual rainfall rises from 1 in 1961-1990 to 4.6 (i.e. about 4 to 5) in 2070-2099. On the other hand, the number of occurrence of extremely low annual rainfall is expected to rise from 1 in 1961-1990 to 1.8 (i.e. about 2) in 2070-2099.

In the past 120 years, the highest and lowest annual rainfall recorded at HKO Headquarters was 3343 mm and 901 mm, respectively. In the 21st century, the multi-model ensemble mean number of occurrences of annual rainfall above 3343 mm is 5.7 (i.e. about 6), while the number of occurrences of annual rainfall below 901 mm is 2.9 (i.e. about 3).

(c) Number of rain days

The number of rain days projected using Equation (2) are listed in Table 5. It can be seen that in 2070-2099, the multi-model ensemble mean number of rain days in a year is 142, slightly higher than the 137 days for 1961-1990.

(d) Number of heavy rain days

The number of heavy rain days projected using equation (3) is also given in Table 5. It can bee seen that the number of days in a year with hourly rainfall greater than 30 mm will increase from the 1961-1990 average of 5.6 to 6.5 in the period 2070-2099.

5. Conclusion

Statistical downscaling of rainfall forecasts made by global climate models shows that under the influence of global warming, annual rainfall in Hong Kong would increase at a rate of about 1% per decade in the 21st century. It can be anticipated that in the years 2090-2099, the annual rainfall at HKO Headquarters would be about 2430 mm, an increase of 216 mm from the 1961-1990 average of 2214.3 mm.

The year-to-year variability in rainfall in Hong Kong would also increase. It is expected that in the 21st century there would be 6 years with annual rainfall exceeding 3343 mm the highest annual rainfall recorded at HKO Headquarters in the past 120 year, and 3 years with annual rainfall less than the lowest of 901 mm.

For the number of days with heavy rain, from the 30-year period 1961-1990 to the 30 years 2070-2099, the number of days in a year with hourly rainfall exceeding 30 mm will increase from about 5.6 to 6.5.

Acknowledgement

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Table 1. Rainfall forecasts sourced from IPCC for different global climate models and different emission scenarios (shaded in light grey).

Model		IS92a		SRES					
		GG	**GS**	**A1FI**	**A1B**	**A1T**	**A2**	**B1**	**B2**
GFDL	R-15	■	■						
	R-30								■
CCSR/NIES		■	■	■	■	■	■	■	■
CSIRO-Mk2		■	■		■		■	■	■
CCCma	CGCM1	■	■						
	CGCM2						■		■
HadCM3		■	■				■		■
NCAR DOE-PCM			■		■		■		■
ECHAM4/OPYC3		■	■						

[*] IS92a: '*Business as Usual*' emission scenario. GG: cooling by sulphates not included, GS: cooling by sulphates included. SRES: *Special Report on Emission Scenarios*. A1FI: fossil fuel intensive, A1B: balanced fossil and non-fossil fuel usage, A1T: emphasis on non-fossil fuels; A2: most rapid population growth but comparatively slow economic and technological growth; B1: global solutions to sustainability; B2: increasing population with regional and local solutions to sustainability.

Table 2. Projected change in annual rainfall in Hong Kong. The change is with reference of the 1961-1990 normal.

Scenario		Model	10-year		30-year		
			2040-2049	2090-2099	2010-2039	2040-2069	2070-2099
IS92a	GG	GFDL-R15	285.0		0.7		
		CCSR/NIES	-220.5	146.6	140.3	18.9	261.0
		CSIRO-Mk2	139.3	71.7	28.3	284.9	228.0
		CCCma CGCM1	96.7	-18.6	31.3	-170.3	124.9
		HadCM3	-188.1	513.7	-136.9	-183.4	188.4
		ECHAM4/OPYC3	-155.2	-564.3	-53.4	-232.4	-287.2
	GS	GFDL-R15	-98.8		-160.4		
		CCSR/NIES	-262.3	129.4	109.4	-120.8	159.1
		CSIRO-Mk2	-33.5	-32.2	43.9	-56.0	139.9
		CCCma CGCM1	-449.5	-1051.2	-488.4	-669.7	-884.2
		HadCM3	105.8	-333.7	123.7	40.1	121.0
		ECHAM4/OPYC3	14.0		-64.8		
SRES	A1FI	CCSR/NIES	300.1	416.3	51.1	191.8	610.4
	A1B	CCSR/NIES	534.4	882.1	415.6	669.3	738.5
		CSIRO-Mk2	473.1	382.0	185.3	538.6	584.2
	A1T	CCSR/NIES	318.1	1028.4	269.8	438.4	786.2
	A2	CCSR/NIES	250.6	628.7	281.1	388.2	670.3
		CSIRO-Mk2	439.3	425.2	296.9	363.5	667.6
		CCCma CGCM2	-305.4	-450.8	24.4	-296.5	-587.6
		HadCM3	-57.7	241.4	101.1	40.4	347.8
	B1	CCSR/NIES	276.5	747.4	207.9	687.8	546.2
		CSIRO-Mk2	250.3	600.8	370.4	220.4	421.9
	B2	GFDL-R30	-198.2	191.0	97.3	40.7	161.0
		CCSR/NIES	351.2	968.4	598.7	788.6	742.8
		CSIRO-Mk2	462.5	602.5	217.3	307.2	504.1
		CCCma CGCM2	98.0	-655.9	-161.7	-280.4	-407.4
		HadCM3	363.6	307.5	-3.8	105.4	226.9
		Ensemble upper limit	534.4	1028.4	598.7	788.6	786.2
		Ensemble mean	103.3	215.7	93.5	129.8	252.7
		Ensemble lower limit	-449.5	-1051.2	-488.4	-669.7	-884.2

* Results of NCAR DOE-PCM model are not given as the model's rainfall data from 1961-1990 are not available from the IPCC DCC website.

Table 3. Projected change in 30-year mean annual rainfall from 1961-1990 to 2070-2099 for different climate models and for different emission scenarios. Scenarios are ranked according to the atmospheric carbon dioxide concentration from low to high, SRES B1 being the lowest and SRES A1FI the highest.

Model \ Scenarios	Atmospheric carbon dioxide concentration								Scenario mean
	lowest ←→ highest								
	SRES				IS92a		SRES		
	B1	A1T	B2	A1B	GG	GS	A2	A1FI	
CCSR/NIES	546.2	786.2	742.8	738.5	261.0	159.1	670.3	610.4	564.3
CSIRO-Mk2	421.9		504.1	584.2	228.0	139.9	667.6		424.3
HadCM3			226.9		188.4	121.0	347.8		221.0
CCCma CGCM1/2			-407.4		124.9	-884.2	-587.6		-438.6
ECHAM4/OPYC3					-287.2				-287.2
GFDL-R30			161.0						161.0
Model mean	484.1	786.2	245.5	661.4	103.0	-116.1	274.5	610.4	252.7

Table 4. Comparison of the projected change in 30-year mean annual rainfall in Hong Kong from 1961-1990 to 2070-2099 obtained in the present study with that obtained by the Climate Research Unit (CRU) of the University of East Anglia.

Model	Scenario	Present study	CRU
CSIRO-Mk2	A2	667.6	312.7
	B1	421.9	288.6
	B2	504.1	265.7
CCCma CGCM2	A2	-587.6	-93.5
	B2	-407.4	-152.8
HadCM3	A2	347.8	386.9
	B2	226.9	377.1

Table 5. Projected annual number of rain days and annual number of days with hourly rainfall exceeding 30 mm.

Parameters	Period	30-year Model Ensemble				1961-90 average
		Lower limit	Mean	Median	Upper limit	
Annual number of rain days (days)	2010-2039	128.2	139.1	139.2	148.6	137.4
	2040-2069	124.7	139.8	138.7	152.2	
	2070-2099	120.7	142.1	142.0	152.1	
Annual number of days with hourly rainfall > 30 mm (days)	2010-2039	3.9	5.9	5.9	7.7	5.6
	2040-2069	3.3	6.0	5.8	8.3	
	2070-2099	2.5	6.5	6.4	8.3	

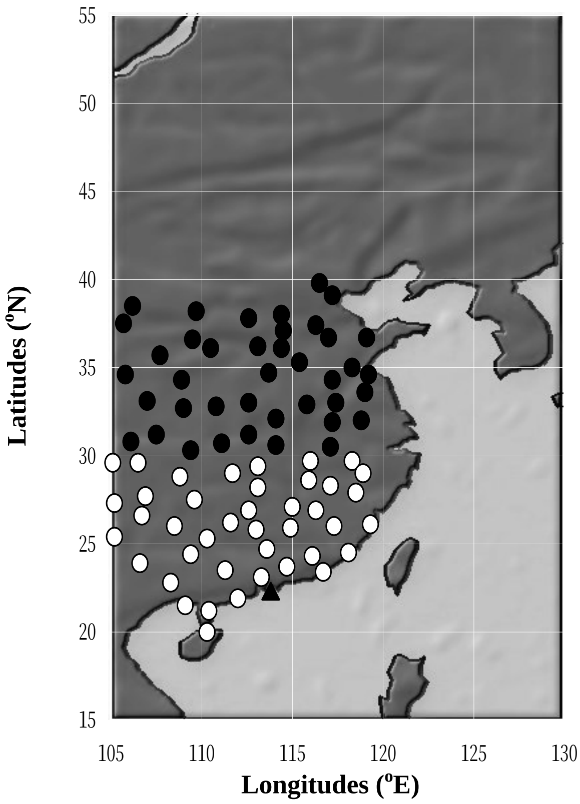

Figure 1. Location of the Hong Kong Observatory Headquarters (indicated by the solid triangle) and 81 rainfall recording stations in Mainland China (indicated by dots). White dots (a total of 41) denote stations in southern China (defined as region X1:20-30°N and 105-120°E). Black dots (a total of 40) denote stations in central China (defined as region X2: 30-40°N and 105-120°E).

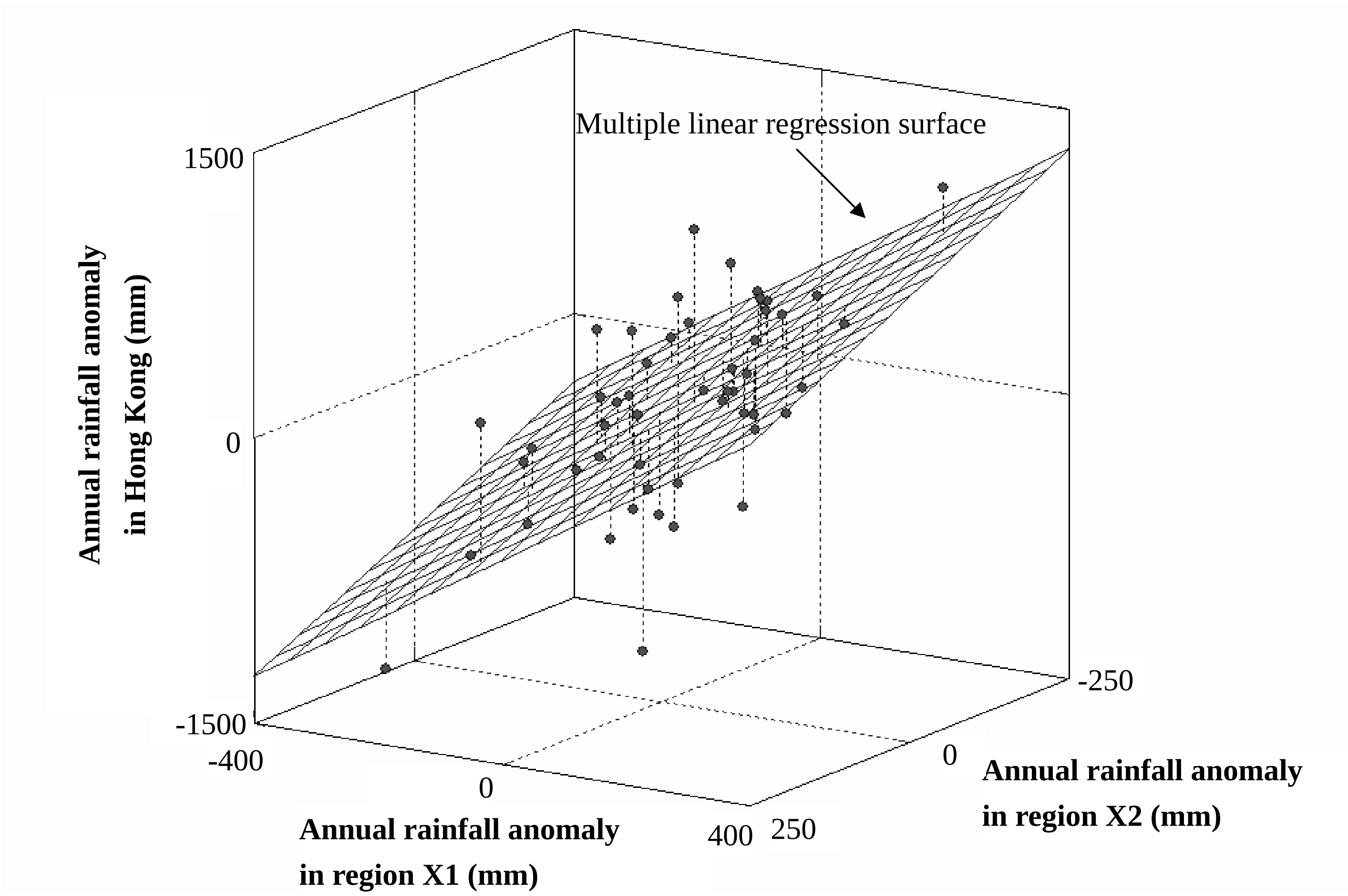

Figure 2. Multiple linear regression of the annual rainfall anomaly in Hong Kong with that in southern China (X1) and in central China (X2).

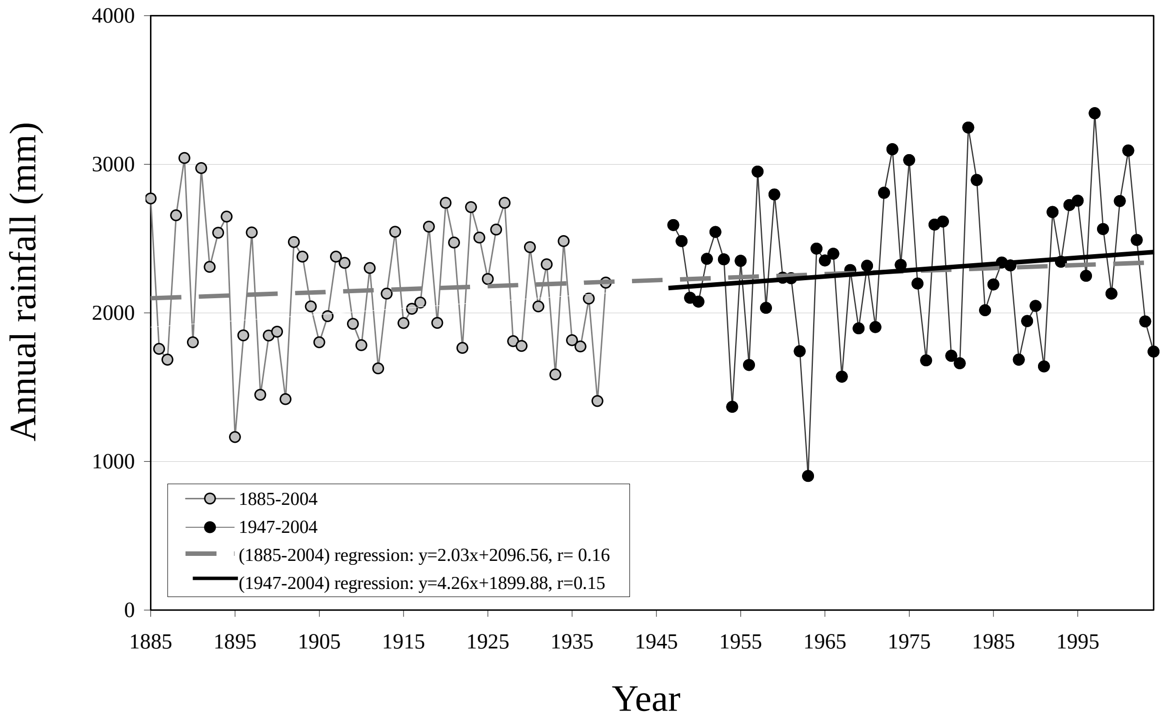

Figure 3. Time series of the annual rainfall in Hong Kong. Both linear trends shown are not significant at the 5% level.

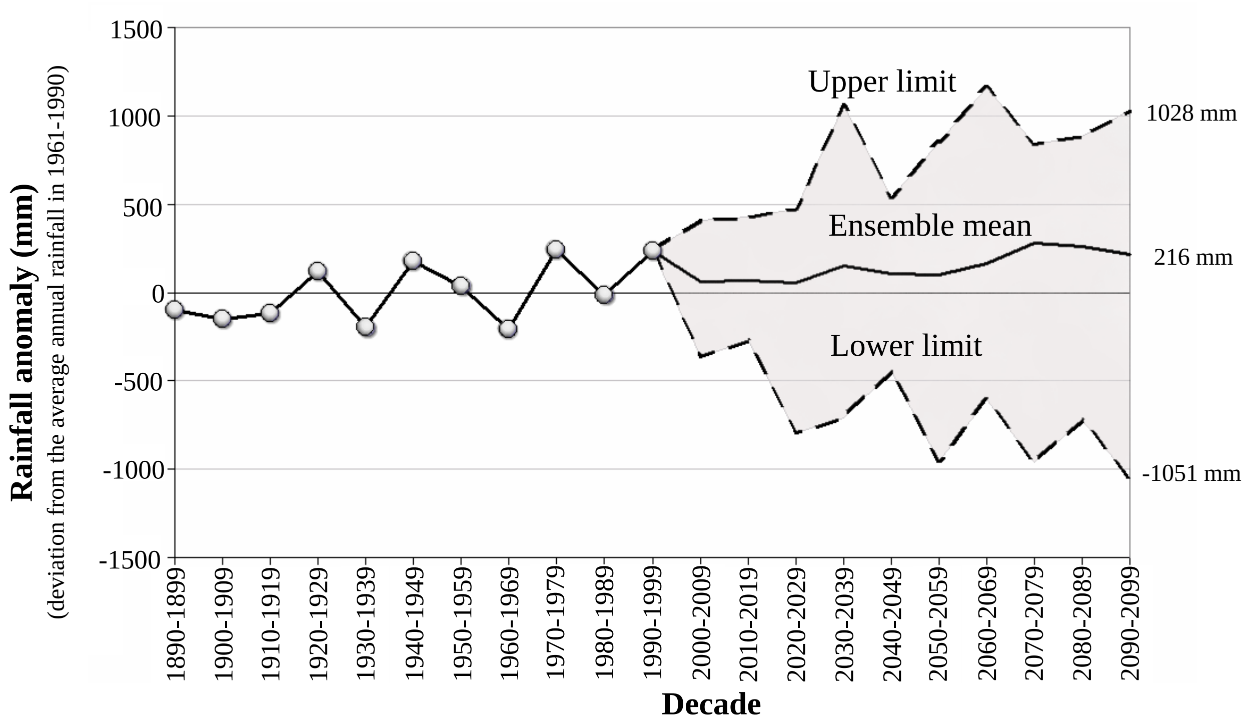

Figure 4. Past and projected changes in annual rainfall in Hong Kong. The change is with reference to the 1961-1990 normal.

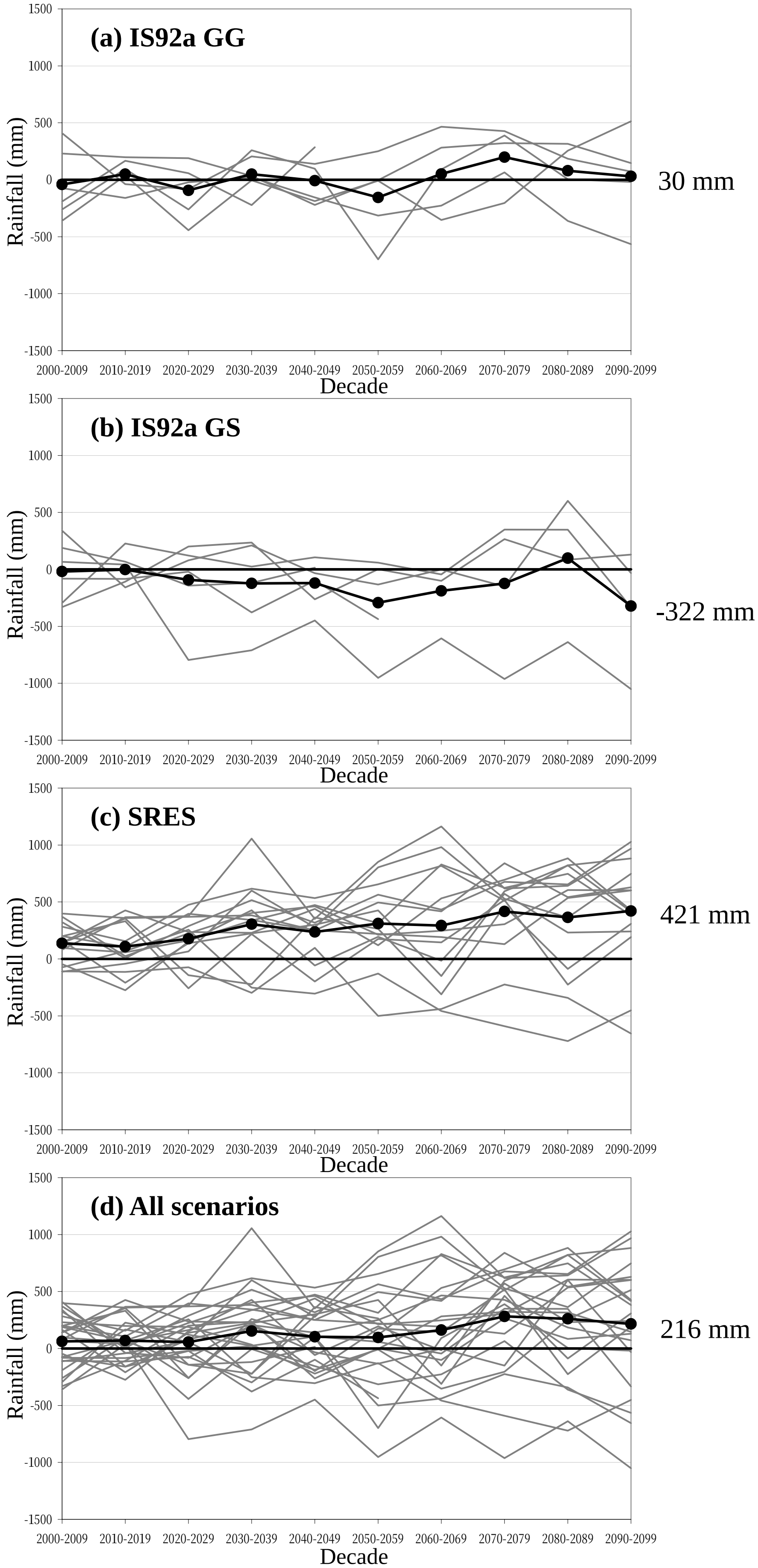

Figure 5. Projected changes in annual rainfall in Hong Kong based on different models under (a) IS92a GG, (b) IS92a GS, (c) SRES and (d) all scenarios. Rainfall change is with reference to the 1961-90 normal. The dark line joining the black dots denotes the multi-model ensemble mean.

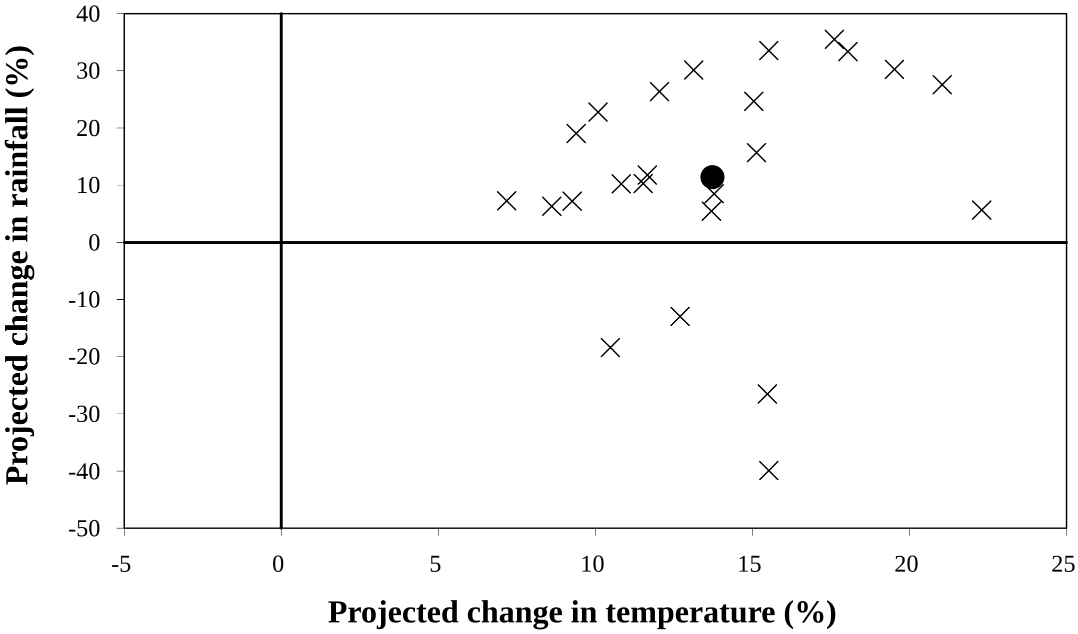

Figure 6. Projected changes in 30-year mean anuual rainfall and annual mean temperature in Hong Kong from 1961-1990 to 2070-2099 for different emission scenarios. Crosses represent projected changes based on different models under various scenarios. The black dot denotes the ensemble mean of all available scenarios and models.

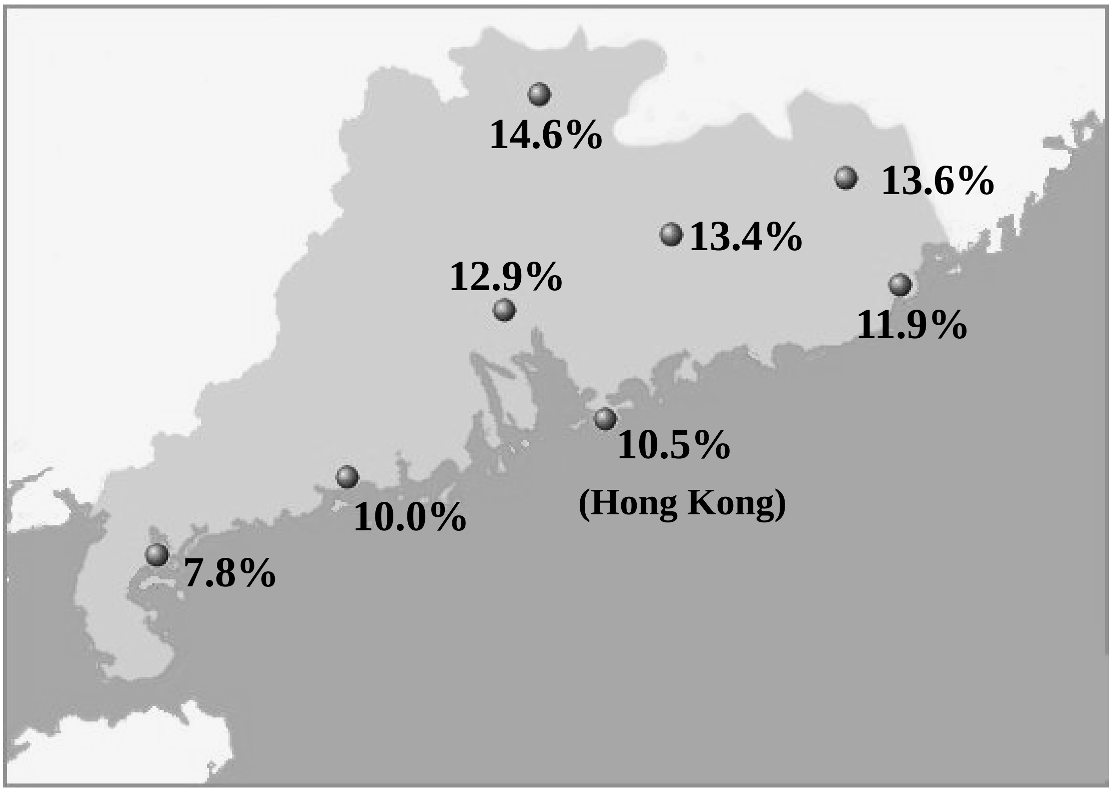

Figure 7. Projected changes in annual rainfall in Hong Kong and in Guangdong in the 21st century (% increase per 100 years). Trends for Guangdong are obtained from http://www.ipcc.cma.gov.cn/cn/MapSys/.

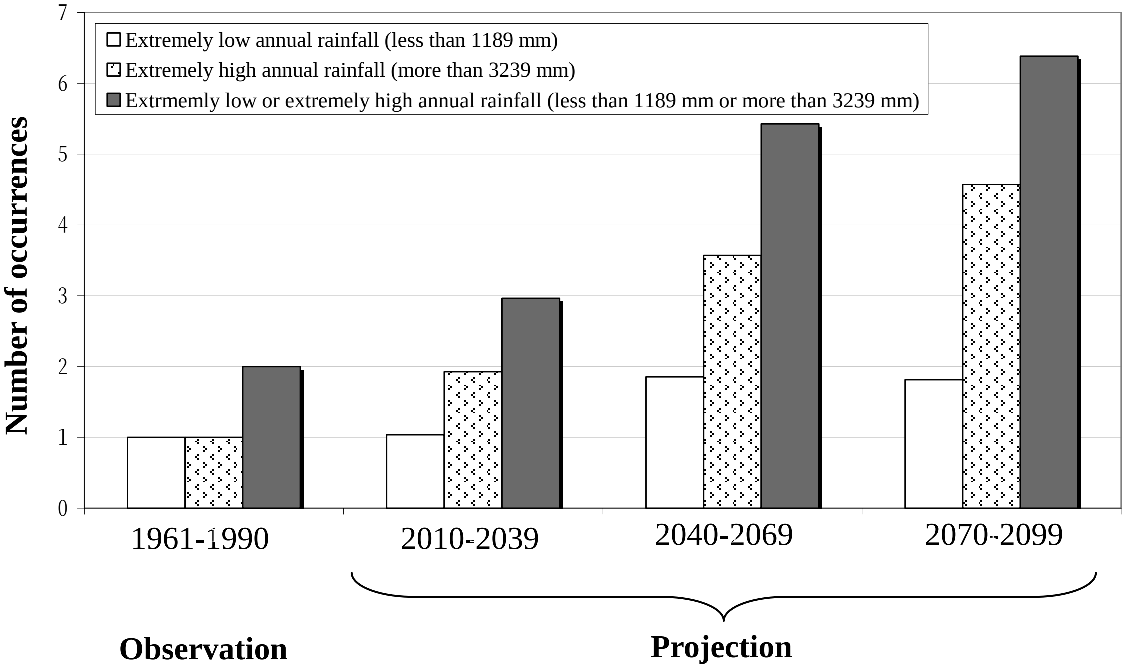

Figure 8. Projected number of years with extremely low or extremely high annual rainfall in 30-year periods in the 21st century.