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

H.S. Chan & H.W. Tong

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CHAN Ho-sun and TONG Hang-wai
Hong Kong Observatory

Abstract

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) Working Group I (WGI) was released in September 2013. Its assessment was based on a new set of global climate simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) as well as a new set of greenhouse gas (GHG) concentration scenarios named Representative Concentration Pathways (RCPs). Projections of Hong Kong's climate have to be updated and evaluated based on the new scenarios and the corresponding new model simulations.

This study focuses on the temperature projection for Hong Kong. CMIP5 models' performance in simulating Hong Kong's present climate (1961-2005) is assessed and discussed. The annual mean temperatures of Hong Kong in the 21st century under the RCP4.5 and RCP8.5 scenarios are derived through statistical downscaling on a monthly basis. Projection results suggest that the annual mean temperature will continue to rise for the rest of the 21st century. The central 90% of the projected temperature increase by 2100 based on the RCP4.5 scenario will be 1.4 to 3.2 ^{o}C, relative to the average temperature of 1986-2005. For the RCP8.5 scenario, which has the closest match with the current situation in terms of carbon dioxide (CO_2) emission, the central 90% of the projected temperature increase by 2100 covers the range from 3.1 to 5.5 ^{o}C. The results are comparable with previous studies of temperature projections for southern China using direct model outputs of the CMIP5 dataset. The new projection results will be compared with those from the Coupled Model Intercomparison Project Phase 3 (CMIP3) and discussed.

1. Introduction

The IPCC WGI AR5 [1] reaffirms the unequivocal global warming and concludes that it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century. Regarding the projection of future climate, AR5 relies on a new set of global climate models participating in CMIP5. In addition, a new set of four GHG concentration scenarios is designed to fulfill the growing interest in scenarios that explicitly explore the impact of different climate policies [2] and to provide higher resolution and more consistent land-use and land-cover data to the ever improving and more comprehensive climate models [3]. Based on the new set of models and the new set of GHG concentration scenarios, AR5 projects that the global average surface temperature would rise by 0.3 – 4.8 ^{o}C towards the end of this century [1].

Almost the whole globe experienced warming in the last hundred years or so, and Hong Kong is no exception. The annual mean temperature of Hong Kong has increased at a rate of 0.12 ^{o}C per decade over the years 1885-2012. Along with the increase in annual mean temperature, there have been more and more extremely hot days but fewer and fewer extremely cold days [4]. Elevated temperatures have implications on public health because of the anticipated increase in heat-related diseases, and on energy consumption because of the increasing need for cooling. Temperature projection is therefore an important piece of information to support planning of adaptation to climate change [5],[6].

In 2004, the Hong Kong Observatory utilized the data of global climate model projections assessed by the IPCC’s Third Assessment Report to project the temperature for Hong Kong in the 21st century [7]. The projection was subsequently updated using monthly model data of IPCC's Fourth Assessment Report (AR4) in 2007 with urbanization effect incorporated [8]. AR4 daily data were later used to project extreme temperature events for Hong Kong [9]. In the last study, the projection of annual mean temperature using a different methodology and urbanization scenario was investigated and compared to the previous results. In light of the new set of climate models and GHG concentration scenarios, another update of the temperature projection for Hong Kong is needed.

Statistical downscaling, which relates large-scale dynamical model parameters to station-specific variable of interest, is a cost effective approach in studying climate projection. It requires much less computer resources than dynamical downscaling while achieving comparable level of skill [10]. In line with previous climate projection studies for Hong Kong, statistical downscaling is also adopted in the present study.

This paper is organized in the following structure: data used in this study will be described in Section 2, followed by an evaluation of the CMIP5 models in temperature simulation in Section 3; the projection method will be presented in Section 4; the projection results are compared with other AR5 climate projection studies and previous temperature projections for Hong Kong in Section 5; and a summary is given in Section 6.

2. Data

2.1 Predictant and predictors

Monthly mean temperature of Hong Kong is the predictant of the statistical downscaling model in this study. Historical temperature data recorded at the Hong Kong Observatory Headquarters during the period 1961-2005 are partitioned appropriately into two groups (1961-1990 and 1991-2005) to support construction and validation of the statistical model. Surface and upper-air parameters of reanalysis data or dynamical climate models averaged over southern China and the northern part of the South China Sea (108-120^{o}E, 16-30^{o}N) are the large-scale predictors of the statistical model.

2.2 Reanalysis data

The NCEP 20th Century Reanalysis (20CR) Data [11] are employed in (i) verifying CMIP5 models' performance in temperature simulation; and (ii) constructing the statistical downscaling model of monthly temperature of Hong Kong. The NCEP 20CR data has a horizontal resolution of 2 degrees x 2 degrees.

2.3 CMIP5 model data

Monthly data of 25 CMIP5 models with different horizontal resolution (Table 1) from the Program for Climate Model Diagnosis and Intercomparison website (http://pcmdi9.llnl.gov) were acquired and then re-gridded using bi-linear interpolation to 2 degrees x 2 degrees in order to match with the horizontal resolution of the NCEP 20CR data. Historical simulations of the CMIP5 models during the period 1961-2005 are used to validate the statistical downscaling model while future simulations under different GHG emission scenarios are used to produce future temperatures for Hong Kong.

In AR5, there are four GHG concentration scenarios, namely RCP2.6, RCP4.5, RCP6.0 and RCP8.5, which are identified by their 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 [1]-[3].

The RCP4.5 and RCP8.5 scenarios belong to the core experiments of CMIP5 for which all the participating modelling groups should provide model simulations [12] and therefore should have the largest number of model simulations for assessment of future climate. Hence, this study will focus on these two scenarios. Nevertheless, the same methodology can be applied to the RCP2.6 and RCP6.0 scenarios. It is noteworthy that the current path of global CO_2 emission has the closest match with the CO_2 emission trajectory described by the RCP8.5 scenario [13].

3. Evaluation of CMIP5 models' performance in temperature simulation

It is imperative that large-scale predictors of the statistical model are reasonably simulated by the climate models as they are used to condition the local predictand. Naturally, surface temperature is the most important predictor as it is directly related to the variable to be projected. As shown in Figure 1, the annual cycle of temperature over southern China (land grid points over 108-120^{o}E, 16-30^{o}N) during the period 1961-1990 is reasonably simulated by the 25 CMIP5 models. However, cold bias in winter months can be seen in almost all the models when compared to the NCEP 20CR data. In Figure 2, Taylor diagram indicates that the performance of the CMIP5 models is satisfactory in terms of spatial correlation. All of the 25 models achieve spatial correlation over 0.9. Besides, the performance of the models is rather homogenous without any obvious outliers depicted on Figure 2.

Apart from surface temperature, specific humidity and circulation parameters such as geopotential height and winds are also relevant and potential predictors to be considered in the statistical downscaling process. Studies have shown that the performance of CMIP5 models in simulating these parameters is reasonable. For instance, Tian et al [14] concluded that CMIP5 models can generally simulate the climatological features of global specific humidity; Chen et al [15] found satisfactory performance of CMIP5 models in simulating the free-troposphere geopotential height gradient and winds over China.

4. Methodology

Hong Kong is a developed city and urbanization effect on its temperature could not be ignored, although previous studies have shown that global warming has a bigger contribution to the city's temperature rising trend over the years. Global climate models usually do not take urbanization effect into account. Hence, in projecting temperature for Hong Kong, the urbanization effect on temperature and the statistical downscaling process have to be dealt with separately. The basic idea is to remove the urbanization effect in the historical temperature records before carrying out the statistical downscaling procedures, and incorporate future urbanization effect in the result of the downscaling process. Key steps and considerations in dealing with the urbanization effect and the statistical downscaling procedures are described in the following sub-sections. Figure 3 illustrates the workflow in a schematic diagram.

4.1 Urbanization effect in the past and future

The urbanization effect on Hong Kong's historical temperature trend is estimated using Macao as the rural station [9]. Macao is located about 65 km to the west of Hong Kong, and is relatively less affected by urbanization before 2000 [16]. Temperature data of Macao during the period 1952-2000 are used to estimate the background temperature rising trend due to global warming, and the difference between Hong Kong's temperature trend and Macao's is considered as the contribution from urbanization [9].

It has been suggested by some studies that urbanization effect is directly proportional to the logarithm of population (log P). Hence, the rate of temperature rise due to urbanization can be related to the rate of change in log P. Future population of Hong Kong up to 2041 is projected by the Census and Statistics Department of Hong Kong and the population projection data are available for download on its website (http://www.censtatd.gov.hk/hkstat/sub/sp190.jsp). It can be estimated from Figure 4 that the average rate of increase in log P between 2001 and 2041 is about 30% of the rate during 1952-2000.

Since there is no population projection for years after 2041, two urbanization scenarios are considered: urbanization continues at the same rate as that between 2001 and 2041 for years beyond 2041 (U1), and urbanization stops after 2041 (U2).

4.2 Predictor selection for the downscaling model

To investigate the sensitivity of downscaling results to the choice of predictors, a number of combination of thermodynamical parameters and low level circulation parameters which also carry the climate change signal, though probably to a weaker extent [17]-[19], are considered. Three predictor sets are examined:

Set 1: Surface temperature
Set 2: Surface temperature, mean sea level pressure
Set 3: Surface temperature, mean sea level pressure, surface specific humidity, 850 hPa wind (zonal and meridional), 850 hPa specific humidity, 850 hPa geopotential height

The three predictor sets have increasing complexity while maintaining a balance between the number of thermodynamical and circulation parameters participating in the regression model. Gutierrez et al [17] suggested that 2-metre air temperature is a preferable predictor to free-tropospheric temperatures like temperature at 850 hPa. Hence, upper-air temperature is not included in the predictor sets so as to keep the sets from expanding too large.

4.3 Regression

The NCEP 20CR data are free from urbanization effect because air temperature observations were not involved in the data assimilation process [11], [20], and hence are good candidate for building regression model with the de-urbanized temperature data. The monthly data are aggregated into four seasons (MAM, JJA, SON and DJF) to establish four regression models, each valid for the months constituting that season.

4.3.1 Standardization

In order to reduce systematic bias, it is common practice to standardize the predictors and predictant in building and applying the regression model. In this study, the de-urbanized Hong Kong temperature data, the NCEP 20CR data and the CMIP5 model parameters are standardized with reference to the period of 1961-1990. Outcomes from the regression model will need to be de-standardized.

4.3.2 Variance adjustment

Normally, the variance of regression outcomes is smaller than the observations [21]-[22], and variance adjustment will be performed to preserve the variance. In the present study, we have adopted 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 a common reference period (1961-1990 in this study).

In temperature projection study, extra care has to be taken to preserve the long-term trend of the regression outcomes [22]. The following procedures are conducted in this study:

(a) the regression outcomes are first detrended using simple linear regression;

(b) variance inflation is applied to the detrended outcomes resulted from (a);
(c) the linear trend obtained in (a) is then added back to the inflated outcomes resulted from (b).

5. Results

5.1 Validation of the statistical model

Historical run of each of the 25 CMIP5 models is downscaled using Set 1 predictor for the period 1961-2005. The ensemble mean of the downscaling results of the 25 CMIP5 models, also with urbanization effect incorporated, is considered. Figure 5 shows the 5-year average of the ensemble mean (the green line). Results using Set 2 and Set 3 predictors are similar and hence not shown. It is clear that the actual warming trend during the period 1991-2005 can be reproduced nicely. Figure 6 shows the annual cycle of the ensemble mean during the period 1991-2005. The actual annual cycle is reasonably reproduced except for some minor deviation in winter months.

5.2 Projection for the 21st century

Table 2a (2b) shows the temperature changes of Hong Kong in the near term (2021-2030), at the mid-21st century (2051-2060) and at the end of the 21st century (2091-2100) given by the ensemble mean of projections of the 25 CMIP5 models under the RCP4.5 (RCP8.5) scenario and the U1 urbanization scenario using different predictor sets. The changes are relative to the average temperature of 1986-2005. Following the convention adopted by IPCC WGI AR5, the 5th and 95th percentile of the ensemble are used to indicate the likely range of projection. Very little difference exists among results from the three predictor sets, showing that the projection is not sensitive to the choice of predictors.

Table 3 shows the temperature changes of Hong Kong in 2091-2100 given by the ensemble mean of projections of the 25 CMIP5 models under RCP 4.5 and RCP 8.5 scenarios and urbanization scenarios using different predictor sets. The difference between the results from the two urbanization scenarios is also small, just 0.1 ^{o}C in the ensemble mean. This indicates that urbanization plays a very limited role in future warming when compared to GHG under RCP 4.5 and RCP 8.5 scenarios. Under the RCP4.5 (RCP8.5) scenario and the U1 urbanization scenario, urbanization contributes around 10% (5%) to the total warming during 2006-2100.

We pooled all the results from different predictor sets under the U1 urbanization scenario to form the temperature projection for Hong Kong. Figure 7 (8) shows the projected temperature change of Hong Kong for the 21st century under the RCP4.5 (RCP8.5) scenario. For the RCP4.5 (RCP8.5) scenario, the ensemble mean of temperature rise could reach 2.2 ^{o}C (4.2 ^{o}C) in 2091-2100, with a likely range of 1.4 - 3.2 ^{o}C (3.1 - 5.5 ^{o}C).

5.3 Comparison with other studies

Some studies have projected temperature changes for East Asia or China by considering the direct model output of CMIP5 models or results from dynamical downscaling using regional climate model. For instance, IPCC WGI AR5 provided regional temperature projections for East Asia in its atlas of global and regional climate projections. Xu and Xu [23] focused on China and investigated the direct model output of 11 CMIP5 models and their temperature and precipitation projections in the 21st century. Gao et al [24] utilized a regional climate model (RegCM4.0) driven by a global model, Beijing Center Climate System Model version 1.1 (BCC_CSM1.1, M2 in Table 1) to downscale the temperature projection for China in the 21st century under the RCP4.5 and RCP8.5 scenarios.

The comparison of the present study with other studies of temperature projection over southern China [1],[23]-[24] is shown in Table 4. The temperature projections of these studies for the vicinity of Hong Kong are read from spatial maps of temperature projection. The reference period of all the studies are the same, i.e. 1986-2005. The temperature projections in this study are comparable to those in [1] and [23], but higher than that in [24]. It should be noted that the projections given by [24] is the result of a single regional climate model driven by a single global climate model, which renders great difficulty in assessing the uncertainty of the projections. Furthermore, there exists cold bias of around 1-2.5 ^{o}C along the coastal region of Guangdong in the regional climate model as revealed by the validation, and this may be a systematic bias which affects the subsequent temperature projections (see Fig. 1c of [24]).

5.4 Comparison with previous projections using AR4 data

It is of interest to compare the results of this study with previous temperature projections computed using AR4 data, i.e. Leung et al [8] and Lee et al [9]. To facilitate direct comparison, the reference period used in the present study was shifted from 1986-2005 to 1980-1999 in order to match with the previous studies. Table 5 lists the temperature projection results at the end of the 21st century given by these three studies.

The RCP4.5 (RCP8.5) scenario in AR5 resembles the B1 (A2) scenario in AR4 in terms of CO_2 emission. However, the CO_2 emission trajectory of RCP4.5 (RCP8.5) is lower (higher) than that of B1 (A2) for a large portion of the 21st century. Hence, it should not be surprising that the temperature projection under the RCP4.5 (RCP8.5) scenario is lower (higher) than the projection under the B1 (A2) scenario in Lee et al [9]. However, projections in Leung et al [8] are significantly higher than the projections in this study. The disparity could be attributed to the difference in the assumption of future urbanization. In Leung et al [8], future urbanization in Hong Kong was assumed to be the same as what was experienced in the past. This assumption may not hold as shown in Figure 4. It would be more reasonable to argue that urbanization would gradually saturate at some point in the future.

6. Summary

In this study, 25 CMIP5 models are statistically downscaled to Hong Kong to project the temperature change in the 21st century. The effect of urbanization has been duly considered and incorporated. Results show that the temperature increase in 2091-2100 is likely in the range of 1.4 - 3.2 ^{o}C (3.1 - 5.5 ^{o}C) under the RCP4.5 (RCP8.5) scenario. Owing to the projected slow-down of population growth, the contribution of urbanization to the total warming will be less than that in the past century. It is estimated that urbanization will only contribute around 5% (10%) to the total warming under the RCP8.5 (RCP4.5) scenario.

The projection results in this study are comparable to some AR5 studies using direct model outputs, boosting the confidence in our projections. Temperature projections from previous studies have also been reviewed and the differences accounted for.

Numerous studies have shown that the shift of mean of the temperature distribution will inevitably change the occurrence probability of extreme temperature events [6], [25]. Previous studies have shown that Hong Kong is expected to have more extremely hot events and fewer extremely cold events using AR4 daily data [9]. Work is underway to update the projection of extreme temperature events using AR5 daily data.

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Table 1. Details of the 25 CMIP5 models used in this study

				Resolution	
	Model	**Center**	**Country**	**Latitude**	**Longitude**
M1	ACCESS1-0	CSIRO	Australia	1.25	1.875
M2	BCC-CSM1-1	BCC	China	~ 2.8	2.8125
M3	BNU-ESM	BNU	China	~ 2.8	2.8125
M4	CanESM2	CCCma	Canada	~ 2.8	2.8125
M5	CCSM4	NCAR	USA	~0.94	1.25
M6	CNRM-CM5	CNRM	France	~1.4	1.40625
M7	CSIRO-Mk36	CSIRO	Australia	~1.86	1.875
M8	FGOALS_g2	IAP	China	~ 2.8	2.8125
M9	GFDL-ESM2G	NOAA GFDL	USA	~2	2.5
M10	GFDL-ESM2M	NOAA GFDL	USA	~2	2.5
M11	GISS-E2-H	NASA GISS	USA	2	2.5
M12	GISS-E2-R	NASA GISS	USA	2	2.5
M13	HadGEM2-AO	NIMR KMA	South Korea	1.25	1.875
M14	HadGEM2-CC	UKMO Had	UK	1.25	1.875
M15	HadGEM2-ES	UKMO Had	UK	1.25	1.875
M16	INM-CM4	INM	Russia	1.5	2
M17	IPSL-CM5A-LR	IPSL	France	~1.88	3.75
M18	IPSL-CM5A-MR	IPSL	France	~1.27	2.5
M19	IPSL-CM5B-LR	IPSL	France	~1.88	3.75
M20	MIROC5	MIROC	Japan	~1.4	1.40625
M21	MIROC-ESM	MIROC	Japan	~ 2.8	2.8125
M22	MIROC-ESM-CHEM	MIROC	Japan	~ 2.8	2.8125
M23	MRI-CGCM	MRI	Japan	~1.12	1.125
M24	Nor-ESM1-M	NCC	Norway	~1.88	2.5
M25	Nor-ESM1-ME	NCC	Norway	~1.88	2.5

Table 2a. Temperature changes (°C) of Hong Kong in the near term (2021-2030), at the mid-21st century (2051-2060) and at the end of the 21st century (2091-2100) given by the ensemble mean of projections of the 25 CMIP5 models under the RCP4.5 scenario and the U1 urbanization scenario using different predictor sets. Changes are relative to the average temperature of 1986-2005. Figures in parentheses indicate the likely range (the 5th and 95th percentile of the ensemble).

	2021-2030	2051-2060	2091-2100
Set 1	0.8 (0.5-1.2)	1.7 (1.0-2.3)	2.2 (1.4-3.0)
Set 2	0.8 (0.5-1.2)	1.7 (1.0-2.3)	2.2 (1.4-3.0)
Set 3	0.8 (0.5-1.2)	1.6 (1.1-2.3)	2.2 (1.3-3.2)

Table 2b. Same as Table 2a but for the RCP8.5 scenario.

	2021-2030	2051-2060	2091-2100
Set 1	0.9 (0.5-1.3)	2.2 (1.6-3.0)	4.2 (3.1-5.5)
Set 2	0.9 (0.5-1.3)	2.2 (1.6-3.0)	4.2 (3.1-5.5)
Set 3	0.9 (0.6-1.3)	2.2 (1.6-3.1)	4.2 (3.1-5.6)

Table 3. Temperature changes (°C) of Hong Kong in 2091-2100 given by the ensemble mean of projections of the 25 CMIP5 models under RCP 4.5 and RCP 8.5 scenarios and urbanization scenarios using different predictor sets. Changes are relative to the average temperature of 1986-2005. Figures in parentheses indicate the likely range (the 5th and 95th percentile).

	Set 1		Set 2		Set 3	
	U1	U2	U1	U2	U1	U2
RCP4.5	2.2 (1.4-3.0)	2.1 (1.3-2.9)	2.2 (1.4-3.0)	2.1 (1.3-2.9)	2.2 (1.3-3.2)	2.1 (1.2-3.1)
RCP8.5	4.2 (3.1-5.5)	4.1 (3.0-5.3)	4.2 (3.1-5.5)	4.1 (2.9-5.4)	4.2 (3.1-5.6)	4.1 (3.0-5.5)

Table 4. Projected temperature change (°C, relative to the average of 1986-2005) for the end of the 21st century by other studies.

	IPCC WGI AR5 [1]		Xu and Xu [23]		Gao et al [24]	
Period	2081-2100		2071-2100		2081-2099	
Scenario	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Projection	1.5-2.0	3.0-4.0	2.0-2.4	3.6-4.0	<1.5	2.5-3.0

Table 5. Comparison of the ensemble mean of temperature projections (^{o}C, relative to the average of 1980-1999) given by the present study and previous studies using AR4 data.

	Present study		Leung et al [8]		Lee et al [9]	
Period	2091-2100		2090-2099		2090-2099	
Scenario	RCP4.5	RCP8.5	B1	A2	B1	A2
Projection	2.3	4.4	3.0	5.2	2.5	4.2

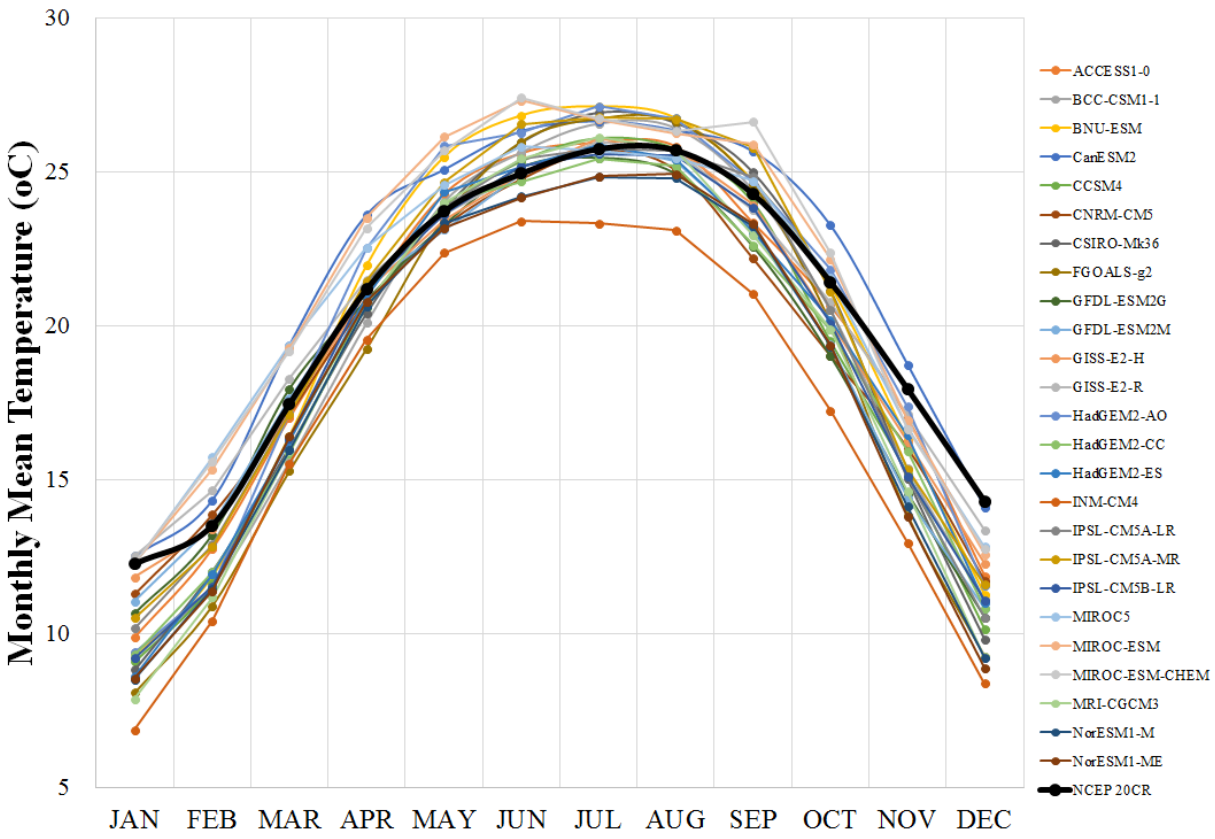

Figure 1. Annual cycle of monthly temperature over southern China during 1961-1990 simulated by the 25 CMIP5 models. The black thick line is NECP 20th Century Reanalysis.

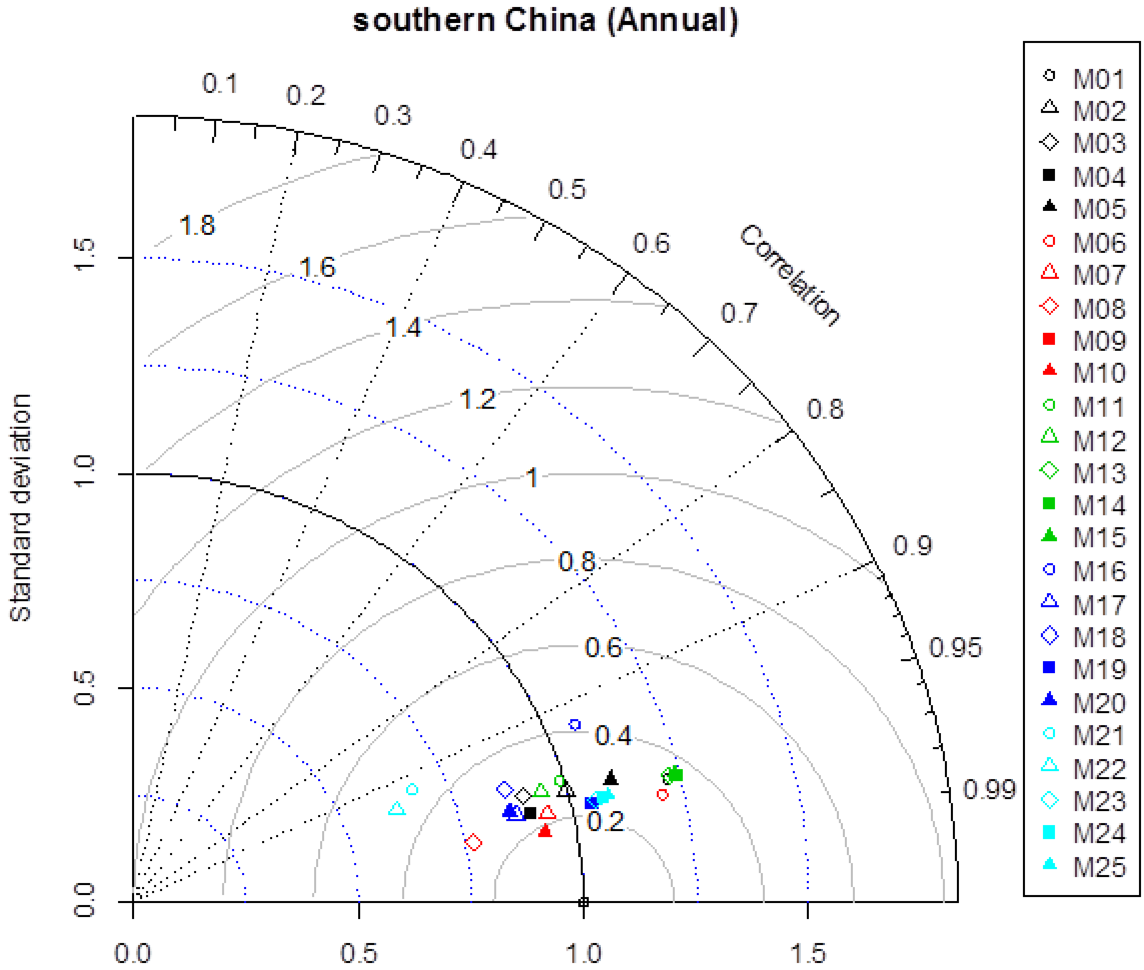

Figure 2. Taylor diagram showing performance of the 25 CMIP5 models in simulating annual mean temperature over southern China during 1961-1990. Names of the models can be found in Table 1.

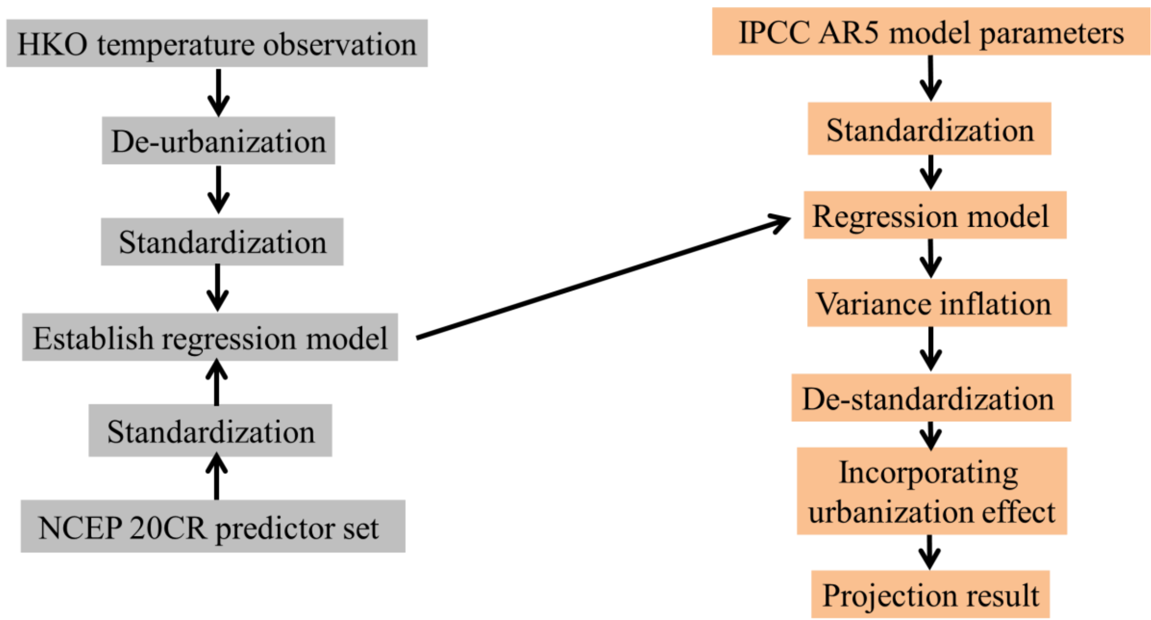

Figure 3. Schematic diagram showing the workflow of projecting temperature for Hong Kong

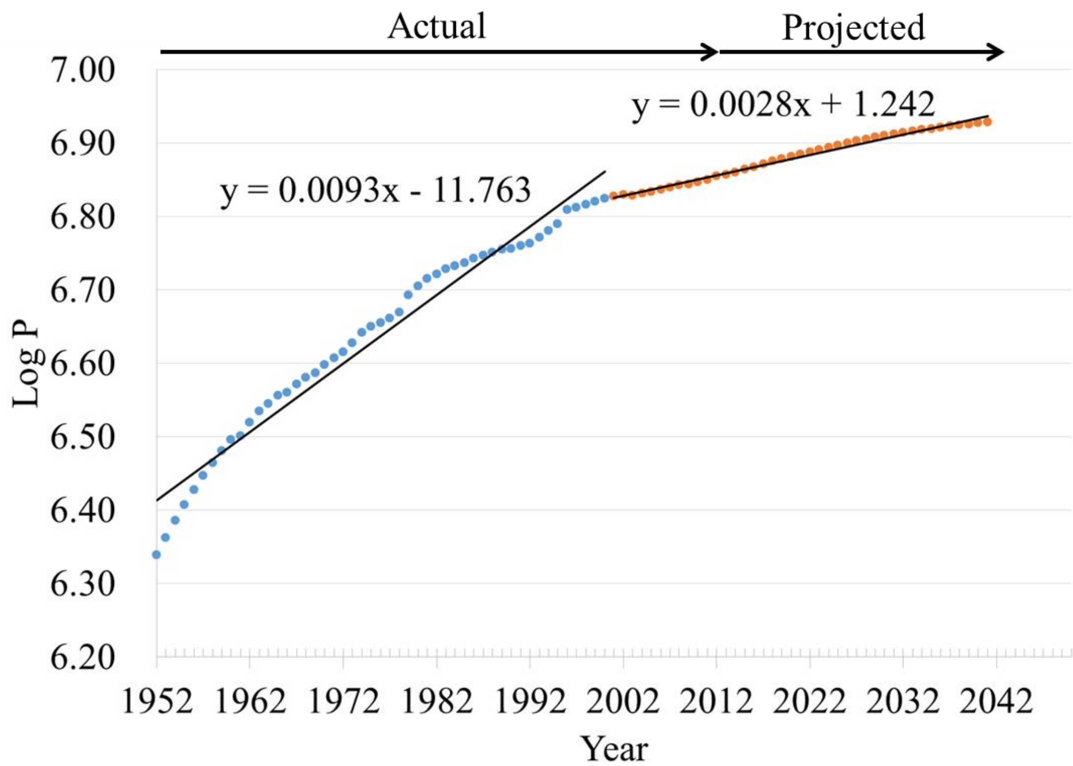

Figure 4. Logarithm of Hong Kong population (log P). The blue (orange) dots represent data of 1952-2000 (2001-2041), with black lines being the corresponding trend. Data for the period 2012-2041 are projected values.

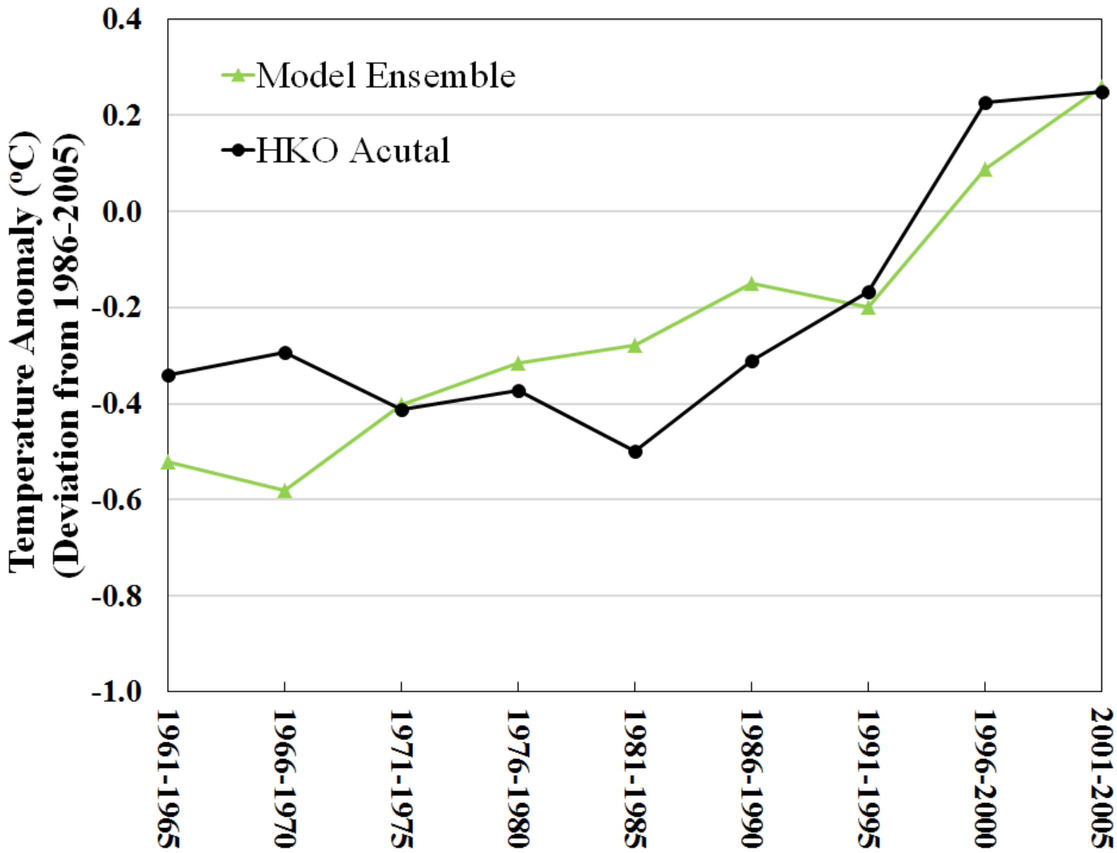

Figure 5. Anomaly of 5-year average temperature of Hong Kong (relative to the average temperature of 1986-2005). The black line is observation. The green line is the mean of downscaling results from the 25 CMIP5 models using Set 1 predictor.

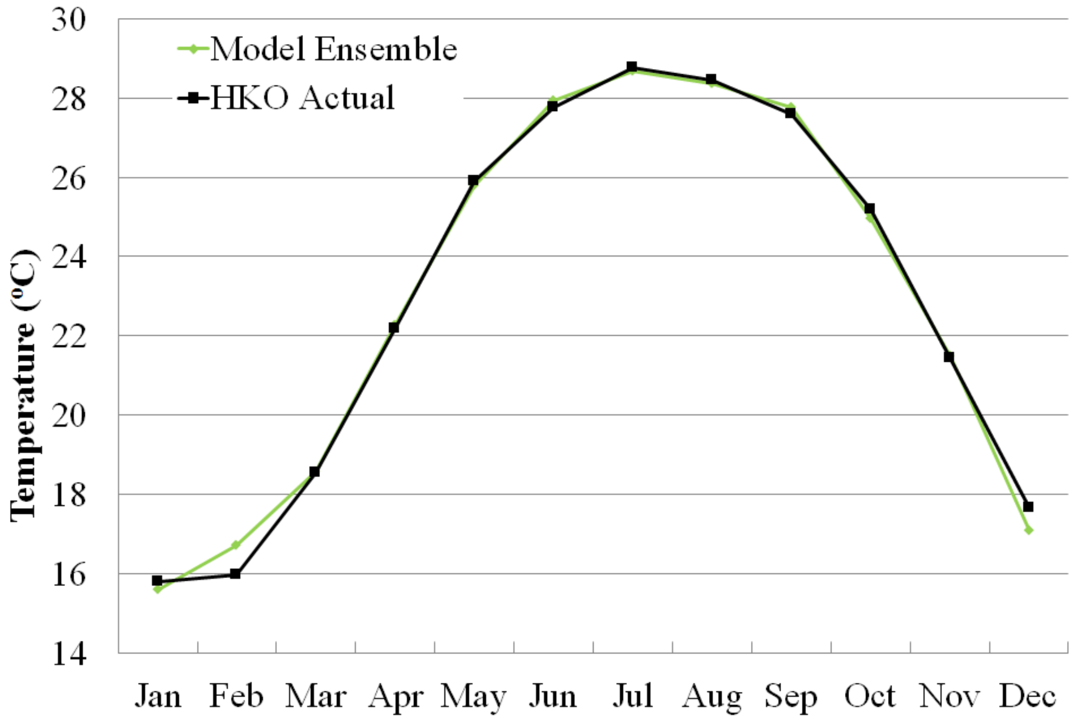

Figure 6. Annual cycle of temperature of Hong Kong during 1991-2005. Black is observation, green is the mean of downscaling results from the 25 CMIP5 models.

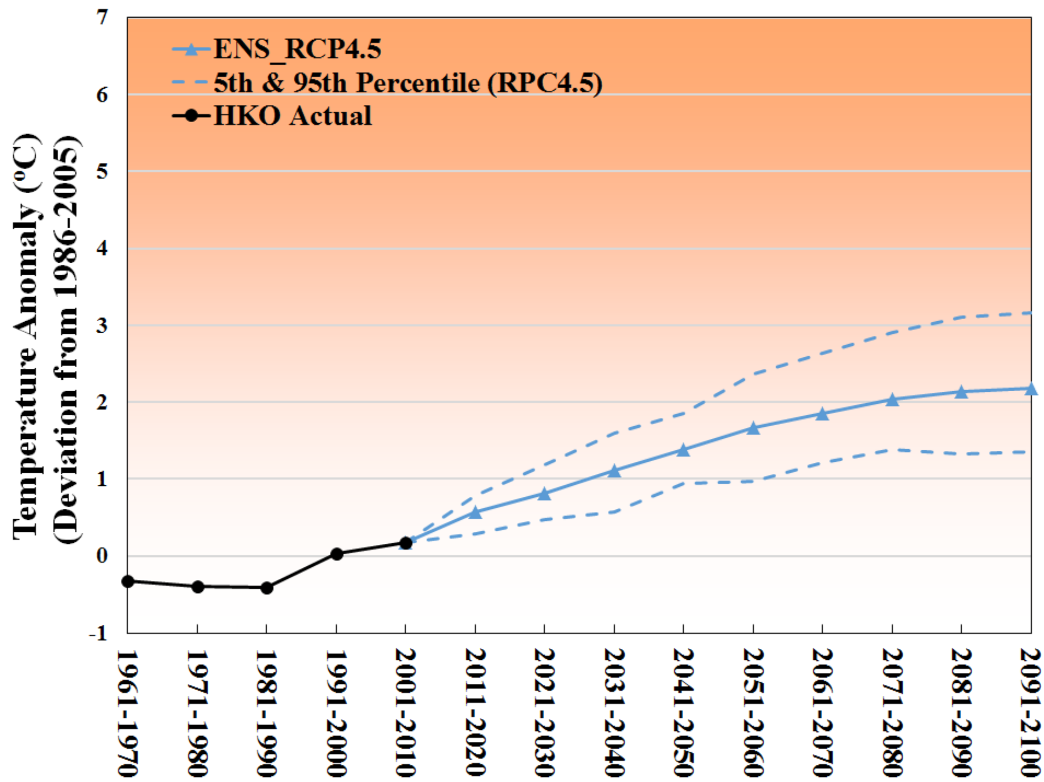

Figure 7. Projected decadal temperature anomaly (relative to the 1986-2005 average) of Hong Kong in the 21st century under the RCP4.5 scenario. The black line is actual observation. The solid blue line is the ensemble mean while the dashed line is the 5th and 95th percentile of the ensemble.

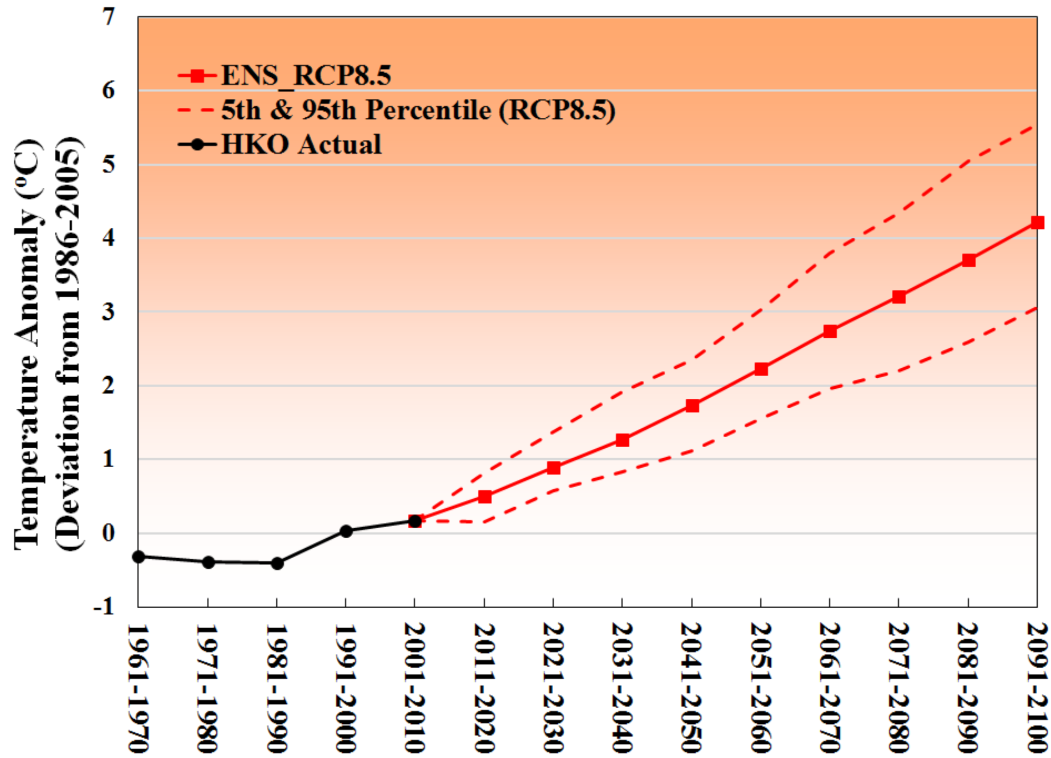

Figure 8. Same as Figure 7, but for the RCP8.5 scenario. Projections indicated in red.