

Research Paper

Comparing climate projections for Asia, East Asia and South Korea

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아시아 대륙, 동아시아, 대한민국을 대상으로 다른 공간적 규모의 기후변화시나리오 예측 비교

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요약 : 우리나라의 많은 기후변화 관련 영향 평가 연구들이 기상청에서 제공하는 기후변화 시나리오를 이용하고 있지만, 하나의 기후 시나리오로 기후변화의 잠정적인 영향을 정확히 예측하기에는 한계가 있다. 본 연구는 세 가지의 지역적 스케일 - 아시아 대륙, 동아시아 6개국, 대한민국 - 을 대상으로 두 가지 대표농도경로 시나리오에서 17개의 지역기후모델을 이용하여 현재와 2070년의 연간 최저 온도와 연간 강수량의 차이를 확인하였다. 대한민국의 경우 최저온도 증가량의 범위는 아시아 규모보다 작았으며 강수량 차이에 대한 편차는 아시아 규모보다 컸다. 최저온도 증가범위는 1.3 °C에서 5.2 °C이며, 연간 강수량 차이는 -42.4 mm (-3.2%) 에서 +389.8 mm (+ 29.6%) 로 기상청의 기후변화 시나리오는 긍정적 기후 시나리오의 예측값에 가까운 것으로 나타났다. 따라서 기후변화 및 관련 영향 평가 연구들은 다양한 기후 변화 시나리오를 이용하여 그 예측 범위에 대비할 필요가 있으며, 본 연구 결과에 따라 GFDL-CM3와 INMCM4의 두 가지 기후모델을 이용하여 우리나라의 지구 온난화에 대한 잠정적인 영향을 평가하기를 권한다.

주요어 : 기후 시나리오, 최저온도, 강수량, CMIP5, RCP

Abstract : Many studies on climate change and its impacts use a single climate scenario. However, one climate scenario may not accurately predict the potential impacts of climate change. We estimated temperature and precipitation changes by 2070 using 17 of the CMIP5 Global Climate Models (GCMs) and two emission scenarios for three spatial domains: the Asian continent, six East Asia countries, and South Korea. For South Korea, the range of increased minimum temperature was lower than for the

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ranges of the larger regions, but the range of projected future precipitation was higher. The range of increased minimum temperatures was between 1.3 °C and 5.2 °C, and the change in precipitation ranged from - 42.4 mm (- 3.2%) and + 389.8 mm (+ 29.6%) for South Korea. The range of increased minimum temperatures was between 2.3 °C and 8.5 °C for East Asia countries and was between 2.1 °C and 7.4 °C for the Asian continent, and the change in precipitation ranged from 28.8 mm (+ 6.3%) and 156.8 mm (+ 34.3%) for East Asia countries and from 32.4 mm (+ 5.5%) and 126.2 mm (+ 21.3%) for the Asian continent. We suggest climate change studies in South Korea should not use a single GCM or only an ensemble climate model's output and we recommend to use GFDL-CM3 and INMCM4 GCMs to bracket projected change for use in other national climate change studies to represent the range of projected future climate conditions.

Keywords : Climate Scenario, CMIP5, Minimum Temperature, Precipitation, RCP

I. Introduction

Impacts of climate change extend over a wide range of the environment, economy, and society (Arnell et al. 2016), so studies on evaluating the potential impacts of climate change are actively being carried out (e.g. Choe 2015; Elsen & Tingley 2015; Prieto-Torres et al. 2016). For example, climate change vulnerability assessments can provide useful information for the establishment of adaptation strategies (Choe et al. 2017).

Even though the Intergovernmental Panel on Climate Change (IPCC) provides various General Circulation Models (GCMs), many Korean studies on climate change and its impacts have often relied on one GCM (e.g. impacts on ecosystem, industry, and climate vulnerability assessments; Park et al. 2014; Park et al. 2015; Kim et al. 2015; Kim et al. 2016), or an ensemble approach using partial GCMs (Lee et al. 2016). The Korea Meteorological Administration has recently developed a 12.5-km scale climate change scenario from a HadGEM2-AO model (KMA 2012). Many modeling studies conducted in South Korea use this climate scenario to suggest national climate change adaptation strategies (Shin & Jung 2015). However, this GCM may not accurately predict

the potential impacts of climate change.

Since climate projections by alternative models can be variable, a single GCM will likely not fully express the uncertainty in climate change scenarios (Araújo & New 2007). Each GCM has uncertainty originating from the variations in initial conditions that each GCM is run on and the structural differences among the models (Murphy et al. 2004; Kim & Cho 2016). Therefore, the evaluation of the differences in predicted future conditions among various GCMs would be helpful for their use in development of climate change studies and for guiding mitigation and adaptation strategies and policy decisions in preparation for uncertain climate change conditions.

An alternative way to address these inter-model variations is the ensemble approach which combines several GCMs to produce a mean model (Sanderson et al. 2015; Giorgi et al. 2016). However, there are recognized challenges for the ensemble approach such as lack of verification, model dependence, and mean bias (Tebaldi & Knutti 2007).

Shin & Jung (2015) analyzed CMIP5 (Coupled Model Intercomparison Project Phase 5; Taylor et al. 2012) climate change projections from 34 GCMs to estimate the range of projected future

climate conditions from GCMs by RCP (Representative Concentration Pathways) scenarios for four spatial extents: Global, South Korea, North Korea, and Japan. However, they only considered regional average values from each GCM and the spatial resolutions of the GCMs they considered were various, generally at coarse resolution, with grid resolutions ranging from approximately 21 km to 619 km at the equator (ENES 2016).

In this study, we assess conditions of future projected climate by 2070 for 17 CMIP5 (Taylor et al. 2012) GCMs under two emission scenarios. We examine these trends for three nested regional scales; the Asian continent, six East Asia countries, and South Korea, and select two GCMs and two emission scenarios that bracket future conditions. We compare the predicted future conditions for Asia with those for six East Asia countries and for South Korea.

Our main objectives in this study were: (1) to estimate temperature and precipitation changes for the Asian continent by 2070; (2) to evaluate the difference of climate projections among various GCMs; and (3) to identify regional climate projection patterns from two GCMs that bracket the range of projected climate futures. The ultimate goal of this study is to provide detail on the uncertainties of climate projections and suggestions on using appropriate GCMs for regional climate change studies to prepare for the impacts of climate change.

II. Materials and Methods

This study analyzed climate change for three nested regions: South Korea, six East Asia countries (China, Japan, Mongolia, Russian Federation,

and South and North Korea), and the Asian continent. The Asian continent was defined using the boundary of "World Countries" provided by Esri Data & Maps, which identifies 53 countries and 42 million km² of land area as part of the continent (Figure 1). Asia is the world's largest and most populous continent containing around 60% of the world's population, and has diverse climates according to location and physical geography (Wheeler 2015).

1. Global Climate Models from CMIP5

We obtained minimum temperature and precipitation for historical and 17 future CMIP5 GCM projections that have results for two RCP (RCP 4.5 and RCP 8.5) emission scenarios from the WorldClim website (WorldClim 1.4; <http://www.worldclim.org>) at 10-minute (of a longitude/latitude degree) spatial resolution (\approx 18.5 km at the equator) (Table 1). The WorldClim website provides monthly minimum and maximum temperature, and precipitation climate variables, and these climate datasets have been used or cited in over 5,917 instances (Web of Science, accessed Nov. 28 2016).

For historical climate representations, we used 30-year means of precipitation and mean temperature (representative of 1960-1990), which were generated through interpolation of climate data from weather stations, at a 30 arc-second resolution (\approx 1 km²) (Hijmans et al. 2005). For future time periods, we used 2070 data representing the 20-year means for 2061-2080 as target year because they are publicly available future data from the WorldClim. These future projections have been downscaled using the current-time WorldClim climate surfaces. This was computed as the difference between the GCM run for the

baseline years and for the target years. These change were interpolated to high resolution grids and then calibrated with WorldClim historical dataset (Hijmans et al. 2005).

The RCPs are future emission scenarios given different assumptions about greenhouse gas concentrations in the atmosphere. RCPs describe the radiative imbalance in W/m^2 of Earth's surface by 2100 as increases from preindustrial emissions. Most GCMs represent four RCPs: 2.6, 4.5, 6.6, and 8.5 (van Vuuren et al. 2011; SCENIC 2014), and we chose two RCPs (RCP 4.5 and RCP 8.5) for this study to compare the differences between RCP scenarios. RCP 4.5 is a scenario of stabilizing radiative forcing at $4.5 W/m^2$ in 2100 without exceeding that value (Thomson et al. 2011). RCP 8.5 is a high greenhouse gas emissions pathway and "baseline" scenario that does not adopt any mitigation target (Riahi et al. 2011).

2. Differences of Future Climate Conditions

We analyzed the differences in annual mean minimum temperature (annual Tmin) and total annual precipitation (annual PPT) between the historical data and the 2070 projections using the all 17 GCM projections for the three spatial domains under the two RCPs. We selected the annual Tmin for this study because it is expected to become warmer at a faster rate than annual mean maximum temperature in most locations (Hartmann et al. 2013). We averaged the 12 monthly minimum temperature values ($^{\circ}C$) representing the historical mean and for 2070 from each GCM for each target region. For precipitation, we added the 12 monthly total precipitation (mm) provided by WorldClim to compute annual precipitation for the historical and future time periods for each GCM and each target region.

Then, we subtracted the historical climate data values from future climate values for each GCM to evaluate climate change ranges among the various GCMs. Finally, we selected two GCMs that bracket most of the climate projections for the Asia continent to see the spatial climate change patterns for 2070.

III. Results

1. Climate Change for the Asian Continent

Annual minimum temperature increased under all GCMs and both RCPs by 2070 for all regional scales (Figure 2 and Table 1). For the Asian continent, the range of increased minimum temperatures was between $2.1^{\circ}C$ (INMCM4; IN) and $5.3^{\circ}C$ (GFDL-CM3; GFDL) under RCP 4.5, and the range of increased minimum temperatures was between $3.4^{\circ}C$ (GISS-E2-R; GISS) and $7.4^{\circ}C$ (GFDL) under RCP 8.5 (from the historic mean of $-1.6^{\circ}C$). For the six East Asia countries, the range of increased minimum temperatures was between $2.3^{\circ}C$ (INMCM4; IN) and $6.1^{\circ}C$ (GFDL) under RCP 4.5, and the range of increased minimum temperatures was between $3.6^{\circ}C$ (GISS) and $8.5^{\circ}C$ (GFDL) under RCP 8.5 (from the historic mean of $-9.1^{\circ}C$). For South Korea, the range of increased minimum temperatures was between $1.3^{\circ}C$ (INMCM4; IN) and $3.6^{\circ}C$ (GFDL) under RCP 4.5, and the range of increased minimum temperatures was between $2.3^{\circ}C$ (INMCM4; IN) and $5.2^{\circ}C$ (GFDL) under RCP 8.5 (from the historic mean of $5.9^{\circ}C$).

On average, all the GCMs project increases in annual precipitation for the Asian continent and for the six East Asia countries by 2070 under the two RCPs, but regional differences could be expected from standard deviation values (Figure

2 and Table 1). For the Asian continent, the range of increased precipitation was between 32.4 mm (+ 5.5%, IN) and 104.3 mm (+ 17.6%, GFDL) under RCP 4.5, and the range of increased precipitation was between 55.7 mm (+ 9.4%, GISS) and 126.2 mm (+ 21.3%, HadGEM2-CC; HG) under RCP 8.5 (from the historic mean of 593.4 mm). For the six East Asia countries, the range of increased precipitation was between 28.8 mm (+ 6.3%, IN) and 125.7 mm (+ 27.5%, GFDL) under RCP 4.5, and the range of increased precipitation was between 52.6 mm (+ 11.5%, MPI-ESM-LR) and 156.8 mm (+ 34.3%, GFDL) under RCP 8.5 (from the historic mean of 456.6 mm). For South Korea, one GCM projected decreases in precipitation under both RCP scenarios. The range of precipitation change was between -8.4 mm (- 0.6%, BCC-CSM1-1; BC) and 271.9 mm (+ 20.6%, MIROC-ESM-CHEM; MI) under RCP 4.5, and the range of changed precipitation was between -42.4 mm (- 3.2%, IN) and 389.8 mm (+ 29.6%, ACCESS1-0; AC) under RCP 8.5 (from the historic mean of 1,317.5 mm).

Under RCP 4.5 scenario, for the larger regions, the climate change trends that 17 GCMs projected were similar. GFDL projects higher precipitation than the other GCMs. For South Korea, projecting trends for minimum temperature were similar, but there were different projecting trends for precipitation. BC projected the lowest precipitation and MI projected the highest precipitation.

We present these climate change ranges from the 17 GCMs in Figure 2. In the figure, the origin of the axes represents mean conditions for the historical 1960-1990 timeframe, used as the baseline. The x axis refers to changes in annual T_{min} (°C), and the y axis to changes in annual PPT (mm). We selected the GFDL-CM3 (GFDL) and

the INMCM4 (IN) GCMs for subsequent spatial assessments of climate change because they bracket most of the variance of future climate conditions for Asia continent and they are suitable to prepare for the uncertainty of climate change.

2. Spatial Assessments of Climate Change for Asia Continent in 2070

GFDL-CM3 (GFDL) and INMCM4 (IN) projected increases in annual minimum temperature in all regions in Asia continent by 2070 (Figure 3). Temperature increases more in the higher latitudes in both GCMs, but the degree of increasing temperature was much higher from the GFDL GCM. However, there were regional differences in temperature projections between the two GCMs. For example, IN projected higher temperature increase in the Tibetan plateau than in surrounding regions, while GFDL identified potential regional climate refugia (refugia have facilitated the persistence of species under changing climates; Keppel et al. 2012) in Tibet. Surrounding this region, local temperature change is high under the GFDL GCM.

On average, the two GCMs under both RCPs each project an increase in annual precipitation on the Asian continent. However, some countries especially in Western Asia including Turkey, Iran, Afghanistan and Central China were projected to have decreases in annual precipitation under the four climate projections (Figure 4). In case of precipitation, regional differences among GCMs were larger than those of temperature. For example, the GFDL projects an increase in precipitation in all East Asia, but some regions in South Korea and Southern Japan were projected to have a decrease in annual precipitation under the IN GCM.

IV. Discussion

We found that various climate projections produce different ranges of climate change for the Asian continent, and the ranges differ under the two RCP scenarios (Figure 2). On average, all of the GCMs we used in this study predicted increasing temperature in Asia continent, but the level of warming and the location was dependent on the GCM and RCP. Similarly, regionally averaged values of all 17 GCMs project an increase in annual precipitation for the Asian continent, but there are significant regional differences in the amount of and location of increases and decreases. These are in part due to the differing circulation patterns present in the various GCMs.

We selected the two GCMs under two RCPs to identify the regional differences from the four climate projections (Figures 3 and 4). Some regions show opposite climate trends from each climate projection by 2070. We conclude that reliance on a single specific GCM is risky for estimating climate change for a certain region in that it is not easy for climate models to predict the future with acceptable levels of accuracy and precision (Millar et al. 2007). In this study, we found that the regions at higher latitudes are at greater risk from increasing temperature, and that the increasing temperature in Western Asia would be higher compared to more easterly regions at the same latitude from the two GCMs bracket most of the future climate conditions of the Asia continent. Model agreement is lower for precipitation, but the regions in the West Asia would experience a decrease in precipitation, under the four climate projections we used to bracket future conditions.

For South Korea, the range of increased minimum temperature from the four GCM/RCP combinations was lower than the range of tempera-

tures predicted for East Asia or Asia (Figure 2). The range of precipitation change for South Korea was greater than the range for the larger regions. Some GCMs projected an increase amount of precipitation in South Korea that was higher than the highest projected precipitation values for Asia as a whole. One GCM under each emission scenario projects a decrease in precipitation for South Korea, while all GCMs predict an increase in precipitation over Asia as a whole.

The GCM developed from Korean Meteorological Administration using HadGEM2-AO projected increasing temperature of +2.4 °C and +3.4 °C from the RCP 4.5 and RCP 8.5, and increasing precipitation of: +10.5% and +15.5%, respectively, for Korean Peninsula by 2070. Compared to our results for South Korea, these amounts fall between the range of the 17 GCMs, but are closer to the optimistic values.

We suggest climate change studies in South Korea should assess the range of future climate conditions projected (e.g. Thorne et al. 2015), and not to stick to a single model's outputs to prepare adaptation strategies. Climate change impacts under different GCMs represent a range of future possible conditions and we should therefore prepare for a range of possibilities under the uncertainty of climate change using a scenario-based approach to represent the range of possible climatic futures. For example, in our former study, *Aconitum austrokoreense*, which is an endangered species in South Korea, was projected to decrease and move northwards by 2050. The extent of suitable areas in 2050 was larger by 2.8 times under the NorESM1-M (warmer GCM) than under the HadGEM2-ES (hotter GCM). The suitable areas spread in Gangwon and Jeolla provinces under the NorESM1-M, but mainly

spread in Gangwon province under the HadGEM2-ES.

Managing uncertainty will require various approaches including short-term and long-term strategies with flexibility, which include enhancing ecosystem resistance and resilience as well as assisting ecosystems to adapt to future climate changes (Millar et al. 2007; Hallegatte 2009; Millar & Stephenson 2015). To reduce the cost associated with various climate change adaptation studies, information on variability and on low-probability and/or high-consequence events is important for decision makers (Webster 2003). In this study, the GFDL and IN GCMs represent the range of minimum temperature of all three regions well, so we recommend Korean studies on climate change to use these two GCMs and to prepare for potential impacts from climate change. However, the range of precipitation change of the two GCMs we looked at in more detail for South Korea does not correspond with the variations for East Asia or Asia. To prepare for the uncertainties of precipitation for South Korea, using additional GCMs including ACCESS1-0, BCC-CSM1-1, and MIROC-ESM-CHEM is recommended to capture the range of precipitation change.

Our simple approach to identify the ranges of future climate change can be applied to identify proper bracketing of projected futures. However, there are some challenges that this study does not address. Increasing extreme weather phenomena is an important aspect of climate change and can be a critical determinant of patterns of ecosystem structure and function (Butt et al. 2016). Further research is required to better understand climate change patterns because our study is only focusing on average projections of climate change.

Moreover, since we found that various GCMs project different trends depending on the region analyzed, identifying the range of climate change should be done respectively depending for a study region and identifying common climate-stable and climate-risky areas across scales could be one of the climate assessment analyses.

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Table 1. The GCMs used in this study and the differences in annual minimum temperature (°C) and annual precipitation (mm) between historical data (representative of 1960-1990) and 2070 projections (average for 2061-2080) under RCP 4.5 and RCP 8.5 (pr means precipitation, tn means minimum temperature). For more information about the GCMs, please visit <http://cmip-pcmdi.llnl.gov/>.

Region	Institute	GCM	Code	RCP 4.5				RCP 8.5			
				pr.mean (mm)	pr.sd	tn.mean (°C)	tn.sd	pr.mean (mm)	pr.sd	tn.mean (°C)	tn.sd
Asia continent	CSIRO/BOM	ACCESS1-0	AC	60.53	83.28	3.87	0.9	79.79	134.15	5.6	1.32
	BCC	BCC-CSM1-1	BC	54.35	95.84	3.03	0.8	71.36	129.03	4.87	1.36
	NCAR	CCSM4	CC	44.84	63.42	3.11	0.98	68.19	112.81	4.88	1.49
	CNRM/CERFACS	CNRM-CM5	CN	49.62	47.9	3.2	1.21	66.65	58.03	4.7	1.59
	NOAA GFDL	GFDL-CM3	GF	104.26	102.48	5.27	2.21	123.11	135.44	7.4	2.74
	NASA GISS	GISS-E2-R	GS	45.04	81.66	2.46	0.44	66.51	112.51	3.39	0.59
	NIMR/KMA	HadGEM2-AO	HD	65.83	98.77	4.44	1.28	81.46	169.98	5.75	1.6
	MOHC	HadGEM2-ES	HE	69.47	90.33	4.46	1.49	103.92	190.22	6.58	1.98
	MOHC	HadGEM2-CC	HG	67.44	111.48	4.15	1.38	126.2	252.98	6.5	2.04
	INM	INMCM4	IN	32.43	56.26	2.08	0.62	55.67	84.9	3.89	1.25
	IPSL	IPSL-CM5A-LR	IP	59.07	114.52	3.85	0.85	80.25	170.89	6.16	1.31
	MIROC	MIROC5	MC	77.14	117.67	3.17	0.93	99.12	133.74	4.93	1.66
	MRI	MRI-CGCM3	MG	55.53	80.5	2.58	0.7	113.97	202.23	4.33	1.04
	MIROC	MIROC-ESM-CHEM	MI	72.57	113.17	4.64	1.66	99.95	141.74	6.86	2.24
	MPI-M	MPI-ESM-LR	MP	37.6	106.62	3.18	0.81	57.5	150.28	5	1.16
MIROC	MIROC-ESM	MR	61.57	100.64	4.92	1.68	88.58	140.61	6.86	2.24	
NCC	NorESM1-M	NO	55.12	83.94	3.48	1.24	74.27	121.25	5.14	1.65	
Six countries	NOAA GFDL	GFDL-CM3	GF	125.72	74.50	6.12	2.24	156.77	103.15	8.50	2.70
	INM	INMCM4	IN	28.85	26.86	2.29	0.54	53.54	33.84	4.36	1.17
South Korea	NOAA GFDL	GFDL-CM3	GF	152.61	127.48	3.62	0.11	308.80	118.80	5.22	0.16
	INM	INMCM4	IN	31.27	26.14	1.33	0.20	-42.39	48.48	2.33	0.32



Figure 1. The location and the countries of the Asian continent and of six East Asia countries. Maps throughout this article were created using ArcGIS® software and “World Countries” dataset by Esri. For more information about the dataset, please visit www.arcgis.com.

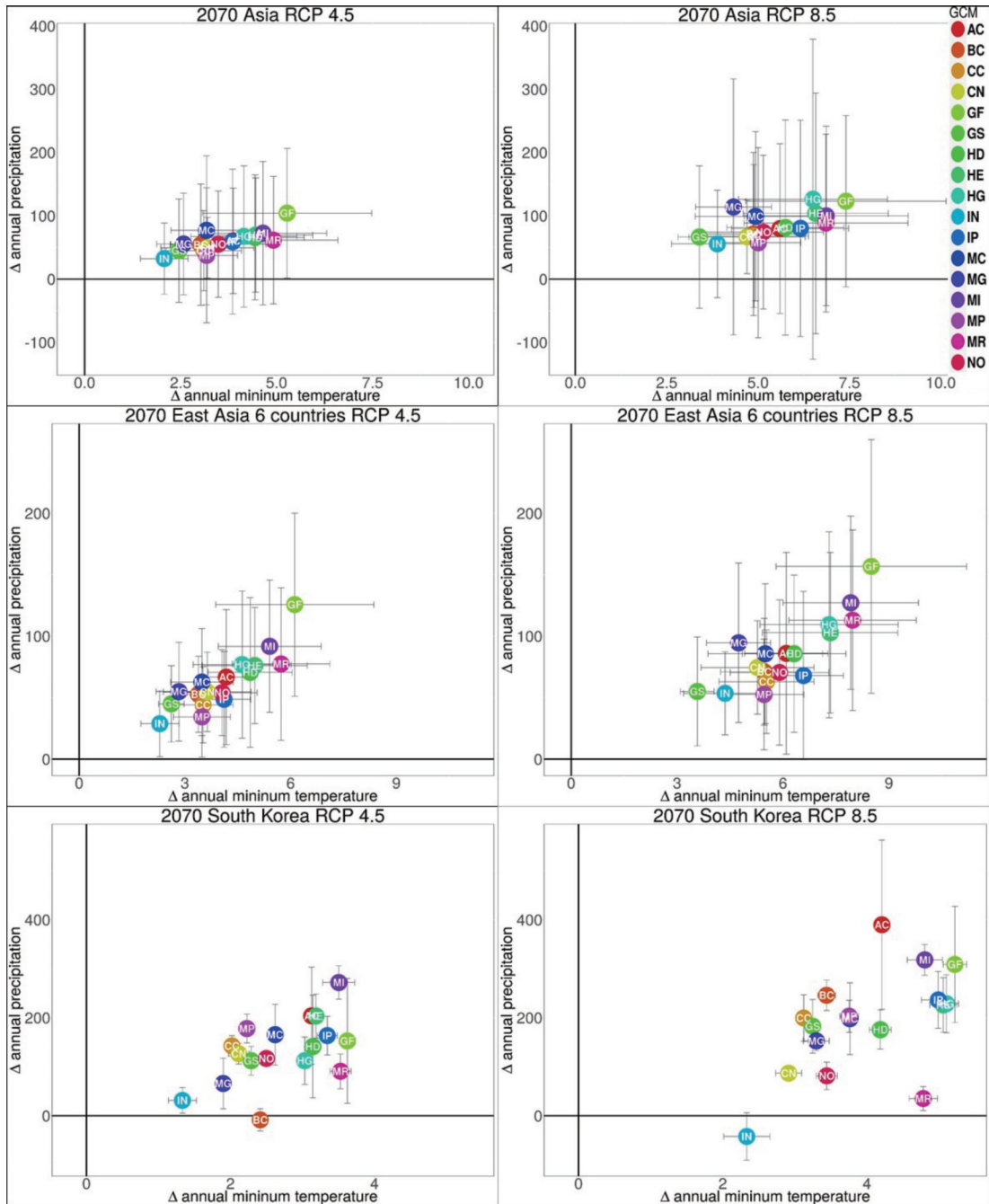


Figure 2. The difference between historical and projected future climate conditions for three spatial domains under the RCP 4.5 (left) and the RCP 8.5 (right) emissions scenarios, and using 17 CMIP5 GCM projections. The origin of the axes represents mean conditions for the 1960-1990 timeframe, used as the baseline. The x axis refers to changes in annual minimum temperature (°C), and the y axis to changes in annual precipitation (mm). The gray lines extending from the GCM dots represent spatial standard deviations.

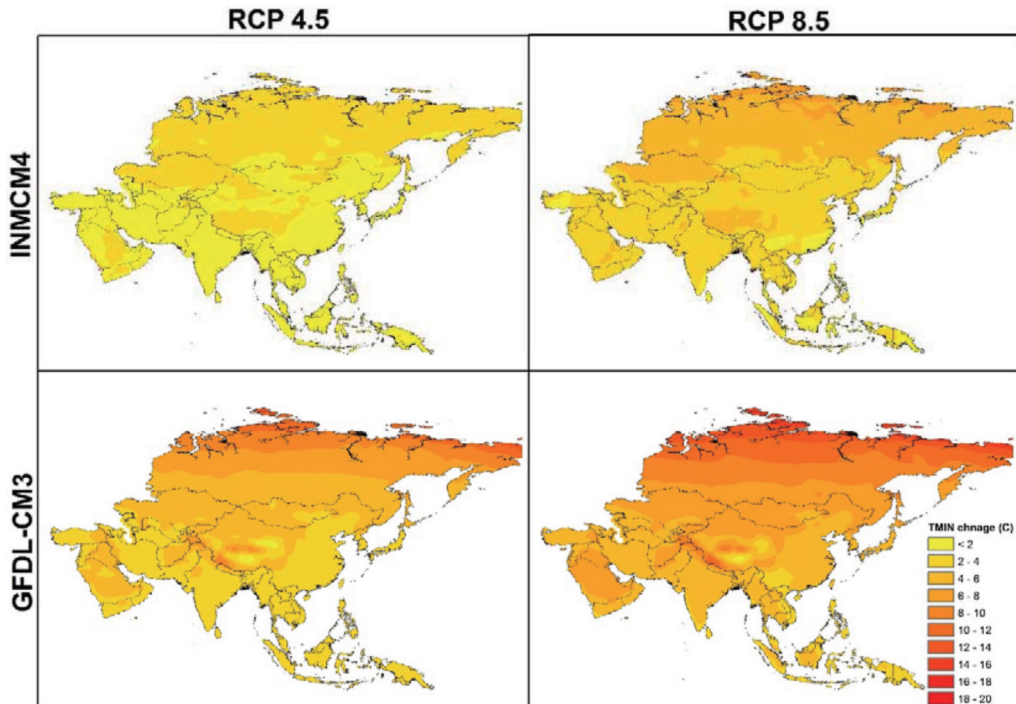


Figure 3. The Change of annual minimum temperature (°C) by 2070 (average of 2061-2080) from historical data (representative of 1960-1990).

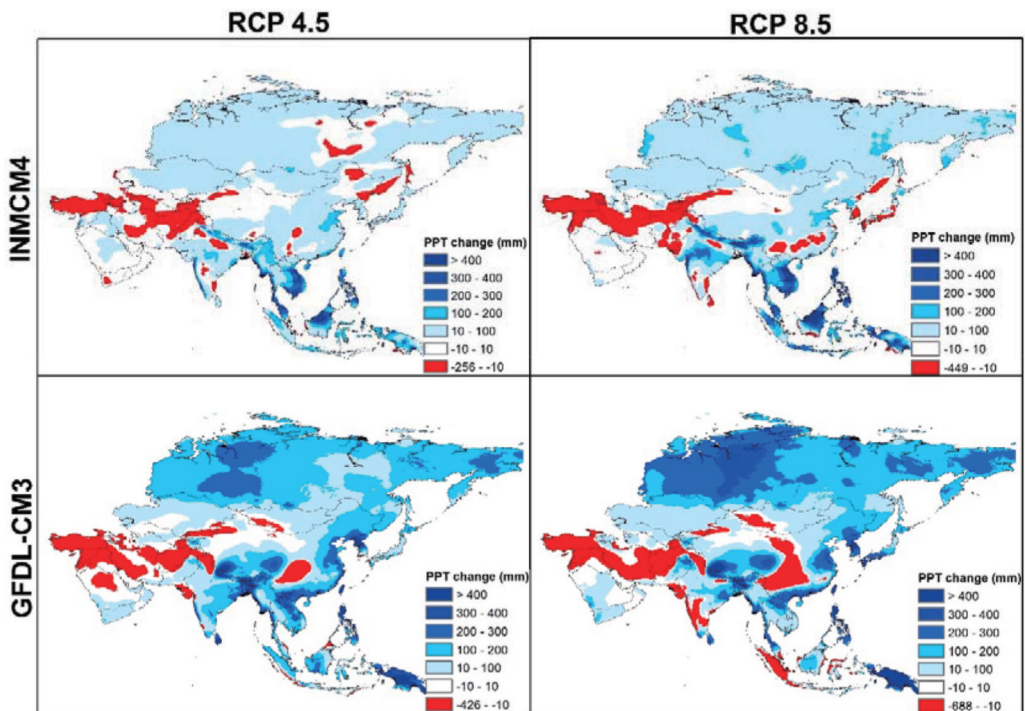


Figure 4. The Change of annual precipitation (mm) by 2070 (average of 2061-2080) from historical data (representative of 1960-1990).