REPLIES TO THE REVIEWERS' COMMENTS

The authors are grateful to the reviewers for their valuable comments that helped to improve the quality of the manuscript. The point-by-point responses are presented as follows:

Reviewer #1

1.This paper reports a useful analysis of model simulations and forecasts of temperature and precipitation over China. Yet the presentation needs improving by avoiding vague and empty statements and the English needs polishing before the paper is publishable.

Response: Thanks for your comments and suggestions. We tried our best to revise the manuscript according to your advices. Hopefully, this revised version will be satisfactory to meet the publication standard.

2. Section 2, Data and methods lacks details. Why selecting these five RCMs? What advantages do they have compared to other regional and global models products? Do the five models have desired features for the purpose of this analysis?

Response: Thanks for your suggestions. Data and methods in section 2 have been modified in the revision. The reason why five RCMs are selected is below:

The selected five RCMs have been demonstrated to have abilities to reasonably reproduce the regional climate over East Asia and have been used for modeling and predicting extreme climate as well as investigating physical processes of East Asia climate (Cha and Lee, 2009; Cha et al., 2011; Hong and Yhang, 2010; Park et al., 2008; Yhang and Hong, 2008). Moreover, the five RCMs used in this work are derived from the CORDEX East Asia experiment that is able to provide a common framework in a global-wide perspective for regional climate projections in order to understand their uncertainties as well as provide model evaluation.

3. CRU and APHRO products are used as "observations". Are they more accurate and reliable than other global temperature and precipitation data products over the study domain (China)?

Response: Thanks. We use the temperature data from CRU and precipitation data from APHRO as the observation climate in this study. Some illustrations about CRU and APHRO products and the reason why they are used in this study are clarified as below:

Some studies have focused on comparing and evaluating the spatio-temporal similarities and differences of several widely used observed gridded datasets over China (Sun et al., 2014; Wu and Gao, 2013; Yin et al., 2015). Table 1 shows the information of several widely used global observed gridded climate datasets (from Sun et al., 2014). According to Sun et al (2014), all temperature datasets in table 1 exhibit similar distribution patterns for the annual average temperature in mainland China. Considering its easier access and wider usage in evaluation of

RCM model used in East Asian/China (Wang et al., 2017), CRU other than UDEL temperature data are used to evaluate the performance of RCM in this study.

Table 1 Detailed information on the datasets in the research of Sun et al (2014)

Dataset	Pre	Tas	Spatial domain	Temporal domain	Reference
APHRO	√		0.25°, East Asia	Daily, 1951-2007	(Yatagai et al., 2012)
CRU	√	√	0.5°, global	Monthly, 1901-2017	(New et al., 2000)
GPCC	√		0.5°, global	Monthly, 1901-2010	(Becker et al., 2013)
UDEL	√	√	0.5°, global	Monthly, 1901-2010	(Willmott and Matsuura, 2001)

Sun et al (2014) suggest that observed precipitation coming from different datasets do have differences, which are caused by differences in raw data sources, quality control schemes, orographic correction and interpolation techniques. Indeed, we have no ability to know the 'truth value'. To some degree, the dataset constructed based on observations from more meteorological stations can be treated as more accurate and reliable one. Among the several precipitation datasets shown in table 1, APHRO's daily gridded precipitation, presently the only long-term, continental-scale, high-resolution daily product, is constructed based on data collected at 5000-12000 stations, which represent 2.3-4.5 times the data made available through the Global Telecommunication System network used for generating global gridded dataset (i.e. CRU, GPCC and UDEL) (Yatagai et al., 2012). Thus, the APHRO dataset would give more confidence in the robustness of the results in comparison with other global precipitation datasets and thus is widely used for evaluating the performance of RCM in East Asia (Gao et al., 2017; Kumar and Dimri, 2017; Lau et al., 2017; Lee et al., 2017; Um et al., 2017).

4. Section 2.3 is somewhat confusing due to lack of details. Why using Taylor diagram? A concise description of the Taylor diagram is needed for those who are not familiar with the method.

Response: Thanks. Detailed illustration for Taylor diagram has been added in the revised manuscript.

The Taylor diagram was designed to quantify the degree of correspondence between the modeled and observed behavior by plotting a 2D graph with three statistics (Pearson correlation coefficient (R), standard deviation (SD), and the root-mean-square error (RMSE)). In the Taylor diagram, a smaller distance between the observation and the compared models means a closer agreement (Baker and Taylor, 2016; Sun et al., 2015; Taylor, 2001). More details about this diagram are available from the above references. In general, The Taylor diagram enable statistics for different fields (with different units) to show in a single plot, facilitating the comparative assessment of different models.

5. Eqs. (4)-(5) appear to come from nowhere with undefined notations. A justification of the statistical method and metrics used in the analysis is helpful.

Response: Thanks. More details about notations in Eqs. (4)-(5) and methods (where Eqs. (4)-(5) are included) to separate and quantify the two sources of uncertainty were added in the revised manuscript. Here we give a brief illustration.

(1) Firstly, the percentage change from the mean of 1980-1999 is calculated for each projection, and a smooth fourth-order polynomial is fitted for 2030-2049. Then the raw simulation of each model $X_{m,t}$ for the model m and year t which can be expressed by

$$X_{m,t} = x_{m,t} + c_m + \varepsilon_{m,t} \qquad \text{(Eqs. 1)}$$

where the smooth fit is represented by $x_{m,t}$, the reference data is denoted by c_m, and the residual is denoted by $\varepsilon_{m,t}$.

The internal variability is represented by the decadal mean residuals from these smooth fits for 2030-2049, which is assumed to be constant with lead time.

The model uncertainty is considered by the model spread around the mean for each scenario.

(2) The RCMs are weighted by their performance in simulating the current climate from the mean of 1980-1999, up to the year 1999. Thus, each model is weighted according to

$$w_m = \frac{1}{x_{obs} + \left| x_{m,1999} - x_{obs} \right|} \qquad \text{(Eqs. 2)}$$

where $x_{m,1999}$ is the model climate changes at the year of 1999, relative to 1980-1999, and x_{obs} is an observational estimate derived from fitting a similar fourth-order polynomial to the observations. The normalized quantities of these weightings can be expressed as

$$W_m = \frac{w_m}{\sum_m w_m} \qquad \text{(Eqs. 3)}$$

(3) **The internal variability** (equ. 4) is defined as the multi-model mean of theses variance of the residuals from the fits for each model. Here $\mathrm{var}_t(.)$ indicates the variance across different time slices.

$$V = \sum_m W_m \,\mathrm{var}_t(\varepsilon_m, t) \qquad \text{(Eqs. 4)}$$

(4) **The intermodel variability** (equ.5) is estimated from the weighted variance (var^w) in the different RCM prediction fits ($x_{m,t}$), where $\mathrm{var}_m(.)$ represents the variance across different models.

$$M(t) = \mathrm{var}_{\mathrm{m}}^{w}(x_{m,t}) \qquad \text{(Eqs. 5)}$$

(5) It was assumed that the two sources of uncertainty can be treated independently (i.e., there is no interaction between them). Thus, **the total variability** V_T is:

$$V_T(t) = V + M(t) \qquad \text{(Eqs. 6)}$$

6. Section 3 is not well organized and thought out. Overall, discussions are somewhat superficial. To make this paper useful, more insightful explanations and suggestions should be made explicit and specific. For example, on page 6 “All RCMs successfully simulate the precipitation patterns but with quite large biases in amounts”. Should we trust more the CRU data or the RCMs simulations?

Response: Thanks. We reorganized the Section 3 and included more specific analysis in our revised manuscript. The response to the question “Should we trust more the CRU data or the RCMs simulations?” is below:

In this paper, we aimed to evaluate the performance of five RCMs within CORDEX-EA in reproducing present-day climate and to analyze the projected future climate changes under the middle emission scenario and uncertainties attributed to RCMs and internal variability. Here the performance of five RCMs in reproducing present-day climate is evaluated by comparing the RCM simulations with the CRU and APHRO products. The CRU and APHRO products are constructed based on observed metrological data during historical period. Thus the CRU and APHRO database can be treated as the proxy for the observed metrological data, with higher reliability than the RCMs simulations during historical period.

7. The authors suggest that “the multi-model ensemble outperforms the individual RCM in reproducing the observed spatial pattern of precipitation” (page 6). Would it be possible to obtain the “true” climate by having infinite ensembles?

Response: Thanks. It is difficult to obtain the “true” climate by having infinite ensembles so far. The reason is listed below:

The skill of climate models in reproducing precipitation or temperature is limited by internal atmospheric variability that is largely unpredictable (Kharin and Zwiers, 2002). Thus, perfect climate model does not exist. Some researchers have concluded the multi-model ensemble outperforms the individual RCM in reproducing climate pattern (Huttunen et al., 2017; Rozante et al., 2014). Moreover, the probability of obtaining “true” climate would rise with increased ensemble number. However, huge computational resource is required for the long-term and high-resolution climate projection. Therefore, to obtain the "true" climate by having infinite ensembles is difficult by now.

8. In section 3.3.2, it was suggested that "the seasonal precipitation change in multi-model ensemble has larger magnitude and variability than driving GCM. This phenomenon concerns the significance of the model physics and processes for future climate projection". Specification of what model physics and processes are important would be very useful. The paper ended with "More reliable future climate information could be provided by coupling GCMs and RCMs through the modifications to model structures and parameters." To be specific about the model structures and parameters to be modified would be the valuable new knowledge that the reader can learn from this analysis.

Response: Thanks for your suggestions. The illustrations for important model physics processes have been added in the revision. They are clarified by two points below:

(1) In section 3.3.2, it was suggested that "the seasonal precipitation change in multi-model ensemble has larger magnitude and variability than driving GCM". The configurations of each RCM were showed in Table 2. For each RCM, optimal schemes of the dynamical and physical processes were determined through the investigation of the model sensitivities to the schemes. In general, convective parameterization is the most important and sensitive physical process associated with the simulation results (Huang and Gao, 2017). Land surface parameterizations, as well as those parameterizations over the ocean, are also very important because they control the quantity of moisture entering into atmosphere from the Earth's surface (Zhao and Li, 2015). Thus, the phenomenon above could be attributed to the difference in convective parameterization, land surface parameterizations, as well as those parameterizations over the ocean between GCMs and RCMs. On the other hand, the discrepancies between the RCMs and driving GCM indicate that the RCM projections are sensitive to local and regional processes and the methods represented in the model (Diallo et al., 2012; Saini et al., 2015).

(2) At the end of this paper, further research in the future was added: More reliable future climate information and uncertainty quantification could be provided by coupling large ensemble of GCMs and RCMs under different emission scenarios.

Table 2. RCMs used in this study[a]

	HadGEM3-RA	RegCM4	MM5	WRF	RSM
Resolution	0.44°	50km	50km	50km	50km
Dynamic process	Non-hydrostatic	Hydrostatic	Non-hydrostatic	Non-hydrostatic	Hydrostatic
Convective scheme	Revised mass flux scheme	MIT-Emanuel	Kain-Fritch II	Kain-Fritch II	Simplified Arakawa-Schubert

Land surface parameterization	MOSES2	CLM3	CLM3	NOAH	NOAH
Planetary boundary layer	MOSES2 non-local	Holtslag	YSU	YSU	YSU
Spectral nudging	No	Yes	Yes	Yes	Yes
Center of research	MOHC	ICTP	NCAR	NCAR	YSU
References	Davies et al.(2005)	Giorgi et al.(2012)	Cha and Lee(2009)	Skamarock et al.(2005)	Hong et al.(2013)

[a]MOSES= Met Office Surface Exchange Scheme, CLM= Community Land Model, NOAH=Noah Land Surface Model, YSU= Yonsei University scheme, MOHC= The Met Office Hadley Centre, ICTP= The International Centre for Theoretical Physics, NCAR= National Center for Atmospheric Research

9.The paper needs a careful text editing to improve its presentation. A long sentence is often confusing such as "Reliable regional future climate projection is important for the evaluation of climate change impacts and vulnerability, as well as the elaboration of appropriate mitigation and adaptation measures, especially for the developing countries like China tend to be one of the most vulnerable to the adverse effects of climate changes" (page 1). English Grammar needs to checked carefully. For example, "The ongoing coordinated regional downscaling experiment (CORDEX) (Giorgi et al., 2009; Jones et al., 2011), whose aim to provide high-resolution regional future climate projections for the majority of populated land regions on the globe by using multi-RCMs, and an interface to the applicants of the climate simulations in climate change impact, adaptation, and mitigation studies." (page 2) is not a sentence as it does not have a verb.

Response: Sorry for the serious language problem in previous manuscript. We consider your criticism thoroughly in revising manuscript. In total, the previous article was severely revised four times, particularly on the presentation, interpretation and language together with the figures and tables. In the revising process, two important co-authors (Prof. W. R. Peltier from University of Toronto, Toronto, Canada and Prof. Guiling Wang from University of Connecticut, USA) with proficient English skills contributed to the thorough control check in language for this version significantly. They read and corrected the language and presentation for the paper sentence by sentence to meet the reviewers' request. As you can see from the track-changes in the main context, tables, and figures, the revised version was really undergone a major revision through which the paper quality has been improved.

Reviewer #2

Major comments

(1) Introduction. The limitation and development of GCMs are reviewed, but the advantages and applications of RCMs are not clearly discussed. A more detailed introduction on the progress and limitation on dynamical downscaling is needed. As mentioned by the authors, "The CORDEX-EA has been evaluated for simulating the precipitation and temperature over East Asia (Huang et al., 2015; Jin et al., 2016; Lee and Hong, 2014; Oh et al., 2013; Park et al., 2013; Suh et al., 2012; Zou et al., 2014)." Therefore, how does this study differ from previous CORDEX-EA studies should be clearly stated.

Response: Thanks for your valuable suggestions. More details on the progress and limitation on dynamical downscaling and the difference between this study and previous CORDEX-EA studies were added in the revision. Two points are clarified as follows:

(1) The resolution of RCMs is approximately 12-50 km, and it accounts for the sub-GCM grid-scale forcing, e.g. complex topographical features and land cover heterogeneities in a physically based manner. However, RCMs inherit the biases from systematic model errors caused by imperfect conceptualization, discretization, and spatial averaging within grid cells. (Dong et al., 2018). Nonetheless, RCM ensembles enable the understanding and characterization of uncertainties which have different origins, from the future scenario, to the forcing data and the regional model physics, and therefore, reduce uncertainties and increase confidence in future projections.

(2) A series of studies based on RCMs within CORDEX-EA have been conducted to project extreme and mean precipitation and temperature over china under different scenarios (Jin et al., 2016; Lee et al., 2014; Niu et al., 2015; Park et al., 2016; Tang et al., 2016; Um et al., 2017), but little attention has been paid to quantify the contributions of the uncertainty arising from RCMs and internal variability in future climate projection over China. Thus, it is necessary to objectively evaluate the capability of RCMs and quantify the uncertainty in future climate projections. In this study, we evaluate the performance of five RCMs within CORDEX-EA to reproduce present-day climate and to anayze the projected future climate changes under the middle emission scenario. More importantly, biases in current climate simulations and uncertainties in future climate projections attributed to the RCMs and internal variability are further analyzed.

(2) Uncertainty quantification method. P5, L5-7. The paper by Hawkins and Sutton (2009, BAMS) used a model-weighted variance when calculating inter-model variability M(t), while eq. 5 in this paper seemed to get an unweighted value. Given that eq. 4 defined a weighted mean of variance as V (same as Hawkins and Sutton's paper), I suggest keeping it consistent in the manuscript, because RCM simulations may differ a lot in both magnitude and variation. If the

eq. 5 is just a typo and this study does calculate weights for different models, both simple multi-model ensemble (MME) and weighted MME should be compared in the evaluation (e.g., Figures 2-4).

Response: Thanks for your valuable suggestions. Equation 5 was modified and the weighted variance was used when calculating the inter-model variability in the revision. As shown in the Figures 1-3 in this response file, no significant difference in the spatial patterns (Figures 1-2) between simple multi-model ensemble (MME) and weighted MME can be found. Similarly, skills of the models in reproducing the precipitation and temperature with simple MME are nearly consistent with that based on weighted MME (Figure 3). Thus, the weighted MME is used in the revised manuscript, instead of the simple MME.

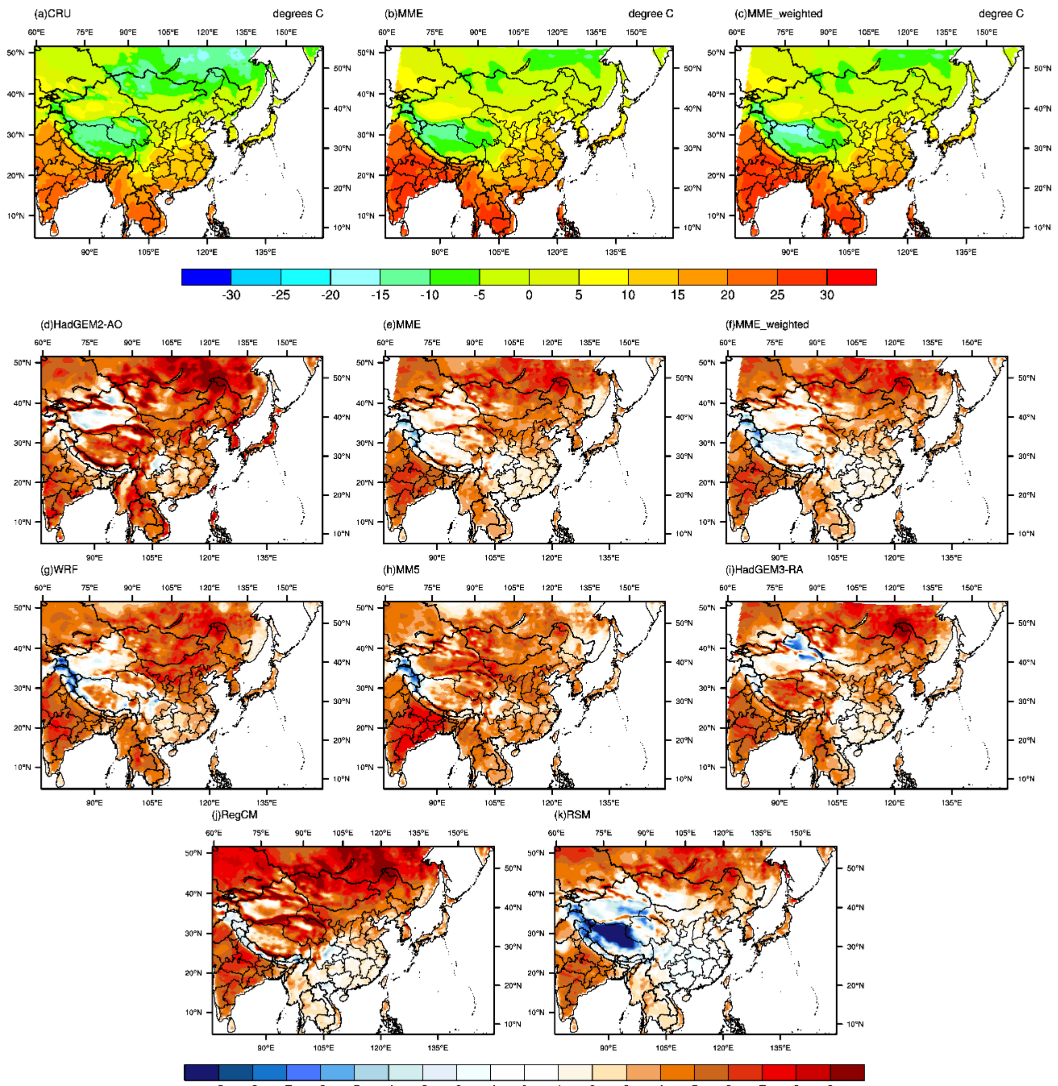

Figure 1. Spatial distributions of annual average temperature (ºC) of CRU (a), multi-model ensemble (b), multi-model ensemble (c), and temperature biases (ºC) of the driving GCM HadGEM2-AO (d), multi-RCM ensemble (e, f) and five RCMs (g-k) during 1980-2005.

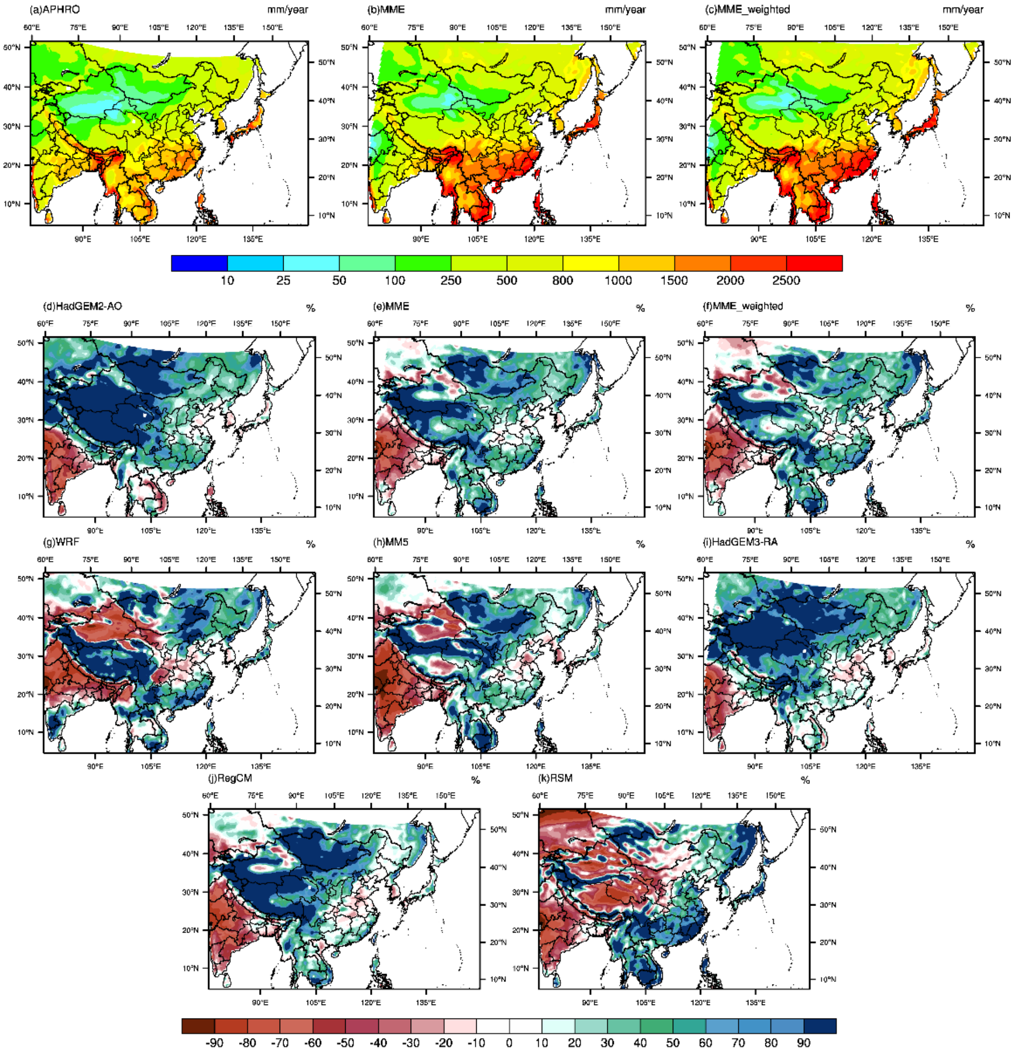

Figure 2. Spatial distributions of annual average precipitation (mm/year) of APHRO (a), multi-model ensemble (b), weighted multi-model ensemble (c), and precipitation biases (%) of the driving GCM HadGEM2-AO (d), multi-RCM ensemble (e and f) and five RCMs (g-k) during 1980-2005.

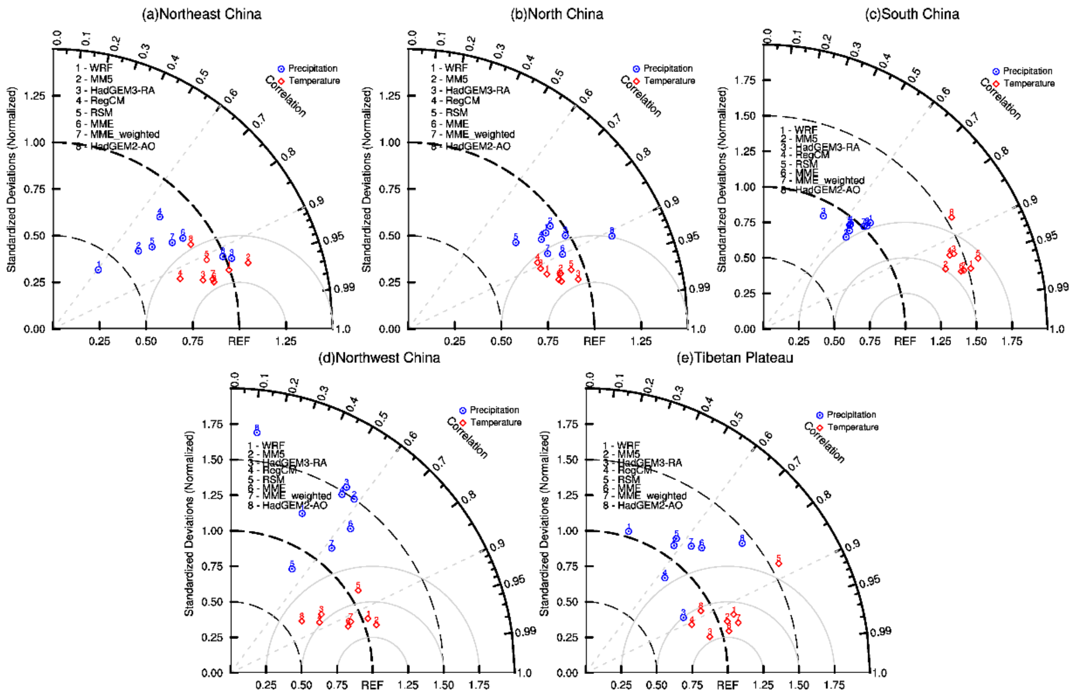

Figure 3. Taylor diagram to compare the skill of the models in representing the annual average temperature and precipitation over the five regions of China, using the CRU (for temperature) and APHRO (for precipitation) data as the REF.

(3) The abstract needs a careful revision. For example, how does the CORDEX-EA future projection over China or East Asia differ from existing reports (e.g., IPCC AR5 report or at least the driven GCM in this study)? Are the 5 models (RCMs) enough to quantify the model variability? What is the added value for dynamical downscaling (e.g., how much error has been reduced)?

Response: Thanks for your suggestion. We tried to compare and add the CORDEX-EA future projection and the simulation by the driven GCM in the revision. Meanwhile, the added value for dynamical downscaling was analyzed in the revised manuscript.

(1) The comparison of the CORDEX-EA future projection over China with the projection by the driven GCM was added. As shown in table 3, increases in annual mean temperature based on the five RCMs' ensemble range from 0.9 ºC to 1.3 ºC in different subregions, which is quite close to the projected increase in annual mean temperature from the forcing GCM (range from 0.7 ºC to 1.4 ºC). Meanwhile, similar spatial patterns for projected change in annual mean temperature by the ensemble method and the driving GCM are shown in Figures 4a-b. Generally, the CORDEX-EA future projected change in mean temperature is nearly consistent with the results from the driving GCM. However, opposite signals for projected changes in average precipitation between the ensemble method and the driving GCM are shown over South china, Northeast china and Tibetan Plateau (table 3). Particularly the spatial and temporal differences in projection from two methods above are largest at the Tibetan Plateau, up to about 10%.

Table 3. The future changes in average temperature (T; °C) and precipitation (P; %) for the five subregions (as shown in Figure 1). The ensemble averages for each statistic are given in the second line. The projections by the forcing GCM are given in the last line.

		WRF	MM5	HadGEM3-RA	RegCM	RSM	Ensemble	HadGEM2-AO
Northeast China	T(°C)	0.2	2.7	1.4	1.4	1.1	1.3	0.8
	P(%)	-21.7	8.2	13.0	4.4	7.1	1.5	-0.4
North China	T(°C)	0.3	1.7	1.1	1.0	1.0	1.0	0.8
	P(%)	-1.5	15.1	3.1	10.2	3.3	6.1	4.9
South China	T(°C)	0.5	1.5	1.0	0.8	0.8	0.9	0.7
	P(%)	-14.6	-1.6	4.8	4.9	1.3	-1.5	2.3
Northwest China	T(°C)	1.3	0.8	1.5	1.3	1.1	1.2	1.2
	P(%)	-27.0	19.4	2.2	4.7	8.9	3.6	7.2
Tibetan Plateau	T(°C)	0.9	1.4	1.2	1.3	1.6	1.3	1.4
	P(%)	-31.6	-17.8	2.4	6.4	7.4	-7.8	2.1

(2) The added values for RCMs were confirmed by comparing the performance of RCM and GCM in reproducing annual mean precipitation and temperature during historical period. According to the Taylor diagram (Figure 3 above), it is found that the added value for RCMs strongly depends on the climate variable and the region of interest. The added value of the RCMs with respect to the driving global climate model was evident in term of annual mean temperature over all five subregions, with higher spatial correlation coefficient for all five RCMs. Compared with the driving global climate model simulations, the spatial patterns of the simulated annual average precipitation over South China, Northwest China and the Tibetan Plateau were improved in most RCMs. The expectations are over Northeast China and North China, where higher performance is shown for the driving global climate model. Please see lines 286-297 in this response file for the reasons resulting in this phenomenon.

Besides, the results shown in above two points were summarized in a couple of sentences in the revised abstract, in view of the length limit for the abstract.

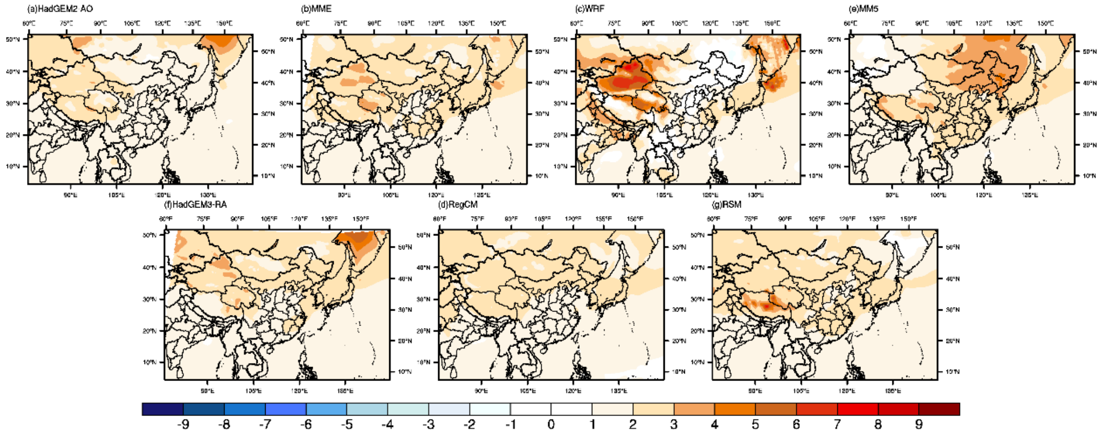

Figure 4. Projected future changes (RCP4.5-Baseline) in surface air temperature for the forcing GCM HadGEM2-AO and each of the five RCMs.

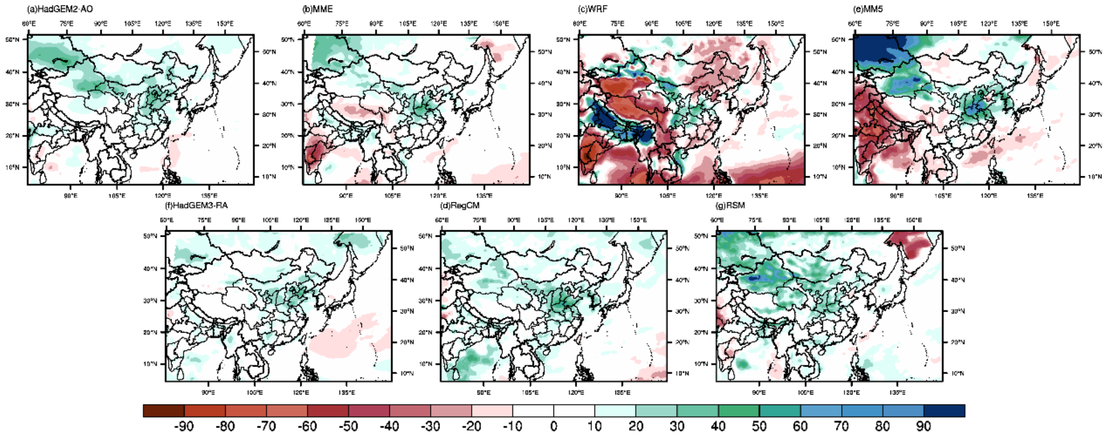

Figure 5. Projected future changes ((RCP4.5-Baseline)/Baseline×100%) in precipitation for the forcing GCM HadGEM2-AO and each of the five RCMs.

(4) Figure 4b. Why there is a decrease in precipitation correlation, where GCM outperforms all RCMs over North China?

Response: Thanks. The reason why there is a decrease in precipitation correlation over North China was added in the revision. In this study, it is found the performance of RCM in reproducing spatial pattern of annual average precipitation is superior to that of the driving GCM in term of correlation coefficient in most sub-regions over China. The only exception is North China. In reality, the added value in RCM simulations (in compaction with GCM) is related to a better representation of spatial variability of surface climate statistics, particularly in regions with fine-scale surface forcing such as orographic and coastal features. Thus, the added value in RCM simulations is commonly significant in regions with fine-scale surface forcing, whereas the performance of RCM is less improved or even worse than that of the driving GCM over relatively flat regions. For instance, Prommel and Geyer (Prömmel et al.,

2010) also found the RCM deteriorates some results compared to the driving GCM in relatively flat subregions surrounding the Alps, particularly during the summer season.

(5) There are a lot of grammar errors while I just mentioned quite a few below. Please proofread the paper carefully or ask a native English speaker for help.

Response: Sorry for the serious language problem in previous manuscript. In the revising process, two important co-authors (Prof. W. R. Peltier from University of Toronto, Toronto, Canada and Prof. Guiling Wang from University of Connecticut, USA) with proficient English skills contributed to the thorough control check in language for this version significantly. As you can see from the track-changes in the main context, tables, and figures, the revised version was really undergone a major revision through which the paper quality has been improved.

Minor comments

(6) P3, Section 2.1. Two datasets were used as reference precipitation, CRU and APHRO. The reason why both datasets are necessary is equivocal, partly because of little comparison between them. Which one was chosen as reference value when calculating precipitation biases (%) in Figure 3 and why?

Response: Thanks for your suggestions. In figure 3 APHRO data was chosen as reference precipitation when calculating precipitation biases (%). Meanwhile, only APHRO dataset other than CRU dataset was used as reference precipitation in the revision, to increase the readability of this paper. The reason why APHRO dataset is used has been detailed in lines 40-53 in this response file.

(7) P1, L16, “decreases -7.8%” -> “decreases by -7.8%”.

Response: Thanks. They have been done.

(8) P1, L20, “contribute” -> “contributes”.

Response: Thanks. They have been done.

(9) P1, L21, “which” -> “where”.

Response: Thanks. They have been done.

(10) P2, L22, “forces on” -> “focusing on”.

Response: Thanks. They have been done.

(11) P2, L24-27, this sentence is awkward.

Response: Thanks. We rewrote this sentence.

(12) P2, L32, “simulating”->”simulation”

Response: Thanks. They have been done.

(13) P3, L2, “will became”->”will become”

Response: Thanks. They have been done.

(14) P3, L13, “Scection 3” ->“Section 3”.

Response: Thanks. They have been done.

(15) P4, L1, “include” -> “including”, “.. of each of the RCM: : :” -> “of each RCM : : :”.

Response: Thanks. They have been done.

(16) Several sentences in the manuscript are difficult to read with grammar mistakes, for instance, P2 L2, P2 L7-L8, P3 L1, P3 L19-21, etc. The authors should improve the presentation, especially for Abstract and Introduction Section.

Response: Thanks. We rewrote these sentences.

(17) Caption of Figure 4 needs revision, where the information for temperature (red rectangles) is missing.

Response: Thanks. We modified this caption in the revised manuscript.

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High-resolution ensemble projections and uncertainty assessment of regional climate change over China in CORDEX East Asia

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Abstract. An ensemble simulation of ~~5~~ five regional climate models (RCMs) from the ~~Coordinated~~ coordinated ~~Regional~~ regional ~~Downscaling~~ downscaling ~~e~~Experiment in East Asia ~~(CORDEX-East Asia)~~ ~~was~~ is evaluated and used ~~for~~to project future regional climate change ~~projection~~ in China. ~~Meanwhile, t~~The ~~contributions~~ influences of model uncertainty and internal variability on projections ~~are~~ are also identified. The RCMs simulated ~~both~~ the historical (1980-2005) climate ~~(1989-2008)~~ and future (2006-2049) climate projections ~~(2030-2049)~~ under the Representative Concentration Pathway (RCP) RCP4.5 scenario. ~~We highlighted~~The simulations for ~~5~~ five subregions in China, including~~viz.~~ Northeast China, North China, South China, Northwest China, and Tibetan Plateau, are highlighted in this study. ~~Our r~~Results showed that (1) ~~the capability of~~ RCMs ~~to~~can capture the climatology, annual cycle and inter-annual variability of temperature and precipitation and a multi-model ensemble (MME) outperforms that of ~~the~~an individual RCM. The added values for RCMs are confirmed by comparing the performance of RCM and GCM in reproducing annual and seasonal mean precipitation and temperature during the historical period. (2) For ~~the~~ future climate, the MME indicate consistent warming trends at around 1 °C ~~were indicated by multi-model ensemble over~~ in the ~~whole~~ entire domain and project ~~more~~ pronounced warming ~~was projected~~ in northern and western China. The annual precipitation is likely to increase in most of the simulation region, except for the Tibetan Plateau ~~which decreases -7.8%~~. (3) Generally, the future projected change in annual and seasonal mean temperature by RCMs is nearly consistent with the results from the driving GCM. However, changes in annual and seasonal mean precipitation ~~Compare with the similar seasonal temperature changes with the driving global climate model (GCM), the seasonal precipitation change shows~~ exhibit significant inter-RCM difference and ~~has~~ possesses larger magnitude and variability than driving GCM. Even opposite signals for projected changes in average precipitation between the MME and the driving GCM are shown over South China, Northeast China and Tibetan Plateau. (4) The ~~model~~ uncertainty ~~for future~~in projected mean temperature ~~projection~~ mainly arises from the internal variability ~~is clearly dominant~~ over ~~the northeast~~north and~~,~~ south~~northwest~~ China and the model uncertainty over the rest three subregions ~~and Tibetan Plateau, reaching up to 70%, and it contribute about 40% of the total uncertainty over north and south China~~. For the projected mean precipitation, the~~the internal variability is~~ dominant uncertainty source is the internal variability over most regions, except for the Tibetan Plateau ~~which~~ where the ~~the~~ model uncertainty~~ies~~

reaches up to 60%. Moreover, the In addition, the mmodel uncertainty increases with prediction lead time over across all subregions.

1 Introduction

The gGlobally averaged surface temperature has increased by 0.65-1.06 °C during the period from 1880 to 2012 according to multiple several independently produced datasets, and further rises increases ranging from on the order of 0.3 °C -to 4.8 °C are projected for 2081-2100 relative to 1986-2005 using a set of global climate models (GCMs) driven by the Representative Concentration Pathway (RCP) scenarios RCP2.6 to RCP8.5 (IPCC, 2013)(IPCC, 2013). Meanwhile, other climate factors, such as precipitation amounts and variability, snow and ice cover patterns and mean sea level, are also changing such as precipitation amounts and variability, snow and ice cover patterns and mean sea level (Alfieri et al., 2015; Kerr, 2008; Patz et al., 2005)(Alfieri et al., 2015; Kerr, 2008; Patz et al., 2005). Reliable projection of regional -future climate projection is important critical for thein evaluatingon of climate change impacts and vulnerability, as well as and the elaboration ofin developing appropriate mitigation and adaptation measures, especially for the developing countries, like such as China which tends to be one of the most vulnerable countries to the adverse effects of climate changes (Kreft et al., 2016; Wang et al., 2017).

The East Asian summer monsoon (EASM) is the most distinctive climate feature in China, and the monsoon area accounts for approximately 60% of the mainland (Ding and Chan, 2005)(Ding and Chan, 2005). EASM system-related precipitation starts around mid-May or even earlier in Indo-China Peninsula, which presents distinct stepwise northward and northeastward advances feature with two abrupt northward jumps and three stationary periods, and begins withdrawing southward in September (Ding, 2004; Hsu, 2005)(Ding, 2004; Hsu, 2005). The rainy seasons of EASM, including the pre-summer rainy season over South China, mei-yu (in China) occur normally occurs during the stationary periods, which are imbedded in the northward advance of the summer monsoon. The anomaly of EASM could cause floods and droughts which plays aare crucial role in the livelihood of more than one billion people (Gu et al., 2015; Webster et al., 1998; Yu et al., 2018)(Webster et al., 1998). However, because of the complex topography and model limitation, how to reliably reproduce thethe manner in which climatological rainfall and interannual variation of EASM can be reliably reproduced still remains a challenge because of the complex topography and model limitation. The CMIP3 (coupled Coupled model intercomparison project phase 3 (CMIP3)) and CMIP5 GCMs, however, have problems simulating precipitation in this region. Recent studies have suggested that the new generation of GCMs from CMIP5 archive shows exhibits some several improvements to reproduce the climatology and interannual variability of EASM compared with the CMIP3 GCMs, but although the simulated biases remained and large intermodel spread existed (Chen and Bordoni, 2014; Gu et al., 2015; Huang et al., 2013; Yang et al., 2017)(Chen and Bordoni, 2014; Gu et al., 2015; Huang et al., 2013). For example, the mei-yu rainfall band in GCMs is missing in the GCMs, although even though the monsoon circulation is well reproduced.

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Because ofConsidering these deficiencies, higher high-resolution GCMs have been developed to improve the capabilities in monsoon features simulation, including orographic precipitation, low-level jet orientation and variability, as well as the mei-yu onset and withdrawal (Kitoh et al., 2013; Kusunoki et al., 2006)(Kitoh and Kusunoki, 2008; Kitoh et al., 2013; Kusunoki et al., 2006). However, these experiments are still remained burdensome due to large computational cost resources required for multi-decadal simulations. Therefore, the regional climate models (RCMs) forces on focusing on a region of interest are commonly used in regional climate projection and climate change impacts studies (Gao et al., 2006; Giorgi and Mearns, 1999; Gu et al., 2012; Wang et al., 2004; Yira et al., 2017; Yu et al., 2006)(Christensen et al., 2007; Gallée et al., 2004; Gao et al., 2006; Giorgi and Mearns, 1999; Gu et al., 2012; Leung et al., 2003; Wang et al., 2004; Yira et al., 2017; Yu et al., 2006). The resolution of RCMs is approximately 12-50 km, and it could consider local scale forcing, e.g. complex terrain features and land cover heterogeneities in a physically based method. However, RCMs inherit the biases from systematic model errors because of the imperfect conceptualization, discretization, and spatial averaging within grid cells (Dong et al., 2018). Nonetheless, RCM ensembles can be used to understand and characterize uncertainties from different sources, such as future climate scenario, the driving GCM and regional model physics, and therefore, reduce the uncertainties and increase credibility in future projections. The ongoing coordinated regional downscaling experiment (CORDEX) (Giorgi et al., 2009; Jones et al., 2011)(Giorgi et al., 2009; Jones et al., 2011), whose aims to provide high-resolution regional future regional climate projections for the majority of populated land regions on the globaelly by using multi-RCMs, and to present an interface to thefor applicants of the climate simulations in climate change impact, adaptation, and mitigation studies (Giorgi et al., 2009; Jones et al., 2011)(Giorgi et al., 2009; Jones et al., 2011). The CORDEX in East Asia -(CORDEX-EA) is the East- Asian branch of the CORDEX experiment, and it provides ensemble regional climate simulations (https://cordex-ea.climate.go.kr/main/modelsPage.do). TheA series of studies based on RCMs within CORDEX-EA has been conducted to project extreme and meanevaluated for simulating the precipitation and temperature over in East Asia (Huang et al., 2015; Jin et al., 2016; Lee and Hong, 2014; Oh et al., 2013; Park et al., 2013; Suh et al., 2012; Zou et al., 2014) (Jin et al., 2016; Lee et al., 2014; Niu et al., 2015; Park et al., 2016; Tang et al., 2016; Um et al., 2017), but little attention has been paid to quantify the contributions of the uncertainty in future climate projection over China..

Despite large improvements in the simulating simulation of local processes, future climate projections are still accompanied by large uncertainties stemming from different sources, including the forcing GCMs, emission scenarios, downscaling methods (RCMs or statistical downscaling methods), and natural climate internal variability (Déqué et al., 2007; Deser et al., 2012)(Déqué et al., 2007; Deser et al., 2012). Numerous previous studies have demonstrated that GCMs being are the main source of uncertainty (Seo et al., 2016)(Seo et al., 2016). However, after excluding the outliers from the GCM ensemble, other Other uncertainty sources, such aslike RCMs and internal variability will becoame more important than GCMs after excluding the outliers from the GCM ensemble (Kay et al., 2009; Wilby and Harris, 2006)(Kay et al., 2009; Wilby and Harris, 2006). In a non-stationary climate, the internal variability of a given GCM-RCM chain can remain high above the trend related to a given emission scenarios forcing (Lafaysse et al., 2014; O'Brien et al., 2011)(Hawkins and Sutton, 2011; Lafaysse et al., 2014; O'Brien et al., 2011). So far, little Little attention has been paid devoted to quantify the contributions of the

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uncertainty arising from RCMs and internal variability in future climate projection over China. ~~Thus, it is necessary to~~ ~~o~~Objectively evaluating~~e~~ the capability of RCMs and quantifying ~~the~~ uncertainty in future climate projections are necessary.

In this study, we evaluate the performance of five RCMs within CORDEX-EA to reproduce present-day climate and ~~to~~ analys~~z~~e the projected future climate changes under the middle emission scenario. ~~In addition~~ More importantly, biases in current climate simulations and uncertainties in future climate projections attributed to ~~the~~ RCMs and internal variability are further analy~~z~~sed. This paper is structured as follows. ~~The d~~Data from observation and model simulation, and analysis method are described in the succeeding~~next~~ section. S~~e~~ection 3 presents the historical performances of RCMs for temperature and precipitation and future climate changes under RCP4.5 emission scenario ~~over~~ in China. The uncertainties in regional future climate projection ~~resulting from~~caused by inter-RCMs and natural climate internal variability are also discussed. The summary and conclusion are ~~given~~ presented in S~~s~~ection 4.

2 Data and methods

2.1 Observations

The reference temperature ~~and precipitation~~ data used to ~~compare~~ evaluate the model results ~~to~~ with observation data develops from the ~~University of East Anglia~~ Climate Research Unit Timeseries 3.23 (CRU~~ TS3.23~~) of the University of East Anglia, with a spatial resolution of 0.5°, derived from gauge measurements ~~, details in Harris et al.,~~(Harris et al., 2014)~~(2014)~~. Meanwhile, the reference precipitation data, namely ~~T~~the Asian Precipitation-Highly Resolved Observational Data Integration Toward Evaluation (APHRODITE, hereafter APHRO) dataset with a spatial resolution of 0.25° ~~also~~ was used ~~for~~to evaluate RCMs ~~evaluation~~ (Yatagai et al., 2012)~~(Yatagai et al., 2012)~~. ~~In order t~~To facilitate the comparison, outputs from a host of RCMs were converted to a common grid of 0.5° × 0.5° latitude/longitude as ~~in the~~ remapped to the CRU and APHRO observations, using bilinear interpolation. The reasons why CRU and APHRO products are used as reference in this study are clarified as below.

Some studies have focused on comparing and evaluating the spatial-temporal similarities and differences of several widely used observed gridded datasets over China (Sun et al., 2014; Wu and Gao, 2013; Yin et al., 2015). Among the widely used gridded dataset, such as the Global Precipitation Climatology Centre (CPCC) product, the University of Delaware (UDEL) product, CRU data and the National Meteorological Information Center dataset from China Meteorological Administration, all temperature datasets exhibit similar distribution patterns for the annual average temperature in mainland China. Considering its easier access and wider usage in the evaluation of RCMs used in China and East Asian (Wang et al., 2017), CRU product is used as the reference temperature data in this study. APHRO's daily gridded precipitation, presently the only long-term, continental-scale, high-resolution daily product, is constructed based on the data collected at 5000-12000 stations, which represent 2.3-4.5 times the data made available through the stations used for generating global gridded (i.e. CRU, GPCC and UDEL) (Yatagai et al., 2012). Thus, the APHRO dataset would give more confidence in the robustness of the results in comparison with other global precipitation datasets and thus is widely used for evaluating the performance of

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RCM in East Asia(Gao et al., 2017; Lau et al., 2017; Um et al., 2017). In addition, the CRU and APHRO product are used instead of station data accessible from China Meteorological Administration, owing to the study area involving in the domain of East Asia extending beyond China territory.The use of two data sets is beneficial not only to the evaluation of RCM's performance but also to the verification of the observation datasets.

2.2 Models and experiments

In this study, we used five RCMs, namely, HadGEM3-RA, MM5, WRF, RegCM4, and RSM for East Asian climate experiments (Table 1). They are derived from the CORDEX East Asia experiment that is able to provide a global holistic framework for regional climate projections so as to understand their uncertainties as well as provide model evaluation. Moreover, the selected five RCMs have been demonstrated to have abilities to reproduce the regional climate over East Asia and have been used for modelling and predicting extreme climate as well as investigating physical processes of East Asia climate (Cha and Lee, 2009; Cha et al., 2011; Hong and Yhang, 2010; Park et al., 2008; Yhang and Hong, 2008). The dataset were produced from multi-RCM national project under Korea Meteorological Administration. The spatial resolution of the data is 50 km (except HadGEM3-RA is 0.44°), and the whole CORDEX-EA domain includes East Asia, India, the Western Pacific Ocean, and the northern part of Australia, as shown in Fig.ure 1. Model configurations includinge physical schemes are summarized in Table 1. The detailed description of each of the RCM simulations can be found inPlease refer to the references Suh et al.(2012)(2012) and Park et al.(2016)(2016) about more details about RCMs used in this study.

Table 1

Figure 1

In this study, two types of current climate experiments from five RCMs were performed, including the evaluation (hereafter EVAL) experiment for the period of from 1989 -to 2007 and the historical (HIST) experiment for the period offrom 1980- to 2005. The EVAL experiment acquires initial and boundary conditions from the National Centers for Environmental Prediction (NCEP) reanalysis, and whereas the HIST experiment is forced by -the Atmosphere-Ocean coupled Hadley Center Global Environmental Model version 2 (HadGEM2-AO) simulation. The HadGEM2-AO (1.875°×1.25° horizontal resolution) has been used for climate simulations in a CMIP5 set of long-term experiments, and has been evaluated demonstrated to have a reasonable ability to capture the East Asian climatology (Baek et al., 2013; Martin et al., 2011; Sperber et al., 2013)(Baek et al., 2013; Martin et al., 2011; Sperber et al., 2013). The fFuture climate simulation is driven from the HadGEM2-AO under RCP 4.5 scenario. The RCP 4.5 scenario, which is an intermediate scenario and a cost-minimizing pathway that total radiative forcing is stabilized at 4.5 W m^{-2} in the year the year 2100 (Thomson et al., 2011)(Thomson et al., 2011). The reference period from 1980 to 1999 and the scenario period from 2030 to 2049 are analyzsed for climate changes research in this studystudy.

The multi-model ensemble (MME) mean, which is defined as the pointwise arithmetic average over all individual model climatologies, is used to narrows down inter-RCM uncertainties because of their differences in model structures and physics. To further evaluate the model performance on smaller spatial scales, we evaluate the performance of RCMs over five selected

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sub-regions (as shown in Figure 1), that isnamely, Northeast China (40-50°N, 115-130°E), North China (30-40 °N, 105-120 °E), South China (22-30 °N, 105-120 °E), Northwest China (35-45 °N, 80-95 °E), and Tibetan Plateau (28-35 °N, 80-95 °E).

2.3 Analysis methods

The root-mean-square error (RMSE), biasWe evaluate climatology from individual RCMs, MME using bias, the root-mean-square error (RMSE), and Taylor diagram analysis are selected for statistical measurements of the performance for the individual RCM and the MME. The former two indexes are used for evaluating the ability of models in reproducing annual and seasonal mean of climatology. The annual and seasonal means are examined by bias and RMSE. The model performance on spatial patterns is evaluated by Taylor diagram (Taylor, 2001).The Taylor diagram is designed to quantify the degree of correspondence between the modelled and observed behavior by plotting a 2D graph with three statistics (correlation coefficient, standard deviation, and RMSE). In the Taylor diagram, a small distance between reference and compared objects indicates close agreement (Baker and Taylor, 2016; Sun et al., 2015)(Sun et al., 2015). In general, the Taylor diagram enable statistics for different fields (with different units) to show in a single plot, facilitating the comparative assessment of different models (Taylor, 2001).

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Uncertainty in projected climate change mainly arises from the internal variability of the climate system, the model uncertainty, and the scenario uncertainty (Niu et al., 2015; Woldemeskel et al., 2016). In this study, all RCMs are driven by the same GCM under the same scenario, soand thus, the uncertainty of the climate projections is mainly caused by the inter-RCM variability and internal variability (Niu et al., 2015). The method developed by Hawkins and Sutton (2009; 2011)(2009; 2011)was is used for to separatinge these two sources of uncertainty. Here we give a brief illustration.

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(1) Firstly, a smooth fourth-order polynomial is used to fit each individual simulation over the years 1980-2049 by using ordinary least squares method. Then Tthe raw simulation of each model $X_{m,t}$ for the model *m* and year *t* which can be expressed by

$$X_{m,t} = z_{m,t} + c_m + \varepsilon_{m,t} \tag{1}$$

where the smooth fit is represented by x_m $z_{m,t}$, represents the simulation from the smooth fit for the model *m* and year *t* minus the reference data; the reference data is denoted by c_m, and the residual (internal variability) is denoted by $\varepsilon_{m,t}$. Here the reference data is the mean of simulation from the smooth fit during the years 1980-1999. Here each individual simulation was fit with a fourth-order polynomial by using ordinary least squares method during the years 2030-2049. The reference data used are the mean of the years 1980 to 1999 and estimated from the smooth fits.

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(2) The RCMs are weighted by their performance in simulating the current climate from the mean of 1980-1999, up to the year 1999. Thus, each model is weighted according to

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$$W_m = \frac{1}{z_{obs} + \left| z_{m,1999} - z_{obs} \right|} \tag{2}$$

where ~~x_m~~$z_{m,1999}$ is the model climate changes ~~at the year of~~in 1999~~,~~ relative to 1980-1999, and ~~x_{obs}~~ z_{obs} is an observational estimate derived from fitting a similar fourth-order polynomial to ~~the~~ observations. The normalized quantities (W_m) of these weightings can be expressed as

$$W_m = \frac{w_m}{\sum_m w_m} \qquad (3)$$

(3) ~~The i~~Internal variability (V, as shown in ~~equ~~Eq. 4) is defined as the multi-model mean of the~~ses~~ variance of the residuals from the fit~~s~~ for each model,

$$V = \sum_m W_m \,\mathrm{var}_t(\varepsilon_{m,t}) \qquad (4)$$

$$M(t) = \mathrm{var}_m^w(z_{m,t}) \qquad (5)$$

(4) ~~And the i~~Intermodel variability (M, as shown in ~~equ~~Eq. 5) is estimated from the weighted variance (var^w) in ~~the~~ different RCM prediction fits (~~x_m~~$z_{m,t}$), where var_t(.) and var_m(.) indicate the variance across time and model, respectively.

(5) It was assumed that the two sources of uncertainty can be treated independently (i.e., ~~there is~~ no interaction exists between them). Thus, the total variability V_T is ~~then~~

$$V_T(t) = V + M(t) \qquad (6)$$

(6) The fraction of variance of internal variability and model uncertainty defined as $V/V_T(t)$ and $M(t)/V_T(t)$, respectively.

3 Results

3.1 Climatology for the ~~control~~ historical climate

3.1.1 Historical annual average climate evaluation

Figure 2 shows the annual average temperature of CRU, the driving GCM HadGEM2-AO and multi-model ensemble, ~~and~~ as well as the temperature biases of five RCMs driv~~ing~~en by HadGEM2-AO ~~during~~ from 1980 to 2005. Obviously, both the MME and ~~The corresponding MME mean is denoted by point ensemble. Similar as the multi-model average results, all~~five RCMs ~~could~~ can capture~~reproduce~~ the spatial pattern of annual mean temperature in China, ~~which demonstrates~~with a decreasing south-north gradient ~~of the observed temperature over China~~ and a cold area ~~over~~ in the Tibetan Plateau. Moreover, the MME presents overall best results to reproduce the temperature spatial distribution and provides less than 1 °C temperature biases over most area in China. However, ~~Generally, a~~all ~~model~~RCMs generally overestimated the mean temperature ~~give warm biases~~ over most of the domain~~,~~, in particular warmer mean temperature is simulated by ~~especially~~ MM5 and HadGEM3-RA ~~give larger warm biases than the other models~~. The only exception is that RSM underestimated the mean temperature ~~Most RCMs give obvious warm biases~~ over the Tibetan Plateau ~~except for RSM which give a cold biases~~. ~~The multi-model ensemble shows overall best results to reproduce the temperature spatial distribution and give less than 1 °C temperature biases over most area of China.~~

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Figure 2

The RCMs ~~give~~ provide reasonably accurate simulations ~~on~~ for mean temperature during the historical period~~,~~, but are less successful at reproducing ~~the~~ precipitation. Figure 3 shows the annual average precipitation ~~of~~ from ~~CRU,~~ APHRO, HadGEM2-AO~~,~~ ~~multi-model ensemble~~and MME, ~~and~~as well as the precipitation biases ~~of~~ from five RCMs in the current period. ~~Observed precipitation amounts also show a~~ It is found that the spatial pattern for annual mean precipitation is characterised by~~with~~ a decreasing southeast-northwest gradient over China~~.~~, which can be ~~All RCMs~~ successfully simulated by all RCMs. However, quite large precipitation biases are found in different RCMs. For instance, WRF underestimated the annual ~~the~~ mean precipitation ~~patterns~~ in northwest China, where mean precipitation was overestimate by the other RCMs. In comparison with the simulation from each RCM,~~but with quite large biases in amounts. The precipitation is overestimated in the arid/semiarid region of northwest China by all RCMs except for WRF which underestimate the precipitation over the whole domain. Comparably, RegCM shows more realistic in current precipitation reproduction. In general,~~ ~~t~~the ~~multi-model ensemble~~MME is better in reproducing annual mean precipitation over most subregions in China.~~outperforms the individual RCM in reproducing the observed spatial pattern of precipitation.~~

Figure 3

The ~~comparison of the~~ spatial variability statistics of the models in reproducing the annual mean temperature and precipitation by the Taylor plot (Taylor, 2001)~~(Taylor, 2001)~~ are exhibited~~summarized~~ in Figure 4. The temperature simulations ~~from~~ of the five RCMs ~~display~~ exhibit a good spatial pattern correlation, rang~~e~~ing from 0.83 to 0.96, ~~while~~ whereas the precipitation simulation show a relatively ~~wide~~ extensive range of spatial pattern correlations from 0.29 to 0.93. Besides, the MME is superior to most RCMs in capturing spatial variability of these climate variables, as reflected by higher spatial correlation coefficient and lower ~~It should be noted that the~~ RMSE~~of the ensemble statistic is less than most of single model simulation. In other words, the apparent biases of the individual models are reduced by the multi-model ensembles~~.

~~There could be s~~Several reasons ~~for~~could explain this phenomenon~~,~~, as noted by ~~which also noticed by o~~other scholars in their studies on model inter-comparisons (Huttunen et al., 2017; Phillips and Gleckler, 2006; Rozante et al., 2014)~~(Phillips and Gleckler, 2006)~~. ~~,~~On the one hand~~First~~, ~~to a certain extent that~~ the bias of a simulated climate field is symptomatic of random errors to a certain extent, and the ~~multi-model ensemble~~MME may reduce or counteract this error from the RCM. On the other hand~~Moreover~~, the pointwise variations of the climate field ~~have been~~are smooth~~ened~~ out by averaging, thereby filtering ~~regional~~ regional-scale simulations, wh~~ere~~ich current climate models are difficult to capture. ~~However, their causes are often difficulty to identify and to remedy, further investigation is needed in model inter-comparison.~~

Figure 4

~~In addition, most of RCMs show better performance than the driving GCM HadGEM2-AO, and it reflect the added value of the high resolution RCMs in simulation of spatial variability of the East Asia monsoon.~~

3.1.2 Interannual and seasonal variability~~Figure 4~~ of historical climate

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The ability of a climate model to capture realistic interannual variability is an importantcritical measure of its performance. The time series of the annual mean temperature and precipitation from RCMs are compared to with CRU and APHRO in Figure 5. Evidently, The the interannual variation of the climatologies climatology is generally well reproduced in the RCMs ensembleMME. In the evaluation experiment for 1989-2007, the correlation coefficient of the annual climatologies climatology time series at five subregions between the observation and RCMs ensemblesimulation from the MME is ranges from 0.52 to 0.78 for temperature, and range from 0.50 to 0.87 for precipitation. The correlation coefficient is always lower in West China compared with that in the East China, especially in Tibetan Plateau. In the historical experiment for from 1980-to 2005, the MME show better performance, in comparison with the RCMs which have difficulty to in reproduceing the interannual variability for precipitation because of the impact of the driving GCM.

Figure 5

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The temporal distributions of rainfall precipitation and temperature throughout the year is are quite importance important for the ecosystems and water resource management. In order toTo evaluate the RCM's ability to capture the seasonal variability of climatologies, the seasonal cycles of simulated temperature and precipitation averaged over five subregions in China wasare examined (Figures 6). It is evident that the seasonal patterns of The observed temperature and precipitation is featured by one peak in June over south China and in July over the rest regions, which can be successfully reproduced by all RCMs and MME. show the steep onset of summer rainfall associated with the summer monsoon, which peaks sharply in July (except south China in June for precipitation). All RCMs successfully reproduce the seasonal variation characteristics of a single peak. All models capture the bell-shape of the monthly temperature profile. However, the inter-model difference in simulated precipitation is large. For instance, monthly precipitation is always underestimated by WRF and overestimated by MM5 and HadGEM3-RA, especially larger bias is shown in summer. Among five RCMs, RegCM is the one with best ability to simulate the seasonal cycles of precipitation. The MME generally provide the most accurate simulation for the temporal distribution of precipitation, in comparison with the RCMs. As for the temperature, the RCMs can capture its temporal pattern over all subregions. Moreover, mean temperature in different months are alwaysBut almost all RCMs overestimated by most RCMsthe temperature the whole year with systematic biases except for WRF which underestimate the temperature over most regions. Overall, theHowever, the MME reduces the bias from the RCMs and therefore generate more accurate temporal distribution for mean temperature. RCMs show better in simulating the twenty-year average monthly temperature than the corresponding precipitation. The multi-model ensemble succeed in reproducing the seasonal variation of precipitation. However, the inter-model difference is quite larger compare with the temperature. Some RCMs always underestimate (i.e. WRF) or overestimate (i.e. MM5 and HadGEM3-RA) the precipitation especially in summer, other RCM (i.e. RSM) overestimate precipitation in some region/season but underestimate precipitation in others. Overall, RegCM and multi-model ensemble give the most accurate twenty-year average climate simulation.

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Figure 6

3.1.3 The added value for RCMs

The added values for high-resolution RCMs were confirmed by comparing the performance of RCMs and driving GCM HadGEM2-AO in reproducing annual mean precipitation and temperature during the historical period. According to the Figure 4-6, it is found that the added value for RCMs depends largely on the climate variable and the area of interest. The added value of the RCMs in comparison with the driving GCM was evident in term of annual mean temperature over all five subregions, with higher spatial and temporal correlation coefficient and less seasonal bias for all five RCMs. Compared with the driving GCM simulations, the historical precipitation over South China, Northwest China and the Tibetan Plateau were improved in most RCMs. The exceptions are over Northeast China and North China where higher performance is shown for the driving global climate model. In reality, the added value in RCM simulations is mainly concerned with a better representation of spatial variability of surface climate statistics, particularly in areas with small-scale land surface forcing such as orographic and coastal features. Thus, the added value in RCM simulations is commonly significant in regions with fine-scale surface forcing, whereas the performance of RCM is less improved or even worse than that of the driving GCM over relatively flat regions. For instance, Prommel and Geyer (Prömmel et al., 2010) also found the RCM deteriorates some results compared to the driving GCM in relatively flat regions surrounding the Alps, especially in summer. In most cases, five RCMs perform better than the driving GCM HadGEM2-AO. It needs to be emphasized that the better model performance tends to increase confidence in the future climate projections from RCMs.

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3.2 Multi-RCM future climate projection

3.2.1 Futur~~ru~~e change in climatology

According to figure 7 showing the projections for mean temperature from the driving GCM, RCMs and the MME, ~~The projected future changes in annual mean temperature show~~ similar warming trends are detected over the ~~whole~~ entire domain ~~for the period~~from 2030 to ~~-~~ 2049 under RCP4.5 ~~emission~~ scenario ~~(Fig. 7)~~. All five models project substantially significant warming while exhibiting~~s~~ different spatial patterns. The ~~ensemble~~ increases ~~averaged~~in annual temperature ~~increases~~ by the MME are 1.3, 1.0, 0.9, 1.2, and 1.3 °C over the Northeast, North, South, Northwest, and Tibetan Plateau subregions, respectively. The warming in northern and western China is more significant than that in southern China, especially in Northeast China and Tibetan Plateau, which ~~are~~ is similar to the results from previous studies ~~with observation and projection of models~~ (Sun et al., 2015; You et al., 2014; Zhou and Yu, 2006)~~(Sun et al., 2015; You et al., 2014; Zhou and Yu, 2006)~~. Moreover, the magnitude for the increase in annual temperature over a given subregion varies with the RCM. For instance, the projected increase in mean temperature over the Tibetan Plateau ranges from 0.9 °C to 1.6 °C.

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Figure 7

Figure 8 shows the spatial distributions of changes in annual mean precipitation ~~changes~~ (RCP4.5~~—~~baseline). ~~In~~ During the period ~~the future period,~~ 2030-2049, increased precipitation is projected by the ~~multi-model averaged precipitation change~~

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is positiveMME and most RCMs over China, with all five individual model exhibiting positive changes over all five subregions. Moreover, the projected spatial pattern from the driving GCM, the MME and RCMs is nearly consistent, with Tthe most prominent increase in precipitation increases are shown in MM5, RSM, and RegCM over the north and northwest China and slightly increase precipitation over the rest regions. The only exception is the results from WRF, by which the declined mean precipitation is projected over China. In particular, wider range for the change in projected annual precipitation are shown over the Tibetan Plateau. This is related to the fact that significant difference in projected precipitation change between WRF and the other RCMs. Therefore, the projected change in annual precipitation over the Tibetan Plateau should be treated with caution. The annual precipitation changes little over central China, northern China and southwestern China. In Tibetan Plateau a decrease in order of -7.8% is projected. There are some broad similarities across RCMs because they have the same parent GCM, but among those, the signal for change is more mixed in WRF. Besides, opposite signals for projected changes in average precipitation between the MME and the driving GCM are detected over South China, Northeast China and Tibetan Plateau (Table 2). Particularly the differences in projection form two methods above are largest at the Tibetan Plateau, up to about 10%.

Figure 8

Table 2

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3.2.2 Change in seasonal cycle

The future changes of temperature and precipitation are characteristic of regionality and seasonality. The ensemble projection (as shown in Figure 9) indicates that the monthly temperature change over five subregions in China is in the ranges from 0.3 °C to 2.2 °C under the RCP4.5 scenario. All RCMs projections show that there is aA more remarkable warming trend to become warm in colder months from November to March than inis detected by all RCMs other months. The seasonal cycle of temperature change in MME is also similar to that of the driving GCM HadGEM-AO. Most RCMs project positive monthly precipitations changes for summer (from June to August) in northeast, north, and southover China, with the exception of the Tibetan Plateau. The spreads in monthly precipitation changes by five RCMs are characteristic of seasonality, with largest appearing in July and the smallest in March. Additionally, the seasonal cycle of temperature change in multi-model ensemble is similar to that of the driving GCM HadGEM-AO. However, the projected monthlyseasonal precipitation change byin multi-model ensembleMME has larger magnitude and variability than the driving GCM. This phenomenon concerns the significance of the model physics and processes for future climate projection. The configurations of each RCM were showed in Table 1. For each RCM, optimal schemes of the dynamical and physical processes were determined through the model sensitivity analysis (Suh et al., 2012). In general, convective parameterization is one of the most important and sensitive process in a RCM (Huang and Gao, 2017). Land surface parameterization, as well as those parameterizations over the ocean, are also very important because they control the quantity of water vapor flux entering into atmosphere from the earth's surface (Zhao and Li, 2015). Thus, the phenomenon above could be attributed to the difference in convective parameterization, land surface

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parameterizations, as well as those parameterizations over the ocean between GCMs and RCMs. On the other hand, the discrepancies between the RCMs and the driving GCM indicate that the RCM projections are sensitive to local and regional processes and the corresponding methods incorporated in the model (Diallo et al., 2012; Saini et al., 2015).

Figure 9

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3.2.3 Inter-RCM variability of ~~Multi~~multi-RCM projections

The uncertainties of regional climate projection ~~are~~ arise~~d~~ from ~~different sources, which include~~ the GCMs, emission scenarios, RCMs, and ~~natural climate~~ internal variability for natural climate. In this study, the regional future climate is projected by using five RCMs forced with the same GCM~~-~~ under an intermediate scenario (RCP4.5). ~~As a c~~Consequen~~ce~~tly, the contribution of inter-RCM variability and ~~natural climate~~ internal variability to total uncertainty in the projections are analyzed in this section.

The contributions of the model uncertainty and natural climate internal variability to the total prediction uncertainty ~~from model uncertainty and natural climate internal variability were~~ are estimated by the method proposed by Hawkins and Sutton (2009)~~(2009),~~. ~~and t~~The results for five subregions ~~were~~ are shown in Figure 10. ~~It shows that t~~The relative importance of ~~the~~ model uncertainty increases with prediction lead time over all subregions. For temperature, the model uncertainty is the primary source of uncertainty over the northeast, northwest China, and Tibetan Plateau ~~during~~ from 2030~~-~~ to 2049, reaching up to 70%. The model uncertainty minimally contributes ~~smaller~~ (~~about~~ approximately 40%) ~~of~~ to the total uncertainty over north and south China before the middle of the 21st century. For the uncertainty on projected precipitation, the internal variability is the dominant uncertainty source over most regions, except ~~for~~ for the Tibetan Plateau where~~which~~ the model uncertainties reached up to 60%. The uncertainties come from the driving GCM, and the emission scenarios are not discussed in this study~~,~~ although they have been recognized as important components for~~-~~ total uncertainty (Déqué et al., 2012)~~(Déqué et al., 2012)~~. Further research on uncertainty quantification on the basis of different ~~More robust estimates include larger ensemble of projections by RCMs forced by different~~ GCMs, RCMs and emission scenarios ~~are necessary for~~is needed in the future~~uncertainty quantification~~.

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Figure 10

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4 Summary and conclusions

In this research, ~~simulation of~~ five RCM models, which ~~run~~ are simulated within the CORDEX-EA initiative at 50km resolution with boundary forcing from a CMIP5 global model applying the RCP4.5 scenario, are employed to derive the future climate change signal for ~~the~~ China and five selected smaller investigation areas. ~~In this study~~Meanwhile, ~~we focus on the future regional climate projection over China and~~ the contribution ~~quantification~~ of the model uncertainty and natural climate internal variability to the total prediction uncertainty are quantified.

The control runs of CORDEX-EA RCMs revealed an overall reasonable representation of the mean climate properties when compared with the observational gridded dataset. ~~In general, a~~All RCMs generally ~~give~~provide warm biases, wh~~ile~~ereas the ~~multi-model ensemble~~MME ~~shows~~ demonstrates the overall best performance, with less than 1 °C annual average temperature biases over most area ~~of~~ in China. ~~The control RCM results have a significant spread, and show quite large biases in annual precipitation.~~ Similarly, the ~~multi-model ensemble~~MME ~~outperforms~~ outperformed the individual RCM in reproducing the observed spatial pattern of precipitation. ~~The RCMs also have the ability to capture realistic interannual variability and seasonal variability of the annual mean temperature and precipitation.~~ Moreover, five RCMs perform better than the driving GCM HadGEM2-AO in reproducing annual and seasonal precipitation over most subregions. ~~Based upon~~Therefore, it is concluded ~~the model performance evaluation, our results show~~ that the MME constructed based on ~~present~~the ~~-~~set of RCMs from CORDEX-EA can be used to provide useful information on climate projections over East Asia.

For ~~the future climate of~~ 2030~~-~~ to 2049, MME indicated consistent warming ~~trends around 1~~ranging from 0.9 °C to 1.6 °C ~~were indicated by multi-model ensemble over~~in the ~~whole~~ entire domain and more pronounced warming was detected ~~was projected~~ in northern and western China. ~~The spread between the single simulations is in the order of 1.3 °C.~~ Seasonal temperature changes drastically in cold months, which is similar to that of the driving GCM. Besides, ~~T~~the annual precipitation is likely to increase in most of ~~the simulation~~ subregions~~, especially in north and northwest China~~. The projected spatial pattern for annual precipitation is characterized by prominent increase over the north and northwest China and slightly increased precipitation over the rest regions. ~~decreases or changes little over northeastern China and south China. In Tibetan Plateau a decrease in order of -7.8% is projected. The seasonal temperature changes more drastically in colder months which are similar to that of the driving GCM. How~~More~~e~~over, ~~the seasonal~~ precipitation ~~show positive changes~~ in summer months are predicted to consistently increase over the entire domain, with the exception of the Tibetan Plateau. ~~with significant inter-RCM difference and has larger magnitude and variability than driving GCM. The above results manifest that the internal model variability play an important role in the regional climate change projection.~~It should be noted that the projected monthly precipitation change by MME has larger magnitude and variability than the driving GCM.

This study identified ~~T~~the contributions of model uncertainty and internal variability ~~are identified in this study~~. The ~~model~~ uncertainty ~~for~~ in projected ~~future~~ temperature mainly arises from the internal variability over north and south China. Whereas, the model uncertainty is clearly dominant over the rest three subregions, ~~projection is clearly dominant over the northeast, northwest China and Tibetan Plateau during 2030-2049, reaching up to 70%, and it can~~ explaining ~~about~~ approximately ~~40~~70% of the total uncertainty. ~~over north and south China.~~ For precipitation, the internal variability is dominant over most regions except for the Tibetan Plateau, in which ~~the~~ model uncertainties reach up to 60%. ~~In addition, the m~~Model uncertainty also increases with prediction lead time over all subregions. ~~The~~ RCM simulation results ~~of RCM~~are also influenced by the internal physics and boundary conditions from GCMs as discussed in other's studies (Mariotti et al., 2011; Syed et al., 2012)~~(Mariotti et al., 2011; Syed et al., 2012)~~. ~~More reliable future climate information could be provided by coupling GCMs and RCMs through the modifications to model structures and parameters.~~More reliable future climate

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information and uncertainty quantification could be provided by coupling large ensemble of GCMs and RCMs under different emission scenarios.

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Table Captions

Table 1. RCMs used in this study.

Table 2. The future changes in average temperature (T; °C) and precipitation (P; %) for the five subregions. The ensemble averages for each statistic are given in the second line. The projections by the forcing GCM are given in the last line.The future changes in average temperature (T; °C) and precipitation (P; %) for the five subregions (as shown in Figure 1). The ensemble averages for each statistic are given in the second line. The projections by the forcing GCM are given in the last line.

Table 1. RCMs used in this study[a] **(Park et al., 2016)~~(Park et al., 2016)~~**

	HadGEM3-RA	RegCM4	MM5	WRF	RSM
Resolution	0.44°	50km	50km	50km	50km
Dynamic process	Non-hydrostatic	Hydrostatic	Non-hydrostatic	Non-hydrostatic	Hydrostatic
Convective scheme	Revised mass flux scheme	MIT-Emanuel	Kain-Fritch II	Kain-Fritch II	Simplified Arakawa-Schubert
Land surface parameterization	MOSES2	CLM3	CLM3	NOAH	NOAH
Planetary boundary layer	MOSES2 non-local	Holtslag	YSU	YSU	YSU
Spectral nudging	No	Yes	Yes	Yes	Yes
Center of research	MOHC	ICTP	NCAR	NCAR	YSU
References	Davies et al.(2005)~~(2005)~~	Giorgi et al.(2012)~~(2012)~~	Cha and Lee(2009)~~(2009)~~	Skamarock et al.(2005)~~(2005)~~	Hong et al.(2013)~~(2013)~~

[a]MOSES= Met Office Surface Exchange Scheme, CLM= Community Land Model, NOAH=Noah Land Surface Model, YSU= Yonsei University scheme, MOHC= The Met Office Hadley Centre, ICTP= The International Centre for Theoretical Physics, NCAR= National Center for Atmospheric Research

Table 2. The future changes in average temperature (T; ℃) and precipitation (P; %) for the five subregions~~(as shown in Figure 1)~~. The ensemble averages for each statistic are given in the second line. The projections by the forcing GCM are given in the last line.

		WRF	MM5	HadGEM3-RA	RegCM	RSM	Ensemble	HadGEM2-AO
Northeast China	T(°C)	0.2	2.7	1.4	1.4	1.1	1.3	0.8
	P(%)	-21.7	8.2	13.0	4.4	7.1	1.5	-0.4
North China	T(°C)	0.3	1.7	1.1	1.0	1.0	1.0	0.8
	P(%)	-1.5	15.1	3.1	10.2	3.3	6.1	4.9
South China	T(°C)	0.5	1.5	1.0	0.8	0.8	0.9	0.7
	P(%)	-14.6	-1.6	4.8	4.9	1.3	-1.5	2.3
Northwest China	T(°C)	1.3	0.8	1.5	1.3	1.1	1.2	1.2
	P(%)	-27.0	19.4	2.2	4.7	8.9	3.6	7.2
Tibetan Plateau	T(°C)	0.9	1.4	1.2	1.3	1.6	1.3	1.4
	P(%)	-31.6	-17.8	2.4	6.4	7.4	-7.8	2.1

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Figure Captions

Figure 1. The simulation domain of CORDEX-EA and the topography of the regional climate models (m). The boxes illustrate the five selected subregions over China: Northeast China (NE), North China (NC), South China (SC), Northwest China (NW), and Tibetan Plateau (TP).~~The simulation domain of CORDEX-EA and the topography of the regional climate models (m). The boxes illustrate the five selected subregions over China: Northeast China (NE), North China (NC), South China (SC), Northwest China (NW), and Tibetan Plateau (TP).~~

Figure 2. ~~Spatial distributions of annual average temperature (ºC) of CRU (a), multi-model ensemble (b), and temperature biases (ºC) of the driving GCM HadGEM2-AO (c), multi-RCM ensemble (d) and five RCMs (e-i) during 1980-2005.~~Spatial distributions of annual average temperature (ºC) from CRU (a), the driving GCM HadGEM2-AO (b), multi-model ensemble (c), and temperature biases (ºC) of the driving GCM HadGEM2-AO (d), multi-RCM ensemble (e, f) and five RCMs (g-k) during 1980-2005.

Figure 3. ~~Spatial distributions of annual average precipitation (mm/year) of CRU (a), APHRO (b), multi-model ensemble (c), and precipitation biases (%) of the driving GCM HadGEM2-AO (d), multi-RCM ensemble (e) and five RCMs (f-j) during 1980-2005.~~ Spatial distributions of annual average precipitation (mm/year) from APHRO (a), the driving GCM HadGEM2-AO (b), MME (c), and precipitation biases (%) of the driving GCM HadGEM2-AO (d), MME (e) and five RCMs (f-j) during 1980-2005.

Figure 4. ~~Taylor diagram to compare the skill of the models in representing the summer precipitation over the five regions of China, using the CRU (for temperature) and APHRO (for precipitation) data as the OBS. The azimuthal axis shows the pattern spatial correlation. The redial distance from the origin represents the spatial variability, while the distance from the OBS point is the centered RMSE difference between the simulated and observed.~~ The Taylor diagram to evaluate the skill of the models in reproducing the annual average temperature and precipitation over the five regions of China, using the CRU (for temperature) and APHRO (for precipitation) data as the reference. The azimuthal axis shows the pattern spatial correlation. The redial distance from the origin represents the spatial variability, whereas the distance from the OBS point is the centred RMSE difference between the simulated and observed.

Figure 5. Temporal evolution of the annual mean temperature (left two panels) and precipitation (right two panels) in RCM simulations and observation over the five subregions during the 1989-2007 (EVAL) and 1980-2005 (HIST) periods. The correlation coefficient between RCMs ensemble and the observation are shown at the top right of each panel.~~The temporal evolution of the annual mean temperature (left two panels) and precipitation (right two panels) in RCM simulations and observation over five subregions during the 1989-2007 (Eval) and 1980-2005 (Hist) periods. The correlation coefficient between RCMs ensemble and the observation are shown at the top right of each panel.~~

Figure 6. Observed and simulated monthly mean temperature and precipitation over the five subregions during the 1989-2007 (EVAL) and 1980-2005 (HIST) periods.Observed and simulated multiyear average of monthly temperature and precipitation over the five subregions during the 1989-2007 (Eval) and 1980-2005 (Hist) periods.

Figure 7. Projected future changes (RCP4.5-Baseline) in surface air temperature for each of the five RCM. Projected future changes (RCP4.5-Baseline) in surface air temperature by the forcing GCM HadGEM2-AO, the MME and each of the five RCMs.

Figure 8. Projected future changes ((RCP4.5-Baseline)/Baseline×100%) in precipitation by the forcing GCM HadGEM2-AO, the MME and each of the five RCMs.Projected future changes ((RCP4.5-Baseline)/Baseline×100%) in precipitation for each of the five RCM.

Figure 9. Projected future changes in monthly mean temperature and precipitation by the forcing GCM HadGEM2-AO, the MME and each of the five RCMs under RCP4.5 scenario. Projected future changes in monthly mean temperature and precipitation for each of the five RCM under RCP4.5 scenario.

Figure 10. Fraction of total variance in future temperature (left panel) and precipitation (right panel) projections explained by intermodel variability (gray) and internal variability (white) over the five subregions.The fraction of total variance in future temperature (left panel) and precipitation (right panel) projections explained by intermodel variability (gray) and internal variability (white) over the five subregions.

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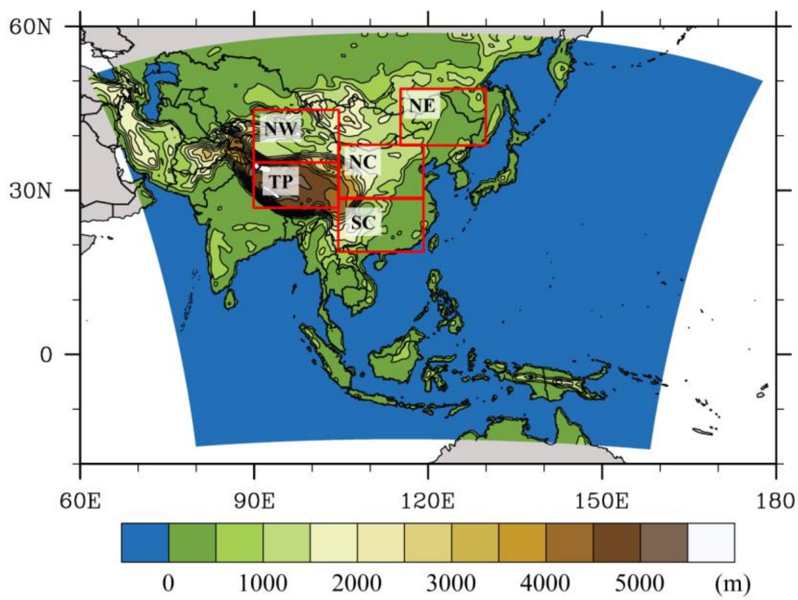

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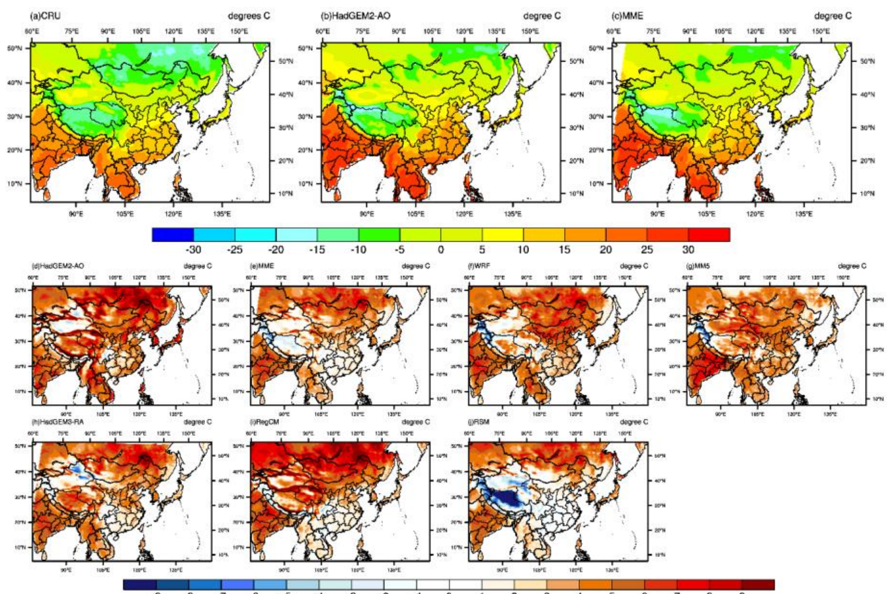

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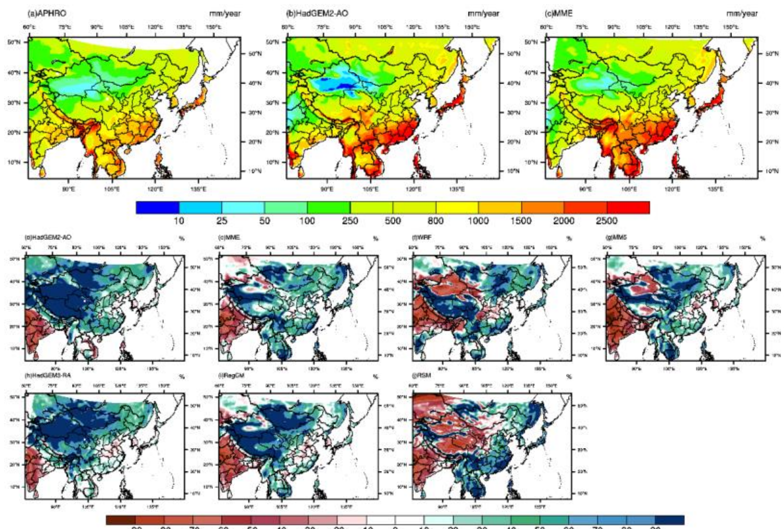
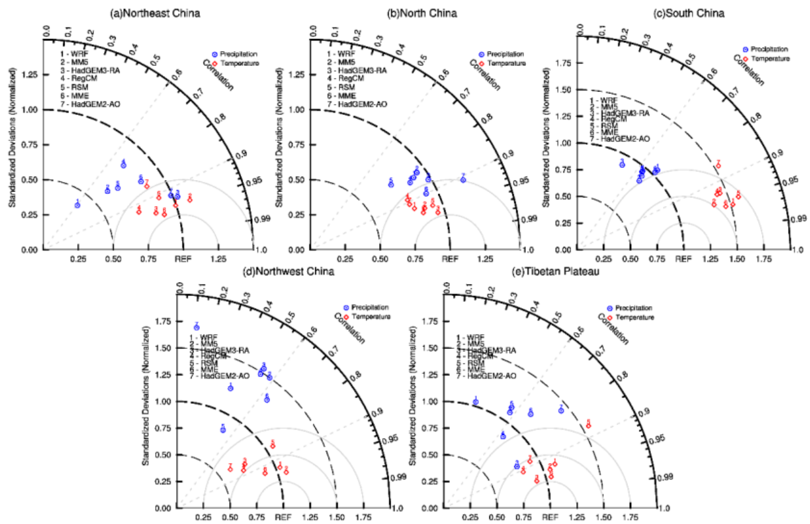


Figure 3. Spatial distributions of annual average precipitation (mm/year) ~~of~~ from ~~CRU (a),~~ APHRO (~~b~~a), the driving GCM HadGEM2-AO (b), ~~multi-model ensemble~~MME (c), and precipitation biases (%) of the driving GCM HadGEM2-AO (d), ~~multi-RCM ensemble~~MME (e) and five RCMs (f-j) during 1980-2005.



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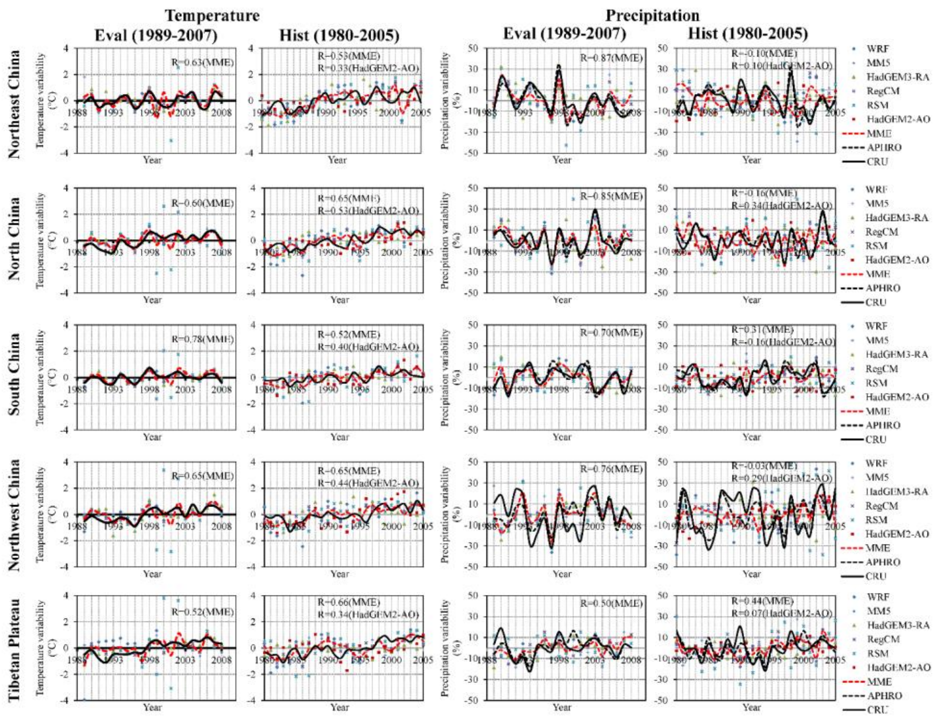

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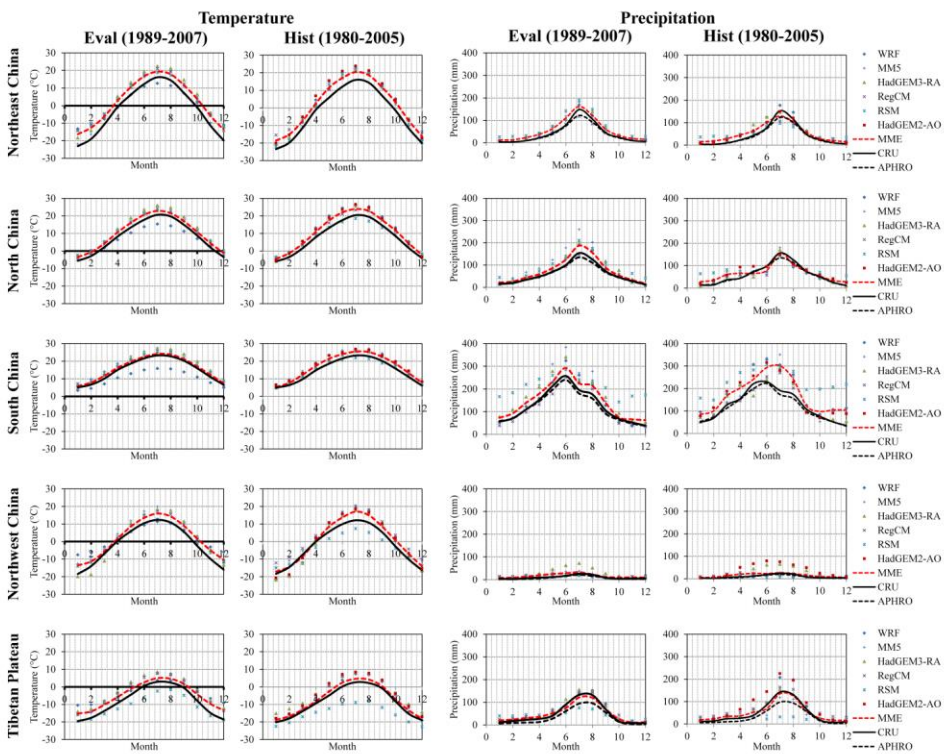
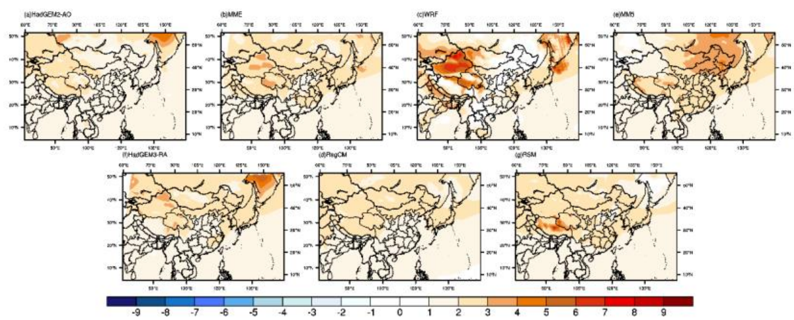


Figure 6. Observed and simulated ~~multiyear average of~~ monthly mean temperature and precipitation over the five subregions during the 1989-2007 (~~Eval~~EVAL) and 1980-2005 (~~Hist~~HIST) periods.



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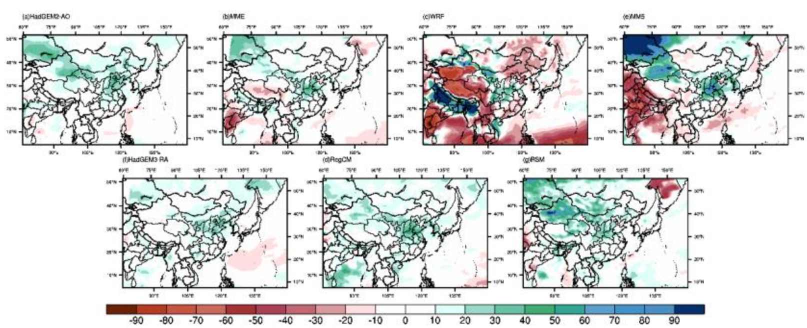

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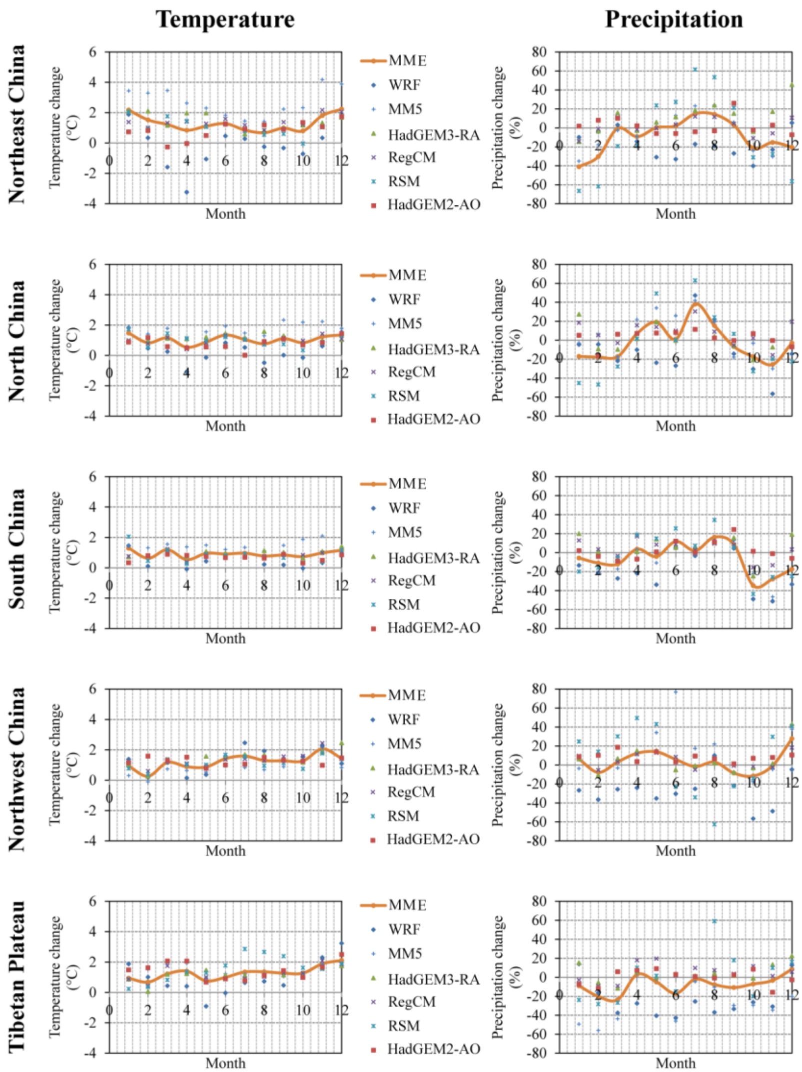

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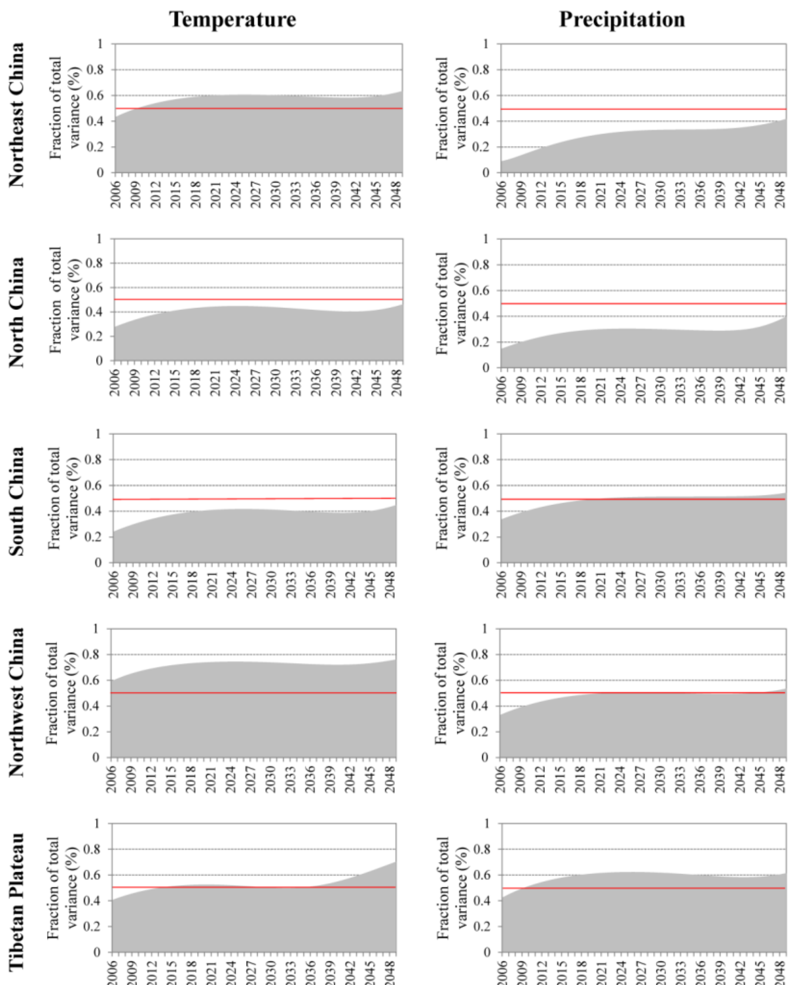

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