ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 26, NO. 4, 2009, 773–782

How the "Best" Models Project the Future Precipitation Change in China

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(Received 19 December 2008; revised 10 March 2009)

ABSTRACT

Projected changes in summer precipitation characteristics in China during the 21st century are assessed using the monthly precipitation outputs of the ensemble of three "best" models under the Special Report on Emissions Scenarios (SRES) A1B, A2, and B1 scenarios. The excellent reproducibility of the models both in spatial and temporal patterns for the precipitation in China makes the projected summer precipitation change more believable for the future 100 years. All the three scenarios experiments indicate a consistent enhancement of summer precipitation in China in the 21st century. However, the projected summer precipitation in China demonstrates large variability between sub-regions. The projected increase in precipitation in South China is significant and persistent, as well as in North China. Meanwhile, in the early period of the 21st century, the region of Northeast China is projected to be much drier than the present. But, this situation changes and the precipitation intensifies later, with a precipitation anomaly increase of 12.4%–20.4% at the end of the 21st century. The region of the Xinjiang Province probably undergoes a drying trend in the future 100 years, and is projected to decrease by 1.7%–3.6% at the end of the 21st century. There is no significant long-term change of the projected summer precipitation in the lower reaches of the Yangtze River valley. A high level of agreement of the ensemble of the regional precipitation change in some parts of China is found across scenarios but smaller changes are projected for the B1 scenario and slightly larger changes for the A2 scenario.

Key words: projection, summer precipitation, "best" models, ensemble

Citation: Chen, H. P., and J. Q. Sun, 2009: How the "best" models project the future precipitation change in China. *Adv. Atmos. Sci.*, **26**(4), 773–782, doi: 10.1007/s00376-009-8211-7.

1. Introduction

The climate in China is characterized by a large variability in space and time because of the complex topography, with the Tibetan Plateau to the west and various mountain chains in the northern and central regions. Agriculture and human lives are substantially sensitive to climate change, especially precipitation in the summer.

Significant climatic changes have been observed over China in the late decades of the 20th century. Several studies have indicated that the Asian summer monsoon has become weaker since the late 1970s (Wang, 2001; Wang, 2002; Guo et al., 2003). In connection with this change, summer precipitation increased over the lower and middle reaches of the Yangtze River valley, while it decreased over the lower reaches of the Yellow River and the Huaihe River (Gong and Ho, 2002; Hu et al., 2003; Yu and Zhou, 2007; Ding et al., 2008). Meanwhile, increasing precipitation has been found over Northwest China in the late 1980s, causing frequent floods (Shi et al., 2003). The region of North China, however, has experienced severe droughts since the late 1970s (Lu, 2003; Wei et al., 2003). These changes have resulted in numerous losses of life and have badly influenced the economic

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development of the country.

How long these changes may persist with the continuing global climate change has aroused broad interest not only in the climate research community (Wang et al., 1992; Xu et al., 2003; Kripalani et al., 2007), but also among the public and decision makers (Ding et al., 2006). Although much effort has been directed toward investigating the evolution of precipitation in future years, no consensus has been reached yet in the previous studies. For example, some studies indicate that the precipitation in China will significantly intensify in the next several decades (Bueh, 2003; Min et al., 2006), while other studies present no obvious changes (Jiang et al., 2004a; Jiang et al., 2004b), or a significant decrease (Gao et al., 2008; Li, 2008). This discrepancy indicates that this issue is far from being understood and deserves to be studied further.

Projections of climatic changes for the 21st century due to anthropogenic forcing are of critical importance for the assessment of climate change impacts on humans and natural systems. Because the long-term instrumental records are not available, it is difficult to project future climate trends based only on observations (Li, 2008). The coupled Atmosphere-Ocean General Circulation Models' (AOGCMs) simulations under the Intergovernmental Panel on Climate Change (IPCC) scenarios are an exclusive tool for projecting the future climate. Many studies are devoted to the temperature projections in China through the simulations provided by the IPCC and an agreement has been reached that the magnitude of temperature at the end of the 21st century will increase by 1.9°C to 5.5°C (e.g., Zhao et al., 2007). Concurrently, some researches focus on the precipitation projections using the latest generation of coupled climate system models (Cook and Vizy, 2006; Sun et al., 2007). However, such projections based on the coupled AOGCMs are characterized by large uncertainty, especially for precipitation. This uncertainty stems from a hierarchy of sources (IPCC, 2001): internal climate variability, the response of a climate model to a given forcing, emissions scenarios, and observations. Fortunately, there are some works that focus on the reduction of these uncertainties. The multi model ensemble (MME) approach has been widely applied as one effort to reduce the uncertainty from the internal variability and inter-model difference (Gillett et al., 2002). Another fundamental criterion for increasing the confidence in simulated regional climatic changes is the agreement of simulations across models, especially when this agreement is maintained under different forcing scenarios (Giorgi et al., 2001). In this paper, the "best" models that can well reproduce the current state of regional precipitation in China are extracted from the IPCC models. We will focus on the multi model averaged changes based on the MME method and analyze three IPCC emission scenarios, A1B, A2 and B1, to project the summer (June–July–August) precipitation variability in China for the future 100 years; of these, B1 is close to the lower end of the IPCC scenario range, A2 is close to the upper end, and A1B lies towards the middle of the range.

2. Data and methodology

The monthly precipitation data of 160 meteorological stations in China for the period from 1951 to 2004 are employed in this paper. The data were collected and edited by the China Meteorological Administration (CMA), and have been subject to quality control procedures of the Climate Data Center of the National Meteorological Center of CMA. The data were relatively homogeneously distributed, especially in eastern China. The gridded global monthly precipitation for the simulations is obtained from the Program for Climate Model Diagnosis and Intercomparison (PCMDI). All the experiments include monthly data for 1951–2000 and 2001–2100 for the three scenarios. Because the models utilize different horizontal grids, for intercomparison purposes, we interpolate the model data onto a common global 2.5 degree grid.

The aim of these simulations of the IPCC models is to assess the ability of AOGCMs to make projections of future climate change. Hence, the mean climate states in spatial and temporal patterns of a model need to be compared against observations. The 20th Century Climate in Coupled Models (experiment acronym "20c3m") runs is available in the IPCC Fourth Assessment Report (AR4) archives and the data are employed to define the mean climate states of the models. Hence, in this study we propose to first analyze the coupled model outputs under the "20c3m" runs and compare them with observational data for period 1980–1999 to find out the "best" models that can well reproduce the current states of regional precipitation that are in space and time in China. Then, a new method named Taylor Diagram is employed. This diagram can provide a concise statistical summary of how well patterns match each other in terms of their spatial correlation, their root-mean-square (RMS) difference, and the ratio of their variances (Taylor, 2001). Figure 1 presents the spatial results of 19 coupled model outputs under the "20c3m" runs referring to the observational data. The climatic mean precipitation is estimated from 1980–1999. Each capital letter represents one model and the RMS difference and standard deviation of each model have been normalized by the standard deviation of the observation field, so the

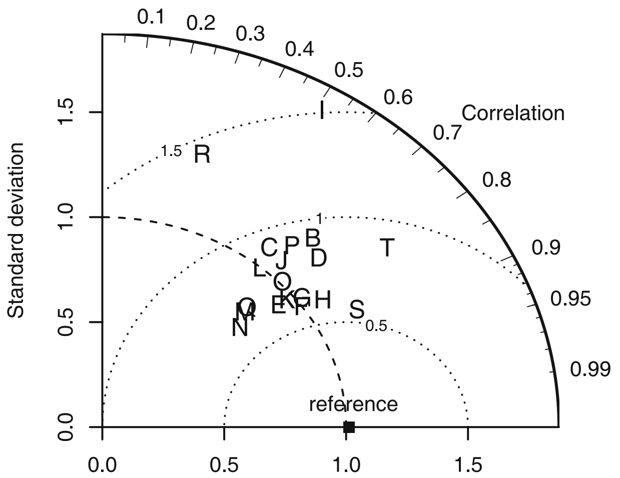

Fig. 1. Diagram for displaying the spatial pattern statistics of the IPCC models under the "20c3m" runs referring to the observational data. Each capital letter in the diagram represents one model and the observation point is labeled by a "reference". The RMS difference and standard deviation of each model have been normalized by the standard deviation of the observation filed. The radial distance from the origin is proportional to the standard deviation of a pattern. The centered RMS difference between the model and observation is proportional to their distance apart (in the same units as the standard deviation). The correlation between the model and the observational field is given by the azimuthal position of the model field referring to the origin point. B: BCCR-BCM2.0, C: CCCMA-CGCM3.1, D: CNRM-CM3, E: CSIRO-MK3.0, F: CSIRO-MK3.5, G: GFDL-CM2.0, H: GFDL-CM2.1, I: GISS-ER, J: IAP-FGOALSg1.0, K: INM-CM3.0, L: IPSL-CM4, M: MIROC3.2-medres, N: MIUB-ECHO-G, O: MPI-ECHAM5, P: MRI-CGCM2.3.2a, Q: NCAR-CCSM3, R: NCAR-PCM1, S: UKMO-HadCM3, T: UKMO-HadGEM1.

standard deviation of the observation is 1 unit. The radial distance from the origin to the model is proportional to the pattern standard deviation, and the azimuthal position gives the correlation coefficient between the model and the observational field. Some studies indicate that the acceptable performances of climate models in reproducing the current state of the regional climate are the basis for developing credible geographical distributions of future climate change through IPCC scenario simulations (e.g., Kimoto, 2005). Thus, the models with a spatial correlation coefficient larger than 0.7 are selected, which results in 12 models remained (D, E, F, G, H, K, M, N, O, Q, S, and T). However, note that the standard deviation of model T is much larger than the other remaining models when compared with the observational field, indicating larger variability of the pattern than the others. Moreover, the RMS error of model T over China is the largest among the 12 models, suggesting larger bias for the model T against the observations. Thus, model T is eliminated and not considered in this paper. So, there are 11 models that can well reproduce the mean climate state of regional precipitation in China from the spatial pattern. Further, the change trends of precipitation in 1980–1999 of the 19 coupled models under the "20c3m" runs are compared against the observations. This temporal result is shown in Fig. 2. It is noted that large differences exist among the models and only five (F, M, N, P, and S) have the capability to reproduce the linear trends of precipitation in China, which exceed the confidence level of 95%. However, models P and N should not be considered because of their larger variability than the others when compared with the observed trend. Finally, only three models (F, M, and S) that have excellent reproducibility of the regional precipitation in China both in the spatial and temporal patterns are used in this paper. The corresponding coupled models are CSIRO_MK3.5 (Australia), MIROC3.2_medres (Japan), and UKMO_HadCM3 (UK), respectively. In the following, we use the capital letters (F, M, and S) to substitute the corresponding models when referred.

The MME method will be used for estimating the ensemble results of the three "best" models and it is necessary to point out that, for the present analysis we only take a simple multiple model mean and have not considered the weights among the models. Another point is that because of the coarse resolution of the models, it is difficult to depict the steep gradient of the Tibetan Plateau and easy to produce artificial precipitation. Thus, the summer precipitation over the Tibetan Plateau will not be considered in the following analysis.

3. Results

3.1 *Projected spatial patterns*

In order to assess the ability of the models to make projection of precipitation in spatial pattern, the comparisons of the three "best" models and the corresponding ensemble results of the mean climate state under the "20c3m" runs for the period 1980–1999 first need to be analyzed against the observational precipitation field, and the results are presented by Fig. 3. The basic precipitation pattern that precipitation decreases from south to north in China is well reproduced by the three models and their spatial correlation coefficients associated with the observations are 0.82, 0.73, and 0.88, respectively. Furthermore, several centers of precipitation are also well captured, such as the centers of the Sichuan basin, South China, and the lower reaches of Yangtze River valley, especially by model S

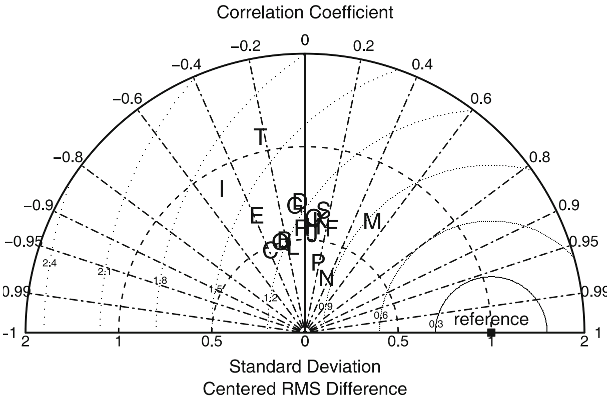

Fig. 2. Same as Fig. 1, but for the temporal pattern of the precipitation's change trends.

(Fig. 3d). Also, model F (Fig. 3b) has an excellent reproducibility of the precipitation in China and the spatial pattern is detailedly depicted. Because of the coarse resolution of model M (Fig. 3c), the precipitation distribution is roughly described relative to the other two models. Furthermore, the intensity of summer precipitation is underestimated by this model, especially in the eastern part of China. This is closely associated with the weaker intensity of the simulated circulation than the observations, which may restrain the development of deep convection and be unfavorable for the occurrence of precipitation. Another reason may be that the simulated low moisture content and the related weak moisture transport result in the underestimate of precipitation in the models (Zhang et al., 2008). From Fig. 3e, it is found that the ensemble results of the three models also underestimates the precipitation in the eastern part of China and this is mainly attributed to the underestimation of model M. However, the ensemble results can well capture the basic features of the precipitation distribution in China and its spatial correlation coefficient is as high as 0.86. In the following analysis, only the ensemble results are given.

Using the MME method for the three selected models, we analyzed the differences, or changes, in the mean precipitation fields between three 20-year periods of the 21st century (2010–2029, 2040–2059, and 2080–2099) in the IPCC scenario A1B and the reference period 1980–1999. The results are explicitly depicted by Fig. 4. A prevailing increase of the projected summer precipitation for the period from 2010–2029 (Fig. 4a) is found along the Yellow River, especially in the Huaihe River valley. This increased precipitation in the future may be mainly attributable to the changes in the horizontal transport of the water vapor flux and its convergence associated with the intensification and northward shift of a subtropical high

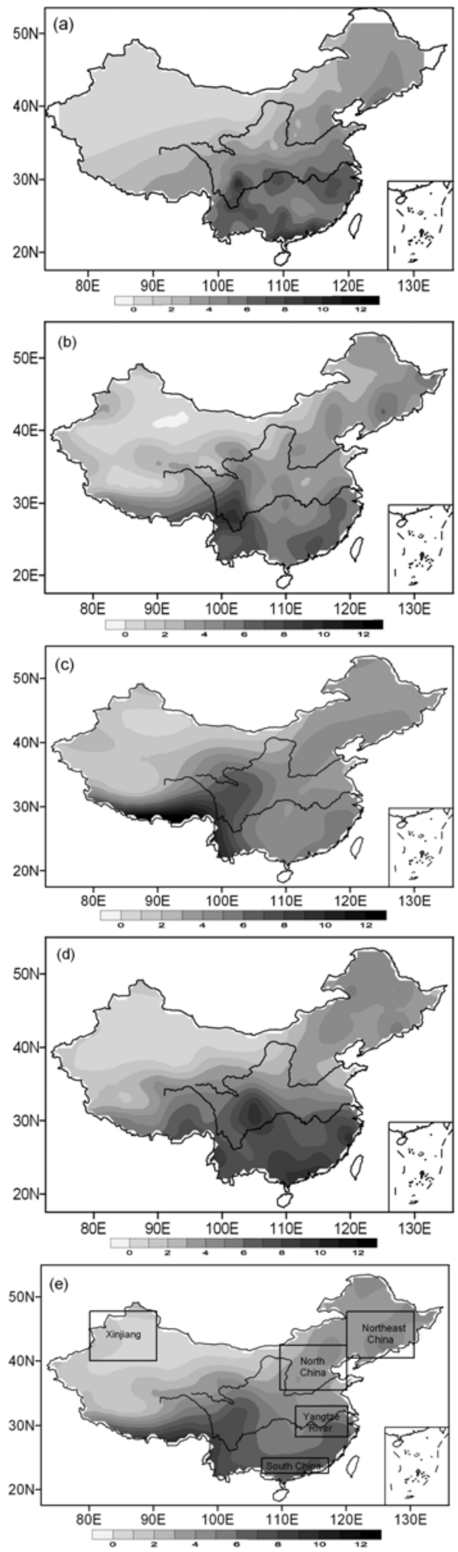

Fig. 3. Spatial distribution of the mean climate state of summer precipitation for the period 1980–1999: (a) observation, (b) CSIRO_MK3.5, (c) MIROC3.2_medres, (d) UKMO_HadCM3, and (e) the ensemble result of the three "best" models under the "20c3m" runs. Units: mm d^{-1}.

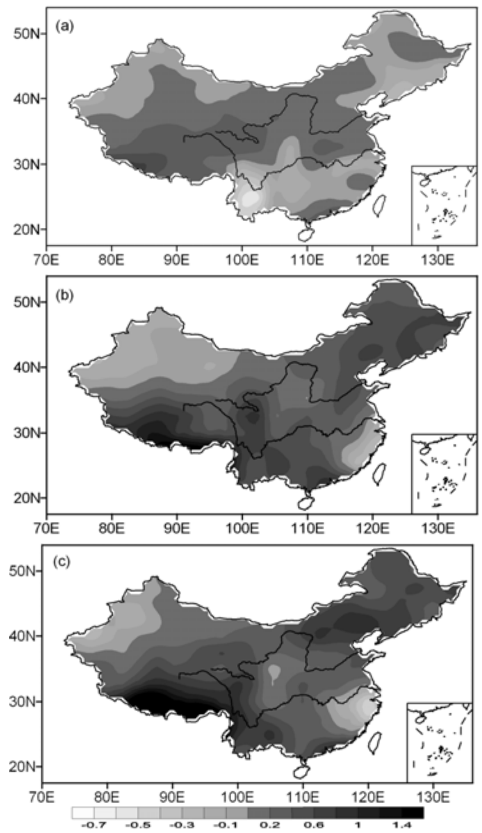

Fig. 4. Spatial distribution of the difference of the mean climate state of the summer precipitation in the IPCC scenario A1B for the time period: (a) 2010–2029, (b) 2040–2059, and (c) 2080–2099 with the reference period from 1980–1999. Units: mm d^{-1}.

(Kusunoki et al., 2006). The phenomena of the "North Drought" in China is weakened, because the summer precipitation in some regions of North China is projected to increase, but the drought, however, in Northeast China is projected to be exacerbated. Over a region extending from west to east in the southern portion of China, especially along the Yangtze River valley, summer precipitation experiences a decrease, and the largest decrease, in excess of 0.6 mm d^{-1}, is found in the Yunnan Province of China. In the next 20 years, the persistent moistening in Northwest China starting from the end of the 1980s is interrupted and the summer precipitation shifts to a decrease, especially in the west of the Xinjiang Province.

The precipitation change signal in 2040–2059 (Fig. 4b) shows some similarities but also substantial differences compared to the period 2010–2029. The decreasing trend of summer precipitation in Northwest China persists and the scope of the drought areas is enlarged by the mid-21st century. Meanwhile, the projected increase in precipitation dominates South China, whereas this region is not strong in the early period of the 21st century. The noticeable trend in this period is that the increasing precipitation is projected over the areas along the Yangtze River valley, except for the lower reaches, where the decrease magnitude is projected to be larger than the early period of the 21st century. This means that the areas over the lower reaches of the Yangtze River valley will become much drier. Additionally, it is greatly exciting to note that the regions of North China and Northeast China are projected to be much wetter than the present, and the increasing precipitation in most parts of the region are in excess of 0.6 mm d^{-1}. This change is critically important and greatly beneficial for the growth of plants there because of the mitigation of the "North Drought" in China.

When in the period 2080–2099 (Fig. 4c), the spatial distribution of the differences resembles that in the period 2040–2059, and only the magnitudes of the differences are intensified. By the end period of the 21st century, the projected decrease of precipitation still dominates the lower reaches of the Yangtze River valley and the areas of the drying trend are enlarged. Similarly, the drying trend persists and intensifies in Northwest China, especially in the west of the Xinjiang Province, but fortunately the drying areas are projected to shrink. The precipitation change over Asia between 1980–1999 and 2080–2099, averaged over 21 models, also shows similar results in this region (IPCC, 2007). Additionally, the IPCC AR4 results indicate that the precipitation by the end of the 21st century over the regions of North China and Northeast China are projected to increase by about 10% compared to that in 1980–1999 under the IPCC A1B scenario (IPCC, 2007). This result is greatly well reflected by the ensemble of the three models, and the amplitude of the increasing center exceeds 1.0 mm d^{-1} in this region.

The spatial patterns of the projected summer precipitation in China for the experiments under the IPCC scenarios A2 and B1 are also analyzed in this study (figures omitted). In the early period of the 21st century, the opposite features (increased precipitation) are predominating over the middle reach of the Yangtze River, concurrent with the projected decreasing precipitation along the Yellow River for both the A2 and B1 scenarios when compared against scenario A1B. Except for this, the patterns of change in precipitation for the future 100 years are similar to scenario A1B, but with smaller changes in B1 and larger changes in A2.

Based on the above analysis, it is clear that the changes of the projected summer precipitation in China are inhomogeneous across the whole country and the detailed variability of sub-regions should be further studied. Hence, five representative areas are selected and the evolutions of summer precipitation in the 21st century are investigated in subsection 3.2.

3.2 *Projected temporal patterns*

Because of the complex topography, the changes of projected summer precipitation in China are not homogeneous across the country, and the precipitation projections demonstrate large variability between sub-regions and should be further analyzed, respectively. Hence, five representative areas (Yangtze River: 27.5°–32.5°N, 112.5°–120°E; North China: 35°–42.5°N, 110°–120°E; Northeast China: 40°–47.5°N, 120°–130°E; South China: 22.5°–25°N, 107.5°–117.5°E; Xinjiang: 40°–47.5°N, 80°–90°E) in China are selected and have been labeled by rectangular boxes in Fig. 3e. The reason of the area selection is that the climate changes, especially the precipitation changes in the future, are critically important for these regions' society and economic developments because of the high-populations and the concentrated industries there. Moreover, the coastal areas, such as South China, are at the greatest risk of flooding. Because of this, thousands of people lost their houses, even their lives. Hence, the projections of precipitation in these regions are greatly necessary and hopefully will provide some highly confident suggestions for the local governments trying to mitigate the possible effects. In order to examine the changing trends of projected summer precipitation in the different regions, the linear fitting method is employed in the following analysis.

In order to assess the ability of the models to make projections of precipitation variability for each subregion in time, the intercomparison of their change trends between the experiments under the "20c3m" runs and the observations from 1980–1999 is proposed to be analyzed firstly. Then, the projected summer precipitation evolutions of each sub-region under the IPPC A1B scenario for the future 100 years are presented. Figure 5 shows the estimation of the model's ability to make projections of precipitation for the five sub-regions in China and the corresponding projected summer precipitation evolutions under the SRES A1B scenario are depicted by Fig. 6. There is a common feature over these sub-regions that the climatic mean values and the variability of precipitation are underestimated by the models under the "20c3m" runs, except for the region of Xinjiang. The projected change in time of summer precipitation for each sub-region is listed as follows.

The summer precipitation in North China (Fig. 5a) undergoes a slight increase since the late 1970s but this wet trend is not well reproduced by the three models. But, it should be pointed out that the wet trend from the observations is mainly attributed to the year 1996 and as a whole, this region has been experiencing a severe drought since the late 1970s. The moist year around 1996 is well simulated by model F, thus the slight wet trend is reproduced by this model, although much weaker than the observations. Model M is the worst among the three models in this region and it reflects opposite features against the observations. Concurrently, no evident change can be found from model S, despite the well reproducibility of the moist year around 1996. Thus, the slight increasing trend in the observations also cannot be well reproduced by the ensemble results in this region. However, the projected summer precipitation (Fig. 6) experiences a significant increase in the future 100 years, with a precipitation anomaly increase of 16.3% by the end of the 21st century (all the increments are relative to the reference period 1980–1999). Although the three models have weak ability to simulate the change trend under the "20c3m" runs in this region, the projected increasing result is similar to the IPCC (2007).

The region of Northeast China (Fig. 5b) is dominated by a slightly wet trend from the observations at the end of the 20th century. This feature is well captured by the three models and the ensemble results, though the precipitation is underestimated. This excellent reproducibility of precipitation in Northeast China makes the coupled models much more believable in projecting the future precipitation there. In this region, the projected significant wet trend is predominated and the ensemble results of the models projects a 13.7% increase in summer precipitation by the end of 21st century.

The area of South China (Fig. 5c) has the largest mean precipitation among these five regions and it experiences a significant increasing trend, especially after 1990. The mean precipitation from 1980–1999 in this region is underestimated but it is of great interest to note that the interannual variability of summer precipitation is well reproduced by models F and M, concurrent with the significant wet trend. Whereas, model S has overestimated the mean precipitation but the linear trend is well captured. Obviously, the ensemble of the three models has an excellent capability to reproduce the main features of precipitation in this region, and that makes it much more believable to project the future climate change. Under the SRES A1B scenario, the area-averaged summer precipitation is projected to increase by 8.3% by the end of the 21st century, with the linear trend of 0.73 mm d^{-1} $(100 \text{ yr})^{-1}$ in the 21st century.

In the late 1980s, an abrupt climate change from warm-dry to warm-wet is predominated in the Xin-

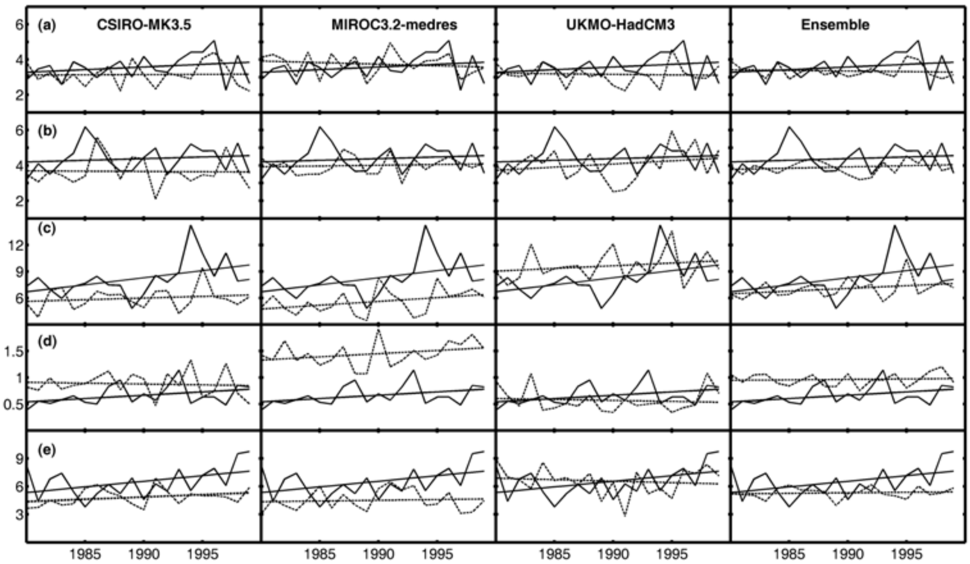

Fig. 5. The time series of precipitation of the three "best" models and the ensemble result under the "20c3m" runs are compared against the observation for the period of 1980–1999 for the five sub-regions in China. (a) North China, (b) Northeast China, (c) South China, (d) Xinjiang Province, and (e) the lower reaches of the Yangtze River. The observation is represented by the solid line and the dashed line denotes the result of the model or the ensemble. The corresponding linear trends of each model and observation are given to assess the ability of the model to make a projection of future precipitation in time.

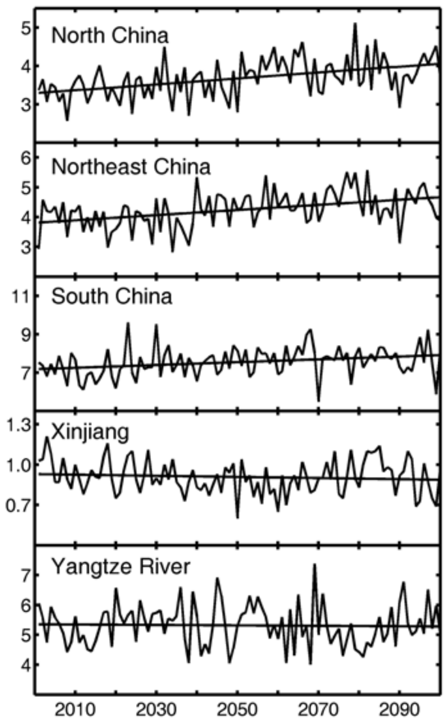

Fig. 6. The time series of the projected summer precipitation for the period of 2001–2100 under the SRES A1B scenario in the five sub-regions of China. Their corresponding linear trends are also shown. Units: mm d^{-1}.

jiang Province (Fig. 5d). This main feature in the last decades of the 20th century is well captured by model M, despite of the overestimation of the mean precipitation. However, it is not well described by F and S. Fortunately, the wet trend is reproduced by the ensemble results, although it is much weaker than the observations. From the projections, we can find that the region of the Xinjiang Province will undergo a slight drying trend in the future 100 years, with a precipitation anomaly decrease of 3.6% at the end of the 21st century. But large uncertainty exists in the projection of precipitation because of the difficulty of the coarse resolution of the AOGCMs to depict the complex topography in the Xinjiang Province and its future climate should be further studied.

A significant increase of summer precipitation in the lower reaches of the Yangtze River valley has been found from the observations filed, shown in Fig. 5e, but it is not well validated by model S, with a slight drying trend. However, although this wet trend is well characterized by models F and M, the ensemble results of the three models are not matched very well with the observations and it presents no obvious changes in the last decades of the 20th century. This weak reproducibility is mainly connected to the underestimation of precipitation by the models, which may be associated with the weaker simulation of the sub-tropical high and the limited capability to depict the deep convection, which is one of the most important systems that have a large contribution to the summer precipitation in the lower reaches of the Yangtze River valley. Hence, using the simulations of the regional climate models with a high horizontal resolution must be better for projecting future precipitation, and is needed to be further studied. Although the reproducibility of precipitation in this region is not well, the evolution of projected summer precipitation from the ensemble of the three "best" models is still discussed here. There is no long-term change trend projected in the lower reaches of the Yangtze River, with a precipitation anomaly decrease of 0.52% by the end of the 21st century. These results are consistent with the analysis in subsection 3.1.

Similar features are documented by the experiments of scenarios A2 and B1 (figures omitted). There are no significant changes of the projected summer precipitation varying from scenario to scenario, though these scenarios are derived from different estimates of future population, economic, and technological development. Both the A2 and B1 experiments indicate a consistent enhancement of summer precipitation in North China (13.9%–17.1%), Northeast China (12.4%–20.4%), and South China (∼14%) at the end of the 21st century. Although there are wet trends of precipitation in the lower reaches of the Yangtze River for both scenarios A2 and B1, they are still less significant. Similarly, the projected precipitation in the Xinjiang region becomes less with the reduction of 1.7%–3.1%, indicative of a much drier pattern by the end of the 21st century.

4. Conclusions

In this study, the three "best" models that can well reproduce the mean climate state in space and time of a region of precipitation in China are selected and all the analyses are based on the ensemble of them. The ensemble results of the models from the spatial patterns can well reproduce the basic precipitation patterns, that precipitation decreases from Southeast China to Northwest China and it also well captures the main precipitation centers in China. The spatial correlation coefficient with the observation field is as high as 0.86. Moreover, the selected models can well reproduce the change trends of precipitation in some regions of China. These excellent reproducibilities of summer precipitation make it much more believable to project the future precipitation in China.

The projected spatial patterns of precipitation under three IPCC emissions scenarios (scenarios A1B, A2, and B1) for three 20-year periods in the future are analyzed in this study. Synthesizing all scenarios, the results show that there is a large variability of the projected precipitation varying from region to region in China. All the three scenarios experiments indicate a consistent enhancement of summer precipitation in North China, Northeast China, and South China in the 21st century, although the region of Northeast China becomes much drier in the early period of the 21st century than the present. These results are exciting because of the mitigation of the "North Drought" in China and it is beneficial for the economic development there. However, over the lower reaches of the Yangtze River valley, the summer precipitation is projected to slightly decrease in the early period of the 21st century and the amplitude of the precipitation decrease, increases with the time stepping. Concurrently, most of the regions in Northwest China, especially in the Xinjiang Province, are projected to be a drought in the future 100 years (IPCC, 2007).

Although the latest generation of coupled model systems cannot well capture the interannual variability of precipitation, the linear trends for some regions in China can be well reproduced. The projected results in some parts of China are substantially similar among the three IPCC scenarios but smaller changes are projected for the B1 scenario and larger changes for the A2 scenario. The precipitation projection in the regions of Northeast China and South China are more believable and they are projected to increase in the future 100 years, with a precipitation anomaly increase of 12.4%–20.4% and 8.3%–14%, respectively. As noted before, the region of Northeast China is projected to be much drier in the early period of the 21st century than the present but it shifts to an increase in precipitation around the 2040s. The projected summer precipitation in the lower reaches of the Yangtze River valley has no evident change in the future. It is needed to be further studied because of the weak reproducibility of historical precipitation there. Although the wet trend in North China is not well captured by the models, the projected increasing result is similar with the IPCC work (2007). Similarly, the signal of abrupt change of precipitation in Xinjiang in the late 1980s cannot be captured by the ensemble of the three "best" models but the linear trend is reproduced. The models project a drying trend there and a 1.7%–3.6% decrease in the summer mean precipitation by the end of the 21st century.

The MME method has been used in this study and the ensemble results of the three "best" models under the "20c3m" runs can well capture the observed precipitation variability in China. This excellent reproducibility of historical precipitation from the AOGCMs argues that the projected future precipitation is believable, implying that the present results may be robust. But large uncertainty still exists in the projection of precipitation, and further studies are needed. Furthermore, the coarse resolution of the AOGCMs is difficult to depict the complex topography in western China, especially the steep gradient of the Tibetan Plateau, where the precipitation should be further analyzed by the regional climate models with a higher horizontal resolution.

Acknowledgements. The authors greatly appreciate the three anonymous reviewers' insightful comments that lead to the significant improvements of the manuscript. This research was jointly supported by the National Basic Research Program of China (Grant No. 2009CB421406), the Chinese Academy of Sciences under Grant KZCX2-YW-Q1-02, National Key Technologies R & D Program Project (Grant No. 2007BAC03A01) and the National Natural Science Foundation of China (Grant No. 40631005).

REFERENCES

Bueh, C., 2003: Simulation of the future change of East Asian monsoon climate using the IPCC A2 and B2 scenarios. *Chinese Science Bulletin*, **48**(10), 1024–1030. (in Chinese)

Cook, K. H., and E. K. Vizy, 2006: Coupled model simulations of the West African monsoon system: 20th century simulations and 21st century predictions. *J. Climate*, **19**, 3681–3703.

Ding, Y. H., and Coauthors, 2006: National assessment report on climate change, part I: historical climate change and future trends in China. *Advances in Climate Change Research*, **2**(1), 3–8. (in Chinese)

Ding, Y. H., Z. Y. Wang, and Y. Sun, 2008: Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences. *International Journal of Climatology*, **28**(9), 1139–1161.

Gao, X. J., Y. Shi, R. Song, F. Giorgi, Y. Wang, and D. Zhang, 2008: Reduction of future monsoon precipitation over China: Comparison between a high resolution RCM simulation and the driving GCM. *Meteor. Atmos. Phys.*, **100**, 73–86, doi: 10.1007/s00703-008-0296-5.

Gillett, N. P., F. W. Zwiers, A. J. Weaver, G. C. Hegerl, M. R. Allen, and P. A. Stott, 2002: Detecting anthropogenic influence with a multi-model ensemble. *Geophys. Res. Lett.*, **29**(20), 1970, doi: 10.1029/2002GL015836.

Giorgi, F., and Coauthors, 2001: Emerging patterns of simulated regional climatic changes for the 21st century due to anthropogenic forcings. *Geophys. Res. Lett.*, **28**(17), 3317–3320.

Gong, D. Y., and C. H. Ho, 2002: Shift in the summer rainfall over the Yangtze River valley in the late 1970s. *Geophys. Res. Lett.*, **29**, doi: 10.1029/2001GL014523.

Guo, Q. Y., J. N. Cai, X. M. Shao, and W. Y. Sha, 2003: Interdecadal variability of East-Asian summer monsoon and its impact on the climate of China. *Acta Geographica Sinica*, **58**(4), 569–576. (in Chinese)

Hu, Z.-Z., S. Yang, and R. Wu, 2003: Long-term climate variations in China and global warming signals. *J. Geophys. Res.*, **108**(D19), 4614, doi: 10.1029/2003JD003651.

IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, UK, 944pp.

IPCC, 2007: *Regional Climate Projections. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 884pp.

Jiang, D. B., H. J. Wang, and X. M. Lang, 2004a: East Asian climate change trend under global warming background. *Chinese Journal of Geophysics*, **47**(4), 590–596. (in Chinese)

Jiang, D. B., H. J. Wang, and X. M. Lang, 2004b: Multimodel ensemble prediction for climate change trend of China under SRES A2 scenario. *Chinese Journal of Geophysics*, **47**(5), 776–784. (in Chinese)

Kimoto, M., 2005: Simulated change of the East Asian circulation under global warming scenario. *Geophys. Res. Lett.*, **32**, L16701, doi: 10.1029/2005GL023383.

Kripalani, R. H., J. H. Oh, and H. S. Chaudhari, 2007: Response of the East Asian summer monsoon to doubled atmospheric CO_2: Coupled climate model simulations and projections under IPCC AR4. *Theor. Appl. Climatol.*, **87**, 1–28, doi: 10.1007/s00704-006-0238-4.

Kusunoki, S., J. Yoshimura, H. Yoshimura, and A. Noda, 2006: Change of baiu rain band in global warming projection by an atmospheric general circulation model with a 20-km grid size. *J. Meteor. Soc. Japan*, **84**(4), 581–611.

Li, S., 2008: Projecting the summer climate of mainland China in the middle 21st century: will the droughts in North China persist? *Atmos. Oceanic Sci. Lett.*, **1**, 12–17.

Lu, R. Y., 2003: Linear relationship of interannual and interdecadal rainfall in North China. *Chinese Science Bulletin*, **48**(7), 718–722. (in Chinese)

Min, S. K., S. Legutke, A. Hense, U. Cubasch, W. T. Kwon, J. H. Oh, and U. Schlese, 2006: East Asian climate change in the 21st century as simulated by the coupled climate model ECHO-G under IPCC SRES scenarios. *J. Meteor. Soc. Japan*, **84**(1), 1–26.

Shi, Y. F., Y. P. Shen, D. L. Li, G. W. Zhang, Y. J. Ding, R. J. Hu, and E. Kang, 2003: Discussion on the present climate change from warm-dry to warm-wet in Northwest China. *Quaternary Sciences*, **23**, 152–164. (in Chinese)

Sun, Y., S. Solomon, A. G. Dai, and R. W. Portmann, 2007: How often will it rain? *J. Climate*, **20**, 4801–4818.

Taylor, K. E., 2001: Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res.*, **106**(D7), 7183–7192.

Wang, H. J., 2001: The weakening of Asian monsoon circulation after the end of 1970s. *Adv. Atmos. Sci.*, **18**(3), 376–386.

Wang, H. J., 2002: The instability of the East Asian summer monsoon-ENSO relations. *Adv. Atmos. Sci.*, **19**(1), 1–11.

Wang, H. J., Q. C. Zeng, and X. H. Zhang, 1992: Simulated climate change due to double CO_2. *Science in China (B)*, **6**, 663–672. (in Chinese)

Wei, J., Q. Y. Zhang, and S. Y. Tao, 2003: Characteristics of atmospheric circulation anomalies during persistent droughts in North China for last two decades. *Journal of Applied Meteorological Science*, **14**(2), 140–151. (in Chinese)

Xu, Y., Y. H. Ding, and Z. C. Zhao, 2003: Scenario of temperature and precipitation changes in Northwest China due to human activity in the 21st century. *Journal of Glaciology and Geocryology*, **25**(3), 327–330. (in Chinese)

Yu, R. C., and T. J. Zhou, 2007: Seasonality and three-dimensional structure of the interdecadal change in East Asian monsoon. *J. Climate*, **20**, 5344–5355.

Zhang, L., Y. H. Ding, and Y. Sun, 2008: Evaluation of precipitation simulation in East Asian monsoon areas by coupled Ocean-Atmosphere General Circulation Models. *Chinese J. Atmos. Sci.*, **32**(2), 261–276. (in Chinese)

Zhao, Z. C., S. W. Wang, and Y. Luo, 2007: Assessments and projections of temperature rising since the establishment of IPCC. *Advances in Climate Change Research*, **3**(3), 183–184. (in Chinese)