Projected changes in climate extremes over China in the 21st century from a high resolution regional climate model (RegCM3)

XU JiYun¹, SHI Ying², GAO XueJie^{2*} & GIORGI Filippo³

¹ Zhejiang Climate Center, Hangzhou 310017, China;

² National Climate Center, China Meteorological Administration, Beijing 100081, China;

³ The Abdus Salam International Centre for Theoretical Physics, Trieste 34100, Italy

Received August 31, 2012; accepted October 9, 2012; published online December 6, 2012

Based on a consecutive simulation of the 21st century conducted by RegCM3, changes in climate extremes over China are investigated, following a basic validation of the model performances in simulating present climate. The model is one-way nested within the global model of CCSR/NIES/FRCGC MIROC3.2_hires. A total of 150-years (1951–2100) transient simulation is carried out at 25 km grid spacing under the IPCC SRES A1B scenario. The indices of the extremes include SU (summer days), FD (frost days), GSL (growing season length) for temperature, SDII (simple daily intensity index), R10 (no. of days with precipitation ≥ 10 mm/d), and CDD (consecutive dry days) for precipitation. Results show that the model can reproduce both the spatial distribution and the values of the present day annual mean temperature and precipitation well, and it also shows good performances in simulating the extreme indices. Following the significant warming, the indices of SU and GSL for warm events will increase while the indices of FD for cold events will decrease over China. Heavy precipitation events as measured by SDII and R10 show a general increase over the region, except the decrease of R10 in the Northeast and central Tibetan Plateau and less change or decrease of it along the middle and lower reaches of the Yangtze River. Decrease of dryness as measured by CDD over northern part of China while increase of it over the Tibetan Plateau, Sichuan Basin and other places in southern China are simulated by the model. This leads to the less change of the regional mean CDD in the time series in the 21st century unlike the other indices, which show a clear trend of change following the time evolution.

climate change, regional climate model, climate extremes, China

Citation: Xu J Y, Shi Y, Gao X J, et al. Projected changes in climate extremes over China in the 21st century from a high resolution regional climate model (RegCM3). *Chin Sci Bull*, 2013, 58: 1443–1452, doi: 10.1007/s11434-012-5548-6

Increases in both frequency and intensity of extreme weather and climate events have been reported both globally and over different regions under the background of the global warming. Due to their critical impact on human society, economic development and natural ecological systems as well as the environment, increasing attention has been paid to the future changes in climate extremes in the studies [1–6].

Similar to other regions in the globe, changes characterized by the increase in warm days and heavy rainfall events and a decrease in light precipitation events have been observed over China in the late decades [7–9]. Increasing

research efforts have also been devoted in the projection of extreme events, either by global or regional climate models (GCMs or RCMs) [10–20]. Due to their coarse resolution, the capability of the GCMs is in general poor over China, while high resolution RCMs show more advantages in simulating present climate and projecting future climate changes, especially on climate extremes [21,22]. However for the existed simulation and projection conducted by RCMs, the resolution used and the duration of the simulations is still relatively low and not long enough to cover the whole 21st century. Thus further research is needed to better address the topic. Based on a 150-years continuous climate change simulation (1951–2100) by a RCM 25-km grid spacing [23,24], we evaluate the capability of the model in

*Corresponding author (email: gaoxj@cma.gov.cn)

simulating present day climate extremes, both for temperature and precipitation, then report their future changes of extremes with the focus on the middle of the 21st century in the present study. Simulation and changes in annual mean temperature and precipitation are also provided as a background of the analysis.

1 Model, experimental design and introduction of climate extreme indices

The RCM simulation employed in the present study is conducted by the regional climate model of the Abdus Salam International Centre for Theoretical Physics (ICTP) RegCM version 3 (RegCM3) [25] which is developed from RegCM2 by Giorgi et al. [26,27]. The model is one-way nested within the global model of CCSR/NIES/FRCGCMIROC3.2_hires [28], with the emission scenario of SRES A1B [29]. Domain of RegCM3 covers China continent and the surrounding areas. Horizontal resolution of RegCM3 is 25 km and the vertical layer is 18 with model top at 10 hPa. The model physics includes the atmospheric radiation transfer computed using the radiation package from the NCAR community climate model CCM3 [30], planetary boundary layer computations employing the non-local formulation of Holtslag [31], resolvable scale precipitation of SUBEX [32], convective precipitation represented using the mass flux scheme of Grell based on Fritsch-Chappell [33,34], surface processes carried out with the biosphere-atmosphere transfer scheme (BATS1e) [35], and the ocean flux parameterization follows Zeng et al. [36]. More detailed information about the model and simulation can be found in Gao et al. [23,24].

The period of 1980–1999 is considered as present day and 2040–2059 as the middle of the 21st century. By comparing the simulation against observation, validation of the model performance in simulating the current climate is presented with the focus on climate extreme indices. Then the spatial distributions of climate extreme changes in the mid-21st century in relative to 1980–1999, as well as the regional mean changes for each index in the 21st century are presented.

To validate model performance, we used the observation dataset at $0.25^\circ \times 0.25^\circ$ (latitude by longitude) resolution

based on the observation from over 2400 meteorological stations over China [37]. To facilitate the analysis, the model outputs are interpolated bi-linearly to this $0.25^\circ \times 0.25^\circ$ grid cell.

Six indices with 3 (SU, FD and GSL) for temperature and the other 3 (SDII, R10 and CDD) for precipitation from Frich et al. [38] and ETCCDI (Expert Team on Climate Change Detection and Indices, <http://cccma.seos.uvic.ca/ETCCDMI/>; Peterson et al., 2001) are employed in the study as shown in Table 1.

2 Validation of the present day climate and extreme indices simulations

2.1 Surface air temperature and precipitation

To evaluate the model performance in a more strict way, distribution of the differences between simulation and observation are plotted and analyzed. The annual mean temperature and precipitation are selected in validating the simulation of the mean climatology, as shown in Figure 1.

In the observation, the temperature in eastern China is largely affected by latitude, characterized by a colder north and warmer south, with the maxima located in the southern coast. In western China a strong dependence on topography can be observed. Lowest temperature less than -10°C are found in northern part of the Tibetan Plateau, as well as portions of Northeast and the mountain peaks in the Northwest (Figure 1(a)). Differences between the model simulation and observation are usually within $\pm 1^\circ\text{C}$, except for a larger cold bias up to $2\text{--}5^\circ\text{C}$ over the Tibetan Plateau (Figure 1(b)). The bias over the Tibetan Plateau is partly introduced from the driving global model [24], in the mean time it also indicates the difficulties for climate models in simulating the climate over this region with complex topography. It is also noted this is a region with few or no meteorological stations available, which can lead to a large uncertainty in the gridded data derived from the station observations [37]. A warm bias of exceeding 2°C can be found in northern part of Northeast and Northwest China which is mostly related to the systematic warm bias of the model in high latitude during the cold seasons [39]. The spatial correlation coefficient of annual mean temperature between model simulation

Table 1 Indices of climate extremes

Indices	Definition
SU (d)	No. of summer days, days with maximum temperature $>25^\circ\text{C}$
FD (d)	No. of frost days, days with minimum temperature $<0^\circ\text{C}$
GSL (d)	Growing season length: period between when $T_{\text{day}} > 5^\circ\text{C}$ for >5 d and $T_{\text{day}} < 5^\circ\text{C}$ for >5 d
SDII (mm/d)	Simple daily intensity index: annual total/number of $R_{\text{day}} \geq 1$ mm d^{-1}
R10 (d)	Number of days with precipitation ≥ 10 mm d^{-1}
CDD (d)	Maximum number of consecutive dry days ($R_{\text{day}} < 1$ mm)

Figure 1 Annual mean temperature (°C) and precipitation (mm/d) over China. (a) Observed temperature; (b) temperature difference between simulation and observation; (c) observed precipitation; (d) precipitation difference between simulation and observation.

and observation is 0.98.

Figure 1(c) and (d) compares annual mean precipitation in the simulation with corresponding observations. As shown in Figure 1(c), observed precipitation maxima are located in southeastern China, and it decreases toward the north and northwest with the minimum found in the basins (also deserts) in the Northwest. The model captures this pattern well although with the discrepancies found mainly as the underestimation in the Southeast and the overestimation of precipitation in the Northeast. The overestimation of precipitation surrounding the Tibetan Plateau (e.g. Kunlun Mountain and the western part of Sichuan) as well as the mountain peaks in North (Taihang Mountains) and Northwest China (Tianshan and Kunlun Mountains) can be partly attributed to the reason that the model is too sensitive to the topography in the precipitation simulation, while in the meantime, the uncertainties in the observation dataset over the areas (usually underestimate the real precipitation there) also contributes to the discrepancies [40,41]. The spatial correlation coefficient of annual mean temperature between model simulation and observation is 0.81.

2.2 Climate extreme indices

The observed temperature indices of SU, FD and GSL and

the differences between the simulation and observation are presented in Figure 2. As shown in the figure, the model in general captures the observed spatial pattern and amount of the 3 indices well. The values of warm events described by GSL and SU show a distribution of high in the south and low in the North, with the lowest exist in the Tibetan Plateau as well as Northeast China, while the cold events described by FD shows a reversed distribution (Figure 2(a), (c), (e)). The model in general reproduces the basic pattern of the spatial distribution although with some discrepancies concerning the amounts. The spatial correlation coefficients of SU, GSL and FD between the simulation and observation are 0.94, 0.99 and 0.99, respectively.

To be more specific, for GSL, the bias in Hua'nán, North China Plain, Junggar and Tarim basin in Northwest are small or with a minor positive value, but a prevailing negative bias (shorter GSL than the observed) are found over most of the other extended areas. The values of the bias are usually in the range of 10–25 d, except over the Tibetan Plateau where the values can be up in excess of 50 d corresponding to the cold bias in simulating spring and winter temperature there [23].

For SU, less than the observed values are found in general over the region except the Tibetan Plateau. The largest bias is found in Hua'nán with the values greater than 75 d.

Figure 2 Annual mean SU, FD and GSL over China. (a) Observed GSL; (b) GSL difference between simulation and observation; (c) observed SU; (d) SU difference between simulation and observation; (e) observed FD; (f) FD difference between simulation and observation.

In the meantime, the cold bias in the cold months over the Tibetan Plateau and Sichuan Basin leads to the overestimation of FD in the places with the bias up to 10–50 d while in northern part of the region, the simulated FD is shorter than that observed with the bias usually in the range of 10–25 d except the even larger values in portions of North and Northeast China, together with the few basins in the Northwest.

The observed precipitation indices of R10, SDII and CDD and the difference between the simulations with the more presented in Figure 3. The spatial correlation coefficients of the three indices between model simulation and

observation are 0.83, 0.95 and 0.84, respectively. For the index of R10, the spatial pattern (Figure 3(a)) is similar to that of annual mean precipitation (Figure 1(c)) with high value in the southeast and low value in the north and northwest indicating that precipitation amount due to heavy rainfall events occupy a large proportion of the total. Simulated R10 shows some underestimation in southeastern China and overestimation in the Northeast, east of the Tibetan Plateau and over the mountains, which also agrees with that in the annual mean. The result indicates that the bias in the precipitation simulation may be partly arise from the poorer capability of the model in simulating heavy rainfall events.

Figure 3 Same as in Figure 2, but for the precipitation indices of R10, SDII and CDD (d & mm/d).

The distribution of SDII (Figure 3(c)) follows that of R10 but with the maxima further penetrated north to the Huanghuai and Jianghuai areas. The main bias is the underestimation of it along and south of the Yangtze River and overestimation of it over the mountain. The error of RegCM3 in simulating heavy precipitation events can also be found when driven by a different GCM which deserves special attention in the future improvement of the model [16].

In the CDD observation, larger values greater than 60 d are found in the west part of the Northeast and most places of the Northwest where arid and semiarid climate prevail. Smaller values of less than 50 d can be found in south of the

Yellow River, with the minimum between 10–25 d exist south of the Yangtze River (Figure 3(e)). The magnitude of the bias varies in the range of –10–10 d in eastern China. Over extended areas of the Northeast and western China, the bias is negative and can be up to 50 d.

3 Changes of climate and climate extremes in the future

3.1 Surface air temperature and precipitation

Changes in annual mean temperature and precipitation are firstly presented in the section to show the background of

the changes in climate extremes. In the mid-21st century, significant warming compared to the present day can be found over China (Figure 4(a)). The warming is to a less extend ($<2.5^{\circ}\text{C}$) south of the Yangtze River, and a greater warming exceeding 3.0°C can be found north of the Yellow River and in western China. The maximum warming greater than 3.5°C exists in the Northeast and portions of the Tibetan Plateau. As can be found in Figure 4(b), the simulated precipitation changes show a decrease in the Northeast and the Tibetan Plateau, little change within $\pm 5\%$ in the Southwest and along the Yangtze River basin, whereas increased precipitation can be found in South China and from west of North China extended to the Northwest with the values greater than 25% located in the basins of Xinjiang and central Inner Mongolia.

3.2 Climate extreme indices

Follow the warming, significant increase of GSL is found over China (Figure 5(a)). The increase is lower in Hua'nán and the area along Kunlun Mountain in the Northwest with the value less than 5 d. In the former area, the value of GSL is already high (>350 d, Figure 2(a)) in the present day, while for the latter, it is a cold area with high altitude thus a warming of a few degrees have little effect on the GSL. Less increase with the values in the range of 10–20 d can also be found north of the Northeast and in the basins in Northwest China. The increase over the area from the Yangtze River Basin extended westward to the Tibetan Plateau and its northeast neighboring places can be more than 30 d with the maxima up to 50 d exists in the Tibetan Plateau. As shown in Figure 5(b), the regional mean GSL during the 21st century increases following the time evolution with the values of the increase in the mid- and end (2080–2099) of the 21st century are 10 and 17 d, respectively.

The change patterns of SU show similar to that of GSL as shown in Figure 5(c), characterized by the general increase over the region, except the Tibetan Plateau and

Tianshan Mountains, as well as other areas with high altitudes. Maximum increase in excess of 50 d can be found in Hua'nán although the local temperature increase is minimum (Figure 4(a)). This is due to the temperature there is high in the present day while a less warming can have great effect on the calculated SU. Except the middle and lower reaches of the Yellow River and northern of the Northeast, the increase of SU in eastern China is in the range of 30–50 d. In Northwest, less increase can be found with the value between 20 and 30 d. Change of regional mean GSL is also similar with that of SU in the 21st century, the values in the mid and end of the 21st century is 8 and 13 d, respectively (Figure 5(d)).

Widespread decrease of FD is observed in Figure 5(e) due to the warming. Except Hua'nán and Kunlun Mountain, the decrease in Sichuan Basin is also small (<5 d). Large decrease can be found from the lower reaches of the Yellow River extended to the Tibetan Plateau, with the value in a range of 30–50 d. Regional mean FD shows a significant trend of decrease (Figure 5(f)), the value in the mid- and end of the 21st century is 9 and 15 d, respectively.

Similar to temperature, changes of the precipitation indices of R10, SDII and CDD in the future, including spatial pattern in the mid-21st century and the time series in the 21st century are presented in Figure 6. As can be found in Figure 6(a), the spatial pattern of R10 changes in the mid-21st century agrees with that of annual mean precipitation (Figure 4(b)), indicating the large portions of the extreme precipitation take in the total amount. The heavy rainfall as measured by R10 increase in the areas where precipitation increase, and *vice versa*. Greater increase can be found in the Northwest with the value greater than 25%, and can be in excess of 50% over portions of the area. For the regional mean changes, R10 shows a general trend of increase in the 21st century, but not so uniform with that of the temperature indices. A kind of decadal variation, for example the relative low value around 2070 can be found. The values in the mid and end of the 21st century are 5% and 10%, respectively.

Figure 4 Changes of temperature ($^{\circ}\text{C}$) and precipitation (%) over China in the mid-21st century (in relative to 1980–1999). (a) Temperature; (b) precipitation.

Figure 5 Changes of SU, FD and GSL over China in the mid-21st century (in relative to 1980–1999). (a) GSL, mid-21st century; (b) GSL, regional mean in 21st century; (c) SU, mid-21st century; (d) SU, regional mean in 21st century; (e) FD, mid-21st century; (f) FD, regional mean in 21st century. The black lines in the right panels are 10-year moving average.

Different from the decrease of R10 in the Northeast and the Tibetan Plateau, less change or a small decrease of the intensity index of precipitation (SDII) over the areas while a general increase elsewhere over the country can be found (Figure 6(c)). The increase can be up to 10%–25% in the areas distributed in South China, Inner-Mongolia, Tibetan Plateau and Northwest China. Regional mean SDII shows a more linear increase compared to that of R10 (Figure 6(d)) while the values in the middle and end of the 21st century are 5% and 12%, respectively.

Change of CDD shows a negative-positive dipole change over the region with a decrease of 10%–25% in the north

and an increase can be larger than 25% in the Tibetan Plateau, middle reaches of the Yangtze River and Hua’nan (Figure 6(e)). This north-south oriented pattern will lead to less drought events in the north, and more droughts in the south. In general, only minor changes in the regional mean CDD can be found in the 21st century (Figure 6(f)).

4 Conclusions and discussions

A 150-year’s transient climate change simulation, from 1951–2100, was conducted over East Asia using the regional

Figure 6 Same as in Figure 5, but for precipitation indices of R10, SDII and CDD (%).

climate model RegCM3 at 25 km grid spacing. The model was driven by the global model of MIROC3.2_hires under the IPCC SRES A1B scenario. We first evaluate the performance of the RegCM3 in simulating the indices of temperature and precipitation by comparing the simulation against observations. In general, RegCM3 can reasonably reproduce the spatial pattern and value of climate extreme indices well. Discrepancies can also be found, e.g. the underestimation of GSL and SU over many areas while the values of FD show less in the north and more in the Tibetan Plateau as compared with that observed. In the meantime, the model capability in simulating heavy rainfall events should be further improved.

Based on the validation of the model above, we then analyze the simulated future changes of climate extreme indices over China. Our main findings include:

(1) Substantial warming in annual mean temperature is simulated over China. The warming shows a latitudinal distribution with less in the south and greater in the north. The largest warming can be found in the Northeast and the Tibetan Plateau. Annual mean precipitation shows a significant decrease in the central part of the Northeast and Tibetan Plateau, less change in the mid and lower reaches of the Yangtze River, and general increase elsewhere.

(2) Broad increase of SU and GSL, decrease of FD are found as expected over the region under the warming, ex-

cept the little change of SU over the Tibetan Plateau. The maximum increase of GSL and decrease of FD in the Tibetan Plateau, while that of SU in Hua'nán are simulated by the model. The change of increase or decrease of the indices becomes more significant following time evolution in the 21st century. The increase of FD in summer in the future can exert impacts on human society and economic life, while the prolonged GSL and shortened FD plus the precipitation change will have great effect on the agriculture production and ecological environment. But further studies on the impacts of the changes in the extremes are indeed needed in the future.

(3) Change of R10 follows that of precipitation. Increase of SDII found in many places indicate the increased precipitation intensity in the warmer conditions with an enhanced hydrological cycle processes, and may lead to more flood. As a drought indicator, pronounced increase of CDD is found in southern China, including south of Sichuan Basin. Although little change of CDD can be found in Yunnan, considering the increased evaporation due to the warming, the events like the successive drought disasters found in the late years over the are a may happen frequently in the future [42]. The decrease of CDD in the North, Northeast and Northwest China may be favorable to the local society and ecosystems. However, further investigations are needed to understand whether this decrease may compensate the greater evapotranspiration in the warming climate or not. It is noted that the changes of R10 and SDII are in the same direction as that of CDD in Hua'nán and Northeast China, indicating the increase of both flood and drought events in the areas in the future.

(4) Large uncertainties exist in the simulation and projection of future climate changes, which arise from emission scenarios of GHGs, limitations in current capabilities of climate models, availability of high resolution observation data to validate the models, and the overall further in-depth knowledge needed of the global climate system. The uncertainties also can be found in simulation and projection of climate extremes. Multi-model ensembles of climate projections are important pathways for reducing these uncertainties. We plan to conduct transient simulations with different driving GCMs and scenarios to obtain more reliable information on climate change in China. Our final goal is to provide more scientifically robust and valuable suggestions for the assessment of impacts and the implementation of adaptation measures.

This work was supported by the National Basic Research Program of China (2009CB421407), Major Science and Technology Projects in Zhejiang Province (2009C03008-2) and the National Natural Science Foundation of China (40975041).

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