



**HAL**  
open science

## Changes in temperature extremes over China under 1.5 °C and 2 °C global warming targets

Chen Shi, Zhi-Hong Jiang, Wei-Lin Chen, Laurent Li

► **To cite this version:**

Chen Shi, Zhi-Hong Jiang, Wei-Lin Chen, Laurent Li. Changes in temperature extremes over China under 1.5 °C and 2 °C global warming targets. *Advances in Climate Change Research*, 2018, 9 (2), pp.120-129. 10.1016/j.accre.2017.11.003 . hal-02414708

**HAL Id: hal-02414708**

**<https://hal.science/hal-02414708>**

Submitted on 16 Dec 2019

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



# Changes in temperature extremes over China under 1.5 °C and 2 °C global warming targets

SHI Chen<sup>a</sup>, JIANG Zhi-Hong<sup>a,\*</sup>, CHEN Wei-Lin<sup>a</sup>, Laurent LI<sup>b</sup>

<sup>a</sup> Key Laboratory of Meteorological Disaster of Ministry of Education, Joint International Research Laboratory of Climate and Environment Change, Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disaster, Nanjing University of Information Science & Technology, Nanjing 210044, China

<sup>b</sup> Laboratoire de Météorologie Dynamique, CNRS, Sorbonne Universités, UPMC Université Paris 06, Paris 75005, France

Received 19 September 2017; revised 24 October 2017; accepted 29 November 2017

Available online 8 December 2017

## Abstract

The long-term goal of the 2015 Paris Agreement is to limit global warming to well below 2 °C above pre-industrial levels and to pursue efforts to limit it to 1.5 °C. However, for climate mitigation and adaption efforts, further studies are still needed to understand the regional consequences between the two global warming limits. Here we provide an assessment of changes in temperature extremes over China (relative to 1986–2005) at 1.5 °C and 2 °C warming levels (relative to 1861–1900) by using the 5th phase of the Coupled Model Intercomparison Project (CMIP5) models under three RCP scenarios (RCP2.6, RCP4.5, RCP8.5). Results show that the increases in mean temperature and temperature extremes over China are greater than that in global mean temperature. With respect to 1986–2005, the temperature of hottest day (TXx) and coldest night (TNn) are projected to increase about 1/1.6 °C and 1.1/1.8 °C, whereas warm days (TX90p) and warm spell duration (WSDI) will increase about 7.5/13.8% and 15/30 d for the 1.5/2 °C global warming target, respectively. Under an additional 0.5 °C global warming, the projected increases of temperature in warmest day/night and coldest day/night are both more than 0.5 °C across almost the whole China. In Northwest China, Northeast China and the Tibetan Plateau, the projected changes are particularly sensitive to the additional 0.5 °C global warming, for example, multi-model mean increase in coldest day (TXn) and coldest night (TNn) will be about 2 times higher than a change of 0.5 °C global warming. Although the area-averaged changes in temperature extremes are very similar for different scenarios, spatial hotspot still exists, such as in Northwest China and North China, the increases in temperatures are apparently larger in RCP8.5 than that in RCP4.5.

**Keywords:** 1.5 °C global warming; 2 °C global warming; Temperature extremes; CMIP5; China

## 1. Introduction

In December 2015, the Paris Agreement was approved by nearly 200 countries at the United Nations Framework Convention on Climate Change (UNFCCC) 21st Conference of the Parties (COP 21). This agreement aims to limit global mean temperature increase to well below 2 °C above pre-

industrial levels and to pursue efforts to limit it to 1.5 °C (UNFCCC, 2015). At the same time, the Intergovernmental Panel on Climate Change (IPCC) has accepted an invitation to prepare a special report on 1.5 °C target in 2018.

For a given increment in global mean temperature, local climate impacts can vary from one region to another (Seneviratne et al., 2016). Previous studies regarding the 1.5 °C and 2 °C global warming targets have found that land areas warm substantially faster than the oceans and high-latitude areas in the Northern Hemisphere show the fastest warming over the globe (Zhang, 2012; Jiang et al., 2016; Seneviratne et al., 2016; Hu et al., 2017; Xu et al., 2017).

\* Corresponding author.

E-mail address: [zhjiang@nuist.edu.cn](mailto:zhjiang@nuist.edu.cn) (JIANG Z.-H.).

Peer review under responsibility of National Climate Center (China Meteorological Administration).

Besides the changes in mean climate, the extreme climate is also of great importance to the society, which is more sensitive to global warming (Knutti et al., 2016). For example, the hot temperature extremes in the Mediterranean will increase about 3 °C and the cold temperature extremes in Arctic will warm about 5.5 °C under the 2 °C global warming target (Seneviratne et al., 2016).

Recent years, studies concerning a specific level of global warming have also gained many significant conclusions in China. Under a 2 °C global warming target, the mean temperature in China will increase greater in the north than in the south and the winter temperature warms strongest among the seasons (Jiang et al., 2009, 2012; Jiang and Fu, 2012; Lang and Sui, 2013). Extreme warm events increase, while extreme cold events decrease (Lang and Sui, 2013; Chen et al., 2015; Guo et al., 2016). However, most of the past efforts have been spent on the 2 °C global warming target, few attention has been paid to the 1.5 °C global warming target, particularly for the local impacts of extreme temperature events under an additional 0.5 °C global warming.

In addition, as climate models are necessary for the assessment of future climate change, most of the current studies are derived from transient simulations of the 5th phase of the Coupled Model Intercomparison Project (CMIP5). The responses can be different for climate variables that respond to a given forcing. For a given warming threshold, Hu et al. (2017) pointed out that projected changes of global mean temperature are very similar for different scenarios. However, it remains an open question whether the intensity of changes in temperature extremes and its distribution over China are related to the considered pathways under 1.5 °C and 2 °C global warming targets.

Based on these premises, this study uses CMIP5 experiments to present an analysis of temperature extremes over China for the 1.5 °C and 2 °C global warming targets. The key questions we address are as follows. 1) What are the possible changes of temperature extremes over China associated with 1.5 °C and 2 °C global warming targets? 2) What are the possible impacts of an additional 0.5 °C global warming on temperature extremes over China? 3) For a specific warming threshold, whether there is any difference in the intensity and spatial patterns of temperature extremes over China between different scenarios?

## 2. Data and methods

### 2.1. Model data

The analysis is based on monthly and daily minimum (maximum) near surface temperature from 27 and 20 CMIP5 global climate models (GCMs), respectively, which are all available under historical and three Representative Concentration Pathways (RCP2.6, RCP4.5, RCP8.5) simulations (Taylor et al., 2012). The first realization was used for each model in order to treat all models equally. The models analyzed in this study are listed in Table 1.

Table 1  
Basic information on 27 CMIP5 models used in this study.

| Model                 | Model center           | Resolution |
|-----------------------|------------------------|------------|
| <b>BCC-CSM1-1</b>     | BCC-CMA, China         | 128 × 64   |
| <b>BCC-CSM1-1-m</b>   | BCC-CMA, China         | 320 × 160  |
| <b>BNU-ESM</b>        | BNU-GCESS, China       | 128 × 64   |
| <b>CanESM2</b>        | CCCMA, Canada          | 128 × 64   |
| <b>CCSM4</b>          | NCAR, America          | 288 × 192  |
| CESM1-CAM5            | NCAR, America          | 288 × 192  |
| <b>CSIRO-MK3-6-0</b>  | CSIRO-QCCCE, Australia | 192 × 96   |
| <b>CNRM-CM5</b>       | CNRM-CERFACS, France   | 256 × 128  |
| <b>FGOALS-g2</b>      | CSA-IAP/CESS, China    | 128 × 60   |
| FIO-ESM               | FIO-SOA, China         | 128 × 64   |
| <b>GFDL-CM3</b>       | NOAA-GFDL, America     | 144 × 90   |
| <b>GFDL-ESM2G</b>     | NOAA-GFDL, America     | 144 × 90   |
| <b>GFDL-ESM2M</b>     | NOAA-GFDL, America     | 144 × 90   |
| GISS-E2-H             | NASA-GISS, America     | 144 × 90   |
| GISS-E2-R             | NASA-GISS, America     | 144 × 90   |
| HadGEM2-AO            | MOHC, UK               | 192 × 145  |
| HadGEM2-ES            | MOHC, UK               | 192 × 145  |
| <b>IPSL-CM5A-LR</b>   | IPSL, France           | 96 × 96    |
| <b>IPSL-CM5A-MR</b>   | IPSL, France           | 144 × 143  |
| <b>MIROC5</b>         | MIROC, Japan           | 256 × 128  |
| <b>MIROC-ESM</b>      | MIROC, Japan           | 128 × 64   |
| <b>MIROC-ESM-CHEM</b> | MIROC, Japan           | 128 × 64   |
| <b>MPI-ESM-LR</b>     | MPI-M, Germany         | 192 × 96   |
| <b>MPI-ESM-MR</b>     | MPI-M, Germany         | 192 × 96   |
| <b>MRI-CGCM3</b>      | MRI, Japan             | 320 × 160  |
| <b>NorESM1-M</b>      | NCC, Norway            | 144 × 96   |
| NorESM1-ME            | NCC, Norway            | 144 × 96   |

Note: The models provide daily outputs for three RCPs are in bold.

### 2.2. Methods

#### 2.2.1. Definition of the time reaching 1.5 °C and 2 °C global warming thresholds

As pointed out in Paris Agreement, the 1.5 °C and 2 °C global warming thresholds are relative to the pre-industrial levels. There are two main principles for the selection of pre-industrial period: First, the pre-industrial period should not be affected by the global warming in 20th century; second, the initial integration time of the historical experiments varies from GCM to GCM (Guo et al., 2016). Hence, 1861–1900 was selected as a common pre-industrial period in this study.

The time series of global mean temperature were first smoothed by a 21-year moving average and then the time of the 1.5/2 °C threshold was defined as the first year when the temperature rise was 1.5/2 °C higher above its pre-industrial counterpart for individual GCMs. In order to determine a relatively stable climate condition, two 10-year periods around the 1.5 °C/2 °C threshold were compared with reference period (1986–2005) to assess the changes in climate extremes. It is worthy to noting that only the models reach both 1.5 °C and 2 °C are included in the analysis.

#### 2.2.2. Climate extreme indices

Twelve indices of temperature extremes are considered following the recommendation of the Expert Team on Climate Change Detection and Indices (ETCCDI, shown in Table 2). The indices were firstly calculated on each model's native grids

Table 2  
Definitions of 8 ETCCDI temperature indices used in this work.

| Label | Index               | Index definition  | Unit |
|-------|---------------------|---|------|
| TXx   | Hottest day         | Annual maximum daily maximum temperature  | °C   |
| TXn   | Coldest day         | Annual minimum daily maximum temperature  | °C   |
| TNx   | Warmest night       | Annual maximum daily minimum temperature  | °C   |
| TNn   | Coldest night       | Annual minimum daily minimum temperature  | °C   |
| TX90p | Warm days           | Percentage of days when TX > 90th percentile                                    | %    |
| TX10p | Cold days           | Percentage of days when TX < 10th percentile                                    | %    |
| TN90p | Warm nights         | Percentage of days when TN > 90th percentile                                    | %    |
| TN10p | Cold nights         | Percentage of days when TN < 10th percentile                                    | %    |
| WSDI  | Warm spell duration | Annual count of days with at least 6 consecutive days when TX > 90th percentile | d    |
| CSDI  | Cold spell duration | Annual count of days with at least 6 consecutive days when TN < 10th percentile | d    |
| FD    | Frost days          | Annual count of days when TN < 0 °C   | d    |
| SU    | Summer days         | Annual count of days when Tx > 25 °C  | d    |

and then regridded to a common  $1^\circ \times 1^\circ$  grid using bilinear interpolation.

### 2.2.3. Signal-to-noise ratio

Following Li and Zhou (2010), we use Signal-to-Noise Ratio (SNR) to measure the credibility of the estimated results, which is defined as,

$$\text{Noise} = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2}, \quad (1)$$

$$\text{Signal} = |\bar{x}|, \quad (2)$$

$$\text{SNR} = \frac{\text{Signal}}{\text{Noise}}, \quad (3)$$

where  $x_i$  denotes the variable simulated in individual model,  $\bar{x}$  denotes the multi-model ensemble (MME) mean and  $n$  is the size of ensemble.  $\text{SNR} > 1$  implies the signal is greater than the noise, hence the projection has a higher confidence level and vice versa.

## 3. Results

### 3.1. Threshold crossing times of 1.5 °C and 2 °C

Fig. 1 shows the global mean temperature anomalies relative to 1861–1900 mean under three RCPs. The RCP2.6 is a mitigation scenario aiming to limit the increase of global mean temperature below 2 °C during the 21st century (van Vuuren et al., 2011). Under this scenario, temperature increase will stable at about 1.7 °C by the middle and late 21st century. The multi-model ensemble (MME) mean temperature will exceed 1.5 °C around the year 2030. The RCP4.5 is a medium scenario that stabilizes radiative forcing at 4.5 W m<sup>-2</sup> by 2100 (van Vuuren et al., 2011). Under this pathway, the MME mean temperature will increase about 2.7 °C by the end of this century. The MME mean temperature is projected to reach 1.5 °C by around 2028 whereas the 2 °C target is reached by around 2049. The RCP8.5 is the highest pathway with the largest radiative forcing by 2100 (van Vuuren et al., 2011), hence the temperature increases the greatest among the three

RCPs. Under this pathway, a 5 °C warming is projected to reach after 2080 by few models. The threshold crossing time (TCT) for 1.5 °C and 2 °C is around 2025 and 2039, respectively.

There are large discrepancies in the TCTs for individual models and each RCP (Fig. 2). In the three RCPs, some models cross the 1.5 °C warming threshold as early as 2010s whereas some other models do not reach the mark until 2050s. As the global mean temperature has increased approximately 1 °C above pre-industrial levels (IPCC, 2013), this disagreement may be attributed to the mismatch in observed and simulated variability on decadal timescales (Schmidt et al., 2014; Smith et al., 2016; Karmalkar and Bradley, 2017). Models with large transient climate response may reach the 1.5 °C and 2 °C warming threshold earlier than those with low transient climate response (Chen and Zhou, 2016; Hu et al., 2017).

### 3.2. Changes in temperature extremes over China under 1.5 °C and 2 °C global warming

Fig. 3 depicts boxplots of the changes in mean temperature and temperature extremes over China relative to 1986–2005 when the temperature increase of individual model reaches the 1.5 °C and 2 °C global warming thresholds. It should be noted that the global mean temperature is also compared with the same reference period (1986–2005) in Fig. 3. The results are very similar for each scenario. This implies that the area-averaged mean temperature and temperature extremes over China are independent on the considered scenario. The multi-model mean warming for China is higher than that for globe and regionally averaged changes over the whole China range from 0.4 to 1.7 °C (1.1–2.6 °C) relative to 1986–2005 for the 1.5/2 °C global warming target. The changes in temperature extremes are greater than that in mean temperature over China. The multi-model mean increase in hottest day (TXx) and coldest night (TNn) for the 1.5/2 °C global warming target is about 1/1.6 °C and 1.1/1.8 °C, respectively. The ensemble mean TNn increases with the maximum magnitude whereas TNx warms with the minimum magnitude. Under 2 °C global warming, for instance, the response is about 1.3–2.7 times greater for the TNn than for the global mean temperature.

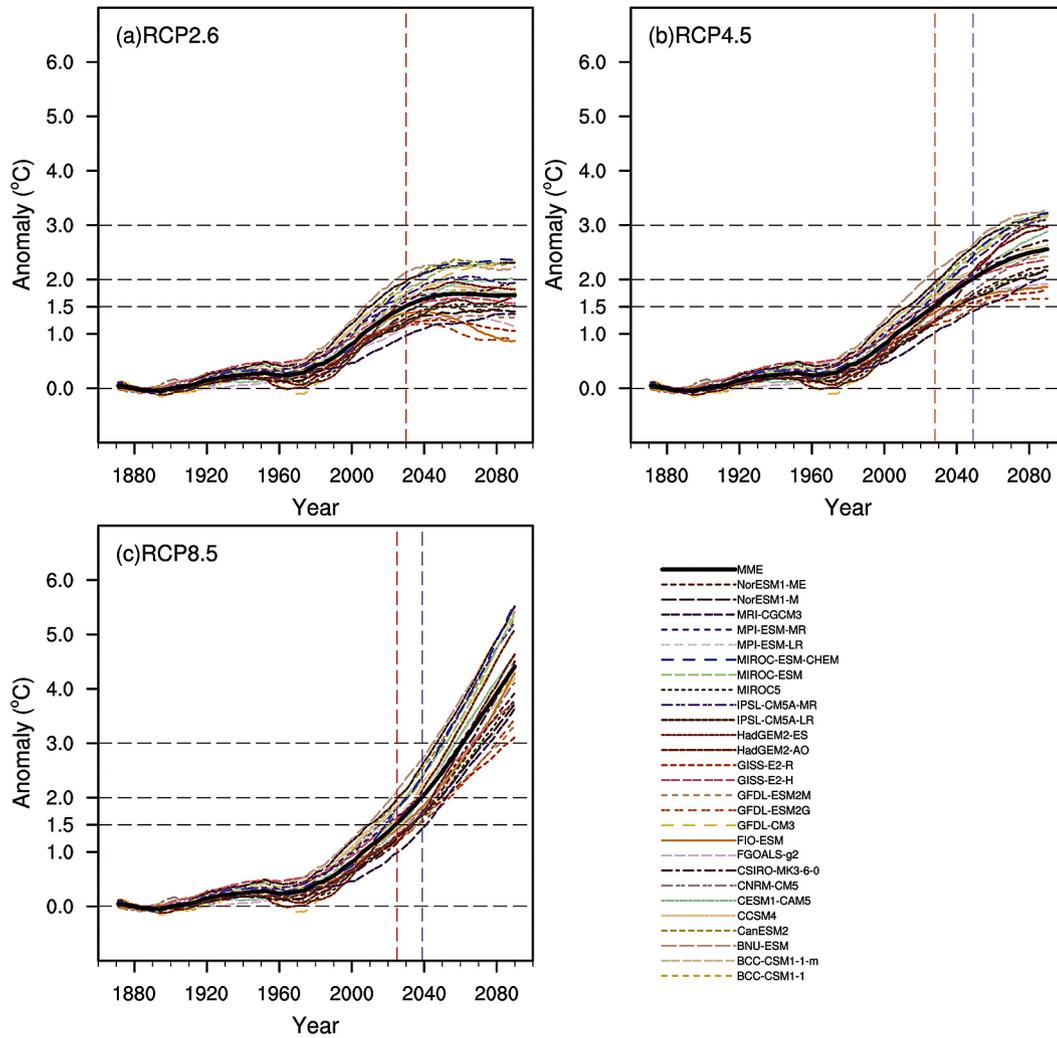


Fig. 1. Time series of 21-year moving average global mean temperature under (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5 relative to 1861–1900 pre-industrial baseline. The vertical dash lines indicate the MME year of 1.5 °C (red) and 2 °C (blue) global warming threshold.

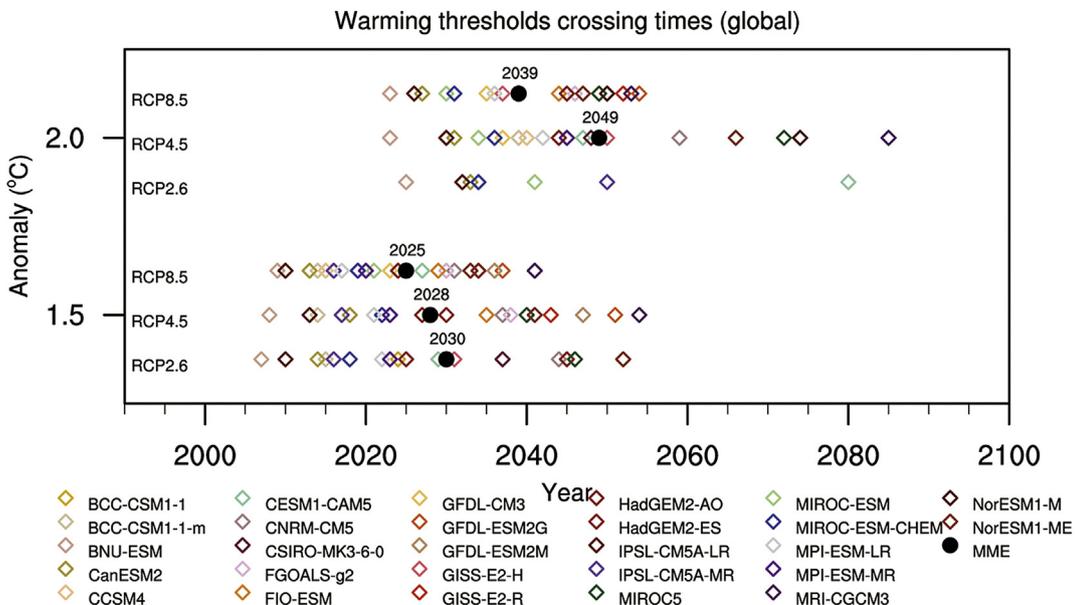


Fig. 2. Timings for when global mean temperature for 27 CMIP5 models cross 1.5 °C and 2 °C global warming thresholds for RCP2.6, RCP4.5 and RCP8.5. The threshold crossing times for the MME are indicated by solid black dots.

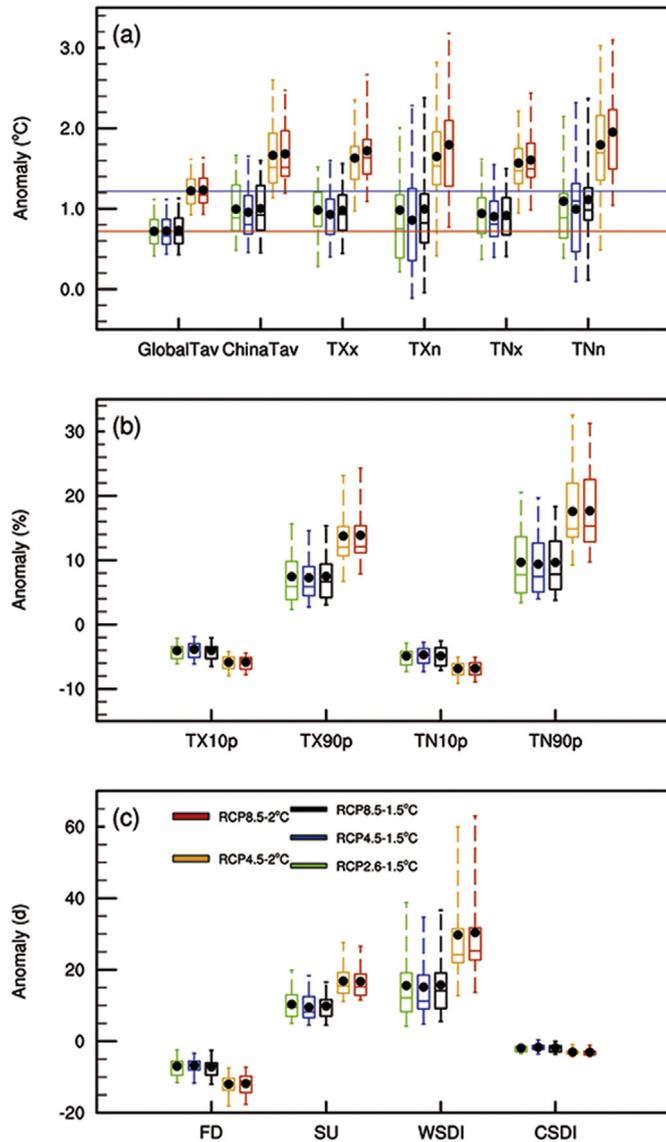


Fig. 3. Boxplots of projected changes in mean temperature and temperature extremes over China relative to 1986–2005 under RCP2.6, RCP4.5 and RCP8.5. The top and bottom whiskers are the maximum and minimum projections for a variable. The top and bottom box are always the first and third quartiles, and the band inside the box is the median. The MME are indicated by solid black dots. The horizontal solid lines indicate the changes of the multi-model global mean temperature relative to 1986–2005 under 1.5 °C (red) and 2 °C (blue) warming thresholds. The black bars are associated with a 1.5 °C warming under RCP2.6, the blue bars are associated with a 1.5 °C warming under RCP4.5 and the green bars are associated with a 1.5 °C warming under RCP8.5, whereas the orange bars are associated with a 2 °C warming under RCP4.5 and the red bars are associated with a 2 °C warming under RCP8.5.

Cold days (TX10p) and cold nights (TN10p) show a consistent decrease in all RCPs. The mean decrease in TX10p and TN10p is from about 4% to about 6.8% for 1.5 °C and 2 °C global warming threshold, respectively. Warm days (TX90p) and warm nights (TN90p) generally increase in all RCPs. For a 1.5/2 °C global warming threshold, the multi-model mean TX90p increases about 7.5/13.8% and TN90p increases about 9.5/17.6%.

The mean decrease in frost days (FD) is about 7 and 12 d under 1.5 °C and 2 °C global warming, respectively. The smallest decrease is found in cold spell duration (CSDI), which remains almost the same for the two global warming levels. There is a consistent increase in summer days (SU) and warm spell duration (WSDI). The multi-model mean SU increases about 10 d under 1.5 °C global warming and further increases 6 d under 2 °C global warming. The increase in WSDI is more pronounced among the four duration indices, with the magnitude of about 15/30 d for 1.5/2 °C global warming targets, respectively.

Fig. 4 and Fig. 5 illustrates the projected changes in mean temperature, hottest day (TXx) and warmest night (TNx) over China at 1.5 °C and 2 °C global warming, respectively. The mean temperature increases across China, with warming greater towards northwest and on the western part of the Tibetan Plateau. This feature is even more obvious for temperature extremes. TXx and TNx warm stronger in the northwest and western Tibetan Plateau. There are larger differences in changes of coldest day (TXn) and coldest night (TNn) than that of TXx and TNx (Fig. 6). This may be due to TXn and TNn usually correspond to the maximum and minimum daily temperature of winter, respectively. This result agrees well with the findings that the temperature increase is relatively higher in high latitudes and altitudes than that in lower latitudes (Knutti and Sedláček, 2013), as a result of reduced temperature variability related to the retreating snow cover (Fischer et al., 2011; Kong and Wang, 2017), decreased surface albedo induced by vegetation expansion (Falloon et al., 2012; Port et al., 2012) and the changes in atmospheric circulation (Haarsma et al., 2009), etc.

Under an additional 0.5 °C global warming, both the mean temperature and the temperature extremes will increase more than 0.5 °C across almost the whole China. Some regions display substantial increases. In Northwest China, Northeast China and the Tibetan Plateau, for instance, the TXn and TNn will warm more than 1 °C, which is about 2 times higher than a change of 0.5 °C global warming. Only a small part of China will keep the increase in temperature extremes below 0.5 °C. For example, the changes in TXn and TNn are both less than 0.5 °C in Southwest China. The TNn also increases not exceeding 0.5 °C in the coastal areas.

The confidences in TXx and TNx are higher than that in TXn and TNn. The areas with greater increases in TXn and TNn usually have larger SNR, i.e., Northeast China and the Tibetan Plateau, which means our results are more robust in these key regions. It is worthy to noting that there are differences in the distribution of SNR between RCP4.5 and RCP8.5. For example, SNR is more uniform on a national scale for TXn and TNn under RCP8.5, while only few areas are greater than 1 under RCP4.5. This implies there has a larger model spread in projections of TXn and TNn under RCP4.5.

Consistent with temperature changes mentioned above, warm days (TX90p) increase whereas cold nights (TN10p) decrease (Fig. 7). The greatest increases in TX90p and largest decreases in TN10p are projected in the Tibetan Plateau with more than 16% and 8% relative to 1986–2005 under 2 °C

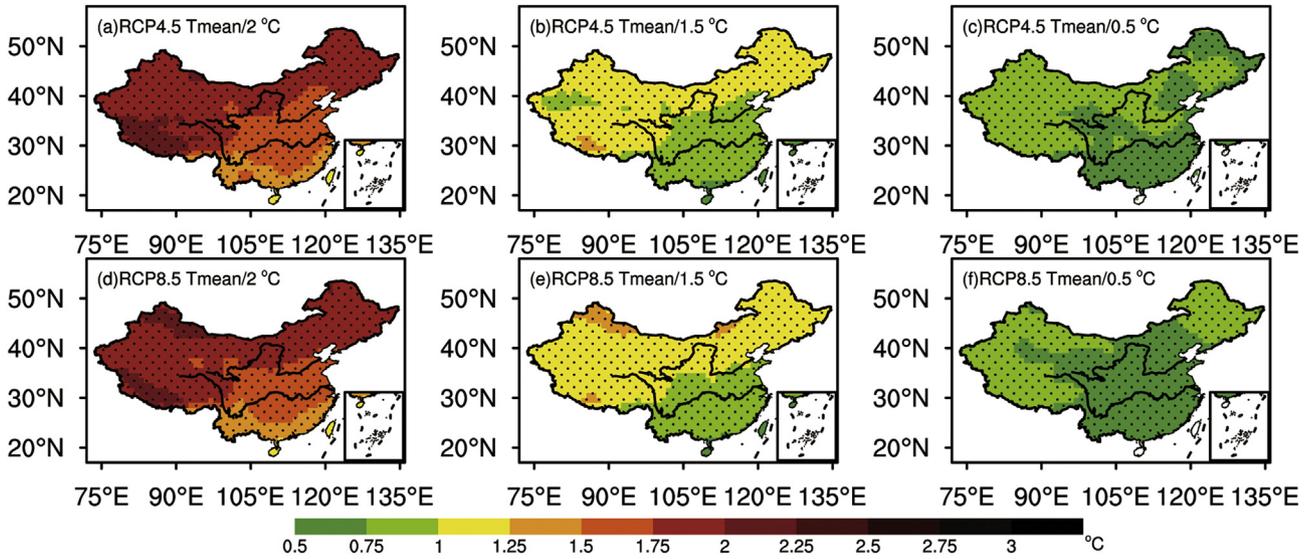


Fig. 4. Spatial distributions of projected changes in mean temperature over China under 1.5 °C and 2 °C global warming and the differences between the two warming levels in the RCP4.5 and RCP8.5. The areas where  $SNR > 1$  are indicated by dots.

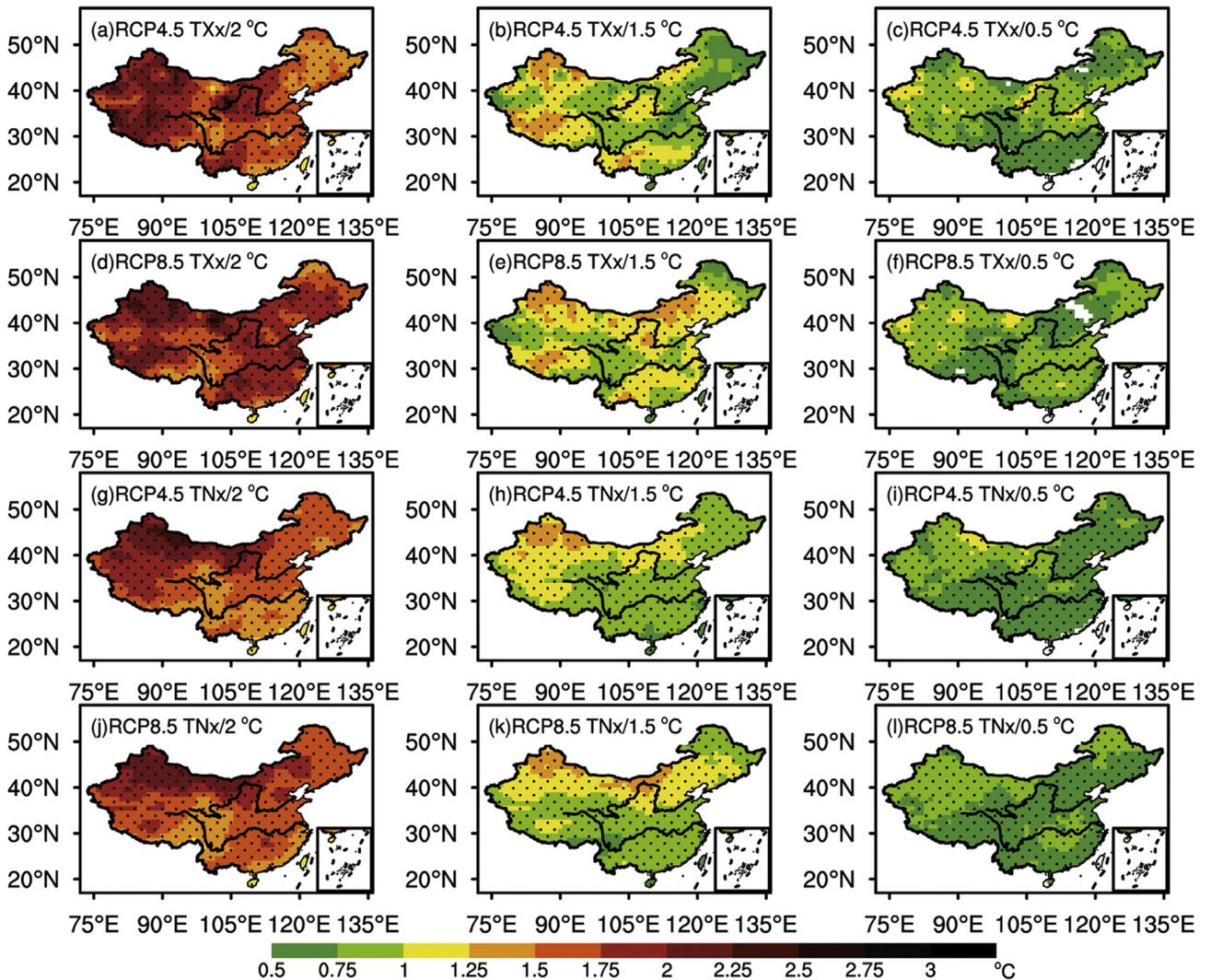


Fig. 5. Same as Fig. 4 but for TXx (a–f) and TNx (g–l).

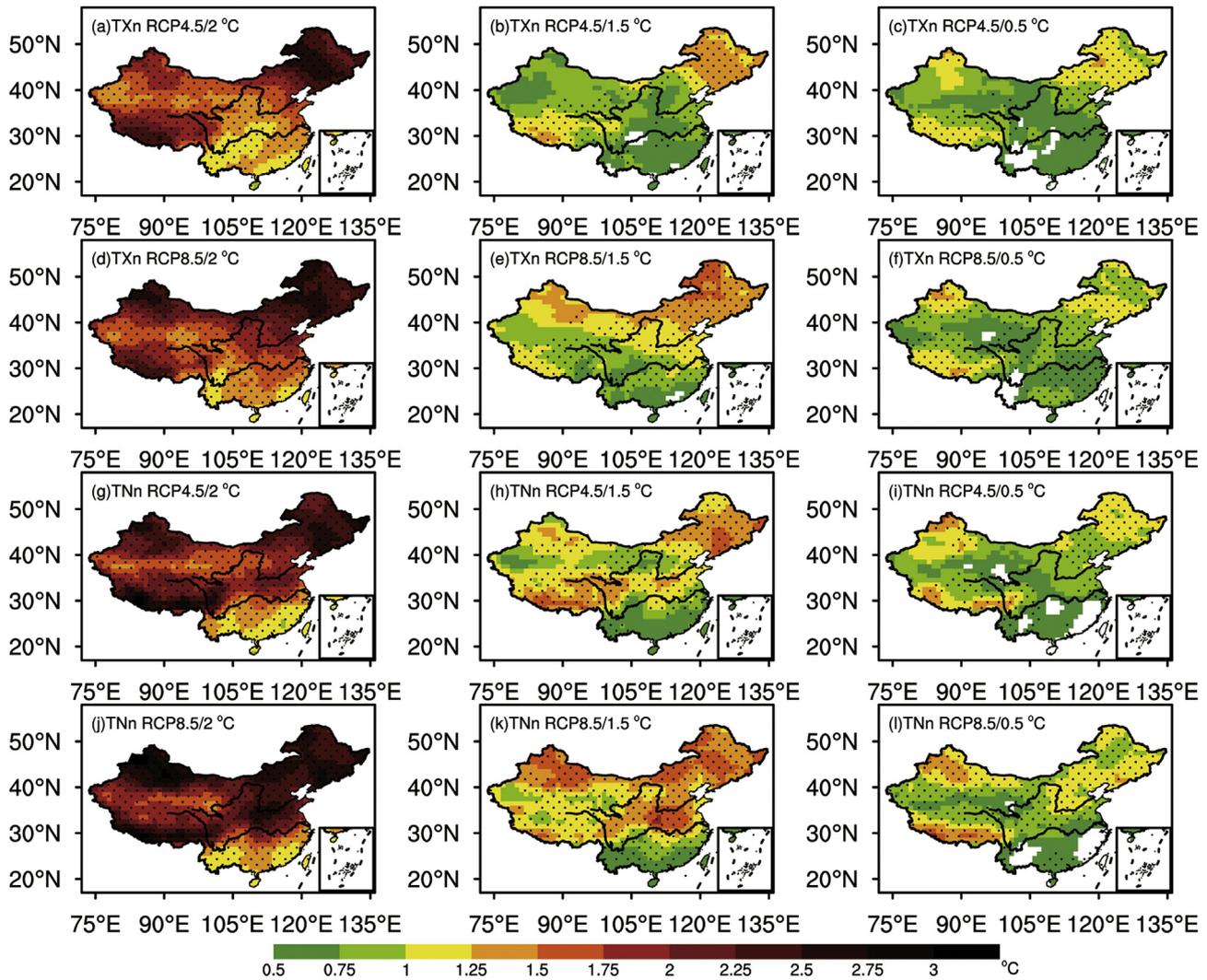


Fig. 6. Same as Fig. 4 but for TXn (a–f) and TNn (g–l).

global warming, respectively. High latitudes are also affected by a strong decrease in TN10p. An additional 0.5 °C warming will lead to an increase in warm spell duration (WSDI) and TX90p whereas a decrease in frost days (FD) and TN10p across China, except for FD in southeastern coastal areas where daily minimum temperature are generally larger than 0 °C. As for TX90p and TN10p, WSDI is projected to increase and FD is projected to decrease (Fig. 8). The strongest increases in WSDI and greatest decreases in FD both occur in the Tibetan Plateau, with more than 40 and 21 d under 2 °C global warming. Greater increases in WSDI are also found in some coastal areas, as the ocean share a large part in the respective grid cells that result in a large amplification of the warming effect compared with pure land grids (Schleussner et al., 2016).

### 3.3. Comparisons of the temperature extremes between different RCP scenarios

As mentioned in Section 3.2, the area-averaged changes in temperature extremes over China are independent on the

considered scenarios. However, whether there is any difference in the intensity and spatial patterns of temperature extremes is still unknown, in other words, is there any hotspot that is sensitive to the scenarios? In this section, we compare the temperature extremes from RCP4.5 and RCP8.5 for a given global warming threshold, as shown in Fig. 9. There are very similar distributional patterns in the differences between RCP4.5 and RCP8.5. However, for a 1.5 °C or 2 °C global warming target, the intensity of changes in temperature extremes under RCP8.5 is higher than that under RCP4.5 across the whole China, except for the Tibetan Plateau. The increases in TXn and TNn are greater in Northwest China and North China, with more than 0.25 °C. This feature are more significant under a 2 °C global warming level and most of the models (more than 2/3) are characterized by consistent increases. As the radiative forcing are very close for RCP4.5 and RCP8.5 under 1.5 °C or 2 °C global warming, this result may be attributed to the changes in land use, which is a crucial element of the RCP scenarios. van Vuuren et al. (2011) pointed out that RCP4.5 is the pathway with higher vegetation cover than RCP8.5. In

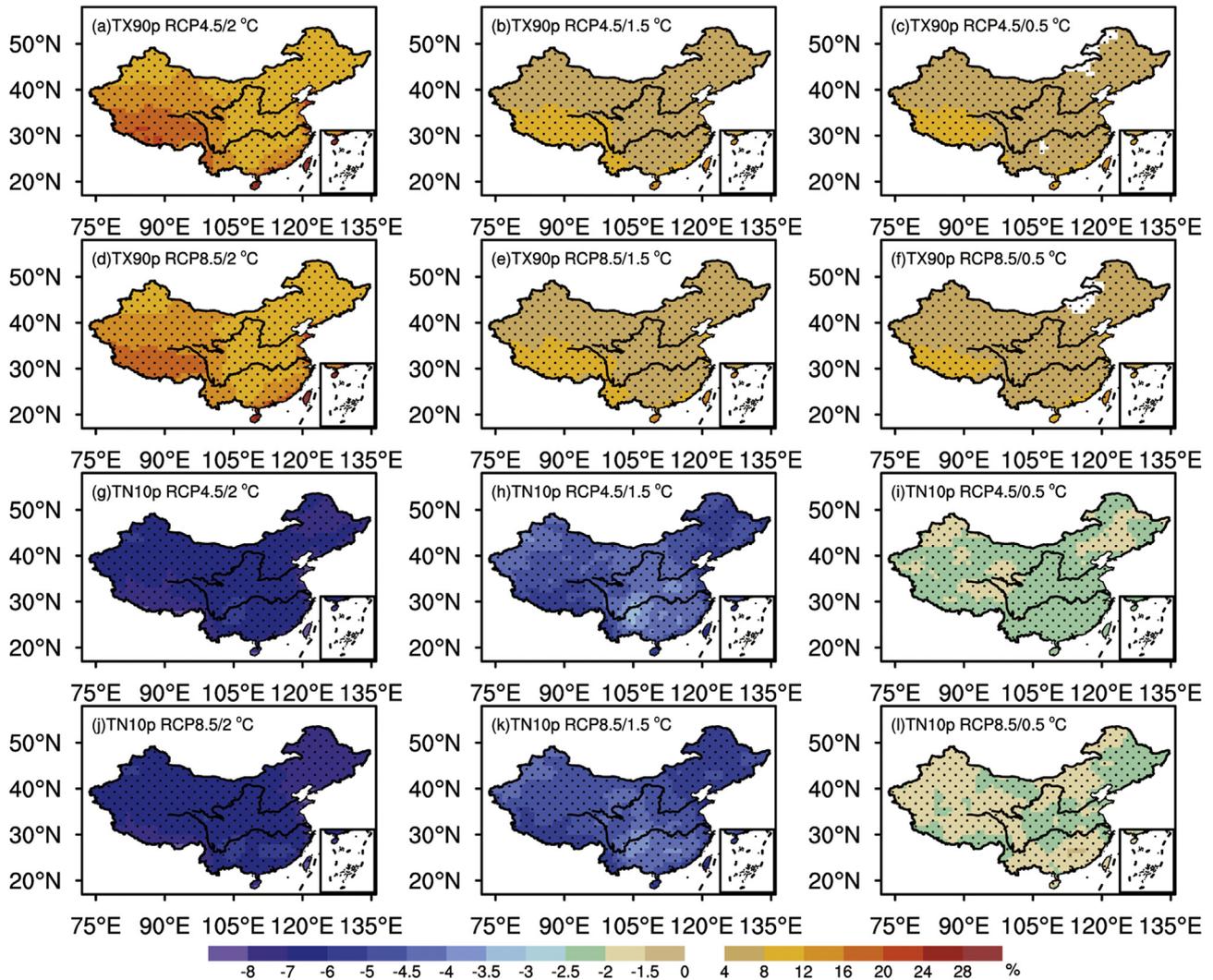


Fig. 7. Same as Fig. 4 but for TX90p (a–f) and TN10p (g–l).

addition, the rates of surface warming increase with the decreasing vegetation cover (Huang et al., 2017). Hence, the regional additional warming may result from the changes in land use. However, further numerical sensitivity experiments are still needed.

#### 4. Conclusions and discussion

In this study, we investigate the impacts of 1.5 °C and 2 °C global warming above pre-industrial levels on temperature extremes over China using CMIP5 models. The major findings are as follows:

- (1) An additional 0.5 °C global warming is projected to have substantial impacts on temperature extremes over China. For a change of 0.5 °C between the two global warming thresholds, the mean temperature, warmest and coldest temperature extremes will warm more than 0.5 °C across almost the whole China. In some key regions, i.e., Northwest China, Northeast China and the Tibetan Plateau, the mean increase in TX<sub>n</sub> and TN<sub>n</sub> will

be about 2 times higher than a change of 0.5 °C global warming. Multi-model mean FD is expected to further decrease about 5 d, while WSDI is projected to further increase about 15 d. In addition, ensemble mean TX10p and TN10p will further decrease about 2.8%, whereas TX90p and TN90p will further increase about 6.3% and 8.1%, respectively.

- (2) For a specific global warming, the area-averaged temperature extremes are independent on the considered scenario. However, there are some hotspots which sensitive to the scenarios such as in Northwest China and North China, the increases in temperature extremes under RCP8.5 are higher than that in RCP4.5. This feature is more significant under a 2 °C global warming.

In summary, our results highlight that there are substantial differences between 1.5 °C and 2 °C global warming targets, especially for the temperature extremes. Therefore, it is necessary for the international community to make joint efforts to limit the global warming below 1.5 °C relative to pre-industrial levels. In addition, further studies regarding 1.5 °C

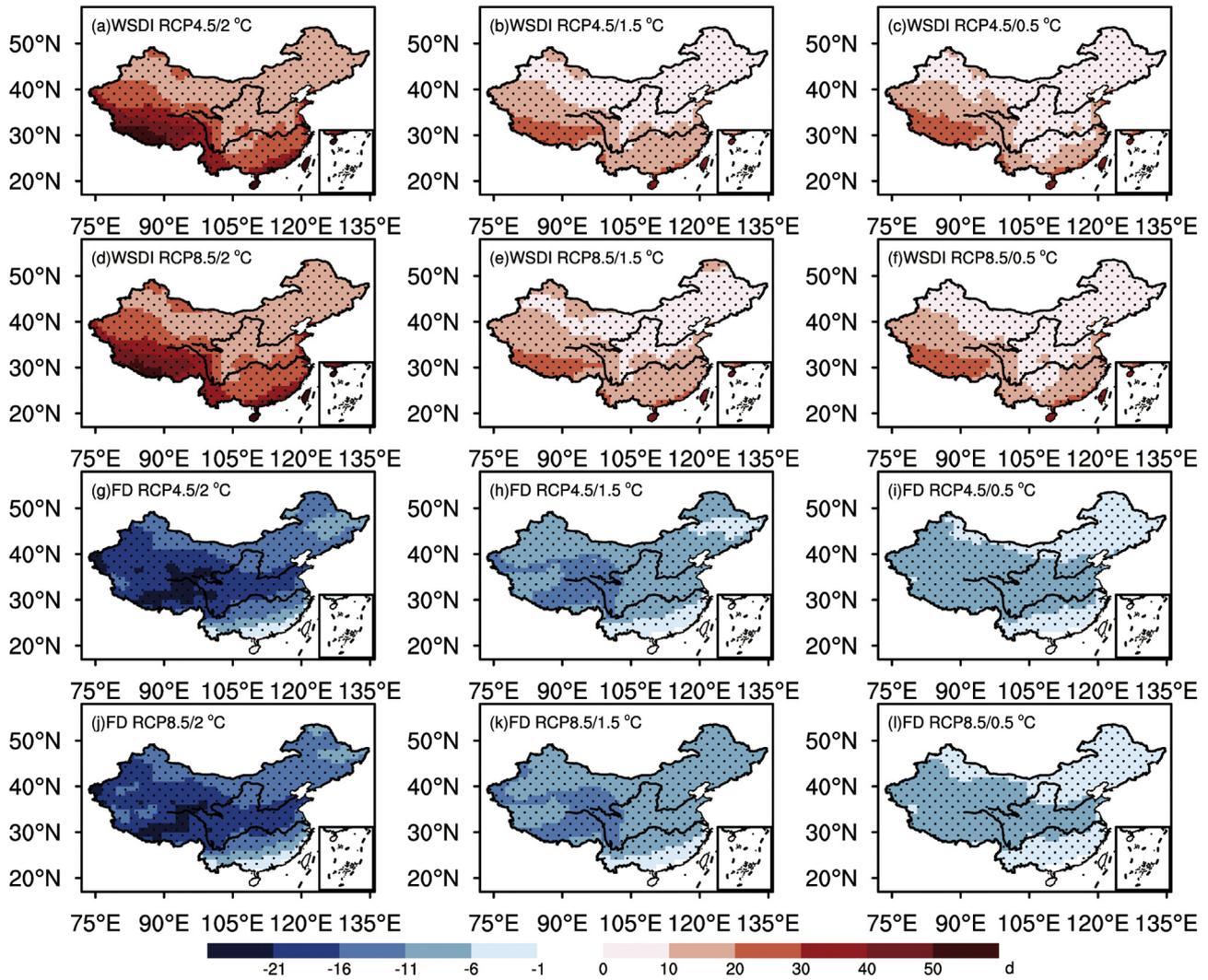


Fig. 8. Same as Fig. 4 but for WSDI (a–f) and FD (g–l).

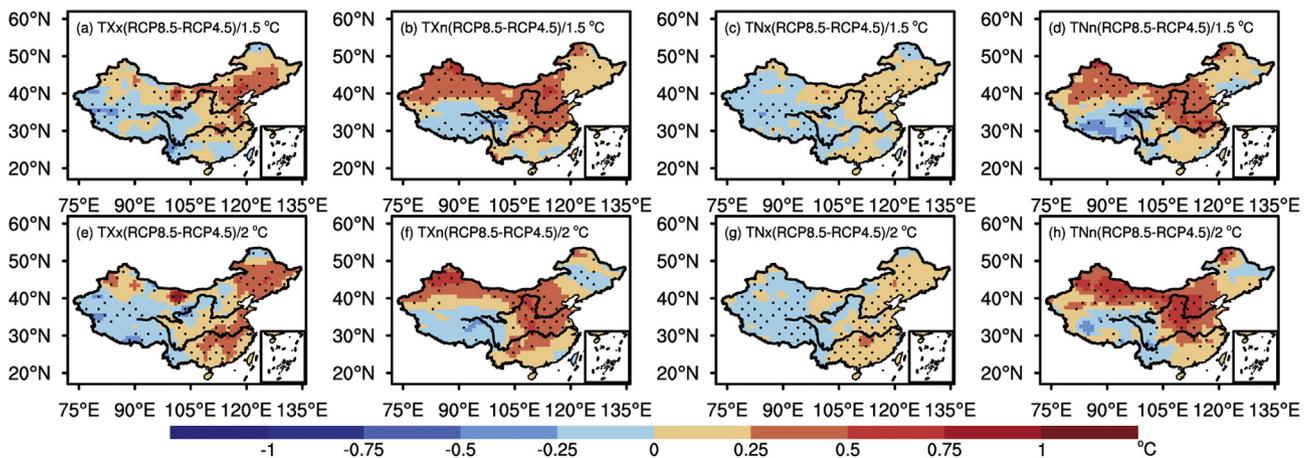


Fig. 9. Differences in TXx, TXn, TNx and TNn over China between RCP4.5 and RCP8.5 under 1.5 °C and 2 °C global warming. The areas which more than 2/3 models agree on the sign of change are indicated by dots.

and 2 °C global warming are still necessary, as the global climate models used in this study are with relatively lower resolutions, which causes uncertainties of projections in regional scales. More attention should be paid to the development of high-resolution regional climate models to address the issue.

## Acknowledgments

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 1) for producing and making available their model output. This research is supported by the National Key Research and Development Program of China (2017YFA0603804) and the State Key Program of National Natural Science Foundation of China (41230528).

## References

- Chen, X.-L., Zhou, T.-J., 2016. Uncertainty in crossing time of 2 °C warming threshold over China. *Sci. Bull.* 61 (18), 1451–1459.
- Chen, X.-C., Xu, Y., Yao, Y., 2015. Changes in climate extremes over China in a 2 °C, 3 °C, and 4 °C warmer world. *Chin. J. Atmos. Sci.* 39 (6), 1123–1135 (in Chinese).
- Falloon, P.D., Dankers, R., Betts, R.A., et al., 2012. Role of vegetation change in future climate under the A1B scenario and a climate stabilisation scenario, using the HadCM3C Earth system model. *Biogeosciences* 9, 4739–4756.
- Fischer, E.M., Lawrence, D.M., Sanderson, B.M., 2011. Quantifying uncertainties in projections of extremes—a perturbed land surface parameter experiment. *Clim. Dyn.* 37, 1381–1398.
- Guo, X.-J., Huang, J., Luo, Y., et al., 2016. Projection of heat waves over China for eight different global warming targets using 12 CMIP5 models. *Theor. Appl. Climatol.* 128 (3–4), 507–522.
- Haarsma, R.J., Selten, F., Hurk, B.V., et al., 2009. Drier Mediterranean soils due to greenhouse warming bring easterly winds over summertime central Europe. *Geophys. Res. Lett.* 36, L04705.
- Hu, T., Sun, Y., Zhang, X.-B., 2017. Temperature and precipitation projection at 1.5 °C and 2.0 °C increase in global mean temperature. *Sci. Bull.* 57, 374 (in Chinese).
- Huang, J.-P., Yu, H.-P., Dai, A.-G., et al., 2017. Drylands face potential threat under 2 °C global warming target. *Nat. Clim. Change* 7 (6), 417–422.
- IPCC, 2013. *Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge and New York.
- Jiang, D.-B., Fu, Y.-H., 2012. Climate change over China with a 2 °C global warming. *Chin. J. Atmos. Sci.* 36 (2), 234–246 (in Chinese).
- Jiang, D.-B., Zhang, Y., Sun, J.-Q., 2009. Ensemble projection of 1–3 °C warming in China. *Chin. Sci. Bull.* 54, 3326–3334.
- Jiang, Z.-H., Song, J., Li, L., et al., 2012. Extreme climate events in China: IPCC-AR4 model evaluation and projection. *Clim. Change* 110 (1–2), 385–401.
- Jiang, D.-B., Sui, Y., Lang, X.-M., 2016. Timing and associated climate change of a 2 °C global warming. *Int. J. Climatol.* 36 (14), 4512–4522.
- Karmalkar, A.V., Bradley, R.S., 2017. Consequences of global warming of 1.5 °C and 2 °C for regional temperature and precipitation changes in the contiguous United States. *PLoS One* 12 (1), e0168697.
- Knutti, R., Sedláček, J., 2013. Robustness and uncertainties in the new CMIP5 climate model projections. *Nat. Clim. Change* 3 (4), 369–373.
- Knutti, R., Rogelj, J., Sedláček, J., 2016. A scientific critique of the two-degree climate change target. *Nat. Geosci.* 9 (1), 13–18.
- Kong, Y., Wang, C.-H., 2017. Responses and changes in the permafrost and snow water equivalent in the Northern Hemisphere under a scenario of 1.5 °C warming. *Adv. Clim. Change. Res.* 8 (4), 235–244.
- Lang, X.-M., Sui, Y., 2013. Changes in mean and extreme climates over China with a 2 °C global warming. *Chin. Sci. Bull.* 58 (12), 1453–1461.
- Li, B., Zhou, T.-J., 2010. Projected climate change over China under SRES A1B scenario: multi-model ensemble and uncertainties. *Adv. Clim. Change. Res.* 6, 270–276 (in Chinese).
- Port, U., Brovkin, V., Claussen, M., 2012. The influence of vegetation dynamics on anthropogenic climate change. *Earth Syst. Dyn.* 3, 233–243.
- Schleussner, C.F., Lissner, T.K., Fischer, E.M., et al., 2016. Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C. *Earth Syst. Dyn.* 7 (2), 327–351.
- Schmidt, G.A., Shindell, D.T., Tsigaridis, K., 2014. Reconciling warming trends. *Nat. Geosci.* 7 (3), 158–160.
- Seneviratne, S.I., Donat, M.G., Pitman, A.J., et al., 2016. Allowable CO<sub>2</sub> emissions based on regional and impact-related climate targets. *Nature* 529 (7587), 477–483.
- Smith, D.M., Booth, B.B.B., Dunstone, N.J., 2016. Role of volcanic and anthropogenic aerosols in the recent global surface warming slowdown. *Nat. Clim. Change* 6 (10), 936–940.
- Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.* 93 (4), 485–498.
- UNFCCC, 2015. *Adoption of the Paris Agreement. Report No. FCCC/CP/2015/L.9/Rev.1.* <http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf>.
- van Vuuren, D.-P., Edmonds, J., Kainuma, M., et al., 2011. The representative concentration pathways: an overview. *Clim. Change* 109 (1–2), 5.
- Xu, Y., Zhou, B.-T., Wu, J., et al., 2017. Asian climate change under 1.5–4 °C warming targets. *Adv. Clim. Change. Res.* 8, 99–107.
- Zhang, Y., 2012. Projections of 2.0 °C warming over the globe and China under RCP4.5. *Atmos. Ocean. Sci. Lett.* 5 (6), 514–520.