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Changes in mean and extreme climates over China with a 2°C global warming

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Based on a 153-year (1948–2100) transient simulation of East Asian climate performed by a high resolution regional climate model (RegCM3) under the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A1B scenario, the potential future changes in mean and extreme climates over China in association with a global warming of 2°C with respect to pre-industrial times are assessed in this study. Results show that annual temperature rises over the whole of China, with a greater magnitude of around 0.6°C compared to the global mean increase, at the time of a 2°C global warming. Large-scale surface warming gets stronger towards the high latitudes and on the Qinghai-Tibetan Plateau, while it is similar in magnitude but somewhat different in spatial pattern between seasons. Annual precipitation increases by 5.2%, and seasonal precipitation increases by 4.2%–8.5% with respect to the 1986–2005 climatology. At the large scale, apart from in boreal winter when precipitation increases in northern China but decreases in southern China, annual and seasonal precipitation increases in western and southeastern China but decreases over the rest of the country. Nationwide extreme warm (cold) temperature events increase (decrease). With respect to the 1986–2005 climatology, the country-averaged annual extreme precipitation events R5d, SDII, R95T, and R10 increase by 5.1 mm, 0.28 mm d^{-1}, 6.6%, and 0.4 d respectively, and CDD decreases by 0.5 d. There is a large spatial variability in R10 and CDD changes.

2°C global warming, regional climate model, mean and extreme climates, China, projection

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Surface air temperature has increased both over China and globally since the pre-industrial era, a trend that is closely linked to anthropogenic emissions of greenhouse gases and aerosols into the atmosphere, as well as land-use and land-cover changes [1,2]. Global warming and the accompanying changes in mean and extreme climates have affected many aspects of the environment, economy, society, and people's daily lives at global and regional scales. The fact, attribution, and projection of climate change attract more and more attention and have become one of the central issues of the geosciences. Accordingly, it is of interest to perform scientific projections of future climate to cope with global change, upon which climate change mitigation and adaptation strategies in the context of sustainable development can be better made.

Based on studies on the influences of climate change on biogeochemical cycles, and on the key vulnerabilities and risks from climate change, a global warming threshold of 2°C above pre-industrial times has been put forward and subsequently supported and advocated by many countries, including the member states of the European Union, and international organizations [3,4]. The idea is that, once this threshold is passed, the corresponding climate change would lead to irreversible or dangerous changes in the

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components of the climate system, particularly in terms of freshwater resources, food production, sea level rise, ocean acidification, biodiversity reduction, extreme weather and climate events, and, ultimately, impacts upon the human living environment [3,5]. Although there is still debate on the 2°C target, limiting global warming to 2°C has been a central issue of climate change negotiation and a goal for setting greenhouse gas emissions reduction strategies worldwide [4,6–10]. Accordingly, more emphasis is being placed upon the related projections of climate change, such as the time when global temperature change will exceed 2°C above pre-industrial levels [11], and the associated potential changes in mean climate, vegetation, and extreme weather and climate events at global and regional scales [12–16].

In recent years, considerable efforts have been made by Chinese scientists to project future climate changes over the globe and East Asia [2,17,18]. Little attention, however, has been placed on studies of the global warming threshold. Previously, the results of 17 climate models participating in the Coupled Model Intercomparison Project Phase 3 (CMIP3) were used to investigate the future spatial and temporal characteristics of 1, 2, and 3°C warming above 1990–1999 levels over China [19]. Actually, this is a different topic to the 2°C target. Recently, the timing, atmospheric concentration of greenhouse gases, and climate change in China associated with a 2°C global warming above pre-industrial times were examined based on the results of 16 of the CMIP3 climate models [20]. However, the horizontal resolutions of those global models are too coarse when the regional scale is concerned. It is thus necessary to apply dynamical downscaling methods to obtain high resolution information, particularly considering that precipitation over China is more reasonably simulated by high resolution regional climate models [21–25]. Furthermore, extreme weather and climate events impact deeply on our environment and society. Apart from the mean climate change assessed in the aforementioned study [20], to what extent climatic extremes would change in China remains an open question. In the context of these issues, a long-term transient simulation of East Asian climate performed by a regional climate model was used in the present study to project future changes in mean and extreme climates over China at a point when global warming reaches 2°C above pre-industrial times.

1 Data and methods

This research is based on the simulations of the Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climate Model version 3 (RegCM3) [26] under the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A1B scenario [27–29]. Initial conditions and time-dependent lateral boundary conditions used to drive RegCM3 were achieved from simulations conducted with MIROC3.2_hires under the same emissions scenario. The horizontal resolution of the atmospheric component of MIROC3.2_hires is T106, roughly equivalent to 125 km, which is the highest in the CMIP3 archive. MIROC3.2_hires is capable of reproducing the main features of the present East Asian climate [30]. The RegCM3 domain covers China and surrounding areas, with a horizontal grid spacing of 25 km and 18 vertical sigma layers with the top at 10 hPa. RegCM3 is integrated consecutively from 1948 to 2100, and the first three years are used for model adjustment. Note that this represents by far the best simulation in terms of horizontal resolution of East Asian climate for the 21st century, and that RegCM3 has been verified to reproduce temperature and precipitation over China reasonably well for the period 1981–2000, showing particularly good agreement between simulated and observed spatial patterns of summer (June–August) rainfall [28].

Towards an objective identification of the time at which 2°C global warming would occur, global mean temperature series from 2001–2100 as simulated by MIROC3.2_hires under the SRES A1B scenario was first smoothed by a 9-year running mean, so as to exclude the interannual variability of temperature. Since the 2°C target is with respect to pre-industrial times, the corresponding baseline period should not be influenced by climate change in the 20th century. However, the MIROC3.2_hires outputs within the 20th Century Climate in Coupled models (20C3M) data, used for driving RegCM3, span only the period 1900–2000. This period is beyond the scope of pre-industrial times, as is the case for most CMIP3 models. Accordingly, the timing of a 1.4°C global warming above the 1990–2000 level was regarded as an alternative to a 2°C global warming according to the literature [3], because the best estimation of global temperature for that period is 0.6°C above pre-industrial times [1]. In this way, a 2°C global warming above pre-industrial times was identified to occur in the year 2029 in the SRES A1B experiments of MIROC3.2_hires. Comparatively, this year is much earlier than those obtained from other CMIP3 models under the same emissions scenario [20], owing to a faster rate of global warming in MIROC3.2_hires. Finally, the nine years surrounding 2029, namely 2025–2033, correspond to a 2°C global warming above pre-industrial times in the RegCM3 simulations. Below, we address climatic differences between the periods 2025–2033 and 1986–2005, and the reason for choosing the latter as the reference period is that this period has been suggested as the baseline in the climate change projection section of the forthcoming IPCC Fifth Assessment Report.

2 Results

2.1 Changes in mean climate over China with a 2°C global warming

Annual and seasonal temperature (2 m surface air temperature) rises notably relative to 1986–2005 over China in association with a 2°C global warming (Figure 1). Large-scale annual and seasonal warming gets stronger towards the high latitudes and on the Qinghai-Tibetan Plateau compared to surrounding areas, which resembles the spatial pattern of temperature change over China as derived both from observation for the second half of the 20th century and global climate model projection for the 21st century [2]. Annual temperature rises by more than 1.4°C over China except in parts of South China and Southwest China (Figure 1(a)), with a regional average of 2.0°C. This means the annual warming is around 2.6°C above pre-industrial times over the country, which is greater than the simultaneous global warming of 2°C. Such a stronger warming is consistent with the corresponding temperature increase of 2.9°C as obtained from 16 global climate models under the SRES A1B scenario [20], but with a smaller magnitude of around 0.3°C. On the seasonal scale, spring (March–May), summer, autumn (September–November), and winter (December–February) temperature over China rises on average by 1.9,

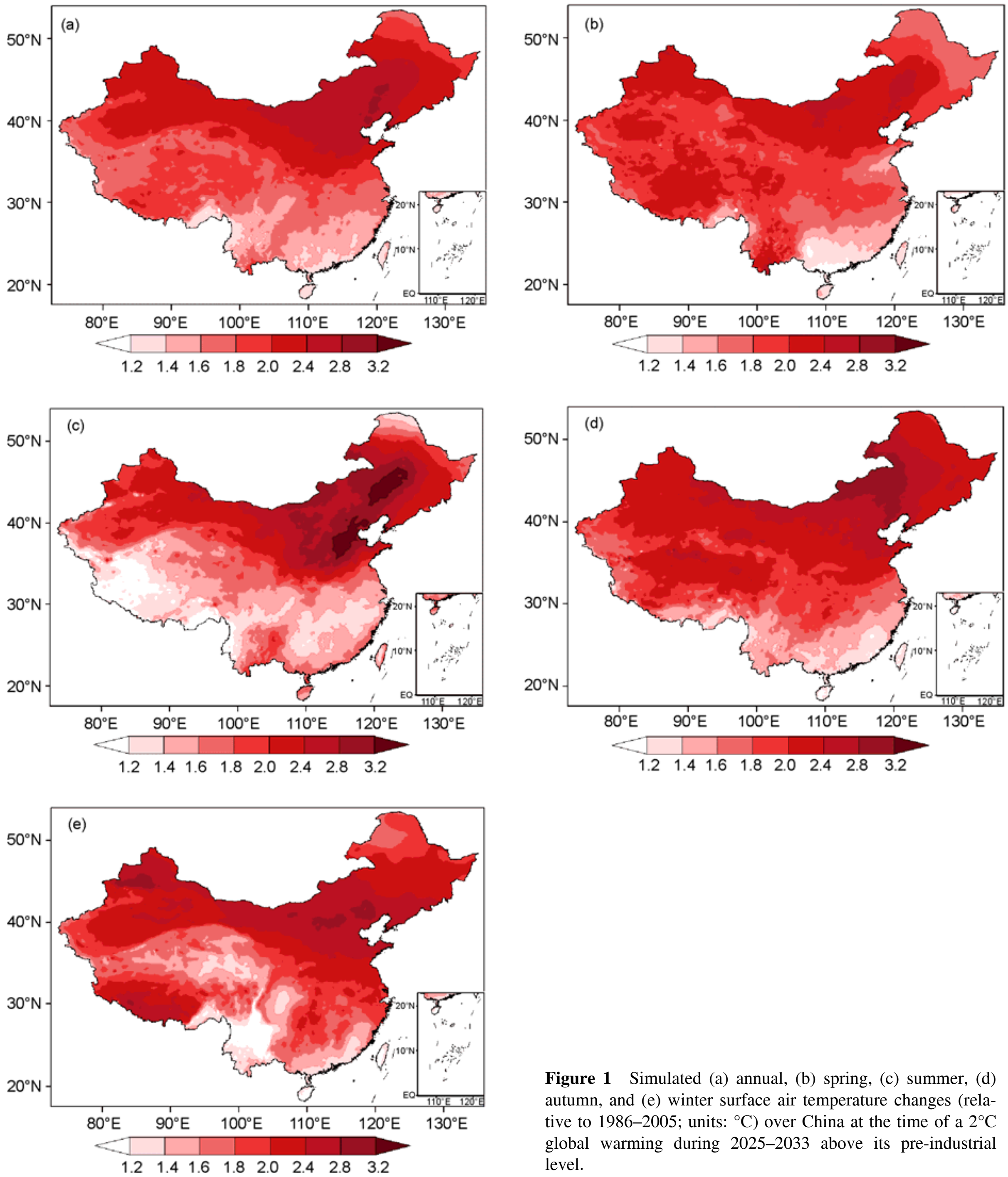


Figure 1 Simulated (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter surface air temperature changes (relative to 1986–2005; units: °C) over China at the time of a 2°C global warming during 2025–2033 above its pre-industrial level.

1.9, 2.0, and 2.0°C respectively, which is near to or the same as the aforementioned annual mean of 2.0°C. The geographical distribution of seasonal temperature changes is similar overall to the annual mean pattern, while there are also differences between them (Figure 1(b)–(e)). For example, warming is greater in northern China, particularly for central and southern Northeast China, and in most parts of North China, but is smaller in South China and on the Qinghai-Tibetan Plateau during summer. Temperature increase is relatively smaller in Southwest China during winter. It is worth noting that these features of seasonal temperature changes still exist by the middle and end of the 21st century [28].

Annual precipitation increases on average by 5.2% relative to 1986–2005 over China in association with a 2°C global warming, and its changes vary regionally and seasonally (Figure 2). As shown in Figure 2(a), annual precipitation increases over western China west of about 105°E and over Southeast China and decreases between those two areas at the large scale. Those changes are mostly less than

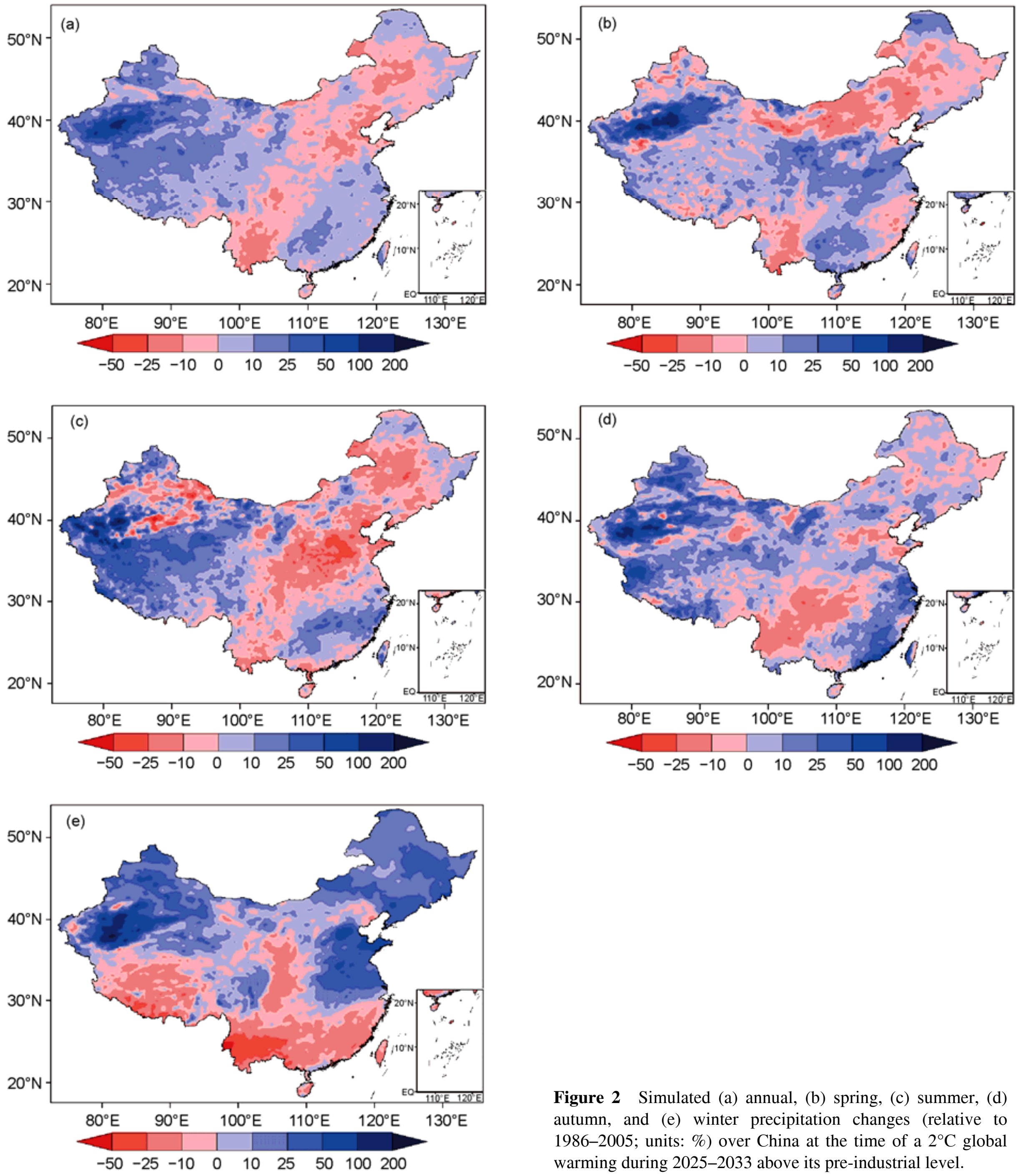


Figure 2 Simulated (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter precipitation changes (relative to 1986–2005; units: %) over China at the time of a 2°C global warming during 2025–2033 above its pre-industrial level.

25% and are relatively larger in the Tarim Basin, and the latter is because annual precipitation is low there for the reference period 1986–2005 in RegCM3 simulations. On the seasonal scale, all spring, summer, autumn, and winter precipitation increases over China, with a regional average of 4.7%, 4.2%, 7.1%, and 8.5% respectively. As is well known, precipitation occurs mainly during the summer rainy season over China, particularly for continental monsoon areas in eastern China. That explains the similarity in the geographical distribution of annual (Figure 2(a)) and summer (Figure 2(c)) precipitation changes. Unlike the annual change, spring precipitation increases over the middle and lower reaches of the Yangtze River and Yellow River valleys (Figure 2(b)), and there are not large-scale precipitation changes over Northeast and North China and the surrounding regions during autumn (Figure 2(d)). Winter precipitation increases over the north but decreases over the south of the country, particularly for the Tarim Basin and the Jianghuai valley (the Qinghai-Tibetan Plateau and South China) where it increases (decreases) mostly by 10%–50% (Figure 2(e)). It is also noted that in Southwest China, including Yunnan Province where severe droughts have frequently occurred in recent years, both annual and seasonal precipitation decreases, as in the cases obtained from RegCM3 for the middle and end of the 21st century [28].

The East Asian monsoon also changes relative to 1986–2005 in association with a 2°C global warming. During summer, atmospheric circulation anomalies at 850 hPa feature northerly winds over central and eastern Northeast China and over the Bohai Sea and adjacent areas but southerly winds over southern China south of about 30°N (Figure 3(a)). Summer monsoon weakening in the former areas occurs because the appearance of an anomalous low pressure system over Japan and the ocean east of Japan weakens the warm high pressure system over the western North Pacific, leading to the western branch of the resulting cyclonic circulation anomalies at 850 hPa being a northerly wind over the former areas. On the contrary, a stronger warming over continental East China than over the South China Sea owing to the smaller heat capacity of the land enhances the meridional thermal contrast, and in turn anomalous southerly winds occur over South China.

During winter, a cold high pressure system dominates over the Eurasian continent, whereas a warm low pressure system dominates over the western North Pacific. This large-scale sea level pressure pattern leads to prevailing northerly winds in the lower troposphere over East China (Figure 3(b)). Relative to 1986–2005, anomalous southerly winds at 850 hPa occur over East China north of about 35°N in association with a 2°C global warming. Such a weakening monsoon circulation occurs because under the same or similar positive radiative forcing, the rate of warming is faster over the mid-high latitudes of the eastern Eurasian continent than over the western North Pacific as a consequence of the difference in heat capacity between land and ocean. As a result, zonal and northwest–southeast thermal and sea level pressure differences between those two areas decrease [31], and in turn northwesterly winds weaken over northern East China.

2.2 Changes in extreme climates over China with a 2°C global warming

Ten extreme climate events widely used in the literature [32] are investigated in this study. Of these, five are extreme temperature events (FD, ETR, GSL, HWDI and Tn90), and five are extreme precipitation events (R10, CDD, R5d, SDII and R95T). Their full names and definitions are given in Table 1.

All indices of extreme temperature events excluding ETR show a consistent trend relative to 1986–2005 over China in association with a 2°C global warming (Figure 4). FD

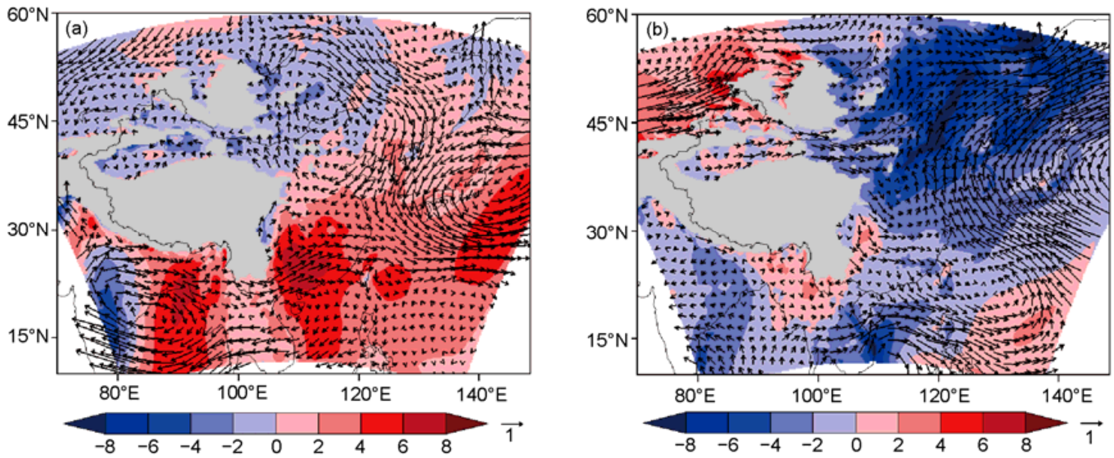


Figure 3 Simulated changes in (a) summer and (b) winter winds at 850 hPa (relative to 1986–2005; vector; units: m s^{-1}), together with their climatological meridional wind at 850 hPa during 1986–2005 (shading; northward wind is positive; units: m s^{-1}), over China at the time of a 2°C global warming during 2025–2033 above its pre-industrial level.

Table 1 Definition of indicators of climatic extremes [32]

Indicator	Definition	Unit
FD	Total number of frost days (days with absolute minimum temperature <0°C)	d
ETR	Intra-annual extreme temperature range: difference between the highest and lowest daily temperature of a given calendar year	°C
GSL	Growing season length: period between when daily temperature >5°C for >5 d and daily temperature <5°C for >5 d	d
HWDI	Heat wave duration index: maximum period >5 consecutive days with daily maximum temperature >5°C above the mean daily maximum temperature during 1986–2005	d
Tn90	Warm night index: percent of time when daily minimum temperature >90th percentile of daily minimum temperature	%
R10	Number of days with precipitation ⩾10 mm d^{-1}	d
CDD	Maximum number of consecutive dry days with daily precipitation <1 mm	d
R5d	Maximum 5-day precipitation total	mm
SDII	Simple daily intensity index: ratio of annual total to the number of precipitation with daily precipitation ⩾1.0 mm	mm d^{-1}
R95T	Fraction of total annual precipitation due to events exceeding the 1986–2005 95th percentile	%

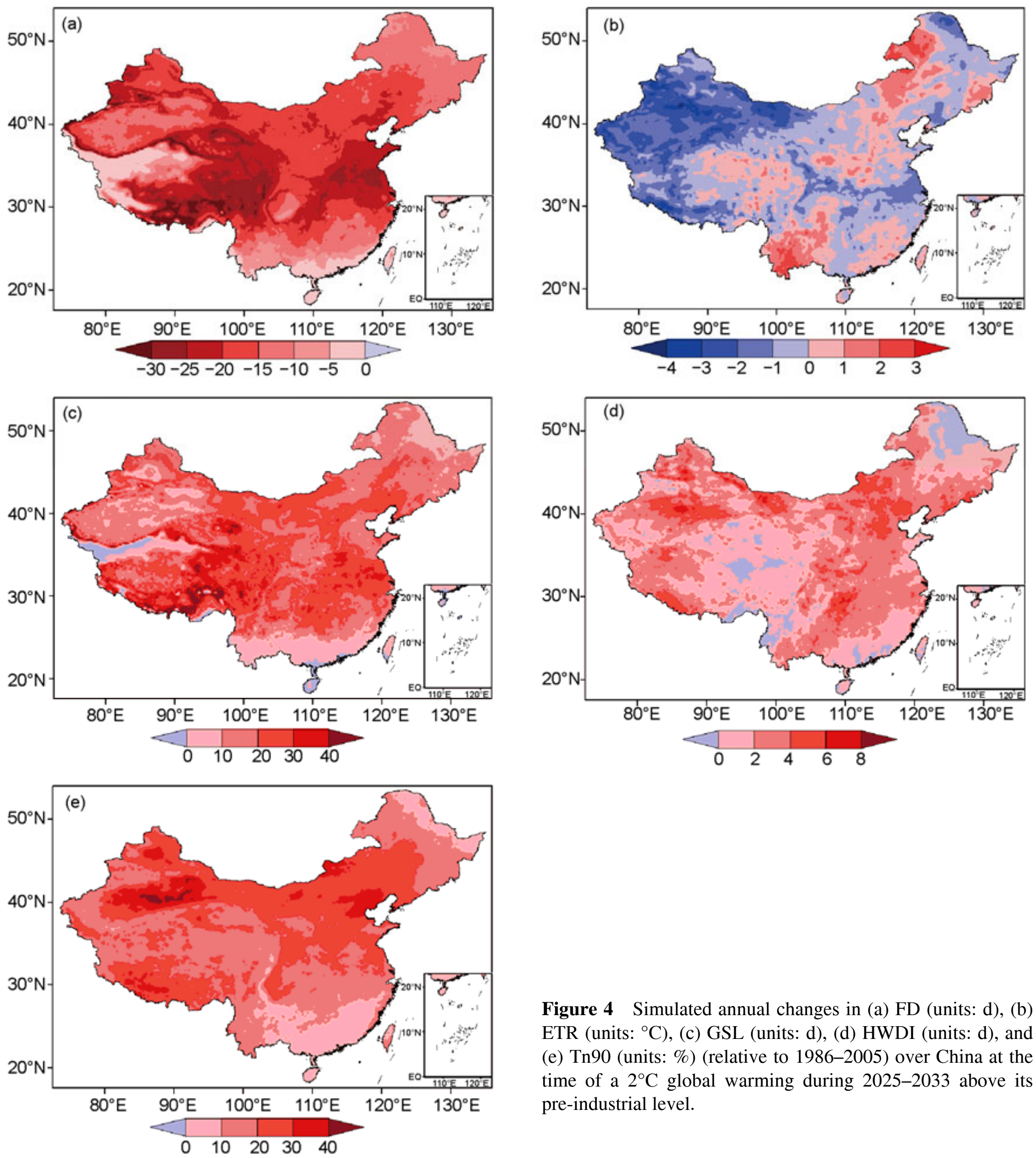


Figure 4 Simulated annual changes in (a) FD (units: d), (b) ETR (units: °C), (c) GSL (units: d), (d) HWDI (units: d), and (e) Tn90 (units: %) (relative to 1986–2005) over China at the time of a 2°C global warming during 2025–2033 above its pre-industrial level.

decreases over China, with a regional average of –17.0 d. It decreases by 0–10 d over part of South China and western Tibet, by 10–20 d over most parts of northern China, and by 20–30 d over the lower reaches of the Yangtze River and Yellow River valleys and over the central and eastern Qinghai-Tibetan Plateau. ETR decreases over Xinjiang, central and western Inner Mongolia, western and southernmost Tibet, northern Northeast China, and over part of the middle and lower reaches of the Yangtze River valley, but increases over the rest of the country, particularly eastern Inner Mongolia and Southwest China. Most of the ETR changes are within the range of ±3°C, with a regional average of –0.5°C. GSL increases over China apart from in northwesternmost Tibet, part of coastal South China, and Hainan Island. It increases by 0–10 d over southern South China, northern Northeast China, and northern Tibet, and by more than 20 d, with a local maximum of more than 40 d, over southeastern Tibet. GSL increases on average by 18.1 d over the whole of the country. HWDI increases by 0–6 d over most parts of China, with a regional average of 2.1 d. In contrast, it decreases slightly over northern Northeast China, coastal South China, the eastern Qinghai-Tibetan Plateau, and part of Southwest China. Tn90 increases on average by 19.2% over China, with relatively small (large) changes over South China and northernmost Northeast China (Beijing, Tianjin, Hebei, and central-southern Xinjiang). Collectively, warm temperature extremes increase, while cold temperature extremes decrease over China. These are consistent with observed changes in extreme temperature changes over China for the second half of the 20th century [18,33].

Extreme precipitation events differ from the period 1986–2005 over China in association with a 2°C global warming (Figure 5). R10 increases over western China west of about 105°E, northern and eastern Northeast China, South China, and the lower reaches of the Jianghuai valley, but decreases over most parts of Southwest China, North China, and central and southern Northeast China, with a regional average of 0.4 d. CDD generally decreases (increases) in the areas north (south) of about 35°N. It decreases by 20–60 d over most parts of the Tarim Basin, but increases by more than 5 d over central and eastern Tibet and part of South China, while it changes mostly within the range of –20 d to 5 d over the rest of the country. CDD decreases by an average of 0.5 d over China. R5d increases over most parts of China except Huanghuai and part of Southwest China, with a regional average of 5.1 mm, and it increases by more than 10 mm over part of South and Northeast China. SDII slightly decreases over part of Southwest China and part of the lower reaches of the Yellow River valley, but increases over most parts of the rest of the country, particularly South China, the lower reaches of the Yangtze River valley, part of southern Northeast China, and part of the Tarim Basin where it increases by 1.0–1.5 mm d^{-1}. SDII increases by an average of 0.28 mm d^{-1} over China, which means an enhanced intensity for each precipitation event. In addition, R95T increases over most parts of China except part of South China, with a regional average of 6.6%, indicating an enhanced contribution of extreme heavy precipitation to total annual precipitation.

3 Conclusions

In this study, the period of time during which a global warming of 2°C above pre-industrial times will occur was first identified as 2025–2033 according to the results of MIROC3.2_hires, which was used to drive a 25-km horizontal resolution version of RegCM3 for the period 1948–2100 under the SRES A1B scenario. The RegCM3 transient simulation of East Asian climate was then used to examine future changes in annual and seasonal mean climates and trends in 10 extreme climate events over China for the period 2025–2033, relative to the period 1986–2005. The primary results in association with a 2°C global warming are as follows.

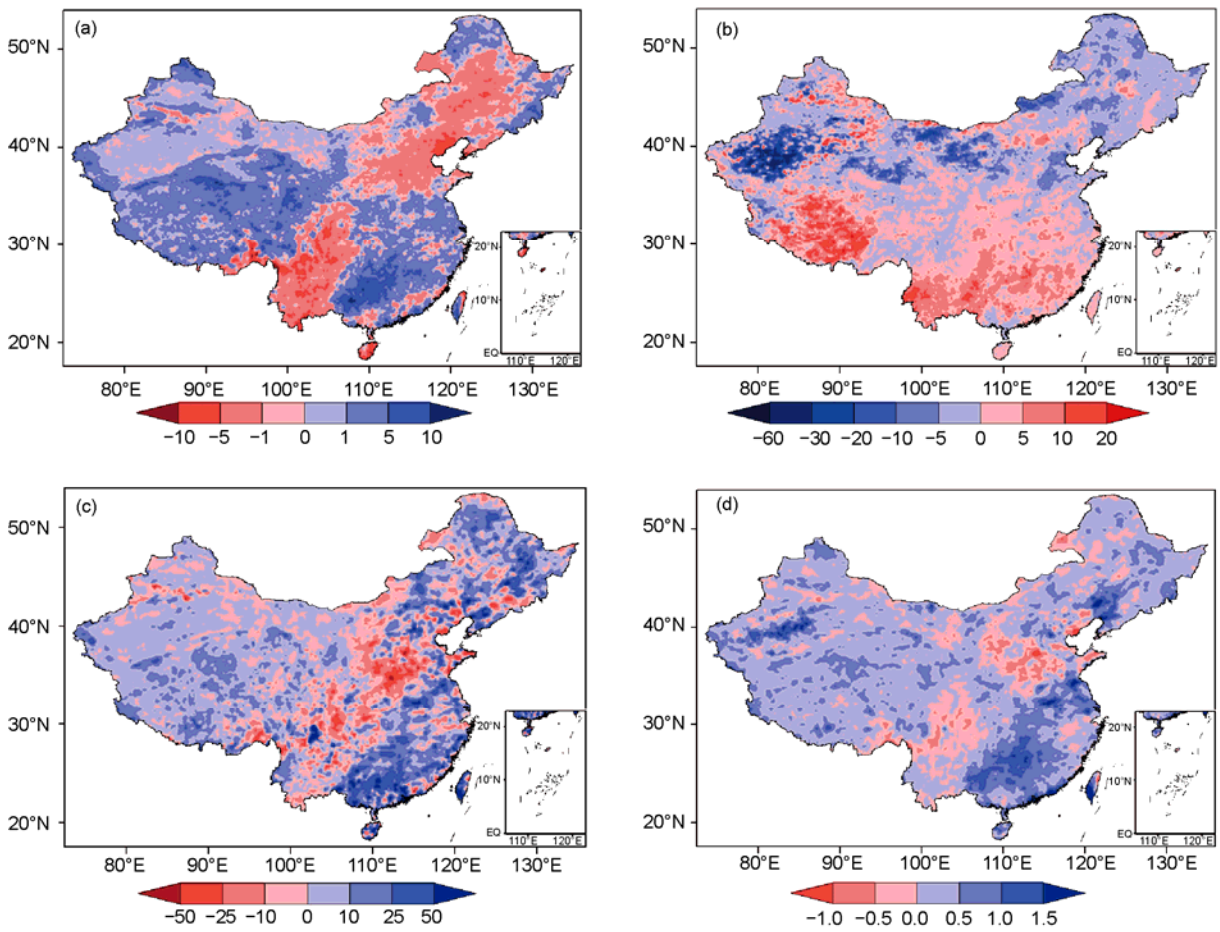
(1) Annual and seasonal temperature rises over China, and the annual warming is around 0.6°C greater than the simultaneous global warming of 2°C. Surface warming becomes stronger towards the high latitudes and over the Qinghai-Tibetan Plateau compared to surrounding areas. There exists a difference in the spatial pattern of temperature changes between seasons.

(2) Annual precipitation increases on average by 5.2% over China. Regionally, it generally increases over western and southeastern China, but decreases between those two areas. Precipitation increases in all seasons, with a similar spatial pattern to the annual mean, except in winter when an increase (decrease) appears over northern (southern) China.

(3) Summer monsoon slightly weakens (strengthens) north (south) of about 30°N over East China, and winter monsoon weakens only north of about 35°N over East China. Both occur because of changes in the land–sea thermal contrast and sea level pressure gradient, as well as associated large-scale atmospheric circulation.

(4) Averaged over China, FD, ETR, and CDD decrease by 17.0 d, 0.5°C, and 0.5 d, while GSL, HWDI, Tn90, R10, R5d, SDII, and R95T increase by 18.1 d, 2.1 d, 19.2%, 0.4 d, 5.1 mm, 0.28 mm d^{-1}, and 6.6% respectively. Changes in those indices differ between the regions to a varying degree.

As reviewed in the introduction, limiting global warming to 2°C has been a target for international negotiation on climate change and for setting greenhouse gas emissions reduction strategies. Although there is still debate on the target, it is necessary to further use high resolution climate change information to investigate regional influence and vulnerability over China associated with a 2°C global warming, particularly for agriculture, hydrology, and surface ecosystems [34,35]. In this way, we can better understand what the 2°C global warming most likely means for



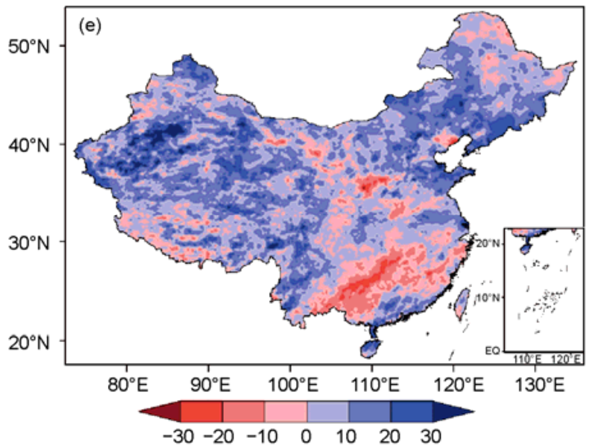


Figure 5 Simulated annual changes in (a) R10 (units: d), (b) CDD (units: d), (c) R5d (units: mm), (d) SDII (units: mm d^{-1}), and (e) R95T (units: %) (relative to 1986–2005) over China at the time of a 2°C global warming during 2025–2033 above its pre-industrial level.

future climate and the environment over China, upon which national policies on climate change can be made more reasonably.

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1 IPCC. Climate Change 2007: The Physical Science Basis. In: Solomon S, Qin D, Manning M, et al., eds. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York: Cambridge University Press, 2007. 1–996
2 Ding Y H, Ren G Y, Zhao Z C, et al. Detection, causes and projection of climate change over China: An overview of recent progress. Adv Atmos Sci, 2007, 24: 954–971
3 Schneider S H, Semenov S, Patwardhan A, et al. Assessing key vulnerabilities and the risk from climate change. In: Parry M L, Canziani O F, Palutikof J P, et al., eds. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the

Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2007. 779–810
4 Meinshausen M, Meinshausen N, Hare W, et al. Greenhouse-gas emission targets for limiting global warming to 2°C. Nature, 2009, 458: 1158–1163
5 Fischlin A, Midgley G F, Price J T, et al. Ecosystems, their properties, goods, and services. In: Parry M L, Canziani O F, Palutikof J P, et al., eds. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2007. 211–272
6 Ding Z L, Duan X N, Ge Q S, et al. Control of atmospheric CO_2 concentrations by 2050: A calculation on the emission rights of different countries. Sci China Ser D-Earth Sci, 2009, 52: 1447–1469
7 Gleick P H, Adams R M, Amasino R M, et al. Climate change and the integrity of science. Science, 2010, 328: 689–690
8 Guivarch C, Hallegatte S. Existing infrastructure and the 2°C target. Clim Change, 2011, 109: 801–805
9 Rogelj J, Hare W, Lowe J, et al. Emission pathways consistent with a 2°C global temperature limit. Nat Clim Chang, 2011, 1: 413–418
10 van Vuuren D P, Stehfest E, den Elzen M G J, et al. RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. Clim Change, 2011, 109: 95–116
11 Joshi M, Hawkins E, Sutton R, et al. Projections of when temperature change will exceed 2°C above pre-industrial levels. Nat Clim Chang, 2011, 1: 407–412
12 Kaplan J O, New M. Arctic climate change with a 2°C global warming: Timing, climate patterns and vegetation change. Clim Change, 2006, 79: 213–241
13 Giannakopoulos C, Le Sager P, Bindi M, et al. Climatic changes and associated impacts in the Mediterranean resulting from a 2°C global warming. Glob Planet Change, 2009, 68: 209–224
14 May W. The sensitivity of the Indian summer monsoon to a global warming of 2°C with respect to pre-industrial times. Clim Dyn, 2011, 37: 1843–1868
15 May W. Assessing the strength of regional changes in near-surface climate associated with a global warming of 2°C. Clim Change, 2012, 110: 619–644
16 Anderson B T. Intensification of seasonal extremes given a 2°C global warming target. Clim Change, 2012, 112: 325–337
17 Xu Y, Xu C H, Gao X J, et al. Projected changes in temperature and precipitation extremes over the Yangtze River Basin of China in the 21st century. Quat Int, 2009, 208: 44–52
18 Wang H J, Sun J Q, Chen H P, et al. Extreme climate in China: Facts, simulation and projection. Meteorol Z, 2012, 21: 279–304
19 Jiang D, Zhang Y, Sun J Q. Ensemble projection of 1–3°C warming in China. Chin Sci Bull, 2009, 54: 3326–3334
20 Jiang D, Fu Y H. Climate change over China with a 2°C global warming (in Chinese). Chin J Atmos Sci, 2012, 36: 234–246
21 Gao X J, Xu Y, Zhao Z C, et al. On the role of resolution and topography in the simulation of East Asia precipitation. Theor Appl Climatol, 2006, 86: 173–185
22 Ju L X, Wang H J, Jiang D. Simulation of the Last Glacial Maximum climate over East Asia with a regional climate model nested in a general circulation model. Palaeogeogr Palaeoclimatol Palaeoecol, 2007, 248: 376–390
23 Zhang D F, Gao X J, Ouyang L C. Simulation of present climate over East Asia by a regional climate model. J Trop Meteorol, 2008, 14: 19–23
24 Gao X, Shi Y, Song R, et al. Reduction of future monsoon precipitation over China: Comparison between a high resolution RCM simulation and the driving GCM. Meteorol Atmos Phys, 2008, 100: 73–86
25 Yu E T, Wang H J, Sun J Q. A quick report on a dynamical downscaling simulation over China using the nested model. Atmos Oceanic Sci Lett, 2010, 3: 325–329
26 Pal J S, Giorgi F, Bi X Q, et al. Regional climate modeling for the developing world: The ICTP RegCM3 and RegCNET. Bull Amer Meteorol Soc, 2007, 88: 1395–1409
27 Shi Y, Gao X J, Zhang D F, et al. Climate change over the Yarlung Zangbo-Brahmaputra River Basin in the 21st century as simulated by a high resolution regional climate model. Quat Int, 244: 159–168
28 Gao X J, Shi Y, Zhang D F, et al. Climate change in China in the 21st century as simulated by a high resolution regional climate model. Chin Sci Bull, 2012, 57: 1188–1195
29 Gao X J, Shi Y, Zhang D F, et al. Uncertainties in monsoon precipitation projections over China: Results from two high-resolution RCM simulations. Clim Res, 2012, 52: 213–226
30 Xu C H, Shen X Y, Xu Y. An analysis of climate change in East Asia by using the IPCC AR4 simulations (in Chinese). Adv Climate Change Res, 2007, 3: 287–292
31 Sui Y, Lang X. Monsoon change in East Asia in the 21st century: Results of RegCM3. Atmos Oceanic Sci Lett, 2012, 5: 504–508
32 Frich P, Alexander L V, Della-Marta P, et al. Observed coherent changes in climatic extremes during the second half of the twentieth century. Clim Res, 2002, 19: 193–212
33 Ren G Y, Feng G L, Yan Z W. Progresses in observation studies of climate extremes and changes in mainland China (in Chinese). Clim Environ Res, 2010, 15: 337–353
34 Chavas D R, Izaurralde R C, Thomson A M, et al. Long-term climate change impacts on agricultural productivity in eastern China. Agric For Meteorol, 2009, 149: 1118–1128
35 Xu H M, Taylor R G, Kingston D G, et al. Hydrological modeling of River Xiangxi using SWAT2005: A comparison of model parameterizations using station and gridded meteorological observations. Quat Int, 2010, 226: 54–59