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Additional Intensification of Seasonal Heat and Flooding Extreme Over China in a 2°C Warmer World Compared to 1.5°C

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Key Points:

- Global warming levels of 1.5°C and 2°C will lead to increases in surface air temperature and precipitation averaged over China
- Seasonal heat and flooding extremes over China will become more frequent in a 1.5°C or 2°C warmer world
- Limiting the global warming at 1.5°C rather than 2°C will substantially reduce the frequency of those seasonal climate extremes in China

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Abstract The Paris Agreement commits to stabilizing global mean surface warming to below 2°C (above preindustrial levels) and strives to limit it to 1.5°C to mitigate the risks of anthropogenic climate change. This study explores the impacts of stabilized 1.5°C and 2°C warming in the late 21st century on seasonal climate extremes over China by using a set of coupled Earth system model simulations explicitly targeting these warming levels. Our results show that global warming levels of 1.5°C and 2°C will lead to increases in surface air temperature (precipitation) averaged over China of 1.3°C and 1.9°C (11.6% and 13.3%), respectively, compared to 1976–2005. Climate extremes over China will become more frequent in a warmer world. Relative to the 1976–2005, the frequency of events similar to the 2013 extreme hot summer in eastern China and extreme flooding during the summer of 2010 in southeastern China will increase by 16 or 33 times and 2 or 3 times, respectively, given a global temperature increase of 1.5°C or 2°C. In particular, events similar to the 2013 extreme hot summer will occur almost yearly in a 2°C warmer world. The likelihood of an event similar to the 2014 extreme hot spring in northeastern China will increase to 8% or 20% in a 1.5°C or 2°C warmer world, whereas such events were rare during 1976–2005. Given these dangerous consequences, we conclude that there are discernible benefits for China to contribute to the global decarbonization effort to limit global warming to below 1.5°C rather than 2°C.

1. Introduction

The 2015 Paris Agreement committed to limiting the increase in global mean surface temperature (GMST) to well below 2°C, with a recommended limit of 1.5°C above preindustrial levels to avoid the impacts of anthropogenic climate change (United Nations Framework Convention on Climate Change, 2015). The Intergovernmental Panel on Climate Change (IPCC) has been invited to provide a special report on the impacts of 1.5°C and 2°C global warming in 2018. Therefore, the scientific community is compelled to widely and rapidly perform corresponding assessments to provide reliable information for policymaking with respect to climate mitigation and adaptation.

Although basic to intermediate climate model studies have reported emission pathways consistent with the 1.5°C and 2°C targets (Meinshausen et al., 2009; Rogelj et al., 2015; Xu & Ramanathan, 2017), simulation scenarios for the 1.5°C and 2°C warming levels have not been performed using global climate models (GCMs) until recently (Sanderson et al., 2017). Most previous modeling studies have adopted an alternative approach: extracting the model output from the Coupled Model Intercomparison Program phase 5 (CMIP5) for periods during the 21st century in which the increase in GMST reaches 1.5°C and 2°C under IPCC Representative Concentration Pathway (RCP) scenarios (the "time sampling" approach, James et al., 2017). For example, Schleussner et al. (2016) extracted the CMIP5 model output for periods of 1.5°C and 2°C warming under the RCP8.5 scenario and assessed the impacts of these warming levels on climate extremes, water availability, agricultural yields, sea level rise, and risk of coral reef loss. Huang et al. (2017) analyzed the influence of 1.5°C and 2°C warming over global drylands using a combination of CMIP5 simulations under four RCP scenarios. Similarly, King et al. (2017) evaluated the effects of different levels of warming on large-scale climate extremes that have occurred in Australia. That study was the first to link past extreme events to future climate change. Some recent studies also explored the changes in mean climate and climate extremes under different levels of global warming using the RCP scenario simulations (e.g., Jiang et al., 2016; Sui et al., 2018; Wang, Jiang, & Lang 2017).

However, there are substantial disadvantages in using the time sampling approach (James et al., 2017), as we will discuss below.

First, the increase in GMST reaches 1.5°C and 2°C only transiently in the CMIP5 simulations under the RCP scenarios (Chen & Zhou, 2016). There are likely to be large differences between the impacts of transient and stabilized 1.5°C and 2°C warming levels, especially at regional scales (James et al., 2017).

Second, the composition of radiative forcing in scenarios with stabilized 1.5°C and 2°C warming is likely to differ from that in scenarios with transient 1.5°C and 2°C warming, such as changes due to short-lived pollutants (Rao et al., 2016). Many studies have indicated that the changes in climate variables (precipitation and climate extremes) per degrees Celsius of surface warming depend significantly on the underlying emission scenarios, that is, the composition of forcing (Lin, Gettelman, et al., 2016; Lin, Wang, et al., 2016; Mitchell et al., 2016; Samset et al., 2016; Tebaldi et al., 2015; Wang, Lin, Zhang, et al., 2017; Xu & Lin, 2017).

Thus, it is crucial to perform climate scenario simulations with stabilization at the warming levels defined by the Paris Agreement. Although the Half a Degree Additional Warming, Projections, Prognosis, and Impacts model intercomparison project generated such simulations (Mitchell et al., 2017) that have been widely used (e.g., Chevuturi et al., 2018; Lewis et al., 2017), they all applied fixed climatological sea surface temperatures and therefore did not account for coupled atmosphere-ocean internal variations such as the El Niño Southern Oscillation and the Pacific Decadal Oscillation. Ignoring this important source of internal ocean-atmosphere variability can lead to significant underestimation of the climate response to extra forcing (Lehner et al., 2017). Recently, Sanderson et al. (2017) performed fully coupled climate simulations specifically targeting stabilized warming levels of 1.5°C and 2°C in the late 21st century, using the Community Earth System Model, Version 1 (CESM1) for the first time; thus, the consequences of 1.5°C and 2°C warming could be assessed across geographical regions and climate fields.

China has experienced significant impacts of anthropogenic warming in recent decades, including more frequent droughts and flooding and intensified heat extremes (Sun et al., 2014; Zhai et al., 2005). It is vital to quantify the potential impact of 1.5°C and 2°C warming over China for the purpose of policymaking with respect to climate change adaptation and mitigation. This study examined the impacts of stabilized 1.5°C and 2°C warming in the late 21st century over China using a set of CESM1 ensemble simulations (Sanderson et al., 2017). We focused specifically on future changes in the likelihoods of disastrous events similar to several recent seasonal climate extremes.

2. Methods

2.1. Model and Simulations

CESM is a fully coupled ocean-atmosphere-land-sea ice model (Hurrell et al., 2013). The horizontal resolution is 0.9° latitude ×1.25° longitude for the atmosphere and land and 1° × 1° for the ocean. The atmosphere vertical resolution is 30 levels, with a rigid lid at 4 hPa. CESM1 includes the main anthropogenic forcing agents, such as greenhouse gases, sulfate, black carbon, primary organic carbon, and tropospheric and stratospheric ozone. The model includes physical representations of direct, semidirect, and indirect aerosol effects (Ghan et al., 2012). CESM1 is able to simulate present-day climate extremes over China reasonably well (Li et al., 2016; Lin et al., 2015; Wang, Lin, et al., 2016; Figure 1). To investigate the impacts of 1.5°C and 2°C warming, four sets of CESM1 ensemble simulations were used.

1. The RCP8.5 large ensemble (LE; Kay et al., 2015). This ensemble simulation consists of 30 members from 1920 to 2100 following the IPCC Fifth Assessment Report historical emissions and RCP8.5 scenario (Riahi et al., 2007). Each member uses the same trajectory for greenhouse gases and aerosol forcings but with slightly different initial atmospheric conditions. This study used only the historical simulation from 1976 to 2005 as the baseline period to assess future changes.
2. The 2°C *never-exceed* scenario (2degNE; Sanderson et al., 2017). This simulation projects that the multiyear increase in GMST will never exceed 2°C above the preindustrial climate (1850–1920). It consists of a 10-member ensemble from 2006 to 2100.

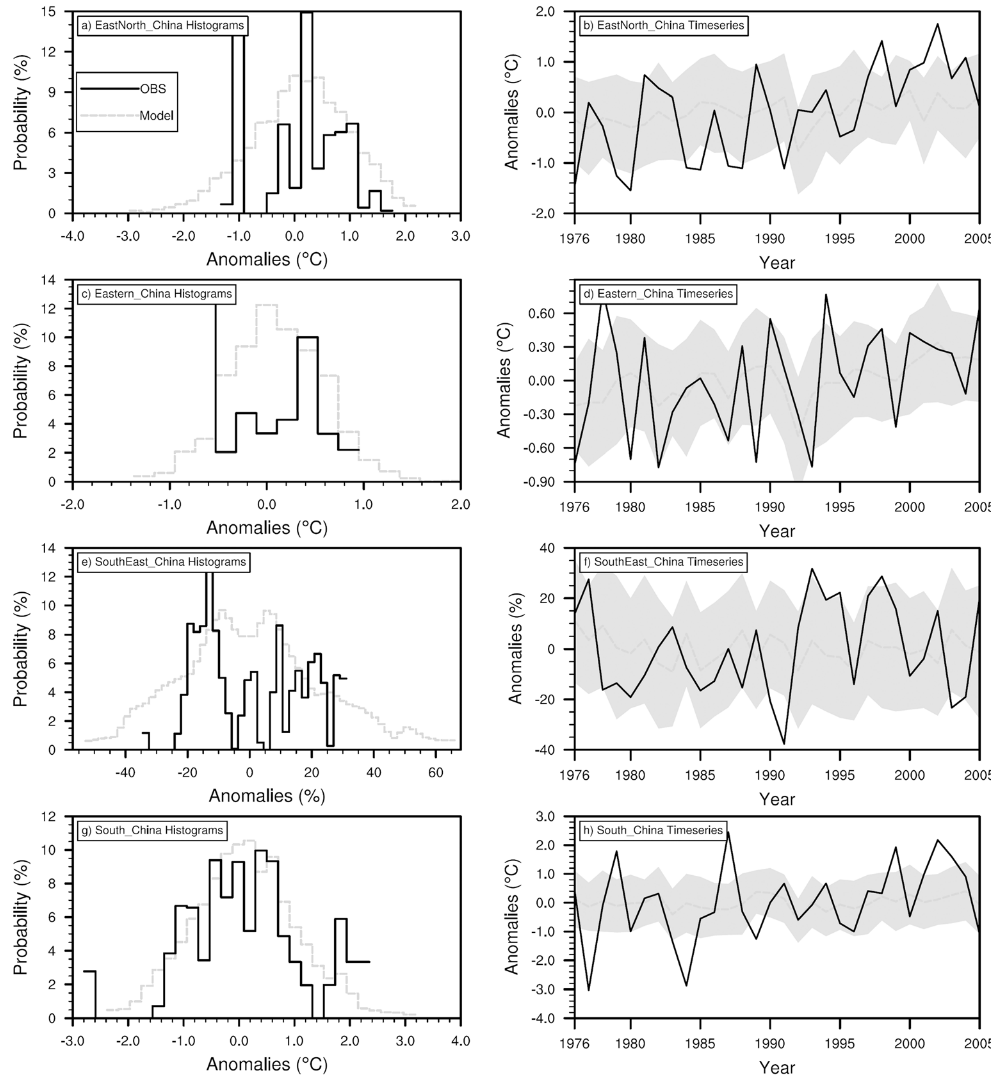

Figure 1. Evaluation of model-simulated probability of seasonal climate anomalies. Histograms (left column) and time series (right column) of (a, b) spring surface air temperature anomalies averaged over northeastern China, (c, d) summer surface air temperature anomalies averaged over eastern China, (e, f) summer precipitation anomalies (%) averaged over southeastern China, and (g, h) winter (January and February) surface air temperature anomalies averaged over southern China from 1976 to 2005 for observations (black; Wu & Gao, 2013) and 30-member historical simulations (gray). The gray shading represents one standard deviation of ensemble simulations.

3. The 1.5°C never-exceed scenario (1.5degNE; Sanderson et al., 2017). This simulation projects that the multiyear increase in GMST will never exceed 1.5°C. It consists of a 10-member ensemble from 2006 to 2100.
4. The 1.5°C *overshoot* scenario (1.5degOS; Sanderson et al., 2017). This simulation projects that the increase in GMST will temporarily overshoot the 1.5°C limit but will return to 1.5°C by the end of the 21st century. It consists of a five-member ensemble from 2006 to 2100.

For simulations (2)–(4), a simple model, the Minimal Complexity Earth Simulator, was used to determine the optimal emission pathway leading CESM1 to a desired warming level. These simulations stem from the historical simulations in RCP8.5 LE performed in 2006 (i.e., replacing the RCP8.5 scenario with specially constructed scenarios for 1.5°C and 2°C warming) and produce sets of ensemble simulations that stabilize warming at 1.5°C and 2°C by the end of the 21st century (Figure 1b in Sanderson et al., 2017). The details of the scenario pathways and simulations can be found in Sanderson et al. (2017). Multimember ensemble simulations are useful in quantifying the uncertainties in our results due to internal climate variability.

2.2. Calculation of Climate Extremes

We selected historical simulations from 1976 to 2005 in the RCP8.5 LE as a baseline (Hist; GMST had increased by about 0.4°C during this period above preindustrial). We selected 2006–2025 in the 1.5degNE scenario to represent the present-day climate (i.e., a 20-year window centered in 2016). The projected 2081–2100 climates under the 1.5degNE, 1.5degOS, and 2degNE scenarios were taken as stabilized 1.5°C or 2°C global warming. Changes in temperature, precipitation, and climate extremes over China in a 1.5°C or 2°C warmer world were relative to the 1976–2005 climate.

This study focused on large-scale seasonal climate extremes, not daily extremes. We selected four specific large-scale extreme climate events that occurred over China during the past decade, including the 2008 cold winter (January and February) in southern China (103.5–114.5°E, 20.5–29.5°N), 2010 summer flood in southeastern China (113–119°E, 24.5–29.5°N), 2013 hot summer in eastern China (110–122°E, 25–38°N), and 2014 hot spring in northeastern China (113–124°E, 34–45°N). These seasonal extreme events have caused considerable economic losses and casualties and were well reported in the news media. We first obtained the spatial pattern of temperature or precipitation anomalies for a specific seasonal extreme event relative to the mean climate of reference period (1976–2005) based on the observations. We then determined the spatial scope and calculated the spatially averaged anomaly of the extreme. The model-simulated annual result from each member was taken as an independent sample. We calculated the simulated temperature or precipitation anomaly averaged over the temporal and spatial scope of the observed extreme event in each sample relative to the 1976–2005 climate. When the anomaly in each sample was equal to or greater than that in the observed extreme listed above, we defined it as an extreme event similar to the specific seasonal climate extreme in the simulations. The probability of an anomaly in each sample during the selected periods (present day and future) was calculated. Finally, the likelihood of events similar to these past extremes under global temperature increases of 1.5°C and 2°C was quantified. A similar approach was used by King et al. (2015, 2017).

Figure 1 shows an evaluation of simulated seasonal mean surface air temperature and precipitation anomalies in the four regions over China, compared to observational data from 1976 to 2005. The observational data set was obtained from the National Climate Center, China Meteorological Administration (Wu & Gao, 2013). In general, the model is able to reasonably capture the probability distributions and time evolution of temperature and precipitation anomalies over these regions. However, there are some deficiencies in the model results. For example, the model overestimates the probability of smaller anomalies (Figures 1c and 1e).

3. Results

3.1. Temporal and Spatial Climate Variation in China in a 1.5°C or 2°C Warmer World

We first examine the time series of projected changes in annual mean surface air temperature and precipitation averaged over China under the 1.5degOS, 1.5degNE, and 2degNE scenarios (Figures 2a and 2b). Compared to the 1976–2005 climate, the 1.5degNE and 2degNE scenarios lead to continuous surface warming over China until the 2050s and stabilization at about 1.3°C and 1.9°C, respectively (Figure 2a). This result is consistent with that reported by Hu et al. (2017) using the CMIP5 multimodel ensemble simulations under the RCP scenarios, which suggested that China would warm more than the global average under 1.5°C and 2°C warming relative to the preindustrial level. Warming over China reaches a peak at 1.6°C in the 2050s before returning to 1.3°C by 2100 under the 1.5degOS scenario relative to the 1976–2005 climate (Figure 2a). Therefore, limiting the GMST increase to 1.5°C rather than 2°C will decrease potential surface warming over China by 0.6°C.

The projected change in precipitation is different from that in surface air temperature in the 21st century (Figure 2b). Average precipitation over China exhibits an almost linear increase with time under all scenarios. There is little difference in the change in precipitation among scenarios before the 2050s. However, after the 2050s, the 2degNE scenario produces more precipitation due to larger warming. As be seen in Figure 2, the precipitation over China still increases while the temperature decreases after the 2050s under the 1.5degNE and 1.5degOS scenarios. This is likely due to the effect of aerosol forcing. Previous studies have indicated that aerosol forcing played a key role in driving the decrease in precipitation over the Asian region during the historical period (Li et al., 2015; Polson et al., 2014). All other forcings including aerosol emissions, ozone, and land use follow RCP8.5 throughout the 21st century in 1.5degNE and 1.5degOS (Sanderson et al., 2017). Therefore, the decreased aerosol emissions will cause an increase in precipitation after the 2050s in those scenarios (Wang, Zhang, & Zhang, 2016). Relative to the 1976–2005 climate, the GMST increases of 1.5°C and 2°C

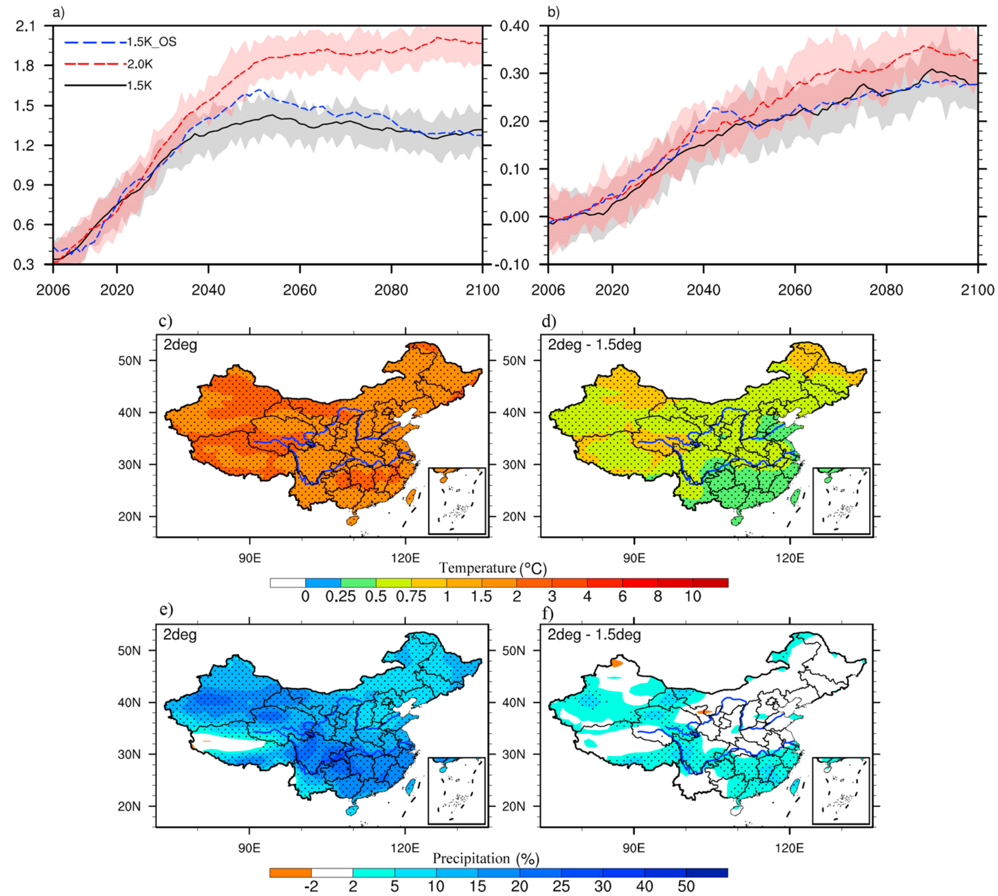

Figure 2. Temporal and spatial climate variation in China in a 1.5°C or 2°C warmer world. Time series of projected changes in annual mean (a) surface air temperature (unit: degree Celsius) and (b) precipitation (unit: mm/day) averaged over China under the 1.5degOS, 1.5degNE, and 2degNE scenarios relative to the 1976–2005 climate. Geographical distributions of changes in annual mean (c) surface air temperature (unit: degree Celsius) and (e) precipitation (unit: percent) over China in a 2°C warmer world relative to the 1976–2005 climate and (d, f) differences in effects between the 1.5°C and 2°C warming levels. Color lines are ensemble average, and the shading represents one standard deviation of ensemble simulations in Figures 2a and 2b. The dots in Figures 2c–2f represent regions with significant changes at 95% confidence level from a *t* test.

lead to increases in nationwide average precipitation of 0.28 and 0.32 mm/day, respectively (i.e., 11.6% and 13.3% of the 1976–2005 baseline).

Figures 2c–2f show the geographical distributions of projected changes in annual mean surface air temperature and precipitation over China in a 2°C warmer world relative to the 1976–2005 climate and differences in effects between the 1.5°C and 2°C warming levels. We use only simulations under the 1.5degNE scenario because the 1.5degOS scenario produces a similar result. Relative to the 1976–2005 climate, the 2°C warming level leads to increases in surface air temperature and precipitation over all of China. Surface warming is generally greater than 1.5°C, and the maximum increase in precipitation exceeds 50% south of the Yangtze River, Sichuan Basin, and northwestern China. Our result is different from that reported by Chen and Sun (2018) based on the RCP scenarios simulations, who suggested that the precipitation significantly decreased over south and southwest China under the 1.5°C and 2°C warming scenarios. Limiting the GMST increase to 1.5°C, as opposed to 2°C, significantly reduces the surface warming (Figure 2d) and precipitation (Figure 2f) over most of China.

3.2. Likelihood of Specific Climate Extreme Events in a 1.5°C or 2°C Warmer World

It is very likely that climate extremes have occurred more frequently in recent decades, due to global warming; these extremes have caused disastrous impacts on humans and ecosystems (Handmer et al., 2012). We

Table 1
The Likelihood of Events Similar to Specific Climate Extremes Over China During the Historical (Hist, 1979–2005), Present-Day (PD, 2006–2025), 1.5°C, and 2°C Periods (Stabilized at 2081–2100 in Our Simulations; Units: Percent)

Events	Hist	PD	1.5°C	2°C
2013 hot summer in eastern China	2.5	8.6 ± 3.8	42 ± 12.5	85.5 ± 8.3
2014 hot spring in northeastern China	0	5	8.3 ± 5.2	19.5 ± 10.1
2010 summer flood in southeastern China	8.4 ± 4.0	9.0 ± 8.1	25.5 ± 9.0	30.0 ± 9.4
2008 cold winter in southern China	0	5	0	0

Note. The numbers following ± are one standard deviation due to internal variability.

estimate the changes in the likelihood of events similar to four specific extreme events over China in a warmer world, including the 2013 hot summer in eastern China, the 2014 hot spring in northeastern China, the 2010 summer flood in southeastern China, and the 2008 cold winter in southern China (Table 1 and Figures 3–5). Anthropogenic influences have been detected in the former two heat events (Ma et al., 2017; Song et al., 2015; Sun et al., 2014).

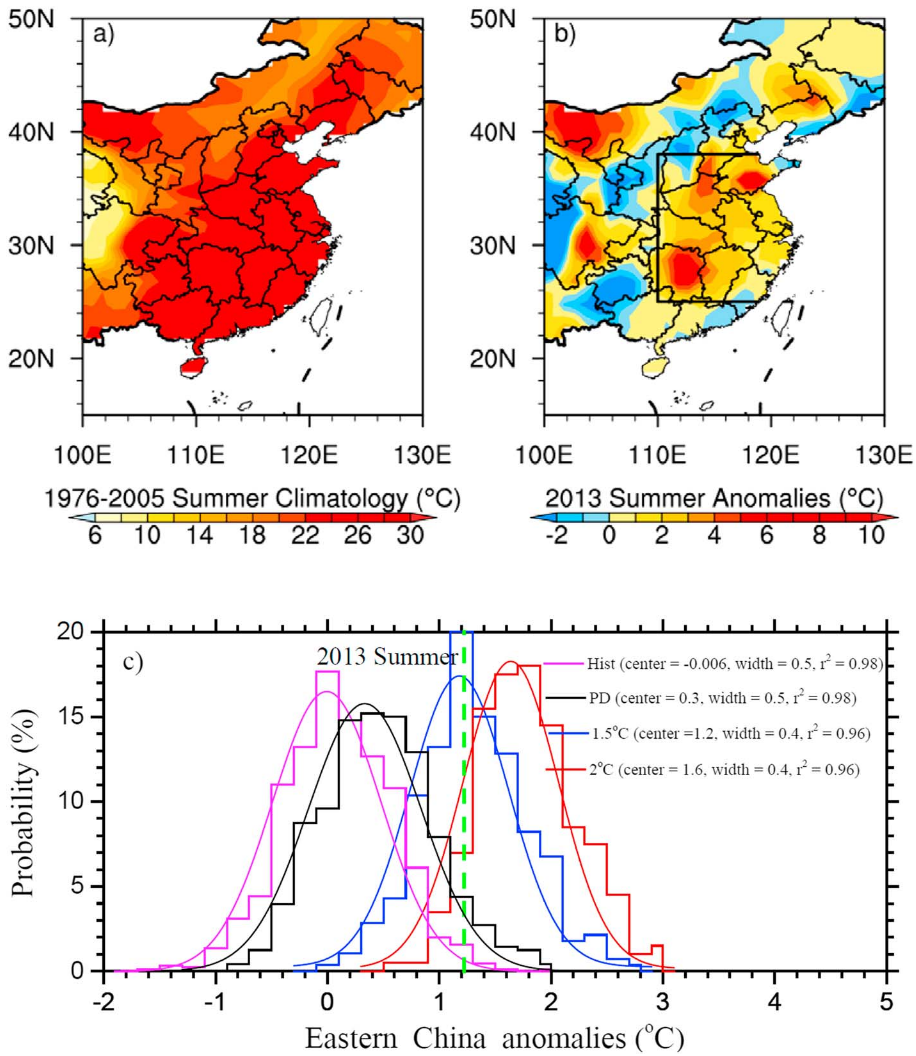

Figure 3. (a) The 1976–2005 summer climatological surface air temperature and (b) anomaly for the 2013 hot summer in observation (units: degree Celsius) and (c) histogram and probability density functions of simulated anomalies of summer surface air temperature averaged over eastern China (box in Figure 3b) during the historical (Hist), present-day (PD), 1.5°C, and 2°C periods (unit: percent). All simulated anomalies are relative to the 1976–2005 summer climate. The vertical dashed line in Figure 3c is the observed 2013 hot summer anomaly. The center and width numbers refer to the parameters of fitted normal distribution curves. The r^2 is the squared correlation coefficient between fitted and real values.

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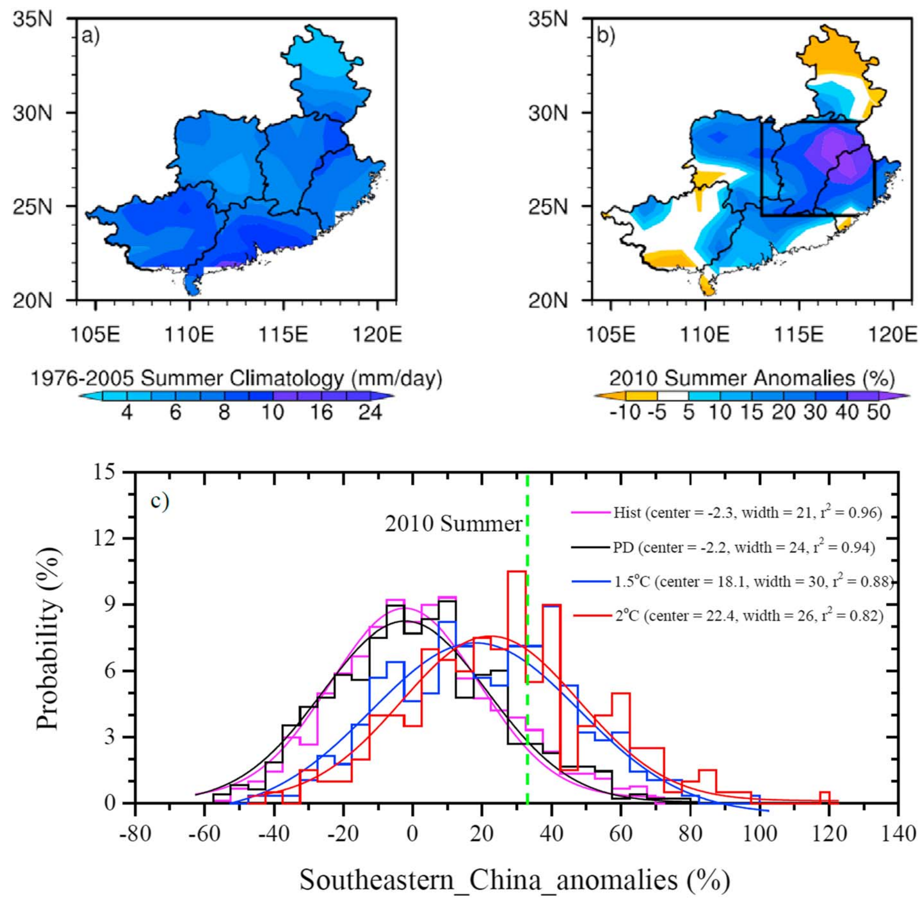

Figure 4. (a) The 1976–2005 summer climatological precipitation (unit: mm/day) and (b) anomaly for the 2010 summer flood in observation (units: percent) and (c) histogram and probability density functions of simulated anomalies of summer precipitation averaged over southeastern China (box in Figure 4b) during the historical (Hist), present-day (PD), 1.5°C, and 2°C periods (unit: percent). All simulated anomalies are relative to the 1976–2005 summer climate. The vertical dashed line in Figure 4c is the observed 2010 summer flood anomaly. Note that the width of fitted normal distribution curve increases in future warming scenarios, suggesting larger interannual variability in the future.

In general, we find that events similar to the high-temperature and flooding extremes become more frequent in a 1.5°C or 2°C warmer world relative to the present-day climate. However, a mitigation of 0.5°C from 2°C to 1.5°C can significantly reduce the probability of such extreme events, especially heat extremes (Table 1). These results are consistent with changes in Australian climate extremes at global warming levels of 1.5°C and 2°C reported by King et al. (2017).

In 2013, eastern China experienced its hottest summer since the 1960s (Sun et al., 2014). Widespread and severe heat waves affected the most populous and prosperous regions of China and led to substantial social and economic effects. The estimated direct economic losses caused by this extreme temperature event exceeded 59 billion RMB (Hou, 2014). As seen in Figure 3, anomalous surface air temperatures averaged over eastern China reach 1.3°C and even exceed 4°C in some areas during the summer of 2013, relative to the 1976–2005 summer climate record. In the context of global warming, summers in China will become warmer and the probability of extreme summer heat will increase. In particular, events similar to the 2013 hot summer in eastern China, which currently have a $<$ 10% chance will happen almost yearly in a 2°C warmer world (86% in Table 1). This finding is consistent with analyses for Europe conducted by Stott et al. (2004) and Christidis et al. (2015). However, our result shows a larger probability of such hot extreme events in a 1.5°C or 2°C warmer world than that in Chen and Sun (2018) using the RCP scenario simulations. Compared to 1976–2005, an event similar to the 2013 hot summer is twice as likely in the present-day climate and will increase by 16 and 33 times under GMST increases of 1.5°C and 2°C, respectively (Figure 3c and Table 1). More importantly, the

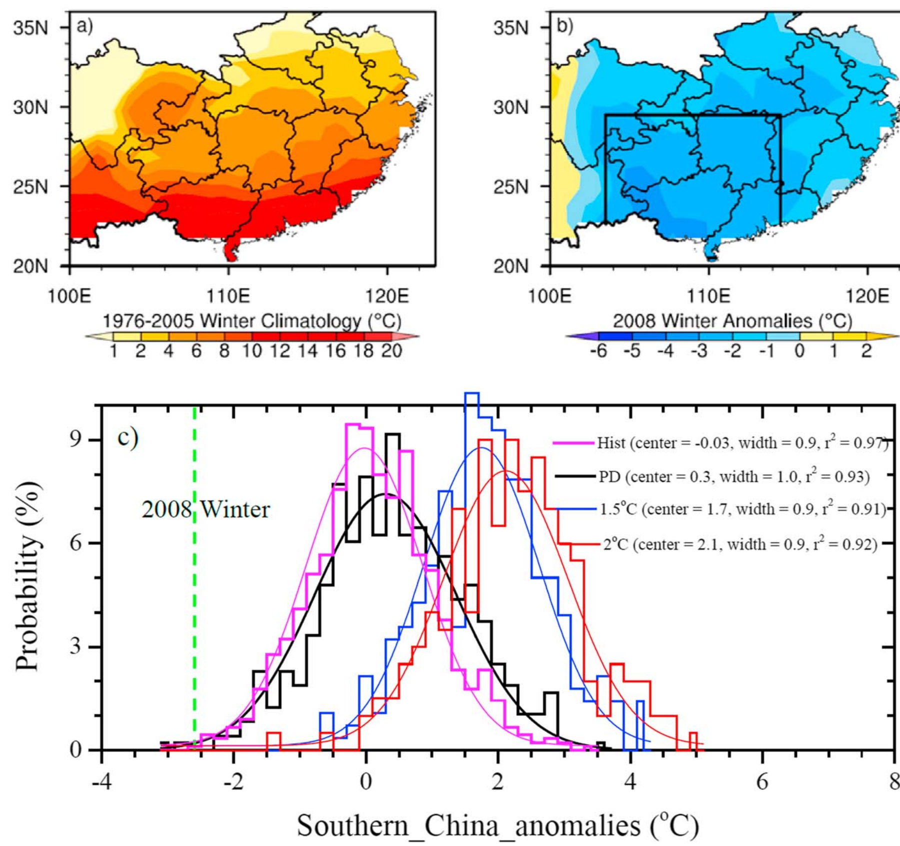

Figure 5. (a) The 1976–2005 winter climatological surface air temperature and (b) anomaly for the 2008 cold winter in observation (units: degree Celsius) and (c) histogram and probability density functions of simulated anomalies of winter surface air temperature averaged over southern China (box in Figure 5b) during the historical (Hist), present-day (PD), 1.5°C, and 2°C periods (unit: percent). All simulated anomalies are relative to the 1976–2005 winter climate. The vertical dashed line in Figure 5c is the observational 2008 cold winter anomaly.

likelihood of such an event will be reduced by half if warming is stabilized at 1.5°C rather than 2°C above the preindustrial climate.

Spring 2014 was the third hottest spring in northeastern China since dependable observations were established in the late 1950s (Song et al., 2015). Daily maximum temperatures broke historical records at 12 ground sites and reached over 40°C in many areas in late May (China Meteorological Administration (CMA), 2015; Song et al., 2015). This hot event led to severe effects on agriculture and other important sectors (CMA, 2015). Table 1 shows that events similar to this extreme hot spring rarely occur during 1976–2005. However, the probability of such events increases to 5% in the present-day climate and will reach 8% and 20% under GMST increases of 1.5°C and 2°C, respectively. This result is consistent with previous findings that anthropogenic warming may have contributed to the high number of hot days in spring over northern China (Song et al., 2015).

We next assess flooding extremes in China in recent decades and in the future. Southeastern China suffered severe flooding in the summer of 2010 (CMA, 2011), with 14 heavy rainfall events occurring from May to July. The cumulative rainfall during this season reached 800–1200 mm in some regions, resulting in serious economic losses and casualties (CMA, 2011). According to the Clausius-Clapyron equation, a warmer climate will hold more moisture and thus tend to produce more precipitation. In addition, future reduced aerosol concentrations will likely enhance moisture transport and precipitation over eastern China (Lin, Wang, et al., 2016; Wang, Lin, Yang, et al., 2017; Wang, Zhang, & Zhang, 2016). It is found that the difference in likelihood of events similar to the 2010 extreme summer flood between 1976 and 2005 and the present-day climate is little (Figure 4c and Table 1). However, the frequency of such events will increase by 2 or 3 times in a 1.5°C or 2°C warmer world (with a return time less than 4 years), respectively, compared to 1976–2005.

One may argue that although global warming causes more frequent high-temperature and precipitation extremes, a *benefit* is that it reduces the likelihood of low-temperature extremes. We test this hypothesis by examining events similar to the 2008 extreme cold winter in southern China (Figure 5). The probability of such extreme cold events is 5% in the present-day climate; however, they will no longer occur under GMST increases of 1.5°C and 2°C (Table 1 and Figure 5c). This is consistent with that given by Chen and Sun (2018), who also indicated that the probability of individual extreme cold event would be rare under the 1.5°C and 2°C warming scenarios. Thus, there is no additional *benefit* of a 2°C warmer world.

Finally, we note that in Figures 3–5, there is a slight shift in the probability density function of temperature anomalies. The shape of the probability density function of precipitation anomalies also changes, with a larger width in a 1.5°C or 2°C warmer climate. This result is consistent with the finding that precipitation extremes tend to increase faster than mean precipitation (Lin, Wang, et al., 2016; Trenberth, 1999).

4. Conclusions

This study examines the changes in seasonal climate extremes over China under a stabilized 1.5°C or 2°C increase in GMST at the end of the 21st century above preindustrial levels, using a set of fully coupled Earth system model simulations explicitly targeting these warming levels. Our results suggest that stabilized 1.5°C and 2°C warming above preindustrial levels lead to increases in surface air temperature (precipitation) averaged over China of 1.3°C and 1.9°C (11.6% and 13.3%), respectively, relative to the 1976–2005 climate. The 2°C warming level leads to increase in surface air temperature over all of China, with the values being generally greater than 1.5°C. The maximum increase in precipitation exceeds 50% south of the Yangtze River, Sichuan Basin, and northwestern China under the warming level of 2°C. However, the surface warming and precipitation are significantly reduced over most of China in a 2°C warmer world compared to 1.5°C.

Our results demonstrate that events similar to some large-scale extreme climate events that occurred in China within the past decade will become more frequent under global warming. Compared to 1976–2005, an event similar to the 2013 hot summer in eastern China is twice as likely in the present-day climate and will increase by 16 and 33 times under increases in GMST of 1.5°C and 2°C, respectively. In particular, such hot extreme events occur almost yearly in a 2°C warmer world. Note that the likelihood of such events will be reduced by half if warming is stabilized at 1.5°C rather than 2°C. The probability of an event similar to the 2014 hot spring in northeastern China increases to 5% in the present-day climate and will arrive at 8% or 20% in a 1.5°C or 2°C warmer world, although such events rarely occur during 1976–2005. The likelihood of an event similar to the 2010 extreme summer flood in southeastern China is almost unchanged in the present-day climate relative to 1976–2005. However, the probability of such events will increase by 2 or 3 times in a 1.5°C or 2°C warmer world (with the probability reaching 25% and 30%), respectively. We find that the likelihood of cold extremes such as the 2008 cold winter in southern China will be reduced to zero under both 1.5°C and 2°C warming scenarios.

In summary, projected surface temperature and extreme heat and flooding in China will significantly increase under global temperature increases of 1.5°C and 2°C. However, limiting the increase in GMST at 1.5°C rather than 2°C would substantially reduce the frequency of climate extremes in China. Therefore, there are potential benefits of limiting the warming to below 1.5°C to prevent dangerous impacts in China, as suggested by Huang et al. (2017) and King et al. (2017). Note that there are still deficiencies in the simulations, which will bring errors to the corresponding projections. In addition, our results are derived from a single GCM, albeit using multiple ensemble members. The sensitivities of temperature and precipitation to global warming differ among GCMs. The transient climate response is 2.3°C in CESM1; however, the transient climate response spans a range from 1°C to 2.5°C based on the CMIP5 models (Hu et al., 2017). Therefore, multimodel ensemble simulations under similar scenarios are necessary to verify the robustness of our results.

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References

Chen, H., & Sun, J. (2018). Projected changes in climate extremes in China in a 1.5°C warmer world. *International Journal of Climatology*, 1–11. https://doi.org/10.1002/joc.5521

Chen, X., & Zhou, T. (2016). Uncertainty in crossing time of 2°C warming threshold over China. *Science Bulletin*, *61*(18), 1451–1459. https://doi.org/10.1007/s11434-016-1166-z

Chevuturi, A., Klingaman, N. P., Turner, A. G., & Hannah, S. (2018). Projected changes in the Asian-Australian monsoon region in 1.5°C and 2.0°C global-warming scenarios. *Earth's Future*, *6*(3), 339–358. https://doi.org/10.1002/2017EF000734

Christidis, N., Jones, G. S., & Stott, P. A. (2015). Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. *Nature Climate Change*, *5*(1), 46–50. https://doi.org/10.1038/nclimate2468

China Meteorological Administration (2011). China Climate Bulletin 2010. China Meteorological Administration, 52 pp.

China Meteorological Administration (2015). China Climate Bulletin 2014. China Meteorological Administration, 50 pp.

Ghan, S. J., Liu, X., Easter, R. C., Zaveri, R., Rasch, P. J., Yoon, J.-H., & Eaton, B. (2012). Toward a minimal representation of aerosols in climate models: Comparative decomposition of aerosol direct, semi-direct and indirect radiative forcing. *Journal of Climate*, *25*(19), 6461–6476. https://doi.org/10.1175/JCLI-D-11-00650.1

Handmer, J., Honda, Y., Kundzewicz, Z. W., Arnell, N., Benito, G., & Hatfield, J., et al. (2012). Changes in impacts of climate extremes: Human systems and ecosystems, Managing the risks of extreme events and disasters to advance climate change adaptation. IPCC Special Report, 231–290.

Hou, W. (2014). Climatic characteristics over China in 2013. *Meteorological Monthly*, *40*, 491–501.

Hu, T., Sun, Y., & Zhang, X. B. (2017). Temperature and precipitation projection at 1.5 and 2°C increase in global mean temperature. *Chinese Science Bulletin*, *62*(26), 3098–3111.

Huang, J., Yu, H., Dai, A., Wei, Y., & Kang, L. (2017). Drylands face potential threat under 2°C global warming target. *Nature Climate Change*, *7*(6), 417–422. https://doi.org/10.1038/nclimate3275

Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., et al. (2013). The Community Earth System Model: A framework for collaborative research. *Bulletin of the American Meteorological Society*, *94*(9), 1339–1360. https://doi.org/10.1175/BAMS-D-12-00121.1

James, R., Washington, R., Schleussner, C. F., Rogelj, J., & Conway, D. (2017). Characterizing half-a-degree difference: A review of methods for identifying regional climate responses to global warming targets. *Wiley Interdisciplinary Reviews: Climate Change*, *8*(2), e457. https://doi.org/10.1002/wcc.457

Jiang, D., Sui, Y., & Lang, X. (2016). Timing and associated climate change of a 2°C global warming. *International Journal of Climatology*, *36*(14), 4512–4522. https://doi.org/10.1002/joc.4647

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., et al. (2015). The Community Earth System Model (CESM1) large ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bulletin of the American Meteorological Society*, *96*, 1333–1349. https://doi.org/10.1175/BAMS-D-13-00255.1

King, A. D., Henley, B. J., & Karoly, D. J. (2017). Australian climate extremes at 1.5°C and 2°C of global warming. *Nature Climate Change*, *7*(6), 412–416. https://doi.org/10.1038/nclimate3296

King, A. D., van Oldenborgh, G. J., Karoly, D. J., Lewis, S. C., & Cullen, H. (2015). Attribution of the record high central England temperature of 2014 to anthropogenic influences. *Environmental Research Letters*, *10*(5), 054002. https://doi.org/10.1088/1748-9326/10/5/054002

Lehner, F., Coats, S., Stocker, T. F., Pendergrass, A. G., Sanderson, B. M., Raible, C. C., et al. (2017). Projected drought risk in 1.5°C and 2°C warmer climates. *Geophysical Research Letters*, *44*, 7419–7428. https://doi.org/10.1002/2017GL074117

Lewis, S. C., King, A. D., & Mitchell, D. M. (2017). Australia's unprecedented future temperature extremes under Paris limits to warming. *Geophysical Research Letters*, *44*, 9947–9956. https://doi.org/10.1002/2017GL074612

Li, J., Zhu, Z., & Dong, W. (2016). Assessing the uncertainty of CESM-LE in simulating the trends of mean and extreme temperature and precipitation over China. *International Journal of Climatology*, *37*(4), 2101–2110. https://doi.org/10.1002/joc.4837

Li, X., Ting, M., Li, C., & Henderson, N. (2015). Mechanisms of Asian summer monsoon changes in response to anthropogenic forcing in CMIP5 models. *Journal of Climate*, *28*, 4107–4125.

Lin, L., Gettelman, A., Feng, S., & Fu, Q. (2015). Simulated climatology and evolution of aridity in the 21st century. *Journal of Geophysical Research: Atmospheres*, *120*, 5795–5815. https://doi.org/10.1002/2014JD022912

Lin, L., Gettelman, A., Fu, Q., & Xu, Y. (2016). Simulated differences in 21st century aridity due to different scenarios of greenhouse gases and aerosols. *Climatic Change*, 1–16. https://doi.org/10.1007/s10584-016-1615-3

Lin, L., Wang, Z., Xu, Y., & Fu, Q. (2016). Sensitivity of precipitation extremes to radiative forcing of greenhouse gases and aerosols. *Geophysical Research Letters*, *43*, 9860–9868. https://doi.org/10.1002/2016GL070869

Ma, S., Zhou, T., Stone, D., Angelil, O., & Shiogama, H. (2017). Attribution of the July–August 2013 heat event in central and eastern China to anthropogenic greenhouse gas emissions. *Environmental Research Letters*, *12*(5). https://doi.org/10.1088/1748-9326/aa69d2

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C., Frieler, K., Knutti, R., et al. (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, *458*(7242), 1158–1162. https://doi.org/10.1038/nature08017

Mitchell, D., Achutarao, K., Allen, M., Bethke, I., Beyerle, U., Ciavarella, A., et al. (2017). Half a degree additional warming, prognosis and projected impacts (HAPPI): Background and experimental design. *Geoscientific Model Development*, *10*(2), 571–583. https://doi.org/10.5194/gmd-10-571-2017

Mitchell, D., James, R., Forster, P. M., Betts, R. A., Shiogama, H., & Allen, M. (2016). Realizing the impacts of a 1.5°C warmer world. *Nature Climate Change*, *6*(8), 735–737. https://doi.org/10.1038/nclimate3055

Polson, D., Bollasina, M., Hegerl, G. C., & Wilcox, L. J. (2014). Decreased monsoon precipitation in the Northern Hemisphere due to anthropogenic aerosols. *Geophysical Research Letters*, *41*, 6023–6029. https://doi.org/10.1002/2014GL060811

Rao, S., Klimont, Z., Smith, S. J., Dingenen, R. V., Dentener, F., Bouwman, L., et al. (2016). Future air pollution in the shared socio-economic pathways. *Global Environmental Change*, *42*, 346–358. https://doi.org/10.1016/j.gloenvcha.2016.05.012

Riahi, K., Grübler, A., & Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change*, *74*(7), 887–935. https://doi.org/10.1016/j.techfore. 2006.05.026

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., et al. (2015). Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Climate Change*, *5*(6), 519–527. https://doi.org/10.1038/nclimate2572

Samset, B. H., Myhre, G., Forster, P. M., Hodnebrog, Ø., Andrews, T., Faluvegi, G., et al. (2016). Fast and slow precipitation responses to individual climate forcers: A PDRMIP multimodel study. *Geophysical Research Letters*, *43*, 2782–2791. https://doi.org/10.1002/2016GL068064

Sanderson, B. M., Xu, Y., Tebaldi, C., Wehner, M., O'Neill, B., Jahn, A., et al. (2017). Community climate simulations to assess avoided impacts in 1.5°C and 2°C futures. *Earth System Dynamics*, *8*(3), 827–847. https://doi.org/10.5194/esd-8-827-2017

Schleussner, C. F., Lissner, T. K., Fischer, E. M., Wohland, J., Perrette, M., Golly, A., et al. (2016). Differential climate impacts for policy-relevant limits to global warming: The case of 1.5°C and 2°C. *Earth System Dynamics*, *7*(2), 327–351. https://doi.org/10.5194/esd-7-327-2016

Song, L., Dong, S., Sun, Y., Ren, G., Zhou, B., & Stott, P. A. (2015). Role of anthropogenic forcing in 2014 hot spring in northern China. *Bulletin of the American Meteorological Society*, *96*(12), S111–S114. https://doi.org/10.1175/BAMS-D-15-00111.1

Stott, P. A., Stone, D. A., & Allen, M. R. (2004). Human contribution to the European heatwave of 2003. *Nature*, *432*(7017), 610–614. https://doi.org/10.1038/nature03089

Sui, Y., Lang, X., & Jiang, D. (2018). Projected signals in climate extremes over China associated with a 2°C global warming under two RCP scenarios. *International Journal of Climatology*, *38*(S1), e678–e697. https://doi.org/10.1002/joc.5399

Sun, Y., Zhang, X., Zwiers, F. W., Song, L., Wan, H., Hu, T., et al. (2014). Rapid increase in the risk of extreme summer heat in eastern China. *Nature Climate Change*, *4*(12), 1082–1085. https://doi.org/10.1038/nclimate2410

Tebaldi, C., O'Neill, B., & Lamarque, J. F. (2015). Sensitivity of regional climate to global temperature and forcing. *Environmental Research Letters*, *10*(7), 074001. https://doi.org/10.1088/1748-9326/10/7/074001

Trenberth, K. E. (1999). Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change*, *42*(1), 327–339. https://doi.org/10.1023/A:1005488920935

United Nations Framework Convention on Climate Change (2015). United Nations Framework Convention on Climate Change Adoption of the Paris Agreement Report No. FCCC/CP/2015/L.9/Rev.1. Retrieved from http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

Wang, X., Jiang, D., & Lang, X. (2017). Future extreme climate changes linked to global warming intensity. *Science Bulletin*, *62*(24), 1673–1680.

Wang, Z., Lin, L., Yang, M., & Xu, Y. (2016). The effect of future reduction in aerosol emissions on climate extremes in China. *Climate Dynamics*, *47*(9–10), 2885–2899. https://doi.org/10.1007/s00382-016-3003-0

Wang, Z., Lin, L., Yang, M., Xu, Y., & Li, J. (2017). Disentangling fast and slow responses of the East Asian summer monsoon to reflecting and absorbing aerosol forcings. *Atmospheric Chemistry and Physics*, *17*, 11,075–11,088. https://doi.org/10.5194/acp-17-11075-2017

Wang, Z., Lin, L., Zhang, X., Zhang, H., Liu, L., & Xu, Y. (2017). Scenario dependence of future changes in climate extremes under 1.5°C and 2°C global warming. *Scientific Reports*, *7*, 46432. https://doi.org/10.1038/srep46432

Wang, Z., Zhang, H., & Zhang, X. (2016). Projected response of East Asian summer monsoon system to future reductions in emissions of anthropogenic aerosols and their precursors. *Climate Dynamics*, *47*(5), 1455–1468. https://doi.org/10.1007/s00382-015-2912-7

Wu, J., & Gao, X. J. (2013). A gridded daily observation dataset over china region and comparison with the other datasets. *Chinese Journal of Geophysics*, *56*(4), 1102–1111.

Xu, Y., & Lin, L. (2017). Pattern scaling based projections for precipitation and potential evapotranspiration: Sensitivity to composition of GHGs and aerosols forcing. *Climatic Change*, *140*(3–4), 1–13. https://doi.org/10.1007/s10584-016-1879-7

Xu, Y., & Ramanathan, V. (2017). Well below 2°C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(39), 10,315–10,323. https://doi.org/10.1073/pnas. 1618481114

Zhai, P., Zhang, X., Wan, H., & Pan, X. (2005). Trends in total precipitation and frequency of daily precipitation extremes over China. *Journal of Climate*, *18*(18), 1096–1108. https://doi.org/10.1175/JCLI-3318.1

Erratum

An earlier version of this article incorrectly ordered the institutional affiliations of the second author. The article has been updated, and this may be considered the official version of record.