Are the Observed Changes in Heat Extremes Associated With a Half-Degree Warming Increment Analogues for Future Projections?

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Abstract Projecting climate impacts of a half-degree warming increment is of high priority on post Paris Agreement science agendas. As the real world has already witnessed a 0.5°C global mean surface temperature warming increment, the observed climate changes associated with the half-degree warming may be analogues for future projections. This hypothesis is examined by comparing the heat extreme changes in China derived from the observational records to projections of the Community Earth System Model (CESM) low-warming experiment, which is the first short-term stabilized simulation dedicated for the 1.5 and 2°C warming targets. The results of the CESM historical simulations are also evaluated. From the perspective of spatially aggregated, the heat extreme changes in China under the historical 0.5°C warming are detectable in observations. The nighttime extremes manifest more significant increase than daytime extremes. Heat extreme changes under the past half-degree warming increment are reasonably captured in the historical simulations with slightly weaker magnitudes. The changes in the intensity indices in observations are better reproduced by the historical simulations than the frequency and duration indices. For the heat extreme changes in the future 0.5°C warming, the observational records can serve as conservative analogues in daytime extremes, while the nighttime extreme indices show comparable or weaker changes. The future reduction of anthropogenic aerosol emissions will amplify the increase of heat extremes in comparison to present day especially during daytime in China. Given the possibly intensified extremes associated with future aerosol reductions, more attention should be paid to the currently heavily polluted regions.

Plain Language Summary Since the Paris Agreement called for limiting the future global warming under 2°C and pursuing efforts to limit under 1.5°C, great efforts have been devoted to exploring the benefits of the 0.5°C less warming on natural and social systems. Since the world has already witnessed a 0.5°C warming increment, whether the associated observed climate changes can be analogues for future projections is an interesting and important question. Focusing on the heat extreme changes over continental China, we revisit the observational data sets to evaluate the performance of the Community Earth System Model (CESM) historical simulations and then compare the observed changes with the CESM 1.5°C/2°C future projections. We find that the heat extreme changes under the past 0.5°C warming increment are detectable in observations and can be well reproduced by the historical simulations. The changes of intensity indices in the observations are better reproduced by the model than the frequency and duration indices. For the daytime heat extremes, the observations only give the lower boundary for the projected changes in future 0.5°C warming. China may experience severer increase in daytime heat extremes due to possible aerosol reductions in the future. Our results would provide useful information to climate change adaption and risk management.

1. Introduction

The Paris Agreement of December 2015 sets a goal of “holding the increase in the global average temperature well below 2°C above the pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels” (United Nations Framework Convention on Climate Change, 2015). On post Paris Agreement science agendas, projecting the climate impacts of a half-degree warming increment has been of the highest priority. Between these two long-term global warming goals (LTGGs), the
impacts avoided by the 1.5°C warming target relative to the 2°C warming target have been assessed by using climate models on both global and regional scales (King & Karoly, 2017; Lehner et al., 2017; Nangombe et al., 2018; W. Zhang, et al., 2018; Zhou et al., 2018). While the results demonstrated that constraining anthropogenic warming to 1.5°C instead of 2°C will significantly lower the risks associated with climate extremes for inhabitants in most parts of the world (Intergovernmental Panel on Climate Change [IPCC], 2018), model-based projections include uncertainties due to different parameterizations and climate sensitivities. Thus, the reliability of climate model projections needs to be assessed.

Since the world has already witnessed a 0.5°C global mean surface temperature (GMST) warming increment, as demonstrated by the instrumental data sets (Hansen et al., 2010), the observed changes are useful metrics for gauging the model performance in the historical simulations. A reliable reproduction of the historical changes also increases the confidence of future projections. More important, the observed climate changes associated with the half-degree warming increment are hypothesized to be analogues for future projections. Preliminary research has found that the changes in heat extremes and heavy rainfall induced by the past 0.5°C GMST warming in the observational records are reasonable analogues for the changes between the 1.5°C and 2°C warming projections of the Coupled Model Inter-comparison Project, Phase 5 (CMIP5) models on a global scale (Carl-Friedrich Schleussner et al., 2017).

However, due to different response to internal variability and anthropogenic influence, climate extreme changes have distinct regional characteristics. During the past ~50 years (1961–2009), a significant long-term increasing trend in temperature extremes in China is found in multiple instrumental observational data sets (Yin et al., 2015). The past half-degree of global warming has a detectable impact on complex summertime hot events defined as days with both extremely elevated daytime and nighttime maximum temperatures (Y. Chen et al., 2018). Detection and attribution of changes in mean and extreme temperatures and in heat wave events in China have enriched the evidence of the inevitable anthropogenic influences (Dong et al., 2015; Ma et al., 2017; Sun et al., 2014; Xu et al., 2015; Yin et al., 2017; Zhai et al., 2018). Nonetheless, whether the observed changes in China can serve as analogues of future projections remains unknown.

In future projections, East Asia manifests severer warming than the global mean under the 1.5°C/2°C warming level (Lin et al., 2018; Ting et al., 2017). The climate impacts of the future 0.5°C GMST warming increment in East Asian countries including China have been assessed in several different approaches by using: global model projections (Lee & Min, 2018; D. Li et al., 2018; Zhou et al., 2018), regional model projections (H. Li et al., 2018), statistical downscaling method (D. Li et al., 2018; Yang et al., 2018), and pattern scaling method (X. Chen & Zhou, 2017; Herger et al., 2015). While analyses based on different methods are qualitatively consistent in highlighting the considerable benefits with regard to minimizing exposure to temperature extremes in China under half-degree less warming, quantitative differences are evident among different projections (James et al., 2017; Tebaldi et al., 2015). Thus, the changes in heat extremes induced by a 0.5°C GMST warming derived from the observational records are hoped to be useful metrics for quantifying the models’ reliability and assess the consistency between different approaches.

In this study, we compare the heat extreme changes in China under a 0.5°C warming derived from the homogenized observational records to the Community Earth System Model (CESM) historical simulations. And further compare the results projected by the CESM low-warming experiments with the observations to examine the analogue hypothesis. The major questions we aim to answer include the following: (1) Under the historical 0.5°C GMST warming increment, are the changes of the heat extremes in model historical simulations similar to those of the observations in China? 2) Are these changes in the observational records reasonable analogues for the future changes projected by climate models? We show evidences that the observed changes of the daytime extremes are only conservative analogues for future projections. The projected changes of daytime extremes would be stronger than the observations due to possible future reductions of anthropogenic aerosol emission.

2. Data and Methods
2.1. Climate Model Data and Observational Data
We use the National Center for Atmospheric Research (NCAR) CESM low-warming simulations (Kay et al., 2015) to evaluate future heat extreme changes. These are the first simulations performed by fully coupled
The impacts of the 0.5°C warming increment on heat extremes are assessed by the difference between the two 20-year period mean, which has been chosen differently among observational records, model historical simulations, and the 1.5°C/2°C warming level projections:

Climate model, specifically targeting stabilized warming levels of 1.5 and 2°C in the late 21st century. Before this, the 1.5 and 2°C warming level studies use alternative approaches such as the “time sampling” approach in CMIP5 model simulations (King et al., 2017; C-F Schleusner et al., 2016) and the Half a Degree Additional Warming, Projections, Prognosis, and Impacts (HAPPI) model intercomparison (Chevuturi et al., 2018; Lewis et al., 2017). These approaches have certain defects due to transient approximate or lack of coupled atmosphere-ocean internal variations. To reach the two LTGGs, a simple Minimal Complexity Earth Simulator model was first used in the CESM low-warming simulations to produce a set of greenhouse gas (GHG) emission pathways and then to drive each of 11 ensemble members (1.5 and 2°C) for the period from 2006 to 2100. The emissions follow the total representative concentration pathway scenarios 8.5 (RCP8.5) protocol until 2017. After that, a well-mixed GHG concentration is redesigned in the emission scenarios, while other anthropogenic forcing agents such as aerosol, ozone, chlorofluorocarbon, and land use still follow the RCP8.5 protocol (Sanderson et al., 2017). To reach the two LTGGs, the combined carbon emissions have to decline to net zero first and then keep negative. The GMST stabilizes at ~1.5°C (~2.1°C) above preindustrial levels at the end of the 21st century.

The historical simulations are derived from a 42-realization ensemble of the CESM cover the period of 1920–2005 (Kay et al., 2015). To match the members in the CESM low-warming experiments, we select the first 11 members from the 42 realizations. The model shows reasonable performances in simulating the climatology of heat extremes in China in the context of spatial pattern (figure not shown), with pattern correlation coefficients between the simulations and the observation higher than 0.99 for most heat extremes except for ~0.95 in warm spell duration (WSDI). In the meantime, the model tends to underestimate the intensity, frequency, and duration of the heat extremes over most part of eastern China as reported previously for both China (Sun et al., 2015; Yang et al., 2014) and global land (IPCC, 2013; Sillmann et al., 2013).

The homogenized gridded observational data sets we use is the CN05.1 (J. Wu & Gao, 2013), which is derived from the records of 2461 meteorological stations in China using the “anomaly approach” (New et al., 2000) during the interpolation step. The data of daily maximum (TX) and minimum (TN) temperatures in the period of 1961–2010 are used.

### 2.2. Methods

We employ five commonly used heat extreme indices that can be separated into three groups following the recommendation of the Expert Team on Climate Change Detection and Indices (ETCCDI): (1) intensity indices: daytime hot extreme (TXx) and nighttime hot extreme (TNx); (2) frequency indices: warm days (TX90p) and warm nights (TN90p); and (3) duration indices: warm spell duration (WSDI; X. Zhang et al., 2011). All these heat extreme indices were assessed by the IPCC Special Report on 1.5°C (IPCC, 2018). Noted that for the percentile-based indices (frequency and duration indices), the reference period is fixed to a commonly used period of 1961–1990 (X. Zhang et al., 2011). The 90th percentile baseline is derived from this fixed period to allow comparison. For details of the calculation, please refer to Table 1.

To detect the changes in heat extremes, a spatially aggregated perspective in extreme changes proposed by Fischer and Knutti (2014) is used. On single grid, the extreme changes might be insignificant; thus, the heat extreme indices are firstly calculated at each grid point and then regionally aggregated in a spatial probability density function (PDF) weighted by grid-cell area, which quantifies the percentage of landmass exhibiting a certain change. Traditional PDF calculations depend on the subjective choice of bins that strongly affects the PDF distribution; here we use the nonparametric assessment: kernel density estimation (Scott, 2015) to estimate all the PDFs. The results are smoothed based on the Silverman’s Rule (Bashtannyk & Hyndman, 2001; Silverman, 1986; Turlach, 1993).

| Table 1 | Definitions and Calculations of the Heat Extreme Indices |
|---------|----------------------------------------------------------|
| Label   | Definition and calculation                                | Unit         |
| TXx     | Annually maximum value of daily maximum temperature       | °C           |
| TNx     | Annually maximum value of daily minimum temperature       | °C           |
| TX90p   | Annual count of days when TX>90th percentile              | Days         |
| TN90p   | Annual count of days when TN>90th percentile              | Days         |
| WSDI    | Annual count of days with at least 6 consecutive days when TX>90th percentile | Days         |
1. For the observational records, the past 0.5°C warming increment took place during the years of 1991–2010 versus the years of 1960–1979 (Hansen et al., 2010); due to the data sets time range in the CN05.1, we measure the changes in the heat extremes between the periods of 1961–1979 and 1991–2010. This minor adjustment does not affect the results. Two global observational data sets of extremes: HadEX2 (Donat et al., 2013b) and GHCNDEX (Donat et al., 2013a) are also used for comparison.

2. For the past 0.5°C warming increment in the CESM historical climate simulations, the period is selected individually in each member. We add the time period of 2006–2010 from the 2°C warming projections to the historical simulations’ time range and then take the 1991–2010 period as the latter 20-year period like in observations. The former 20-year period selection is not fixed to the years 1961–1979 as the observations because for each model members, the GMST increment between these two 20-year periods may not be exactly 0.5°C. Therefore, we select the 20-year periods when the GMST difference versus the 1991–2010 time period is closest to 0.5°C. The ensemble mean of the GMST increase of these 11 members is 0.48°C. For each member, the selected former 20-year period time range can be found in Table 2.

3. For the 0.5°C warming increment between the two LTGGs, the period from 2071–2100 is commonly used to represent the stable equilibrium period for a 1.5 and 2°C warming relative to preindustrial levels (Sanderson et al., 2017). In our analysis, to maintain consistency with the observational records, we chose the 20-year period 2080–2099 from the stable equilibrium period to represent the 1.5 and 2°C warmer worlds. The 0.5°C warming increment is calculated as the difference between the 20-year period mean derived from the 2 and 1.5°C model projections in each model member.

In addition, to assess whether the impact of past 0.5°C warming increment on heat extremes in China is detectable in the observational data sets, we randomly choose 100 pairs of 20-year period mean differences from 1961 to 2010, which are expected to be the internal variability, and the 25–75% range is shown in the figures. Observational results that shift out of the expected internal variability are regarded as detectable (Y. Chen et al., 2018; Carl-Friedrich Schleussner et al., 2017).

Different or even opposite signs among individual model member can be attributed to the unpredictable natural internal variability in certain extent (Deser et al., 2012; Deser et al., 2012). Thus, we take the model spread among members as an irreducible uncertainty in model simulation. To assess whether the model simulation captures the observational changes, we take the 25–75% of model spread range as a rather strict criterion to avoid the “minority effect.” If the observations fall into this criterion, then we conclude that the model simulations capture the observational changes. Similar approach has been utilized by J. Li, et al. (2017).

### 3. Results

#### 3.1. Heat Extreme Changes in Observational Records

The instrumental records show increasing trend in heat extreme changes in China during the period of 1961–2009 (Yin et al., 2015). But the changes associated with the historical 0.5°C warming in the three categories of general heat extremes remain unknown. To reveal the changes under the past 0.5°C warming increment and also develop observational metric for later model comparison, we evaluate the changes of the heat extremes using the CN05.1 data sets. All five of the heat extremes see distinct increases in China’s domain, with their PDFs shifting to positive (Fig. 1). The land fractions exhibiting positive changes in nighttime extremes (TNx and TN90p) are larger than those of daytime extremes (TXx and TX90p), respectively. For the intensity indices, approximately 46.7% (12.3%) of the landmass in continental China has experienced an intensification of more than 0.5°C (1.0°C) in daytime hot extreme (TXx; Fig.1a). In comparison, an
intensification in nighttime hot extreme (TNx) by at least 0.5°C (1.0°C) is seen over more than 76.0% (30.4%) of the China's landmass (Fig. 1b). Similar distinct shifts in difference distributions are also evident in the frequency indices: the warm days (TX90p) have increased by almost 19 days over more than 50% of the landmass (Fig. 1c), while an increase in warm nights (TN90p) of at least 33 days is seen over 50% of the landmass (Fig. 1d). The duration of warm spell (WSDI) has increased by approximately 8 days over 50% of continental China (Fig. 1e). The PDF shapes of internal variability exhibit quasi-normal distributions centered on zero for all five extreme indices. The observed changes in heat extremes in China's mainland all shifted to positive than the internal variability range in certain extent, indicating that these changes can be clearly identified and differ from what would be expected due to natural variability. The emergence of increments distinct from internal variability in nighttime indices (TNx and TN90p) is more pronounced than that of the corresponding daytime indices (TXx and TX90p). It should be noted that approximately 17.6%, 1.0%, and 1.6% of China's landmass has witnessed decreases in the daytime hot extreme (TXx), warm days (TX90p), and warm spell duration (WSDI). The decreases in nighttime indices are not so pronounced (less than 1%).

We also compared the consistency between the CN05.1 data sets and the two global gridded observational data sets GHCNDEX and HadEX2. Take daytime hot extreme (TXx) as an example, the two global gridded observations manifest similar intensification under the past half-degree warming increment, but still have certain differences compared to the homogenized CN05.1. More than 58.2% (16.7%) and 48.8% (15.2%) of land fractions in China have seen at least 0.5°C (1.0°C) intensification in HadEX2 and GHCNDEX respectively, which are both larger than the CN05.1. Compared to the relatively coarse resolution of the two global gridded data sets (2.5° × 2.5° for GHCNDEX and 3.75° × 2.5° for HadEX2), the CN05.1 is based on the interpolation from more than 2400 observing stations in China (J. Wu & Gao, 2013) and thus should be more reliable on regional scales.

Inspection on the spatial patterns of the changes in the heat extreme indices (Fig. 2), distinct spatial differences are found in China. Part of central-western area in China sees the severest increases in heat extremes: the intensification of daytime/nighttime hot extremes (TXx/TNx) is between 0.5 and 1.5°C, the frequency indices (TX90p and TN90p) increase by at least 20 days, and the warm spell duration (WSDI) increases by more than 8 days. Only minor regions of central eastern China located between the Yangtze River valley (~30°N) and the Yellow River valley (~40°N) has experienced insignificant decreases: the daytime hot extreme (TXx) decreases by approximately 1.0°C, the warm days (TX90p) reduces by less than 4 days, and warm spell duration (WSDI) reduces by ~2 days. The decreases in nighttime hot extreme (TNx) and warm nights (TN90p) are less evident. Noted that these minor regions dominated by decreasing changes are also regions affected by strong emission of anthropogenic aerosols (Xie et al., 2017), which tend to mask out some of the warming effects of the GHG (Lin et al., 2016; Wang et al., 2016). Generally, the intensification magnitudes of daytime hot extreme (TXx) are less pronounced than that of nighttime hot extreme (TNx) and this is similar to other parts of the world in terms of long-term trends (Fischer & Knutti, 2014).

Figure 1. Changes in the heat extremes under the historical 0.5°C warming increment in China from observational records. The probability density functions represent the percentage of landmass in continental China that experienced certain changes during the period of 1991–2010 compared to the period of 1961–1979. The red lines are the results derived from the CN05.1 data sets, and the light orange ribbons represent the internal variability in the CN05.1 data sets. The magenta line in (a) is the result of the GHCNDEX, and the light blue line is the HadEX2. The dark blue lines in (a) and (b) denote a 0.5°C change and in (c–e) denote 50% of the aggregated area.
3.2. Heat Extreme Changes in CESM Historical Simulations

We evaluate the changes in heat extremes under the past 0.5°C warming increment in the CESM historical simulations by comparing with the observational records (Fig. 3). The PDFs of the intensity index changes in the observational records fall perfectly into the model spread of the historical simulations. The historical simulations’ ensemble mean results show more than 44.1%/72.8% of the China’s landmass with an 0.5°C intensification of the daytime hot extreme (TXx)/nighttime hot extreme (TNx), which is comparable but slightly weaker than the observational records (46.7%/76.5%). However, for the frequency and duration indices (TX90p, TN90p, and WSDI), the differences between the observational records and the CESM historical simulations are relatively evident. More than 50% of China’s landmass sees an increase by at least 12 days in warm days (TX90p),

Figure 2. Patterns of the heat extreme changes under the historical 0.5°C warming increment in China derived from the observational records CN05.1. Differences are calculated between the period of 1991–2010 and the period of 1961–1979. The black dashed lines denote the 5% significance level.

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20 days in warm nights (TN90p), and 4 days in warm spell duration (WSDI) in the historical simulations, compared with approximately 19 days (TX90p), 33 days (TN90p), and 8 days (WSDI), in the observational records.

We quantitatively assess the consistency of heat extreme changes between the observational records and the model simulations in Fig. 4. Generally, the scatter plots reveal that the CESM historical simulations systematically underestimate the increases of heat extremes in China under the past half-degree warming increment. The historical simulations have the highest consistency with observations in intensity indices: daytime/nighttime hot extremes (TXx/TNx). The intensification of the two indices in over 47.6%/38.8% of China’s landmass in observations is captured by the historical simulations. The consistency in frequency and duration indices is slightly weaker than the intensity indices. In about 24.8% and 14.7% of landmass in continental China, the observational increases in warm days (TX90p) and warm nights (TN90p) are captured by the historical simulations. For the warm spell duration (WSDI), the model simulations are consistent with the observations in more than 20.0% of China’s landmass. Noted that here we utilized a rather strict criterion to assess the consistency of model simulations. We note that over half of the areas over China’s mainland, the differences of the historical simulations are only 29.9–51.2% relative to observational changes in the five heat extreme indices. The larger differences in the percentile-based indices may be resulted from the model response deficiency to the forcings.

We further compare the spatial patterns of the heat extreme changes associated with the 0.5°C warming in the observations and the historical simulations (Fig. 5). The general distributions of the changes under the 0.5°C warming in observational records (Fig. 2) are well captured in the historical simulations but with weaker magnitudes. The severest warming regions over central-western China are evitable in historical simulations. The daytime/nighttime hot extremes (TXx/TNx) show ~0.4°C weaker magnitudes than observations in some regions over central-western China. The frequency of warm nights (TN90p) shows a difference of more than 4 days compared to the observations. The minor regions of central eastern China experienced slight decrease in daytime indices (TXx, TX90p, and WSDI) in the observational records are reasonably reproduced by the historical simulations. For TX90p and WSDI, the decrease signal is not as strong as the observations in central-eastern China, but the increase is still far less than the adjacent regions as in the observations.

### 3.3. Heat Extreme Changes in CESM Low-Warming Projections

As the ability of reproducing the heat extreme changes under the past half-degree warming increment in the CESM historical simulations been assessed, we try to verify the hypothesis: for the heat extreme changes between the future two LTGGs, the past 0.5°C warming increment in observational records would be an analogue for the future projections. We first examine the PDFs of heat extreme changes in Fig. 6. For the daytime indices including daytime hot extreme (TXx), warm days (TX90p), and warm spell duration (WSDI), we find that the changes in the heat extremes under the past 0.5°C warming in the observational records are conservative analogues of the future 0.5°C warming between the two LTGGs. The future projections have a
larger land fraction (more than 62.9% of China’s landmass) that will see at least 0.5°C intensification in daytime hot extremes (TXx) compared to 46.7% in observational records. Likewise, the warm days (TX90p) will increase by at least 23 days in more than half of China’s landmass (19 days in observations). More than 50% of continental China will see an increase by at least 12 days in warm spell

Figure 4. Heat extreme changes under the historical 0.5°C warming increment in CN05.1 observational records and in Community Earth System Model (CESM) historical simulations. Each dot represents a grid point in China. The gray dots are the results of all the simulation members, and the blue dots are the model ensemble mean results. The black diagonal line represents that the results in the observations are the same in simulations.
duration (WSDI) in the future projected 0.5°C warming increment, compared with approximately 8 days in the observational records under the past half-degree warming. For the nighttime extremes (TNx and TN90p), the changes in the observational records can no longer serve as conservative analogues under the future 0.5°C warming. The nighttime hot extreme (TNx) exhibits an intensification of 0.5°C over

Figure 5. Patterns of the heat extreme changes under the historical 0.5°C warming increment of the Community Earth System Model (CESM) historical simulations ensemble mean. The black crosses denote that at least eight model members agree on the same sign on a certain grid.
more than 60.3%/76.5% of Chinese land mass (10.5%/30.4% over 1.0°C) in the projections/observations. An increase of at least 25 days in warm nights (TN90p) in 50% of China’s landmass will be seen in future projections compared to approximately 33 days in observational records.

Similar to Fig. 4, we also quantify the relationship between the observational records and the CESM low-warming projections in heat extreme changes under 0.5°C warming increment in Fig. 7. Opposite features are found in daytime and nighttime extreme indices. For the daytime indices, the observational increases are rather conservative compared to the projections. In more than 72.0% of China’s landmass, the observational increase is weaker than the model ensemble mean. In more than 47.0% of China’s landmass, the observational changes in daytime hot extreme (TXx) drop out of the 25th percent model spread criterion. For the percentile-based indices such as warm days (TX90p) and warm spell duration (WSDI), the 0.5°C warming in the future will also lead to significant changes on a regional scale. The increase in observational records is lower than the 25th percent of model spread increment in more than 72.0% of land fractions in TX90p and warm spell duration (WSDI). The changes of these two indices in observations are lower than the model ensemble mean in more than 68.8%/79.7% land fractions respectively. In contrast, less land fractions in China see this kind of conservative estimation in nighttime indices including the nighttime hot extreme (TNx) and warm nights (TN90p). The observational changes in these two indices are less than the 25th percent of model spread criterion only in about 15.9% and 14.8% of land fractions in China. In summary, the changes in heat extremes in China under half-degree warming increment in the observational records only serve as conservative analogues for the future changes between the two LTGGs in the daytime extreme indices.

The spatial patterns of the heat extreme changes under 0.5°C warming between the two LTGGs in the CESM low-warming projections are given in Fig. 8. The largest differences between the observations and the projections are seen over the region between the Yangtze River valley (~30°N) and the Yellow River valley (~40°N). The observational records show decreases in the daytime hot extreme (TXx), warm days (TX90p), and warm spell duration (WSDI) in this region, while uniformly increases are seen in the projections. In comparison, the intensifications and increases in nighttime extremes (TNx and TN90p) in the projections are similar to that seen in the observations. The above differences can be attributed to the anticipated future reduction of aerosol emissions in China. The anthropogenic aerosols are able to mask out some of the warming impacts induced by the GHG (IPCC, 2013). In CESM low-warming experiments, the aerosol emissions follow the protocol of RCP8.5, which will be sharply reduced in the future (Riahi et al., 2011). It has been noted that the reduction of anthropogenic aerosols will induce the increases of heat extremes on both global and regional scales in the context of long-term trend (Wang et al., 2016; Wang et al., 2017; Yangyang Xu et al., 2018). The projected continuous increase in daytime extremes in the region between the Yangtze River valley (~30°N) and the Yellow River valley (~40°N) should be deduced by the reduction of aerosol emissions in the

Figure 6. Same as Fig. 3 but for the future 0.5°C warming increment between the two long-term global warming goals from the Community Earth System Model (CESM) low-warming projections. The red lines are the results from the CN05.1. The purple solid lines are the model ensemble mean results of the CESM low-warming experiment, and the light purple dashed lines are the model spread.
Figure 7. Same as Fig. 4 but for future heat extreme changes between the two long-term global warming goals in the Community Earth System Model (CESM) low-warming projections.
future in eastern China, since this region has the largest aerosol emissions in present day (Z. Li et al., 2017; G. Wu et al., 2016). Since the direct radiative forcing induced by aerosols in the daytime is significantly higher than the nighttime (H. Zhang, et al., 2018), the continuous increase of the daytime extremes is more evident than the nighttime extremes in eastern China.
4. Conclusions

In this study, we investigate the changes of heat extremes induced by 0.5°C global warming increment in observational records and compare the results with historical simulations and projections from the CESM. The spatially aggregated changes in heat extremes are used to quantify the impacts of a half-degree global warming increment. The major findings are summarized below:

Firstly, we find that the impacts of the historical half-degree GMST warming on the general heat extreme indices, including TXx, TX90p, TN90p, and WSDI, are detectable in China based on the homogenized CN05.1 observational records. The increments in nighttime extremes (TNx and TN90p) are more evident than those in the daytime extremes (TXx and TX90p).

Secondly, the changes in heat extremes associated with the past 0.5°C GMST warming increment in the observational records are reasonably reproduced by the CESM historical simulations, with similar spatial patterns but slightly weaker magnitudes. The changes of intensity indices (TXx and TX90p) in the observational records are better reproduced by the model simulations than the frequency and duration indices (TX90p, TN90p, and WSDI).

Thirdly, The changes in daytime heat extremes (TXx, TX90p, and WSDI) induced by a 0.5°C GMST warming in the observational records can serve as conservative analogues for the model projections. The remarkable reduction of aerosol emissions in the future (following the RCP8.5 emission protocol) will lead to larger increases of daytime heat extremes in China under the 0.5°C GMST warming increment compared to the observational records. The projected changes of nighttime extremes (TNx and TN90p) are comparable or slightly weaker/less than those derived from the observational records. This kind of response is explained by the direct radiative forcing of aerosols, which is significantly stronger in daytime than in nighttime.

Along with global warming, changes in heat extremes have already caused impacts on natural and social systems including “food production and food security, human health (increasing mortality and morbidity in vulnerable groups), security, livelihoods, and poverty” (Hijijkia et al., 2014). We note that the observational records only present the lower bound for future 0.5°C warming, since threshold extreme indices will increase nonlinearly with global warming (Schleussner et al., 2017), more pronounced consequences are expected to occur in the frequency and the duration heat extremes. Revisiting the heat extreme changes in the observational records that occurred under the past 0.5°C warming has benefits in many aspects. First, the findings would provide strong evidence for climate change adaptation and risk management; Second, the observational records can serve as a metric for the evaluation of climate models. The close resemblance of the historical simulations to the observations adds crediblity to the results of the projections. In addition, the stronger daytime responses in the projections compared to those in the observations remind us to consider the amplified influence of future global warming due to possible reduction of anthropogenic aerosol emissions in areas that are currently heavily polluted, such as the eastern China and India.

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