Reduced Risks of Temperature Extremes From 0.5°C less Global Warming in the Earth's Three Poles

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Abstract Future projection of temperature extremes in the “Earth's three poles” (the Arctic, Antarctica, and Third Pole-Tibetan Plateau) is of importance to risk assessment and policymaking owing to the high sensitivity to climate change in these regions. In this study, future projections of four extreme temperature indices were constructed after the application of a bias correction method in models of Phase 6 of the Coupled Model Intercomparison Project (CMIP6). The reduced intensification of temperature extremes in the Earth’s three poles if warming can be limited to 1.5°C instead of 2°C above the pre-industrial level was examined. Results showed that all the extreme temperature indices show significant increasing trends under both the SSP2–4.5 and SSP5–8.5 scenarios over the Earth's three poles (SSP: Shared Socioeconomic Pathway). For the coldest night (TNN), warmest night (TXn), and warmest day (TXx), the greatest increase by the end of the 21st century under SSP5–8.5 occurs in the Arctic, followed by the TP and finally Antarctica. For the coldest day (TXn), the greatest increase occurs in the Arctic, followed by Antarctica and finally the TP. If global warming can be limited to 1.5°C rather than 2°C, the intensification of TNN, TNx, TXn, and TXx in the Arctic (Antarctica/TP) under SSP5–8.5 is projected to reduce by 66% (21.7%/44.26%), 50.31% (54.79%/60.52%), 71.58% (12.91%/65.81%), and 41.73% (81.3%/57.34%), respectively, and the results are similar for SSP2–4.5. Therefore, keeping a lower warming target is essential for reducing the risk of extreme events in the Earth's three poles.

Plain Language Summary Efforts to understand and project climate change over the Earth's three poles (the Arctic, Antarctica, and Third Pole-Tibetan Plateau) under global warming scenarios are crucial for risk assessment and policymaking aimed at coping with future climate change. This study reports the future change of four extreme temperature indices over the Earth's three poles based on the observational data sets and outputs from models of Phase 6 of the Coupled Model Intercomparison Project with bias correction. We find that global warming will lead to substantial changes in extreme temperature indices over the Earth's three poles. All the four extreme temperature indices with bias correction show consistent increasing trends under both Shared Socioeconomic Pathway (SSP2–4.5 and SSP5–8.5) over the Earth's three poles. Although the future changes in extreme temperature indices under a 1.5°C or 2°C warming world are not uniform in space, the risk of temperature extremes over the Earth's three poles is likely to decrease when global warming is limited to 1.5°C instead of 2°C under both SSP2–4.5 and SSP5–8.5. This means that a lower warming target is necessary for reducing the risks of extreme temperature over the three poles.

1. Introduction

The Arctic (north of 60°N), Antarctica (south of 60°S), and the so-called “Third Pole,” the Tibetan Plateau (TP; 25°–45°N, 65°–105°E; altitude >2,000 m), together termed “Earth's three poles,” are highly sensitive to global warming (Gao et al., 2019; X. Li et al., 2020; Rintoul et al., 2018; Sui et al., 2017). Climate change in these regions may trigger a series of climatic responses that can lead to global consequences (Fang et al., 2021; X. Li et al., 2020; You et al., 2021). For instance, the decline in sea ice under global warming in the Arctic and Antarctica will likely cause a rise in sea level in the coming centuries, thus affecting corresponding plans or measures to adapt to and mitigate against such changes (Rintoul et al., 2018). Likewise, warming in the TP region may affect water resources in downstream areas (Pithan, 2010; You et al., 2016). Since enormous challenges are inevitable in polar regions in terms of sustainable development alongside increasing human activities, efforts to understand and project climate change over the Earth's three poles under global warming scenarios are crucial.
During the past few decades, unprecedented changes have taken place over the Earth's three poles (Mountain Research Initiative EDW Working Group, 2015; Sui et al., 2017; Ding et al., 2018; Wei et al., 2019). For example, the surface air temperature in the Arctic is unequivocally warming at a rate of about twice the global mean (Cohen et al., 2014; Screen & Simmonds, 2010), which is a phenomenon known as “Arctic amplification.” Under the influence of Arctic amplification, Greenland's glaciers are retreating rapidly (Mouginit et al., 2019), and there is an acceleration in the level of disturbance in both marine and terrestrial ecosystems (You et al., 2021). Meanwhile, an accelerating loss of Antarctica's ice shelves has been observed in recent years (Fauria et al., 2010; Kinnard et al., 2011; Parkinson & Comiso, 2013), along with a greening tendency in the region (Amesbury et al., 2017), and the TP has suffered a rapid cryospheric melt and intensification of its water cycle (Yao et al., 2018). In addition to the change in mean temperature, the Earth's three poles have witnessed an increasing number of record-breaking climate extremes (e.g., the unprecedented extreme high temperature in the Arctic during July 2021), which is obviously important because the natural environment and economies are more vulnerable to extreme temperature events than mean temperature change (Yu et al., 2017). In addition, a thorough understanding of temperature extremes and their evolution in the Earth's three poles are also highly relevant to human lives. However, our comprehension of the likely future change in climate extremes in the Earth's three poles remains poor (Sui et al., 2017).

The 2015 Paris Agreement, approved by a total of 175 parties including 174 countries and the European Union under the United Nations Framework Convention on Climate Change (UNFCCC), set a goal to hold the global mean temperature increase to “well below 2°C” and make efforts to limit the warming to 1.5°C above pre-industrial levels (UNFCCC, 2015). In this respect, there have to date already been many studies that have focused on climate change in 1.5°C and 2°C warmer worlds above the pre-industrial level in different regions of the world (Dosio & Fischer, 2018; King et al., 2017; Nangombe et al., 2018; Peng et al., 2019; Sun et al., 2019). You et al. (2020), for example, examined the changes in surface temperature extremes over the TP derived from the multi-model ensemble (MME) mean of the models that participated in Phase 5 of the Coupled Model Intercomparison Project, under global warming of 1.5°C, 2°C, and 3°C above the pre-industrial level. The results indicated that the warming magnitudes of extreme temperature indices in the TP region are greater than those for the whole of China, the Northern Hemisphere, and the global mean. However, the changes in temperature extremes over the Arctic and Antarctica under different global warming levels have been relatively less well studied in comparison to those elsewhere in the rest of the world (Saurral et al., 2020). Considering the hypothesis that a 0.5°C difference in the global mean temperature (from 1.5°C to 2.0°C) may lead to an ice-free North Pole (Jahn, 2018), the changes in extreme temperature indices over the Earth's three poles under 1.5°C and 2°C global warming above the pre-industrial level in CMIP6 (Phase 6 of the Coupled Model Intercomparison Project) models are also worthy of investigation.

Although the future changes in extreme events for one of the three poles have been discussed previously (e.g., Saha et al., 2006; Saurral et al., 2020; You et al., 2020), to the best of our knowledge there has been no comparative analysis of the future projection of extreme temperature indices for the Earth's three poles. Also, it remains an as yet unstudied issue to use CMIP6 data with bias correction to project future changes in temperature extremes in the Earth's three poles. Since limiting global warming to 1.5°C might translate into substantial benefits (e.g., conservation of the ecological environment) across the Earth's three poles, there is considerable importance in assessing the reduction in risk from temperature extremes under 0.5°C less global warming in the Earth's three poles. Thus, our main goals in this study were to carry out future projections of extreme temperature indices and evaluate the impacts of 1.5°C and 2°C global warming scenarios on extreme temperature indices over the Earth's three poles using CMIP6 model outputs after applying bias correction. On this basis, the similarities and differences in the corresponding changes in temperature extremes over the Earth's three poles can then be further discussed in this paper. Finally, we examine the reduction in the intensification of temperature extremes in the Earth's three poles if warming is limited to 1.5°C, instead of 2°C, above the pre-industrial level.

The remainder of the paper is organized as follows: The data and methods are briefly described in Section 2. Section 3 presents first the performance of CMIP6 models in simulating the historical spatiotemporal variation of extreme temperature indices over the Earth's three poles, and then the changes in extreme temperature indices in
1.5°C and 2°C warmer worlds based on the bias-corrected extreme temperature indices. Finally, a summary and discussion are provided in Section 4.

2. Data and Methods

2.1. Observations and CMIP6 Model Outputs

Daily gridded minimum and maximum temperature data at a resolution of 0.5° × 0.5° provided by the European Center for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) data set were employed as observational data to evaluate the historical simulations of CMIP6 models in this study (Dee et al., 2011). ERA-Interim can be regarded as a good observational data set for the evaluation of climate model performance and has been widely used in previous studies in research on the Earth’s three poles (Dee et al., 2011; Gao et al., 2019; Matthes et al., 2015; Turner et al., 2021). The data can be accessed (at https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/).

For future projection, CMIP6 advocates emission scenarios based on the Shared Socioeconomic Pathways (SSPs) which describe and quantify both emissions trajectories and land-use changes (Eyring et al., 2019; O’Neill et al., 2016). Five different narratives are elaborated for SSP, with model quantifications spanning from potential futures of green and fossil-fueled growth (SSP1 and SSP5), high inequality between and within countries (SSP3 and SSP4), to a “middle-of-the-road” scenario (SSP2). The available data of the future projections under SSP1–2.6, SSP3–7.0, and SSP4–6.0 are relatively less than that under SSP2–4.5 and SSP5–8.5. In order to have as many models as possible, the outputs of future projections under SSP2–4.5 and SSP5–8.5 during 2015–2100 as well as the historical simulations during 1979–2014 derived from 25 CMIP6 models (Table 1) were used in this study. The variables used in this study were the daily maximum and minimum temperature and the monthly mean temperature. Only the first realization (usually r1i1p1f1) of each model was used. However, not all models include the variant “r1i1p1f1.” Therefore, in order to have as many models as possible, r1i1p1f2 for CNRM-CM6-1-HR, CNRM-CM6-1, CNRM-ESM2-1, MIROC-ES2L, and UKESM1-0-LL, as well as r1i1p1f3 for HadGEM3-GC31-LL, were also utilized. As the period 1979–2014 is covered by both ERA-Interim and the CMIP6 historical experiments, this period was used for model assessment.

2.2. Extreme Temperature Indices

Following the definitions from the Expert Team on Climate Change Detection and Indices (ETCCDI; X. Zhang et al., 2011), four extreme temperature indices (Table 2) were used in this study, including coldest night (TNn), warmest night (TNx), coldest day (TXn), and warmest day (TXx). These four extreme temperature indices can reflect the basic characteristics of temperature extremes and have been widely used in previous studies (e.g., Dunn et al., 2014; Peng et al., 2019; Kim et al., 2020). More details of these extreme temperature indices can be found on the ETCCDI website (http://etccdi.pacificclimate.org/list_27_indices.shtml). To facilitate the intercomparison among different CMIP6 models, the extreme temperature indices were first calculated for the observational data and models on their native grids and then interpolated to a common 1° latitude by 1° longitude grid via bilinear interpolation (Jiang et al., 2016; Ou et al., 2013; X. Wang et al., 2018; H. Zhang et al., 2013).

2.3. Model Evaluation Metrics

2.3.1. Taylor Skill Score

To quantify the performances of the CMIP6 models in simulating the spatial patterns of the climatological extreme temperature indices, the Taylor skill score (TS; Taylor, 2001; B. Wang et al., 2018; Peng et al., 2019) was used, which is defined as follows:

$$TS = \frac{(1 + R)^2}{(SDR + \frac{1}{SDR})}$$

(1)
Table 1
Details of the 25 Models of Phase 6 of the Coupled Model Intercomparison Project Employed in This Study

| Institution ID | Modeling center and country | Model name | Atmospheric resolution (lat × lon) |
|----------------|-----------------------------|------------|-----------------------------------|
| CSIRO-ARCSS    | Commonwealth Scientific and Industrial Research Organization, Australian Research Council Center of Excellence for Climate System Science, Australia | ACCESS-CM2 | 1.25° × 1.875° |
| CSIRO          | Commonwealth Scientific and Industrial Research Organization, Australia | ACCESS-ESM1-5 | 1.25° × 1.875° |
| AWI            | Alfred Wegener Institute, Germany | AWI-ESM1-1-MR | 0.938° × 0.938° |
| BCC            | Beijing Climate Center, China | BCC-CSM2-MR | 1.125° × 1.225° |
| CCCma          | Canadian Center for Climate Modeling and Analysis, Environment and Climate Change Canada, Canada | CanESM5 | 1.406° × 1.406° |
| CNRM-CERFACS   | Center National de Recherches Meteorologiques, Center Europeen de Recherche et de Formation Avancee en Calcul Scientifique, France | CNRM-CM6-1-HR | 0.5° × 0.5° |
|                |                             | CNRM-CM6-1 | 1.406° × 1.406° |
|                |                             | CNRM-ESM2-1 | 1.406° × 1.406° |
| EC-Earth-Consortium | EC-EARTH consortium | EC-Earth3 | 0.703° × 0.703° |
|                |                             | EC-Earth3-Veg | 0.703° × 0.703° |
|                |                             | EC-Earth3-Veg-LR | 1.125° × 1.25° |
| CAS            | Chinese Academy of Sciences, China | FGOALS-g3 | 2.25° × 2° |
| NOAA-GFDL      | National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, United States | GFDL-ESM4 | 1° × 1.25° |
| MOHC           | Met Office Hadley Center, United Kingdom | HadGEM3-GC31-LL | 1.25° × 1.875° |
|                |                             | UKESM1-0-LL | 1.25° × 1.875° |
| INM            | Institute for Numerical Mathematics, Russian Academy of Science, Russia | INM-CM4-8 | 1.5° × 2° |
|                |                             | INM-CM5-0 | 1.5° × 2° |
| IPSL           | Institute Pierre Simon Laplace, France | IPSL-CM6A-LR | 1.259° × 2.5° |
| MIROC          | Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, The University of Tokyo, National Institute for Environmental Studies, RIKEN Center for Computational Science, Japan | MIROC6 | 1.406° × 1.406° |
|                |                             | MIROC-ES2L | 1.25° × 1.875° |
| DKRZ           | Deutsches Klimarechenzentrum, Germany | MPI-ESM1-2-HR | 0.938° × 0.938° |
| MPI-M          | Max Planck Institute for Meteorology, Germany | MPI-ESM1-2-LR | 1.875° × 2.5° |
| NUIST          | Nanjing University of Information Science and Technology, China | NESM3 | 1.875° × 1.875° |
| NCC            | NorESM Climate modeling Consortium, Norway | NorESM2-LM | 1.875° × 2.5° |
|                |                             | NorESM2-MM | 0.938° × 1.25° |

Note. CMIP6, models of Phase 6 of the Coupled Model Intercomparison Project.

Table 2
Brief Description of the Four Extreme Temperature Indices Used in This Study

| Index | Name        | Definition                               | Unit |
|-------|-------------|------------------------------------------|------|
| TNn   | Coldest night | Annual minimum value of daily minimum temperature | °C   |
| TNx   | Warmest night  | Annual maximum value of daily minimum temperature | °C   |
| TXn   | Coldest day   | Annual minimum value of daily maximum temperature | °C   |
| TXx   | Warmest day   | Annual maximum value of daily maximum temperature | °C   |
where, \( R \) is the spatial pattern correlation between the observations and model simulations, and SDR is the ratio of the spatial standard deviations of the modeled and observed values (SDR = \( \frac{\sqrt{\sum_{i=1}^{m} \sum_{j=1}^{n} (x_{i,j} - \bar{x})^2}}{\sqrt{m \times n}} \)), \( m \) is the grid points of latitude in the study region, \( n \) is the grid points of longitude, \( x_{i,j} \) is the value of each extreme temperature index in each grid point in CMIP6 model, \( y_{i,j} \) is the value of each extreme temperature index in each grid point in observation, \( \bar{x} \) and \( \bar{y} \) are the average value of each extreme temperature index for all grid points in CMIP6 model and observation). A TS equal to 1 indicates a perfect match, in this case between the CMIP6 models and observations, and vice versa for a score of 0, that is, no match at all.

2.3.2. Interannual Variability Skill Score

To quantify the performances of CMIP6 models in simulating the interannual variability of extreme temperature indices, we utilized the interannual variability skill (IVS) score defined by W. Chen et al. (2011) as follows:

\[
IVS = \left( \frac{\text{STD}_m}{\text{STD}_o} - \frac{\text{STD}_o}{\text{STD}_m} \right)^2
\]

where, \( \text{STD}_m \) and \( \text{STD}_o \) are the interannual standard deviations of the model simulations and observations, respectively (\( \text{STD} = \sqrt{\sum_{i=1}^{n} (x_{i} - \bar{x})^2} \)), \( x_i \) is the single yearly data for each extreme temperature index, \( \bar{x} \) is the average value of each extreme temperature index for all years, \( n \) is years). It should be mentioned that the IVS of each extreme index was first calculated at each grid point and then area-averaged over the Earth’s three poles. The smaller the IVS, the better the model’s simulation skill in terms of interannual variability.

2.4. Bias Correction Method

Since there is model bias in simulating extreme temperature, particularly in polar and mountain regions, bias correction is needed for CMIP6 model simulations (Gumindoga et al., 2019; Peng et al., 2019; Sperna et al., 2010; Teutschbein & Seibert, 2012). We utilized a variance scaling method in this study, as it can guarantee that the climatological mean and standard deviation of the model simulations are the same as those of the observations during the reference period, while the model biases are time-variant (Peng et al., 2019; Teutschbein & Seibert, 2012). The specific steps involved in applying the bias correction method (i.e., variance scaling) are outlined in the supplementary material.

2.5. Definition of the 1.5°C/2°C Period of CMIP6 Models

As pointed out in the 2015 Paris Agreement, the 1.5°C or 2°C targets in terms of the increase in global warming are relative to the pre-industrial level. For the selection of the pre-industrial period, there are two main principles: (a) the global warming in the 20th century should have no effect on the pre-industrial period (S. Chen et al., 2018); and (b) the initial integration time of the historical experiments are different for different models (Guo et al., 2017). Therefore, we selected 1861–1890 as the pre-industrial period in this study (S. Chen et al., 2018; Peng et al., 2019).

We used the 21-year time-slice approach in this study to discern the time at which 1.5°C or 2°C global warming above the pre-industrial period had been reached. The uncertainties associated with climate sensitivities in different CMIP6 models can be eliminated through this approach, while the nonlinearities in global mean temperature resulting from internal variability can be retained (Hawkins et al., 2014; James et al., 2017). For each CMIP6 model, the 1.5°C (2°C) period is determined by the time when the 21-year running mean of global mean temperature is between 1.3° and 1.7°C (between 1.8° and 2.2°C) warmer than the pre-industrial period (Y. Zhang et al., 2018). During this period, the specific year when crossing the 1.5°C/2°C threshold is defined as the accu-
rate arrival year of 1.5°C/2°C warming. Note that the 1.5°C/2°C period and the corresponding accurate arrival year are calculated for CMIP6 models but not for observation.

2.6. Response of Extreme Temperature Indices to Global Warming and Signal-To-Noise Ratio

To investigate the response of extreme temperature indices to global warming, we used two steps: (a) obtain the time series by applying a 5-year overlapping mean over decadal periods (i.e., 2015–2024, 2020–2029, up to 2085–2094) to the projected extreme temperature indices averaged over the Earth's three poles and global mean temperature; and (b) calculate the response rate through a linear regression between the time series of projected extreme temperature indices over the Earth's three poles and the time series of global mean temperature. Note that the response rate of each CMIP6 model was calculated separately.

Following B. Li and Zhou (2010), the signal-to-noise ratio (SNR) was used to measure the credibility of the projected results in this study. The SNR is defined as the ratio of the multimodel ensemble median and the inter-model standard deviation. The projected results are robust when SNRs are greater than 1.

2.7. Avoided Intensification of Extreme Temperature Indices Between the 1.5°C and 2°C Global Warming Levels

The avoided intensification (D. Li et al., 2018) is defined as follows:

\[
\text{Avoided intensification} = \frac{C_{2.0} - C_{1.5}}{C_{2.0}} \times 100\%.
\]

(3)

In this formula, \(C_{1.5}\) and \(C_{2.0}\) indicate the changes in extreme temperature indices at the 1.5°C and 2°C global warming levels with respect to the pre-industrial period, respectively.

3. Results

3.1. Model Evaluation

The climatological spatial distributions of the four extreme temperature indices according to the observational data and the CMIP6 MME mean over the Earth's three poles for the period 1979–2014 are shown in Figures 1–3. The spatial distributions of all four extreme temperature indices can be basically captured by the CMIP6 MME, whether in the Arctic, Antarctica, or the TP. Specifically, a cold bias is apparent for both the TNn (Figure 1c) and TNx (Figure 1f) indices over almost the entire Arctic. However, the CMIP6 MME overestimates the TXn (Figure 1i) and TXx (Figure 1l) over Siberia and northern North America, respectively. For Antarctica, the CMIP6 MME overestimates TNn (Figure 2c) and TNx (Figure 2f) over the ocean, but shows an underestimation inland over eastern Antarctica. In addition, TXn (Figure 2i) and TXx (Figure 2l) are overestimated in almost the whole of Antarctica by the CMIP6 MME. For the TP, the bias between the CMIP6 MME and observation for TNn (Figure 3c), TNx (Figure 3f), and TXn (Figure 3i) is negative over the entire region, and negative for TXx (Figure 3l) over the central TP but positive elsewhere. This indicates that the CMIP6 MME shows consistent underestimation for the TNn, TNx, and TXn over the whole of the TP, but only a slight underestimation for the TXx over the central TP.

The TS is used to provide a concise summary of the simulation skill in each CMIP6 model with respect to the spatial pattern of the four extreme temperature indices over the Earth's three poles, and the results are presented in Figure 4. Most of the CMIP6 models perform well in simulating the spatial distribution of these extreme temperature indices, as the TS values are always larger than 0.7 in the Arctic (Figure 4a), Antarctica (Figure 4b), and the TP (Figure 4c). The CMIP6 models tend to show better spatial simulation skill for the TXx compared with the other three indices in the Arctic (Figure 4a). In contrast, the spatial patterns of all extreme indices are generally well simulated in Antarctica (Figure 4b). In the TP (Figure 4c), the cold indices (TNn and TXn) are better simulated by most of the CMIP6 models when compared with the warm indices (TNx and TXx). In general, the CMIP6 models perform best in Antarctica, followed by the TP, and finally the Arctic.
Figure 1. Spatial patterns for the climatological mean extreme temperature indices (unit: °C) over the Arctic (north of 60°N) during 1979–2014. The left, middle, and right columns indicate the results from the European Center for Medium-Range Weather Forecasts Interim Re-Analysis (ERA-Interim), the models of Phase 6 of the Coupled Model Intercomparison Project and multi-model ensemble (CMIP6 MME), and the bias between ERA-Interim and the CMIP6 MME (bias = CMIP6 MME – ERA-Interim), respectively. The rows, from top to bottom, indicate coldest night, warmest night, coldest day, and warmest day, respectively.
Figure 2. As in Figure 1 but for Antarctica (south of 60°S).
Figure 5 plots the IVS score (described in Section 2.3.4), which we use to measure the similarity in the interannual variability between the CMIP6 models and observations in the Arctic, Antarctica, and the TP. Given that the IVS scores of most of the models are below 2.0, it can be concluded that the CMIP6 models are generally able to capture the observed interannual variability of the four extreme temperature indices in the Arctic, Antarctica, and the TP. However, the ability to simulate the four extreme temperature indices is not equal in these three regions. In the Arctic, the CMIP6 models show limited simulation skill for the TNx, as demonstrated by the IVS scores for TNx being larger than those for the other indices (Figure 5a). For Antarctica, all models except INM-CM4-8, INM-CM5-0, MIROC-ES2L, and MIROC6 capture the observed interannual variability of the four extreme temperature indices well (Figure 5b). In the TP region, TNn and TNx are relatively poorly simulated compared with the other two indices (Figure 5c). This indicates that the CMIP6 models show better simulation skill for the coldest and warmest days than they do for the coldest and TNx in the TP, which may be related to the limited simulation skill for nighttime cloud-radiation in models (You et al., 2017).

Figure 3. As in Figure 1 but for the Third Pole-Tibetan Plateau (25°–45°N, 65°–105°E; altitude >2,000 m).
Figure 4. Skill of each model of Phase 6 of the Coupled Model Intercomparison Project in simulating the spatial patterns of the mean state of extreme temperature indices during 1979–2014: (a) Arctic; (b) Antarctica; (c) Third Pole-Tibetan Plateau.
In summary, most of the CMIP6 models can reasonably reproduce both the spatial pattern and interannual variability of temperature extremes over the Earth's three poles. The spatial patterns of the extreme temperature indices are better simulated in Antarctica, while better simulation skill in terms of the interannual variability of temperature extremes can be found in the TP region.

3.2. Response of Extreme Temperature Indices to Global Warming

Considering that there are, as shown above, some biases in the CMIP6 model simulations with respect to the four extreme indices, a bias correction method—namely, the variance scaling method (see Section 2.4 for details)—was therefore employed to constrain the future projection based on the observations. The following projection results are all bias-corrected, and the projected regionally averaged changes in the extreme temperature indices under SSP2–4.5 (blue lines) and SSP5–8.5 (red lines) in the Arctic, Antarctica, and the TP are shown in Figure 6. All the extreme temperature indices show significant increasing trends under both SSP2–4.5 and SSP5–8.5, whether in the Arctic (Figures 6a–6d), Antarctica (Figures 6e–6h), or the TP (Figures 6i–6l). By comparing the SSP2–4.5 and SSP5–8.5 results, there is a suggestion that the increase in extreme temperature indices grows larger with more greenhouse gas emissions. For the TNn, TNx, and TXx indices, the greatest increase at the end of the 21st century under SSP5–8.5 occurs in the Arctic, followed by the TP, and finally Antarctica. For the TXn, the greatest increase occurs in the Arctic, followed by Antarctica, and finally the TP. Quantitatively speaking, TNn, TNx, and TXx in the Arctic under SSP5–8.5 are projected to increase by 16.64 (±5.32) °C, 6.59 (±3.23) °C, and 16.01 (±5.12) °C by the end of the 21st century, respectively. For Antarctica, TNn, TNx, and TXx under SSP5–8.5 are projected to increase by 6.06 (±1.65) °C, 2.93 (±0.91) °C, and 5.78 (±2.03) °C; while in the TP region the increases are 6.09 (±2.1) °C, 6.31 (±1.61) °C, 5.43 (±1.84) °C, and 5.69 (±1.56) °C. The indication is that the level of warming for the cold indices (TNn and TXn) by the end of the 21st century in the Arctic will be about twice that in the TP region, while the level of warming for the warm indices (TNx and TXx) in the TP region will be close to that in the Arctic. One possible reason for this is that a large amount of energy in the Arctic is stored in the Arctic Ocean, whereas on the TP it is stored in the soil, meaning the release of energy to the atmosphere mainly occurs during the cold season in the Arctic but in the warm season over the TP. Therefore, the cold indices and warm indices show different levels of warming between the Arctic and the TP (You et al., 2021).

The responses of the projected changes in the extreme temperature indices in the Earth's three poles to the global mean temperature are further investigated under SSP2–4.5 and SSP5–8.5 (Figure S1 in Supporting Information S1 and Figure 7). All the extreme temperature indices respond approximately linearly to global warming under SSP5–8.5 in the Arctic (Figures 7a–7d), Antarctica (Figures 7e–7h), and the TP (Figures 7i–7l). For the cold indices (TNn and TXn), the Arctic shows the largest response rates, followed by Antarctica and finally the TP. For example, the response rate under SSP5–8.5 for TNn in the Arctic, Antarctica, and the TP is 3.57 (25%–75% uncertainties: 3.17–4.31), 1.36 (1.13–1.39), and 1.13 (1.01–1.36), respectively (Figures 7a, 7e, and 7i). For the TNx, the TP shows the largest response rates (Figure 7j), followed by the Arctic (Figure 7b) and finally Antarctica (Figure 7f). For the TXx, meanwhile, the Arctic shows the largest response rates (Figure 7d), followed by the TP (Figure 7l) and finally Antarctica (Figure 7h).
The results are similar to those under SSP2–4.5 (see Figure S1 in Supporting Information S1). Meanwhile, the response rates of the cold indices (TNn and TXn) are larger than those of the warm indices (TNx and TXx) over the Arctic and Antarctica. This may result from a faster rate of increase in winter than summer temperature (S. Chen et al., 2018; Peng et al., 2019).

Figure 6. The 21-year running mean of the anomalies of the regionally averaged extreme climate indices over the Arctic, Antarctica, and the Third Pole-Tibetan Plateau during 1979–2100 (relative to the period 1995–2014). The rows, from top to bottom, indicate coldest night, warmest night, coldest day, and warmest day. The blue and red lines indicate the projections from the models of Phase 6 of the Coupled Model Intercomparison Project and multi-model ensemble under the Shared Socioeconomic Pathway (SSP)2–4.5 and SSP5–8.5 scenarios, respectively. Shading represents plus/minus one standard deviation among the models from their ensemble mean. The black and gray colors indicate the corresponding results from the historical simulations.
Figure 8 shows the response rates and SNRs of the extreme indices over the Earth’s three poles to the changes in global mean surface air temperature under the SSP2–4.5 and SSP5–8.5 scenarios. As all the SNRs are larger than 1 under both SSP2–4.5 (Figure 8b) and SSP5–8.5 (Figure 8d), these responses are all robust against the model spread. For the cold indices (TNn and TXn), the SNRs in the TP region are always the largest, while the largest SNRs of the warm indices (TNx and TXx) occur in Antarctica under both scenarios (Figures 8b and 8d). This indicates that the changes in the cold indices in the TP region and the changes in the warm indices in Antarctica, are relatively more credible.
3.3. Changes in Extreme Temperature Indices Over the Earth’s Three Poles Under 1.5°C and 2°C Global Warmings

Table 3 shows the 1.5°C and 2°C periods as well as the corresponding accurate arrival years of each CMIP6 model and the MME. For MME, we first obtained the average of the corresponding changes from different models, and then calculated the timing of the MME in reaching 1.5°C and 2°C global warmings based on the averaged changes of all models. The global warming in most of the CMIP6 models is projected to exceed 1.5°C by around the year 2020 under both SSP2–4.5 and SSP5–8.5, and the 2°C target is projected to be reached by around 2040 under SSP2–4.5. In contrast, the 2°C target is reached by around 2030 under SSP5–8.5. There are considerable discrepancies in the timing for individual CMIP6 models under different SSPs. For example, some of the models (e.g., CNRM-CM6-1-HR) cross the 1.5°C warming threshold before the 2010s under SSP5–8.5, while others (e.g., NorESM2-LM) even do not reach that mark until the 2030s.

The spatial patterns of the changes in the extreme temperature indices with a 1.5°C and 2°C increase in global warmings above the pre-industrial level over the Earth’s three poles under SSP5–8.5 are shown in Figures 9–12. The results under SSP2–4.5 are similar but with relatively small changes (Figures S2–S4 in Supporting Information S1). The Arctic (Figure 9) shows consistent warming over most of the region under both 1.5°C and 2°C global warmings in terms of the four extreme temperature indices. Under both 1.5°C and 2°C global warmings, the amplitude of the increase in the cold indices (TNN and TXn) is largest in Iceland, over the Beaufort Sea, and over the East Siberian Sea (Figures 9a, 9b, 9g, and 9h), while the warm indices (Tnx and TXx) show their greatest warming over the Greenland Sea and Kara Sea (Figures 9d, 9e, 9j, and 9k). Meanwhile, the cold indices show...
larger increases than the warm indices in the Arctic, possibly because of the increased absorption of sunlight by the Arctic Ocean during the warm season as a result of the significant decrease in Arctic sea ice. As more of the Arctic Ocean becomes ice-free, the Arctic warming in the cold season may be amplified (Dai et al., 2019). Therefore, the cold indices, which usually correspond to the maximum and minimum daily temperature of the winter season (S. Chen et al., 2018), will increase more than the warm indices. With an extra 0.5°C global warming, all the extreme temperature indices show increases across almost the entire Arctic (Figures 9c, 9f, 9i, and 9l).

For Antarctica (Figure 10), the warming of the cold indices (TNn and TXn) is mainly concentrated over the ocean area (Figures 10a, 10b, 10g, and 10h), whereas for the warm indices (TNx and TXx) it is inland over eastern Antarctica (Figures 10d, 10e, 10j, and 10k) under both 1.5°C and 2°C global warming. With an extra 0.5°C global warming, the cold indices show some decreases over the Ross Sea (Figures 10c and 10i), whereas the warm indices are warmer across nearly the whole of Antarctica, with the largest warming in eastern Wilkes Land (Figures 10f, 10i).

| Model name          | 1.5°C period (accurate arrival year) under SSP2-4.5 | 2°C period (accurate arrival year) under SSP2-4.5 | 1.5°C period (accurate arrival year) under SSP5-8.5 | 2°C period (accurate arrival year) under SSP5-8.5 |
|---------------------|----------------------------------------------------|----------------------------------------------------|----------------------------------------------------|----------------------------------------------------|
| ACCESS-CM2          | 2018–2027 (2022)                                   | 2029–2036 (2032)                                   | 2017–2025 (2021)                                   | 2027–2035 (2031)                                   |
| ACCESS-ESM1-5       | 2017–2028 (2023)                                   | 2030–2039 (2035)                                   | 2015–2027 (2022)                                   | 2029–2036 (2033)                                   |
| AWI-CM-1-1-MR       | 2004–2017 (2011)                                   | 2019–2032 (2026)                                   | 2004–2017 (2012)                                   | 2020–2030 (2025)                                   |
| BCC-CSM2-MR         | 2021–2034 (2028)                                   | 2036–2050 (2044)                                   | 2019–2028 (2024)                                   | 2030–2039 (2035)                                   |
| CanESM5             | 2004–2013 (2008)                                   | 2014–2019 (2017)                                   | 2004–2012 (2008)                                   | 2014–2020 (2017)                                   |
| CNRM-CM6-1-HR       | 2004–2014 (2009)                                   | 2015–2024 (2021)                                   | 2004–2013 (2008)                                   | 2015–2022 (2019)                                   |
| CNRM-CM6-1          | 2013–2025 (2020)                                   | 2029–2041 (2037)                                   | 2013–2024 (2019)                                   | 2026–2036 (2030)                                   |
| CNRM-ESM2-1         | 2017–2034 (2025)                                   | 2039–2052 (2046)                                   | 2017–2029 (2023)                                   | 2032–2041 (2037)                                   |
| EC-Earth3-Veg-LR    | 2009–2022 (2014)                                   | 2027–2046 (2039)                                   | 2009–2026 (2017)                                   | 2029–2039 (2035)                                   |
| EC-Earth3-Veg       | 1994–2006 (2000)                                   | 2010–2023 (2017)                                   | 1994–2006 (2000)                                   | 2009–2019 (2015)                                   |
| EC-Earth3           | 2010–2019 (2014)                                   | 2023–2040 (2033)                                   | 2012–2022 (2017)                                   | 2025–2032 (2030)                                   |
| FGOALS-g3           | 2012–2030 (2023)                                   | 2033–2054 (2040)                                   | 2012–2028 (2020)                                   | 2033–2044 (2040)                                   |
| GFDL-ESM4           | 2025–2045 (2035)                                   | 2050–2070 (2059)                                   | 2029–2040 (2035)                                   | 2043–2052 (2048)                                   |
| HadGEM3-GC31-LL     | 2011–2018 (2014)                                   | 2019–2027 (2023)                                   | 2011–2018 (2015)                                   | 2019–2025 (2023)                                   |
| INM-CM4-8           | 2021–2033 (2028)                                   | 2036–2052 (2045)                                   | 2018–2029 (2024)                                   | 2032–2042 (2037)                                   |
| INM-CM5-0           | 2019–2031 (2026)                                   | 2037–2062 (2054)                                   | 2017–2028 (2023)                                   | 2030–2040 (2035)                                   |
| IPSL-CM6A-LR        | 2005–2015 (2011)                                   | 2018–2027 (2023)                                   | 2005–2015 (2010)                                   | 2018–2031 (2024)                                   |
| MIROC-ES2L          | 2025–2040 (2032)                                   | 2042–2055 (2049)                                   | 2024–2033 (2029)                                   | 2035–2044 (2039)                                   |
| MIROC6              | 2027–2038 (2033)                                   | 2043–2057 (2050)                                   | 2026–2036 (2031)                                   | 2040–2047 (2044)                                   |
| MPI-ESM1-2-HR       | 2018–2037 (2026)                                   | 2040–2056 (2049)                                   | 2019–2033 (2027)                                   | 2036–2047 (2041)                                   |
| MPI-ESM1-2-LR       | 2021–2036 (2029)                                   | 2039–2054 (2046)                                   | 2019–2033 (2028)                                   | 2037–2046 (2042)                                   |
| NEM3                | 2010–2019 (2014)                                   | 2021–2036 (2028)                                   | 2009–2017 (2013)                                   | 2019–2027 (2023)                                   |
| NorESM2-LM          | 2036–2057 (2043)                                   | 2062–2080 (2072)                                   | 2032–2045 (2038)                                   | 2047–2056 (2051)                                   |
| NorESM2-MM          | 2037–2050 (2043)                                   | 2053–2077 (2069)                                   | 2032–2042 (2037)                                   | 2044–2055 (2050)                                   |
| UKESM1-0-LL         | 2016–2022 (2019)                                   | 2024–2030 (2027)                                   | 2016–2022 (2019)                                   | 2023–2028 (2026)                                   |

Note: SSP, Shared Socioeconomic Pathway.
Figure 9. Spatial patterns for the changes in extreme temperature indices (unit: °C) in 1.5°C and 2°C warmer worlds from the models of Phase 6 of the Coupled Model Intercomparison Project and multi-model ensemble mean under the Shared Socioeconomic Pathway 5–8.5 scenario (relative to the period 1861–1890) over the Arctic. The left, middle, and right columns show the results in 1.5°C and 2°C warmer worlds and the results due to an increase of 0.5°C, respectively. The rows, from top to bottom, denote coldest night, warmest night, coldest day, and warmest day. Dots indicate where more than 70% of the models agree on the sign of the changes.
Figure 10. As in Figure 9 but for Antarctica.
For the TP (Figure 11), the TNn (Figures 11a and 11b), TXn (Figures 11g and 11h), and TXx (Figures 11j and 11k) increase across nearly the whole of the TP both under 1.5°C and 2°C global warming, while the TNx (Figures 11d and 11e) shows a decrease over most of the TP. Under the additional 0.5°C global warming, the cold indices (TNn and TXn) increase by more than 0.5°C over the southern TP (Figures 11c and 11i), while the increase is more than 0.5°C over the northern TP for the warm indices (TNx and TXx; Figures 9f and 9l). In short, all the extreme temperature indices except the TNx for the TP are projected to increase under both 1.5°C and 2°C global warming. The largest warming for the cold indices with an additional 0.5°C global warming is mainly concentrated in the southern TP, whereas it is in the northern TP for the warm indices.

The avoided intensification of extreme temperature indices in the Earth’s three poles from 0.5°C less warming was further quantified and the results are shown in Figure 12. If global warming can be limited to 1.5°C instead of 2°C, all of the indices in the Arctic (Figure 12a), the TNx and day in Antarctica (Figure 12b), and the TNn and TXx in the TP region (Figure 12c) are projected under SSP2–4.5 to benefit from a consistently avoided intensification, since there is the same sign of changes in more than 70% of the models (solid circles). However, under SSP5–8.5, only the TXn, TXn, and TXx in the Arctic (Figure 12a), and the
TXx in Antarctica and the TP (Figures 12b and 12c) will benefit from a consistently avoided intensification. The exact values of the avoided intensification, as well as their 25%–75% uncertainties, are summarized in Table 4. The multimodel medians of avoided intensification in the Arctic under SSP2–4.5 and SSP5–8.5 for TNn, TNx, TXn, and TXx are estimated to be 37.11% and 66%, 95.91% and 50.31%, 45.98% and 71.58%, and 38.35% and 41.73%, respectively. For Antarctica, the multimodel medians of avoided intensification under SSP2–4.5 and SSP5–8.5 are about 20.4% and 21.7%, 69.18%, and 54.79%, 16.6% and 12.91%, and 84.59% and 81.3% for TNn, TNx, TXn, and TXx, respectively. Finally, for the TP, the multimodel medians of avoided intensification under SSP2–4.5 and SSP5–8.5 are approximately 36.95% and 44.26%, 96.39% and 60.52%, 40.76% and 65.81%, and 47.47% and 57.34% for TNn, TNx, TXn, and TXx, respectively. In summary, the TNx in the TP region and TXx in Antarctica show the largest avoided intensification from 0.5°C less warming under SSP2–4.5 and SSP5–8.5, respectively. Meanwhile, scenario–and region–dependence also exist for the avoided intensification of extreme temperature indices. For example, the avoided intensification of TNx (TNn, TXn, and TXx) over the TP tends to be larger (smaller) under SSP2–4.5 compared with that under SSP5–8.5 when limiting the global warming to 1.5°C rather than 2°C. Since the multimodel medians of avoided intensification are positive for all four extreme temperature indices, the risk of temperature extremes over the Earth's three poles is likely to decrease when global warming is limited to 1.5°C instead of 2°C under both SSP2–4.5 and SSP5–8.5. Thus, keeping a lower warming target is necessary for reducing the potential risk of extreme temperature events in the Earth's three poles.

As shown above, all the extreme temperature indices show consistent increasing trends and respond approximately linearly to global warming whether in the Arctic, Antarctica, or the TP. Besides, the intensification of all extreme temperature indices will reduce when global warming is limited to 1.5°C instead of 2°C. However, the warming rates, response rates, the credibility of future change, and the avoided intensification of extreme temperature indices vary among the Earth's three poles. The warming rates of cold indices (TNn and TXn) in Arctic are about twice that in Antarctica and TP, while the warming rates of warm indices (TNx and TXx) in Arctic and TP are roughly the same, and twice as much as that in Antarctica under both two SSPs. The results are similar for response rates. Meanwhile, with an additional 0.5°C global warming, all the extreme temperature indices show increase in nearly the whole region of Arctic and TP, while this is not for Antarctica, given that the cold indices (TNn and TXn) show some decreases over the Ross Sea. Besides, different avoided intensifications can be found in the Earth's three poles for the same extreme temperature index.

4. Summary and Discussion

As previous investigations focused mostly on the future changes in extreme events for one certain pole (e.g., the Arctic), comparative analysis of future projections of extreme temperature indices for the Earth's three poles was in need of further investigation. Moreover, due to the large uncertainties that exist in model projections—particularly in polar and mountain regions—bias correction was utilized in this study to constrain the projection results and reduce the projection uncertainty effectively. On this basis, we constructed future projections of four extreme temperature indices and assessed the impacts of 1.5°C and 2°C global warming scenarios on them over the Earth's three poles through CMIP6 model simulations. The similarities and differences in the corresponding
changes in climate extremes over the Earth's three poles have also been discussed. Finally, the reduced intensification of temperature extremes in the Earth's three poles if warming can be limited to 1.5°C instead of 2°C above the pre-industrial level was examined. The main conclusions can be summarized as follows:

1. CMIP6 models generally show reasonable capability in reproducing both the spatial patterns of the mean state and the interannual variation of the four extreme indices examined in this study. The spatial patterns of the extreme temperature indices are best simulated in Antarctica, and most of the CMIP6 models have better simulation skill in terms of the interannual variability of temperature extremes in the TP region.

2. As revealed in the corrected projections, all the extreme temperature indices show consistent increasing trends under both SSP2–4.5 and SSP5–8.5, whether in the Arctic, Antarctica, or the TP. For the TNn, TNx, and TXn, the greatest increase occurs in the Arctic, followed by the TP and finally Antarctica. For the TXx, the greatest increase occurs in the Arctic, followed by Antarctica and finally the TP.

3. Under an additional 0.5°C global warming, the intensification of all the extreme temperature indices increases over nearly the entire Arctic. For Antarctica, a warming of TNn and TXn can be expected over the most region except at Cape Cross and over the Ross Sea when the global warming level increases from 1.5°C to 2°C; whereas, for TNx and TXx, eastern mainland Antarctica is the affected area. As for TP, the largest warming for the cold indices with an extra 0.5°C global warming is mainly concentrated over the southern TP, whereas it is over the northern TP for the warm indices.

4. If global warming can be limited to 1.5°C instead of 2°C, the intensification of TNn, TNx, TXn, and TXx in the Arctic (Antarctica/TP) under SSP2–4.5 is projected to reduce by 37.11% (9.97%–68.68%), 95.91% (35.54%–155.84%), 45.98% (18.96%–66.73%), and 38.35% (18.1%–85.43%), respectively. Under SSP5–8.5, the avoided intensifications of TNn, TNx, TXn, and TXx in the Arctic (Antarctica/TP) are 66% (21.1%–115.52%), 50.31% (−109.61%–138.13%), 71.58% (33.02%–107.42%), and 41.73% (12.4%–107.29%), respectively. The TNx in the TP region and the TXx in Antarctica show the largest avoided intensification from 0.5°C less warming under SSP2–4.5 and SSP5–8.5, respectively. The positive multimodel medians of avoided intensification for all four extreme temperature indices imply that the risk of temperature extremes over the Earth's three poles is likely to decrease when global warming is limited to 1.5°C instead of 2°C under both SSP2–4.5 and SSP5–8.5. The indication is that keeping a lower warming target is necessary to avoid the risk of temperature extremes in the Earth's three poles.

As the resolutions of the CMIP6 models used in this study are relatively low, there are some uncertainties in projection results at regional scales. Therefore, the application of regional climate models with higher resolution is needed in future work. Besides, we only focused on four extreme temperature indices in this study; other extreme indices, such as growing season length, will be included in the work of our group in the future. In addition, we utilized a bias correction method for the future projections, but the results may have been influenced by the selection...
of observational data to a certain degree. Therefore, more adequate and accurate data are needed. Finally, it was not within the scope of this study to discuss the impacts brought by the projected future changes in temperature extremes, or indeed the mitigation efforts required in order to avoid such impacts.

**Data Availability Statement**

The European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) data set can be accessed (at [https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/](https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/)). The outputs of models of Phase 6 of the Coupled Model Intercomparison Project (CMIP6) can be obtained (at [https://esgf-node.llnl.gov/search/cmip6](https://esgf-node.llnl.gov/search/cmip6)). The details of extreme temperature indices can be found on the ETCCDI website (http://etccdi.pacificclimate.org/list_27_indices.shtml).

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