Future Projections of Daily Maximum and Minimum Temperatures Over East Asia for the Carbon Neutrality Period of 2050-2060

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Research Article

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Abstract

Future climate projections provide vital information for preventing and reducing disaster risks induced by the global warming. However, little attention has been paid to climate change projections oriented towards carbon neutrality. In this study, we address projected changes in daily maximum (Tmax) and minimum (Tmin) temperatures as well as diurnal temperature range (DTR) over East Asia for the carbon neutrality period of 2050–2060 under the newly available SSP1-1.9 pathway of sustainable development by using CMIP6 model simulations. CMIP6 multi-model ensemble results show that Tmax and Tmin will significantly increase with varying magnitudes during the carbon neutrality period of 2050–2060 under SSP1-1.9 over the whole East Asia while both upward and downward changes will occur for the DTR. Projected Tmax, Tmin and DTR changes all exhibit new spatial patterns during 2050–2060 under SSP1-1.9 compared with those over the same period under SSP2-4.5 and SSP5-8.5. Compared to 1995–2014, projected Tmax and Tmin averaged over East Asia during 2050–2060 will significantly warm up by 1.43℃ and 1.40℃ under SSP1-1.9, while the warming magnitudes are 1.93℃ and 2.04℃ under SSP2-4.5, and 2.67℃ and 2.85℃ under SSP5-8.5. Research on carbon neutrality-oriented climate change projections needs to be strengthened for jointly achieving a net-zero future.

1 Introduction

Limiting global warming to 1.5℃/2℃ above pre-industrial levels set by the Paris Agreement requires rapidly and dramatically reducing global emissions of CO_2 to achieve a net-zero emissions future (UNFCCC, 2015; IPCC, 2018, 2021). In the past 2–3 years, the number of countries with net-zero target announcements have grown rapidly. Until now, more than 130 countries have pledged to achieve net-zero targets mostly by 2050 or 2060 (Energy and Climate Intelligence, 2022). For example, China's target to become carbon neutral before 2060 is estimated to induce global temperature reduction in 0.2–0.4℃ (Höhne et al., 2021). To reach this important milestone on the way to a global sustainable future, the international community needs to jointly make enormous efforts to become carbon neutral in the coming decades (IPCC, 2018, 2021; Tong et al., 2019; UNEP, 2020; WMO, UNEP, IPCC et al., 2021).

Future model projections make vital contribution to physical science basis for coping with climate change impacts and risks (IPCC,2014, 2021; Hausfather et al., 2020). Projected changes in mean climate and extreme events have been widely addressed for the near term, mid-term and long-term and under different global warming targets using model simulations particularly from the continuing Coupled Model Intercomparison Project (CMIP) (Meehl et al., 2000; Eyring et al., 2016; Watts et al., 2019). Carbon neutrality-oriented climate change projections are of great importance, yet have so far received little attention.

The impacts of temperature-related climate disasters are on the rise under global warming (WMO, UNEP, IPCC et al., 2021; Watts et al., 2019; Thiery et al., 2021). In particular, intensified heat extremes which are often characterized by daily maximum and/or minimum surface air temperatures produce profound devastating effects on human health, urban and rural infrastructure, agricultural yields, energy demand, natural ecosystem and biodiversity, water resources, and more (Horton et al., 2016; Mora et al., 2017; Obradovich et al., 2017; Yang and Zhang, 2020; Yang et al., 2021; WMO, 2021). In this study, we focus on the carbon neutrality (net-zero CO_2 emissions) period of 2050–2060 under the SSP1-1.9 pathway of sustainable development (Fig. 1), and address CMIP6 Multiple Model Ensemble (MME) projections of daily maximum (Tmax) and minimum (Tmin) temperatures and diurnal temperature range (DTR) over East Asia based on historical, SSP1-1.9, SSP2-4.5, and SSP5-8.5 simulations.

2 Data And Methods

The observed Tmax, Tmin and DTR data at a spatial resolution of $0.5^{o}\times0.5^{o}$ produced by Climatic Research Unit (CRU) at the University of East Anglia were downloaded from https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.05/ (Harriset al., 2020). For CMIP6, we use daily output from the historical, SSP1-1.9, SSP2-4.5 and SSP5-8.5 simulations of the following global coupled models: CNRM-ESM-2-1, EC-Earth3-Veg, EC-Earth3-Veg-LR, GFDL-ESM4, IPSL-CM6A-LR, MIROC6, MIROC-ES2L, MRI-ESM2-0, and UKESM1-0-LL (downloaded from https://esgf-node.llnl.gov/search/cmip6/). The CMIP6 data were re-gridded through bilinear interpolation to the same $0.5^{o}\times0.5^{o}$ grid point as CRU before the analysis was performed.

We mainly use Taylor diagrams to evaluate the performance of CMIP6 models and their ensemble means in simulating annual mean Tmax, Tmin and DTR over East Asia for the historical baseline of 1995–2014 compared to the CRU observations in terms of the spatial correlation coefficient and the ratio of the simulated to observed variance (Taylor, 2001). The CMIP6 model simulations of spatial patterns of annual mean Tmax, Tmin and DTR and annual cycles of regional mean three temperature variables are also compared to the CRU observations over East Asia.

In CMIP6, the SSP1-1.9 scenario represents a pathway of sustainable development with an approximate anthropogenic radiative forcing level of 1.9 W m^{-2} in 2100 relative to preindustrial level, which was designed to match the Paris Agreement goal of 1.5°C global warming (Rogelj, 2018; Gidden et al., 2019; O’Neill, 2020). Based on Fig. 1 and our previous research (Zhang et al., 2021), the carbon neutrality period is defined as 2050–2060 for SSP1-1.9. Under SSP1-1.9, global mean temperature is projected to roughly reach the peak at the middle of this century (IPCC, 2021; Zhang et al., 2021). The Multi-Model Ensemble (MME) method is adopted to project future Tmax, Tmin and DTR changes over the carbon neutrality period of 2050–2060 under SSP1-1.9 based on evaluation of model performance in historical baseline period of 1995–2014. In addition, projected changes of Tmax, Tmin and DTR for 2050–2060 under SSP1-1.9 are compared with those for the same period under SSP2-4.5 along approximately current emissions trajectory and SSP5-8.5 of highest emissions pathway in CMIP6 simulations (Gidden et al., 2019).

3 Results

Over East Asia for the historical baseline period of 1995–2014, Taylor diagrams show that 9 CMIP6 global coupled models generally perform well in simulating annual mean Tmax and Tmin with spatial correlation coefficients larger than 0.95 for most models (Fig. 2). CMIP6 models also can capture the main characteristics of the DTR against CRU observations, yet the model spread is relatively large. As a whole, Taylor diagrams indicate that CMIP6 MME simulations reproduce the CRU observations well for all three temperature variables over East Asia for 1995–2014.

Figure 3 presents spatial patterns of annual mean Tmax, Tmin and DTR over East Asia for 1995–2014 in CRU observations and CMIP6 MME simulations. Except for the Tibetan Plateau, observed annual mean Tmax and Tmin exhibit a clear south-to-north gradient with highest temperatures appearing over the tropics. CMIP6 MME simulations generally agree quite well with observed Tmax and Tmin over East Asia in term of geographical distribution, and also capture well their magnitudes though some biases exist. For the DTR, CMIP6 MME simulations generally resemble the observations with respect with spatial pattern, but underestimate the magnitude especially over the northern part of East Asia.

Averaged over East Asia, observed 1995–2014 mean Tmax, Tmin and DTR are 14.16℃, 2.94℃ and 11.22℃, respectively (Fig. 4). Generally speaking, CMIP6 MME simulations successfully reproduce regional mean observed values of the three temperature variables. Specifically, the simulated Tmin is very close to the observed value while a cold bias of around 1.85℃ exists for Tmax, thus leading to the DTR underestimation. In addition, observed annual cycles of Tmax, Tmin and DTR over East Asia for 1995–2014 are well captured by CMIP6 MME simulations (Fig. 5). Their differences show that CMIP6 MME simulations underestimate Tmax for all months particularly during March-to-May, yet only have small biases for Tmin, leading to underestimations of the DTR for all months.

The carbon neutrality period under SSP1-1.9 is defined as 2050–2060. Figure 6 presents spatial patterns of future Tmax and Tmin changes for 2050–2060 under SSP1-1.9 as well as under SSP2-4.5 and SSP5-8.5 relative to 1995–2014 over East Asia based on CMIP6 MME projections. For the period of 2050–2060 under each of three emissions pathways, both Tmax and Tmin warm up significantly over the whole East Asian region. Under SSP1-1.9, the warming magnitudes of Tmax and Tmin generally increase from southwest to northeast with the largest values mainly appearing over the North and Northeast China. In contrast, under SSP2-4.5 and SSP5-8.5, Tmax and Tmin changes manifest a south-to-north warming gradient with the largest magnitudes occurring over the most northern part of East Asia. The results show that spatial patterns of Tmax and Tmin changes for 2050–2060 under SSP1-1.9 are substantially different with those under SSP2-4.5 and SSP5-8.5. In addition, the warming magnitudes of Tmax and Tmin under SSP1-1.9 are much smaller than those under SSP2-4.5 and SSP5-8.5.

Meanwhile, it should be noted that the increasing magnitudes of Tmax and Tmin for 2050–2060 under each of three emissions pathways are asymmetric over East Asia based on CMIP6 MME projections. For SSP1-1.9, over eastern and southern China, some areas of northwest China and Mongolia, Korean Peninsula and central and southern Japan, the increases are substantially stronger for Tmax than for Tmin, resulting in the larger DTR while the DTR generally becomes smaller over the remaining areas of

East Asia due to the more rapid warming in Tmax than in Tmin (Fig. 7). For SSP2-4.5 and SSP5-8.5, the DTR increases over most areas of the Yangtze River basin and southern China caused by the stronger warming in Tmax than in Tmin, yet decreases over most of the remaining areas as the warming is more rapid in Tmin than in Tmax. In summary, Tmax, Tmin and DTR changes for 2050–2060 under SSP1-1.9 all exhibit new spatial patterns with respect to those for the same period under SSP2-4.5 and SSP5-8.5.

Tmax and Tmin averaged over East Asia are projected to rise up by 1.43℃ and 1.40℃ for the carbon neutrality period of 2050–2060 under SSP1-1.9 relative to 1995–2014 (Fig. 8a) while their warming magnitudes are 2.02℃ and 2.26℃ compared to 1850–1900. These increases over East Asia are all significant at the 99% confidence level, and are much larger than those averaged over the globe. For 2050–2060 relative to 1995–2014, CMIP6 ensemble projections show that Tmax and Tmin averaged over East Asia significantly warm up by 1.93℃ and 2.04 ℃ under SSP2-4.5, and by 2.67℃ and 2.85℃ under SSP5-8.5 (Fig. 8). In comparison, the warming magnitudes of Tmax and Tmin for 2050–2060 under SSP2-4.5 and SSP5-8.5 are all much larger than those for the same period under SSP1-1.9.

Regarding the annual cycles, CMIP6 MME projections display that Tmax and Tmin averaged over East Asia during the carbon neutrality period of 2050–2060 under SSP1-1.9 consistently and remarkably warm up during all months (from January to December) relative to 1995–2014 (Fig. 9). The increases in Tmax are stronger than those in Tmin from April to October while the opposite changes appear from November to March. As a consequence, the DTR is projected to increase from April to October, yet decrease during the remaining months.

4 Conclusions And Discussion

Limiting global warming to the 1.5℃ goal requires achieving global carbon neutrality by making sharp and deep decarbonations in the coming decades. Here, we address future changes in Tmax and Tmin as well as DTR over East Asia for the carbon neutrality period of 2050–2060 under SSP1-1.9 based on ensemble mean projections of 9 CMIP6 global coupled models as their ensemble mean simulations perform well in the historical baseline 1995–2014 compared to the observations. Furthermore, projected Tmax, Tmin and DTR changes for 2050–2060 under SSP1-1.9 are compared to those over the same period under SSP2-4.5 along approximately current emissions trajectory and SSP5-8.5 on the high end of emissions trajectories in CMIP6 experiments. This work is expected to motivate further efforts to advance climate change projections oriented towards carbon neutrality.

We find that Tmax, Tmin and DTR changes over the carbon neutrality period of 2050–2060 under SSP1-1.9 (the newly available pathway of sustainable development in CMIP6 is in line with the Paris Agreement goal of 1.5℃) all exhibit new spatial patterns over East Asia, compared to those for the same period under SSP2-4.5 and SSP5-8.5. With respect to the 1995–2014 baseline, projected Tmax and Tmin averaged over East Asia for 2050–2060 will significantly warm up by 1.43℃ and 1.40℃ under SSP1-1.9, which are much smaller than the warming magnitudes under SSP2-4.5 and SSP5-8.5.

These findings contribute to the scientific knowledge for tackling regional climate change impacts and risks over East Asia under the carbon neutrality target of 1.5°C global warming pathway. Meanwhile, the uncertainties of projected changes in three temperature variables are reduced by employing multi-model mean changes, yet still present key challenges. In addition, the underlying physical mechanisms behind Tmax, Tmin and DTR changes are quite complex as many factors such as land surface, cloud cover and aerosols can make different and interlinked roles (Dai et al., 1999; Roy et al., 2005; Zhang et al., 2009). These issues deserve further investigation.

SSP1-1.9 is newly designed to address the 1.5°C goal of the Paris Agreement in CMIP6 (Rogelj et al., 2018; Gidden et al., 2019). However, the sustainable development pathways used in CMIP6 were developed based on lagged social, economic and environmental information which needs to keep up to date (O'Neill et al., 2020). The frequently updated and more realistic sustainable development pathways towards a net-zero future followed by net negative CO_2 emissions need to be further developed to better inform the Paris Agreement goal of 1.5°C. Furthermore, these newly designed pathways should be employed to drive global coupled earth system models to better project future climate change and provide physical climate science basis for sustainable development of our planet.

Declarations

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Author contributions

Jingyong Zhang conceived and designed the research. Feng Chen performed the analysis and prepared figures. Jingyong Zhang wrote the manuscript with contribution from Feng Chen.

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Data availability

The data that support these findings are freely available: The global CO_2 emissions data arestored at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about; The observed Tmax, Tmin and DTR data are stored at https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.05/; . The data from the historical, SSP1-1.9, SSP2-4.5 and SSP5-8.5 simulations in CMIP6 are stored at https://esgf-node.llnl.gov/search/cmip6/.

Code availability

The codes usedin this study are available from the corresponding authorupon reasonable request.

Ethics approval

The authors paid attention to the ethical rules in the study. There is no violation of ethics.

Consent to participate

All the authors admitted that they have contributed to the study.

Consent for publication

All the authors agree with the publication of the content of the manuscript.

Conflict of interest

The authors declare no competing interests.

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Figures

Figure 1

Global CO_2 emissions from 2020–2100 under the SSP1-1.9 pathway used in CMIP6. 2050-2060 is defined as the carbon neutrality (net-zero CO_2 emissions) period. The data were downloaded from https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.

Figure 2

Taylor diagrams for CMIP6 multiple model simulations of annual mean temperatures with respect to the CRU observations over East Asia for the historical baseline of 1995–2014: (a) daily maximum surface air temperature (Tmax); (b) daily minimum surface air temperature (Tmin); (c) Diurnal temperature range (DTR). MME_9 represents the ensemble mean simulation of 9 CMIP6 models.

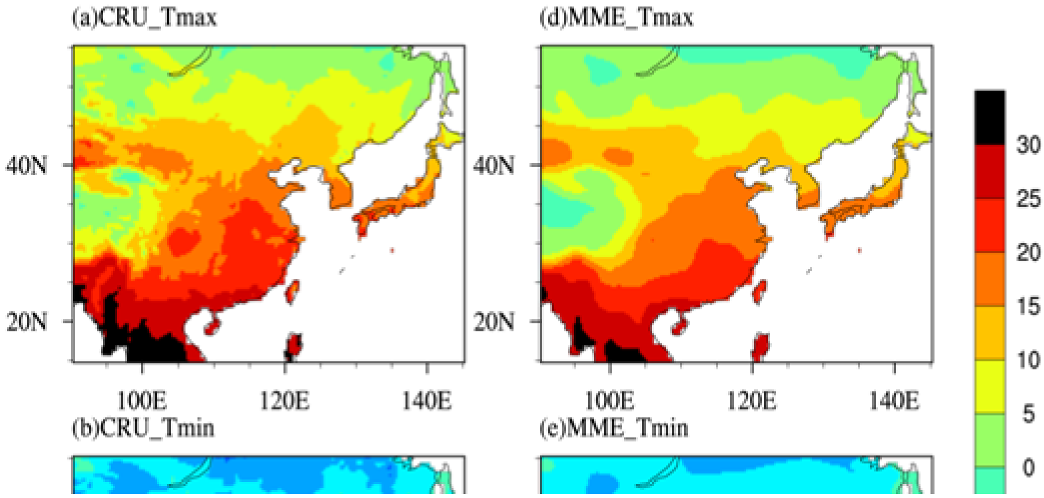

Figure 3

Spatial patterns of annual mean Tmax, Tmin and DTR over East Asia for the historical baseline of 1995–2014 in the CRU observations (left panel) and CMIP6 multi-model ensemble mean simulations (right panel) (unit: °C): (a), (d), Tmax; (b), (d), Tmin; (c), (e), DTR.

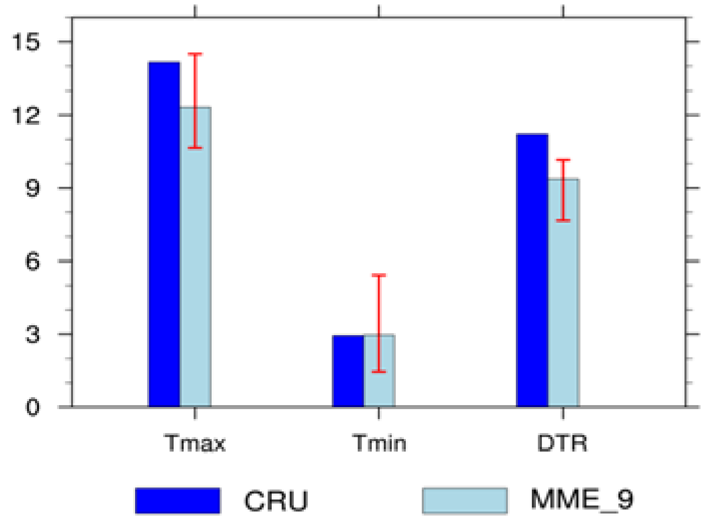

Figure 4

Annual mean Tmax, Tmin and DTR averaged over East Asia for the historical baseline of 1995–2014 in the CRU observations and CMIP6 multi-model ensemble mean simulations. The red bar represents the range among 9 CMIP6 models.

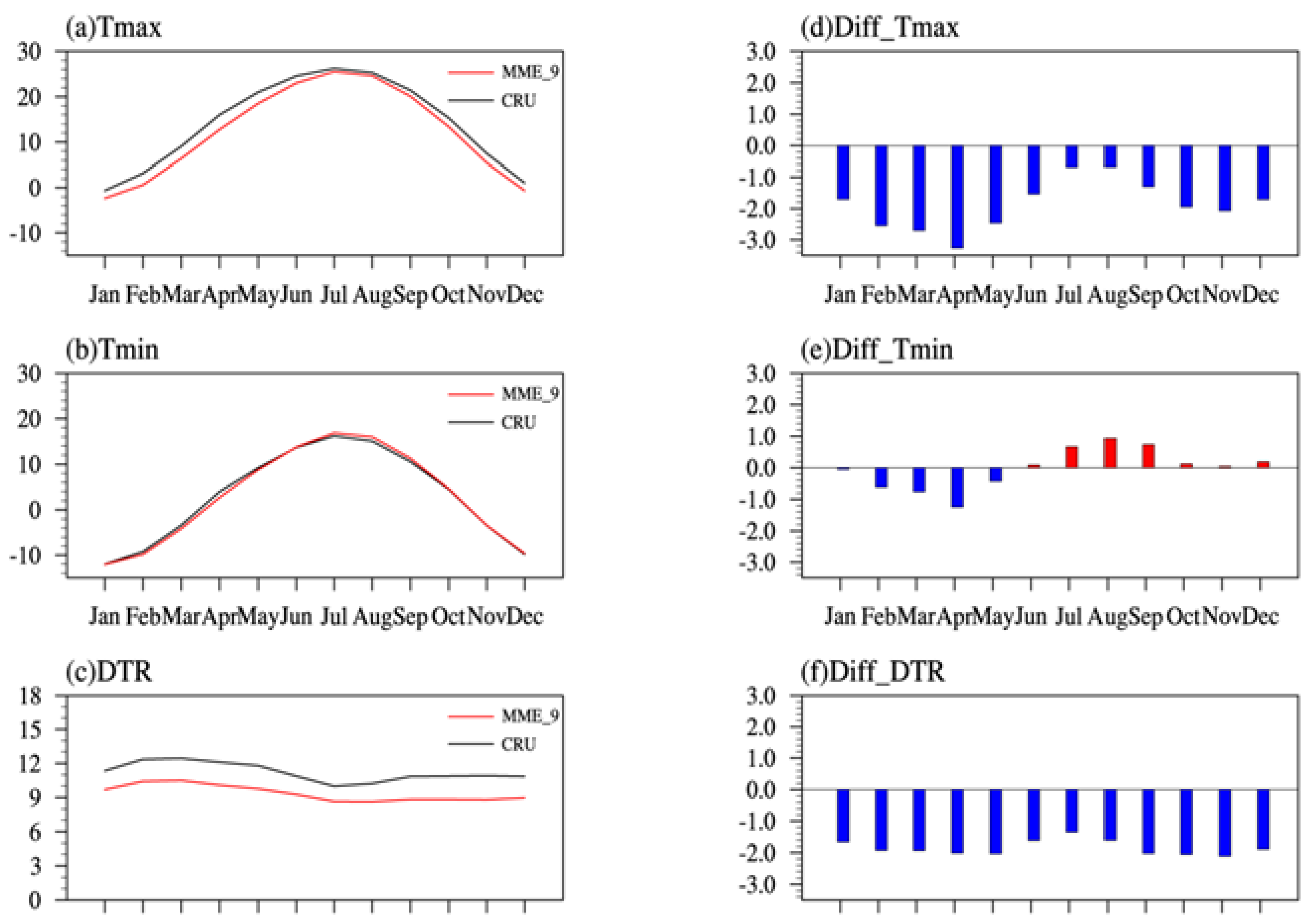

Figure 5

Annual cycles of Tmax, Tmin and DTR averaged over East Asia for the historical baseline of 1995-2014 in the CRU Observations and CMIP6 multi-model ensemble mean simulations, and their differences (simulation minus observation).

Figure 6

CMIP6 ensemble mean projections of Tmax (left panel) and Tmin (right panel) changes over East Asia for 2050-2060 under SSP1-1.9, SSP2-4.5 and SSP5-8.5 relative to 1995–2014 (unit: °C). 2050-2060 is the carbon neutrality period for SSP1-1.9. The slash areas represent the 99% confidence level.

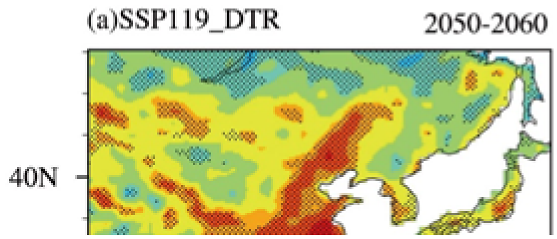

Figure 7

CMIP6 ensemble mean projections of DTR changes over East Asia for 2050-2060 under SSP1-1.9, SSP2-4.5 and SSP5-8.5 relative to 1995-2014 (unit: °C). 2050-2060 is the carbon neutrality period for SSP1-1.9. The black dots represent the 95% confidence level.

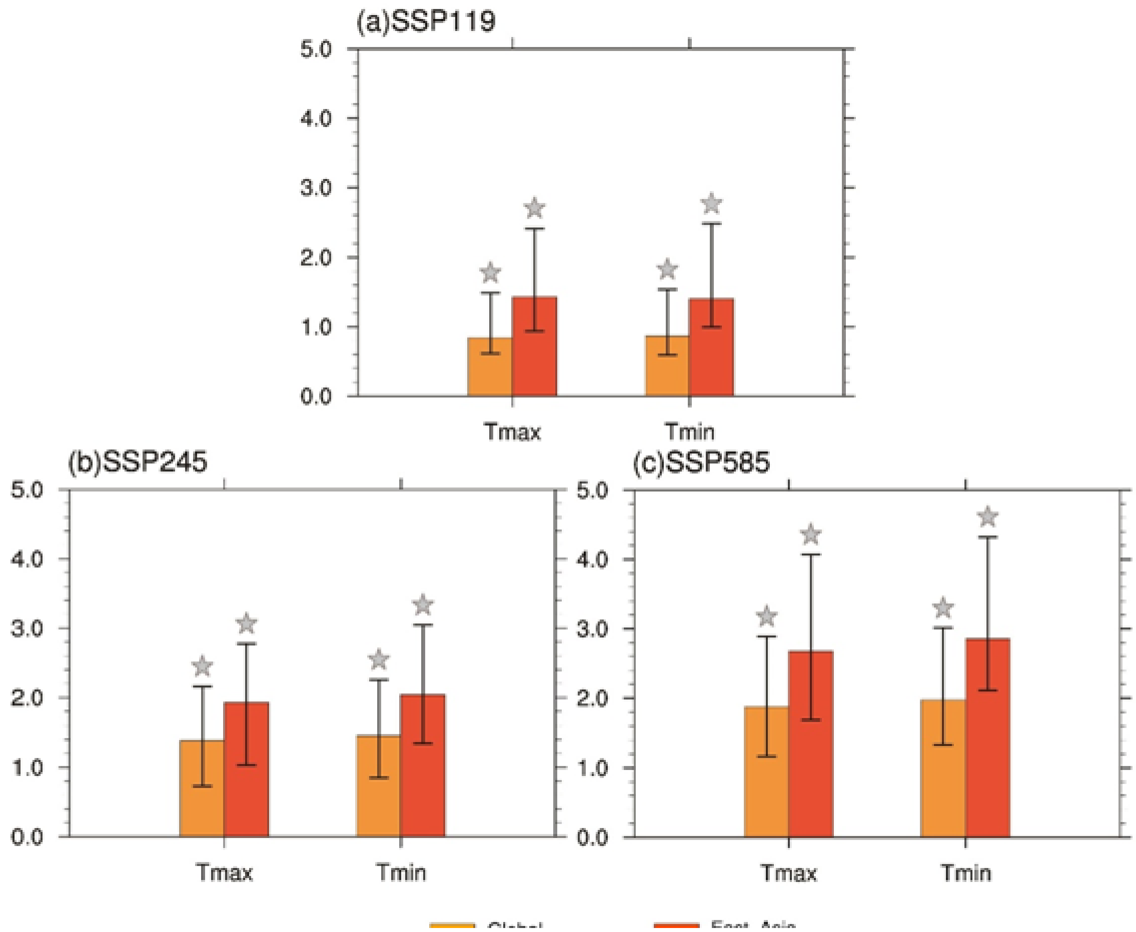

Figure 8

CMIP6 ensemble mean projections of Tmax, Tmin and DTR changes averaged over the globe and East Asia for 2050-2060 under SSP1-1.9, SSP2-4.5 and SSP5-8.5 relative to 1995–2014 (unit: °C). 2050-2060 is the carbon neutrality period for SSP1-1.9. The black bar shows the spread of projected change among 9 CMIP6 models, and the grey star represents the 99% confidence level.

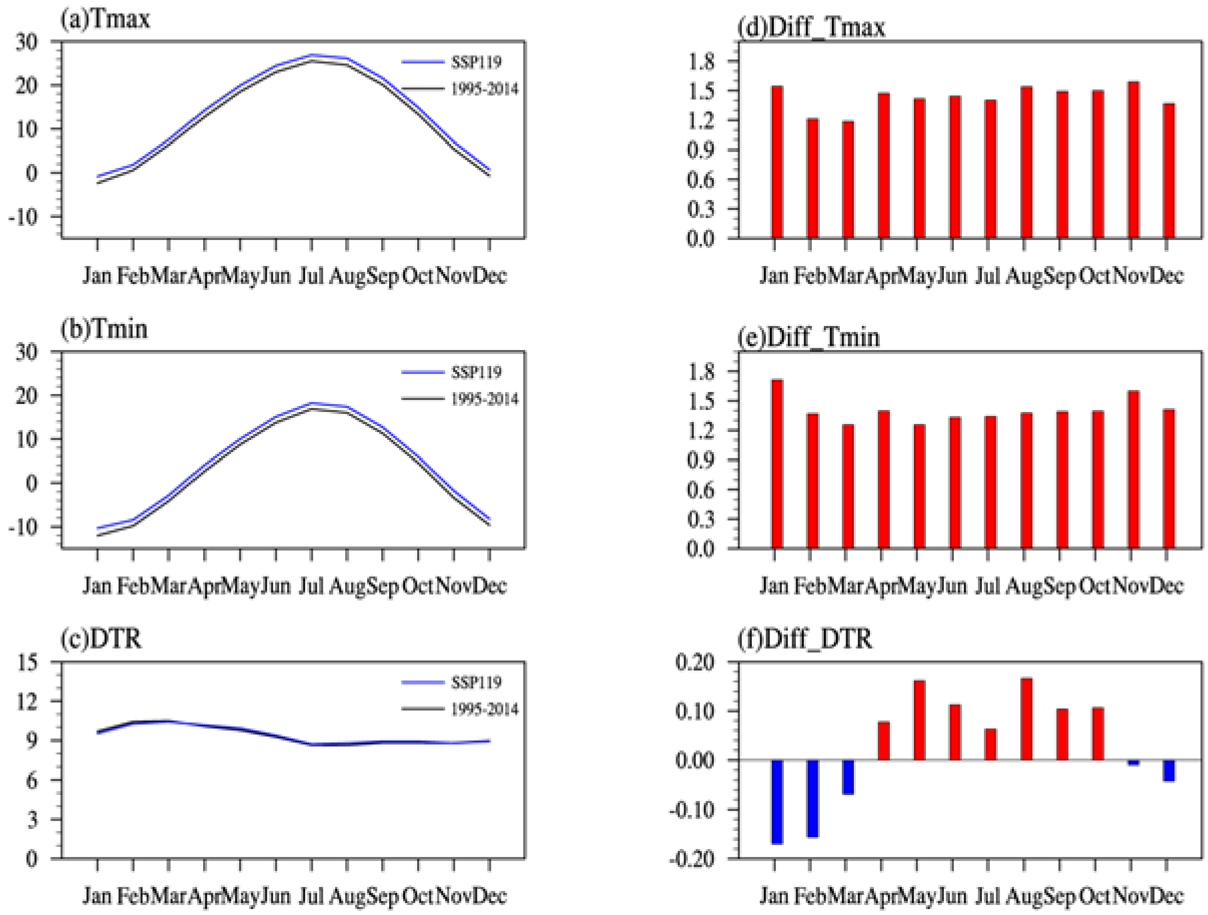

Figure 9

Annual cycles of CMIP6 multi-model ensemble mean Tmax, Tmin and DTR averaged over East Asia for the historical baseline of 1995-2014 and the carbon neutrality period of 2050-2060 under SSP1-1.9, and their differences (the carbon neutrality period minus the historical baseline).