Future projections of daily maximum and minimum temperatures over East Asia for the carbon neutrality period of 2050–2060

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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 °C and 1.40 °C under SSP1-1.9, while the warming magnitudes are 1.93 °C and 2.04 °C under SSP2-4.5, and 2.67 °C and 2.85 °C 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 °C/2 °C above pre-industrial levels set by the Paris Agreement requires rapidly and dramatically reducing global emissions of CO₂ to achieve a net-zero emissions future (UNFCCC 2015; IPCC 2018, 2021; WMO 2022). In the past 2–3 years, the number of countries with net-zero target announcements has rapidly grown, and the importance and urgency of achieving carbon neutrality have been widely recognized. Until now, more than 130 countries have pledged to achieve net-zero targets mostly by around the middle of the century (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 °C and may therefore reduce climate change losses dramatically (Höhne et al. 2021; Teng 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; IEA 2021).

Future model projections make vital contribution to physical science basis for coping with climate change impacts and risks (IPCC 2014, 2021, 2022a; 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; Taylor et al. 2012; Eyring et al. 2016; Watts et al. 2019). Achieving the carbon neutrality is a necessity to limit the global warming to the Paris Agreement goal of 1.5 °C/2 °C and to effectively tackle and manage more severe climate risks (UNFCCC 2015; IPCC 2021). Meanwhile, it is expected to and likely to become carbon neutral globally by around the middle of the century though enormous challenges need to be faced by the whole world (IPCC 2021, 2022b; Teng et al. 2021; Moore et al. 2022; Meinshausen et al. 2022). 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; IPCC 2022a; WMO 2022). 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, 2022). Achieving the carbon neutrality by the middle of the century can effectively prevent rapidly increasing climate change risks relative to current development pathways and represents a pivotal milestone towards the Paris Agreement goal of 1.5 °C (IPCC 2021, 2022a, 2022b). In this study, we focus on the carbon neutrality (net-zero CO₂ 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° × 0.5° 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) and were used to evaluate the model performance in this study. 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 listed in Table 1: 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/). These models have all simulation data which can be obtained when this study was performed. The CMIP6 model data were regridded through bilinear interpolation to the same 0.5° × 0.5° grid.

Fig. 1 Global CO₂ emissions from 2020 to 2100 under the SSP1-1.9 pathway used in CMIP6. 2050–2060 are defined as the carbon neutrality (net-zero CO₂ emissions) period. The data were downloaded from https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about

Table 1 List of CMIP6 global coupled models (GCMs) used in this study

| No | Modeling center                                                                 | GCM                  | Acronyms   | Resolution |
|----|--------------------------------------------------------------------------------|----------------------|------------|------------|
| 1  | Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique | CNRM-ESM2-1          | CNRM       | 128*256    |
| 2  | EC-Earth-Consortium                                                             | EC-Earth3-Veg        | ICHEC      | 256*512    |
| 3  | EC-Earth-Consortium                                                             | EC-Earth3-Veg-LR     | ICHEC      | 160*320    |
| 4  | Geophysical Fluid Dynamics Laboratory                                          | GFDL-ESM4            | GFDL       | 180*288    |
| 5  | Institut Pierre-Simon Laplace                                                  | IPSL-CM6A-LR         | IPSL       | 143*144    |
| 6  | MIROC team                                                                      | MIROC6               | MIROC      | 128*256    |
| 7  | MIROC team                                                                      | MIROC-ES2L           | MIROC      | 64*128     |
| 8  | Meteorological Research Institute of the Japan Meteorological Agency            | MRI-ESM2-0           | MRI        | 160*320    |
| 9  | Met Office Hadley Center                                                        | UKESM1-0-LL          | MOHC       | 144*192    |

*MIROC team consisted of the following agencies: Atmosphere and Ocean Research Institute (AORI), Center for Climate System Research-National Institute for Environmental Studies (CCSR-NIES), and Atmosphere and Ocean Research Institute (AORI) team
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For the evaluation of the CMIP6 model ability to simulate the historical climate, the historical baseline period of 1995–2014 was used in this study following the IPCC sixth assessment report (IPCC 2021). We firstly 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). Then, three metrics including space correlation, time correlation, and the bias are selected for further evaluation based on the previous studies (Adeyeri et al. 2020; Dieng et al. 2022) and are listed in Table 2. Finally, the CMIP6 model simulations of spatial patterns of annual mean Tmax, Tmin, and DTR and annual cycles of regional mean three temperature variables are compared directly 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 et al. 2018; Gidden et al. 2019; O’Neill et al. 2020). Based on Fig. 1 and our previous research (Zhang et al. 2021), the carbon neutrality period (the focus period for future CMIP6 model projections in this study) 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 CMIP6 model performance using different methods 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. The model performance in simulating Tmax, Tmin, and DTR is further evaluated using three metrics of space correlation, time correlation, and the bias over the East Asia for the historical baseline of 1995–2014 with respect to the CRU observations (Table 2). For space and time correlations, the CMIP6 MME simulations outperform most of the 9 CMIP6 models for all three temperature variables. The CMIP6 MME simulations exhibit a quite small bias of 0.025 °C for Tmin, and relatively larger biases for Tmax and DTR. 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 the highest temperatures appearing over the tropics. CMIP6 MME simulations generally agree quite well with observed Tmax and

### Table 2

| Variable | Tmax | Tmin | DTR |
|----------|------|------|-----|
| Model/indicator | SC | TC | Bias | SC | TC | Bias | SC | TC | Bias |
| MME_9 | 0.981 | 0.962 | −1.835 | 0.980 | 0.982 | 0.025 | 0.771 | 0.510 | −1.853 |
| CNRM-ESM2-1 | 0.967 | 0.936 | −1.573 | 0.957 | 0.968 | −0.496 | 0.625 | 0.446 | −1.076 |
| EC-Earth3-Veg | 0.979 | 0.936 | −2.077 | 0.986 | 0.961 | −0.952 | 0.768 | 0.407 | −1.053 |
| EC-Earth3-Veg-LR | 0.974 | 0.935 | −2.715 | 0.982 | 0.959 | −1.475 | 0.764 | 0.293 | −1.247 |
| GFDL-ESM4 | 0.979 | 0.943 | −2.857 | 0.981 | 0.968 | −0.925 | 0.754 | 0.332 | −1.931 |
| IPSL-CM6a-LR | 0.967 | 0.935 | −3.560 | 0.950 | 0.968 | −1.555 | 0.707 | 0.322 | −2.004 |
| MIROC6 | 0.965 | 0.929 | 0.278 | 0.975 | 0.966 | 2.427 | 0.570 | 0.322 | −2.148 |
| MIROC-ES2L | 0.956 | 0.931 | −1.248 | 0.957 | 0.958 | 2.304 | 0.657 | 0.396 | −3.552 |
| MRI-ESM2-0 | 0.977 | 0.939 | −1.584 | 0.980 | 0.968 | 0.932 | 0.750 | 0.386 | −2.517 |
| UKESM1-0-LL | 0.974 | 0.943 | −1.618 | 0.976 | 0.969 | −0.521 | 0.810 | 0.274 | −1.097 |

MME_9 represents the ensemble mean simulation of 9 CMIP6 models
Tmin over East Asia in terms 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 °C, 2.94 °C, and 11.22 °C, 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 °C 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 Tmin than in Tmax (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 °C and 1.40 °C 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 °C and 2.26 °C 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 °C and 2.04 °C under SSP2-4.5, and by 2.67 °C and 2.85 °C under SSP5-8.5 relative to 1995–2014 (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 °C goal requires that the globe become carbon neutral by around the middle of century. The carbon neutrality target which represents a pivotal indicator of global sustainable development could be achieved by making sharp and deep decarbonations in the coming decades though enormous efforts need to be taken (IPCC 2021, 2022b; Teng et al. 2021; Moore et al. 2022; Meinshausen et al. 2022). 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. SSP1-1.9 is a newly available pathway of sustainable development in CMIP6 which is in line with the Paris Agreement goal of 1.5 °C. 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.

The MME simulations of the 9 CMIP6 models perform well in the historical baseline 1995–2014 compared to the observations. Our new findings based on CMIP6 MME projections highlight that Tmax, Tmin, and DTR
Changes over the carbon neutrality period of 2050–2060 under SSP1-1.9 relative to 1995–2014 all exhibit new spatial patterns over East Asia, compared to those changes under SSP2-4.5 and SSP5-8.5. In general, the warming magnitudes of Tmax and Tmin increase from southwest to northeast for 2050–2060 relative to 1995–2014 over East Asia under SSP1-1.9 while their changes display a south-to-north warming gradient under SSP2-4.5 and SSP5-8.5. For DTR changes over East Asia for 2050–2060 relative to 1995–2014, the spatial pattern under SSP1-1.9 also largely differs from those 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 °C and 1.40 °C under SSP1-1.9, which are much smaller than the warming magnitudes under SSP2-4.5 and SSP5-8.5.

These new 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. The underlying physical mechanisms behind Tmax, Tmin, and DTR changes are quite complex. During 2050–2060, there are rapidly increasing trends in global CO₂ emissions under both SSP2-4.5 and SSP5-8.5 along their previous trajectories while global CO₂ emission decreases from slightly positive to negative under SSP1-1.9 (IPCC 2021). These differences may subsequently make different changes in regional atmospheric circulation pattern and other processes such as cloud-aerosol interaction.
Fig. 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 are the carbon neutrality period for SSP1-1.9. The black dots represent the 95% confidence level.

Fig. 8 CMIP6 ensemble mean projections of Tmax and Tmin 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 are the carbon neutrality period for SSP1-1.9. The black bar shows the spread of projected changes among 9 CMIP6 models, and the grey star represents the 99% confidence level.
Fig. 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).

and land–atmosphere interaction (Dai et al. 1999; Roy et al. 2005; Zhang et al. 2009; Moore et al. 2022; Meinshausen et al. 2022), thus providing possible physical explanation for our findings. These complex physical processes involved need to be further investigated in the future. Meanwhile, the uncertainties of projected changes in three temperature variables are reduced by employing multi-model mean changes, yet still present key challenges and need to be further reduced in the following studies. In addition, future climate change impacts and risks would be largely reduced if global carbon neutrality target around the middle of the century and the Paris Agreement goal of 1.5 °C can be achieved (IPCC 2021, 2022a; Teng et al. 2021). How climate change impacts and risks change over East Asia and other regions during the carbon neutrality period of 2050–2060 deserve further investigation. In this study, we focus on the carbon neutrality period of 2050–2060 under SSP1-1.9. Under another important sustainable pathway of SSP1-2.6 which is in line with the Paris Agreement goal of 2 °C, more studies should also be conducted for the corresponding carbon neutrality period of 2070–2080 in the future (Zhang et al. 2021). 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 CO2 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.

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Author contribution 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 CO2 emissions data are stored at https://tntcat.iiasa.ac.at/SspDb/ds?Action=htmlpage&page=about; the observed Tmax, Tmin, and DTR data are stored at https://crudata.uea.ac.uk/cru/data/lrg/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 used in this study are available from the corresponding author upon reasonable request.

Declarations

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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