



Emerging extreme heat conditions as part of the new climate normal

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Abstract

As a result of global warming, extreme heat conditions have become more frequent and severe. This will likely continue or accelerate in the future, particularly under high radiative forcing scenarios. In the present study, based on an ensemble of global climate model simulations, we identify the absolute historical extremes expressed by several temperature indices. Considering projections under two future pathways (SSP1–2.6, SSP5–8.5), we investigate to what extent extreme heat conditions will become predominant during the rest of the century. The timing of a transition to prevailing hot weather extremes is critical for the development of mitigation and adaptation strategies; therefore, we also identify the projected first year of such a transition, as well as the persistence in subsequent decades. Different aspects of heat extremes are investigated, including both maximum and minimum temperature. For some climate zones, our results highlight that regardless of mitigation efforts, hot weather conditions will be at least similar but likely more harsh compared to historical extremes within the following decades. By the end of the century, under a business-as-usual pathway, successive years will be much more extreme than the most severe conditions in the recent past virtually everywhere.

1 Introduction

According to observational evidence, it is certain that high-temperature extremes (including heatwaves) have become more widespread, frequent, and intense across most land regions since the 1950s (IPCC 2021). This latest Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) highlights with high confidence that human-induced climate change is the main driver of these changes. The approximately linear observed global warming trend of 0.2 °C/decade, since about the beginning of the 1980s, has resulted in a nonlinear increase in the number and intensity of extreme heat events (Robinson et al. 2021). Some recent record-breaking heat events in the Northern Hemisphere would have been impossible without human influence, and current climate models often underestimate the observed trends (Ciavarella et al. 2021; Vautard et al. 2020; Perkins-Kirkpatrick and Lewis 2020; Barriopedro et al. 2011). Those high-impact hot weather events were often associated with

excess mortality, devastating wildfires, and extensive harvest losses (Coumou and Rahmstorf 2012; Liss et al. 2017; Guo et al. 2017; Gasparrini et al. 2017; Royé et al. 2020; Vicedo-Cabrera et al. 2022).

For the future, global and regional climate projections robustly suggest that the frequency and intensity of extreme heat events will increase, particularly under high emission pathways, and unprecedented events will likely become commonplace by the end of the twenty-first century (Almazroui et al. 2021; Zittis et al. 2021a; Kang et al. 2019; Fischer et al. 2021; Dong et al. 2021).

Unless greenhouse gas emissions and concentrations are substantially and timely decreased (i.e., reach zero or negative net emissions within the next few decades), the abrupt warming can imply irreversible impacts, as global and regional temperature levels are expected to exceed critical tipping points in the climate system (IPCC 2018). These tipping points are related to the collapse of ice sheets, sea-ice reduction, permafrost thawing, ocean circulation, and biosphere transformation boundaries (Lenton et al. 2019). Under such unfortunate scenarios, heat extremes and associated implications (including excess morbidity and mortality) will be exacerbated during summers, particularly in the warmest and poorest parts of the world (Ahmadalipour and Moradkhani 2018; Harrington et al. 2016). Many socioeconomic sectors will be severely impacted, directly and indirectly affecting

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the well-being of the exposed populations. The extensive list of impacted sectors includes water and energy resource management, agriculture, tourism, and labor productivity (Dunne et al. 2013; Casanueva et al. 2020; Waha et al. 2017; Leó et al. 2021; Spinoni et al. 2021; Orlov et al. 2020; Siebert and Ewert 2014; Cronin et al. 2018).

Avoiding or slowing down such abrupt changes is critical for providing ecosystems and societies with a reasonable window of opportunity to shift pathways towards more climate-resilient development futures, as reflected by the adaptation limits and increasing climate risks (IPCC 2022). Therefore, estimating the time of emergence of such extreme conditions is essential for designing or revising adaptation strategies and urging policymakers to develop and implement effective mitigation strategies (King et al. 2015). Several methods have been proposed for estimating the time of emergence (ToE), time of anthropogenic emergence (TAE), or time of emergence of a new normal (ToENN). Some are based on signal-to-noise ratios or probabilities of exceedance for reference extremes, while others are on deviations from baseline statistical distributions (King et al. 2015; Hawkins and Sutton 2012; Lewis et al. 2017). Moreover, some studies focus on mean changes of annual or seasonal scales and others on climate extremes.

By analyzing a state-of-the-art ensemble of global climate projections and considering five extreme temperature indices, the present work investigates the probability of mean future climate conditions being hotter than the most extreme historical cases. In addition, we aim to estimate the time of emergence of these “new normal” conditions. By comparing two future pathways, we also explore the potential benefits of adopting aggressive mitigation strategies.

2 Data and methodology

2.1 Data

We analyze daily maximum (TX) and minimum (TN) 2-m air temperature over land from an ensemble set of global earth system models (ESMs) participating in the coupled Model Intercomparison Project Phase 6 (CMIP6). Our final selection of 11 state-of-the-art ESMs (see Table S1), is based on their spatial resolution (close to 100 km), access to daily maximum and minimum temperature data, and the availability of both historical simulations and projections under the selected future pathways (see next section). Before the analysis (calculation of indices, time of emergence, visualization, etc.), all data were interpolated bilinearly into the median-resolution model grid ($0.9 \times 0.9^\circ$). For interpretation of the results, we divide parts of the analysis into three 35-year periods. A historical one, representing the recent past (HIST: 1980–2014) and two future periods (21C1: 2021–2055, and

21C2: 2056–2090), representing the near future and the second half of the twenty-first century, respectively. With respect to other studies (King et al. 2015; Mahlstein et al. 2011), we use a more recent baseline period, which, however, ensures a more robust modeling of the historical climate conditions and a better perception of extreme events and associated impacts.

The CMIP6 projections (after the year 2015) are driven by the latest set of emissions and land-use scenarios (Riahi et al. 2017). These are based on future pathways of societal development, the so-called Shared Socioeconomic Pathways (SSPs), and are related to the previous generation of Representative Concentration Pathways or RCPs (O’Neill et al. 2017). Here, we focus on two SSP pathways: SSP1–2.6 and SSP5–8.5. The SSP1–2.6 pathway reflects a 2 °C target under the Paris Agreement and corresponds to the RCP2.6 scenario with a radiative forcing level of 2.6 W/m² by 2100. Pathway SSP5–8.5 is the “worst-case” family of scenarios, marking a high fossil fuel development throughout the twenty-first century (radiative forcing of 8.5 W/m²) (O’Neill et al. 2017).

Although a model evaluation is not within our primary objectives, we have compared the CMIP6 simulations with the Berkeley Earth gridded observations (Rohde and Hausfather 2020) (see Fig. S1). In accordance with previous studies (Almazroui et al. 2020; Kim et al. 2020; Coppola et al. 2021), we highlight a good agreement between CMIP6 temperature and observations for both the mean climate conditions and temperature extremes. We believe that this type of analysis is not strongly affected by systematic biases since future projections are compared to historical simulations, and any model discrepancies identified in the recent past are assumed to propagate in the future.

2.2 Methodology

We analyzed five extreme climate indices, among the ones proposed by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Karl et al. 1999; Peterson et al. 2001), to test if and when the absolute hottest extremes of the historical period will become the predominant climate conditions in the future for the selected indices. We focus on temperature-related indices, considering the characteristics of both hot and cold extremes (Table 1). This selection is based on weather conditions that strongly impact ecosystems and several socioeconomic sectors such as human health, agriculture, transportation, and energy and water management.

Particularly, for estimating the probability of events that are more extreme than any that have already been observed, extreme value analysis is meaningful under the assumption of stability (or stationarity) in the prevailing processes (Coles 2001). Under long-term climate change, these techniques can be challenged (e.g., Zittis et al. 2021b); therefore, we do not

Table 1 Description of the selected climate indices of extremes

Index	Description	Units
TXx	Annual absolute maximum daily temperature	°C
TNn	Annual absolute minimum daily temperature	°C
SU	Summer days - number of days per year with TX > 25 °C	Days/year
FD	Frost days - number of days per year with TN < 0 °C	Days/year
TR	Tropical nights - number of nights per year with TN > 20 °C	Nights/year

use statistical approaches for extrapolating and estimating extremes or probabilities of occurrence but only analyze the available time series (historical and future projections).

The selected indices were calculated on an annual basis for the full extent of our analysis (1980–2100) and for each CMIP6 model separately. We then extracted the absolute extreme values of the period 1980–2014. For calculating the future mean conditions of these extremes, we used a 21-year moving average for all years between 2015 and 2090, centered on each year. For example, the mean index value for the year 2050 is the average of the index values from the period 2040–2060. Hence, the presented future results are limited to 2090, with 2090 values being the average of 2080–2100. An example of the methodological approach for the TXx index is presented in Fig. 1. This example is based on HadGEM3 data for the nearest grid point to Riyadh in Saudi Arabia, under pathway SSP5–8.5. The same approach was applied to the rest of the indices. Finally, we calculated the ensemble mean of the selected CMIP6 models. For facilitating the interpretation of results, parts of the discussion are presented for different latitudinal climate zones (Fig. S2). These zones include tropical, subtropical, temperate, and polar regions in both Hemispheres.

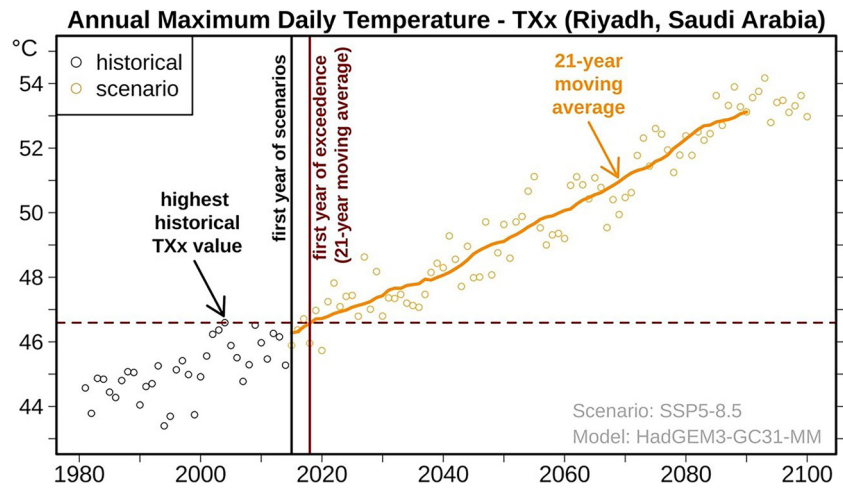
3 Results

Absolute maximum daily temperature (TXx) For the annual absolute maximum temperature (TXx), the historically most extreme values (based on CMIP6 simulations) range from below the freezing point (up to -20 °C) in the polar and sub-polar regions (e.g., Greenland and Antarctic) and high-elevation mountain ranges (e.g., the Himalayas) to higher than 50 – 55 °C in the sub-tropics and hottest deserts (Fig. 2). For extended areas in the Middle East and North Africa, tropical South America, and parts of the USA, models suggest that we are already experiencing prevailing conditions which are comparable to the recent-past historical extremes. For the rest of the world (mainly in tropical, sub-tropical, and parts of temperate zones), these absolute extremes are expected to become the normal conditions (i.e., occurring at least on an annual basis or more frequently) within the following years

or decades. Exceptions are high-latitude regions (temperate and polar zones) for pathway SSP1–2.6, where this transition is either projected for the second half of the twenty-first century or not to occur at all. For SSP5–8.5, the exceedances in higher latitudes are mostly expected after 2050, except for Antarctica, where the historical extreme TXx is projected to emerge at a slower pace. For the second half of the twenty-first century, in such a scenario, virtually all continental parts of the planet will be experiencing TXx values hotter than the absolute historical extremes. On average, this type of exceedance is higher in the northern (2.7 – 3.4 °C) than the Southern Hemisphere (1.2 – 3.1 °C) (Fig. 3a), with the highest anomalies expected for boreal sub-tropical and temperate climate zones.

Summer days (SU) On average, the historical maximum number of summer days per year (i.e., days with a maximum temperature greater than 25 °C) ranges from zero in the polar zones to more than 300 days per year in tropical regions (Fig. S3). Overall, maximum values are simulated in the Northern Hemisphere. In general, similarly to TXx, the average values of this index have already exceeded (e.g., in southeast Asia and central Africa) or are near to exceeding the highest historical values within the next years or decades. Exceptions are the polar zones and high mountain ranges, where the maximum temperatures have or are projected to increase, but they will likely not exceed the 25 °C threshold that characterizes summer days. For the coming decades (2021–2055), this prevalence of extreme values is evident in more than half of the years (50–80%), reaching 100% of years in central and eastern parts of Asia, as well as in parts of central Africa. The proportion of exceedance is lower in some boreal temperate climate zones (e.g., parts of Siberia and North America). This is the case for both pathways; however, for SSP1–2.6, the exceedance of the historical extremes is only marginal. For example, in the boreal temperate and subtropical regions, this exceedance will, on average, range between 2 and 9 days, with more notable changes, however, expected for 2056–2090 (Fig. 3c). For the second half of the century, the annual count of summer days will be exceeding the historical extremes in almost every year. On average, the exceedances will be higher in the sub-tropical zones (more

Fig. 1 Example of the comparison between the highest historical TXx value and the future prevailing conditions for the same index, described by the 21-year moving average. Data for the city of Riyadh in Saudi Arabia are derived from the HadGEM3 earth system model under pathway SSP5–8.5



than 30 days per year under SSP5–8.5), highlighting an expansion of the warm season in the late spring and early autumn months.

Tropical nights (TR) The absolute maximum number of tropical nights per year for the reference period ranges from zero or near zero in the polar and temperate regions to more than 300 nights in locations within the tropical zone (Fig. S4). As the absolute-threshold index of summer days, no tropical nights are expected in the future for polar regions or in the highest mountain ranges (e.g., the Himalayas and the Andes). In the rest of the world, the mean climatological values (i.e., 21-year moving average) have already or will soon exceed the historical extremes (for example, in parts of Africa, the Middle East, Atlantic US coast, tropical America,

Southeast Asia). Exceptions are regions in the transitional zone between temperate and polar climates in the Northern Hemisphere (e.g., parts of Siberia and North America), where this is projected to occur after 2050. For the high-emission pathway (SSP5–8.5), the CMIP6 projections suggest that deviations from the historical extremes will be larger for the tropical and sub-tropical zones, particularly in the Southern Hemisphere. For example, in the southern tropical zone, the end-of-century mean climate conditions are projected to comprise up to 65 additional tropical nights relative to the most extreme year of the historical period (Fig. 3d). Such a scenario implies an intensification of heat discomfort and associated human health implications. Moreover, it will likely cause dramatic increases in the energy demand for cooling.

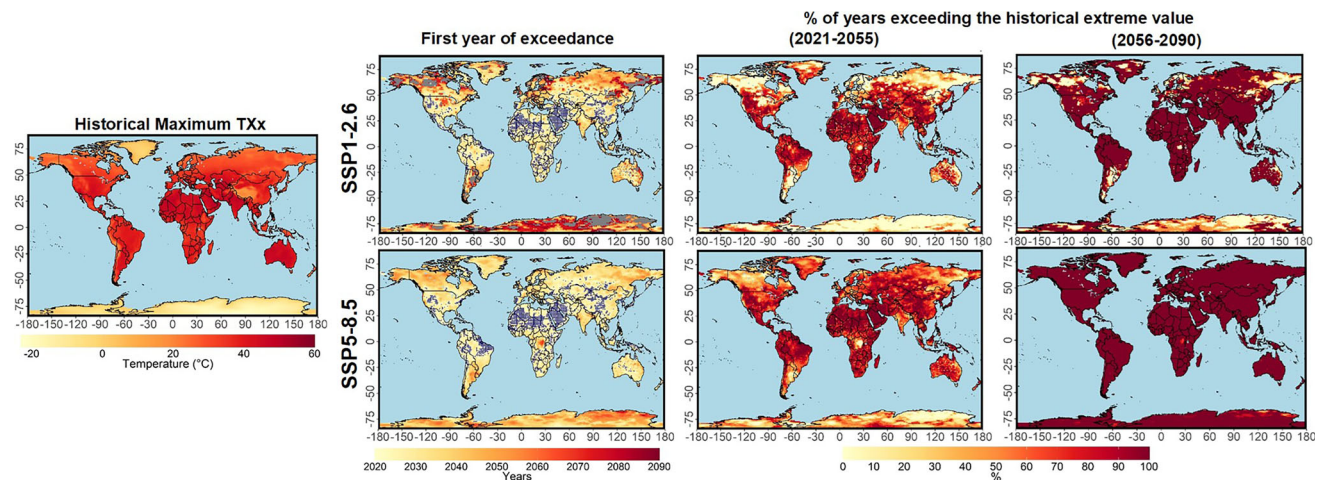


Fig. 2 Historical extreme hot maximum daily temperature (TXx) as simulated by an ensemble of CMIP6 global models (left). The first year (ensemble median) that the absolute extreme TXx value is exceeded for the 21-year running mean (second column). Areas where the first year

of exceedance is 2021 or earlier are highlighted in blue. Percentage of years where mean conditions are projected to exceed the absolute historical extreme TXx value for 2021–2055 and 2056–2090 (third and fourth columns)

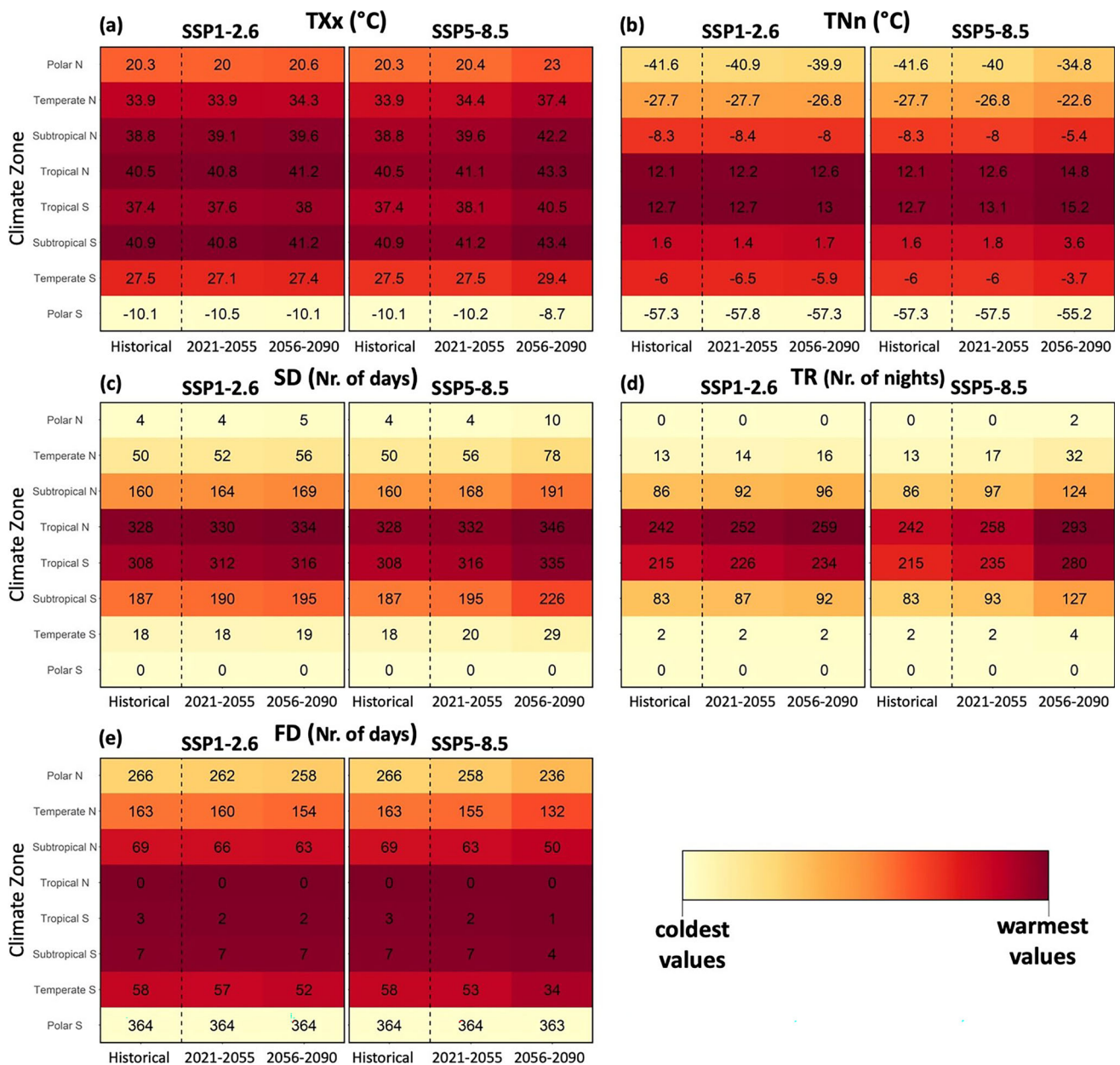


Fig. 3 Historical extreme warm values and future prevailing extreme conditions for five temperature indices, based on an ensemble of CMIP6 model projections and averaged over different climatic zones. TXx, absolute maximum daily temperature per year; TNn, absolute mini-

um daily temperature per year; SD, number of summer days per year; TR, number of tropical nights per year; FD, number of frost days per year

Absolute minimum daily temperature (TNn) The absolute warmest minimum temperature is a parameter critical for ecosystems, agriculture, human health, transportation, and critical infrastructures. In the historical part of the CMIP6 model simulations, it ranges from $-60\text{ }^{\circ}\text{C}$ in the continental part of the Antarctic to more than $20\text{ }^{\circ}\text{C}$ in the tropics (Fig. 4). For the near future under pathway SSP5–8.5, mean conditions will rise above the historical warm TNn extremes within

the next decades for most locations. This criterion is already met along parts of the Atlantic coast of North America, the Caribbean coastal areas of South America, and more limited locations in the Middle East and North Africa (blue hatching in Fig. 4). By 2050s–2060s, this is projected to occur in all parts of the world, including the Antarctic, South America, the USA, and central Asia, where TNn is overall warming slower than the rest of the world. Under SSP1–2.6, in part

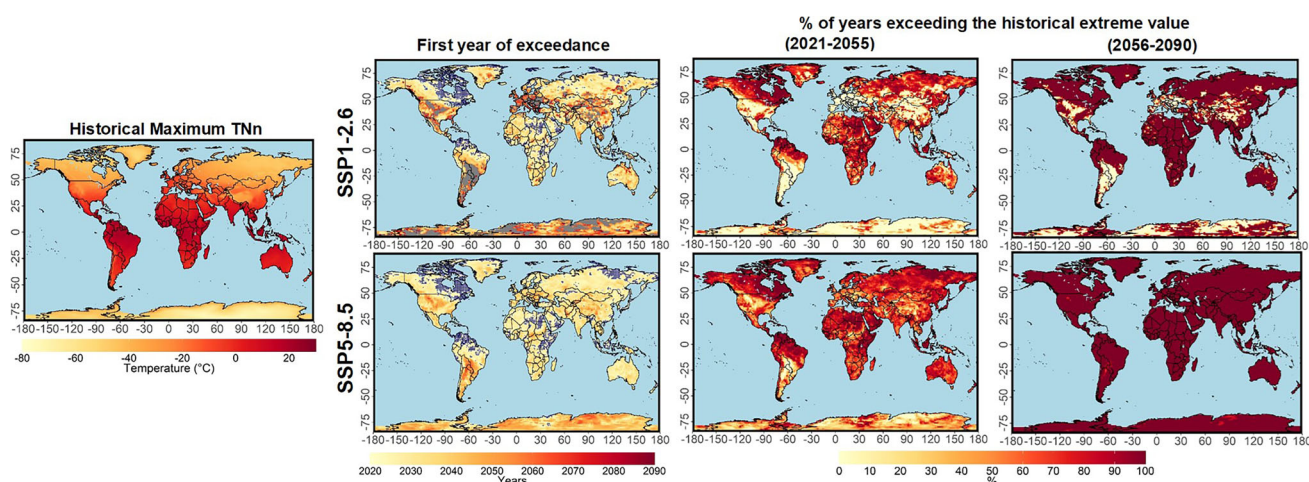


Fig. 4 Historical extreme warm minimum daily temperature (TNn) as simulated by an ensemble of CMIP6 global models (left). The first year (ensemble median) that the absolute extreme TNn value is exceeded for the 21-year running mean (second column). Areas where the first year

of exceedance is in 2021 or earlier are highlighted in blue. Percentage of years where mean conditions are projected to exceed the absolute historical extreme TNn value for 2021–2055 and 2056–2090 (third and fourth columns)

of these regions, and also areas in east and central Europe, the future average TNn values are not expected to be warmer than the hottest ones of the historical period. This implies a relatively more adaptable future, particularly for the fragile mountainous and polar climate zones and ecosystems. In contrast, under the high-emission SSP5–8.5 pathway, in all future years of the second half of the twenty-first century, the mean TNn values will be warmer than the historical extremes. On average, in the northern temperate and polar regions, this exceedance will be between 5.1 and 6.8 °C, whereas it is projected to be lower (between 2 and 3 °C) in the sub-tropical and tropical zones (Fig. 3b).

Frost days (FD) Frost days (days with minimum temperature below 0 °C) are widespread in the high-latitude polar and temperate zones and the highest-elevation mountain ranges that are resolved by the selected CMIP6 models. For example, in most of Greenland and Antarctica, such low temperatures prevail throughout the year, even during extremely warm periods (Fig. S5). For extended regions in the high boreal latitudes (e.g., in North America, Scandinavia, and Siberia), the current mean conditions imply fewer frost days per year than the historical minimum number (blue-shaded areas in Supplementary Fig. S5). In some permafrost regions of Siberia, North America, and the Tibetan Plateau, the number of frost days during the hottest years can further drop to 240–300 days. In temperate continental regions elsewhere, this number is significantly lower (between 40 and 90 frost days), while in limited parts of the subtropics, the few frost days per year will be further reduced (Fig. 3e).

4 Summary and conclusions

We have investigated to what extent future prevailing extreme climate conditions will be comparable to historical extremes for five hot and cold weather indices. Our analysis suggests that for several indices and locations, we have already entered an era where mean climate conditions are near or slightly hotter than the most extreme conditions during the 35-year historical reference period (1980–2014). This occurs mainly in lower latitudes for extreme high-temperature indicators (e.g., TXx, SU, and TR). On the contrary, for TNn and the annual count of frost days, this is more evident in higher latitudes (parts of temperate and polar zones).

These findings agree with previous model-based studies that have used different approaches and more distant baseline periods (e.g., pre-industrial) (King et al. 2015; Mahlstein et al. 2011). In the near term, we anticipate that this will be the case for many regions even when they will be subject to relatively moderate mean temperature anomalies (e.g., under pathway SSP1–2.6). Therefore, the major mitigation efforts needed to achieve such an (optimistically) low radiative forcing scenario still need to be accompanied by considerable climate change adaptation measures, being already relevant for the coming decades. Nevertheless, we agree with previous studies that the benefits of adopting effective mitigation policies become more evident in the second half of the century, and the majority of places would benefit, as the temperature extremes of the world today would not become the new normal in the future (Lewis et al. 2017).

Projections for the second half of the twenty-first century under a business-as-usual future pathway (SSP5–8.5) imply that in every future year, hot and cold extremes will be much warmer than in the historical period. Under such a scenario, the mean conditions in the hottest parts of the world (i.e., subtropics) could become life-threatening for humans and ecosystems. Such severe temperature conditions are thus far unprecedented everywhere on the globe. Despite the different datasets and methodologies, this corroborates previous estimates that such emergence occurs several decades sooner in low latitudes than in mid-latitudes, particularly in the spring and summer seasons (Hawkins and Sutton 2012). Such climate zones exhibit a 50% likelihood of permanently moving into a novel seasonal heat regime in the next two decades (Diffenbaugh and Scherer 2011).

According to our findings under a high-emission pathway, the warmer conditions (up to 30 fewer frost days per year and nearly 7 °C warmer minimum temperatures on average) expected in the temperate, polar, and mountainous zones will be most likely accompanied by irreversible environmental impacts such as earlier snowmelt, permafrost thawing, and the retreat of continental ice caps and glaciers.

We emphasize that the projected future conditions describe the average characteristics of the indices of climate extremes. We expect that during individual extreme years, the conditions can be much more severe than indicated by the presented results. This will likely be the case for both future pathways. Moreover, future exceedance of extreme thresholds (defined by historical events) could occur multiple times within the year, which was not assessed in the present study.

Although the historical values mostly demonstrate heat extremes in the Northern Hemisphere, future deviations are relatively stronger in the Southern Hemisphere. Hot weather extremes are expected to be particularly severe in the tropical and subtropical zones. On the other hand, relatively warm weather extremes in cold temperature regimes will increase most strongly in the polar and temperate zones.

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Author contribution G.Z. and G.L. conceived and designed the project. G.Z. and G.L. led manuscript writing. G.L. analyzed the data. G.L., G.Z., P.H., and J.L. interpreted the results. All authors assisted in manuscript writing and preparation.

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Data availability All datasets used are publicly available through the Earth System Grid Federation data portals (e.g., <https://esg-dn1.nsc.liu.se/search/esgf-liu/>).

Code Availability The analysis was performed using the Climate Data Operators - CDO (<https://code.mpimet.mpg.de/projects/cdo/>) and the R Project for Statistical Computing (<https://www.r-project.org/>). Codes are available upon request.

Declarations

Consent to participate Not applicable

Consent for publication Not applicable

Conflict of interest The authors declare that they have no conflict of interest.

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