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Dynamically downscaled seasonal heat wave projections in the CONUS

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Heat waves are a well-documented hazard that are projected to increase in intensity, duration, and frequency with climate change. Regions of the US experience widely varying temperatures; for example, 35 °C is extremely hot for spring in the Northeast but not for summer in the Southeast. It is important to evaluate projections within a regional context and at a high enough resolution to understand the risks to populations. We identify heat waves across the Conterminous US (CONUS) under SSP5–8.5 from 2020 to 2059 with an ensemble of dynamically downscaled Coupled Model Intercomparison Project Phase 6 (CMIP6) model outputs. We demonstrate that there are regional differences caused by seasonal and local drivers of persistent hot temperatures. Summer heat waves are increasing in intensity and duration faster than winter heat waves because of the atmospheric conditions that promote these events. Our analysis emphasizes the value of fine-resolution modeling for projecting future climate risks.

As the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report states, hot extremes such as heat waves will become more intense, more frequent, and lengthier due to climate change[1–5]. The societal disruption caused by heat waves exacerbates a looming health crisis driven by climate change, especially for vulnerable segments of the population—the youngest, the oldest, and the homeless[6,7]. Heat waves can cause a range of health impacts: heat stress, heat exhaustion, heat stroke[8], and increased risk of heart attacks, strokes, and other cardiovascular diseases[9,10]. Additionally, heat waves can cause significant financial loss from power outages and disruption to public infrastructure[11,12]. While the general impact of heat waves is clear[13], the development and specific risks of future heat waves to regions of the US remain limited by coarse-resolution model outputs.

To study how heat waves may evolve in the future, projections made by global climate models (GCMs) provide physics-based insights. The Coupled Model Intercomparison Project Phase 6 (CMIP6) coordinates the latest generation of GCM experiments worldwide using common protocols, climate forcings, and output formats to provide intercomparable future climate predictions[14]. O'Neill et al. (2016) described the design of CMIP6 emissions scenarios that combine a representative concentration pathway (RCP) with radiative forcing levels between 1.9 and 8.5 W/m^2 and a Socioeconomic Development Pathway (SSP 1–5). Among the scenarios, we consider the "worst-case" SSP5–8.5 to investigate the upper bounds of what the US could experience. RCP8.5 has been widely used in other studies to investigate potential climate change impacts[5,15–17].

However, the raw spatial resolution of GCMs is coarse and cannot resolve fine-scale processes to support regional (e.g., state-level and county-level) risk assessment and decision-making[18]. Suitable downscaling techniques, either dynamical or statistical, are required to refine the projection at a finer spatial resolution. Statistical downscaling uses observations of the modeled phenomenon during a reference period to build a statistical relationship and then apply it to future events[19]. It is computationally inexpensive and widely used but limited only to variables with long-term historic observations. It also relies on the premise that the relationship between observed and modeled events will remain unchanged in the future, which may not hold as climate change disrupts previously consistent processes[20]. Dynamical downscaling uses regional climate models to incorporate the effects of climate processes with respect to future emission scenarios to estimate local impacts. It is more computationally intensive and requires several sub-daily GCM outputs. Using a new dataset[20] that provides dynamically downscaled CMIP6 outputs, we explore the regional evolution and driving mechanisms of near-future heat waves in the US projected by the latest GCMs.

The IPCC defines a heat wave as an extreme weather event often associated with climate change[21]. There are numerous ways to quantify heat waves according to the research purpose and domain[11,22–28]. The heat wave duration index (HWDI) defines a heat wave as the total period >5 consecutive days with a maximum temperature >5 °C above the historical normal daily maximum temperature value[29]. While it is a useful approach for exploring deviations from normal values, a fixed threshold of 5 °C is not

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applicable in all regions[30]. The heat wave magnitude index (HWMI) defines a heat wave as at least 3 consecutive days where the daily maximum temperature exceeds the 90th percentile threshold of the average of a 31-day reference window during 1981–2020[31]. Researchers used a similar definition to analyze heat wave occurrences with varying numbers of consecutive days, temperature scales, thresholds, and reference windows[32–34]. Because the length of the reference window and the percentile threshold can easily be changed, we use the HWMI to reach a more comprehensive view of future heat waves by varying the percentile threshold. The HWMI has been used to holistically examine the entire evolution of a heat wave, rather than looking only at individual characteristics with no spatiotemporal consideration[35].

We include winter heat waves in our analysis rather than limiting our work to the more commonly studied summer heat waves. Because winter heat waves (or “warm spells”) receive less attention compared to summer heat waves[36], the negative side effects of warm winters can be underestimated. Biogeochemical and carbon cycles can be interrupted by these warm spells and this results in increased nitrogen leaching[37] and carbon loss from respiration[38], which feeds into a positive feedback loop of worsening climate change. Additionally, increased temperatures can influence yearly snow accumulation, which is a challenge for farming domestic food staples that rely on a steady water supply[39–42].

This research aims to understand how regional heat waves, an urgent climate hazard, may evolve across the Conterminous US (CONUS) in the near-term future using a newly released dataset with downscaled CMIP6 projection. Our work emphasizes the importance of fine spatial and temporal resolution for regional-scale projections and demonstrates that dynamical downscaling, though computationally intensive, can lead to reliable results for the purpose of human health, ecosystem, crop damages, and other regionally focused impact assessments.

Results

Historically (1980–2019), summer heat waves lasted an average of 2.6 ± 0.4 days and winter heat waves lasted 2.7 ± 0.5 days (Fig. 1). In the near future, however, under SSP5–8.5 summer heat waves are projected to last an average of 4 ± 0.6 days and winter heat waves are projected to last 3.7 ± 0.6 days (Fig. 1). The average duration of heat waves is not constant across the US; future summer heat waves are projected to last 9–12 days on average in the South and Southwest while winter heat waves are projected to last 9–12 days on average in the Northern Midwest and Rocky Mountain regions.

A Mann–Kendall test on the summer dataset returns a tau value of 0.705 ($p < 0.01$), indicating that there is a statistically significant trend of heat waves lasting longer over the 80-year length of the time series. The same statistical test for winter heat waves returns a tau value of 0.544 ($p < 0.01$), indicating that there is a positive trend in future winter heat waves, as well.

The average temperature of historical summer heat wave days is estimated to be 34.9 °C across the CONUS and the average temperature of historical winter heat wave days is estimated to be 24.7 °C (Fig. 2A). The average temperature of future summer heat wave days is estimated to be 35.4 °C across the CONUS and the average temperature of future winter heat wave days is estimated to be 25.2 °C. The regions experiencing the highest temperatures on these days are consistently in the South and Southwest during both summer and winter (Fig. 2B).

A Mann–Kendall test on the summer dataset returns a tau value of 0.702 ($p < 0.01$), indicating that there is a statistically significant trend of heat waves becoming hotter over the length of the time series. The same analysis for winter heat waves returns a tau value of 0.623 ($p < 0.01$), indicating that there is a positive trend in future winter heat wave temperatures, as well.

The number of heat wave events in a given year is projected to increase in the near future for both summer and winter heat waves (Fig. 3). This metric of a number of events is a count of the number of distinct (separated by more than a day) heat waves as calculated with a 95th percentile index that persist longer than 3 days in any given location.

The number of projected future heat-wave-person-days in the CONUS under SSP5–8.5 is shown in Fig. 4. This is a calculation based on heat-wave days that meet the given threshold (85th, 90th, or 95th percentile of historical temperatures) for at least 3 days. The population under SSP5–8.5 is projected to steadily increase, so this measurement is primarily driven by variations in annual heat wave days. The different thresholds for which events are counted as a heat wave (shown in red, blue, and black) demonstrate that while the population affected by extremely hot days will change depending on the level, the trend is still increasing quickly and in a concerning direction from a public health perspective.

Discussion

While the average duration of heat waves in the CONUS is projected to increase over the next 40 years in both the summer and winter (Fig. 1A), these averages are primarily driven by large increases in just a few regions. In the summer, the Southwest and the South could see a tripling in the average duration of heat wave events even with the most conservative percentile threshold (95th) whereas regions that are not soil-moisture-limited do not show such a dramatic change (Fig. 1B). This emphasizes the importance of the interaction between soil moisture and temperatures where once soils become dry enough, there is a shift in the sensitivity of daytime maximum temperatures and radiative energy at the soil surface becomes sensible heat, deviating from the expected linear trend in soil moisture and temperature[43]. This is clear when comparing the southwest to the southeast, which is not projected to have the same magnitude of increase in heat waves even though it is at the same latitude, primarily because it is much more humid[44].

Heat wave temperatures are projected to steadily increase throughout the CONUS (Fig. 2A), although with large regional and seasonal differences (Fig. 2B). Temperatures are generally hotter at lower latitudes and elevations, and the midwestern and southeastern “warming hole”[45] no longer persists to the same extent in future projections. While increased irrigation, reforestation, and ocean–atmosphere circulation patterns have historically combined to minimize summertime warming in this region[46–48], those forcings will no longer be enough to counteract the extreme warming projected under SSP5–8.5. However, it is also possible that the CMIP6 models are in fact underestimating the atmospheric circulation-induced cooling that could offset heating trends[49], despite the downscaling and bias correction with Daymet. However, the overall spatial pattern of temperatures remains consistent in the projected future as in the past, even though the magnitude is greater. Regions that historically have remained cooler, such as coastal locations that are cooled by proximity to ocean water[50] do tend to remain cooler than inland areas in the future as well.

The number of heat wave events in a given year is increasing. This means that either events are becoming more common or a single long event is now being broken up by a day of cooler temperatures; looking at the increase in the total number of heat wave days in a season (Fig. 4) as well as the increasing duration of events (Fig. 1) points to the increasing frequency of heat waves rather than the disruption of heat wave events by cooler temperatures as the cause. Figure 3B demonstrates that this heat wave persistence is anomalously high along the coastlines in the summer. In particular, Florida is expected to experience 4 times as many heat waves during the summer in the near future relative to the recent past (Fig. 3B). This is corroborated by other recent literature[51–53] that explains that heat waves in Florida are particularly impacted by a flattening temperature distribution where a small increase in temperature results in a large increase in events that qualify as heat waves, therefore increasing heat wave duration. Heat wave duration or persistence is particularly important when evaluating the long-term impacts of heat waves and deciding which areas need improved management and mitigation plans[54,55].

Winter heat waves are also projected to increase in intensity, duration, and frequency in the near future (Figs. 1–3). These warm spells have been shown to interrupt cold stratification, a process in seeds that is required for germination[56], and impact the temperature of streams that function as important winter habitats[57]. Additionally, warmer winters mean that less precipitation will fall as snow, reducing the reliability of snowpack as an input to streamflow and increasing interannual variability, exacerbating droughts, particularly in areas like the western US that rely on snowpack for

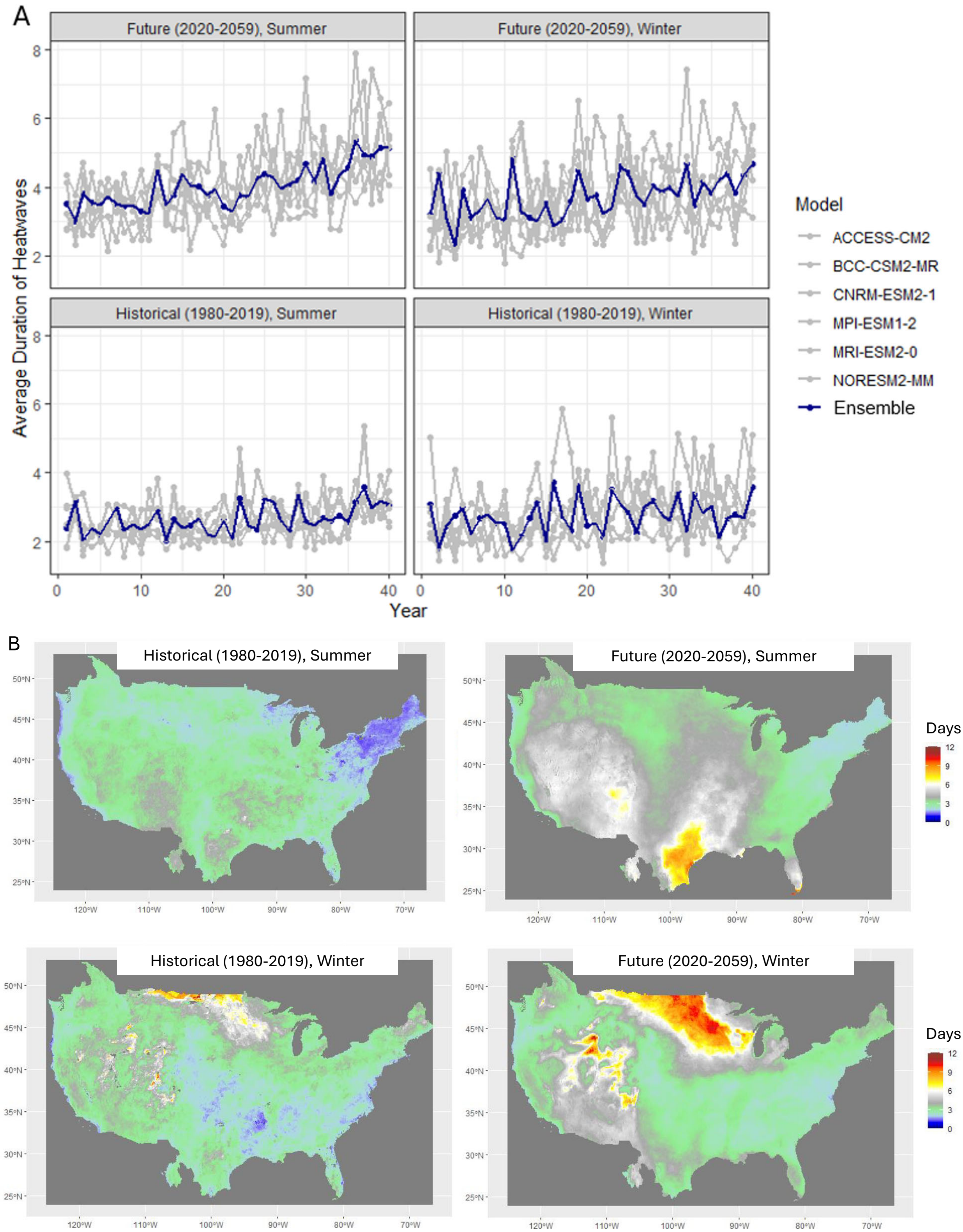

Fig. 1 | Historical and future projected heat wave duration in the CONUS. A The average duration of a heat wave in the CONUS is projected to increase in the near future. **B** The average duration of a heat wave in the CONUS varies by region.

streamflow in the summer[58–60]. The spatial pattern of winter heat wave duration is markedly different (Fig. 1B), although the duration of winter heat waves is also increasing on average (Fig. 1A). There are two regions projected to have large increases in duration—the Western US, near the Rocky Mountains, and the Upper Midwest, near the Great Lakes. The Rocky Mountain region is likely influenced by the high altitude of the mountains that disrupt zonal air mass transport[61]. Similarly, in the Upper Midwest, warm air advection of warm terrestrial air[62] can cause extremely intense and long-lasting heat waves[63].

Summer heat waves are increasing in intensity and duration faster than winter heat waves (Figs. 1–3). Summer heat waves are primarily driven by atmospheric blocking where convection is suppressed and heat builds up at

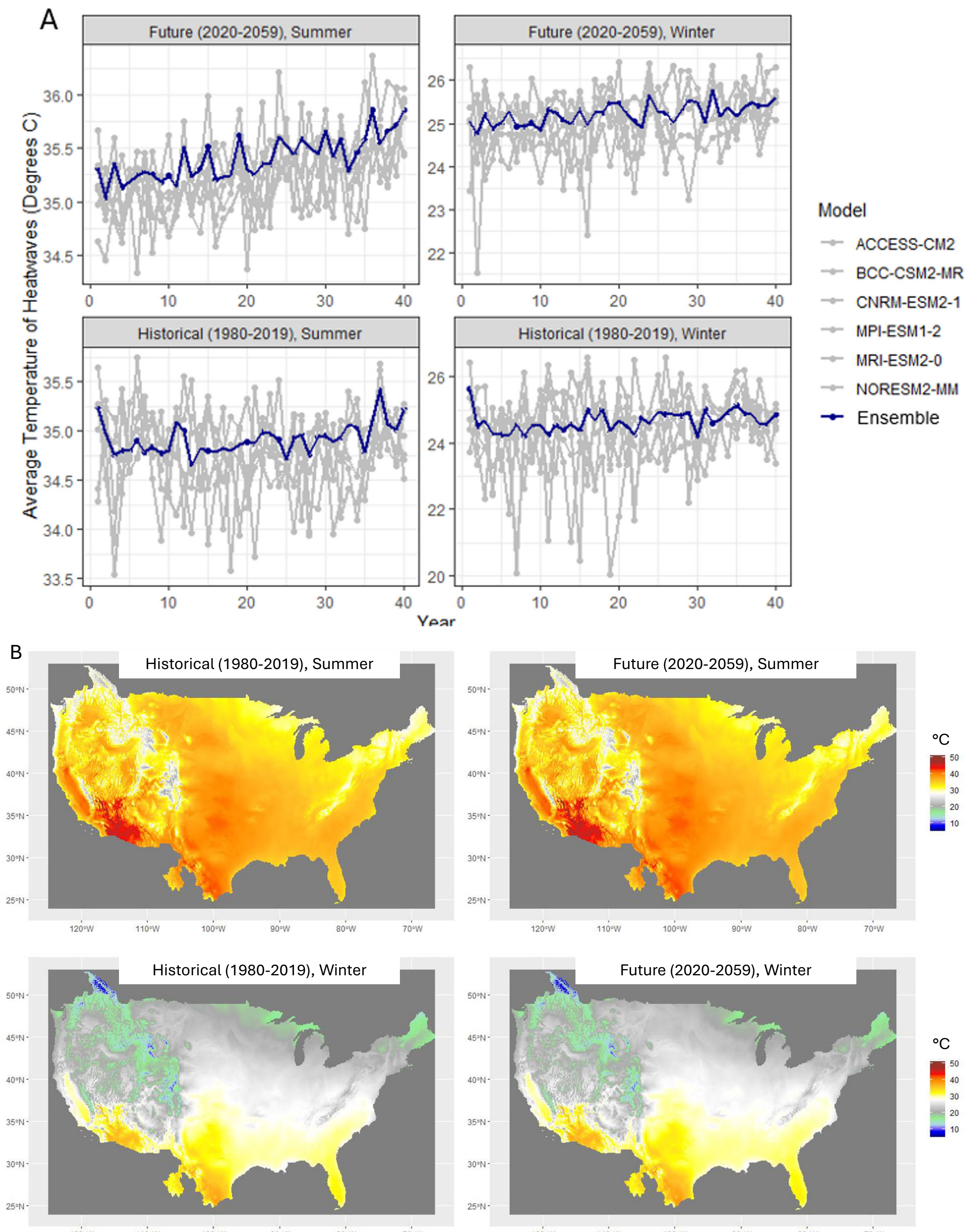

Fig. 2 | Historical and future projected average temperature of heat wave days in the CONUS. A The average temperature of heat wave days in the CONUS is projected to increase in the near future. **B** The average temperature of heat wave days in the CONUS varies by region.

the surface, causing adiabatic warming to occur and a build-up of sensible heat[64–66]. In the summer, local conditions such as soil moisture tend to be more impactful in terms of heat wave formation, particularly in the interior CONUS, away from coastlines[67]. The blocking anticyclones that form and tend to promote these conditions are associated with warmer surface conditions. Future winter heat wave temperatures are more uncertain, as the models do not agree nearly as well as they do when projecting summer heat wave temperatures. This occurs because in the winter, soil moisture has little impact, and large-scale factors like Pacific Ocean sea surface temperature cause cyclone and anticyclone formations that impact temperatures far

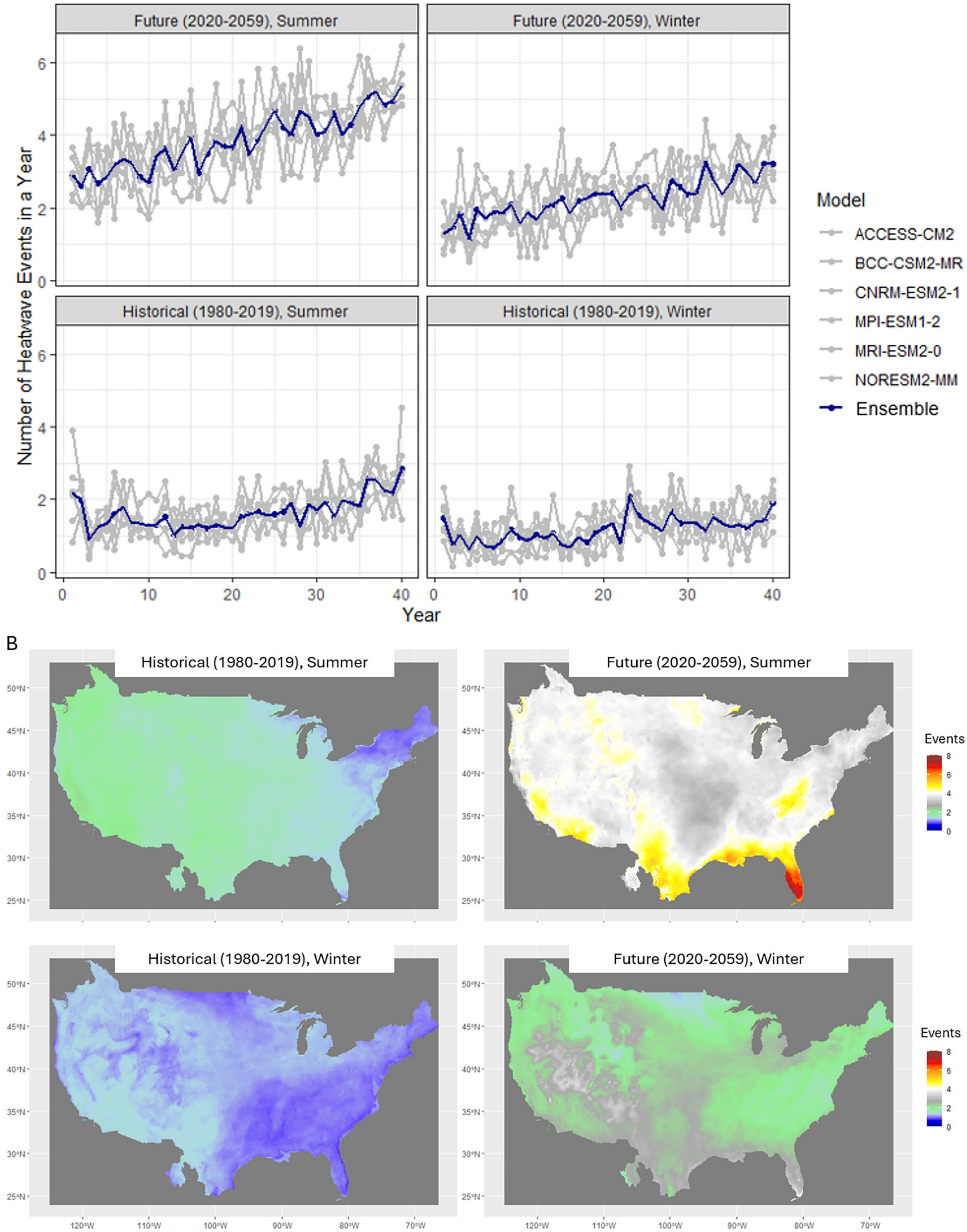

Fig. 3 | Historical and future projected heat wave events in the CONUS. A The number of events in a given year is increasing. **B** There are large differences in the number of events projected in the near future by different regions of the USA.

from the coast[67]. Winter heat waves tend to be caused by warm air advection, although atmospheric blocking also plays a role in starting the warm air advection[65,68]. That means that indices that can be used to predict summer heat waves from related variables such as soil moisture and cloud cover will not perform as well in the winter because of the lack of coupling between these local-scale variables and the temperatures; this demonstrates the importance of using a model that incorporates large-scale atmospheric circulation.

It is not only large-scale land–atmosphere dynamics that contribute to heat waves. The feedback between land cover change and temperatures

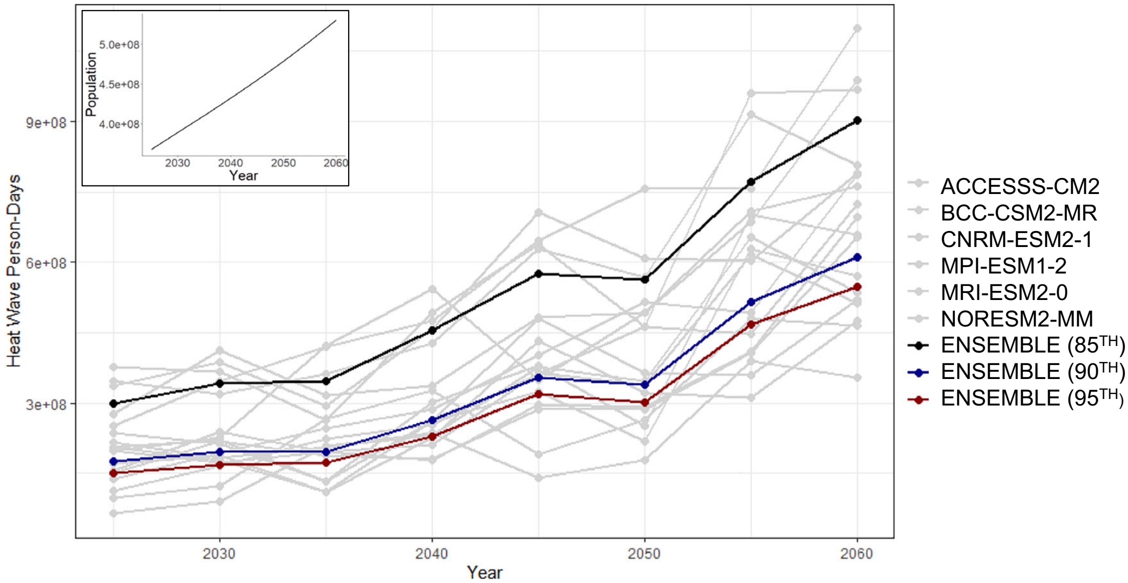

Fig. 4 | Projected future heat wave person-days in the US under SSP5-8.5 with 85th, 90th, and 95th percentile thresholds.

means that urban areas experience hotter conditions[69]. This connection has important implications for the populations at risk. Earlier, more intense, and longer heat waves are associated with higher mortality risk, with a 2.49% increase in mortality associated with every 1 °F increase in intensity and 0.38% for every 1-day increase in duration[70]. Our results show that across the US even with the most conservative threshold (95th percentile), there is projected to be an increase from 170 million heat wave person-days to 550 million heat wave person-days. While this increase is driven partially by the linear increase in population projected under SSP5–8.5, the location of populations also matters in determining risk.

There are numerous heat wave indices in existence and comparisons can lead to differing conclusions in the same region[71]. But even with different percentile thresholds, there is projected to be a sizeable increase in the number of people experiencing heat wave days in the near future (Fig. 4). Despite this clear risk, predicting heat waves alone may not be enough to establish human health impacts. Heat waves can also be more deadly when they are humid heat waves—when temperatures rise but humidity remains constant—because this increases heat stress and limits the body's ability to use evaporative cooling to maintain homeostasis[72,73]. On the other hand, heat waves commonly occur at the same time as droughts, leading to greater mortality and environmental impacts from the compound event[74].

One further concern is that downscaling daily maximum temperature projections becomes more challenging under greater warming conditions, during the summer, and in some particular geographic areas such as regions with steep elevation changes[75,76]. For example, steep elevation can cause local weather conditions to differ from the surrounding area and observations may not capture this effect, making it hard to constrain a model. In fact, downscaling contributes substantial uncertainty to future climate estimates, particularly when projecting extremes, in regions with complex terrain, or where historical observations do agree[77].

We evaluate near-future heat waves in the US under SSP5–8.5 with an ensemble of 6 dynamically downscaled CMIP6 GCM. Our work demonstrates that while the entire region is expected to experience an increase in intensity, duration, and frequency, there are meaningful regional differences caused by different regional and seasonal drivers of persistent hot temperatures. We show that while summer heat waves are increasing in intensity and duration faster than winter heat waves because of differences in the atmospheric conditions that promote these events, winter heat waves are still projected to increase in intensity, duration, and frequency in the near future. In particular, regional- and local-scale meteorological patterns are very important; dynamical downscaling can resolve these fine-scale processes and offer high-resolution projections of climate risk in the near future. These changes in heat wave patterns are projected to increase the number of people at risk as the US population grows if people do not take climate risk into account when deciding where to live.

Methods

Six CMIP6 GCMs under SSP5-RCP8.5 (Table S1) were selected given their model performance[78] and availability of 6-hr data to support dynamical downscaling. Dynamical downscaling was done using the fourth version of the Regional Climate Model system (RegCM4) which relies on physics-based models and provides a large suite of physically consistent variables[79], and it refines the horizontal resolution from GCM's original resolution (>150 km) to 25 km across the CONUS[20]. A daily bias correction was then performed on RegCM4 output using Daymet observations and it further refines the spatial resolution from 25 km to 1/24° (~4 km).

We calculated the heat wave magnitude index[31] and used the daily maximum temperatures during the 40-year reference period to calculate the 85th, 90th, and 95th percentile threshold, with a 31-day reference window. Each heat wave event was only classified as such if it lasted at least three consecutive days; for example, a 2-day period of greater than the 95th percentile of historical daily maximum temperatures would not qualify as a heat wave. We calculated an ensemble mean of the six CMIP6 models (Table S1) using raw and downscaled outputs for both historical (1980–2019) and near-term future (2020–2059) periods for the entire study area.

We also performed a Mann–Kendall test[80,81] to determine if there is an upward or downward trend in duration, temperature, and the annual number of heat waves throughout the study time period, from 1980 to 2059.

Data availability

All data used in this study are publicly available. The CMIP6 models were from the Earth System Grid Federation (ESGF, https://aims2.llnl.gov/search). Daymet Version 4 is available through the Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) (https://daymet.ornl.gov/). The NClimGrid dataset is available through the NOAA-NCEI website (https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00332). PRISM is available from the PRISM Climate Group at Oregon State University (https://prism.oregonstate.edu/). All data analysis was done using the R programming language[77] and Climate Data Operators[82]. For access to the RegCM4 ensembles, please contact the corresponding author.

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Author contributions

J.S.F. and S.-C.K. conceptualized the study. D.R., S.-C.K., M.A. provided and verified the model data. H.J.R. and L.Z. developed the methodology and did the data analysis. H.J.R. created the data visualizations and wrote the original draft. J.S.F., L.Z., D.R., S.-C.K., and M.A. reviewed and edited the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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