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Review article

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Prediction and projection of heatwaves

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Abstract

Heatwaves constitute a major threat to human health and ecosystems. Projected increases in heatwave frequency and severity thus lead to the need for prediction to enhance preparedness and minimize adverse impacts. In this Review, we document current capabilities for heatwave prediction at daily to decadal timescales and outline projected changes under anthropogenic warming. Various local and remote drivers and feedbacks influence heatwave development. On daily timescales, extratropical atmospheric blocking and global land–atmosphere coupling are most pertinent, and on subseasonal to seasonal timescales, soil moisture and ocean surface anomalies contribute. Knowledge of these drivers allows heatwaves to be skilfully predicted at daily to weekly lead times. Predictions are challenging beyond timescales of a few weeks, but tendencies for above-average temperatures can be estimated. Further into the future, heatwaves are anticipated to become more frequent, persistent and intense in nearly all inhabited regions, with trends amplified by soil drying in some areas, especially the mid-latitudes. There is also an increased occurrence of humid heatwaves, especially in southern Asia. A better understanding of the relevant drivers and their model representation, including atmospheric dynamics, atmospheric and soil moisture, and surface cover should be prioritized to improve heatwave prediction and projection.

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Introduction

Land heatwaves (distinguished from marine events, and hereafter referred to as heatwaves) describe events in which temperatures are excessively higher than normal for several consecutive days (Box 1). These persistent temperature extremes directly affect various systems, including forest and agriculture[1–3], infrastructure[4], energy demand[5,6], ecosystems[7], permafrost[8] and human health[9,10]; the latter is particularly affected by humid heatwaves, a combination of temperature and specific humidity[9,11] (Box 2). In addition to their direct impacts, heatwaves can also lead to compounding extreme events[12]. A common example includes compound heat and drought[13–15], associated with enhanced fire risk[16], plant mortality[17] and crop failure[18].

Since at least the 1950s, the frequency and duration of heatwaves has been increasing globally[19]. Cumulative intensity (Box 1) has also increased in most locations[20,21], mainly owing to rises in heatwave frequency. For example, in central Europe, the coldest summers of the modern period (1993–2022) are already warmer than average summer temperatures from 1864–1992 (Fig. 1). Temperature distributions are skewed towards warmer temperatures, indicating that hot extremes occur more frequently than for a normal distribution. Temperature variance is similarly increasing[22]. In addition, heatwaves are increasingly occurring in places where they have not previously been a major threat, as for example evidenced by the North American Pacific Northwest heatwave of 2021[23]. These changes in heat extremes are increasingly attributed to human influence[24–27]. Indeed, observed heatwaves such as those in Europe during 2003 and 2018 are extremely unlikely in the absence of human-induced climate change[28,29], with the IPCC Sixth Assessment Report (AR6) concluding that it is virtually certain that human-induced greenhouse gas forcing is the main driver of observed changes[19]. These trends are also likely detectable on the regional scale in more than 80% of all IPCC regions[19].

Given the devastating impacts of heatwaves, coupled with their increasing frequency and magnitude, preparedness for these extreme events is needed at a range of lead times. For example, on timescales of days to weeks, municipalities have to take action by establishing cooling centres, warning the general population, and contacting and implementing protection measures for vulnerable groups. At monthly to yearly timescales, preparatory work includes developing heat-health action plans and establishing links and collaborations between decision makers and meteorological and health services[30]. On timescales of years to decades, urban and infrastructure planning[31], and climate change mitigation and adaptation are needed. Such preparedness can be expected to alleviate heatwave impacts, especially in light of a changing climate[32]. Indeed, regions that have experienced heatwaves in the past are more likely to implement emergency measures and hence are better prepared for subsequent events[33]. Thus, there is a clear need to anticipate the timing and severity of heatwaves on timescales of weeks to seasons, as well as location-specific changes in frequency and intensity beyond yearly timescales.

In this Review, we synthesize the understanding of the prediction and projection of heatwaves. We begin by outlining the drivers of, and feedbacks associated with, heatwaves. We next outline heatwave prediction on timescales of several days to decades, followed by heatwave projection in future climates. We end with recommendations for future research. The focus here is on land heatwaves, with an overview of marine heatwaves and their impacts available elsewhere[34–37].

Drivers and feedbacks for heatwave prediction

Understanding of the processes influencing heatwave development and characteristics enables improved representation in models, thereby enhancing long-range prediction capabilities. These processes include those from the atmosphere as well as the land or ocean surface (Fig. 2), encompassing drivers (large-scale local and remote processes communicated to the heatwave location as changes in temperature, humidity and circulation) and feedbacks (a combination of regional-scale processes of mutual influence on a subcontinental scale). These atmospheric drivers, and surface drivers and feedbacks, are now discussed.

Atmospheric processes

The driving mechanisms of heatwaves and their relative importance depend on the region where the heatwave occurs. In the extratropics, heatwaves are typically associated with anomalously long-lived quasistationary anticyclonic flow anomalies (Fig. 2), including high-amplitude upper tropospheric ridges[38]. In the mid- and high latitudes, these ridges are particularly stationary and can often (in approximately 80% of all cases) be identified as atmospheric blocks[39–41], increasing the likelihood of heatwaves being long-lasting[42]. However, at lower mid-latitudes, including the Mediterranean, upper-level ridges are typically weaker and so cannot be classified as blocks[43]. Specific examples of heatwaves associated with blocks are found in Europe[44], North America[45,46], southeastern Australia[47] and eastern China[48]. In the subtropics, heatwaves can also be associated with persistent blocking, especially in South America[49–53]. In the subtropical Asian monsoon regions, heatwaves tend to occur predominantly in the pre-monsoon season. A late monsoon onset[54] or anomalously weak pre-monsoon precipitation can lead to an extended hot period, as during the extreme humid heatwave in India and Pakistan in 2015[55].

The physical processes that drive heatwaves can be separated into horizontal advection of air from climatologically warmer regions, adiabatic warming from subsidence and diabatic heating owing to radiation and surface sensible heat fluxes (Fig. 2). The formation of a heatwave tends to involve a combination of these processes, the relative importance of which varies between daytime and nighttime heatwaves, and between the considered regions. For instance, in southern China, daytime heatwaves are accompanied by clear-sky conditions and subsidence, while nighttime heatwaves are associated with cloudy and moist conditions[56] and therefore anomalous diabatic processes. In contrast, polar heat extremes are predominantly driven by advection from lower latitudes[57,58], as in the Antarctic heatwave of March 2022[59]. Horizontal advection is a less important process for heatwaves in mid-latitudes (including Europe[43,60] and southeastern Australia[61]). In these regions, upper-level ridges and blocks contribute to surface heatwaves via subsidence, associated with clear-sky conditions and increased incoming solar radiation[62], complemented by diabatic heating within the boundary layer, as also observed in the 2010 Russian summer heatwave[63–65]. An important process for the formation and maintenance of the ridges and blocks and for reinforcing heatwave persistence is upstream latent heating in moist ascending airstreams[66,67], which are associated with cloud formation and precipitation along the western flank of the ridge or block[68–70]. Continental summer heat extremes are also suggested to be connected with low upstream storm-track activity[71].

On the planetary scale, persistent tropical and extratropical atmospheric patterns can also drive remote responses that lead to extratropical heatwaves[72]. Stationary atmospheric ridges (that is, wave crests that are anomalously persistent) associated with heatwaves in the extratropics can occur when the jet stream becomes organized in a large-scale or circumglobal wave train[73–75] or in situations with recurrent wave patterns[76], exhibiting stationary behaviour enhanced by orographic and thermal forcing[77,78]. Such stationary behaviour has been suggested to exhibit a potential for resonant wave amplification, which,

Box 1

Heatwave definitions

A heatwave occurs when several consecutive days exhibit temperatures that are excessively higher than normal. Most definitions use a temperature threshold such as the 90th percentile or higher, and include a persistence of at least three consecutive days[240–242]. This threshold and persistence-based heatwave definition is primarily meaningful in the extratropics where pronounced heat occurs episodically. In the tropics, however, such a definition is less applicable given that high temperatures often prevail over extended periods. The exact heatwave definition and its characteristics, including frequency, intensity, timing, duration and spatial extent, therefore depend on the application[169,240,243,244].

Frequency: A measure of how often heatwaves occur, often expressed as the total number of discrete heatwave events over a season[240,245]. The number of individual heatwave days (where each day must fit the underlying heatwave criteria) can also be used. Frequency measures are useful to understand human health and infrastructure impacts, as well as energy demands[20,169,240,246].

Intensity: A measure of how extreme heatwaves are, either via absolute temperatures or an anomaly from a baseline. Various different intensity measures exist, which can be defined for individual events (for example, the peak intensity as per the hottest day of a heatwave, or the average temperature across all days in the event)[20] or for all events across a season (average intensity across all heatwaves, total heatwave magnitude, or the cumulative exceedance of the temperature threshold across all events, also called cumulative intensity). The overall heatwave magnitude can also be measured as standardized combinations of frequency and intensity[244,247]. Similar to frequency, heatwave intensity is important for human health and infrastructure impacts[20,182,246].

Timing: When the heatwave season starts in a given year. This metric is determined by the first day of the first recorded event, and the end of the season by the last day of the last recorded event[248]. The timing of heatwave occurrence is important for ecosystem impacts[249].

Duration: The total length of an event, from start to finish. Duration can be measured for individual events or for all events in a season (for example, median or maximum length). Heatwave length is useful in understanding heatwave interactions with drought and wildfire fuel[250], as well as permafrost melt[251,252].

Spatial extent: The geographical area associated with an event. Metrics such as three-dimensional clusters of days meeting heatwave criteria[253] measure the spatial extent of heatwaves[254–256], as well as their movement in space and time[182,257], which is useful for characterizing compound events[258].

in turn, can cause temperature extremes[79–81]. Conversely, extreme temperature events associated with more localized Rossby wave packets[82], rather than circumglobal patterns[83], have been emphasized. However, this linkage between jet waviness and heat extremes varies strongly between regions[84] and is subject to ongoing research.

Surface drivers and feedbacks

In addition to atmospheric processes, local and remote drivers and feedbacks associated with land and ocean surfaces can also influence heatwave occurrence, and thereby prediction.

A key regional driver for heatwaves is soil moisture deficits or droughts[13,85,86] (Fig. 2). These deficits reduce evaporative cooling through latent heat flux at the land surface, leading to extreme local heat[13,87,88]. These effects contribute substantially to the occurrence of hot days on all continents, particularly in mid-latitude[13,88,89] and monsoon regions[90]. In addition, soil moisture forcing can feed back onto the large-scale atmospheric circulation[91–94], exacerbating a heatwave. Heat advection from regions affected by soil moisture limitation further demonstrates the importance of non-local land–surface interactions[65,95,96].

The land surface also influences heatwaves via land cover properties[19,97]. For example, compared with grassland and agricultural land, forests can amplify heatwave conditions in the short term but dampen them in the longer term[98,99]. Forest type is also relevant, with broadleaf trees reducing heatwave intensity compared with coniferous trees owing to their higher albedo and stomatal conductance[100]. Agricultural management further affects heatwave properties. For instance, irrigation and intense agriculture increase evapotranspiration on hot days, comparatively cooling the surface[101–103].

Feedbacks between the land surface and cloud cover are also important (Fig. 2). Cloud cover can decline as a result of drier air when latent heat flux is limited (as in heatwave conditions), in turn increasing incoming shortwave radiation[104,105]. Furthermore, reduced cloud cover can further decrease precipitation, lowering soil moisture and thereby amplifying the heatwave[105]. Nonetheless, this possible feedback loop between soil moisture and precipitation is less well established in observations[105–108].

However, it is not just the land surface that influences heatwaves; surface forcing associated with anomalous sea surface temperature (SST) patterns is also important. In particular, persistent SST anomalies can give rise to persistent atmospheric circulation patterns that lead to heatwaves over adjacent continents. For example, the 2003 European heatwave has been related to anomalously warm SSTs in the Indian Ocean and the Mediterranean, which have been suggested to affect the distribution of geopotential height and precipitation across Europe[109]. In contrast, the 2015 European heatwave is thought to have been driven by anomalously cold SSTs in the North Atlantic. These SST anomalies induced a persistent atmospheric wave pattern and a stationary position of the jet stream that, in turn, favoured hot temperatures over central Europe[110]. The Pacific Extreme Pattern (describing anomalously warm SSTs in the central North Pacific and cold SSTs along the North American coast) has been linked to hot days in the eastern United States[111]. However, these extratropical Atlantic and Pacific SST anomalies exhibit strong non-stationarity and thus cannot often be successfully used for long-range prediction[88,112].

Box 2

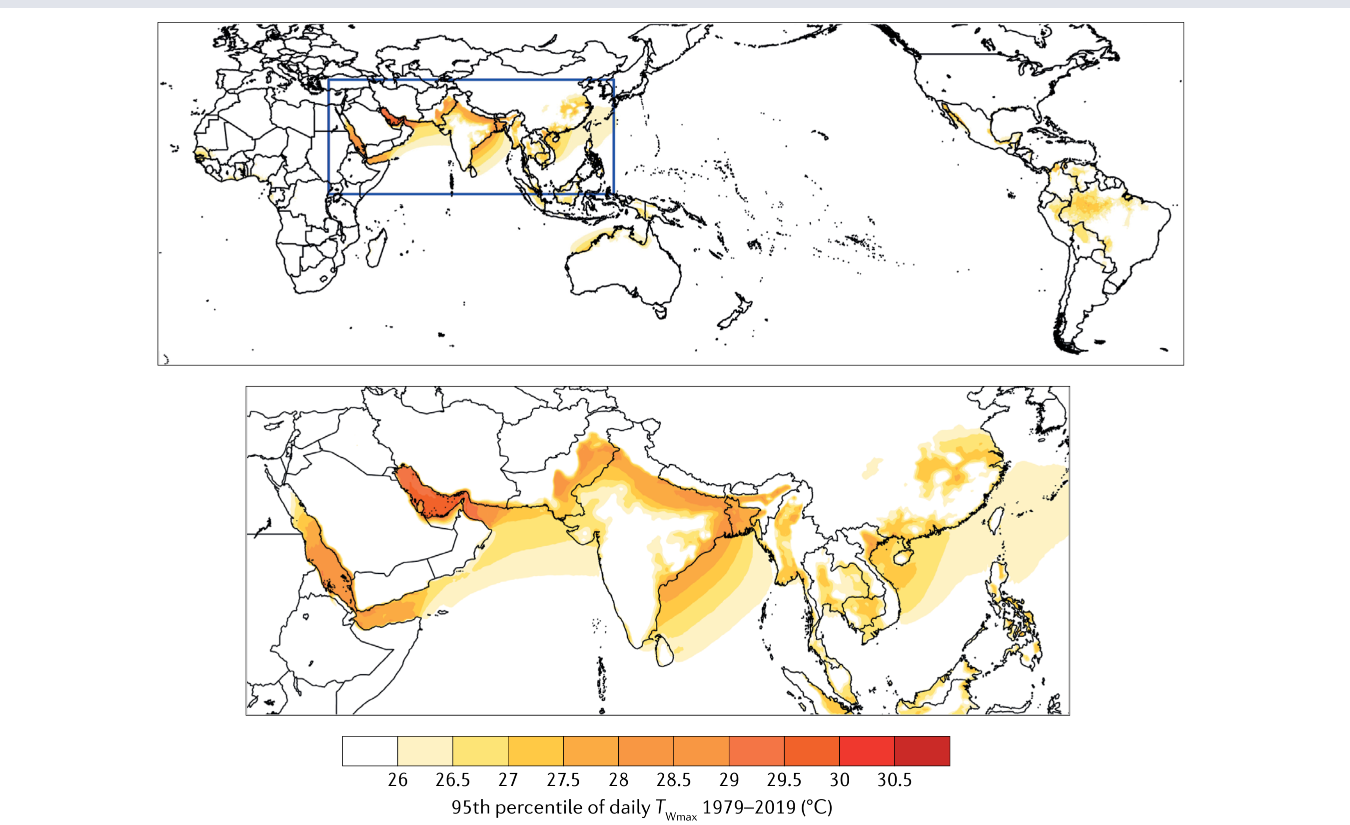
Humid heatwaves

Humid heatwaves represent a particular threat to human health in a future climate.

Definition: For health applications, a measure of humidity is often incorporated into heatwave definitions[10,259–261]. A useful variable in this regard is the wet-bulb temperature, the temperature obtained if air were cooled by evaporating water until saturation. Although the wet-bulb temperature is a good indicator of heat stress, several other indicators based on combinations of temperature and humidity serve a similar purpose[262], such as the US Weather Service Heat Index. Under well ventilated conditions, wet-bulb temperature is correlated with skin temperature, and hence provides a direct link to morbidity and mortality responses to heat stress[259]. Wet-bulb temperatures above around 30 °C (corresponding to a temperature of 36 °C and relative humidity of 65%) are considered dangerous levels for humans.

Processes: Regions experiencing extreme humid heatwaves include the low-lying tropical regions of India and Pakistan (particularly the Indus and Ganges river basins); the Persian Gulf, Arabian Gulf and Red Sea; and eastern China[263] (box figure). These regions exhibit maximum wet-bulb temperatures (T_{Wmax}) up to 32 °C, corresponding to levels dangerous for human health. In the Persian Gulf, high-intensity humid heatwaves are associated with very high sea surface temperatures and hot and dry northwesterly *shamal* winds that efficiently evaporate moisture[264]. In Pakistan, humid heatwaves relate to onshore flow from the Arabian Sea during summer monsoon onset[11]. Such air masses are advected over hot and often irrigated agricultural land, where the moistening effects of irrigation dominate[263,265] and result in elevated web-bulb temperatures[234]. Irrigation is also important in enhancing heatwave intensity over the North China Plain of eastern China[265].

Projection: By 2100, 6-hour wet-bulb temperatures in tropical and subtropical Asia are projected to climb into the dangerous range above 30 °C, episodically approaching and exceeding 35 °C. This specific magnitude of the wet-bulb temperature, averaged for a time window of 6 hours, is assumed to be the threshold for human survival[266]. Areas most at risk from these extreme humid heatwaves are the densely populated agricultural valleys of the Ganges and Indus river basins, or the southern part of Asia more broadly, owing to acute vulnerability and increasing occurrence of these conditions[11,267,268]. Transport of moisture from the warm Indian ocean is another important factor for atmospheric humidity increases under climate change in southwest Asia[269].



Tropical SST drivers for heatwaves are more firmly established and largely involve interactions with large-scale modes of climate variability. In particular, El Niño–Southern Oscillation (ENSO) is a dominant driver of heatwaves over land regions adjacent to the tropical Pacific, whose temperatures mimic the adjacent ocean surface. In addition, ENSO influences heatwaves across large parts of the globe[113,114], including China[115], India[116], North America[117], Europe[118] and Australia[119]. In Australia, ENSO teleconnections often interact with forcing from the Indian Ocean Dipole (IOD)[120]. Furthermore, forcing from the Madden–Julian Oscillation (MJO) can also induce heatwaves; increased MJO-related convection over the Indian Ocean and the eastern Pacific has been linked to heatwaves in the western United States[121], and anomalous MJO-related convection in the western Pacific is associated with heatwaves in northeastern Asia[122]. East Asian monsoon convection can further drive remote heatwaves in the United States[123].

For most heatwaves, several of these local and remote surface factors and atmospheric processes contribute towards establishing and maintaining a heatwave. The European heatwave of 2003, for example, is suggested to have been affected by a persistent atmospheric flow pattern, soil moisture deficits and remote SST patterns[124–127]. Because many of these forcings are long-lived, they allow for an improved prediction of heatwaves at long lead times.

Heatwave prediction

A range of local and remote physical mechanisms contribute to the predictability of heatwaves on timescales of days to decades (Fig. 3). These processes act seamlessly across timescales, meaning that prediction systems will have to consider all dominant predictors to generate successful forecasts. However, the relative contribution of each process, and hence where accurate initialization is needed, can vary across the full range of lead times. The prediction of heatwaves from days to decades is now discussed.

Based on a minimum three-day duration of heatwaves, confident predictions of heatwave occurrence and amplitude are possible in weather prediction systems two to three days ahead. Several processes are essential for an accurate heatwave forecast at these timescales: the processes leading to the formation of a quasistationary ridge or block[40,41], maintenance of these anticyclonic flow anomalies leading to subsidence, and diabatic heating in the boundary layer from surface sensible heat fluxes. The location and strength of these atmospheric flow patterns are generally not well represented in models[128–130], and often several types of atmospheric drivers contribute to the evolution of a heatwave[131], affecting its prediction.

On timescales of up to 10 days, the presence of long-lived Rossby wave packets in mid-latitudes can improve subseasonal predictability[83,132,133], as can inclusion of the MJO for prediction over the contiguous United States[134] and in the Sahel region[135]. In the tropics, however, forecast skill on these timescales is generally lower and varies strongly by location; particularly low predictability is evident for islands that are not accurately represented in global forecast models[136].

Beyond the traditional deterministic predictability limit of approximately 10–15 days[137,138] (that is, the exact determination of the synoptic flow[139]), forecasts have to be expressed probabilistically. Summer heatwaves are among the most predictable meteorological extremes on subseasonal timescales[140,141] and can often be predicted at lead times of two to three weeks[142]. For extreme heatwaves, this predictability generally manifests as a tendency towards a warm anomaly in the model ensemble, often at lead times of four weeks or more. Over the subsequent weeks, the ensemble shifts further toward warm anomalies, followed by a clustering of the ensemble members around the observed value up to two weeks before the heatwave event[141]. This predictability evolution is typical for heatwaves around the globe[143,144], including the June 2021 heatwaves across the Northern Hemisphere mid-latitudes (Fig. 4).

For this particular set of heatwaves, early initializations indicate above-normal temperatures but with an underestimated amplitude and misplaced location of maximum temperatures. With decreasing lead time, the model starts to capture the correct location and higher amplitude of both North American and European heat from about a

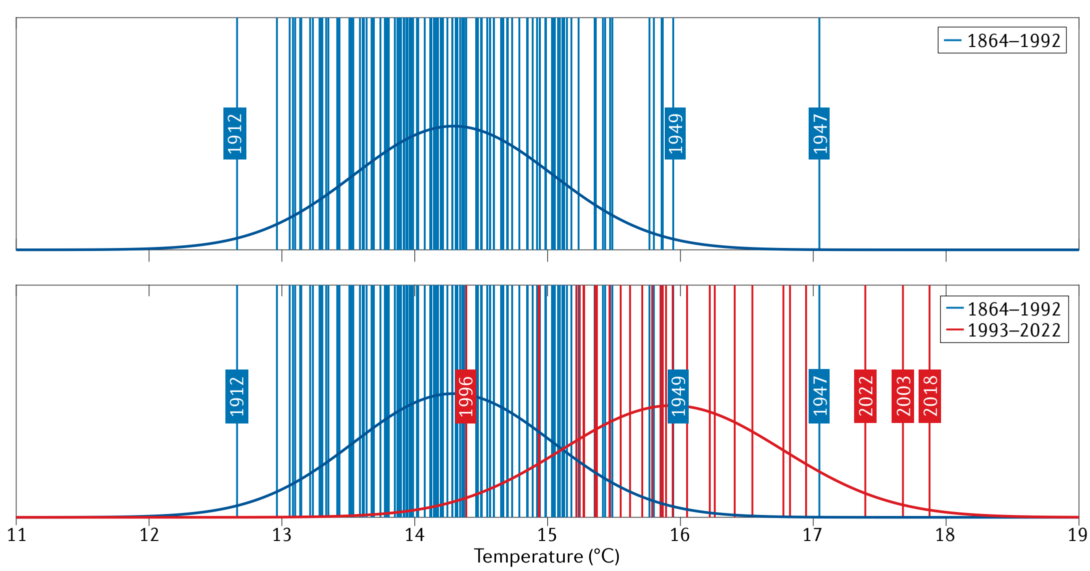


Fig. 1 | Summer temperatures under climate change. Distribution of extended summer temperatures (averaged over April–September) for Switzerland, based on four homogenized temperature records from Basel, Bern, Geneva and Zurich[22]. Blue and red bars denote the periods 1864–1992 and 1993–2022, respectively, with normal distributions fitted to the data. Summer temperature distributions have experienced a strong shift towards warmer temperatures in Switzerland, representative of the global temperature increase.

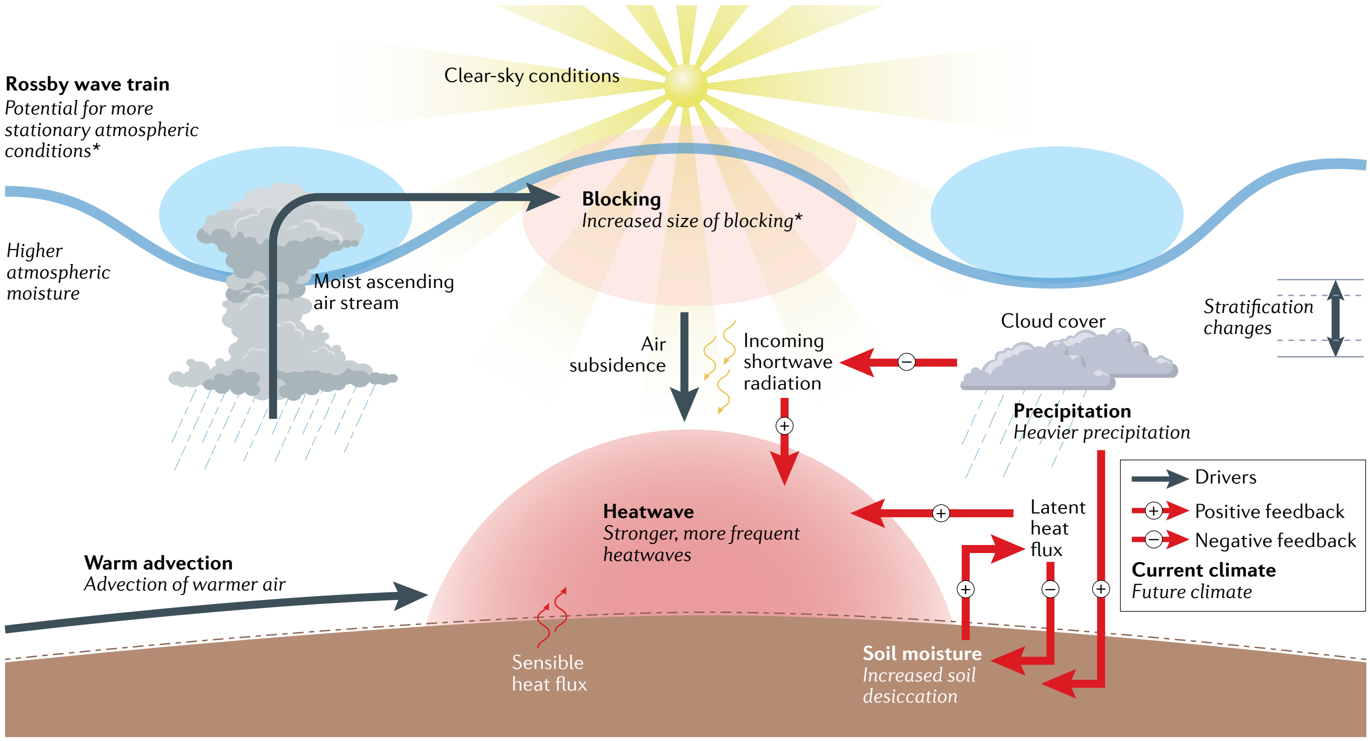


Fig. 2 | Schematic representation of processes contributing to mid-latitude summer heatwaves. Black arrows represent driving mechanisms and red arrows feedbacks, wherein + indicates a positive feedback and − a negative feedback. Boldface text indicates processes in current climate and italic text projected changes under anthropogenic warming. Asterisks indicate projected changes with high uncertainty. Not all of the depicted processes have to be present for a heatwave to occur. Many of the depicted processes will change under climate change, leading to an amplification of heatwaves, although the dynamical atmospheric processes have the least certainty.

week before the onset of the event[23]. This overarching predictable lead time of several weeks has been documented across a range of regions, including Northern Africa[135], North America[134] and Europe[145], but successful prediction of heatwave amplitude is often only possible on lead times of up to one week both in the extratropics[146,270] and tropics[136]. On longer timescales of up to two months, initialization using soil moisture anomalies can markedly increase the skill of air temperature forecasts, as in North America[147]. The correction of SST biases can further enhance prediction skill at these subseasonal timescales[148].

Beyond timescales of a few weeks, heatwave prediction remains challenging. These challenges arise from the generally poor forecast skill of persistent circulation anomalies in the warm season[133,149], the poorly understood role of remote ocean[150,151] and upper-atmosphere drivers[152], and the complexity of the coupling between the land surface and the atmosphere[13,86,153,154]. However, despite these challenges, there is predictive skill for warmer-than-average summer temperatures in seasonal forecasting systems[155–158]. For example, ECMWF's seasonal prediction system successfully represented the upper temperature distribution tail in summer for southern Europe, as well as the probabilistic hit rate versus false alarm rate for upper-tercile warm events[155]. These relatively high levels of predictability can, in part, be attributed to the positive linear temperature trend from the late 1970s onward; long-term trends and variability can positively impact the prediction and predictability of heatwaves on seasonal and longer timescales[159].

Yet, beyond these climate change trends, seasonal forecast models can provide potentially useful information on the tendency of a season to be predisposed to the occurrence of heatwaves. In particular, eastern Europe and the Mediterranean have been identified as regions where skilful forecasts of strong heatwaves can be provided up to three months in advance[158], owing to strong land–atmosphere coupling[87] and surface preconditioning[86,160]. Land–atmosphere coupling is also important elsewhere. Across Europe, heatwave predictability is influenced by rainfall in the preceding season[85,86,89]; in southern Europe, positive precipitation anomalies in January to May are linked to a reduced frequency of hot days in June to August, whereas this relationship is weaker in northern Europe[86]. Similarly, over many global land areas, there is higher probability of hot-day occurrence following negative precipitation anomalies for a season or longer[89]. Initial soil moisture conditions and their evolution are therefore critical factors influencing heatwave prediction[88,161]. Indeed, ECMWF's simulations of the European heatwave in 2003 initialized at the beginning of May 2003 showed no indication of an extremely hot summer season, even when using prescribed observed SSTs[155]. But subsequent model improvements in the representation of the land-surface component, radiation transfer and deep convection led to a distinct heat signal over central Europe, accompanied by negative precipitation anomalies and realistic mid-tropospheric circulation anomalies. However, re-forecasts using the latest ECMWF operational seasonal forecasting system[158] can no longer reproduce the heatwave signal.

Heatwave predictions are also performed on decadal timescales. For example, the UK Met Office's Decadal Prediction System exhibits significant and robust skill that exceeds persistence and climatology for many temperature extremes in Europe and the Mediterranean basin[162,163]. As longer averaging periods reduce the impact of unpredictable variations on sub-annual timescales, prediction skill improves for multiyear forecast periods. The skill in the summer temperature extremes largely originates from the realistic response to the external drivers (radiative forcing from atmospheric composition and aerosols) in the model, which recreates the observed trend in seasonal averages. Initializing decadal predictions resulted in little impact beyond the first year, suggesting that skill arises largely from external forcings.

Heatwave projections

In addition to heatwave predictions at daily to decadal timescales, there is also societal demand for projections of heatwave strength and frequency on decadal to centennial timescales, necessitating consideration of external factors such as greenhouse gas and aerosol emissions. Through knowledge of such factors, adaptation and mitigation strategies can be planned so as to minimize adverse impacts. Heatwave projections are now discussed, including their general characteristics and corresponding drivers.

Projected heatwave characteristics

With high certainty, observed trends across multiple heatwave metrics – the number of hot days and hot nights, as well as heatwave duration, frequency, area and intensity – are projected to continue and accelerate in nearly all inhabited regions as anthropogenic climate change intensifies[19,164]. Accelerated trends are tightly coupled to future emission scenarios, and thereby levels of anthropogenic warming; the higher the emission scenario, the faster warmer temperatures are reached, and so the larger the changes in heatwave metrics[165–167]. Indeed, even at 1.5 °C and 2 °C warming, heatwave characteristics increase substantially[7,168]. These changes in seasonal mean warming and extreme temperatures[169,170] arise from thermodynamical changes (such as changes in temperature, soil moisture and associated land–atmosphere interactions) and changes in atmospheric dynamics, and their interactions[171,172]. Enhanced temperature variability is also important for certain land regions in the mid-latitudes[22,173–175].

For example, the number of very hot days over global land nearly doubles from 1.5 °C to 2 °C warming[176]. Days with maximum temperatures above 35 °C increase across the tropics, subtropics and large parts of mid-latitudes; larger changes occur for higher levels of warming (Fig. 5). As such, extreme temperatures that were 1-in-10-year events during 1850–1900 occur 2.8 (1.8–3.2), 4.1 (2.8–4.7), 5.6 (3.8–6.0) and 9.4 (8.3–9.6) times per 10 years in the present climate and for 1.5 °C, 2 °C and 4 °C warming, respectively[19,164,177]. The relative increase in the number of heat extremes is even more pronounced for rare events[176,178]; 1-in-50-year extremes from 1850–1900 are projected to occur 4.8 times (2.3–6.4) more often at 1.5 °C global warming, increasing to 13.9 times (6.9–16.6) for 2 °C warming levels[164,177].

Accordingly, the frequency of heatwave days – the number of days per year when daily maximum temperatures exceed the 90th percentile of the historical period – is also anticipated to increase[179]. The largest regional changes are evident over global tropical regions, with relatively small changes projected for mid- and high latitudes[166]. Particularly strong increases are expected in densely populated regions of Southeast Asia, where changes in annual heatwave days could reach 300 by end of century under a high emissions scenario[179]; in this case, most of the year would reach temperatures that would be considered as heatwave days in today's climate. As the majority of CMIP5 and CMIP6 models tend to underestimate heatwave-day frequency changes over tropical land regions[180], future climates might be even more severe than this projection.

Along with the changes in heatwave-day frequency are increases in the number of heatwave events. Per degree Celsius of warming, events typically increased by 1.5–2 per year across most regions, based on CMIP5 analyses[166]. Tropical locations display a peak and decline in the number of individual events at 2–3 °C global warming[166], whereby long periods start to be classified as single heatwave events. Consequently, fewer but very persistent heatwaves are projected at low latitudes at large degrees of warming. Changes in local mean temperatures account for most of the changes in the number and duration of heatwaves, which implies that future heatwave characteristics have a similar relationship

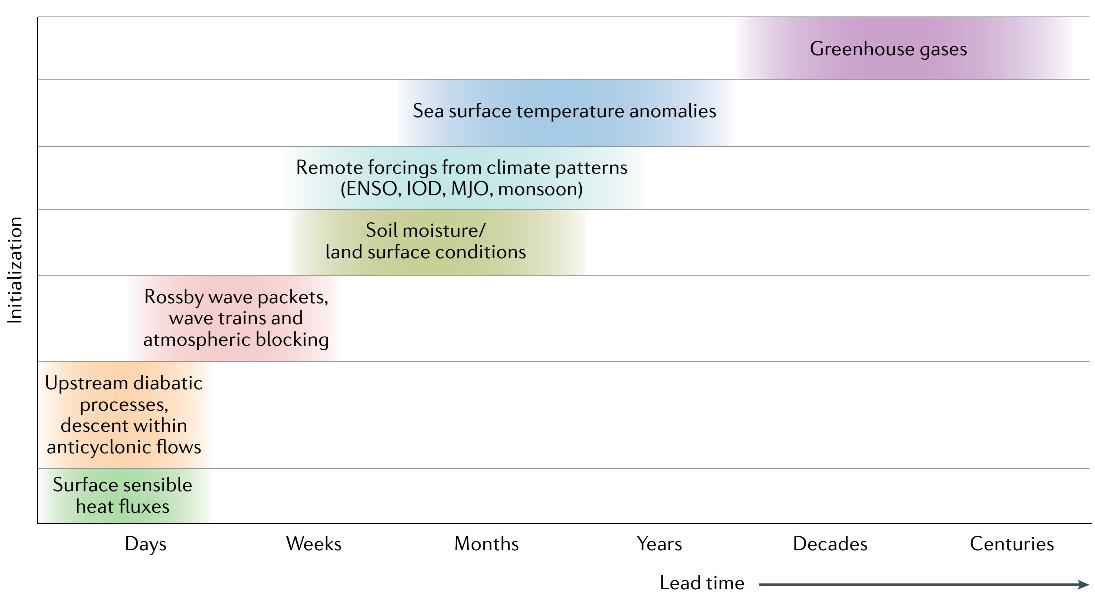


Fig. 3 | Predictors for heatwaves over timescales from days to centuries. The shaded horizontal range of each predictor gives an indication of the lead times for which its influence on predictability is dominant. Each timescale is associated with one or several dominant processes that allow for the prediction and projection of heatwaves. ENSO, El Nino–Southern Oscillation; IOD, Indian Ocean Dipole; MJO, Madden–Julian Oscillation.

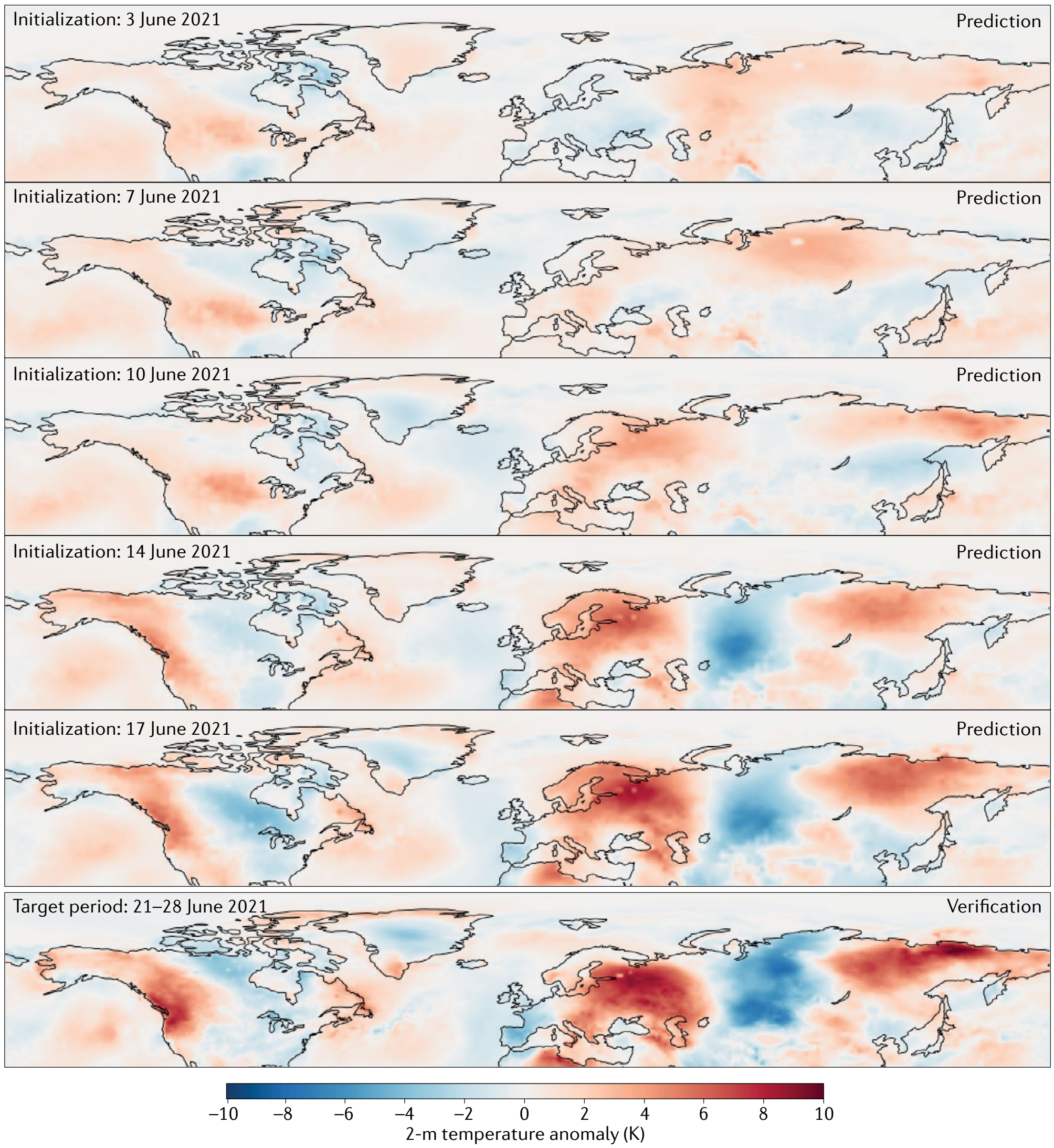


Fig. 4 | Subseasonal predictability of concurrent heatwaves in June 2021. European Centre for Medium-Range Weather Forecasts (ECMWF) extended-range forecasts[237] of weekly mean 2-m temperature anomalies for the target period of 21 June 2021, 00 Universal Time (UTC), to 28 June 2021, 00 UTC, initialized on 3, 7, 10, 14 and 17 June 2021. The bottom panel depicts the validation for the same target period from ERA5 reanalysis[238]. As in this typical evolution of heatwave prediction on subseasonal timescales, there are early indications of warm anomalies several weeks ahead, and an improved prediction of the amplitude and location of the heatwaves at one to two weeks' lead time.

to the corresponding future climatology as today's characteristics do to today's climatology[181,182].

The probability of record-breaking and record-shattering heatwaves is also rapidly increasing[183]. Such events include, for instance, the 2021 Pacific Northwest heatwave in North America[184] and the 2022 heatwave in the United Kingdom[185]. In contrast to heatwaves defined as anomalies relative to a baseline period, the probability of record-breaking and record-shattering heatwaves depends on warming rate, rather than global warming level, and is thus emission-pathway dependent[183]. In high-emission scenarios, week-long heat extremes that break records by 3 or more standard deviations are 2–7 times more probable in 2021–2050 and 3–21 times more probable in 2051–2080, compared with the three decades 1991–2020[183].

Changes in heatwave drivers and feedbacks in a future climate

Because climate change affects both the thermodynamic and dynamical drivers of heatwaves, it can be expected that the prediction of heatwaves will also be affected by climate change (Fig. 2). An important thermodynamic driver of the higher frequency and intensity of heatwaves is the increasing occurrence of soil moisture limitation and droughts in some regions. Soil moisture conditions in spring are projected to become a more prevalent factor preconditioning the occurrence of heatwaves in mid-latitude summer[19,104,167]. Indeed, soil moisture–temperature feedbacks are found to be the main factor driving projected increases in hot extremes in mid-latitudes, warming hot extremes more substantially than global mean temperature[104,167]. In a warmer climate, the atmosphere can also hold more moisture (as dictated by the Clausius–Clapeyron relation), which is of key importance for humid heatwaves (Box 2).

Anthropogenic warming will also alter both the thermodynamics in terms of the atmospheric stratification[186–188] and atmospheric dynamics in the form of the atmospheric circulation, including the

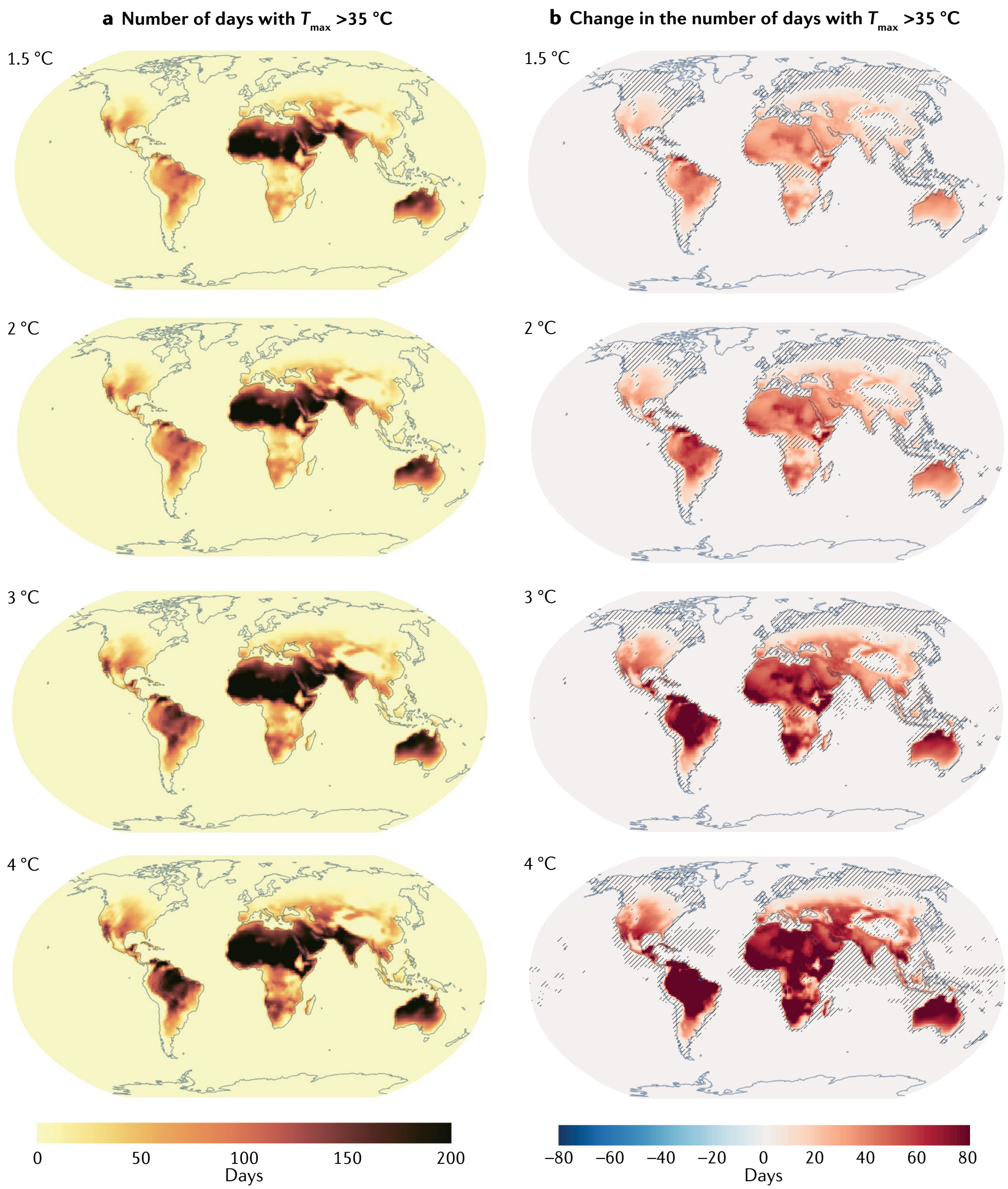


Fig. 5 | Occurrence of very hot days under different warming levels. a, The projected number of days per year with maximum temperatures above 35 °C over land for (from top to bottom) warming levels of 1.5 °C, 2 °C, 3 °C and 4 °C. Warming levels represent average global temperatures relative to 1850–1900 from CMIP6 models from the SSP5-8.5 scenario. T_{max}, daily maximum temperature. **b**, As in **a**, but the change in the number of days per year with maximum temperatures above 35 °C over land with respect to the reference period 1850–1900. Hatching represents regions with low model agreement. An increasing area of the globe will experience increasingly hotter temperatures, which become more extreme under more extreme global warming scenarios. Adapted with permission from ref.[239], IPCC.

strength of the North Atlantic circulation[189]. The dynamical changes are more uncertain than their thermodynamic counterparts[19,190,191], although some can be considered robust, as with shifts in the extratropical storm tracks[192]. For instance, while changes in atmospheric blocking are expected, confidence in these projections is low[193]: increases in blocking size are anticipated with some certainty, especially in summer[194], but there is no detectable change in blocking duration[195]. Northern Hemisphere blocking frequency is expected to decrease by 1.5% per 100 years in winter and by close to 1% per 100 years in summer[196]. Moreover, future trends in Greenland blocking – important for melt events – are inconclusive, with projections covering the entire space between a decrease and an increase[196–199]. This uncertainty can be linked to blocking frequency biases in climate models[200] (although some improvements in these model biases are apparent[196]), sensitivity to the definition of blocking[193,196,201], and an incomplete physical understanding of the processes contributing to blocking[193]. This uncertainty can have consequences for the projection of heatwaves, particularly for regions where heatwave changes are dynamically driven.

Summary and discussion

Heatwaves are driven by a combination of atmospheric processes alongside surface forcings and feedbacks, each operating over various timescales. Knowledge of these processes allows for heatwave prediction, which is vital given the severe socioeconomic impacts of heatwaves, including loss of life. Temperature extremes are generally well predicted on timescales of several days to a couple of weeks. Beyond subseasonal timescales, prediction is more challenging, but is still able to reveal tendencies for above-average temperatures based on persistent boundary conditions. Heatwaves have already become more prevalent in past observations, and their frequency and intensity are projected to increase further with anthropogenic warming. Given the acceleration in the occurrence of heatwaves, it can be anticipated that preparedness and emergency measures currently in place will not be sufficient for unprecedented changes in heatwave frequency, intensity and duration. As such, it is vital to further understand, predict and project heatwaves, requiring that remaining challenges and knowledge gaps be addressed.

One crucial component needed for improved heatwave prediction is a better representation of large-scale stationary atmospheric waves in weather and climate models[130,202]. These waves determine the location of storm tracks, as well as the moisture and temperature distribution in the extratropics[203]. Even small biases in the large-scale circulation can thus lead to large errors in the distribution of precipitation and its changes, influencing drought evolution[204]. Improved representation of the large-scale circulation also benefits the simulation of atmospheric blocking events, whose projections are highly uncertain. These developments can be achieved, in part, by higher model resolution, but summertime improvements, key for heatwaves, are small in most models[205]. Progress in the representation of blocking has been achieved from CMIP5 to CMIP6, but the simulation of blocking persistence remains challenging[206]. Nevertheless, model improvements and updates do not always lead to increased representation of the relevant processes, and hence their predictability.

Although model resolution might have limited benefit in simulating blocking, it does still offer benefit. In the tropics, for instance, improved model resolution is expected to improve heatwave prediction on timescales of days to weeks, given that many tropical islands are not yet sufficiently resolved[136]. Moreover, humid heatwaves, which predominantly threaten tropical regions, would benefit from model simulations that resolve convective scales[207]. Enhanced resolution would therefore allow better analysis and prediction of these understudied tropical regions, providing advance warnings to protect vulnerable populations[208].

Alternative approaches to heatwave projection, such as tales of future weather[209] or physical climate storylines[210], have been introduced as ways to quantify and illustrate future changes in extreme events[211–213]. These storylines allow for future projections conditional on uncertain changes in the dynamical drivers. Although such approaches cannot be interpreted in a probabilistic way, they can characterize potential worst-case events to stress-test a system[212,214] and communicate heatwave evolution. As an example, based on climate model experiments that nudge the observed tropospheric wind fields, it has been demonstrated that the setup for an event like the 2018 Northern Hemisphere heatwave would cause much more widespread exceedance of a 40 °C threshold in a 2 °C or 4 °C warmer world than under present-day conditions[210]. Furthermore, iterative reinitialization of large fully coupled climate model ensembles, an approach referred to as ensemble boosting, suggests that heatwaves substantially more intense than the ones observed are possible without further warming[215], which is consistent with statistical approaches generating very rare heatwaves by importance sampling[216]. Computational methods such as rare event algorithms allow for focusing only on those trajectories that lead to extreme heatwaves, hence optimizing computational resources[217]. Furthermore, data science methods such as causal methods[112,218,219] are increasingly used for identifying drivers of extreme events on a range of timescales[220–222], which can lead to improved predictions[223]. Deep learning methods based on analogue forecasting are further used for forecasting of heat extremes[224].

Given that every time period tends to be associated with several drivers that, in turn, cover a range of different timescales, there is also a need for 'seamless prediction' across multiple timescales[225–227]. The potential of seamless prediction has so far been evaluated across daily to weekly timescales[228], but there remains substantial potential across other timescales. Hence, connections and collaborations across prediction timescales will have to be enhanced further[229]. A promising example of how more seamless approaches for understanding, modelling and attributing heatwaves under climate change can be achieved has been demonstrated with a reliable, high-resolution state-of-the-art operational weather prediction model[230]. To advance knowledge further, innovative ideas will need to be expanded to cover a wider range of meteorological extremes.

Finally, the wide range of heatwave definitions complicates the simultaneous characterization of predictability, impacts and adaptation measures. However, they allow for targeting specific applications and impacts. Furthermore, heatwave definitions under climate change can be adapted to a moving base period due to the climate change trend, depending on the application. The moving base period can also have a detectable influence on the predictability of temperatures, in particular for timescales longer than a few weeks[231].

Although moving base periods are now often used for characterizing heatwaves under climate change, it is unknown to what extent different parts of the climate system, in particular ecosystems, are able to adapt to increases in extreme temperatures, and over which timescales this afdaptation might occur. Many systems are inherently unable to adapt, or not able to adapt fast enough to keep pace with the current level of change. Since heatwaves constitute threshold events, adapting to an increasing mean level of warming is not sufficient, but being able to survive persistent periods of markedly increased temperatures during longer, more widespread, and more intense heatwaves becomes crucial in a warming climate.

In particular, human health is one area where adaptation is not possible for human physiological parameters, and hence where further excess mortality is expected with future warming, especially in the tropics and subtropics[232]. Technology such as air conditioning will therefore need increased and widespread use to allow human survival in an increasing number of regions, in turn contributing to climate change. Surges in electricity use during heatwaves from increased air conditioning puts pressure on electric grids[233], which, in the case of outages, can lead to deadly traps. Other short-term adaptation measures to reduce human health impacts include reduced irrigation to lower the atmospheric humidity[234], albeit with potential risks for agricultural yield. Agricultural adaptation measures, in turn, occur on seasonal to annual timescales and include planting of crops with a higher tolerance for heat and drought[235]. Likewise, ecosystem health across the globe is severely threatened by heatwaves. This sensitivity will worsen in the future owing to limited or slow adaptation of ecosystems to increasing levels of warming and associated heat extremes. Hence, although there are regions and sectors where adaptation to and preparation for projected changes in heatwaves as well as progress towards increased predictability is beneficial to a certain extent, an overall reduction of atmospheric greenhouse gases remains the only possible solution to avoid – or at least alleviate – the increasing mortality[236] and the damage induced by heat extremes in a changing climate.

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