# Prediction and projection of heatwaves

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**Abstract**

Heatwaves constitute a major threat to human health and ecosystems. Their severity and frequency have increased in most regions of the world as a result of human-induced global warming, and are projected to increase further as greenhouse gas concentrations rise. It is therefore crucial to predict the occurrence and characteristics of heatwaves on a range of timescales, both in current and future climates, to improve preparedness and reduce impacts. In this Review, we investigate the factors responsible for the prediction of heatwaves on timescales of weeks to decades, and the projection of these extremes for future climates. Factors that allow for an improved prediction of heatwaves are atmospheric blocking and land-atmosphere coupling at daily timescales, and soil moisture and ocean surface anomalies on sub-seasonal to seasonal timescales. On timescales of seasons to decades, the climate change trend contributes strongly to predictability. On timescales of decades to centuries, emission scenarios provide good estimates of heatwave changes. The main limitations in the prediction and projection of heatwaves lie in the representation of the atmospheric circulation and land surface processes. A better understanding of the dynamical changes in the atmosphere and their coupling with the surface under global warming therefore has the potential to strongly improve long-term outlooks on timescales of weeks to decades. Despite these limitations it is clear that improved long-range prediction of heat extremes can save lives, while a reduction of atmospheric greenhouse gases will benefit the long-term consequences of heatwaves on humans, infrastructure, and ecosystems.

**Key points:**

1. Heatwaves become more frequent, persistent, and extreme with increasing global warming.

2. A wide range of predictors exist on timescales from days to centuries that allow for the prediction and projection of heatwaves, but many of these are not yet sufficiently well represented in model systems.

3. A better understanding of the relevant drivers and their representation in models, including soil moisture, surface cover, and atmospheric dynamics, should be prioritized to improve heatwave prediction and projection.

4. Changes in atmospheric dynamics with climate change are highly uncertain and their contribution to future heatwaves is therefore difficult to predict.
5. Robust changes in climate projections include an increase in humid heatwaves in southern Asia, threatening human health, and a drying of soils in the Mediterranean, making heatwaves more intense.
6. Methods such as storylines and machine learning methods can support the prediction and projection of future heatwaves.

## 1 Introduction

Heatwaves are characterized as persistent temperature extremes whose frequency and intensity is strongly increasing with rising global temperature[1–3]. Heatwaves over land impact a wide range of sectors including forest and agriculture[4–6], permafrost melting[7], infrastructure[8], energy demand[9,10], and human and ecosystem health[11–16]. An overview of marine heatwaves and their impacts is also available in the literature[17–20]. Apart from their direct impacts, land heatwaves can lead to compounding extreme events[21], such as compound hot and dry events[22–24], where feedbacks between droughts and heatwaves tend to amplify these events[22], which can lead to enhanced fire risk, plant mortality, and crop failure[2,23–26]. Further compounding factors are pollution events[27] and increased humidity[12,28,29]. Humid heatwaves, extreme combinations of temperature and specific humidity, present a serious hazard to human health[12,28,29] (Figure 1 and textbox *Humid heatwaves and human health in a future climate*).

**Heatwave definitions:**

A heatwave occurs when numerous 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[30–32]. The exact heatwave definition depends on the application, but is generally based on different measures of temperature, such as maximum, minimum, or average temperature[30,33–40].

Heatwave characteristics, including frequency, intensity, timing, duration, and spatial extent are used for different applications, as detailed here:

*Frequency:* Over a season, measuring the total number of discrete heatwave events is a common way to assess heatwave frequency[30,35,37,40]. Investigating the number of individual heatwave days (where each day must fit the underlying criteria of prolonged and excessive) also provides information on how heatwave frequency may be changing, but for a finer temporal resolution[30,35,40–42].

*Intensity:* Heatwave intensity can be defined by focusing on individual events (for example, the hottest day of a heatwave[41] or an average heatwave intensity), or across a season (average intensity across all heatwaves, total heatwave magnitude, or the cumulative exceedance of the extreme temperature threshold across all events)[35,41–43]. In addition there are metrics that measure the overall heatwave magnitude as standardized combinations of frequency and intensity[36,44].

*Timing:* The start of a heatwave season is determined by the first day of the first recorded event, while the end of the season can be given by the last day of the last recorded event[45], yielding the length of a heatwave season. The timing of heatwave occurrence is important for ecosystem impacts[46].

*Duration:* Heatwave length is measured in days for individual events and also for statistics of heatwaves across all events in a season (for example, median or maximum length). Heatwave length is useful in understanding heatwave interactions with wildfire fuel[40].

*Spatial extent:* Emerging metrics measure the spatial extent of heatwaves[47–49], as well as their movement in space and time[39,43,50,51], which is useful for characterizing compound events.

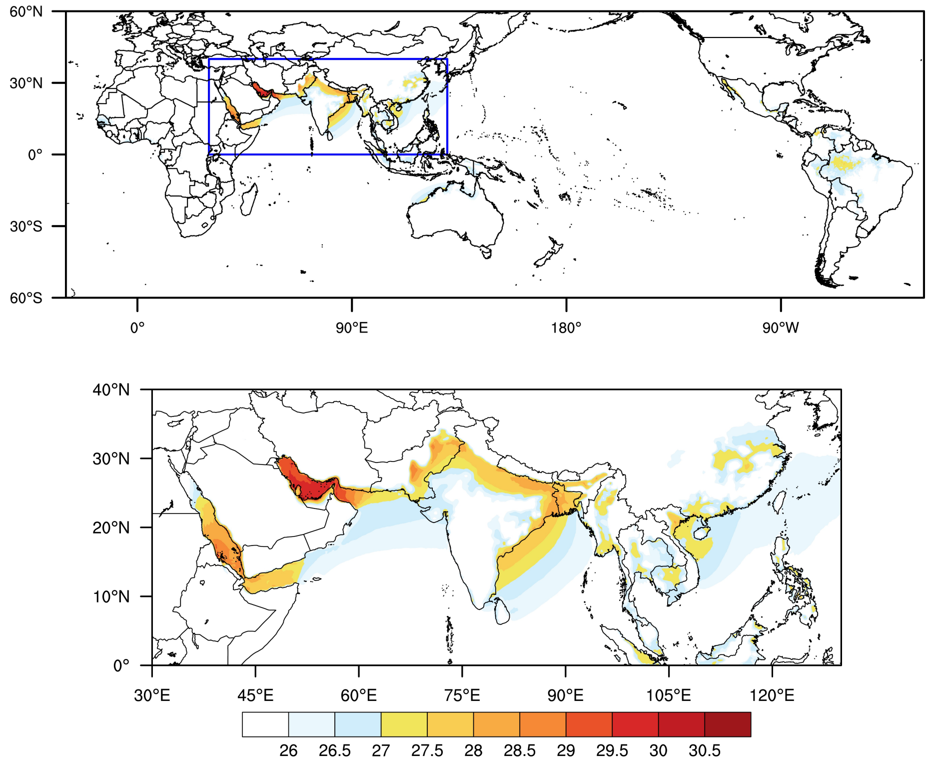


**Figure 1.** Spatial distribution of the 95th percentile of daily maximum wet-bulb temperature, TWmax (°C), for 1979 - 2019. The global distribution of TWmax is computed using ERA5 3-hourly data at 0.25° × 0.25° horizontal resolution. The enlarged domain highlights three distinguishable regions with higher TWmax: southwest Asia around the Persian/Arabian Gulf and the Red Sea, South Asia in the Indus and Ganges river valleys, and eastern China. Maximum values of the wet bulb temperature up to 32 ° C are found, corresponding to a dangerous level for human heat stress.

Heatwave frequency and duration have been increasing almost everywhere globally since at least the 1950s[2,38,40,41,52,53]. While observed trends in the average and peak heatwave intensity are small[41,54], the cumulative intensity of heatwaves (see textbox *Heatwave definitions*), which is mainly driven by rises in heatwave frequency, is increasing almost everywhere[40,41]. Extremely hot seasons and high-impact heatwaves are increasingly attributed to human influence on the global climate[55–60]. Moreover, the anthropogenic influence on heatwaves increases as climate change intensifies[61], with extreme heatwaves becoming extremely unlikely without human-induced climate change[1,2] As an illustration, the coldest summers for the modern period in Europe (with greater levels of human-induced global warming) are already warmer than average summer temperatures of earlier periods (Fig. 2). The extreme European heatwaves of 2003 and 2018 dramatically surpass the previous record summer of 1947[62]. Even summer 2021, which has commonly been perceived as cold in northern continental Europe, was 1.7°C warmer than the average of the earlier period (1864-1991). A further important feature is the skewness of the distributions towards warmer temperatures, even when removing the warmest year (which could be an outlier). This implies a *fat tail* on the warm

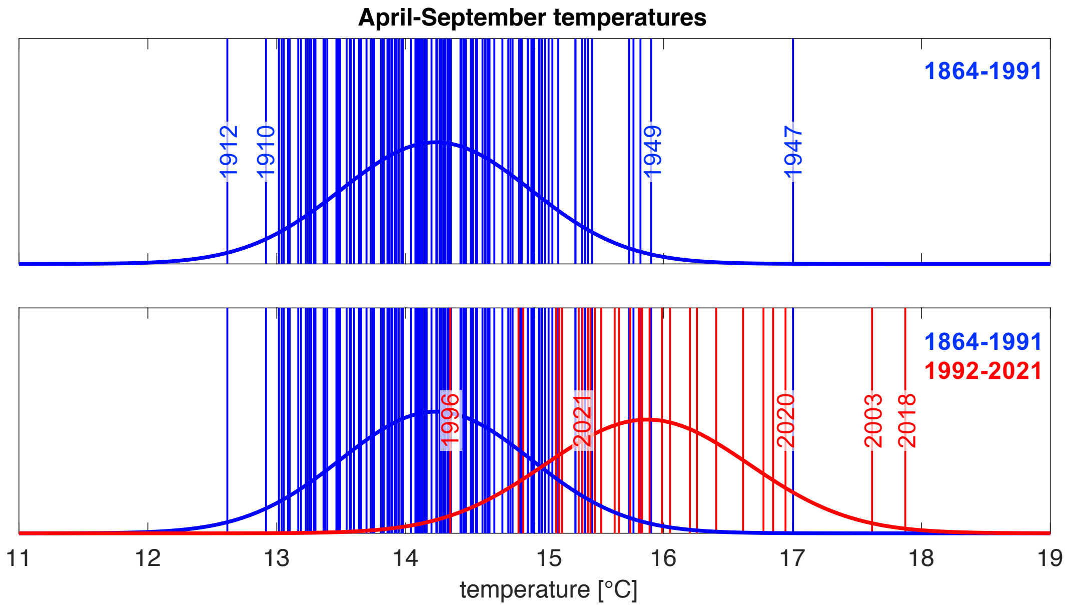


**Figure 2.** Distribution of average summer temperatures in Switzerland, based on the four homogenized temperature records of Basel, Bern, Geneva and Zurich for the extended summer period (April-September). Blue and red bars denote the 1864-1991 and 1992-2021 periods, respectively, and the normal distributions fitted to the data are indicated by the corresponding lines. Updated from Schär et al. (2004)[62].

side, that is, hot extremes occur more frequently than for a normal distribution. A fat tail is consistent with an amplification of warm summers and an accelerated rate of warming, for instance due to land-surface atmosphere feedbacks. In addition, there is a slight increase in variance (corresponding to the width of the distribution) in the modern period. Such a change has been suggested as an important element of climate change[62].

Given the increasing frequency and the devastating impacts of heatwaves it is important to anticipate the timing of occurrence and severity for heatwaves on timescales of weeks to seasons, as well as their frequency and intensity beyond yearly timescales. The time needed to prepare for an anticipated extreme event is generally on the order of several weeks to months[63]. Given the devastating impacts of heatwaves, improved prediction and preparedness can be expected to alleviate the impacts that are expected to worsen with the changing climate. In particular, regions that have experienced heatwaves in the past have often implemented emergency measures and are hence better prepared for future heatwaves[64]. An example is the 2018 European heatwave, which led to excess mortality on the order of several hundred[65] as compared to several tens of thousand during the 2003 heatwave[66] in the respective most heavily affected countries. Nevertheless, preparing for heatwaves remains a challenge, as these extremes are now occurring at a higher frequency and more often drastically exceed previous records in places where heatwaves have not been a major threat in the past, such as for example the Pacific Northwest heatwave in 2021. The fat tails in the temperature distribution towards extreme positive anomalies, and hence hot summers (Figure 2), suggest that the occurrence of unprecedented heatwaves may be more common in a changing climate. An increased understanding of the drivers and characteristics of heatwaves will therefore help to improve predictability of heatwaves and their impacts in current and future climates.

In this review, we provide an overview over the progress in predicting heatwaves on timescales from weeks to decades, and an outlook on our future ability for heatwave prediction. We begin by outlining the drivers of and feedbacks of heatwaves. We next outline heatwave prediction on timescales of days to decades, followed by projection of heatwaves related to future climates. We end with recommendations for future research.

## 2 Drivers and feedbacks for heatwave prediction

Prediction and projection skill for heatwaves is expected to be improved through a better understanding and simulation of the underlying physical drivers of extreme heat events. In this section we review the major known drivers of heatwaves and how they can be utilized to enhance long-range prediction. While there is existing literature on the driving mechanisms for heatwaves as well as attribution to climate change[67,68], the present study will focus on how the drivers can be used to improve the prediction and projection of heatwaves.

For the prediction of heatwaves, it is useful to distinguish between remote drivers and local feedbacks (Fig. 3). Here, the term *drivers* refer to large-scale processes in the climate system that are communicated to the regional scale as changes in large-scale temperature, humidity and circulation, while *feedbacks* refer to regional-scale processes on a sub-continental scale, as for example land-surface and cloud feedbacks[69]. The following subsections separate the atmospheric drivers from the forcings and feedbacks arising from the land and ocean surface.

### 2.1 Atmospheric drivers

Due to their persistent nature, heatwaves are in most cases associated with anomalously long-lived quasi-stationary flow patterns. Candidates for such persistent flow patterns are high-amplitude upper tropospheric ridges, atmospheric blocks[70–76], and recurrent amplified Rossby wave patterns (Figure 3). The exact driving mechanisms and their relative importance depend strongly on the region where the heatwave occurs. Most heatwaves in the extratropics occur underneath intense upper-level ridges, that is, strong anticyclonic flow anomalies in the upper troposphere[33,77–81]. For high-latitude heatwaves (for example over Scandinavia) these ridges are particularly strong and stationary and can often be identified as atmospheric blocks[82]. Heatwaves at lower mid-latitudes (for example over the Mediterranean) are associated with weaker upper-level ridges that typically do not classify as blocks[82]. Similar connections to upper-level anticyclones are present for heatwaves in North America[80,81], southeast Australia[83], and eastern China[84]. Since blocks are particularly persistent flow anomalies, heatwaves that co-occur with blocks have strongly increased odds to become long-lasting[85]. Recurrent Rossby wave patterns, that is, the repeated amplification of individual troughs and ridges in the same region, have been suggested as an alternative formation pathway of heatwaves[86].

The mechanism for upper level ridges and blocks to cause surface heatwaves is their association with subsiding motion and hence clear-sky conditions and increased incoming solar radiation[87]. The formation and maintenance of these ridges and blocks

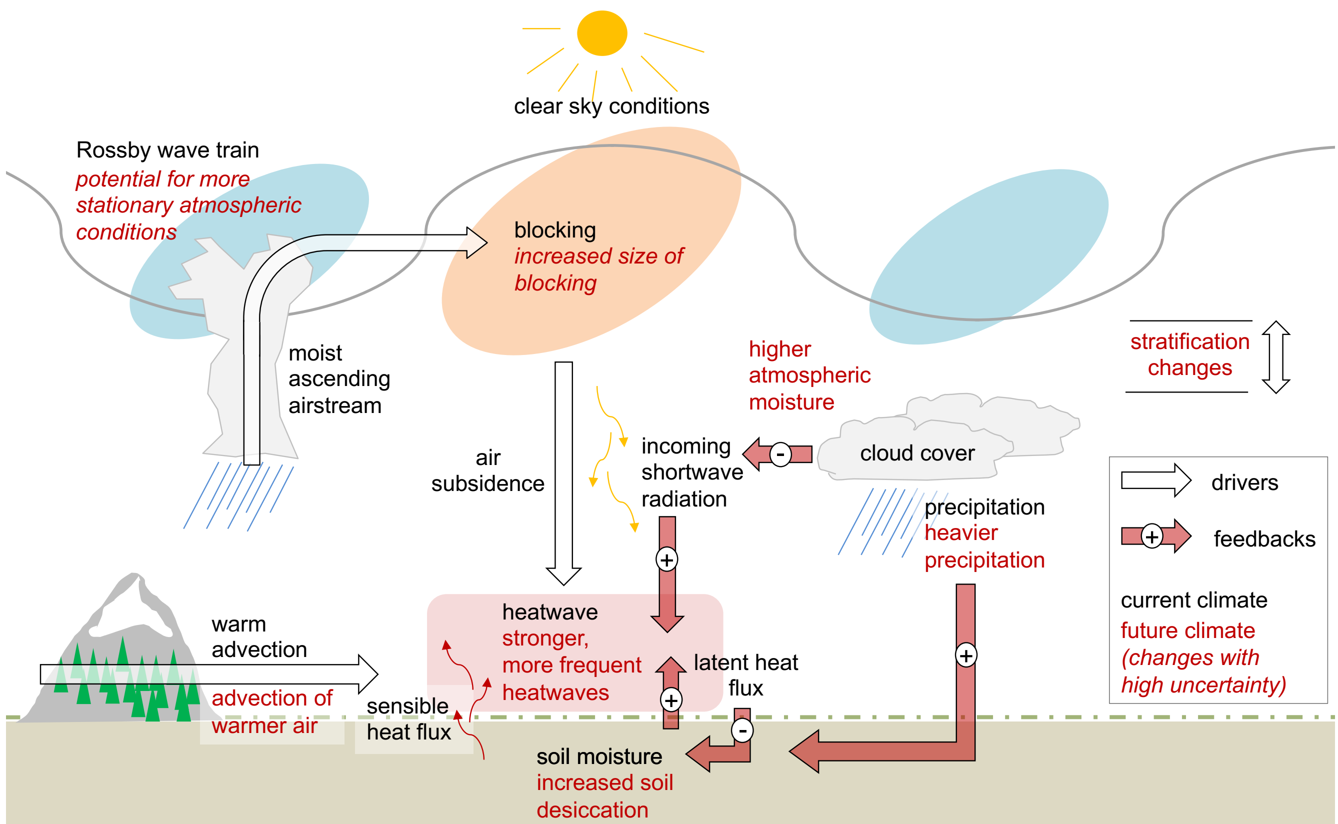


**Figure 3.** Schematic representation of the dominant processes that can contribute to a summer heatwave in mid-latitudes. Note that not all of the depicted processes have to be present for a heatwave to occur. White arrows represent driving mechanisms, red arrows represent feedbacks, with '+' indicating a positive and '-' indicating a negative feedback. Black text indicates processes in current climate, and red text indicates anticipated changes under global warming. Text in *italics* indicates a high uncertainty in the projected changes of the denoted process.

typically go along with upstream latent heating in moist ascending airstreams[88,89], which manifests in strongly ascending motions, cloud formation, and precipitation along the western flank of the ridge or block[90–92]. These moist airstreams transport air with low potential vorticity into the ridge or block and thereby contribute to their formation and maintenance. Over Europe, two such airstreams are typically involved for heatwave-related ridges[92], one occurring close to the heatwave over north-western Africa and Europe, in addition to a remote airstream upstream over the western North Atlantic, which can regenerate for particularly long-lasting heatwaves.

Through Lagrangian analysis, the driving processes of heatwaves on daily timescales can be further separated into horizontal advection of air from climatologically warmer regions, adiabatic warming due to subsidence, and diabatic heating in particular due to surface sensible heat fluxes (Fig. 3). These processes indicate that the persistent nature of heatwaves arises due to constantly renewed air parcels that are heated by subsidence from the free troposphere and surface fluxes in the boundary layer. The relative importance of these processes varies by region. For example, polar heat extremes are dominantly driven by advection from lower latitudes[93,94], while advection is found to be less important in midlatitudes, as for example in Europe[82,95] and southeastern Australia[96]. A major part of the warming in midlatitudes occurs due to subsidence, complemented by diabatic heating within the boundary layer. As an example, for the 2010 Russian summer heatwave, which was characterized as a drought-heat compound event with severe consequences for human health[97,98], contributions from both subsidence[99] and heat import from upwind drought regions[100] have been found.

On the planetary scale, both tropical and extratropical persistent atmospheric patterns can drive remote responses that can lead to heatwaves[101]. Stationary atmospheric ridges in the extratropics can occur when the jet stream becomes organized in a large-scale or circumglobal wave train[102,103] exhibiting stationary behavior and/or phase locking with orographic and thermal forcing.[104–106]. Phase locking has further been suggested to exhibit a potential for resonant wave amplification, which in turn has been suggested as a cause for temperature extremes[107–109]. On daily timescales, these circumglobal patterns are made up of Rossby wave packets[110] that are linked to extreme events, though this link is not yet fully understood[110–112]. Continental summer heat extremes are also suggested to be connected with low upstream storm track activity[113], and with increased upper-level jet waviness[114]. However, this linkage between jet waviness and heat extremes varies between regions[114], and should be further investigated with respect to the resonant wave concept.

### 2.2 Surface forcings and feedbacks

The land and ocean surface can further influence the prediction of heatwaves in terms of both local and remote forcings and feedbacks with the atmosphere. A key local and regional forcing for heatwaves arises from soil moisture deficits that reduce evaporative cooling through latent heat flux at the land surface, leading to extreme local heat[22,115–121]. These effects have been shown to substantially contribute to the occurrence of hot days on all continents, in particular in mid-latitude regions[22,119,122]. In particular, surface effects on the magnitude of heatwaves in midlatitudes can be of similar magnitude as those from circulation anomalies[119]. In addition, soil moisture forcing can itself feed back onto the large-scale atmospheric circulation[123,124] and further exacerbate a heatwave.

Another contribution of the land surface to heatwaves is the role of land cover properties[2,125]. Forest cover can amplify heatwave conditions in the short term but dampen them in the longer term compared to grassland or agricultural land[126,127]. Forest type is also relevant, with broadleaf trees leading to more widespread cooler temperatures during heatwaves than coniferous trees due to their higher albedo and higher stomatal conductance[128]. Agricultural management is also highly relevant, for example, irrigation allows for increased cooling due to increased evapotranspiration on hot days, similarly to intense agriculture, which is associated with more plant activity.[129–132].

Additional feedback mechanisms include interactions of the land surface with cloud cover, which reduces when latent heat flux is limited and in turn increases incoming shortwave radiation. Reduced cloud cover furthermore decreases precipitation, which further decreases soil moisture and thereby amplifies the heatwave (Figure 3). These feedbacks are particularly important in the context of projections for higher levels of global warming, as the coupling strength between the land and the atmosphere in models can influence the regional trend in heatwaves[133]. In addition, non-local feedbacks can play a role, through heat advection from regions affected by soil moisture limitation and associated enhanced sensible heating[100,134,135].

Surface forcing related to anomalous sea surface temperature (SST) patterns can also contribute to heatwaves. In particular, persistent anomalous ocean surface temperature patterns can give rise to persistent anomalous atmospheric wave patterns that can in turn lead to heatwaves over adjacent continents. For example, the *Pacific Extreme Pattern*, an SST pattern in the North Pacific with anomalously warm temperatures in the central North Pacific and cold temperature anomalies along the North American coast has been linked to hot days in the eastern United States[136]. Likewise, the 2003 European heatwave has been linked to anomalously warm SSTs in the Indian Ocean and the Mediterranean[137]. The 2015 European heatwave has been suggested to be driven by anomalously cold SSTs in the North Atlantic, which induced a persistent atmospheric wave pattern and a stationary position of the jet stream that in turn favored the hot temperatures over central Europe[138]. The 2015 heatwave has further been linked to anomalies in the Caribbean region associated with the developing El Niño Southern Oscillation (ENSO)[139]. In fact, ENSO is a dominant driver for heatwaves in a large part of the globe, including China[140], India[141], Europe[142], and Australia, where it often interacts with forcing from the Indian Ocean Dipole (IOD)[143]. Furthermore, tropical forcing from the Madden-Julian Oscillation (MJO) can induce heatwaves, for example, increased convection over the Indian ocean and the eastern Pacific associated with the MJO can lead to heatwaves in the western United States[144], and anomalous convection in the western Pacific associated with the MJO has been linked to heatwaves in northeastern Asia[145].

For most heatwaves, several of the factors mentioned above contribute towards establishing and maintaining a heatwave. The European heatwave of 2003 is a particularly well-studied example, which has been suggested to have been affected by a persistent atmospheric flow pattern, soil moisture deficits, and remote sea surface temperature patterns[146,147], with severe effects on marine ecosystems[148], human health[66,149], and electricity production and use[150]. Since many of these forcings are long-lived, they allow for an improved prediction of heatwaves at long lead times. So far, increased predictability based on such precursors has been successfully shown for case studies, though given the many factors and their interplay, as well as the strong differences in characteristics between individual heatwaves, establishing a general framework for improved heatwave prediction remains challenging.

## 3 Heatwave prediction

A wide range of local and remote physical mechanisms in the form of drivers or feedbacks contributes to the predictability of heatwaves on timescales of days to decades (Fig. 4). Depending on the geographical region, season and lead time, different processes govern the predictability of heatwaves. Hence, the predictability of heatwaves depends on an understanding of how these processes and precursors are linked to heatwaves, including the successful representation of these processes and their connections in models. The prediction of heatwaves spanning the time range from days to decades are now discussed.

Based on a minimum 3-day duration of heatwaves, deterministic heatwave predictions are possible in weather prediction systems 2-3 days ahead. Data-driven methods can successfully predict extreme heatwaves on timescales of up to 5 days[151]. Several processes are essential for an accurate heatwave forecast on deterministic timescales of a few days: First, the processes

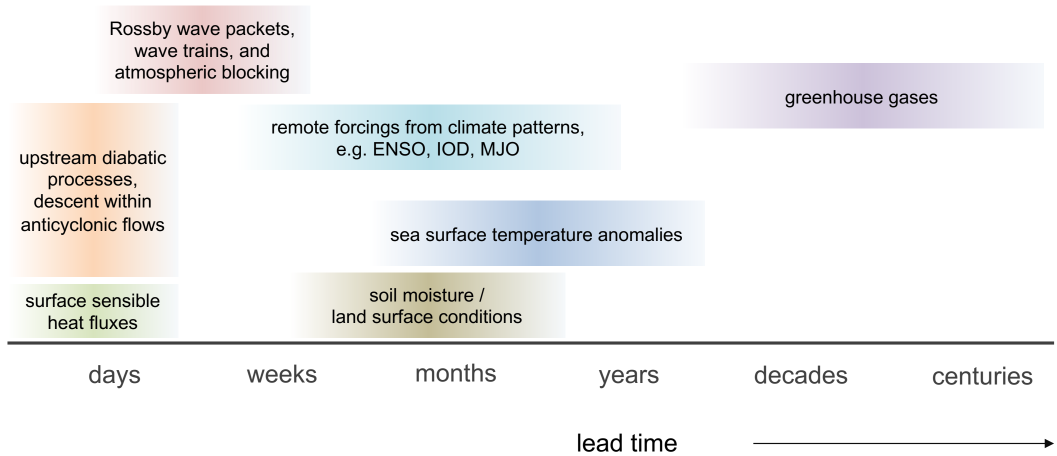


**Figure 4.** Predictors for heatwaves on timescales of days to centuries. The horizontal range of each predictor gives an indication of the lead times where its influence is dominant.

leading to the formation of a quasi-stationary ridge or block[71,72], including upstream diabatic processes in ascending airstreams, secondly, the maintenance of these anticyclonic flow anomalies leading to persistent descent in their core of air parcels from the mid-troposphere close to the surface, and thirdly, the diabatic heating in the boundary layer mainly due to surface sensible heat fluxes. These atmospheric flow patterns are generally not well represented in climate models in terms of their location and strength[152–154], and often several types of atmospheric forcings can determine the evolution of a heatwave[155], affecting its prediction.

On timescales of up to 10 days, heatwave prediction tends to be most skillful in the midlatitudes, including Eastern Europe, the Middle East, Eastern India, most of Russia, the Central US and Canada, while in the tropics, skill on these timescales is generally lower[156]. The presence of long-lived Rossby wave packets in midlatitudes can further improve sub-seasonal predictability[111,157,158].

On subseasonal timescales, heatwaves can often be predicted probabilistically at lead times of 2-3 weeks[159]. In fact, summer heatwaves are among the most predictable meteorological extremes on these timescales, as for example compared to summer cold spells[160] or precipitation extremes[161]. This predictable lead time of several weeks has been documented across a range of regions, including Northern Africa[162], North America[163], and Europe[160]. On longer timescales of up to two months, the initialization of land surface conditions in terms of initial soil moisture anomalies can markedly increase the skill of air temperature forecasts, as has been shown for North America[164].

The exceptional Pacific Northwest heatwave in June 2021, which has been suggested to be about a one in a thousand year event in today's climate, and virtually impossible without human-caused climate change[166], serves as an illustration for a typical evolution of extended predictability on sub-seasonal timescales. For the target period from June 21 - 28 there was an indication of above normal temperatures already in early June (Figure 5), while the model underestimates the amplitude of the anomalies and misplaces the location of the maximum temperatures. In comparison, at the same lead time there is no indication

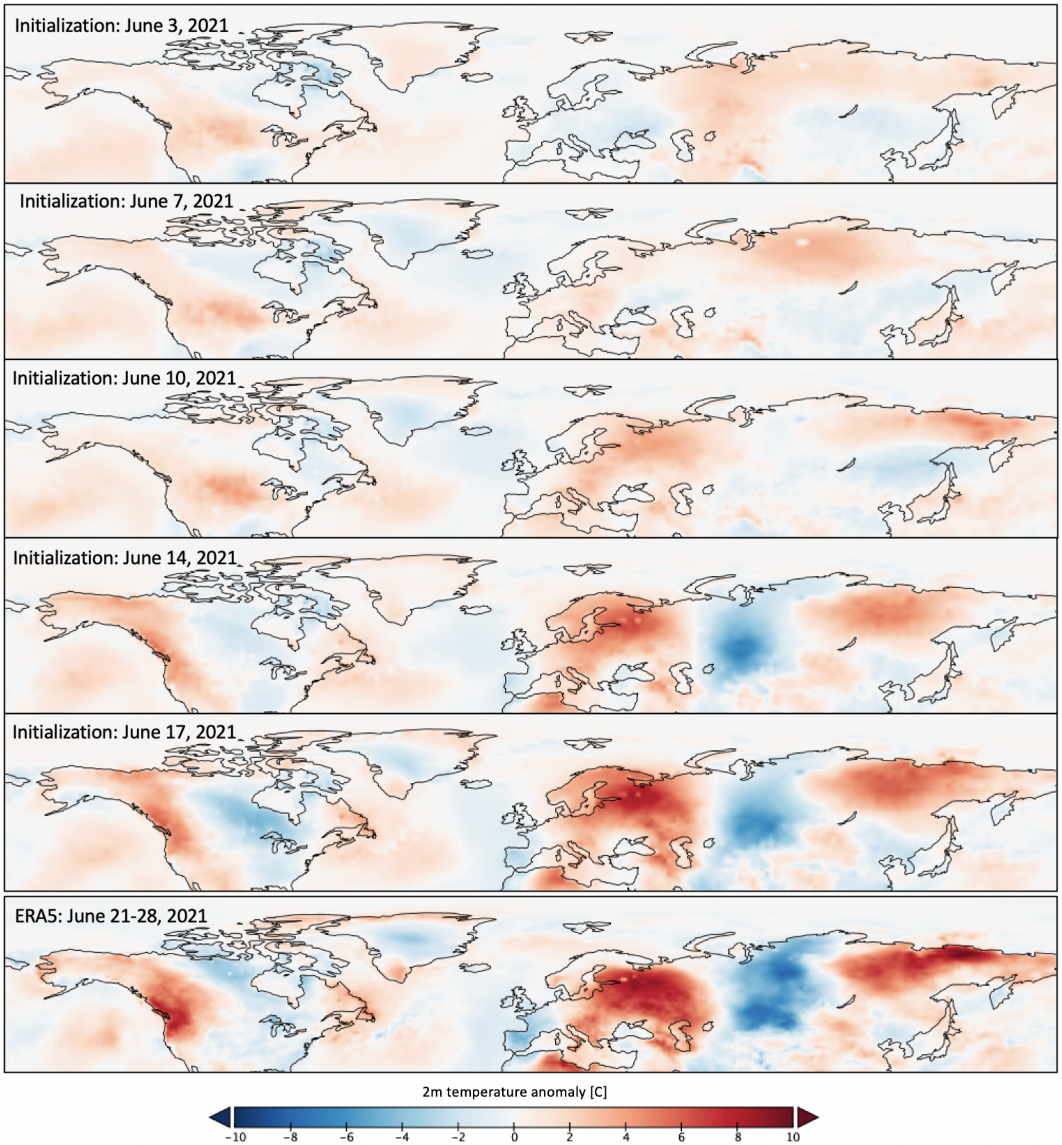


**Figure 5.** Illustration of the extended range predictability of the Pacific Northwest heatwave and the concurrent European and Siberian heatwaves in June 2021 in ECMWF's extended-range forecasts. Weekly mean anomaly of 2m temperature [°C] for June 21, 00UTC - June 28, 00UTC based on forecasts initialized on (from top to bottom) 3, 7, 10, 14, 17 June 2021 and (bottom panel) the validation for the same target period from ERA5[165]. Data source: ECMWF.

of the heat extreme over eastern Europe that was observed at the same time. With decreasing lead times, the model starts to capture the correct location and higher amplitude of both the Pacific Northwest and the European heatwave starting about a week before the onset of the event. This evolution of the predictability is very typical for the prediction of heatwaves, where indications of warm anomalies are present early on, but the amplitude is often severely underestimated at long lead times. A successful prediction of the amplitude is often only possible on deterministic lead times of up to one week[167].

While predicting the amplitude of heatwaves at long lead times is a challenge, less is known about the predictability of the onset and duration of heatwaves several weeks to months ahead, but this predictability is often found to be lower[167]. However, there is strong case-by-case variability; as an example, the onset of the 2010 Russian heatwave was well predicted, but its duration and decay was poorly represented in models[168].

Predicting heatwaves on time scales longer than a few weeks remains a challenge due to the generally poor forecast skill of persistent circulation anomalies in the warm season[158,169], the poorly understood role of remote ocean[78,137,139,170–172] and upper atmosphere forcings[173], and the complexity of the coupling between the land surface and the atmosphere[22,117,122,123,174–176]. Despite these challenges, there is indeed predictive skill for warmer-than-average summer temperatures in seasonal forecasting systems[177–179]. For example, earlier ECMWF seasonal prediction systems successfully represented the upper tail of the temperature distribution for Southern Europe as well as the probabilistic hit rate versus false alarm rate for upper tercile warm events[177]. These relatively high levels of predictability can be attributed in large parts to the positive linear temperature trend from the late 1970s onward, demonstrating that long-term trends and variability can positively impact the prediction and predictability of heatwaves on seasonal and longer time scales[180]. As an illustration, the 2010 Russian heatwave event has been found to likely have arisen through internal atmospheric dynamics as opposed to a climate change trend[181], and might therefore have been less predictable[182].

In addition, evidence for seasonal predictability of heatwaves beyond the warming trends has also been found. Although heatwave predictability varies strongly depending on the considered heatwave definition, regions, seasons and forecast horizons, the latest generation of 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[183]. The heatwave predictability in these regions is consistent with a strong land–atmosphere coupling[118] and the impact of surface pre-conditioning[117,184]. In particular, a profound asymmetry in the predictability of summer heat days depending on whether the preceding season was wet or dry was found in observations across Europe[115,117,122]. Positive precipitation anomalies in the months January to May are linked to a reduced frequency of hot days during the subsequent summer months June to August over Southern Europe such that wet spring conditions are generally followed by a lack of hot extremes. With a five-fold increase in the uncertainty range compared to wet winter and spring seasons, spring drought conditions are, however, not considered a necessary (but sufficient) condition for heat waves to occur in the subsequent summer. For Northern Europe this relationship is generally weaker[117]. Precipitation variability leading to soil moisture anomalies in springtime can also act as a potential predictor for summertime hot day occurrences in dynamical seasonal forecast models[174,183–186]. For instance, there is a higher probability of hot day occurrence in the hottest month in a substantial part of the global land areas following negative precipitation anomalies during a season or longer[122]. The contribution of initial soil moisture conditions and of the evolution of soil moisture during heatwaves have also been shown to be critical factors[116,119].

As an example, the European heatwave of summer 2003 was analyzed extensively to understand the processes that contributed to its formation and predictability across forecast time scales[123,137,170,171,174,187]. Operational seasonal forecasts initialised at the beginning of May 2003 showed no indication of an extremely hot summer season, even when using prescribed observed SSTs[177]. However, sensitivity experiments with major 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, demonstrating that only the combination of improved hydrological and atmospheric processes together enabled the successful retrospective predictions of this record breaking event[177]. However, the interplay between the different physical processes leading to successful heatwave predictions in seasonal forecast models is a fine and delicate balance. Despite the complex further developments of the forecast model since earlier successful predictions, re-forecasts of the summer 2003 in the latest ECMWF operational seasonal forecasting system SEAS5[183,188] do not reproduce the heatwave signal over Europe obtained with the previous prediction system. These findings point to the need to further improve the representation of the relevant processes and their interplay, in particular with respect to model uncertainty in the land surface component[187] and the soil hydrology[185].

On decadal timescales, the UK Met Office's Decadal Prediction System shows significant and robust skill that exceeds persistence and climatology for many temperature extremes in Europe and the Mediterranean basin[189,190]. The skill improved for multi-year forecast periods as longer averaging periods reduce the impact of unpredictable variations on sub-annual time scales. The skill in the summer average temperatures is due to the realistic response to the external forcings (radiative forcings from atmospheric composition and aerosols) in the model, which recreates the observed trend in seasonal averages. Initialising decadal predictions resulted in little impact beyond the first year, suggesting that skill arises largely from external forcings.

## 4 Heatwave projection and characteristics of future heatwaves

While it is possible, albeit challenging, to predict heatwave occurrence on daily to decadal timescales, there is also important societal demand to understand longer-term projections of heatwaves on decadal to centennial timescales. Through such knowledge, adaptation and mitigation strategies can be planned so as to minimise loss of life and other societal impacts. Heatwave projections are now discussed, including their general characteristics and corresponding drivers.

Observed trends in the frequency of heatwaves are projected to continue – and accelerate – as anthropogenic climate change intensifies[1,2]. The IPCC AR6 report assessed that the frequency and intensity of hot extremes will continue to increase at both global and continental scales and in nearly all inhabited regions with increasing global warming levels[1]. The IPCC AR6 further assessed that it is virtually certain that the number of hot days and hot nights and the length, frequency, and/or intensity of warm spells or heatwaves will increase over most land areas. Climate models project strong increases in all heatwave characteristics including intensity, area, duration, and magnitude[33,35,43,62,191–193], with stronger relative increases for more rare events[194,195].

Projected changes in heatwave day frequency in terms of the number and duration of heatwaves can mostly be explained by seasonal mean warming[35,196], However, exact projections of heatwave frequency are difficult, as these changes scale non-linearly with the level of global warming[197,198]. The number of very hot days over global land nearly doubles between a level of global warming from 1.5°C to 2°C[197]. As an illustration, the number of days with maximum temperatures above 35°C increases in all land areas in the tropics, subtropics, and large parts of midlatitudes, with more extreme values for higher levels of warming (Figure 6). Extreme temperatures that in 1850-1900 on average were expected to occur only about once in 10 years, now occur 2.8 times (1.8–3.2) in 10 years, and are projected to occur 4.1 times (2.8–4.7) at 1.5°C, 5.6 times (3.8–6.0) at 2°C, 9.4 times (8.3–9.6) at 4°C global warming[1,195]. The relative increase in the number of heat extremes is even more pronounced for more extreme and rare events[197], with extreme temperatures that in 1850-1900 on average were expected only about once in 50 years, projected to occur 4.8 times (2.3–6.4) more often at 1.5°C global warming[1,195]. Projected changes in the number of yearly heatwave days by 2050 range between an increase by 20-60 days in lower emission scenarios SSP1-2.6 (Shared Socioeconomic Pathways 1) and 30-90 days in high emission scenarios SSP3-7.0 across global land regions[199]. The largest changes in heatwave day frequency in all emission scenarios is projected over low latitudes including densely populated regions like Southeast Asia, where the frequency of heatwave days is projected to increase by up to 300 days in high emission scenarios[199], which implies that the majority of days per year reach temperatures that would be considered as heatwave days in today's climate. Future climates might be even more severe than this projection, as the majority of models in CMIP5 and CMIP6 tend to underestimate the changes in heatwave day frequency in Southeast Asia and the tropical land regions[200].

Along with the changes in heatwave day frequency also the number of heatwave events is projected to increase. The number of heatwaves increases with the level of global warming, with tropical locations displaying a peak and decline in the number of individual events at 2-3°C global warming[201] because periods of several months start to be classified as single heatwave events. Consequently at large degrees of warming fewer but very persistent heatwaves are projected at low latitudes. The above future changes are based on fixed heatwave thresholds. Heatwave metrics that are defined on temporally moving base periods (and thus assuming some adaptation) show less severe changes[43,202].

Projected changes in heatwave intensity go beyond the changes in mean annual temperatures and may be substantially amplified by enhanced temperature variability[62,203–206]. Accelerated trends are tightly coupled to future emission scenarios; the higher the emission scenario, the larger the changes in heatwave metrics[37,42,44,202,207–210]. Similarly, when scaled against global warming thresholds, future projections of heatwaves consistently increase[43,201,211–213], with higher emission scenarios reaching hotter global average temperatures sooner. Even at a warming level of 1.5°C and 2°C, large-scale heatwave characteristics increase substantially[16,214]. Extreme temperatures that in 1850-1900 on average were expected to occur only about once in 50 years are projected to be warmer across global land areas by +2.0°C (median change across global land) at 1.5°C global warming, by +2.7°C at 2°C global warming, and by +5.3°C at 4°C global warming. Changes are most pronounced over mid-latitude land regions, and are found to scale close to linearly with the level of global warming[215,216]. Heatwave intensity over the Mediterranean and Northern Europe increases the fastest relative to global warming, at 1.5-2 times greater than the rise in global average temperature[201,211].

These observed and projected trends also imply that the probability of record-breaking heat waves including record-shattering heat waves that break previously observed temperature records by very large margins as in the 2021 Pacific Northwest heat-wave is rapidly increasing[217]. 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 emis-

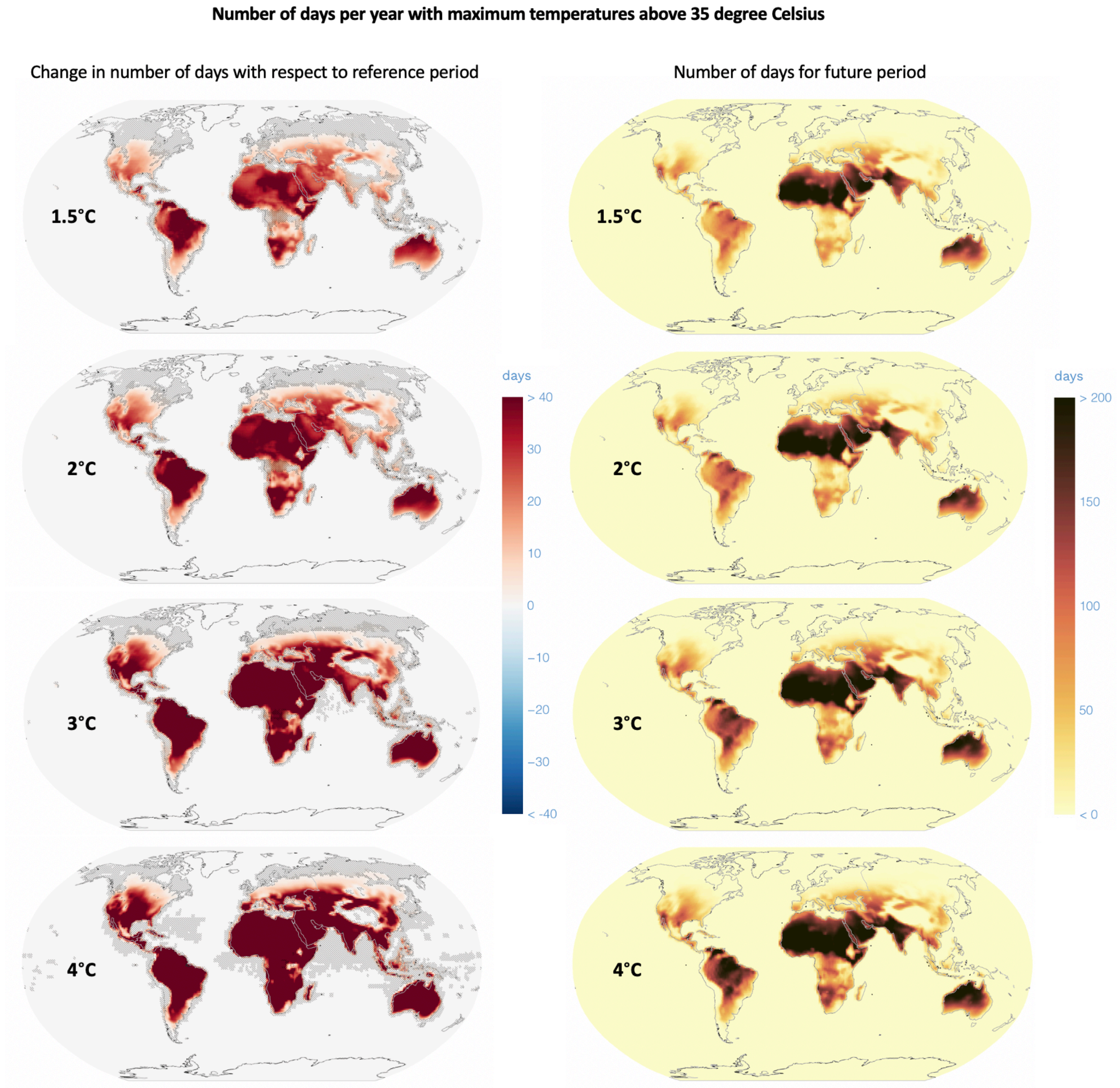


**Figure 6.** The number of days per year with maximum temperatures above 35°C for (from top to bottom) 1.5, 2, 3, and 4 °C warming levels for (left) the change in the number of days per year with respect to the reference period and (right) the number of days per year for the future period. Source for figure panels: IPCC interactive atlas (https://interactive-atlas.ipcc.ch).

sion pathway-dependent. In high-emission scenarios, week-long heat extremes that break records by three or more standard deviations are two to seven times more probable in 2021–2050 and three to 21 times more probable in 2051–2080, compared to the last three decades[217].

**Humid heatwaves in a future climate**

Humid heatwaves represent a particular threat in a future climate due to their impact on human health.

*Definition:* For health applications, a measure of humidity is often incorporated into heatwave definitions[14,15,29,38,218–221]. A useful variable to characterize humid heatwaves is the wet bulb temperature (Figure 1), defined as the temperature obtained if air was cooled by evaporating water until saturation. Under well ventilated conditions, the wet bulb temperature closely matches the human skin temperature and hence provides a direct link to the human physiological response to heat stress, and hence human morbidity and mortality[218]. Wet bulb temperatures above values around 30°C correspond to dangerous levels for human heat stress. For comparison, a temperature of 37.8°C (100 F) and relative humidity of 65% corresponds to a wet bulb temperature of 31.2°C.

*Projection:* For the last few decades of the 21st century, extreme humid heatwaves in tropical and subtropical Asia are projected under different emissions scenarios (RCP 4.5 and RCP 8.5)[219,222,223], with the 6-hour wet bulb temperature often climbing into the dangerous range above 30°C, episodically approaching and exceeding 35°C in several locations across the region. 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 outdoors, without air conditioning[207].

*Processes:* The tropical Asian regions experiencing extreme heatwaves tend to be located in low lying areas subject to strong adiabatic warming. These regions often include agricultural lands where the moistening effects of irrigation dominate over the cooling effects[223], resulting in elevated web bulb temperatures. Transport of moisture from the warm oceans is another important factor[207,219]. For example, the Gulf region is located further downwind from a region of the Indian Ocean that is projected to experience elevated relative humidity conditions[224]. This geographical location could be an important contributing factor to the outstanding warming trend in the Gulf region.

*Impacts:* The low-lying areas where the most intense hazard from extreme future heatwaves is projected are the densely populated agricultural valleys of the Ganges and Indus river basins. Climate change without mitigation therefore presents a serious and unique risk in the southern part of Asia, a region inhabited by about one-fifth of the global human population, due to the unique combination of severe natural hazards from humid heatwaves and acute vulnerability[29,219].

## 5 Changes in heatwave drivers and feedbacks in a future climate

Since climate change affects the drivers of heatwaves, it can be expected that the prediction of heatwaves will also be impacted by climate change. These changes are illustrated in Figure 3 (red text) and will be discussed further here, including changes in soil moisture feedbacks, atmospheric moisture, and changes in the atmospheric circulation.

An important reason for the higher frequency and intensity of heatwaves is that they are projected to more often be associated and enhanced by the increasing occurrence of soil moisture limitation and droughts[2,216,225]. Soil moisture conditions in spring are projected to become a more prevalent factor pre-conditioning the occurrence of heatwaves in mid-latitude summer. In particular, soil moisture-temperature feedbacks are found to be the main factor leading to projected hot spots of increases in hot extremes, leading to a substantially higher warming of hot extremes compared to changes in mean global temperature[211,225].

A further thermodynamic effect is that the warmer atmosphere is able to hold more moisture under global warming, leading to changes in humid heatwaves with climate change, with dangerous consequences for human health (see textbox *Humid heatwaves and human health in a future climate*).

Furthermore, climate change will alter the atmospheric circulation, which for many drivers is crucial in communicating between different parts of the climate system, as for example the ocean. However, the dynamical changes in the atmospheric circulation with climate change are the most uncertain part in climate change projections as compared to the thermodynamic changes discussed above, and these changes differ strongly across climate models[226,227]. The drivers responsible for changes in the circulation include polar amplification and changes in the location and strength of the general circulation, for example in terms of the jet stream location and strength[228–232], as well as changes in atmospheric stratification[229,233,234]. On smaller scales, a crucial development is a potential change in atmospheric blocking, as midlatitude heatwaves are associated with blocking in roughly 80% of all cases[70]. However, while changes in atmospheric blocking with climate change are anticipated, confidence in these projections of blocking is low[235]. The more robust trends include a positive trend in blocking size, especially in summer[236], potentially creating larger heatwaves, while there is no detectable projected trend in blocking duration[237]. The vast majority of CMIP6 models shows a decrease of blocking frequency in most regions of of the Northern Hemisphere by -1.5% / 100 years in winter and less than 1% / 100 years in summer for the period up to 2100[238]. However, much remains unknown about future trends in blocking due to a number of reasons, including blocking frequency biases in climate models[239], although there have been improvements in these biases[238]. Furthermore, there is poor agreement between simulated trends over the historical period with observations, with large regional differences[238]. The results are further sensitive to the employed definition of blocking[235,238,240], and the incomplete physical understanding of the processes contributing to blocking[235].

Changes in blocking over Greenland are particularly important, as blocks and intense upper-level ridges can lead to local heatwaves related to ice melt events[241,242], though this connection as well as observed trends in Greenland blocking are poorly represented in models[243]. However, the current assessment of future trends of Greenland blocking is inconclusive, with projections covering the entire space between a decrease and an increase in blocking[238,244–246].

## 6 Summary and Outlook

In summary, heatwaves have devastating impacts on a range of sectors, including human and ecosystem health. Although temperature tends to be very predictable on deterministic timescales, and heat extremes are among the most predictable extreme meteorological events on sub-seasonal timescales, heatwaves continue to lead to large and increasing human death tolls. Heatwaves often occur as compound events with drought and wildfires, and have further severe consequences such as extreme levels of permafrost and ice melting, pest infestations, and permanent ecosystem damage. Heatwaves have become more prevalent over the past decades, and heatwave frequency and intensity are projected to further increase with global warming. With climate change, temperature and humidity thresholds that adversely affect human morbidity and mortality are reached increasingly often. Given the acceleration in the occurrence of heatwaves it can be anticipated that preparedness and emergency measures that are currently in place will not be sufficient and may not be able to keep up with the unprecedented levels of warming and the increased frequency, intensity, and duration of heat extremes. Given the devastating impacts of heatwaves it is clear that the observed and projected adverse changes in heatwaves leads to a stronger need for accurate prediction of these extreme events, in addition to effective planning and emergency measures.

There remain major challenges in understanding, predicting, and projecting heatwaves for future climates. While thermodynamic changes in a future climate are better understood and can often be traced directly to the level of greenhouse gas emissions, the unresolved changes in the atmospheric circulation in a future climate add uncertainty to the projection of heatwaves for future climates. Furthermore, the changes in the drivers and the characteristics of heatwaves make it difficult to anticipate if and how their predictability may change in a future climate. For example, it has been suggested that quasi-resonant amplification of planetary-scale Rossby waves[247], that is, the formation of a waveguide that allows for Rossby waves to become amplified and more stationary, may occur more frequently under global warming[248,249], and that this mechanism is already contributing to extreme events[250]. It is however unclear if such a potential amplification of waves will indeed occur more frequently, and how it may affect the prediction and projection of heatwaves.

One crucial component of an improved prediction of heatwaves is an improved representation of large-scale stationary atmospheric waves in weather and climate models[154,251]. These waves determine the location of storm tracks, as well as the moisture and temperature distribution in the extratropics[252], and even small biases in the large-scale circulation can lead to large errors, for example in the distribution of precipitation and its changes with climate change[253]. An improved representation of the large-scale circulation also benefits the simulation of atmospheric blocking events, whose projections are highly uncertain with climate change. An improved representation of blocking can be achieved in part by higher resolution in climate models, however the improvements are small for summer in most models[254], which would be crucial for the simulation of heatwaves. Progress in the representation of blocking has been achieved from CMIP5 to CMIP6, but the simulation of blocking persistence, which is crucial for heatwaves, remains challenging[255]. Despite this progress it therefore has to be kept in mind that model improvements and updates do not always lead to increased representation of specific processes and their predictability.

Furthermore, model uncertainties in projected regional changes in heatwave intensities are still substantial and again relate to uncertain potential changes in the large-scale dynamical drivers, in addition to changes in soil moisture conditions that potentially pre-condition heatwaves, as well as local land-vegetation-atmosphere coupling during heatwaves. Some of the uncertainties due to parametric land surface model uncertainties have been quantified in perturbed physics ensembles[256].

Alternative approaches to heatwave projection, such as *tales of future weather*[257] or physical climate storylines[258], defined as self-consistent and plausible unfoldings of a future weather or climate event, have been introduced as one way to quantify and illustrate future changes in extreme events[259–261]. These storylines allow for future projections conditional on uncertain changes in the dynamical drivers of heatwaves such as potential changes in the persistence of atmospheric blocking. While such approaches cannot be interpreted in a probabilistic way, they can characterize potential worst case events to stress test a system[260,262] and can be used as an effective way to communicate how heatwaves could evolve in the future. 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 or 4°C warmer world than under present-day conditions[258]. Furthermore, using iterative re-initialization of large fully-coupled climate model ensembles, an approach referred to as ensemble boosting, it has been suggested that heatwaves substantially more intense than the ones observed are possible without further warming[263], which is consistent with statistical approaches generating very rare heatwaves by importance sampling[264].

Furthermore, data science methods such as causal methods for identifying precursors of extreme events[265,266] are increasingly used for identifying event precursors on a range of timescales[267,268], which can lead to improved predictions. 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 so-called *seamless* prediction across multiple timescales[269–271]. The potential of seamless prediction has so far been evaluated across daily to weekly timescales[272], but there remains substantial potential for further evaluation of seamless prediction across a wider range of timescales. Hence, connections and collaborations across prediction timescales will have to be enhanced further[273].

Lastly, the definition of heatwaves themselves leaves room for interpretation. Although moving base periods are now often used to characterize heatwaves in order to account for the climate change trend, it is unknown whether and which systems are able to adapt to increases in extreme temperatures, and over which timescales this adaptation may occur. However, it is clear that many systems are inherently unable to adapt, or not able to adapt fast enough to keep pace with the current level of warming. 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 heatwave becomes crucial in a warming climate. In particular, human health is one area where adaptation is not possible for human physiological parameters, and where increased use of technology such as air conditioning would need increased and widespread use to allow for human survivability in an increasing number of regions. Surges in electricity use during heatwaves due to increased air conditioning increases the pressure on electric grids[150], which in the case of outages can lead to deadly traps. Likewise, ecosystem health across the globe is severely threatened by heatwaves and their future projections due to the limited or slow adaptation of these systems to increasing levels of warming and associated heat extremes. Hence, while 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 – lasting damage induced by heat extremes in a changing climate.

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