

# Prediction and projection of heatwaves

Daniela I. V. Domeisen<sup>1,2</sup>✉, Elfatih A. B. Eltahir<sup>3</sup>, Erich M. Fischer<sup>2</sup>, Reto Knutti<sup>2</sup>, Sarah E. Perkins-Kirkpatrick<sup>4</sup>, Christoph Schär<sup>2</sup>, Sonia I. Seneviratne<sup>2</sup>, Antje Weisheimer<sup>5,6</sup> & Heini Wernli<sup>2</sup>

## 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.

## Sections

Introduction

Drivers and feedbacks for heatwave prediction

Heatwave prediction

Heatwave projections

Summary and discussion

<sup>1</sup>Faculty of Geosciences and Environment, University of Lausanne, Lausanne, Switzerland. <sup>2</sup>Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland. <sup>3</sup>Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA. <sup>4</sup>ARC Centre of Excellence for Climate Extremes, University of New South Wales, Canberra, Australian Capital Territory, Australia. <sup>5</sup>Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford, Oxford, UK. <sup>6</sup>Research Department, European Centre for Medium Range Weather Forecasts (ECMWF), Reading, UK. ✉e-mail: [daniela.domeisen@unil.ch](mailto:daniela.domeisen@unil.ch)

## 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<sup>1–3</sup>, infrastructure<sup>4</sup>, energy demand<sup>5,6</sup>, ecosystems<sup>7</sup>, permafrost<sup>8</sup> and human health<sup>9,10</sup>; the latter is particularly affected by humid heatwaves, a combination of temperature and specific humidity<sup>9,11</sup> (Box 2). In addition to their direct impacts, heatwaves can also lead to compounding extreme events<sup>12</sup>. A common example includes compound heat and drought<sup>13–15</sup>, associated with enhanced fire risk<sup>16</sup>, plant mortality<sup>17</sup> and crop failure<sup>18</sup>.

Since at least the 1950s, the frequency and duration of heatwaves has been increasing globally<sup>19</sup>. Cumulative intensity (Box 1) has also increased in most locations<sup>20,21</sup>, 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<sup>22</sup>. 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<sup>23</sup>. These changes in heat extremes are increasingly attributed to human influence<sup>24–27</sup>. Indeed, observed heatwaves such as those in Europe during 2003 and 2018 are extremely unlikely in the absence of human-induced climate change<sup>28,29</sup>, 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<sup>19</sup>. These trends are also likely detectable on the regional scale in more than 80% of all IPCC regions<sup>19</sup>.

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<sup>30</sup>. On timescales of years to decades, urban and infrastructure planning<sup>31</sup>, and climate change mitigation and adaptation are needed. Such preparedness can be expected to alleviate heatwave impacts, especially in light of a changing climate<sup>32</sup>. Indeed, regions that have experienced heatwaves in the past are more likely to implement emergency measures and hence are better prepared for subsequent events<sup>33</sup>. 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<sup>34–37</sup>.

## 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<sup>38</sup>. 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<sup>39–41</sup>, increasing the likelihood of heatwaves being long-lasting<sup>42</sup>. However, at lower mid-latitudes, including the Mediterranean, upper-level ridges are typically weaker and so cannot be classified as blocks<sup>43</sup>. Specific examples of heatwaves associated with blocks are found in Europe<sup>44</sup>, North America<sup>45,46</sup>, southeastern Australia<sup>47</sup> and eastern China<sup>48</sup>. In the subtropics, heatwaves can also be associated with persistent blocking, especially in South America<sup>49–53</sup>. In the subtropical Asian monsoon regions, heatwaves tend to occur predominantly in the pre-monsoon season. A late monsoon onset<sup>54</sup> 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<sup>55</sup>.

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<sup>56</sup> and therefore anomalous diabatic processes. In contrast, polar heat extremes are predominantly driven by advection from lower latitudes<sup>57,58</sup>, as in the Antarctic heatwave of March 2022<sup>59</sup>. Horizontal advection is a less important process for heatwaves in mid-latitudes (including Europe<sup>43,60</sup> and southeastern Australia<sup>61</sup>). In these regions, upper-level ridges and blocks contribute to surface heatwaves via subsidence, associated with clear-sky conditions and increased incoming solar radiation<sup>62</sup>, complemented by diabatic heating within the boundary layer, as also observed in the 2010 Russian summer heatwave<sup>63–65</sup>. 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<sup>66,67</sup>, which are associated with cloud formation and precipitation along the western flank of the ridge or block<sup>68–70</sup>. Continental summer heat extremes are also suggested to be connected with low upstream storm-track activity<sup>71</sup>.

On the planetary scale, persistent tropical and extratropical atmospheric patterns can also drive remote responses that lead to extratropical heatwaves<sup>72</sup>. 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<sup>73–75</sup> or in situations with recurrent wave patterns<sup>76</sup>, exhibiting stationary behaviour enhanced by orographic and thermal forcing<sup>77,78</sup>. 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<sup>240–242</sup>. 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<sup>169,240,243,244</sup>.

**Frequency:** A measure of how often heatwaves occur, often expressed as the total number of discrete heatwave events over a season<sup>240,245</sup>. 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<sup>20,169,240,246</sup>.

**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)<sup>20</sup> 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<sup>244,247</sup>. Similar to frequency, heatwave intensity is important for human health and infrastructure impacts<sup>20,182,246</sup>.

**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<sup>248</sup>. The timing of heatwave occurrence is important for ecosystem impacts<sup>249</sup>.

**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<sup>250</sup>, as well as permafrost melt<sup>251,252</sup>.

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

in turn, can cause temperature extremes<sup>79–81</sup>. Conversely, extreme temperature events associated with more localized Rossby wave packets<sup>82</sup>, rather than circumglobal patterns<sup>83</sup>, have been emphasized. However, this linkage between jet waviness and heat extremes varies strongly between regions<sup>84</sup> 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<sup>13,85,86</sup> (Fig. 2). These deficits reduce evaporative cooling through latent heat flux at the land surface, leading to extreme local heat<sup>13,87,88</sup>. These effects contribute substantially to the occurrence of hot days on all continents, particularly in mid-latitude<sup>13,88,89</sup> and monsoon regions<sup>90</sup>. In addition, soil moisture forcing can feed back onto the large-scale atmospheric circulation<sup>91–94</sup>, exacerbating a heatwave. Heat advection from regions affected by soil moisture limitation further demonstrates the importance of non-local land–surface interactions<sup>65,95,96</sup>.

The land surface also influences heatwaves via land cover properties<sup>19,97</sup>. For example, compared with grassland and agricultural land, forests can amplify heatwave conditions in the short term but dampen them in the longer term<sup>98,99</sup>. Forest type is also relevant, with broadleaf trees reducing heatwave intensity compared with coniferous trees owing to their higher albedo and stomatal conductance<sup>100</sup>. Agricultural management further affects heatwave properties. For instance,

irrigation and intense agriculture increase evapotranspiration on hot days, comparatively cooling the surface<sup>101–103</sup>.

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<sup>104,105</sup>. Furthermore, reduced cloud cover can further decrease precipitation, lowering soil moisture and thereby amplifying the heatwave<sup>105</sup>. Nonetheless, this possible feedback loop between soil moisture and precipitation is less well established in observations<sup>105–108</sup>.

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<sup>109</sup>. 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<sup>110</sup>. 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<sup>111</sup>. However, these extratropical Atlantic and Pacific SST anomalies exhibit strong non-stationarity and thus cannot often be successfully used for long-range prediction<sup>88,112</sup>.

## 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<sup>10,259–261</sup>. 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<sup>262</sup>, 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<sup>259</sup>. 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<sup>263</sup> (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<sup>264</sup>. In Pakistan, humid heatwaves relate to onshore flow from the Arabian Sea during summer monsoon onset<sup>11</sup>. Such air masses are advected over hot and often irrigated agricultural land, where the moistening effects of irrigation dominate<sup>263,265</sup> and result in elevated wet-bulb temperatures<sup>234</sup>. Irrigation is also important in enhancing heatwave intensity over the North China Plain of eastern China<sup>265</sup>.

**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<sup>266</sup>. 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<sup>11,267,268</sup>. Transport of moisture from the warm Indian ocean is another important factor for atmospheric humidity increases under climate change in southwest Asia<sup>269</sup>.

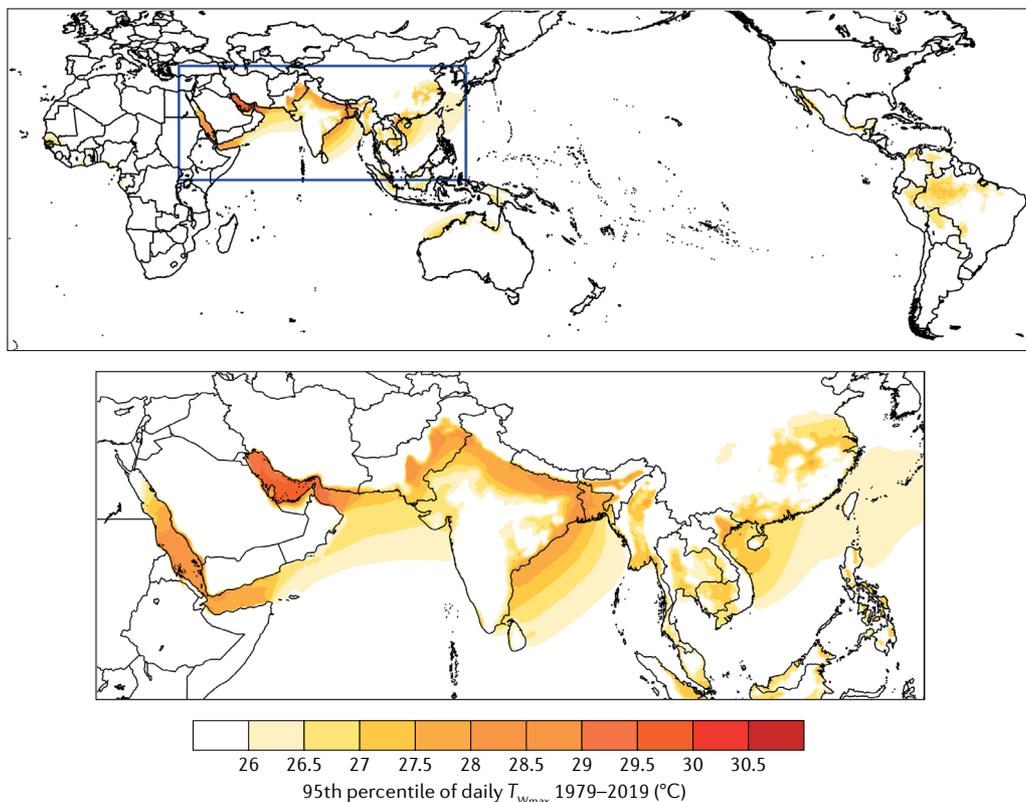


Image adapted from ref.<sup>267</sup> under a Creative Commons licence [CC BY-NC 4.0](https://creativecommons.org/licenses/by-nc/4.0/).

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<sup>113,114</sup>, including China<sup>115</sup>, India<sup>116</sup>, North America<sup>117</sup>, Europe<sup>118</sup> and Australia<sup>119</sup>. In Australia, ENSO teleconnections often interact with forcing from the Indian Ocean Dipole (IOD)<sup>120</sup>. 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<sup>121</sup>, and anomalous MJO-related convection in the western Pacific is associated with heatwaves in northeastern Asia<sup>122</sup>. East Asian monsoon convection can further drive remote heatwaves in the United States<sup>123</sup>.

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<sup>124–127</sup>. 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.

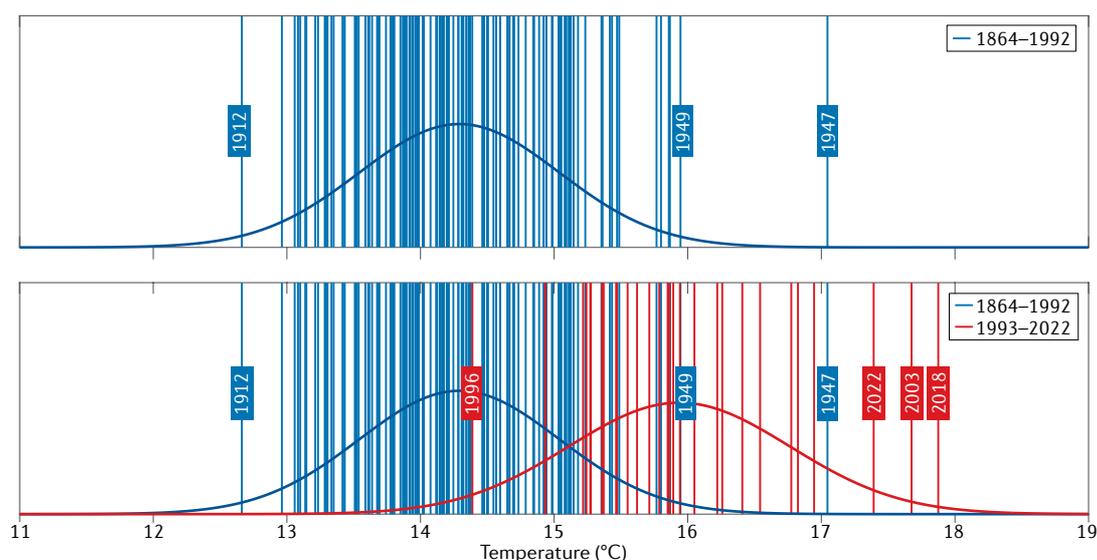
Based on a minimum three-day duration of heatwaves, confident predictions of heatwave occurrence and amplitude are possible in

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<sup>40,41</sup>, 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<sup>128–130</sup>, and often several types of atmospheric drivers contribute to the evolution of a heatwave<sup>131</sup>, 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<sup>83,132,133</sup>, as can inclusion of the MJO for prediction over the contiguous United States<sup>134</sup> and in the Sahel region<sup>135</sup>. 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<sup>136</sup>.

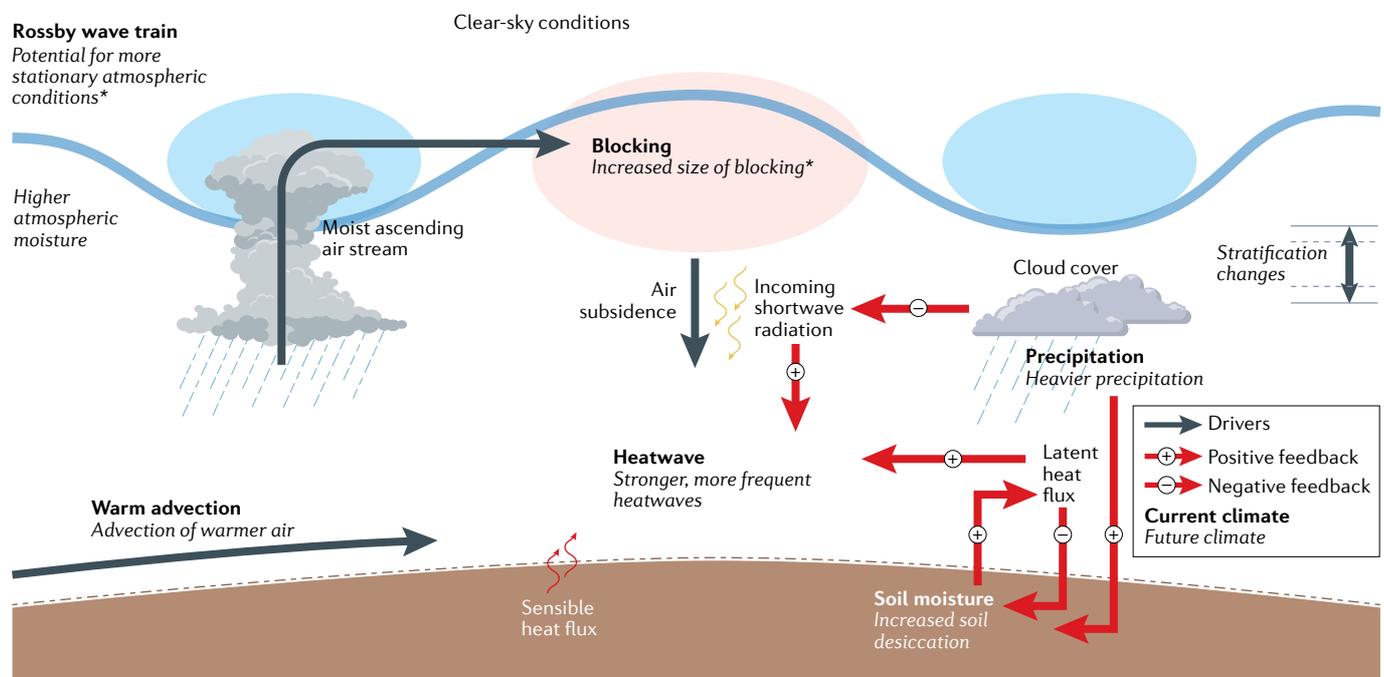
Beyond the traditional deterministic predictability limit of approximately 10–15 days<sup>137,138</sup> (that is, the exact determination of the synoptic flow<sup>139</sup>), forecasts have to be expressed probabilistically. Summer heatwaves are among the most predictable meteorological extremes on subseasonal timescales<sup>140,141</sup> and can often be predicted at lead times of two to three weeks<sup>142</sup>. 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<sup>141</sup>. This predictability evolution is typical for heatwaves around the globe<sup>143,144</sup>, 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<sup>22</sup>. 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<sup>23</sup>. This overarching predictable lead time of several weeks has been documented across a range of regions, including Northern Africa<sup>133</sup>, North America<sup>134</sup> and Europe<sup>145</sup>, but successful prediction of heatwave amplitude is often only possible on lead times of up to one week both in the extratropics<sup>146,270</sup> and tropics<sup>136</sup>. 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<sup>147</sup>. The correction of SST biases can further enhance prediction skill at these subseasonal timescales<sup>148</sup>.

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<sup>133,149</sup>, the poorly understood role of remote ocean<sup>150,151</sup> and upper-atmosphere drivers<sup>152</sup>, and the complexity of the coupling between the land surface and the atmosphere<sup>13,86,153,154</sup>. However, despite these challenges, there is predictive skill for warmer-than-average summer temperatures in seasonal forecasting systems<sup>155–158</sup>. 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<sup>155</sup>. 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<sup>159</sup>.

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<sup>158</sup>, owing to strong land–atmosphere coupling<sup>87</sup> and surface preconditioning<sup>86,160</sup>. Land–atmosphere coupling is also important elsewhere. Across Europe, heatwave predictability is influenced by rainfall in the preceding season<sup>85,86,89</sup>; 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<sup>86</sup>. Similarly, over many global land areas, there is higher probability of hot-day occurrence following negative precipitation anomalies for a season or longer<sup>89</sup>. Initial soil moisture conditions and their evolution are therefore critical factors influencing heatwave prediction<sup>88,161</sup>. 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<sup>155</sup>. 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<sup>158</sup> 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<sup>162,163</sup>. 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.

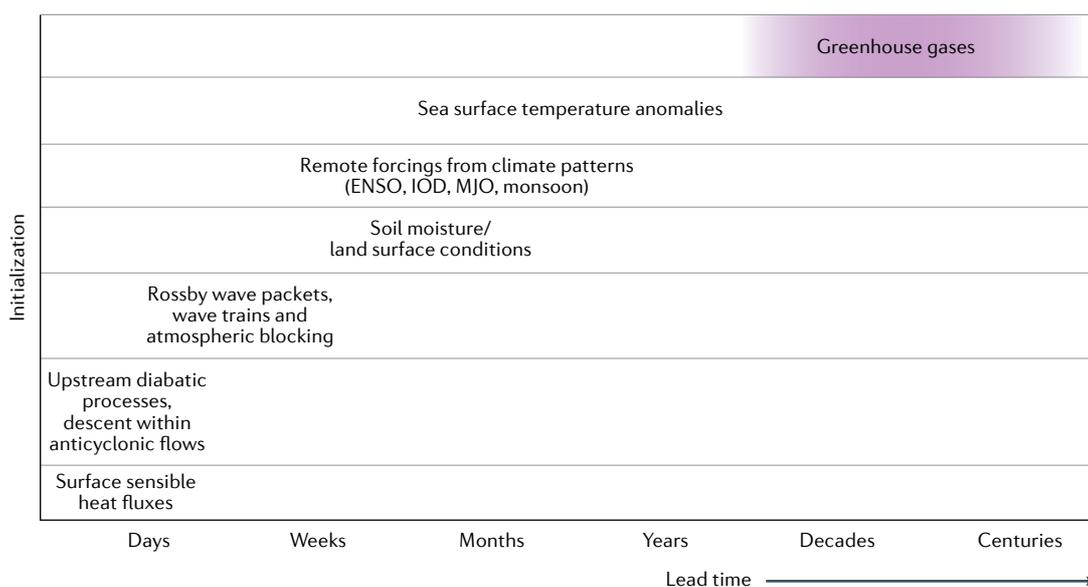
## Projected heatwave characteristics

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<sup>19,164</sup>. 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<sup>165–167</sup>. Indeed, even at 1.5 °C and 2 °C warming, heatwave characteristics increase substantially<sup>7,168</sup>. These changes in seasonal mean warming and extreme temperatures<sup>169,170</sup> arise from thermodynamical changes (such as changes in temperature, soil moisture and associated land–atmosphere interactions) and changes in atmospheric dynamics, and their interactions<sup>171,172</sup>. Enhanced temperature variability is also important for certain land regions in the mid-latitudes<sup>22,173–175</sup>.

For example, the number of very hot days over global land nearly doubles from 1.5 °C to 2 °C warming<sup>176</sup>. 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<sup>19,164,177</sup>. The relative increase in the number of heat extremes is even more pronounced for rare events<sup>176,178</sup>; 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<sup>164,177</sup>.

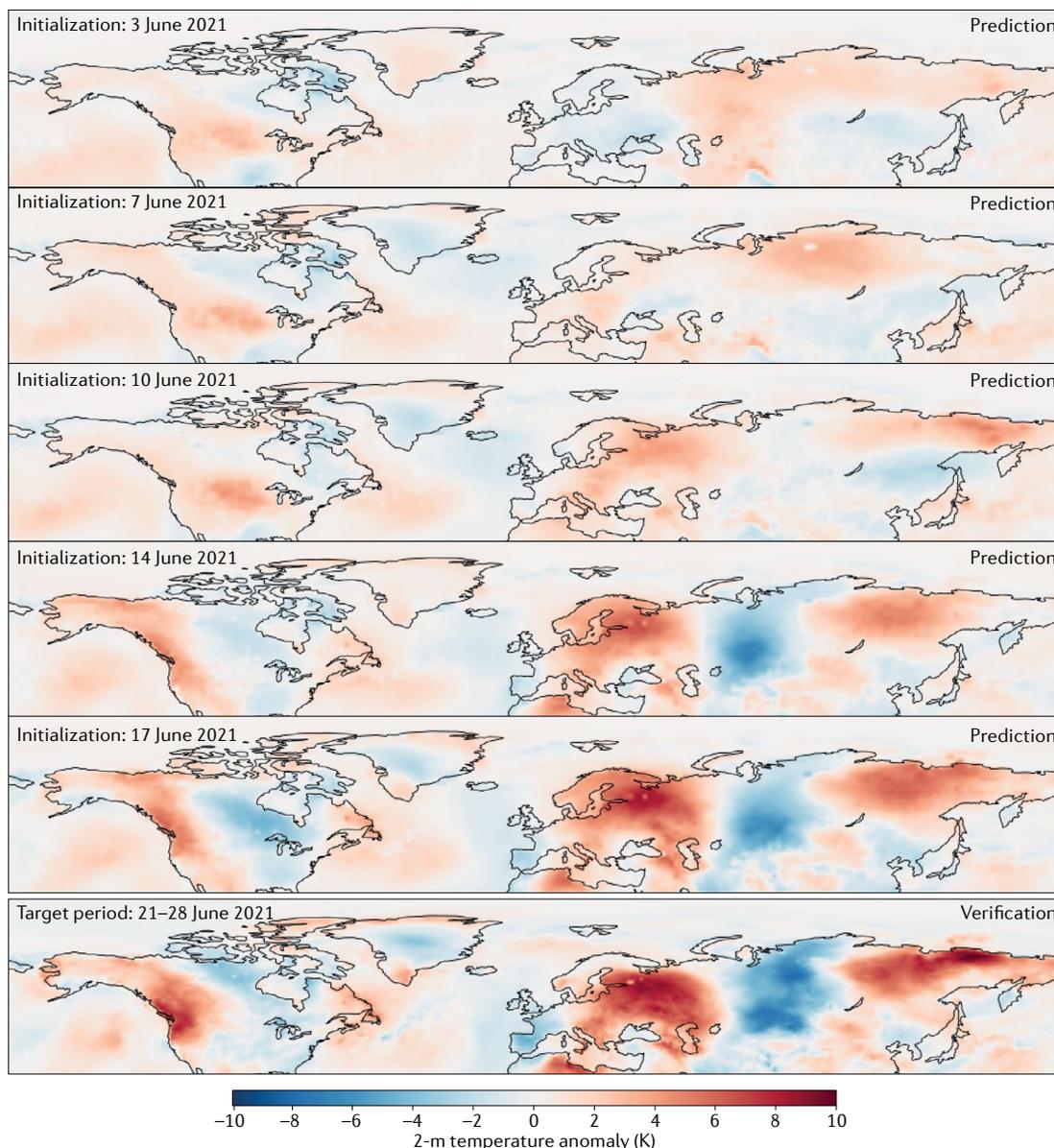
Accordingly, the frequency of heatwave days – the number of days per year when daily maximum temperatures exceed the 90th percentile of the historical period – is also anticipated to increase<sup>179</sup>. The largest regional changes are evident over global tropical regions, with relatively small changes projected for mid- and high latitudes<sup>166</sup>. 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<sup>179</sup>; 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<sup>180</sup>, 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<sup>166</sup>. Tropical locations display a peak and decline in the number of individual events at 2–3 °C global warming<sup>166</sup>, 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 Niño–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<sup>237</sup> 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<sup>238</sup>. 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<sup>181,182</sup>.

The probability of record-breaking and record-shattering heatwaves is also rapidly increasing<sup>183</sup>. Such events include, for instance, the 2021 Pacific Northwest heatwave in North America<sup>184</sup> and the 2022 heatwave in the United Kingdom<sup>185</sup>. 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<sup>183</sup>. 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<sup>183</sup>.

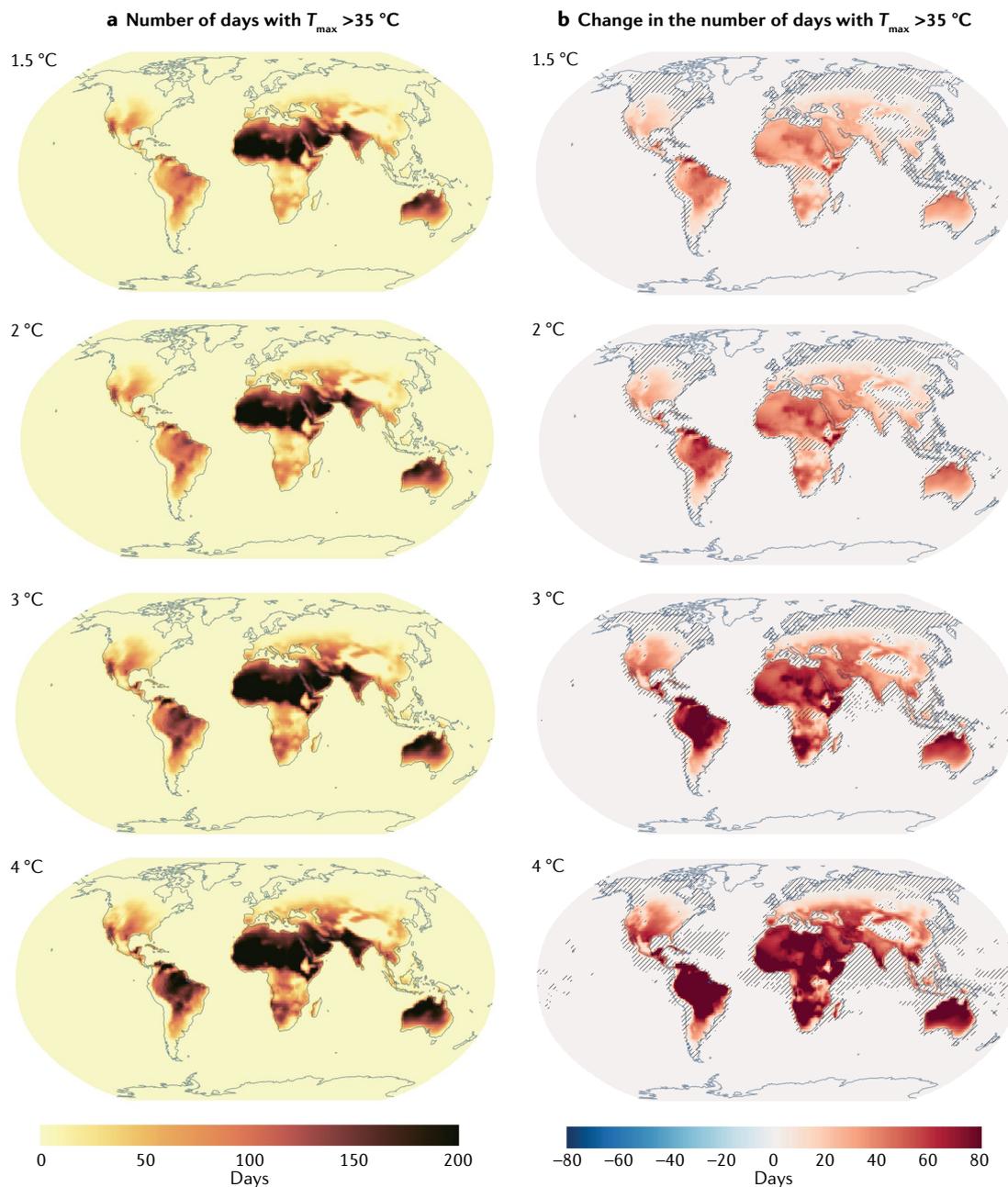
**Changes in heatwave drivers and feedbacks in a future climate**  
Because climate change affects both the thermodynamic and dynamical drivers of heatwaves, it can be expected that the prediction of heatwaves will also be affected by climate change (Fig. 2). An important

# Review article

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<sup>19,104,167</sup>. 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<sup>104,167</sup>. 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<sup>186–188</sup> 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  $35^\circ\text{C}$  over land for (from top to bottom) warming levels of  $1.5^\circ\text{C}$ ,  $2^\circ\text{C}$ ,  $3^\circ\text{C}$  and  $4^\circ\text{C}$ . 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  $35^\circ\text{C}$  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.<sup>239</sup>, IPCC.

strength of the North Atlantic circulation<sup>189</sup>. The dynamical changes are more uncertain than their thermodynamic counterparts<sup>19,190,191</sup>, although some can be considered robust, as with shifts in the extratropical storm tracks<sup>192</sup>. For instance, while changes in atmospheric blocking are expected, confidence in these projections is low<sup>193</sup>: increases in blocking size are anticipated with some certainty, especially in summer<sup>194</sup>, but there is no detectable change in blocking duration<sup>195</sup>. 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<sup>196</sup>. Moreover, future trends in Greenland blocking – important for melt events – are inconclusive, with projections covering the entire space between a decrease and an increase<sup>196–199</sup>. This uncertainty can be linked to blocking frequency biases in climate models<sup>200</sup> (although some improvements in these model biases are apparent<sup>196</sup>), sensitivity to the definition of blocking<sup>193,196,201</sup>, and an incomplete physical understanding of the processes contributing to blocking<sup>193</sup>. 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<sup>130,202</sup>. These waves determine the location of storm tracks, as well as the moisture and temperature distribution in the extratropics<sup>203</sup>. 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<sup>204</sup>. 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<sup>205</sup>. Progress in the representation of blocking has been achieved from CMIP5 to CMIP6, but the simulation of blocking persistence remains challenging<sup>206</sup>. 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<sup>136</sup>. Moreover, humid heatwaves, which predominantly threaten tropical regions, would benefit from model simulations that resolve convective scales<sup>207</sup>. Enhanced resolution would therefore allow

better analysis and prediction of these understudied tropical regions, providing advance warnings to protect vulnerable populations<sup>208</sup>.

Alternative approaches to heatwave projection, such as tales of future weather<sup>209</sup> or physical climate storylines<sup>210</sup>, have been introduced as ways to quantify and illustrate future changes in extreme events<sup>211–213</sup>. 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<sup>212,214</sup> 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<sup>210</sup>. 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<sup>215</sup>, which is consistent with statistical approaches generating very rare heatwaves by importance sampling<sup>216</sup>. Computational methods such as rare event algorithms allow for focusing only on those trajectories that lead to extreme heatwaves, hence optimizing computational resources<sup>217</sup>. Furthermore, data science methods such as causal methods<sup>112,218,219</sup> are increasingly used for identifying drivers of extreme events on a range of timescales<sup>220–222</sup>, which can lead to improved predictions<sup>223</sup>. Deep learning methods based on analogue forecasting are further used for forecasting of heat extremes<sup>224</sup>.

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<sup>225–227</sup>. The potential of seamless prediction has so far been evaluated across daily to weekly timescales<sup>228</sup>, but there remains substantial potential across other timescales. Hence, connections and collaborations across prediction timescales will have to be enhanced further<sup>229</sup>. 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<sup>230</sup>. 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<sup>231</sup>.

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 adaptation 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<sup>232</sup>. 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<sup>233</sup>, 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<sup>234</sup>, 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<sup>235</sup>. 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<sup>236</sup> and the damage induced by heat extremes in a changing climate.

Published online: 13 December 2022

## References

- Albergel, C. et al. Monitoring and forecasting the impact of the 2018 summer heatwave on vegetation. *Remote Sens.* **11**, 520 (2019).
- Brás, T. A., Seixas, J., Carvalhais, N. & Jägermeyr, J. Severity of drought and heatwave crop losses tripled over the last five decades in Europe. *Environ. Res. Lett.* **16**, 065012 (2021).
- Breshears, D. D. et al. Underappreciated plant vulnerabilities to heat waves. *New Phytol.* **231**, 32–39 (2021).
- Nguyen, M., Wang, X. & Chen, D. *An Investigation of Extreme Heatwave Events and their Effects on Building & Infrastructure*. CSIRO Climate Adaptation Flagship Working Paper Series no. 9 (CSIRO, 2010).
- Auffhammer, M., Baylis, P. & Hausman, C. H. Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. *Proc. Natl Acad. Sci. USA* **114**, 1886–1891 (2017).
- Bloomfield, H., Sutters, C. & Drew, D. Meteorological drivers of European power system stress. *J. Renew. Energy* <https://doi.org/10.1155/2020/5481010> (2020).
- Hoegh-Guldberg, O. et al. in *Special Report on Global Warming of 1.5°C* (eds Masson-Delmotte, V. et al.) Ch. 3 (IPCC, WMO, 2018).
- Overland, J. E. & Wang, M. The 2020 Siberian heat wave. *Int. J. Climatol.* <https://doi.org/10.1002/joc.6850> (2020).
- Campbell, S., Remenyi, T. A., White, C. J. & Johnston, F. H. Heatwave and health impact research: a global review. *Health Place* **53**, 210–218 (2018).
- Ebi, K. L. et al. Hot weather and heat extremes: health risks. *Lancet* **398**, 698–708 (2021).
- Raymond, C., Matthews, T. & Horton, R. M. The emergence of heat and humidity too severe for human tolerance. *Sci. Adv.* **6**, eaaw1838 (2020).
- Zscheischler, J. et al. A typology of compound weather and climate events. *Nat. Rev. Earth Environ.* **1**, 333–347 (2020).
- Seneviratne, S. I. et al. Investigating soil moisture–climate interactions in a changing climate: a review. *Earth Sci. Rev.* **99**, 125–161 (2010).
- Zscheischler, J. & Seneviratne, S. I. Dependence of drivers affects risks associated with compound events. *Sci. Adv.* **3**, e1700263 (2017).
- AghaKouchak, A., Cheng, L., Mazdiyasni, O. & Farahmand, A. Global warming and changes in risk of concurrent climate extremes: insights from the 2014 California drought. *Geophys. Res. Lett.* **41**, 8847–8852 (2014).
- Libonati, R. et al. Assessing the role of compound drought and heatwave events on unprecedented 2020 wildfires in the Pantanal. *Environ. Res. Lett.* **17**, 015005 (2022).
- Allen, C. D., Breshears, D. D. & McDowell, N. G. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere* **6**, 1–55 (2015).
- Ribeiro, A. F. S., Russo, A., Gouveia, C. M., Páscoa, P. & Zscheischler, J. Risk of crop failure due to compound dry and hot extremes estimated with nested copulas. *Biogeosciences* **17**, 4815–4830 (2020).
- Seneviratne, S. I. et al. in *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) Ch. 11 (IPCC, Cambridge Univ. Press, 2021).
- Perkins-Kirkpatrick, S. & Lewis, S. Increasing trends in regional heatwaves. *Nat. Commun.* **11**, 1–8 (2020).
- Jyoteeshkumar Reddy, P., Perkins-Kirkpatrick, S. E. & Sharples, J. J. Intensifying Australian heatwave trends and their sensitivity to observational data. *Earth's Future* **9**, e2020EF001924 (2021).
- Schär, C. et al. The role of increasing temperature variability in European summer heatwaves. *Nature* **427**, 332–336 (2004).
- Emerton, R. et al. Predicting the unprecedented: forecasting the June 2021 Pacific Northwest heatwave. *Weather* <https://doi.org/10.1002/wea.4257> (2022).
- Lewis, S. C. & Karoly, D. J. Anthropogenic contributions to Australia's record summer temperatures of 2013. *Geophys. Res. Lett.* **40**, 3705–3709 (2013).
- Van Oldenborgh, G. J. et al. *Human contribution to the record-breaking June 2019 heat wave in France* (World Weather Attribution, 2019); [https://www.worldweatherattribution.org/wp-content/uploads/WWA-Science\\_France\\_heat\\_June\\_2019.pdf](https://www.worldweatherattribution.org/wp-content/uploads/WWA-Science_France_heat_June_2019.pdf)
- Vautard, R. et al. Human contribution to the record-breaking June and July 2019 heatwaves in Western Europe. *Environ. Res. Lett.* **15**, 094077 (2020).
- Ciavarella, A. et al. Prolonged Siberian heat of 2020 almost impossible without human influence. *Clim. Change* **166**, 1–18 (2021).
- Stott, P. A., Stone, D. A. & Allen, M. R. Human contribution to the European heatwave of 2003. *Nature* **432**, 610–614 (2004).
- Yiou, P. et al. Analyses of the northern European summer heatwave of 2018. *Bull. Am. Meteorol. Soc.* **101**, S35–S40 (2020).
- Casanueva, A. et al. Overview of existing heat-health warning systems in Europe. *Int. J. Environ. Res. Public Health* **16**, 2657 (2019).
- Kotharkar, R. & Ghosh, A. Progress in extreme heat management and warning systems: a systematic review of heat-health action plans (1995–2020). *Sustain. Cities Soc.* **76**, 103487 (2022).
- White, C. J. et al. Potential applications of subseasonal-to-seasonal (S2S) predictions. *Meteorol. Appl.* **24**, 315–325 (2017).
- Merz, B. et al. Impact forecasting to support emergency management of natural hazards. *Rev. Geophys.* **58**, 1–52 (2020).
- Smale, D. A. et al. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nat. Clim. Change* **9**, 306–312 (2019).
- Benthuisen, J. A., Oliver, E. C. J., Chen, K. & Wernberg, T. Editorial: advances in understanding marine heatwaves and their impacts. *Front. Mar. Sci.* **7**, 1301 (2020).
- Oliver, E. C. J. et al. Longer and more frequent marine heatwaves over the past century. *Nat. Commun.* **9**, 1324 (2018).
- Holbrook, N. J. et al. Keeping pace with marine heatwaves. *Nat. Rev. Earth Environ.* **1**, 482–493 (2020).
- Sousa, P. M., Trigo, R. M., Barriopedro, D., Soares, P. M. & Santos, J. A. European temperature responses to blocking and ridge regional patterns. *Clim. Dyn.* **50**, 457–477 (2018).
- Pfahl, S. & Wernli, H. Quantifying the relevance of atmospheric blocking for co-located temperature extremes in the Northern Hemisphere on (sub-)daily time scales. *Geophys. Res. Lett.* <https://doi.org/10.1029/2012GL052261> (2012).
- Schaller, N. et al. Influence of blocking on Northern European and western Russian heatwaves in large climate model ensembles. *Environ. Res. Lett.* **13**, 054015 (2018).
- Brunner, L., Schaller, N., Anstey, J., Sillmann, J. & Steiner, A. K. Dependence of present and future European temperature extremes on the location of atmospheric blocking. *Geophys. Res. Lett.* **45**, 6311–6320 (2018).
- Röthlisberger, M. & Martius, O. Quantifying the local effect of Northern Hemisphere atmospheric blocks on the persistence of summer hot and dry spells. *Geophys. Res. Lett.* **46**, 10101–10111 (2019).
- Zschenderlein, P., Fink, A. H., Pfahl, S. & Wernli, H. Processes determining heat waves across different European climates. *Q. J. R. Meteorol. Soc.* **145**, 2973–2989 (2019).
- Stefanon, M., D'Andrea, F. & Drobninski, P. Heatwave classification over Europe and the Mediterranean region. *Environ. Res. Lett.* **7**, 014023 (2012).
- Loikith, P. C. & Broccoli, A. J. Characteristics of observed atmospheric circulation patterns associated with temperature extremes over North America. *J. Clim.* **25**, 7266–7281 (2012).
- Namias, J. Anatomy of Great Plains protracted heat waves (especially the 1980 U.S. summer drought). *Mon. Weather Rev.* **110**, 824–838 (1982).
- Parker, T. J., Berry, G. J. & Reeder, M. J. The structure and evolution of heat waves in southeastern Australia. *J. Clim.* **27**, 5768–5785 (2014).
- Chen, R. & Lu, R. Comparisons of the circulation anomalies associated with extreme heat in different regions of Eastern China. *J. Clim.* **28**, 5830–5844 (2015).
- Silva, W. L., Nascimento, M. X. & Menezes, W. F. Atmospheric blocking in the South Atlantic during the summer 2014: a synoptic analysis of the phenomenon. *Atmos. Clim. Sci.* **05**, 386–393 (2015).
- Coelho, C. A. S. et al. The 2014 southeast Brazil austral summer drought: regional scale mechanisms and teleconnections. *Clim. Dyn.* **46**, 3737–3752 (2015).
- Rodrigues, R. R. & Woollings, T. Impact of atmospheric blocking on South America in austral summer. *J. Clim.* **30**, 1821–1837 (2017).
- Finke, K. et al. Revisiting remote drivers of the 2014 drought in South-Eastern Brazil. *Clim. Dyn.* **55**, 3197–3211 (2020).
- Marengo, J. A. et al. The heat wave of October 2020 in central South America. *Int. J. Climatol.* <https://doi.org/10.1002/joc.7365> (2021).
- Röthlisberger, M., Sprenger, M., Flaounas, E., Beyerle, U. & Wernli, H. The substructure of extremely hot summers in the Northern Hemisphere. *Weather Clim. Dyn.* **1**, 45–62 (2020).
- Wehner, M., Stone, D., Krishnan, H., Achuta Rao, K. & Castillo, F. The deadly combination of heat and humidity in India and Pakistan in summer 2015. *Bull. Am. Meteorol. Soc.* **97**, s81–s86 (2016).
- Luo, M., Lau, N.-C. & Liu, Z. Different mechanisms for daytime, nighttime, and compound heatwaves in southern China. *Weather Clim. Extremes* **36**, 100449 (2022).
- Binder, H. et al. Exceptional air mass transport and dynamical drivers of an extreme wintertime Arctic Warm Event. *Geophys. Res. Lett.* **44**, 12,028–12,036 (2017).

# Review article

58. Hermann, M., Papritz, L. & Wernli, H. A Lagrangian analysis of the dynamical and thermodynamic drivers of large-scale Greenland melt events during 1979–2017. *Weather Clim. Dyn.* **1**, 497–518 (2020).
59. Turner, J. et al. An extreme high temperature event in coastal east Antarctica associated with an atmospheric river and record summer downslope winds. *Geophys. Res. Lett.* **49**, e2021GL097108 (2022).
60. Bieli, M., Pfahl, S. & Wernli, H. A Lagrangian investigation of hot and cold temperature extremes in Europe. *Q. J. R. Meteorol. Soc.* **141**, 98–108 (2015).
61. Quinting, J. F. & Reeder, M. J. Southeastern Australian heat waves from a trajectory viewpoint. *Mon. Weather Rev.* **145**, 4109–4125 (2017).
62. Trigo, R. M., Trigo, I. F., DaCamara, C. C. & Osborn, T. J. Climate impact of the European winter blocking episodes from the NCEP/NCAR Reanalyses. *Clim. Dyn.* **23**, 17–28 (2004).
63. Galarneau, T. J., Hamill, T. M., Dole, R. M. & Perlwitz, J. A multiscale analysis of the extreme weather events over Western Russia and Northern Pakistan during July 2010. *Mon. Weather Rev.* **140**, 1639–1664 (2012).
64. Schneider, A. et al. Large-scale flow and the long-lasting blocking high over Russia: summer 2010. *Mon. Weather Rev.* **140**, 2967–2981 (2012).
65. Schumacher, D. L. et al. Amplification of mega-heatwaves through heat torrents fuelled by upwind drought. *Nat. Geosci.* **12**, 712 (2019).
66. Madonna, E., Wernli, H., Joos, H. & Martius, O. Warm conveyor belts in the ERA-Interim Dataset (1979–2010). Part I: Climatology and potential vorticity evolution. *J. Clim.* <https://doi.org/10.1175/JCLI-D-12-00720.1> (2014).
67. Browning, K. A. in *Extratropical Cyclones*, 129–153 (American Meteorological Society, 1990).
68. Pfahl, S., Schwierz, C., Croci-Maspoli, M., Grams, C. M. & Wernli, H. Importance of latent heat release in ascending air streams for atmospheric blocking. *Nat. Geosci.* **8**, 610–615 (2015).
69. Steinfeld, D. & Pfahl, S. The role of latent heating in atmospheric blocking dynamics: a global climatology. *Clim. Dyn.* **53**, 6159–6180 (2019).
70. Zschenderlein, P., Pfahl, S., Wernli, H. & Fink, A. H. A Lagrangian analysis of upper-tropospheric anticyclones associated with heat waves in Europe. *Weather Clim. Dyn.* **1**, 191–206 (2020).
71. Lehmann, J. & Coumou, D. The influence of mid-latitude storm tracks on hot, cold, dry and wet extremes. *Sci. Rep.* **5**, 3220 (2015).
72. Ratnam, J. V., Behera, S. K., Ratna, S. B., Rajeevan, M. & Yamagata, T. Anatomy of Indian heatwaves. *Sci. Rep.* **6**, 24395–11 (2016).
73. Branstator, G. Circumglobal teleconnections, the jet stream waveguide, and the North Atlantic Oscillation. *J. Clim.* **15**, 1893–1910 (2002).
74. Davies, H. C. Weather chains during the 2013/2014 winter and their significance for seasonal prediction. *Nat. Geosci.* **8**, 833–837 (2015).
75. O'Reilly, C. H., Woollings, T., Zanna, L. & Weisheimer, A. The impact of tropical precipitation on summertime Euro-Atlantic circulation via a circumglobal wave train. *J. Clim.* **31**, 6481–6504 (2018).
76. Röthlisberger, M. et al. Recurrent synoptic-scale Rossby wave patterns and their effect on the persistence of cold and hot spells. *J. Clim.* **32**, 3207–3226 (2019).
77. Teng, H., Branstator, G., Wang, H., Meehl, G. A. & Washington, W. M. Probability of US heat waves affected by a subseasonal planetary wave pattern. *Nat. Geosci.* **6**, 1056–1061 (2013).
78. Jiménez-Esteve, B. & Domeisen, D. I. The role of atmospheric dynamics and large-scale topography in driving heatwaves. *Q. J. R. Meteorol. Soc.* **148**, 2344–2367 (2022).
79. Petoukhov, V., Rahmstorf, S., Petri, S. & Schellnhuber, H. J. Quasiresonant amplification of planetary waves and recent Northern Hemisphere weather extremes. *Proc. Natl Acad. Sci. USA* **110**, 5336–5341 (2013).
80. Petoukhov, V. et al. Role of quasiresonant planetary wave dynamics in recent boreal spring-to-autumn extreme events. *Proc. Natl Acad. Sci. USA* **113**, 6862–6867 (2016).
81. Mann, M. E. et al. Influence of anthropogenic climate change on planetary wave resonance and extreme weather events. *Sci. Rep.* **7**, 45242 (2017).
82. Wirth, V., Riemer, M., Chang, E. K. M. & Martius, O. Rossby wave packets on the midlatitude waveguide — a review. *Mon. Weather Rev.* **146**, 1965–2001 (2018).
83. Fragkoulidis, G., Wirth, V., Bossmann, P. & Fink, A. H. Linking Northern Hemisphere temperature extremes to Rossby wave packets. *Q. J. R. Meteorol. Soc.* **144**, 553–566 (2018).
84. Röthlisberger, M., Pfahl, S. & Martius, O. Regional-scale jet waviness modulates the occurrence of midlatitude weather extremes. *Geophys. Res. Lett.* **43**, 10,989–10,997 (2016).
85. Hirschi, M. et al. Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. *Nat. Geosci.* **4**, 17–21 (2010).
86. Quesada, B., Vautard, R., Yiou, P., Hirschi, M. & Seneviratne, S. I. Asymmetric European summer heat predictability from wet and dry southern winters and springs. *Nat. Clim. Change* **2**, 736–741 (2012).
87. Miralles, D., Teuling, A. & Heerwaarden, C. Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. *Nat. Geosci.* **7**, 345–349 (2014).
88. Wehrl, K., Guillod, B. P., Hauser, M., Leclair, M. & Seneviratne, S. I. Identifying key driving processes of major recent heat waves. *J. Geophys. Res. Atmos.* **124**, 11746–11765 (2019).
89. Mueller, B. & Seneviratne, S. I. Hot days induced by precipitation deficits at the global scale. *Proc. Natl Acad. Sci. USA* **109**, 12398–12403 (2012).
90. Nissan, H., Burkart, K., Coughlan de Perez, E., Van Aalst, M. & Mason, S. Defining and predicting heat waves in Bangladesh. *J. Appl. Meteorol. Climatol.* **56**, 2653–2670 (2017).
91. Fischer, E., Seneviratne, S., Vidale, P., Lüthi, D. & Schär, C. Soil moisture: atmosphere interactions during the 2003 European summer heat wave. *J. Clim.* **20**, 5081–5099 (2007).
92. Haarsma, R. J., Selten, F., Hurk, B. v., Hazeleger, W. & Wang, X. Drier Mediterranean soils due to greenhouse warming bring easterly winds over summertime central Europe. *Geophys. Res. Lett.* <https://doi.org/10.1029/2008GL036617> (2009).
93. Zampieri, M. et al. Hot European summers and the role of soil moisture in the propagation of Mediterranean drought. *J. Clim.* **22**, 4747–4758 (2009).
94. Orth, R., Dutra, E. & Pappenberger, F. Improving weather predictability by including land surface model parameter uncertainty. *Mon. Weather Rev.* **144**, 1551–1569 (2016).
95. Seneviratne, S. I. et al. Impact of soil moisture-climate feedbacks on CMIP5 projections: first results from the GLACE-CMIP5 experiment. *Geophys. Res. Lett.* **40**, 5212–5217 (2013).
96. Schwingshackl, C., Hirschi, M. & Seneviratne, S. I. A theoretical approach to assess soil moisture-climate coupling across CMIP5 and GLACE-CMIP5 experiments. *Earth Syst. Dyn.* **9**, 1217–1234 (2018).
97. Jia, G. et al. in *Special Report on Climate Change and Land* (eds Shukla, P. R. et al.) Ch. 2, 131–247 (IPCC, in the press).
98. Teuling, A. J. et al. Contrasting response of European forest and grassland energy exchange to heatwaves. *Nat. Geosci.* **3**, 722–727 (2010).
99. Lejeune, Q., Davin, E. L., Gudmundsson, L., Winckler, J. & Seneviratne, S. I. Historical deforestation locally increased the intensity of hot days in northern mid-latitudes. *Nat. Clim. Change* **8**, 386–390 (2018).
100. Schwaab, J. et al. Increasing the broad-leaved tree fraction in European forests mitigates hot temperature extremes. *Sci. Rep.* **10**, 14153–9 (2020).
101. Thiery, W. et al. Present-day irrigation mitigates heat extremes. *J. Geophys. Res. Atmos.* **122**, 1403–1422 (2017).
102. Thiery, W. et al. Warming of hot extremes alleviated by expanding irrigation. *Nat. Commun.* **11**, 290–7 (2020).
103. Mueller, N. D. et al. Cooling of US Midwest summer temperature extremes from cropland intensification. *Nat. Clim. Change* **6**, 317–322 (2016).
104. Vogel, M. M. et al. Regional amplification of projected changes in extreme temperatures strongly controlled by soil moisture-temperature feedbacks. *Geophys. Res. Lett.* **44**, 1511–1519 (2017).
105. Vogel, M. M., Zscheischler, J. & Seneviratne, S. I. Varying soil moisture-atmosphere feedbacks explain divergent temperature extremes and precipitation projections in central Europe. *Earth Syst. Dyn.* **9**, 1107–1125 (2018).
106. Miralles, D. G., Gentile, P., Seneviratne, S. I. & Teuling, A. J. Land-atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges. *Ann. NY Acad. Sci.* **1436**, 19–35 (2019).
107. Guillod, B. P., Orlowsky, B., Miralles, D. G., Teuling, A. J. & Seneviratne, S. I. Reconciling spatial and temporal soil moisture effects on afternoon rainfall. *Nat. Commun.* **6**, 1–6 (2015).
108. Roundy, J. K., Ferguson, C. R. & Wood, E. F. Impact of land-atmospheric coupling in CFSv2 on drought prediction. *Clim. Dyn.* **43**, 421–434 (2014).
109. Black, E. & Sutton, R. The influence of oceanic conditions on the hot European summer of 2003. *Clim. Dyn.* **28**, 53–66 (2007).
110. Duchez, A. et al. Drivers of exceptionally cold North Atlantic Ocean temperatures and their link to the 2015 European heat wave. *Environ. Res. Lett.* **11**, 074004–10 (2016).
111. McKinnon, K. A., Rhines, A., Tingley, M. P. & Huybers, P. Long-lead predictions of eastern United States hot days from Pacific sea surface temperatures. *Nat. Geosci.* **9**, 389–394 (2016).
112. Vijverberg, S., Schmeits, M., Van der Wiel, K. & Coumou, D. Subseasonal statistical forecasts of eastern us hot temperature events. *Mon. Weather Rev.* **148**, 4799–4822 (2020).
113. Arblaster, J. M. & Alexander, L. V. The impact of the El Niño–Southern Oscillation on maximum temperature extremes. *Geophys. Res. Lett.* **39**, L20702 (2012).
114. Luo, M. & Lau, N.-C. Summer heat extremes in northern continents linked to developing ENSO events. *Environ. Res. Lett.* **15**, 074042 (2020).
115. Luo, M. & Lau, N.-C. Amplifying effect of ENSO on heat waves in China. *Clim. Dyn.* **52**, 3277–3289 (2019).
116. Naveena, N., Satyanarayana, G. C., Rao, K. K., Umakanth, N. & Srinivas, D. Heat wave characteristics over India during ENSO events. *J. Earth Syst. Sci.* **130**, 1–16 (2021).
117. Loikith, P. C. & Broccoli, A. J. The influence of recurrent modes of climate variability on the occurrence of winter and summer extreme temperatures over North America. *J. Clim.* **27**, 1600–1618 (2014).
118. Martija-Diez, M., Rodríguez-Fonseca, B. & López-Parages, J. ENSO influence on Western European summer and fall temperatures. *J. Clim.* **34**, 8013–8031 (2021).
119. Loughran, T. F., Pitman, A. J. & Perkins-Kirkpatrick, S. E. The El Niño–Southern Oscillation's effect on summer heatwave development mechanisms in Australia. *Clim. Dyn.* **52**, 6279–6300 (2019).
120. Reddy, P. J., Perkins-Kirkpatrick, S. E. & Sharples, J. J. Interactive influence of ENSO and IOD on contiguous heatwaves in Australia. *Environ. Res. Lett.* **17**, 014004 (2021).
121. Lee, Y.-Y. & Grotjahn, R. Evidence of specific MJO phase occurrence with summertime California Central Valley extreme hot weather. *Adv. Atmos. Sci.* **36**, 589–602 (2019).
122. Hsu, P.-C., Qian, Y., Liu, Y., Murakami, H. & Gao, Y. Role of abnormally enhanced MJO over the Western Pacific in the formation and subseasonal predictability of the record-breaking northeast Asian heatwave in the summer of 2018. *J. Clim.* **33**, 3333–3349 (2020).
123. Lopez, H. et al. East Asian monsoon as a modulator of US Great Plains heat waves. *J. Geophys. Res. Atmos.* **124**, 6342–6358 (2019).
124. Garcia-Herrera, R., Diaz, J., Trigo, R. M., Luterbacher, J. & Fischer, E. M. A review of the European summer heat wave of 2003. *Crit. Rev. Environ. Sci. Technol.* **40**, 267–306 (2010).

125. Black, E., Blackburn, M., Harrison, G., Hoskins, B. & Methven, J. Factors contributing to the summer 2003 European heatwave. *Weather* **59**, 217–223 (2004).
126. Feudale, L. & Shukla, J. Role of Mediterranean SST in enhancing the European heat wave of summer 2003. *Geophys. Res. Lett.* <https://doi.org/10.1029/2006GL027991> (2007).
127. Feudale, L. & Shukla, J. Influence of sea surface temperature on the European heat wave of 2003 summer. Part II: a modeling study. *Clim. Dyn.* **36**, 1705–1715 (2011).
128. Grotjahn, R. et al. North American extreme temperature events and related large scale meteorological patterns: a review of statistical methods, dynamics, modeling, and trends. *Clim. Dyn.* **46**, 1151–1184 (2015).
129. Sutton, R. Attributing extreme weather to climate change is not a done deal. *Nature* **561**, 177–177 (2018).
130. Garfinkel, C. I., White, I., Gerber, E. P., Jucker, M. & Erez, M. The building blocks of Northern Hemisphere wintertime stationary waves. *J. Clim.* <https://doi.org/10.1175/JCLI-D-19-01811> (2020).
131. Drouard, M., Kornhuber, K. & Woollings, T. Disentangling dynamic contributions to summer 2018 anomalous weather over Europe. *Geophys. Res. Lett.* **46**, 12537–12546 (2019).
132. Grazzini, F. & Vitart, F. Atmospheric predictability and Rossby wave packets. *Q. J. R. Meteorol. Soc.* **141**, 2793–2802 (2015).
133. Beverley, J. D. The Northern Hemisphere circumglobal teleconnection in a seasonal forecast model and its relationship to European summer forecast skill. *Clim. Dyn.* **52**, 3759–3771 (2019).
134. Tian, D., Wood, E. F. & Yuan, X. CFSv2-based sub-seasonal precipitation and temperature forecast skill over the contiguous United States. *Hydrol. Earth Syst. Sci.* **21**, 1477–1490 (2017).
135. Guigma, K. H., MacLeod, D., Todd, M. & Wang, Y. Prediction skill of Sahelian heatwaves out to subseasonal lead times and importance of atmospheric tropical modes of variability. *Clim. Dynam.* **57**, 537–556 (2021).
136. Coughlan de Perez, E. et al. Global predictability of temperature extremes. *Environ. Res. Lett.* **13**, 054017 (2018).
137. Lorenz, E. N. Deterministic nonperiodic flow. *J. Atmos. Sci.* **20**, 130–141 (1963).
138. Lorenz, E. N. The predictability of a flow which possesses many scales of motion. *Tellus* **21**, 289–307 (1969).
139. Hoskins, B. Predictability beyond the deterministic limit. *WMO Bull.* **61**, 33–36 (2012).
140. Vitart, F. & Robertson, A. W. The sub-seasonal to seasonal prediction project (S2S) and the prediction of extreme events. *npj Clim. Atmos. Sci.* **1**, 3 (2018).
141. Domeisen, D. I. et al. Advances in the subseasonal prediction of extreme events: relevant case studies across the globe. *Bull. Am. Meteorol. Soc.* <https://doi.org/10.1175/BAMS-D-20-02211> (2022).
142. Vitart, F. et al. *Sub-seasonal to Seasonal Prediction of Weather Extremes* Ch. 17 (Elsevier, 2019).
143. Mandal, R. et al. Real time extended range prediction of heat waves over India. *Sci. Rep.* **9**, 9008 (2019).
144. Magnusson, L., Emerton, R. & Simmons, A. *Spring heatwave in India and Pakistan* ECMWF Newsletter 172 (European Centre for Medium Range Weather Forecasts, 2022).
145. Wulff, C. O. & Domeisen, D. I. V. Higher subseasonal predictability of extreme hot European summer temperatures as compared to average summers. *Geophys. Res. Lett.* **46**, 11520–11529 (2019).
146. Lavaysse, C., Naumann, G., Alfieri, L., Salamon, P. & Vogt, J. Predictability of the European heat and cold waves. *Clim. Dyn.* **52**, 2481–2495 (2019).
147. Koster, R. D. et al. Contribution of land surface initialization to subseasonal forecast skill: first results from a multi-model experiment. *Geophys. Res. Lett.* <https://doi.org/10.1029/2009GL041677> (2010).
148. Vitart, F. & Balmaseda, M. *Impact of sea surface temperature biases on extended-range forecasts* (European Centre for Medium Range Weather Forecasts, 2018).
149. Beverley, J. et al. Dynamical mechanisms linking Indian monsoon precipitation and the circumglobal teleconnection. *Clim. Dynam.* **57**, 2615–2636 (2021).
150. Cassou, C., Terray, L. & Phillips, A. Tropical Atlantic influence on European heat waves. *J. Clim.* **18**, 2805–2811 (2005).
151. Liu, Q., Zhou, T., Mao, H. & Fu, C. Decadal variations in the relationship between the Western Pacific subtropical high and summer heat waves in east China. *J. Clim.* **32**, 1627–1640 (2019).
152. Lim, E.-P. et al. Australian hot and dry extremes induced by weakenings of the stratospheric polar vortex. *Nat. Geosci.* **12**, 896–901 (2019).
153. Miralles, D. G. et al. El Niño–La Niña cycle and recent trends in continental evaporation. *Nat. Clim. Change* **4**, 1–5 (2013).
154. Ardilouze, C. et al. Multi-model assessment of the impact of soil moisture initialization on mid-latitude summer predictability. *Clim. Dyn.* **49**, 3959–3974 (2017).
155. Weisheimer, A., Doblas-Reyes, F. J., Jung, T. & Palmer, T. N. On the predictability of the extreme summer 2003 over Europe. *Geophys. Res. Lett.* **38**, L05704 (2011).
156. Luo, L. & Zhang, Y. Did we see the 2011 summer heat wave coming? *Geophys. Res. Lett.* <https://doi.org/10.1029/2012GL051383> (2012).
157. Pepler, A. S., Diaz, L. B., Prodhomme, C., Doblas-Reyes, F. J. & Kumar, A. The ability of a multi-model seasonal forecasting ensemble to forecast the frequency of warm, cold and wet extremes. *Weather Clim. Extremes* **9**, 68–77 (2015).
158. Prodhomme, C. et al. Seasonal prediction of European summer heatwaves. *Clim. Dynam.* **58**, 2149–2166 (2021).
159. Doblas Reyes, F. J. & Hagedorn, R. Impact of increasing greenhouse gas concentrations in seasonal ensemble forecasts. *Geophys. Res. Lett.* <https://doi.org/10.1029/2005GL025061> (2006).
160. Ardilouze, C., Batté, L., Déqué, M., van Meijgaard, E. & van den Hurk, B. Investigating the impact of soil moisture on European summer climate in ensemble numerical experiments. *Clim. Dyn.* **52**, 4011–4026 (2019).
161. Hauser, M., Orth, R. & Seneviratne, S. I. Role of soil moisture versus recent climate change for the 2010 heat wave in western Russia. *Geophys. Res. Lett.* **43**, 2819–2826 (2016).
162. Eade, R., Hamilton, E., Smith, D., Graham, R. & Scaife, A. Forecasting the number of extreme daily events out to a decade ahead. *J. Geophys. Res.* <https://doi.org/10.1029/2012JD018015> (2012).
163. Hanlon, H., Hegerl, G., Tett, S. & Smith, D. Can a decadal forecasting system predict temperature extreme indices? *J. Clim.* **26**, 3728–3744 (2013).
164. IPCC. Summary for Policymakers. In *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) (Cambridge Univ. Press, 2021).
165. Dosio, A. Projection of temperature and heat waves for Africa with an ensemble of corDEX regional climate models. *Clim. Dyn.* **49**, 493–519 (2017).
166. Perkins-Kirkpatrick, S. & Gibson, P. Changes in regional heatwave characteristics as a function of increasing global temperature. *Sci. Rep.* **7**, 1–12 (2017).
167. Seneviratne, S. I., Donat, M. G., Pitman, A. J., Knutti, R. & Wilby, R. L. Allowable CO<sub>2</sub> emissions based on regional and impact-related climate targets. *Nature* **529**, 477–483 (2016).
168. Wartenburger, R. et al. Changes in regional climate extremes as a function of global mean temperature: an interactive plotting framework. *Geosci. Model Dev. Discussions* **10**, 3609–3634 (2017).
169. Fischer, E. M. & Schär, C. Consistent geographical patterns of changes in high-impact European heatwaves. *Nat. Geosci.* **3**, 398–403 (2010).
170. Ballester, J., Giorgi, F. & Rodó, X. Changes in European temperature extremes can be predicted from changes in PDF central statistics. *Clim. Change* **98**, 277–284 (2010).
171. Suarez-Gutierrez, L., Müller, W. A., Li, C. & Marotzke, J. Dynamical and thermodynamical drivers of variability in European summer heat extremes. *Clim. Dynam.* **54**, 4351–4366 (2020).
172. Rogers, C. D., Kornhuber, K., Perkins-Kirkpatrick, S. E., Loikith, P. C. & Singh, D. Sixfold increase in historical Northern Hemisphere concurrent large heatwaves driven by warming and changing atmospheric circulations. *J. Clim.* **35**, 10663–10678 (2022).
173. Fischer, E. M. & Schär, C. Future changes in daily summer temperature variability: driving processes and role for temperature extremes. *Clim. Dyn.* **33**, 917 (2009).
174. Seneviratne, S. I., Koster, R. D. & Guo, Z. Soil moisture memory in AGCM simulations: analysis of Global Land-atmosphere Coupling Experiment (GLACE) data. *J. Hydrometeorol.* **7**, 1090–1112 (2006).
175. Cattiaux, J., Douville, H., Schoetter, R., Parey, S. & Yiou, P. Projected increase in diurnal and interdiurnal variations of European summer temperatures. *Geophys. Res. Lett.* **42**, 899–907 (2015).
176. Fischer, E. M. & Knutti, R. Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nat. Clim. Change* **5**, 560–564 (2015).
177. Li, C. et al. Changes in annual extremes of daily temperature and precipitation in CMIP6 models. *J. Clim.* **34**, 3441–3460 (2021).
178. Harrington, L. J. et al. Poorest countries experience earlier anthropogenic emergence of daily temperature extremes. *Environ. Res. Lett.* **11**, 055007 (2016).
179. Almazroui, M. et al. Projected changes in climate extremes using CMIP6 simulations over SREX regions. *Earth Systems and Environment* **5**, 481–497 (2021).
180. Freychet, N., Hegerl, G., Mitchell, D. & Collins, M. Future changes in the frequency of temperature extremes may be underestimated in tropical and subtropical regions. *Commun. Earth Environ.* **2**, 1–8 (2021).
181. Cowan, T. et al. More frequent, longer, and hotter heat waves for Australia in the twenty-first century. *J. Clim.* **27**, 5851–5871 (2014).
182. Vogel, M. M., Zscheischler, J., Fischer, E. M. & Seneviratne, S. I. Development of future heatwaves for different hazard thresholds. *J. Geophys. Res. Atmos.* **125**, e2019JD032070 (2020).
183. Fischer, E. M., Sippel, S. & Knutti, R. Increasing probability of record-shattering climate extremes. *Nat. Clim. Change* **11**, 689–695 (2021).
184. Philip, S. Y. et al. *Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021* (World Weather Attribution, 2021); <https://www.worldweatherattribution.org/wp-content/uploads/NW-US-extreme-heat-2021-scientific-report-WWA.pdf>
185. Zachariah, M. et al. *Without human-caused climate change temperatures of 40°C in the UK would have been extremely unlikely* (World Weather Attribution, 2022); <https://www.worldweatherattribution.org/wp-content/uploads/UK-heat-scientific-report.pdf>
186. Sherwood, S. & Fu, Q. Climate change. A drier future? *Science* **343**, 737–739 (2014).
187. Byrne, M. P. & O’Gorman, P. A. Land–ocean warming contrast over a wide range of climates: convective quasi-equilibrium theory and idealized simulations. *J. Clim.* **26**, 4000–4016 (2013).
188. Brogli, R., Kröner, N., Sørland, S. L., Lüthi, D. & Schär, C. The role of Hadley circulation and lapse-rate changes for the future European summer climate. *J. Clim.* **32**, 385–404 (2019).
189. Bladé, I., Liebmann, B., Fortuny, D. & van Oldenborgh, G. J. Observed and simulated impacts of the summer NAO in Europe: implications for projected drying in the Mediterranean region. *Clim. Dyn.* **39**, 709–727 (2012).
190. Shepherd, T. Atmospheric circulation as a source of uncertainty in climate change projections. *Nat. Geosci.* **7**, 703–708 (2014).
191. Shepherd, T. G. Climate science: the dynamics of temperature extremes. *Nature* **522**, 425–427 (2015).

192. Harvey, B., Cook, P., Shaffrey, L. & Schiemann, R. The response of the Northern Hemisphere storm tracks and jet streams to climate change in the CMIP3, CMIP5, and CMIP6 climate models. *J. Geophys. Res. Atmos.* **125**, e2020JD032701 (2020).
193. Woollings, T. et al. Blocking and its response to climate change. *Curr. Clim. Change Rep.* **4**, 287–300 (2018).
194. Nabizadeh, E., Lubis, S. & Hassanzadeh, P. The 3D structure of Northern Hemisphere blocking events: climatology, role of moisture, and response to climate change. *J. Clim.* <https://doi.org/10.1175/JCLI-D-21-0141.1> (2021).
195. Dunn Sigouin, E. & Son, S.-W. Northern Hemisphere blocking frequency and duration in the CMIP5 models. *J. Geophys. Res. Atmos.* **118**, 1179–1188 (2013).
196. Davini, P. & D'Andrea, F. From CMIP3 to CMIP6: Northern Hemisphere atmospheric blocking simulation in present and future climate. *J. Clim.* **33**, 10021–10038 (2020).
197. Gillett, N. P. & Fyfe, J. C. Annular mode changes in the CMIP5 simulations. *Geophys. Res. Lett.* **40**, 1189–1193 (2013).
198. Hanna, E., Cropper, T. E., Hall, R. J. & Cappelen, J. Greenland Blocking Index 1851–2015: a regional climate change signal. *Int. J. Climatol.* **36**, 4847–4861 (2016).
199. Hanna, E., Fettweis, X. & Hall, R. J. Brief communication: recent changes in summer Greenland blocking captured by none of the CMIP5 models. *Cryosphere* **12**, 3287–3292 (2018).
200. Masato, G., Hoskins, B. J. & Woollings, T. Winter and summer Northern Hemisphere blocking in CMIP5 Models. *J. Clim.* **26**, 7044–7059 (2013).
201. Barnes, E. A., Dunn Sigouin, E., Masato, G. & Woollings, T. Exploring recent trends in Northern Hemisphere blocking. *Geophys. Res. Lett.* **41**, 638–644 (2014).
202. Schwartz, C., Garfinkel, C. I., Yadav, P., Chen, W. & Domeisen, D. Stationary waves and upward troposphere-stratosphere coupling in S2S models. *Weather Clim. Dynam.* **3**, 679–692 (2022).
203. Simpson, I. R., Seager, R., Ting, M. & Shaw, T. A. Causes of change in Northern Hemisphere winter meridional winds and regional hydroclimate. *Nat. Clim. Change* **6**, 65–70 (2016).
204. Neelin, J. D., Langenbrunner, B., Meyerling, J. E., Hall, A. & Berg, N. California winter precipitation change under global warming in the Coupled Model Intercomparison Project Phase 5 Ensemble. *J. Clim.* **26**, 6238–6256 (2013).
205. Schiemann, R. et al. The resolution sensitivity of Northern Hemisphere blocking in four 25-km atmospheric global circulation models. *J. Clim.* **30**, 337–358 (2017).
206. Schiemann, R. et al. Northern Hemisphere blocking simulation in current climate models: evaluating progress from the Climate Model Intercomparison Project Phase 5 to 6 and sensitivity to resolution. *Weather Clim. Dyn.* **1**, 277–292 (2020).
207. Birch, C. et al. Future changes in African heatwaves and their drivers at the convective scale. *J. Clim.* **35**, 5981–6006 (2022).
208. Dwyer, I. J., Barry, S. J., Megidlo, I. & White, C. J. Evaluations of heat action plans for reducing the health impacts of extreme heat: methodological developments (2012–2021) and remaining challenges. *Int. J. Biometeorol.* **66**, 1915–1927 (2022).
209. Hazeleger, W. et al. Tales of future weather. *Nat. Clim. Change* **5**, 107–113 (2015).
210. Wehrli, K., Hauser, M. & Seneviratne, S. I. Storylines of the 2018 Northern Hemisphere heatwave at pre-industrial and higher global warming levels. *Earth Syst. Dyn.* **11**, 855–873 (2020).
211. Zappa, G. & Shepherd, T. G. Storylines of atmospheric circulation change for European Regional Climate Impact Assessment. *J. Clim.* **30**, 6561–6577 (2017).
212. Shepherd, T. G. et al. Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Clim. Change* **151**, 555–571 (2018).
213. Sillmann, J. & Sippel, S. Climate extremes and their implications for impact and risk assessment: a short introduction. In *Climate Extremes and Their Implications for Impact and Risk Assessment* (eds Sillmann, J. et al.) 1–9 (Elsevier, 2020).
214. Shepherd, T. G. Storyline approach to the construction of regional climate change information. *Proc. R. Soc. A* <https://doi.org/10.1098/rspa.2019.0013> (2019).
215. Gessner, C., Fischer, E. M., Beyerle, U. & Knutti, R. Very rare heat extremes: quantifying and understanding using ensemble reinitialization. *J. Clim.* **34**, 6619–6634 (2021).
216. Yiou, P. & Jézéquel, A. Simulation of extreme heat waves with empirical importance sampling. *Geosci. Model Dev. Discussions* **13**, 763–781 (2020).
217. Ragone, F. & Bouchet, F. Rare event algorithm study of extreme warm summers and heatwaves over Europe. *Geophys. Res. Lett.* **48**, e2020GL091197 (2021).
218. Runge, J. Causal network reconstruction from time series: from theoretical assumptions to practical estimation. *Chaos* **28**, 075310 (2018).
219. Runge, J., Nowack, P., Kretschmer, M., Flaxman, S. & Sejdinovic, D. Detecting and quantifying causal associations in large nonlinear time series datasets. *Sci. Adv.* <https://doi.org/10.1126/sciadv.aau4996> (2019).
220. Di Capua, G. et al. Dominant patterns of interaction between the tropics and mid-latitudes in boreal summer: causal relationships and the role of timescales. *Weather Clim. Dyn.* **1**, 519–539 (2020).
221. Kretschmer, M., Runge, J. & Coumou, D. Early prediction of extreme stratospheric polar vortex states based on causal precursors. *Geophys. Res. Lett.* **44**, 8592–8600 (2017).
222. van Straaten, C., Whan, K., Coumou, D., van den Hurk, B. & Schmeits, M. Using explainable machine learning forecasts to discover subseasonal drivers of high summer temperatures in western and central Europe. *Mon. Weather Rev.* **150**, 1115–1134 (2022).
223. Benet, E. W. et al. Sub-seasonal prediction of central European summer heatwaves with linear and random forest machine learning models. *EarthArXiv preprint* at <https://doi.org/10.31223/X5663G> (2022).
224. Chattopadhyay, A., Nabizadeh, E. & Hassanzadeh, P. Analog forecasting of extreme-causing weather patterns using deep learning. *J. Adv. Model. Earth Syst.* <https://doi.org/10.1029/2019MS001958> (2020).
225. Hazeleger, W., Jones, C., McGrath, R. & Hesselbjerg-Christensen, J. EC-Earth: a seamless prediction approach to Earth System modelling. *IOP Conf. Ser. Earth Environ. Sci.* **6**, 052002 (2009).
226. Palmer, T. N., Doblado-Reyes, F. J., Weisheimer, A. & Rodwell, M. J. Toward seamless prediction: calibration of climate change projections using seasonal forecasts. *Bull. Am. Meteorol. Soc.* **89**, 459–470 (2008).
227. Meehl, G. A. et al. Initialized Earth System prediction from subseasonal to decadal timescales. *Nat. Rev. Earth Environ.* **2**, 340–357 (2021).
228. Ford, T. W., Dirmeyer, P. A. & Benson, D. O. Evaluation of heat wave forecasts seamlessly across subseasonal timescales. *npj Clim. Atmos. Sci.* **1**, 20 (2018).
229. Merryfield, W. J. et al. Current and emerging developments in subseasonal to decadal prediction. *Bull. Am. Meteorol. Soc.* <https://doi.org/10.1175/BAMS-D-19-0037.1> (2020).
230. Leach, N. J., Weisheimer, A., Allen, M. R. & Palmer, T. Forecast-based attribution of a winter heatwave within the limit of predictability. *Proc. Natl Acad. Sci. USA* **118**, e2112087118 (2021).
231. Wulff, C. O., Vitart, F. & Domeisen, D. I. Influence of trends on subseasonal temperature prediction skill. *Q. J. R. Meteorol. Soc.* **148**, 1280–1299 (2022).
232. Mora, C. et al. Global risk of deadly heat. *Nat. Clim. Change* **7**, 501–506 (2017).
233. Salagnac, J.-L. Lessons from the 2003 heat wave: a French perspective. *Build. Res. Inf.* **35**, 450–457 (2011).
234. Wouters, H. et al. Soil drought can mitigate deadly heat stress thanks to a reduction of air humidity. *Sci. Adv.* **8**, eabe6653 (2022).
235. Fahad, S. et al. Crop production under drought and heat stress: plant responses and management options. *Front. Plant Sci.* <https://doi.org/10.3389/fpls.2017.0> (2017).
236. Vicedo-Cabrera, A. M. et al. Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios. *Clim. Change* **150**, 391–402 (2018).
237. Vitart, F. et al. The Subseasonal to Seasonal (S2S) Prediction Project database. *Bull. Am. Meteorol. Soc.* **98**, 163–173 (2017).
238. Hersbach, H. et al. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **64**, 29 (2020).
239. Gutiérrez, J. et al. Atlas. In *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) (IPCC, Cambridge Univ. Press, 2021); <http://interactive-atlas.ipcc.ch/>
240. Perkins, S. E. & Alexander, L. V. On the measurement of heat waves. *J. Clim.* **26**, 4500–4517 (2013).
241. Hobday, A. J. et al. A hierarchical approach to defining marine heatwaves. *Progr. Oceanogr.* **141**, 227–238 (2016).
242. Zhang, X. et al. Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Wiley Interdiscip. Rev. Clim. Change* **2**, 851–870 (2011).
243. Meehl, G. A. & Tebaldi, C. More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* **305**, 994–997 (2004).
244. Russo, S. et al. Magnitude of extreme heat waves in present climate and their projection in a warming world. *J. Geophys. Res. Atmos.* **119**, 12–500 (2014).
245. Schoetter, R., Cattiaux, J. & Douville, H. Changes of Western European heat wave characteristics projected by the CMIP5 ensemble. *Clim. Dyn.* **45**, 1601–1616 (2015).
246. Feron, S. et al. Observations and projections of heat waves in South America. *Sci. Rep.* **9**, 1–15 (2019).
247. Russo, S., Sillmann, J. & Fischer, E. M. Top ten European heatwaves since 1950 and their occurrence in the coming decades. *Environ. Res. Lett.* **10**, 124003 (2015).
248. Perkins, S. E., Argueeso, D. & White, C. J. Relationships between climate variability, soil moisture, and Australian heatwaves. *J. Geophys. Res. Atmos.* **120**, 8144–8164 (2015).
249. Sippel, S., Zscheischler, J. & Reichstein, M. Ecosystem impacts of climate extremes crucially depend on the timing. *Proc. Natl Acad. Sci. USA* **113**, 5768–5770 (2016).
250. Sharples, J. J., Lewis, S. C. & Perkins-Kirkpatrick, S. E. et al. Modulating influence of drought on the synergy between heatwaves and dead fine fuel moisture content of bushfire fuels in the southeast Australian region. *Weather Clim. Extremes* **31**, 100300 (2021).
251. Gruber, S., Hoelzle, M. & Haerberli, W. Permafrost thaw and destabilization of alpine rock walls in the hot summer of 2003. *Geophys. Res. Lett.* <https://doi.org/10.1029/2004GL020051> (2004).
252. Ravanel, L., Magnin, F. & Deline, P. Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif. *Sci. Total Environ.* **609**, 132–143 (2017).
253. Vogel, M. M., Zscheischler, J., Wartenburger, R., Dee, D. & Seneviratne, S. I. Concurrent 2018 hot extremes across Northern Hemisphere due to human-induced climate change. *Earth's Future* **7**, 692–703 (2019).
254. Seneviratne, S. I., Donat, M. G., Mueller, B. & Alexander, L. V. No pause in the increase of hot temperature extremes. *Nat. Clim. Change* **4**, 161–163 (2014).
255. Sippel, S. et al. Quantifying changes in climate variability and extremes: pitfalls and their overcoming. *Geophys. Res. Lett.* **42**, 9990–9998 (2015).
256. Stefanou, M., D'Andrea, F. & Drobinski, P. Heatwave classification over Europe and the Mediterranean region. *Environ. Res. Lett.* **7**, 014023 (2012).
257. Lyon, B., Barnston, A. G., Coffel, E. & Horton, R. M. Projected increase in the spatial extent of contiguous US summer heat waves and associated attributes. *Environ. Res. Lett.* **14**, 114029 (2019).
258. Baldwin, J. W., Dessy, J. B., Vecchi, G. A. & Oppenheimer, M. Temporally compound heat wave events and global warming: an emerging hazard. *Earth's Future* **7**, 411–427 (2019).
259. Sherwood, S. C. & Huber, M. An adaptability limit to climate change due to heat stress. *Proc. Natl Acad. Sci. USA* **107**, 9552–9555 (2010).
260. Vicedo-Cabrera, A. M. et al. The burden of heat-related mortality attributable to recent human-induced climate change. *Nat. Clim. Change* **11**, 492–500 (2021).

261. Russo, S., Sillmann, J. & Sterl, A. Humid heat waves at different warming levels. *Sci. Rep.* **7**, 1–7 (2017).
262. Buzan, J., Oleson, K. & Huber, M. Implementation and comparison of a suite of heat stress metrics within the Community Land Model version 4.5. *Geosci. Model Dev.* **8**, 151–170 (2015).
263. Raymond, C. et al. On the controlling factors for globally extreme humid heat. *Geophys. Res. Lett.* **48**, e2021GL096082 (2021).
264. Xue, P. & Eltahir, E. A. Estimation of the heat and water budgets of the Persian (Arabian) Gulf using a regional climate model. *J. Clim.* **28**, 5041–5062 (2015).
265. Kang, S. & Eltahir, E. A. B. North China Plain threatened by deadly heatwaves due to climate change and irrigation. *Nat. Commun.* **9**, 1–9 (2018).
266. Pal, J. S. & Eltahir, E. A. Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nat. Clim. Change* **6**, 197–200 (2016).
267. Im, E.-S., Pal, J. S. & Eltahir, E. A. B. Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Sci. Adv.* **3**, e1603322 (2017).
268. Nageswararao, M., Sinha, P., Mohanty, U. & Mishra, S. Occurrence of more heat waves over the central east coast of India in the recent warming era. *Pure Appl. Geophys.* **177**, 1143–1155 (2020).
269. Tuel, A., Choi, Y.-W., AlRukaibi, D. & Eltahir, E. A. B. Extreme storms in southwest Asia (Northern Arabian Peninsula) under current and future climates. *Clim. Dynam.* **58**, 1509–1524 (2021).
270. Pyrina, M. & Domeisen, D. I. V. Sub-seasonal predictability of onset, duration, and intensity of European heat extremes. *Q. J. R. Meteorol. Soc.* <https://doi.org/10.1002/qj.4394> (2022).

## Acknowledgements

The authors thank Y.-W. Choi for help with creating the Box figure and R. W.-Y. Wu for the data download for Fig. 4. Support from the Swiss National Science Foundation through projects PPOOP2\_170523 and PPOOP2\_198896 to D.I.V.D. is gratefully acknowledged. S.E.P.-K. is supported by Australian Research Council grant numbers FT170100106 and CE170100023. A.W. received funding from the EU Horizon 2020 Project European Climate Prediction system

(EUCP) grant agreement 776613. S.I.S. acknowledges funding from the EU Horizon 2020 Project XAIDA (grant agreement 101003469). E.M.F. acknowledges funding from the EU Horizon 2020 Project XAIDA (grant agreement 101003469) and by the Swiss National Science Foundation (grant 200020\_178778).

## Author contributions

D.I.V.D. initiated and led the Review, wrote the draft manuscript and created Figs. 2–5. C.S. made Fig. 1 and E.A.B.E. the box figure. All authors contributed to the writing and/or editing of the Review and gave feedback on the figures.

## Competing interests

The authors declare no competing interests.

## Additional information

**Correspondence** should be addressed to Daniela I. V. Domeisen.

**Peer review information** *Nature Reviews Earth & Environment* thank Dáithí Stone and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

**Reprints and permissions information** is available at [www.nature.com/reprints](http://www.nature.com/reprints).

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

© Springer Nature Limited 2022