Projections and Hazards of Future Extreme Heat

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Abstract and Keywords

This chapter surveys how the state of knowledge about the physical processes that cause extreme heat and the societal factors that determine its impacts can be used to better predict these aspects of future climate change. Covering global projections; event attribution; atmospheric dynamics; regional and local effects; and impacts on health, agriculture, and the economy, this chapter aims to provide a guide to the rapidly growing body of literature on extreme heat and its impacts, as well as to highlight where there remain significant areas in need of further research.

Keywords: climate extremes, heat projections, event attribution, heat-wave dynamics, regional climate feedbacks, urban heat islands, agricultural heat impacts

Introduction

Many lines of evidence converge on the conclusion that the heat extremes of the next fifty to one hundred years will be more severe, by any measure, than those of the past. As global mean temperatures increase, heat extremes and their impacts increase at an even faster rate, a consequence of pure statistics as well as a web of feedbacks involving atmospheric and cryospheric dynamics, ecological responses, and economic and social behaviors. This complexity means that there is much yet to discover about the changing behavior of heat extremes of particular kinds and under particular conditions, even if the overall picture is clear. The impacts of extreme heat on agriculture, health, productivity, and the environment, combined with the growing wealth and interconnectedness of the global population, mean that adapting successfully to the future will require more than just turning up the air conditioning. Understanding what hazards extreme heat presents, where these hazards will be located, and when they can be expected are therefore key pieces of knowledge, and climate scientists are tackling these questions with increasing determination and success. The results discussed here provide evidence for the benefits of such research programs in preparing for a hotter and ever more human-managed world.

Global Projections

Multiple studies have established that extreme heat is increasing over nearly the entire globe (Coumou & Rahmstorf, 2012; Meehl & Tebaldi, 2004; Russo, Sillmann, & Sterl, 2017). In the coming decades, the global land fraction with a high probability of occurrence of extreme heat is expected to continue to increase at a rapid rate (Sillmann, Kharin, Zhang, Zwiers, & Bronaugh, 2013). According to many studies, the most exceptional heat wave in the modern observational record occurred in Russia in 2010 (Barriopedro, Fischer, Luterbacher, Trigo, & Garcia-Herrera, 2011; Russo, Sillmann, & Fischer, 2015; Russo, Sillmann, & Sterl, 2017), perhaps rivaled only by the western European heat wave of 2003 (Coumou & Rahmstorf, 2012; Luterbacher, Dietrich, Xoplaki, Grosjean, & Wanner, 2004). According to Coupled Model Intercomparison Project Phase 5 [CMIP5] simulations, heat like that which characterized these events is expected to occur regularly in the future, as the probability of occurrence of heat waves exceeding various extreme thresholds is a strong function of global mean temperature (Russo et al., 2017; Russo & Sterl, 2011; Sillmann et al., 2013). Under the most severe CMIP5 emissions scenarios, global climate projections show an approximately sixfold increase by 2100 in the number of annual nights and days with temperatures above the 1961–1990 90th percentile, accompanied by increases in annual maximum nighttime and daytime temperature of 6.7°C and 5.4°C respectively (Sillmann et al., 2013).

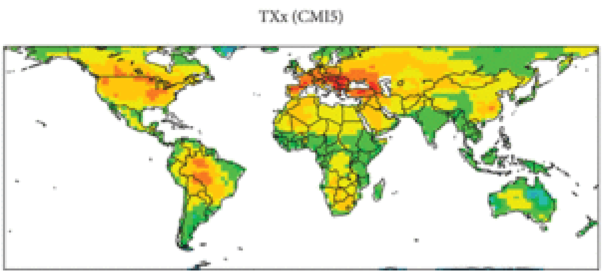
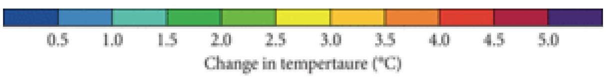


Figure 1A Projected changes in intensity of hot extremes in 2041-2060 with respect to 1986-2005 for multimodel-mean average changes across 25 CMIP5 models for the RCP8.5 scenario.

Source: Fischer et al. 2013



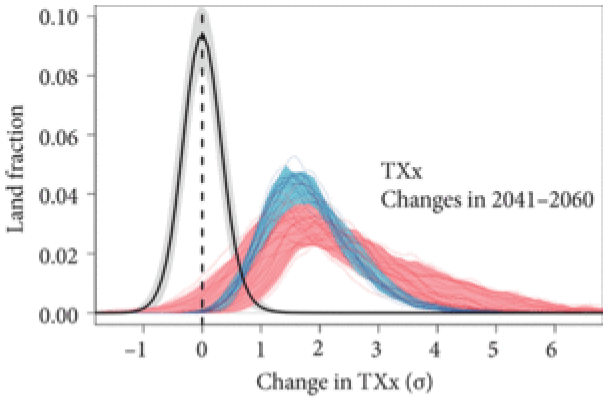
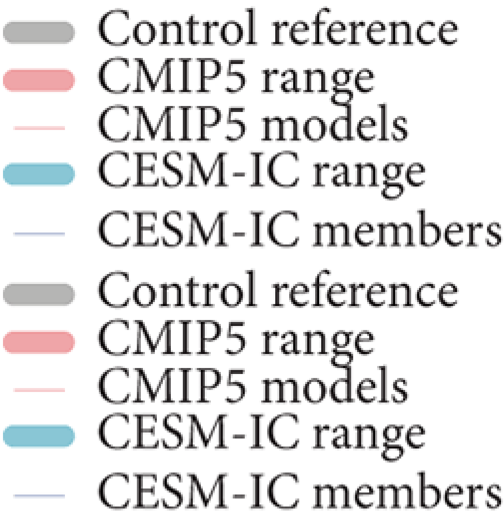


Figure 1B Probability distribution function of the land fraction (66◦S-66◦N) experiencing a certain 20-year mean change in hot extremes in 2041-2060 relative to 1986-2005. Red lines mark individual CMIP5 models and red shading the 5th to 95th percentile across the models for each bin. Likewise, blue lines show individual CESM-IC members and blue shading the respective inter-model range. Changes owing to internal variability are shown as gray shading, with the solid black line marking the mean. Twenty-year mean changes at each grid point are normalized by the interannual standard deviation of the annual extreme index value for 1986-2005.

Source: Fischer et al. 2013



All heat-related climate extremes indices show a general increase in the coming decades. Consequently, heat waves are expected to become longer and more intense (Meehl & Tebaldi, 2004). These increases will also result in values above anything yet recorded. They are especially robust for regions where hot days occur in combination with high relative humidity, due to the strong dependence of apparent temperature on humidity (Mora et al., 2017a; Russo et al., 2017). In regions such as the midwestern and eastern United States, eastern China, northern Latin America, and southern Asia, high relative humidity amplifies the effect of extreme heat that occurs under high-pressure systems (Conti et al., 2005; Dematte et al., 1998; Fischer et al., 2012; Im, Pal, & Eltahir, 2017). The high health impacts of the Chicago heat wave of 1995 and the Shanghai heat wave of 2003 were in large part attributable to high relative humidity (Russo et al., 2017). Heat and humidity are expected to occur in such extreme combinations by the end of the century as to put into serious question the habitability of densely populated parts of the Persian Gulf and South Asia (Im et al., 2017; Pal & Eltahir, 2015).

Future extreme heat will have multiple and severe impacts, not least on human health, economic productivity, and ecosystems through the heightened risk of hyperthermia in humans and other endothermic animals (Crimmins et al., 2016; Sherwood et al., 2010; Sherwood & Huber, 2010). Due to the humidity and urban-heat-island effects across highly density populated cities, it is there that future extreme heat is projected to reach its most severe values (Argüeso, Evans, Fita, & Bormann, 2014; Im et al., 2017; Mora et al., 2017a).

Event Attribution and Time of Emergence

Extreme heat events are projected to become more frequent and intense around the world in the coming century. But, we can already observe and quantify the effects of anthropogenic climate change on extreme heat events occurring in today's climate, and answer questions like:

1. *Did climate change alter the likelihood or intensity of this event?*
2. *When did the fingerprint of climate change first emerge for events like this, or when will it emerge in the future?*

There is a growing area of climate science called event attribution that specifically seeks to answer questions of the first type. Climate simulations representing the world of today, including the human contribution to greenhouse gases and aerosols, are compared with climate simulations where those human contributions have been removed. If there is a statistically significant difference in the frequency or intensity of the extreme event in question between those two groups of simulations, then a probabilistic statement of the influence of climate change can be made (e.g., climate change doubled the likelihood of a given extreme heat event).

Event attribution is useful both in terms of increasing scientific understanding of how an event and the associated relevant processes have changed, and in communicating the effects of climate change to the public. In the last decade and a half there have been numerous attribution studies of extreme heat events including the first event-specific attribution study, which found that human-caused climate change at least doubled the likelihood of the European record hot summer of 2003 (Stott, Stone, & Allen, 2004). Event attribution analyses have since been conducted on other heat waves, such as in Russia in 2010 (Dole et al., 2011; Otto, Massey, van Oldenborgh, Jones, & Allen, 2012; Rahmstorf & Coumou, 2011), and also shorter-duration smaller-scale heat extremes where the climate-change signal is harder to detect, such as the heat wave during the Australian Open tennis tournament in Melbourne in 2014 (Black, Karoly, & King, 2015).

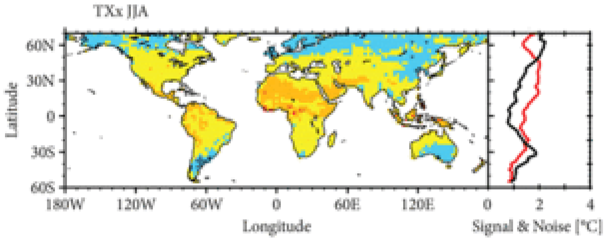


Figure 2A Median time of anthropogenic emergence and zonally averaged signal and noise across 23 model simulations for highest daily maximum temperature in boreal summer. Signal (red) is defined as the mean difference between 1989-2039 and 1860-1910, and noise (black) is the standard deviation for 1860-1910.

Source: King et al. 2015

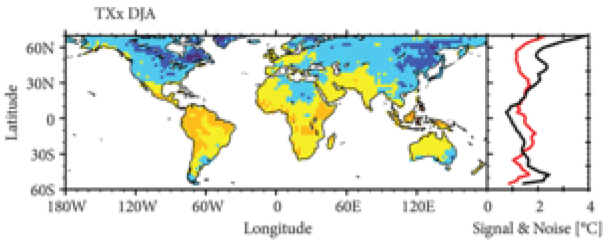


Figure 2B Median time of anthropogenic emergence and zonally averaged signal and noise across 23 model simulations for highest daily maximum temperature in austral summer. Signal (red) is defined as the mean difference between 1989-2039 and 1860-1910, and noise (black) is the standard deviation for 1860-1910.

Source: King et al. 2015

The results of event attribution studies are often misinterpreted, so clear communication of findings is vital. This can be achieved by scientists writing their own articles for the media and through working with journalists to tailor the message that needs to be delivered. The use of phrases such as "very likely" or "highly unlikely" to accompany quantitative statements can aid the public in correctly interpreting the conclusions of event analyses. For a fuller discussion of event attribution the reader is referred to several review papers on the topic (Easterling, Kunkel, Wehner, & Sun, 2016; Otto, et al., 2016; Stott et al., 2016).

The second type of question can be answered by considering the "time of emergence" of extreme events. If our "real" and "counterfactual" sets of simulations are both transient (i.e., the climate reacts as human society continues to affect it), we can look backward or forward in time and estimate when the statistically detectable human influence on a given extreme heat event first appeared or will appear in future.

Recent record-breaking hot summers in many regions of the world have been found to be both more likely to occur and more intense due to anthropogenic climate change. For example, the record hot "Angry Summer" of 2012/13 in Australia was made at least 2.5 times as likely by anthropogenic climate change (Lewis & Karoly, 2013). In addition, previous record hot summers in Australia, like 1997–1998, can also be attributed to human influences on the climate (King et al., 2016). It is harder to detect the anthropogenic influence in more localized heat extremes and shorter events, due to the greater natural spatiotemporal variability on these scales, so generally for these events the signal has yet to emerge from the statistical noise.

Analyses of heat waves and hot summers over recent decades and the past century show that human-caused climate change is already altering the likelihood and intensity of extreme heat events. As the effects of climate change become more pervasive, the human influence on extreme heat will continue to increase and become clearer on shorter timescales and for smaller regions.

Dynamical Mechanisms

Evidence is mounting that, partly due to dynamical changes, midlatitude heat waves are intensifying more than what would be expected from only the thermodynamic warming effect induced by greenhouse gases (Horton, Mankin, Lesk, Coffel, & Raymond, 2016; Mann et al., 2017; Petoukhov, Rahmstorf, Petri, Schellnhuber, & Joachim, 2013). Recent heat waves in Russia in 2010 and Europe in 2015 and 2017 are exemplary. They were intensified by anomalously persistent dynamics and concomitant land-atmosphere feedbacks (Lhotka, Kysely, & Plavcová, 2018; Miralles, Teuling, van Heerwaarden, & De Arellano, 2014). In Figure 1 we elaborate on how specific midlatitude circulation states favor heat waves. The following text describes why dynamical changes are expected; what changes have been observed; what changes are projected for the future; and how these changes affect heat wave genesis and persistence. We focus on the midlatitudes since extreme heat there is much more driven by large-scale dynamics than is the case in the tropics.

Midlatitude heat waves are substantially more likely to occur during persistent high-pressure systems (anticyclonic circulations) (Alvarez-Castro, Faranda, & Yiou, 2018; Horton et al., 2016; Jézéquel et al., 2018; Pfahl, 2014). Trends in the frequency of persistent anticyclones have sometimes been quantified using methods designed to capture "blocking circulations" (e.g. Barnes, Dunn-Sigouin, Masato, & Woollings, 2014), which refer to slow-moving or stationary portions of the jet stream that result in a persistent anticyclone over a region (Altenhoff, Martius, Croci-Maspoli, Schwierz, & Davies, 2008), thus favoring heat-wave genesis. However, this approach is more statistically than physically based (Nakamura & Huang 2018; Scaife Woollings, Knight, Martin, & Hinton, 2010). More importantly, blocking circulations are only one type of persistent circulation that favors warm anomalies, particularly in the higher latitudes (Sousa, Trigo, Barriopedro, Soares, & Santos, 2018). Therefore, this review focuses on dynamical mechanisms. It is well established that persistent anticyclones originate from a complex synergy between quasi-stationary Rossby waves, jet streams (Duchez et al., 2016; Kennedy, Parker, Woollings, Harvey, & Shaffrey, 2016), and storm tracks (Lehmann and Coumou, 2015; Woollings, 2010). Jet streams and Rossby waves in particular are strongly affected by large-scale temperature gradients (Totz, Petri, Lehmann, Peukert, & Coumou, 2019) (see Text Box).

Large-scale temperature gradients are changing over time due to the heterogeneous warming of the atmosphere (Barnes and Polvani, 2015; Oudar et al., 2017; Petrie, Shaffrey, & Sutton, 2015; Screen and Simmonds, 2013; Wang and Overland, 2012) (Figure 2), which provides the first-order reason to expect midlatitude circulation changes (Horton et al., 2016). Another arises from the projected strengthening of deep convection in the tropics (Lau and Kim, 2015). Figure 1a depicts this large-scale deep convection, which is part of the Hadley Cell. Both stronger convection and weaker meridional temperature gradients will broaden the branch of downward-moving air (i.e., expanding the subtropics), in a process known as Hadley Cell expansion (Adam, Schneider, & Harnik, 2014; Lau and Kim, 2015). Although this trend is robust in all seasons except summer (Hu, Tao, & Liu, 2013), the subtropical desiccation that builds up in winter and spring can exacerbate summer drought (Quesada, Vautard, Yiou, Hirschi, & Seneviratne, 2012), favoring warmer temperatures in the subtropics (Seneviratne et al., 2010).

The projected strengthening of deep convection will also cause more rapid warming in the tropics at high altitudes (Figure 2b), referred to as Upper Tropospheric Warming [UTW]. This will increase the equator-to-pole temperature gradient at high altitudes, thereby strengthening and shifting the jet streams and storm tracks poleward (Lorenz and DeWeaver, 2007; Oudar et al., 2017; Shaw et al., 2016). Arctic Amplification [AA], induced largely by the ice-albedo feedback, refers to the more rapid Arctic warming in the lower troposphere (see Figure 2a). AA reduces the equator-to-pole temperature gradient at lower altitudes, thereby weakening and shifting the jet streams and storm tracks equatorward (Harvey, Shaffrey, & Woollings, 2014; Oudar et al., 2017; Vavrus et al., 2017). The direct CO_2 greenhouse effect will also lead to heterogeneous warming, with the dynamical response being also a poleward shift of the jet stream and storm tracks (Ceppi, Zappa, Shepherd, & Gregory, 2018). Note that AA has an opposite dynamical effect compared to UTW and the direct CO_2 effect—the competition between these processes is known as the "tug-of-war" (Shaw et al., 2016). The timescale of the processes also differs, leading to dynamical responses that change over time (Ceppi et al., 2018). Additional changes in temperature gradients are expected due to changes in land-sea temperature contrast (Dong, Gregory, & Sutton, 2009; Horton et al., 2016), snowmelt (Vavrus et al., 2017), and sea surface temperature gradients due to changes in large-scale ocean circulation (Caesar et al., 2018; Deng, Ting, Yang, & Tan, 2018; Haarsma, Selten, & Drijjfhout, 2015).

Text Box: Mid-latitude dynamics that favor heat waves

Latitudinal differences in incoming solar radiation result in an equator-to-pole temperature gradient. The induced large-scale circulation creates a strong separation between subtropical, tropical, and polar air masses, causing temperature gradients to be strongest at the interfaces between these air masses. These, in turn, result in strong winds at high altitudes, leading to the formation of the subtropical and polar jet streams (Figure 1a). Especially at the polar front, the temperature contrast between subtropical and polar air is high. Thus, the latitudinal position of the polar jet, varying between 30° and 75°, has a large impact on surface weather conditions (e.g. temperature and precipitation), especially when the position of the jet stream is persistent (Hoskins and Woollings 2015; Mahlstein et al. 2012).

As schematically shown in Figure 1b, the polar jet stream displays wavy patterns that are the result of large-scale Rossby waves (also called ‘planetary waves’, with wavelengths longer than ~4000km). Rossby waves come in two types: ‘free’ Rossby waves are generated primarily by transient atmospheric instabilities, whereas ‘forced’ Rossby waves are induced by more spatially fixed forcings such as mountains, sea surface temperature patterns, land-ocean temperature differences, or diabatic heating. The latter type can cause high-amplitude poleward excursions of the polar jet stream, which favors hot extremes (Screen and Simmonds 2014; Teng et al. 2013).

The aforementioned high temperature gradient at the polar front also provides energy for smaller-scale Rossby waves (with wavelengths shorter than ~2000km), which can lead to the formation of smaller rotating circulations termed eddies, known more colloquially as storms (O’Gorman 2010). The Atlantic and Pacific oceans show particularly strong eddy activity in the ‘storm track’ regions, which result from the contrast between warm ocean currents and cold continental temperatures. In summer, seasonally weak storm tracks carry less moist and cool air from oceans to land, thereby favoring heat build-up over land (Lehmann et al. 2014).

Like the aforementioned “tug-of-war,” there are competing and interacting processes that influence temperature gradients, which complicates the final dynamical outcome (Peings, Cattiaux, Vavrus, & Magnusdottir, 2017; Shaw & Voigt, 2015; Shaw et al., 2016). Accurately simulating dynamical processes on a large scale (Haarsma et al., 2015; Lau & Kim, 2015), and more so on a regional scale (Lhotka et al., 2018; Plavcová and Kysely, 2016; Sigmond, Kushner, & Scinocca, 2007), is difficult for global climate models. Furthermore, detection of dynamical changes is statistically difficult to detect due to the large internal variability of the climate system. Despite these aspects, robust circulation changes in summer are already detectable in our current climate and are generally expected to become more pronounced in the future.

For example, over the recent (1979–2013) period, storm tracks have significantly weakened 8 to 15 percent in summer (Coumou, Lehmann, & Beckmann, 2015), meaning that less cool and moist air is transported from ocean to land, favoring the buildup of hot and dry conditions (Lehmann and Coumou, 2015) (see Text Box). The weakening is attributed to the recent reduction in the equator-to-pole temperature gradient and is also seen in the weakening of the zonal (west-to-east) mean wind, which serves as a proxy for the jet stream (Coumou et al., 2015). How this weakening will affect quasi-stationary Rossby waves and persistent blocking is still fairly uncertain.

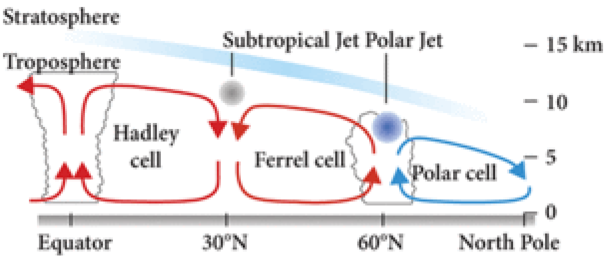


Figure 3A The simplified large-scale circulation, depicting the sharp temperature contrast between subtropical (orange arrows) and polar air (blue arrows), and the deep convection near the equator that results in descending air over the subtropics around 30∘N, which suppresses cloud formation.

Source: Adapted from NASA Earth Observatory.

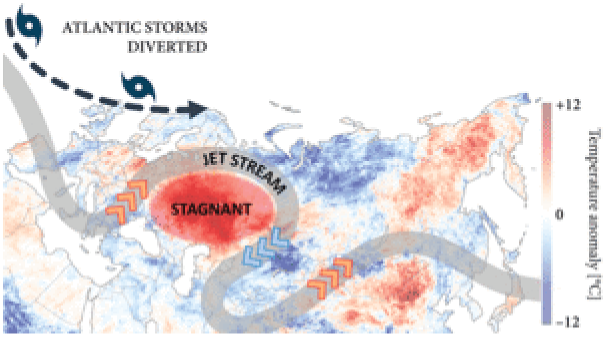


Figure 3B The 2010 Russian heat wave and co-occurring Pakistan flood was characterized by a persistent (high-amplitude) wave pattern of the jet stream, together with diverted storm tracks (Lau and Kim 2012). Such a combination is often referred to as a 'blocking circulation', as it impedes the usual west-to-east flow for days or weeks at a time.

Source: Adapted from NASA Earth Observatory.

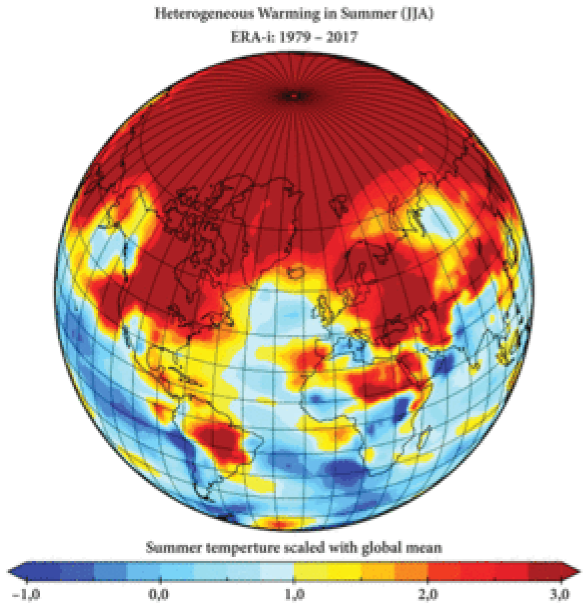


Figure 4A Warming rates of regions that are warming faster (> 1) or slower (< 1) than the global mean temperature at 900 hPa in summer, e.g. dark red areas have warmed 3 times faster than global average.

Source: O'Gorman, 2010.

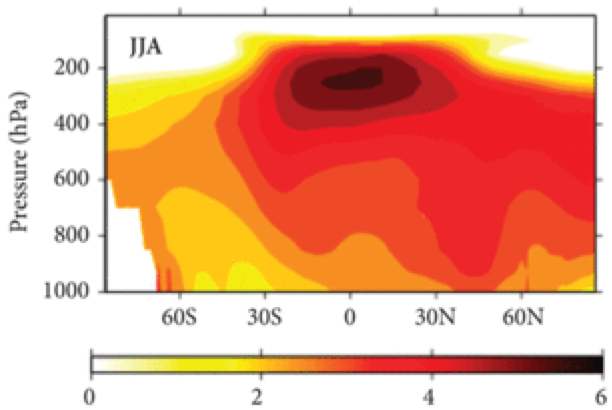


Figure 4B Mean boreal-summer (JJA) temperature difference in ◦C of future (2080-2100) minus present climate (2000-2020) from CMIP3 climate model simulations. The zonal mean at different altitudes (pressure levels) versus latitude is shown. Upper Tropospheric Warming is clearly visible in the future climate.

Source: O'Gorman, 2010.

Future (end of the twenty-first century) projections of summer storm tracks also show a continued weakening over the Atlantic and Pacific Oceans (Chang, Guo, & Xia, 2012; Lehmann, Coumou, Frieler, Eliseev, & Levermann, 2014; Simpson, Shaw, & Seager, 2014; Zappa Shaffrey, Hodges, Sansom, & Stephenson, 2013). The projected Northern Hemisphere summertime poleward shift in the polar jet is fairly robust over the Atlantic and eastern United States (Brewer and Mass, 2016; Lorenz and DeWeaver, 2007; Simpson et al., 2014), which will cause climate regimes to shift accordingly (see Text Box).

The jet stream position can be nudged into forming persistent anticyclones by quasi-stationary Rossby waves (Screen and Simmonds, 2014; Teng, Branstator, Wang, Meehl, & Washington, 2013) (see Text Box). The frequency and amplitude of some Rossby waves have increased in recent decades (Coumou, Kornhuber, Lehmann, & Petoukhov, 2017; Coumou, Petoukhov, Rahmstorf, Petri, & Schellnhuber, 2014; Lee, Lee, Song, & Ho, 2017), although this trend is not robust.

Importantly, the mean jet stream can also interact with forced Rossby waves, thereby creating coherent spatial wave patterns around the entire hemisphere, inducing alternating patterns of persistent high- and low-pressure anomalies called circumglobal wavetrains (Branstator, 2002; Branstator and Teng, 2017; Hoskins and Ambrizzi, 1993). Quasi-resonant amplification [QRA] can be interpreted as a dynamical mechanism that promotes "extreme" circumglobal wavetrains. During QRA, a stationary free Rossby wave resonates in concert with a forced circumglobal wavetrain (see Text Box), thereby favoring the occurrence of persistent and high-amplitude excursions of the jet stream during certain background atmospheric states (Coumou et al., 2017; Kornhuber et al., 2017a; Kornhuber, Petoukhov, Petri, Rahmstorf, & Coumou 2017b; Petoukhov et al., 2013). Ongoing Arctic Amplification, Hadley Cell expansion, and changes in land-sea temperature contrast appear to favor these background-state conditions, potentially explaining the increasing QRA occurrences in recent decades (Coumou et al., 2014; Coumou et al., 2017) and the projected additional increase in the future (Mann et al., 2017).

Atmospheric dynamics are changing mainly due to heterogeneous warming of the climate and a more vigorous tropical convection. Dynamical changes can regionally either mitigate or exacerbate heat wave genesis substantially. Some evidence suggests that dynamical changes are favoring more persistent heat waves in the midlatitudes (Coumou et al., 2018; Horton et al., 2015; Lhotka et al., 2018; Mann et al., 2017; Pfleiderer and Coumou, 2018), but uncertainties are large about this and not all studies have come to similar conclusions (Barnes et al., 2014; Cattiaux, Peings, Saint-Martin, Trou-Kechout, & Vavrus, 2016; Horton et al., 2016; Screen and Simmonds, 2013).

Regional and Local Interactions

Current Land and Atmosphere Interactions

The exact workings of land and atmospheric interactions vary across regions. However, the overall processes in creating extreme heat events are similar. Over regions where soil moisture is high, periods of drought prior to summer can cause a dramatic increase in the likelihood of hot weather (Hirschi et al., 2011; Mueller and Seneviratne, 2012; Quesada, Vautard, Yiou, Hirschi, & Seneviratne, 2012). Over parts of Europe, increased drought severity is associated with longer heat waves (Hirschi et al., 2011), where the sensible heat flux increases and the latent heat flux decreases (Alexander, 2011). This also requires favorable synoptic conditions such as persistent or blocking high-pressure systems; otherwise, heat wave frequency is reduced, even if the preceding seasons were dry (Quesada et al., 2012). Conversely, preceding wet conditions greatly reduce the likelihood of this feedback. Over moisture-limited regions such as Australia, seasonal-scale dry conditions have a heterogeneous influence on heat waves (Perkins, Argüeso, & White, 2015), where droughts make only the long heat waves longer, and mild heat waves warmer (Herold et al., 2016).

Future Projections in Land and Atmosphere Interactions

The influence of antecedent drought will likely continue to have a key role in future temperature extremes (Dirmeyer et al., 2012; Seneviratne et al., 2006; Vautard et al., 2007). Drier local soils have been linked to regional "hotspots" of accelerated 21st-century warming in temperature extremes over Europe, North and South America, and southeast China (Donat et al., 2017). Future intensifying heat waves and warm seasons have also been linked with enhanced soil desiccation (Diffenbaugh, Pal, Giorgi, & Gao, 2007; Seneviratne, Lüthi, Litschi, & Schär, 2006). However, precise future directions of land surface changes and associated feedbacks are uncertain (Donat et al., 2017; Gibson, Pitman, Lorenz, & Perkins-Kirkpatrick, 2017), influenced by large variations in soil moisture trends across climate models (Lorenz, Pitman, Hirsch, & Srbinovsky, 2015). It is unknown whether land surface fluxes will exacerbate or weaken future heat waves, due to climate-model deficiencies in simulating land surface and atmosphere interactions (Fischer, Lawrence, & Sanderson et al., 2011; Hirsch et al., 2014: Lorenz et al., 2015). Increased frequencies and intensities of heat-driving persistent highs are projected over some areas (Meehl and Tebaldi, 2004; Diffenbaugh and Ashfaq, 2010). However, there is little evidence suggesting any change in the synoptic drivers of heat waves over Europe (Cattiaux Yiou, & Vautard, 2012; Schaller, Sillmann, Anstey, Fischer, Grams, & Russo, 2018) or Australia (Cowan et al., 2014; Purich et al., 2014).

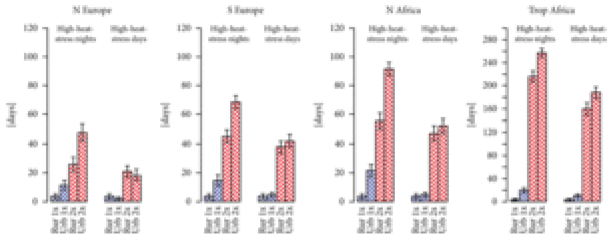


Figure 5 Number of days per year with wet-bulb globe temperature minima (left bars) and maxima (right bars) exceeding the local current rural 99th percentiles. Information is averaged across all land grid points that contain an urban area. Blue bars show the exceedance of these values in a 1 x CO2 simulation for rural (left) and urban (right) grid points, with red bars illustrating the exceedances for a 2 x CO2 simulation. Note the differing scale used for tropical Africa. Error bars denote sampling uncertainty, i.e. the 95% confidence interval around the mean estimate, but do not take into account structural or parameterization uncertainties.

Source: Fischer et al. 2012

Human-Modulated Land Surface Effects

By changing land surface use, human activity can influence the surface energy balance. Clearing from dense vegetation to farmland or urban environments or both dramatically reduces the amount of moisture available for evapotranspiration (Foley et al., 2005). This decreases the latent heat flux while increasing the sensible heat flux, thus driving local increases in the frequency and intensity of extremes (e.g., Coseo and Larsen, 2014). Regionally, increased irrigation has dampened rising trends of observed hot temperatures over the United States (Mueller et al., 2016), and over China and India, where irrigation growth since the 1960s has been rapid (Lobell, Bonfils, & Faurès, 2008; Im et al., 2017). However, future projections from regional climate models indicate that the masking effect of irrigation on extreme temperatures will diminish in the coming decades, due to the intensification of anthropogenic climate change and the slowing of irrigation expansion (Lobell et al., 2008). Moreover, future increases in maximum temperatures may be exacerbated by reduced evapotranspiration from plants in response to enhanced carbon dioxide. A recent study has suggested that refining the stomatal conductance of plants in climate models to better match observations may result in heat waves being 4°–5°C warmer by the middle of this century, compared to current projections (Kala et al., 2016).

Urban Heat Island Effects

Urban heat islands [UHIs] result from heat generation and trapping within cities, and from the partitioning of this heat into sensible rather than latent forms (Argüeso et al., 2014; Kanda, 2007). UHI magnitude is typically largest in the warm season, at night, and in calm conditions, though this varies as a function of background local climate (McCarthy et al., 2010; Zhou, Zhao, Liu, Zhang, & Zhu, 2014) and built-environment characteristics (Georgescu et al., 2013; Stone, Hess, & Frumkin, 2010). Interaction effects between heat waves and UHI in the midlatitudes increase urban temperatures by an additional 0.5°–2.0°C compared to non-heat-wave UHI (Oleson, Anderson, Jones, McGinnis, & Sanderson, 2015; Zhao et al., 2018). The limited tropical studies suggest positive UHI during the dry season (Lazzarini et al., 2013), whereas in arid subtropical regions, urban vegetation effects can result in daytime "cool islands" (Ooi, Chan, Subramaniam, Morris, & Oozeer, 2017). Combined heat-humidity "island" metrics are nearly always positive, however, with warmer urban temperatures dominating over lower relative humidity (Fischer, Oleson, & Lawrence, 2012).

Urban extreme heat is a growing challenge, with annual maximum temperatures increasing about 0.3°C per decade in megacities compared to 0.2°C globally (Mishra, Ganguly, Nijssen, & Lettenmaier, 2015; Papalexiou et al., 2018). Future spatial expansion of urban areas will strongly influence local and regional temperatures, especially on warm season nights, due primarily to large positive water vapor feedbacks outweighing those associated with clouds and soil moisture (Argüeso et al., 2014; Georgescu, Moustaoui, Mahalov, & Dudhia, 2013; McCarthy, Best, & Betts, 2010). Cities in the coastal Mideast and northern India will be the first to near or surpass the 35°C survivability limit of wet-bulb temperature, with serious but as-yet-uncertain consequences (Im et al., 2017; Pal and Eltahir, 2015; Sherwood and Huber, 2010). Overall, urban heat stress will increase significantly more than in rural areas, particularly in the midlatitudes and tropics (Fischer et al., 2012; McCarthy et al., 2010).

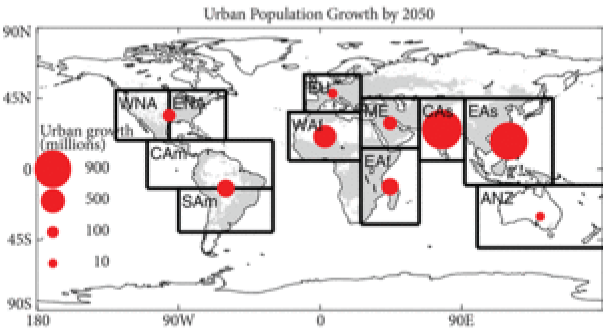


Figure 6 Estimates of urban population growth between the years 2000 and 2050 for a number of global regions, with gray shading representing major populated areas in 2050 (>10,000 people per 0.5◦ latitude, longitude cell).

Source: McCarthy et al. 2010

Intraurban exposure to extreme heat varies considerably, with measurable health effects (Hass, Ellis, Mason, Hathaway, & Howe, 2016; Rosenthal, Kinney, & Metzger, 2014; Uejio et al., 2011). An increasing area of focus has been indoor temperatures, which are both higher and harder to regulate in urban housing (Quinn, Kinney, & Shaman, 2017; Sailor, 2014). Extreme heat is also correlated with urban hazards such as severe air-pollution episodes and increased probability of power failures (Chapman, Azevedo, & Prieto-Lopez, 2013; Fischer and Knutti, 2013). The combination of UHI and air-conditioning waste heat will likely contribute to large increases in future cooling demand (Kolokotroni, Ren, Davies, & Mavrogianni, 2012).

Model simulations have provided support for the heat-mitigation benefits of street-level vegetation and green roofs, but these may also have unintended consequences like weakened lake/sea breezes (Lynn et al., 2009; Sharma, Conry, Fernando, Hamlet, Hellmann, & Chen, 2016). Such city-planning-based heat-mitigation strategies have not yet been implemented widely enough for their ultimate effects to be empirically tested.

SSTs and Teleconnections

Compared to land, atmospheric, and urban influences on heat waves, relatively little research has been conducted on the influence of sea surface temperatures (SSTs). This is likely because SST influences on heat waves are implicitly linked with preconditional drying or certain circulation patterns or both. What research has been done is focused on influences of the Pacific Ocean.

The influence of Pacific SSTs is largely constrained to bordering regions (Kenyon and Hegerl, 2008). Over North America, the La Niña phase of El Niño/Southern Oscillation [ENSO] is associated with increased frequencies of warm temperature extremes and heat waves (Hoerling et al., 2013; Kenyon and Hegerl, 2008; Koster, Wang, Schubert, Suarez, & Mahanama, 2009). The mechanism is embedded within the drought associations discussed above (Hoerling et al., 2013). A Pacific tripole SST pattern with lead times of almost two months has also been associated with observed hot summer days over the much of the contiguous United States (Loughran, Perkins-Kirkpatrick, & Alexander, 2017; McKinnon, Rhines, Tingley, & Huybers, 2016).

Over Australia, increased heat wave frequency over the northern and eastern regions is associated with El Niño (Perkins et al., 2015). Conversely, La Niña has been shown to influence heat waves in the southeast (Parker, Berry, & Reeder, 2014), due to enhanced convection during the Asian/Australian monsoon (Parker, Berry, & Reeder, 2013). There have also been indications that local SSTs influence heat waves over southeast Australia (Boschat et al., 2015), although the underpinning mechanism is not clear. Some studies have suggested that warm SSTs contribute to European heat waves as well. For example, Mediterranean SSTs were anomalously warm before, during, and after the 2003 European heat wave, with a tripole pattern in the Atlantic intensifying throughout that summer (Black, Blackburn, Harrison, Hoskins, & Methven, 2004; Feudale and Shukla, 2011).

Aside from being limited in number, the above studies are constrained to observations. Thus, there is little understanding on how SSTs may continue to influence heat waves in the future, other than potential changes in the SST patterns themselves. While some studies report a change in SST patterns such as ENSO (e.g., Cai et al., 2014), no conclusions have been drawn on the effect on heat waves. A larger focus on how SSTs influence heat waves—both presently and in the future—is an area where future research could be concentrated, as understanding the large-scale influences and linkages of SSTs and heat waves may lead to a better understanding of how they affect local-scale processes.

Health Impacts

Extreme heat poses a direct risk to human health (Basu & Samet, 2002; Davis, Hondula, & Patel, 2016; Kovats & Hajat, 2008; Mora, Counsell, Bielecki, & Louis, 2017b; Olsson et al., 2014). An optimum body core temperature of about 37°C and a metabolism that generates ~100 W of heat even while at rest, combined with the fact that an object cannot lose heat to a surrounding environment of equal or higher temperature, dictates that exposure to air temperatures above 37°C can lead to body heat accumulation and a dangerous exceedance of the body core temperature (i.e., hyperthermia). However, lower air temperatures could also be dangerous when combined with high relative humidity, as high humidity prevents evaporation of sweat, which is the body's primary cooling mechanism. Given the interactive role of temperature and humidity in human thermoregulation, over 100 indices have been devised that combine both variables in some way (Blazejczyk et al., 2012), of which web-bulb temperature is among the most common. Several studies have demonstrated that web-bulb temperatures above 35°C (not far above the currently observed global maximum) are the "hard and absolute upper limit for human heat tolerance" (Matthews, 2018; Sherwood & Huber, 2010). The impact of humidity in body heat exchange is particularly important for tropical and subtropical humid areas as high air temperature during the daylight allows air to store more water vapor, but at night when temperature drops, the capacity of the air to hold water is reduced, thus increasing humidity. Under these conditions, the body can experience non-stop heat stress from high air temperatures during the day and high humidity at night.

A climatic change causes an impact only when a given system is sensitive to that change. Unfortunately, the human body is very sensitive to heat, raising serious concerns about the projected human health impacts of increases in frequency and intensity of heat waves. Mora et al. (2017b) reviewed the medical literature and found evidence for at least twenty-seven different physiological pathways in which heat exposure can damage the human body. A reduction in blood flow to critical organs (resulting from shunting of blood to the skin to maximize body cooling, called ischemia) and direct thermal damage of cells (called heat cytotoxity) can impair cell functioning in the brain, heart, kidneys, liver, and can also break down cell membranes, increasing the permeability of organs to pathogens and toxins (Mora et al., 2017b). The breaking of cell membranes can lead to epithelial wounds and internal infection, in turn triggering an inflammatory response to facilitate movement of white blood cells. If hyperthermia persists, this positive response can become systemic, exacerbating organ leakage. These physiological responses, among others (Mora et al., 2017b), are interrelated such that dysfunction in one organ impairs others, causing a cascade of multiorgan failure; this often results in lengthy recovery times, permanent disabilities, and at times death (Aström, Bertil, & Joacim, 2011; Bouchama & Knochel, 2002; Hanna & Taiti, 2015; Leon & Helwig, 2010; Sherwood & Huber, 2010). Physiological sensitivity to heat is characteristic to all people, but may have earlier onset among individuals with compromised thermoregulatory capacity (such as the elderly or the very young) and those frequently exposed to heat (e.g., due to working outside, doing strenuous exercise, etc.) (Aström et al., 2011; Bouchama & Knochel, 2002; Harlan et al., 2014; Kenny, Yardley, Brown, Sigal, & Jay, 2010; Leon & Helwig, 2010; Miyake, 2013; Varghese, John, Thomas, Abraham, & Mathai, 2005).

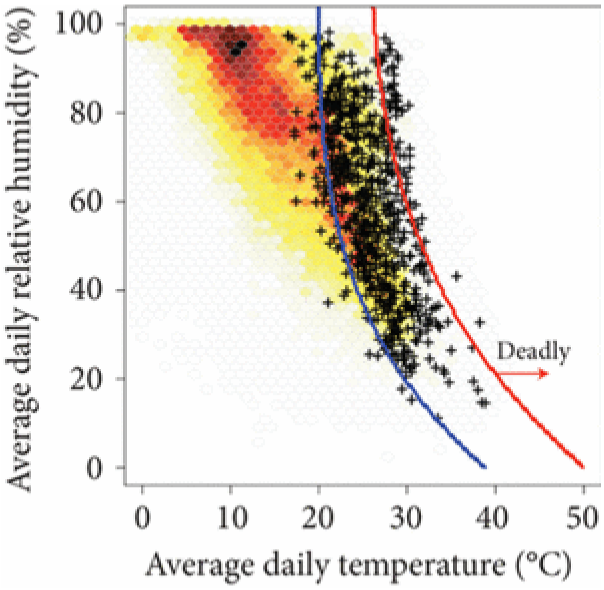


Figure 7A Mean daily surface air temperature and relative humidity during lethal heat events (black crosses) and during periods of equal duration from the same cities on randomly selected dates (that is, non-lethal heat events, where the red-to-yellow gradient indicates the density of such events). The blue line is the support-vector-machine-calculated threshold that best separates lethal and non-lethal heat events, and the red line is the 95% probability threshold; areas to the right of the thresholds are classified as deadly, those to the left as non-deadly.

Source: Mora et al. 2017

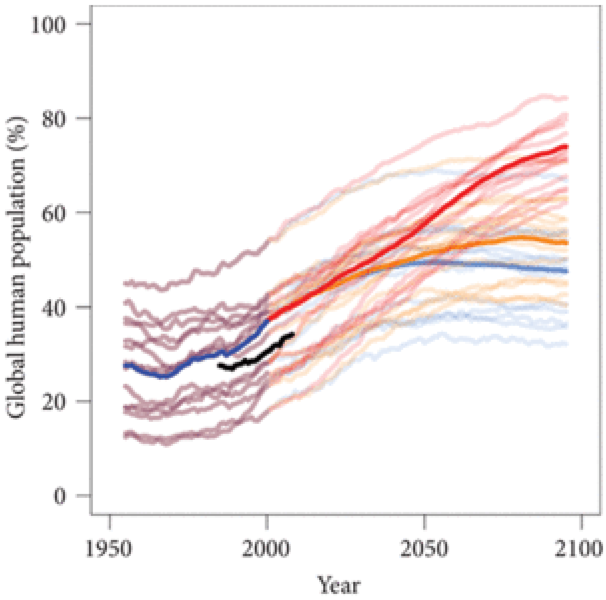


Figure 7B Percentage of human population exposed to climatic conditions beyond the 95%-probability deadly threshold (red line in left panel) for at least 20 days in a year under various emission scenarios. Bold lines represent multimodel medians, black lines are reanalysis, and faded lines indicate projections for different Earth System Models. Time series have been smoothed with a 10-year-average moving window.

Source: Mora et al. 2017

While the climatic conditions that can cause hyperthermia have been increasing and are projected to continue to do so even with strong mitigation of greenhouse gases, the lethality of recent extreme heat waves has somewhat reduced, indicating the potential for human adaptation (Bassil & Cole, 2010; Basu & Samet, 2002; Kovats & Kristie, 2006; Petkova et al., 2014). This likely level of adaptation generates a large uncertainty for the quantification of human mortality or morbidity or both under projected climate change, but does not preclude the conclusion that outdoor conditions will become dangerously hot in the hottest and most humid parts of the world (Mora et al., 2017b). Contributing to the uncertainty is the fact that extreme heat is correlated with other environmental health risks, such as air pollution, whose occurrence may change significantly due to climatic changes as well as political, economic, and technological development pathways (Schnell & Prather, 2017).

Because of physiological constraints, human evolutionary adaptation to extreme heat will be limited (i.e., our rate of adaptation is unlikely to be able to match the forecast rate of temperature change) (Hanna & Tait, 2015). Most likely, any reductions in human mortality from extreme heat are likely to result from behavioral changes or considerable expenditure in technological adaptations or both to reduce heat exposure. These include expanding the usage of air conditioning, upgrading electrical grids, improving heat warning systems, and modifying the energy-efficiency and heat-retention characteristics of buildings and urban areas (Hanna & Tait, 2015; Sherwood & Huber, 2010). Such precautions would not be affordable for all, and, even among those who can afford them, a warming world will regularly “imprison” people indoors, with any system failure (such as a power outage) potentially resulting in disaster (Hanna & Tait, 2015; Sherwood & Huber, 2010). Even in the present climate, extreme heat regularly prompts warnings and advisories by meteorological and public health agencies. In the absence of legislation or other incentives, preventative adaptation measures are likely to increase wealth-related impact disparities, both within and between countries. The health impacts of future extreme heat are thus likely to be most severe in the tropical and subtropical countries which comprise most of the developing world.

Agricultural Impacts

Extreme heat is associated with reduced yields in several major global crops such as maize, soybean, and wheat. The European heat wave of 2003 caused yield reductions of up to 20 percent and excess livestock mortality (Ciais et al., 2005; Morignat et al., 2014; van der Velde, Wriedt, & Bouraoui, 2010), while export interruptions in response to the 2010 Russian heat wave reverberated through global trade (Wegren, 2013; Welton, 2011). Extreme heat impacts on crops are globally costly and pose a mounting threat to global food security in a warming climate (Challinor et al., 2014; Porter and Xie, 2014).

High temperatures can impact crops through diverse mechanisms including reduction of net carbon assimilation due to elevated respiration, stomatal closure and water stress due to elevated vapor pressure deficit, and direct damage to vegetative and reproductive plant tissues (Bita & Gerats, 2013; Prasad et al., 2008; Rezaei, Webber, Gaiser, Naab, & Ewert, 2015a; Wahid, Gelani, Ashraf, & Foolad, 2007). Threshold temperatures for crop yield damage have been identified between 29° and 34°C (Lobell & Gourdji, 2012; Luo, 2011; Schlenker & Roberts, 2009), with generally lower heat tolerance in species of temperate origin such as wheat and barley than those of tropical origin like maize (Lobell & Gourdji, 2012).

Crop yield sensitivity to extreme high temperatures varies substantially across development stages, with particular susceptibility during the reproductive phases, such as flowering (Butler & Huybers, 2015; Cicchino, Rattalino Edreira, Uribelarrea, & Otegui, 2010; Deryng, Conway, Ramankutty, Price, & Warren, 2014; Gourdji, Sibley, & Lobell, 2013; Tashiro & Wardlaw, 1990). Uncertain future changes in the timing of extreme heat relative to shifting crop phenology due to mean warming could moderate or exacerbate damage to crops (Rezaei, 2015b). Despite this, it is projected that warming overall will reduce net crop productivity (Deryng, et al. 2014; Rosenzweig, et al., 2014; Zhao et al., 2016).

Recent research has emphasized the importance of irrigation in mitigating extreme heat impacts on crops, for example by modulating local temperatures abiotically through evaporative cooling or by sustaining stomatal conductance and photosynthesis (Rezaei et al., 2015a; Siebert, Webber, Zhao, & Ewert, 2017; Tack, Barkley, & Hendricks, 2017; Troy, Kipgen, & Pal, 2015; van der Velde et al., 2010; Zhang, Lin, & Sassenrath, 2015). Conversely, elevated CO_2 can exacerbate heat extremes by reducing transpiration (Kimball, 2016; Skinner, Poulsen, & Mankin, 2018), negating its yield benefit in soy (Gray et al., 2016), although effects vary among crops and regions (Leakey, Bishop, & Ainsworth, 2012). These findings raise questions about the separability of yield impacts due to heat from those due to low moisture availability and support a holistic view of canopy thermodynamics and physiology. Compounding moisture and heat stress on crops is especially salient in the context of changing dependence structure between rainfall and temperature (Chen et al., 2016; Kent et al., 2017; Zscheischler & Seneviratne, 2017). Increased irrigation may help adapt cropping systems to a warmer climate (Jägermeyr et al., 2016) but is projected to be limited by freshwater availability across much of globe including South Asia and China (Elliott et al., 2014).

Relatively less attention has been paid to impacts of extreme heat on livestock; regionally important staple crops such as tubers and millets; and non-staple crops such as legumes, pulses, and vegetables (Bishop-Williams, Berke, Pearl, Hand, & Kelton, 2015; Iizumi et al., 2014; Morignat et al., 2014; Sultan et al., 2014; Savage, 1991; West, 2003; Wolf, Olesinski, Rudich, & Marani, 1990;). Such crops merit more attention as they provide an important nutritional complement to staple carbohydrates and may prove instrumental in climate-adaptive cropping systems.

Economic Impacts

There is increasing evidence that temperature extremes are damaging to economic activity, from individual productivity to macroeconomic outcomes. Using within-country comparisons, annual average temperatures above 13°C have been shown to be associated with lower overall economic production on the national level, and microeconomic studies have provided evidence that most of these declines are driven by the number of extremely hot days (Burke, Hsiang, & Miguel, 2015). Much of the developing world experiences average temperatures above this range, meaning increasing temperatures are particularly damaging there. Under an unmitigated climate-change scenario, economic output in the tropics and subtropics is projected to be reduced 25–75 percent relative to a no-climate-change scenario (Burke et al., 2015). Poorer countries also experience larger declines in economic production for a given increase in temperature compared to wealthier countries, meaning that existing income disparities in the world will likely be worsened, but also that economic development has the potential to mitigate some of the damages (Dell, Jones, & Olken, 2012).

In the United States, economic impacts of climate on various sectors have been extensively studied. Temperatures above 30°C can cause significant losses in worker output per hour, as well as total hours worked (Hsiang et al., 2014). Workers in “highly exposed” sectors such as agriculture, construction, and manufacturing decrease their time spent working by 9–13 percent, while workers in less-exposed sectors decrease by 3–4 percent (Zivin & Neidell, 2014). There is little evidence that this missing work is made up on other days, meaning that the potential output of these workers is probably lost. As developing economies transition from agriculture and industry to services, these highly exposed sectors rely less on manual labor and also become less important to overall economic output.

Across the rest of the world, our understanding of the processes determining economic losses due to increased temperatures are more limited. Preliminary studies have estimated that a day at 40°C decreases average time spent working by about thirty minutes compared to a day at 27°C (Baker et al., 2017). While agricultural productivity decreases due to extreme heat are expected in both rich and poor countries, agriculture accounts for a much larger share of economic production in the less-developed world. Countries in sub-Saharan Africa are expected to see yield losses of 10–20 percent by 2050 (Schlenker & Lobell, 2010), which could lead to drastic increases in food insecurity. Yield losses in the United States could reach 50 percent by 2100 in the areas where crops are currently grown. The extent to which adaptation to such conditions will reduce these damages is not well understood, but to date there have been no indications that agriculture or other sectors have become more economically resilient to extreme heat, in either developed or less-developed places (Burke & Emerick, 2016). While adaptation capacity may be limited in a given location, spatially reallocating production is one approach to mitigating the overall damage, particularly in agriculture (Costinot, Donaldson, & Smith, 2016). Another possible means of adaptation is to shift labor from agriculture to less-impacted sectors such as manufacturing (Colmer, 2017). While this may provide substantial benefits in a context where there are adequate opportunities for employment outside of agriculture, it also relies on the existence of a relatively open labor market, assumptions from which reality often deviates significantly.

Energy costs are also expected to mount over the twenty-first century, with an increase of about 0.3 percent of GDP under unmitigated climate change (Auffhammer & Aroonruengsawat, 2011). However, these estimates are made using current energy technologies, and thus do not account for changes in energy efficiency or sources. As air conditioners become more widespread in middle-income countries, these will likely translate into large increases in electricity use, both due to higher temperatures and increasing incomes (Davis & Gertler, 2015), putting pressure on energy grids and making emissions targets more difficult to achieve. Air conditioning is also a key adaptation strategy for reducing the economic and mortality effects of extreme heat, so it will be important to increase electricity capacity where necessary, in concert with other mitigation and adaptation efforts (Deschênes & Greenstone, 2011). Extreme heat can also affect key infrastructure like water supply and power grids; natural resources like forests; and societies writ large through economic instability and migration (AghaKouchak, Cheng, Mazdiyasni, & Farahmand, 2014; Bartos & Chester, 2015; Chapman, Azevedo, & Prieto-Lopez, 2013; Mueller, Gray, & Kosec, 2014). All of these associated indirect effects can have severe economic consequences on a variety of scales, but the linkages have not been well enough studied for firm conclusions to be drawn.

Summary

Increases in extreme heat due to anthropogenic activity are becoming clearer, as global average temperatures continue to rise and the climate system adjusts accordingly. Feedbacks are the subject of much ongoing work but are less definitively understood, as many of them are characteristically regional or local, while others are evolving in response to rapidly changing conditions (such as deforestation or the melting of Arctic sea ice). The most salient aspect of projected extreme-heat impacts, and especially challenging from a political perspective, is how they are highly regional in nature, with severe or life-threatening impacts in some places sharply contrasting with benign impacts in others. Tropical and subtropical countries, though expected to experience the least absolute warming, will suffer large increases relative to their historical climatological range and the highest values of extreme heat overall. Future extreme heat will test the capacity for collective action and adaptation of many (perhaps most) societies around the world, but developing ones are particularly vulnerable. By underscoring the confidence in the changes and the severity of the impacts, this chapter highlights the importance of taking seriously the prospect of more frequent and intense extreme heat in the decades to come.

References

Adam, O., Schneider, T., & Harnik, N. (2014). Role of changes in mean temperatures versus temperature gradients in the recent widening of the Hadley circulation. *Journal of Climate 27*(19), 7450–7461. doi: 10.1175/JCLI-D-14-00140.1

AghaKouchak, A., Cheng, L., Mazdiyasni, O., & Farahmand, A. (2014). Global warming and changes in risk of concurrent climate extremes: insights from the 2014 California drought. *Geophysical Research Letters 41*, 8847–8852. doi: 10.1002/2014gl062308

Alexander, L. (2011). Climate science: Extreme heat rooted in dry soils. *Nature Geoscience* 4(1), 12–13. doi: 10.1038/ngeo1045

Altenhoff, A. M., Martius, O., Croci-Maspoli, M., Schwierz, C., & Davies, H. C. (2008). Linkage of atmospheric blocks and synoptic-scale Rossby waves: A climatological analysis. *Tellus A 60*(5), 1053–1063. doi: 10.1111/j.1600-0870.2008.00354.x

Alvarez-Castro, M. C., Faranda, D., & Yiou, P. (2018). Atmospheric dynamics leading to West European summer hot temperatures since 1851. *Complexity*, 2018 (2494509), 1–10. doi: 10.1155/2018/2494509. Retrieved from **https://www.hindawi.com/journals/complexity/2018/2494509/**

Argüeso, D., Evans, J. P., Fita, L., & Bormann, K. J. (2014). Temperature response to future urbanization and climate change. *Climate Dynamics 42*(7–8), 2183–2199. doi: 10.1007/s00382-013-1789-6

Åström, D. O., Bertil, F. & Joacim, R. (2011). Heat wave impact on morbidity and mortality in the elderly population: A review of recent studies. *Maturitas 69*(2), 99–105. doi: 10.1016/j.maturitas.2011.03.008

Auffhammer, M., & Aroonruengsawat, A. (2011). Simulating the impacts of climate change, prices and population on California's residential electricity consumption. *Climate Change* 109 (supp. 1), 191–210. doi: 10.1007/s10584-011-0299-y

Baker, R., Carleton, T., D'Agostino, A., Foreman, T., Greenstone, M., Hsiang, … Yuan, J. (2017). Human productivity in a warmer world: The impact of climate change on the global workforce. Working Paper FP917804. EPA. Retrieved from **https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/10708/report/0**

Barnes, E. A., Dunn-Sigouin, E., Masato, G., & Woollings, T. (2014). Exploring recent trends in Northern Hemisphere blocking. *Geophysical Research Letters 2*, 638–644. doi: 10.1002/2013GL058745

Barnes, E. A., & Polvani, L. M. (2015). CMIP5 projections of Arctic Amplification, of the North American/North Atlantic circulation, and of their relationship. *Journal of Climate 28*(13), 5254–5271. doi: 10.1175/JCLI-D-14-00589.1

Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M., & Garcia-Herrera, R. (2011). The hot summer of 2010: Redrawing the temperature record map of Europe. *Science, 332*(6026), 220–224. doi: 10.1126/science.1201224

Bartos, M. D., & Chester, M. V. (2015). Impacts of climate change on electric power supply in the Western United States. *Nature Climate Change 5*, 748–752. doi: 10.1038/nclimate2648

Basu, R., & Samet, J. M. (2002). Relation between elevated ambient temperature and mortality: A review of the epidemiologic evidence. *Epidemiology Review 24*, 190–202. doi: 10.1093/epirev/mxf007

Bassil, K. L., & Cole, D. C. (2010). Effectiveness of public health interventions in reducing morbidity and mortality during heat episodes: A structured review. *International Journal of Environmental Research and Public Health 7*, 991–1001. doi: 10.3390/ijerph7030991

Bishop-Williams, K. E., Berke, O., Pearl, D. L., Hand, K., & Kelton, D. F. (2015). Heat stress related dairy cow mortality during heat waves and control periods in rural Southern Ontario from 2010–2012. *BMC Veterinary Research 11*(1), 1–10. doi: 10.1186/s12917-015-0607-2

Bita, C. E., & Gerats, T. (2013). Plant tolerance to high temperature in a changing environment: Scientific fundamentals and production of heat stress-tolerant crops. *Frontiers of Plant Science 4*(July), 1–18. doi: 10.3389/fpls.2013.00273

Black, E., Blackburn, M., Harrison, R. G., Hoskins, B. J., & Methven, J. (2004). Factors contributing to the summer 2003 European heatwave. *Weather 59*(8), 217–223. doi: 10.1256/wea.74.04

Black, M. T., Karoly, D. J., & King, A. D. (2015). The contribution of anthropogenic forcing to the Adelaide and Melbourne heatwaves of January 2014. *Bulletin of the American Meteorological Society 96*, S145–S148. doi: 10.1175/BAMS-D-15-00097.1

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., & Tinz, B. (2012). Comparison of UTCI to selected thermal indices. *International Journal of Biometeorology 56*(3), 515–535. doi: 10.1007/s00484-011-0453-2

Boschat, G., Pezza, A., Simmonds, I., Perkins, S., Cowan, T., & Purich, A. (2015). Large scale and sub-regional connections in the lead up to summer heat wave and extreme rainfall events in eastern Australia. *Climate Dynamics, 44*, 1823-1840. doi: 10.1007/s00382-014-2214-5.

Bouchama, A., & Knochel, J. P. (2002). Heat stroke. *New England Journal of Medicine 346*, 1978–1988. **http://doi.org/10.1056/nejmra011089**

Branstator, G. (2002). Circumglobal teleconnections, the jet stream waveguide, and the North Atlantic Oscillation. *Journal of Climate 15*(14), 1893–1910. doi: 10.1175/2008JCLI2517.1

Branstator, G., & Teng, H. (2017). Tropospheric waveguide teleconnections and their seasonality. *Journal of Atmospheric Sciences 74*(5), 1513–1532. doi: 10.1175/jas-d-16-0305.1

Brewer, M. C., & Mass, C. F. (2016). Projected changes in western U.S. large-scale summer synoptic circulations and variability in CMIP5 models. *Journal of Climate 29*(16), 5965–5978. doi: 10.1175/JCLI-D-15-0598.1

Burke, M., & Emerick, K. (2016). Adaptation to climate change: Evidence from US Agriculture. *American Economic Journal: Economic Policy 8*(3), 106–140. doi: 10.1257/pol.20130025

Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature, 527*(7577), 235–239. doi: 10.1038/nature15725

Butler, E. E., & Huybers, P. (2015). Variations in the sensitivity of US maize yield to extreme temperatures by region and growth phase. *Environmental Research Letters 10*(3), 34009. doi: 10.1088/1748-9326/10/3/034009. Retrieved from **http://iopscience.iop.org/article/10.1088/1748-9326/10/3/034009/pdf**

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature, 556*(7700), 191–196. doi: 10.1038/s41586-018-0006-5

Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., … Guilyardi, E. (2014). Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change 4*(2), 111–116. doi: 10.1038/nclimate2100

Cattiaux, J., Peings, Y., Saint-Martin, D., Trou-Kechout, & Vavrus, S. J. (2016). Sinuosity of mid-latitude atmospheric flow in a warming world. *Geophysical Research Letters 43*(15), 8259–8268. doi: 10.1002/2016GL070309. Retrieved from **https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016GL070309**

Cattiaux, J., Yiou, P. & Vautard, R. (2012). Dynamics of future seasonal temperature trends and extremes in Europe: A multi-model analysis from CMIP3. *Climate Dynamics 38*(9–10), 1949–1964. doi: 10.1007/s00382-011-1211-1

Ceppi, P., Zappa, G., Shepherd, T. G., and Gregory, J. M. (2018). Fast and slow components of the extratropical atmospheric circulation response to CO2 forcing. *Journal of Climate, 31*(3), 1091–1105. doi: 10.1175/jcli-d-17-0323.1

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change 4*(4), 287–291. doi: 10.1038/nclimate2153

Chang, E. K. M., Guo, Y., & Xia, X. (2012). CMIP5 multimodel ensemble projection of storm track change under global warming. *Journal of Geophysical Research Atmospheres 117*(23), 1–19. doi: 10.1029/2012JD018578

Chapman, L., Azevedo, J. A., & Prieto-Lopez, T. (2013). Urban heat and critical infrastructure networks: A viewpoint. *Urban Climate 3*, 7–12. doi: 10.1016/j.uclim.2013.04.001

Chen, Y., Zhang, Z., Wang, P., Song, X., Wei, X., & Tao, F. (2016). Identifying the impact of multi-hazards on crop yield: A case for heat stress and dry stress on winter wheat yield in northern China. *European Journal of Agronomy 73*, 55–63. doi: 10.1016/j.eja.2015.10.009

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., … Bernhofer, C. (2005). Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature 437*(7058), 529–533. doi: 10.1038/nature03972

Cicchino, M., Rattalino Edreira, J. I., Uribelarrea, M., & Otegui, M. E. (2010). Heat stress in field-grown maize: Response of physiological determinants of grain yield. *Crop Science 50*(4), 1438–1448. doi: 10.2135/cropsci2009.10.0574

Colmer, J. (2017). Weather, labour reallocation, and industrial production: Evidence from India. Working Paper, London School of Economics. Retrieved from **https://urbanisation.econ.ox.ac.uk/materials/papers/57/weather-labour-reallocation-and-industrial-production-evidence-from-india.pdf**

Conti, S., Meli, P., Minelli, G., Solimini, R., Toccaceli, V., Vichi, M., … Perini, L. (2005). Epidemiologic study of mortality during the summer 2003 heatwave in Italy. *Environmental Research 98*, 390–399. doi: 10.1016/j.envres.2004.10.009

Coseo, P., & Larsen, L. (2014). How factors of land use/land cover, building configuration, and adjacent heat sources and sinks explain urban heat islands in Chicago. *Landscape and Urban Planning 125*, 117–129. doi: 10.1016/j.landurbplan.2014.02.019

Costinot, A., Donaldson, D., & Smith, C. (2016). Evolving comparative advantage and the impact of climate change in agricultural markets: Evidence from 1.7 million fields around the world. *Journal of Political Economy 124*(1), 205–248. doi: 10.1086/684719

Coumou, D., Di Capua, G., Vavrus, S., Wang, L., & Wang, S. (2018). The influence of Arctic amplification on mid-latitude summer circulation. *Nature Communications 9*(1), 2959. doi: 10.1038/s41467-018-05256-8. Retrieved from **https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6102303/**

Coumou, D., Kornhuber, K., Lehmann, J., & Petoukhov, V. (2017). Weakened flow, persistent circulation, and prolonged weather extremes in boreal summer. In S. S. Wang, J. Yoon, C. C. Funk & R. R. Gillies (Eds.), *Climate Extremes* (pp. 61–73). Washington, DC: American Geophysical Union.

Coumou, D., Lehmann, J., & Beckmann, J. (2015). The weakening summer circulation in the Northern Hemisphere mid-latitudes. *Science, 348*(6232), 324–327. doi: 10.1126/science.1261768

Coumou, D., Petoukhov, V., Rahmstorf, S., Petri, S., & Schellnhuber, H. J. (2014). Quasi-resonant circulation regimes and hemispheric synchronization of extreme weather in boreal summer. *Proceedings of the National Academy of Sciences 111*(34), 12331–12336. doi: 10.1073/pnas.1412797111

Coumou, D., & Rahmstorf, S. (2012). A decade of weather extremes. *Nature Climate Change, 2*, 491–496.

Cowan, T., Purich, A., Perkins, S., Pezza, A., Boschat, G. & Sadler, K. (2014). More frequent, longer, and hotter heat waves for Australia in the twenty-first century. *Journal of Climate 27*(15), 5851–5871. doi: 10.1175/jcli-d-14-00092.1

Crimmins, A., Balbus, J., Gamble, J. L., Beard, C. B., Bell, J. E., Dodgen, D.,… Ziska, L., eds. (2016). Temperature-related death and illness: The impacts of climate change on human health in the United States: A scientific assessment. *U.S. Global Change Research Program 21*, 43–68. Retrieved from **https://health2016.globalchange.gov**

Davis, R. E., Hondula, D. M., & Patel, A. P. (2016). Temperature observation time and type influence estimates of heat-related mortality in seven U.S. cities. *Environmental Health Perspectives 124*, 795–804. doi: 10.1289/ehp.1509946

Davis, L. W., & Gertler, P. J. (2015). Contribution of air conditioning adoption to future energy use under global warming. *Proceedings of the National Academy of Sciences 112*(19), 5962–5967. doi: 10.1073/pnas.1423558112

Dell, M., Jones, B. F., & Olken, B. A. (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics 4*(3), 66–95. doi: 10.1257/mac.4.3.66

Dematte, J. E., O'Mara, K., Buescher, J., Whitney, C. G., Forsythe, S., McNamee, T., … Ndukwu, I. M. (1998). Near-fatal heat stroke during the 1995 heat wave in Chicago. *Annals of Internal Medicine 129*, 173–181. doi: 10.7326/0003-4819-129-3-199808010-00001

Deng, K., Ting, M., Yang, S., & Tan, Y. (2018). Increased frequency of summer extreme heat waves over Texas area tied to the amplification of Pacific zonal SST gradient. *Journal of Climate 31*(14), 5629–5647. doi: 10.1175/jcli-d-17-0554.1

Deryng, D., Conway, D., Ramankutty, N., Price, J., & Warren, R. (2014). Global crop yield response to extreme heat stress under multiple climate change futures. *Environmental Research Letters 9*(3). doi: 10.1088/1748-9326/9/3/034011. Retrieved from: **http://iopscience.iop.org/article/10.1088/1748-9326/9/3/034011/pdf**

Deschênes, O., & Greenstone, M. (2011). Climate change, mortality, and adaptation: evidence from annual fluctuations in weather in the US. *American Economic Journal of Applied Economics 3*(4), 152–185. **http://doi.org/10.1257/app.3.4.152**

Diffenbaugh, N. S., & Ashfaq, M. (2010). Intensification of hot extremes in the United States. *Geophysical Research Letters 37*(15), L15701, 1-5. doi: 10.1029/2010gl043888

Diffenbaugh, N.S., Pal, J. S., Giorgi, F., & Gao, X. (2007). Heat stress intensification in the Mediterranean climate change hotspot. *Geophysical Research Letters 34*(11), L11706, 1-6. doi: 10.1029/2007gl030000

Dirmeyer, P.A., Cash, B.A., Kinter III, J.L., Stan, C., Jung, T., Marx, L., … Huang, B. (2012). Evidence for enhanced land–atmosphere feedback in a warming climate. *Journal of Hydrometeorology 13*(3), 981–995. doi: 10.1175/jhm-d-11-0104.1

Dole, R., Hoerling, M., Perlwitz, J., Eischeid, J., Pegion, P., Quan, T., … Murray, D. (2011). Was there a basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters*, *38*, L06702, 1-5. doi: 10.1029/2010GL046582.

Donat, M. G., Pitman, A. J., & Seneviratne, S. I. (2017). Regional warming of hot extremes accelerated by surface energy fluxes. *Geophysical Research Letters 44*(13), 7011–7019. doi: 10.1002/2017GL073733

Dong, B., Gregory, J. M., & Sutton, R. T. (2009). Understanding land-sea warming contrast in response to increasing greenhouse gases. Part I: Transient adjustment. *Journal of Climate 22*(11), 3079–3097. doi: 10.1175/2009JCLI2652.1

Duchez, A., Frajka-Williams, E., Josey, S. A., Evans, D. G., Grist, J. P., Marsh, R., … Hirschi, J. J. (2016). Drivers of exceptionally cold North Atlantic Ocean temperatures and their link to the 2015 European heat wave. *Environmental Research Letters 11*(7), doi:

10.1088/1748-9326/11/7/074004. Retrieved from **http://iopscience.iop.org/article/10.1088/1748-9326/11/7/074004/meta**

Easterling, D. R., Kunkel, K. E., Wehner, M. F., & Sun, L. (2016). Detection and attribution of climate extremes in the observed record. *Weather and Climate Extremes 11*, 17–27. doi: 10.1016/J.WACE.2016.01.001

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., … Wisser, D. (2014). Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences 111*(9), 3239–3244. doi: 10.1073/pnas.1222474110

Feudale, L., & Shukla, J. (2011). Influence of sea surface temperature on the European heat wave of 2003 summer. Part I: an observational study. *Climate Dynamics 36*, 1691–1703. doi: 10.1007/s00382-010-0788-0

Fischer, E. M., Beyerle, U., & Knutti, R. (2013). Robust spatially aggregated projections of climate extremes. *Nature Climate Change, 3*, 1033-1038. doi: 10.1038/nclimate2051.

Fischer, E. M., & Knutti, R. (2013). Robust projections of combined humidity and temperature extremes. *Nature Climate Change 3*, 126–130. doi: 10.1038/nclimate1682

Fischer, E.M., Lawrence, D.M., & Sanderson, B.M. (2011). Quantifying uncertainties in projections of extremes—a perturbed land surface parameter experiment. *Climate Dynamics 37*(7–8), 1381–1398. doi: 10.1007/s00382-010-0915-y

Fischer, E. M., Oleson, K. W., & Lawrence, D. M. (2012). Contrasting urban and rural heat stress responses to climate change. *Geophysical Research Letters 39*(3), 1–8. doi: 10.1029/2011GL050576

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., … Helkowski, J. H. (2005). Global consequences of land use. *Science, 309*(5734), 570–574. doi: 10.1126/science.1111772

Georgescu, M., Moustaoui, M., Mahalov, A., & Dudhia, J. (2013). Summer-time climate impacts of projected megapolitan expansion in Arizona. *Nature Climate Change 3*(1), 37–41. doi: 10.1038/nclimate1656

Gibson, P.B., Pitman, A.J., Lorenz, R. & Perkins-Kirkpatrick, S.E. (2017). The role of circulation and land surface conditions in current and future Australian heat waves. *Journal of Climate 30*(24), 9933–9948. doi: 10.1175/jcli-d-17-0265.1

Gourdji, S. M., Sibley, A. M., & Lobell, D. B. (2013). Global crop exposure to critical high temperatures in the reproductive period: Historical trends and future projections. *Environmental Research Letters 8*(2). doi: 10.1088/1748-9326/8/2/024041. Retrieved from: **http://iopscience.iop.org/article/10.1088/1748-9326/8/2/024041/pdf**

Gray, S. B., and Dermody O., Klein, S. P., Locke, A. M., McGrath, J. M., Paul, R. E.,… Rosenthal, D.M. (2016). Intensifying drought eliminates the expected benefits of elevated carbon dioxide for soybean. *Nature Plants 2*(9), 1–8. doi: 10.1038/nplants.2016.132

Haarsma, R. J., Selten, F. M., & Drijjfhout, S. S. (2015). Decelerating Atlantic meridional overturning circulation main cause of future west European summer atmospheric circulation changes. *Environmental Research Letters 10*. doi: 10.1088/1748-9326/10/9/094007. Retrieved from: **http://iopscience.iop.org/article/10.1088/1748-9326/10/9/094007/meta**

Hanna, E. G., & Tait, P. W. (2015). Limitations to thermoregulation and acclimatization challenge human adaptation to global warming. *International Journal of Environmental Research and Public Health 12*, 8034–8074. doi: 10.3390/ijerph120708034

Harlan, S. L., Gerardo C., Yang, S., Petitti, D. B., Morales, E. J., Ruddell, B. L., … Ruddell, D. M. (2014). Heat-related deaths in hot cities: Estimates of human tolerance to high temperature thresholds. *International Journal of Environmental Research and Public Health 11*, 3304–3326. doi: 10.3390/ijerph110303304

Harvey, B. J., Shaffrey, L. C., & Woollings, T. J. (2014). Equator-to-pole temperature differences and the extra-tropical storm track responses of the CMIP5 climate models. *Climate Dynamics 43*(5–6), 1171–1182. doi: 10.1007/s00382-013-1883-9

Hass, A. L., Ellis, K. N., Mason, L. R., Hathaway, J. M., & Howe, D. A. (2016). Heat and humidity in the city: Neighborhood heat index variability in a mid-sized city in the southeastern United States. *International Journal of Environmental Research and Public Health, 13*(117). doi: 10.3390/ijerph13010117. Retrieved from: **https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4730508/**

Herold, N., Kala, J., & Alexander, L. V. (2016). The influence of soil moisture deficits on Australian heatwaves. *Environmental Research Letters 11*(6). doi: 10.1088/1748-9326/11/6/064003. Retrieved from **http://iopscience.iop.org/article/10.1088/1748-9326/11/6/064003/pdf**.

Hirsch, A.L., Kala, J., Pitman, A.J., Carouge, C., Evans, J.P., Haverd, … Mocko, D. (2014). Impact of land surface initialization approach on subseasonal forecast skill: A regional analysis in the Southern Hemisphere. *Journal of Hydrometeorology 15*(1), 300–319. doi: 10.1175/jhm-d-13-05.1

Hirschi, M., Seneviratne, S. I., Alexandrov, V., Boberg, F., Boroneant, C., Christensen, O. B., …Stepanek, P. (2011). Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. *Nature Geoscience 4*(1), 17–21. doi: 10.1038/ngeo1032

Hoerling, M., Kumar, A., Dole, R., Nielsen-Gammon, J.W., Eischeid, J., Perlwitz, J., … Chen, M. (2013). Anatomy of an extreme event. *Journal of Climate 26*(9), 2811–2832. doi: 10.1175/jcli-d-12-00270.1

Horton, D. E., Johnson, N. C., Singh, D., Swain, D. L., Rajaratnam, B., & Diffenbaugh, N. S. (2015). Contribution of changes in atmospheric circulation patterns to extreme temperature trends. *Nature 522*(7557), 465–469. doi: 10.1038/nature14550

Horton, R. M., Mankin, J. S., Lesk, C., Coffel, E., & Raymond, C. (2016). A review of recent advances in research on extreme heat events. *Current Climate Change Reports 2*(4), 242–259. doi: 10.1007/s40641-016-0042-x

Hoskins, B., & Woollings, T. (2015). Persistent extratropical regimes and climate extremes. *Current Climate Change Reports 1*(3), 115–124. doi: 10.1007/s40641-015-0020-8

Hoskins, B. J., & Ambrizzi, T. (1993). Rossby wave propagation on a realistic longitudinally varying flow. *Journal of the Atmospheric Sciences 50* (12), 1661–1671. doi: 10.1175/1520-0469(1993)050<1661:RWPOAR>2.0.CO;2

Hoskins, B. & Woollings, T. (2015). Persistent extratropical regimes and climate extremes. *Current Climate Change Reports 1*(3), 115–124. doi: 10.1007/s40641-015-0020-8

Hsiang, S. M., Kopp, R., Jina, A., Delgado, M., Rising, J., Mohan, S., … Houser, T. (2014). *American Climate Prospectus: Economic Risks in the United States*. New York: Rhodium Group. Retrieved from: **http://www.impactlab.org/wp-content/uploads/2017/10/AmericanClimateProspectus_v1.2.pdf**.

Hu, Y., Tao, L., & Liu, J. (2013). Poleward expansion of the Hadley Circulation in CMIP5 simulations. *Advances in Atmospheric Sciences 30*(3), 790–795. doi: 10.1007/s00376-012-2187-4

Iizumi, T., Yokozawa, M., Sakurai, G., Travasso, M. I., Romanernkov, V., Oettli, P., … Furuya, J. (2014). Historical changes in global yields: Major cereal and legume crops from 1982 to 2006. *Global Ecology and Biogeography 23*(3), 346–357. doi: 10.1111/geb.12120

Im, E.-S., Pal, J. S., & Eltahir, E. A. B. (2017). Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Science Advances*, *3*(8), 1–8. doi: 10.1126/sciadv.1603322

Jägermeyr, J., Gerten, D., Schaphoff, S., Heinke, J., Lucht, W., & Rockström, J. (2016). Integrated crop water management might sustainably halve the global food gap. *Environmental Research Letters 11*(2), 25002. doi: 10.1088/1748-9326/11/2/025002. Retrieved from: http://iopscience.iop.org/article/10.1088/1748-9326/11/2/025002/pdf.

Jézéquel, A., Yiou, P., & Radanovics, S. (2018). Role of circulation in European heatwaves using flow analogues. *Clim. Dyn., 50*, 1145-1159. doi: 10.1007/s00382-017-3667-0.

Kala, J., De Kauwe, M. G., Pitman, A.J., Medlyn, B. E., Wang, Y. P., Lorenz, R., …Perkins-Kirkpatrick, S. E., 2016. Impact of the representation of stomatal conductance on model projections of heatwave intensity. *Scientific Reports 6*, 23418. doi: 10.1038/srep23418. Retrieved from: **https://www.nature.com/articles/srep23418**

Kanda, M. (2007). Progress in urban meteorology: A review. *Journal of the Meteorological Society of Japan 85B*, 363–383. doi: 10.2151/jmsj.85B.363

Kennedy, D., Parker, T., Woollings, T., Harvey, B., & Shaffrey, L. (2016). The response of high-impact blocking weather systems to climate change. *Geophysical Research Letters 43*(13), 7250–7258. doi: 10.1002/2016GL069725

Kenny, G. P., Yardley, J., Brown, C., Sigal, R. J. & Jay, O. (2010). Heat stress in older individuals and patients with common chronic diseases. *CMAJ Group 182*(10), 1053–1060. doi: 10.1503/cmaj.081050. Retrieved from **http://www.cmaj.ca/content/182/10/1053**.

Kent, C., Pope, E., Thompson, V., Lewis, K., Scaife, A. A., & Dunstone, N. (2017). Using climate model simulations to assess the current climate risk to maize production. *Environmental Research Letters 12*(5). doi: 10.1088/1748-9326/aa6cb9. Retrieved from **http://iopscience.iop.org/article/10.1088/1748-9326/aa6cb9/pdf**

Kenyon, J., & Hegerl, G. C. (2008). Influence of modes of climate variability on global temperature extremes. *Journal of Climate 21*(15), 3872–3889. doi: 10.1175/2008jcli2125.1

Kimball, B. A. (2016). Crop responses to elevated CO2 and interactions with H2O, N, and temperature. *Current Opinions Plant Biology 31*, 36–43. doi: 10.1016/j.pbi.2016.03.006

King, A. D., Black, M. T., Min, S. K., Fischer, E. M., Mitchell, D. M., Harrington, L. J., … Perkins-Kirkpatrick, S. E. (2016). Emergence of heat extremes attributable to anthropogenic influences. *Geophysical Research Letters 43*(7), 3438–3443. doi: 10.1002/2015GL067448

King, A. D., Donat, M. G., Fischer, E. M., Hawkins, E., Alexander, L. V., Karoly, D. J., Dittus, A. J., Lewis, S. C., and Perkins, S. E. (2015). The timing of anthropogenic emergence in simulated heat extremes. *Environmental Research Letters, 10*, 094015. doi: 10.1088/1748-9326/10/9/094015

Kolokotroni, M., Ren, X., Davies, M., & Mavrogianni, A. (2012). London's urban heat island: Impact on current and future energy consumption in office buildings. *Energy and Buildings 47*, 302–311. doi: 10.1016/j.enbuild.2011.12.019

Kornhuber, K., Petoukhov, V., Karoly, D., Petri, S., Rahmstorf, S., & Coumou, D. (2017a). Summertime planetary wave resonance in the northern and southern hemispheres. *Journal of Climate 30*(16), 6133–6150. doi: 10.1175/JCLI-D-16-0703.1

Kornhuber, K., Petoukhov, V., Petri, S., Rahmstorf, S., & Coumou, D. (2017b). Evidence for wave resonance as a key mechanism for generating high-amplitude quasi-stationary waves in boreal summer. *Climate Dynamics 49*(5–6), 1961–1979. doi: 10.1007/s00382-016-3399-6

Koster, R.D., Wang, H., Schubert, S.D., Suarez, M.J., & Mahanama, S. (2009). Drought-induced warming in the continental United States under different SST regimes. *Journal of Climate 22*(20), 5385–5400. doi: 10.1175/2009jcli3075.1

Kovats, R. S., & Hajat, S. (2008). Heat stress and public health: A critical review. *Annual Review of Public Health 29*, 41–55. doi: 10.1146/annurev.publhealth.29.020907.090843

Kovats, R. S., & Kristie, L. E. (2006). Heatwaves and public health in Europe. *European Journal of Public Health 16*(6), 592–599. doi: 10.1093/eurpub/ckl049

Lau, W. K. M., & Kim, K.-M. (2012). The 2010 Pakistan flood and Russian heat wave: Teleconnection of hydrometeorological extremes. *Journal of Hydrometeorology 13*(1), 392–403. doi: 10.1175/JHM-D-11-016.1

Lau, W. K. M., & Kim, K.-M. (2015). Robust Hadley Circulation changes and increasing global dryness due to CO2 warming from CMIP5 model projections. *Proceedings of the National Academy of Sciences 112*(12), 201418682. doi: 10.1073/pnas.1418682112

Lazzarini, M., Marpu, P. R., & Ghedira, H. (2013). Temperature-land cover interactions: The inversion of urban heat island phenomenon in desert city areas. *Remote Sensing of Environment 130*, 136–152. doi: 10.1016/j.rse.2012.11.007

Leakey, A. D. B., Bishop, K. A., & Ainsworth, E. A. (2012). A multi-biome gap in understanding of crop and ecosystem responses to elevated CO2. *Current Opinion Plant Biology 15*(3), 228–236. doi: 10.1016/j.pbi.2012.01.009

Lee, M. H., Lee, S., Song, H. J., & Ho, C. H. (2017). The recent increase in the occurrence of a boreal summer teleconnection and its relationship with temperature extremes. *Journal of Climate 30*(18), 7493–7504. doi: 10.1175/jcli-d-16-0094.1

Lehmann, J., & Coumou, D. (2015). The influence of mid-latitude storm tracks on hot, cold, dry, and wet extremes. *Scientific Reports 5* (17491). doi: 10.1038/srep17491. Retrieved from **https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4675986/**

Lehmann, J., Coumou, D., Frieler, K., Eliseev, A. V., & Levermann, A. (2014). Future changes in extratropical storm tracks and baroclinicity under climate change. *Environmental Research Letters 9*, 084002. doi: 10.1088/1748-9326/9/8/084002. Retrieved from: **http://iopscience.iop.org/article/10.1088/1748-9326/9/8/084002/pdf**

Leon, L. R., & Helwig, B. G. (2010). Heat stroke: Role of the systemic inflammatory response. *Journal of Applied Physiology 109*, 1980–1988. doi: 10.1152/japplphysiol.00301.2010

Lewis, S. C., & Karoly, D. J. (2013). Anthropogenic contributions to Australia's record summer temperatures of 2013. *Geophysical Research Letters 40*(14), 3705–3709. doi: 10.1002/grl.50673

Lhotka, O., Kysely, J., & Plavcová, E. (2018). Evaluation of major heat waves' mechanisms in EURO-CORDEX RCMs over Central Europe. *Climate Dynamics 50*(11–12), 4249–4262. doi: 10.1007/s00382-017-3873-9

Lobell, D. B., Bonfils, C., & Faurès, J. M. (2008). The role of irrigation expansion in past and future temperature trends. *Earth Interactions 12*(3), 1–11. doi: 10.1175/2007ei241.1

Lobell, D. B., & Gourdji, S. M. (2012). The influence of climate change on global crop productivity. *Plant Physiology 160*(4), 1686–1697. doi: 10.1104/pp.112.208298

Lorenz, D. J., & DeWeaver, E. T. (2007). Tropopause height and zonal wind response to global warming in the IPCC scenario integrations. *Journal of Geographical Research Atmospheres 112*(10), 1–11. doi: 10.1029/2006JD008087

Lorenz, R., Pitman, A. J., Hirsch, A. L., & Srbinovsky, J. (2015). Intraseasonal versus interannual measures of land–atmosphere coupling strength in a global climate model: GLACE-1 versus GLACE-CMIP5 experiments in ACCESS1. 3b. *Journal of Hydrometeorology 16*(5), 2276–2295. doi: 10.1175/jhm-d-14-0206.1

Loughran, T. F., Perkins-Kirkpatrick, S. E., & Alexander, L. V. (2017). Understanding the spatio-temporal influence of climate variability on Australian heatwaves. *International Journal of Climate 37*(10), 3963–3975. doi: 10.1002/joc.4971

Luo, Q. (2011). Temperature thresholds and crop production: A review. *Climate Change 109*(3–4), 583–598. doi: 10.1007/s10584-011-0028-6

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., & Wanner, H. (2004). European seasonal and annual temperature variability, trends, and extremes since 1500. *Science 303*(5663), 1499–1503. doi: 10.1126/science.1093877

Lynn, B. H., Carlson, T. N., Rosenzweig, C., Goldberg, R., Druyan, L., Cox, J., …Civerolo, K. (2009). A modification to the NOAH LSM to simulate heat mitigation strategies in the New York City metropolitan area. *Journal of Applied Meteorology and Climatology 48*(2), 199–216. doi: 10.1175/2008JAMC1774.1

Mahlstein, I., Martius, O., Chevalier, C., & Ginsbourger, D. (2012). Changes in the odds of extreme events in the Atlantic basin depending on the position of the extratropical jet. *Geophysical Research Letters 39* (22). doi: 10.1029/2012GL053993. **https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2012GL053993**

Mann, M. E., Rahmstorf, S., Kornhuber, K., Steinman, B. A., Miller, S. K., & Coumou, D. (2017). Influence of anthropogenic climate change on planetary wave resonance and extreme weather events. *Scientific Reports 7* (45252). doi: 10.1038/srep45242. Retrieved from **https://www.nature.com/articles/srep45242**

Matthews, T. (2018). Humid heat and climate change. *Progress in Physical Geography 42*(3), 391–405. doi: 10.1177/0309133318776490

McCarthy, M. P., Best, M. J., & Betts, R. A. (2010). Climate change in cities due to global warming and urban effects. *Geophysical Research Letters 37*(9), 1–5. doi: 10.1029/2010GL042845

McKinnon, K. A., Rhines, A., Tingley, M. P., & Huybers, P. (2016). Long-lead predictions of eastern United States hot days from Pacific sea surface temperatures. *Nature Geoscience 9*, 389–396. doi: 10.1038/ngeo2687

Meehl, G. A., & Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. *Science 305*(5686), 994–997. doi: 10.1126/science.1098704

Miralles, D. G., Teuling, A. J., Van Heerwaarden, C. C., & De Arellano, J. V. G. (2014). Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. *Nature Geoscience 7*(5), 345–349. doi: 10.1038/ngeo2141

Mishra, V., Ganguly, A. R., Nijssen, B., & Lettenmaier, D. (2015). Changes in observed climate extremes in global urban areas. *Environmental Research Letters 10*(2), 024005. doi: 10.1088/1748-9326/10/2/024005. Reviewed from: **http://iopscience.iop.org/article/10.1088/1748-9326/10/2/024005/pdf**

Miyake, Y. (2013). Pathophysiology of heat illness: Thermoregulation risk factors and indicators of aggravation. *Japan Medical Association Journal 56*(3), 167–173.

Mora, C., Dousset, B., Caldwell, … Trauernicht, C. (2017a). Global risk of deadly heat. *Nature Climate Change 7*, 501–506. doi: 10.1038/nclimate3322

Mora, C., Counsell, C. W. W., Bielecki, C. R., & Louis, L. V. (2017b). Twenty-seven ways a heat wave can kill you: Deadly heat in the era of climate change. *Circulation: Cardiovascular Quality and Outcomes 10*, e004233, 1-3. doi: 10.1161/circoutcomes.117.004233

Morignat, E., Perrin, J. B., Gay, E., Vinard, J. L., Calavas, D., & Hénaux, V. (2014). Assessment of the impact of the 2003 and 2006 heat waves on cattle mortality in France. *PLoS ONE 9*(3). doi: 10.1371/journal.pone.0093176. Retrieved from: **https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0093176**

Mueller, B., & Seneviratne, S. I. (2012). Hot days induced by precipitation deficits at the global scale. *Proceedings of the National Academy of Sciences 109*(31), 12398–12403. doi: 10.1073/pnas.1204330109

Mueller, N. D., Butler, E. E., McKinnon, K. A., Rhines, A., Tingley, M., Holbrook, N. M., … Huybers, P. (2016). Cooling of US Midwest summer temperature extremes from cropland intensification. *Nature Climate Change 6*, 317-324. doi: 10.1038/nclimate2825

Mueller, V., Gray, C., & Kosec, K. (2014). Heat stress increases long-term human migration in rural Pakistan. *Nature Climate Change 4*, 182–185. doi: 10.1038/nclimate2103

Nakamura, N. & Huang, C. S. Y. (2018). Atmospheric blocking as a traffic jam in the jet stream. *Science 361*(6397), 42–47, doi: 10.1126/science.aat0721

O'Gorman, P. A. (2010). Understanding the varied response of the extratropical storm tracks to climate change. *Proceedings of the National Academy of Sciences 107*(45), 19176–19180. doi: 10.1073/pnas.1011547107

Oleson, K., Anderson, G. B., Jones, B., McGinnis, S. A., & Sanderson, B. M. (2015). Avoided climate impacts of urban and rural heat and cold waves over the U.S. using large climate model ensembles for RCP8.5 and RCP4.5. *Climate Change 146*(3-4): 377–392. doi: 10.1007/s10584-015-1504-1. Retrieved from: **https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5839517/**

Olsson, L., Opondo, M., Tschakert … Zakieldeen, S. A. (2014). Livelihoods and poverty. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Ooi, M. C. G., Chan, A., Subramaniam, K., Morris, K. I., & Oozeer, M. Y. (2017). Interaction of urban heating and local winds during the calm intermonsoon seasons in the tropics. *Journal of Geophysical Research Atmospheres 122*(21), 11,499–11,523. doi: 10.1002/2017JD026690

Otto, F. E. L., Massey, N., van Oldenborgh, G. J., Jones, R. G., & Allen, M. R. (2012). Reconciling two approaches to attribution of the 2010 Russian heat wave. *Geophysical Research Letters 39*(4), 1–5. doi: 10.1029/2011GL050422

Otto, F. E. L., van Oldenborgh, G. J., Eden, J., Stott, P. A., Karoly, D. J., & Allen, M. R. (2016). The attribution question. *Nature Climate Change 6*, 813–816. doi: 10.1038/nclimate3089

Oudar, T., Sanchez-Gomez, E., Chauvin, F., Cattiaux, J., Terray, L., & Cassou, C. (2017). Respective roles of direct GHG radiative forcing and induced Arctic sea ice loss on the Northern Hemisphere atmospheric circulation. *Climate Dynamics 49*(11–12), 3693–3713. doi: 10.1007/s00382-017-3541-0

Pal, J. S., & Eltahir, E. A. B. (2015). Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change 6*(2), 1–4. doi: 10.1038/nclimate2833

Papalexiou, S. M., AghaKouchak, A., Trenberth, K. E., & Foufoula-Georgiou, E. (2018). Global, regional, and megacity trends in the highest temperature of the year: diagnostics and evidence for accelerating trends. *Earth's Future, 6*(1), 1-9. doi: 10.1002/2017ef000709.

Parker, T.J., Berry, G.J. & Reeder, M.J. (2013). The influence of tropical cyclones on heat waves in southeastern Australia. *Geophysical Research Letters 40*(23), 6264–6270. doi: 10.1002/2013gl058257

Parker, T.J., Berry, G.J. & Reeder, M.J. (2014). The structure and evolution of heat waves in southeastern Australia. *Journal of Climate 27*(15), 5768–5785. doi: 10.1175/jcli-d-13-00740.1

Peings, Y., Cattiaux, J., Vavrus, S., & Magnusdottir, G. (2017). Late twenty-first-century changes in the midlatitude atmospheric circulation in the CESM large ensemble. *Journal of Climate 30*(15), 5943–5960. doi: 10.1175/JCLI-D-16-0340.1

Perkins, S.E., Argüeso, D., & White, C.J. (2015). Relationships between climate variability, soil moisture, and Australian heatwaves. *Journal of Geophysical Research Atmospheres 120*(16), 8144–8164. doi: 10.1002/2015jd023592

Petkova, E. P., Bader, D. A., Brooke Anderson, G., Horton, R. M., Knowlton, K., & Kinney, P. L. (2014). Heat-related mortality in a warming climate: Projections for 12 U.S. cities. *International Journal Environmental Research and Public Health 11*(11), 11371–11383. doi: 10.3390/ijerph111111371

Petoukhov, V., Rahmstorf, S., Petri, S., Schellnhuber, H. J., & Joachim, H. (2013). Quasiresonant amplification of planetary waves and recent Northern Hemisphere weather extremes. *Proceedings of the National Academy of Sciences 110*(14), 5336–5341. doi: 10.1073/pnas.1222000110

Petrie, R. E., Shaffrey, L. C., & Sutton, R. T. (2015). Atmospheric response in summer linked to recent Arctic sea ice loss. *Quarterly Journal of the Royal Meteorological Society, 141*(691), 2070–2076. doi: 10.1002/qj.2502

Pfahl, S. (2014). Characterizing the relationship between weather extremes in Europe and synoptic circulation features. *Natural Hazards and Earth System Sciences 14*(6), 1461–1475. doi: 10.5194/nhess-14-1461-2014

Pfleiderer, P., & Coumou, D. (2018). Quantification of temperature persistence over the Northern Hemisphere land-area. *Climate Dynamics 51*(1–2), 627–637. **http://doi.org/10.1007/s00382-017-3945-x**

Plavcová, E., & Kysely, J. (2016). Overly persistent circulation in climate models contributes to overestimated frequency and duration of heat waves and cold spells. *Climate Dynamics 46*(9–10), 2805–2820. doi: 10.1007/s00382-015-2733-8

Porter, J. R., & Xie, L. (2014). Food security and food production systems. In C. B. Field, V. R. Barros, D J. Dokken, K. J. Mach, M. D. Mastrandrea, T. Eren Bilir, … P. R. Mastrandrea (Eds.), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects* (pp. 485–533) New York: Cambridge University Press.

Prasad, P. V. V., Staggenborg, S. A., Ristic, Z., Ahuja, L. R., Reddy, V. R., Saseendran, S. A., … Yu, Q. (2008). Impacts of drought and/or heat stress on physiological, developmental, growth, and yield processes of crop plants. In L. R. Ahuja, V. Reddy, S. A. Saseendran, & Q. Yu (Eds.), *Advances in agricultural systems modeling: Response of crops to limited water: understanding and modeling water stress effects on plant growth processes* (pp. 301–355). Madison, WI: American Society of Agronomy.

Purich, A., Cowan, T., Cai, W., van Rensch, P., Uotila, P., Pezza, A., … Perkins, S. (2014). Atmospheric and oceanic conditions associated with Southern Australian heat waves: A CMIP5 analysis. *Journal of Climate 27*(20), 7807–7829. doi: 10.1175/jcli-d-14-00098.1

Quesada, B., Vautard, R., Yiou, P., Hirschi, M., & Seneviratne, S. I. (2012). Asymmetric European summer heat predictability from wet and dry southern winters and springs. *Nature Climate Change 2*(10), 736–741. doi: 10.1038/nclimate1536

Quinn, A., Kinney, P., & Shaman, J. (2017). Predictors of summertime heat index levels in New York City apartments. *Indoor Air 27*(4), 840–851. doi: 10.1111/ina.12367

Rahmstorf, S., & Coumou, D. (2011). Increase of extreme events in a warming world. *Proceedings of the National Academy of Sciences 108*, 17905–17909. doi: 10.1073/pnas.1101766108

Rezaei, E. E., Webber, H., Gaiser, T., Naab, J., & Ewert, F. (2015a). Heat stress in cereals: mechanisms and modelling. *European Journal of Agronomy 64*, 98–113. doi: 10.1016/j.eja.2014.10.003

Rezaei, E. E., Siebert, S., & Ewert, F. (2015b). Intensity of heat stress in winter wheat—Phenology compensates for the adverse effect of global warming. *Environmental Research Letters 10*. doi: 10.1088/1748-9326/10/2/024012.

Rosenthal, J. K., Kinney, P. L., & Metzger, K. B. (2014). Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006. *Health and Place 30*, 45–60. doi: 10.1016/j.healthplace.2014.07.014

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., … Jones, J. W. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences 111*(9), 3268–3273. doi: 10.1073/pnas.1222463110

Russo, S., Sillmann, J., & Fischer, E. M. (2015). Top ten European heatwaves since 1950 and their occurrence in the coming decades. *Environmental Research Letters 10*, 124003. Retrieved from **http://iopscience.iop.org/article/10.1088/1748-9326/10/12/124003/meta**

Russo, S., Sillmann, J., & Sterl, A. (2017). Humid heat waves at different warming levels. *Scientific Reports, 7*, 7477. doi: 10.1038/s41598-017-07536-7

Russo, S., & Sterl, A. (2011). Global changes in indices describing moderate temperature extremes from the daily output of a climate model. *JGR Atmospheres 116*, D03104. doi: 10.1029/2010jd014727

Sailor, D. J. (2014). Risks of summertime extreme thermal conditions in buildings as a result of climate change and exacerbation of urban heat islands. *Building and Environment 78*, 81–88. doi: 10.1016/j.buildenv.2014.04.012

Savage, G. P. (1991). Lentils: a forgotten crop. *Outlook on Agriculture 20* (2), 109–112.

Scaife, A. A., Woollings, T., Knight, J., Martin, G., & Hinton, T. (2010). Atmospheric blocking and mean biases in climate models. *Journal of Climate 23*(23), 6143–6152. doi: 10.1175/2010JCLI3728.1

Schaller, N., Sillmann, J., Anstey, J., Fischer, E. M., Grams, C. M., & Russo, S. (2018). Influence of blocking on Northern European and Western Russian heatwaves in large climate model ensembles. *Environmental Research Letters 13*, 054015. doi: 10.1088/1748-9326/aaba55. Retrieved from: **http://iopscience.iop.org/article/10.1088/1748-9326/aaba55/pdf**

Schlenker, W., & Lobell, D. B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters 5*(1), 014010. doi: 10.1088/1748-9326/5/1/014010

Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences 106*(37), 15594–15598. doi: 10.1073/pnas.0906865106

Schnell, J. L., & Prather, M. P. (2017). Co-occurrence of extremes in surface ozone, particulate matter, and temperature over eastern North America. *Proceedings of the National Academy of Sciences 114*(11), 2854–2859. doi: 10.1073/pnas.1614453114

Screen, J. A., & Simmonds, I. (2013). Caution needed when linking weather extremes to amplified planetary waves. *Proceedings of the National Academy of Sciences 110*(26), E2327– E2327. doi: 10.1073/pnas.1304867110

Screen, J. A., & Simmonds, I. (2014). Amplified mid-latitude planetary waves favour particular regional weather extremes. *Nature Climate Change 4*(8), 704-709. doi: 10.1038/nclimate2271

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., … Teuling, A. J. (2010). Investigating soil moisture: Climate interactions in a changing climate: A review. *Earth Science Reviews 99*, 125–161. doi: 10.1016/j.earscirev.2010.02.004

Seneviratne, S. I., Lüthi, D., Litschi, M., & Schär, C. (2006). Land-atmosphere coupling and climate change in Europe. *Nature 443*(7108), 205–209. doi: 10.1038/nature05095

Sharma, A., Conry, P., Fernando, H. J. S., Hamlet, A. F., Hellmann, J. J., & Chen, F. (2016). Green and cool roofs to mitigate urban heat island effects in the Chicago metropolitan area: Evaluation with a regional climate model. *Environmental Research Letters 11*(6), 1–16. doi: 10.1088/1748-9326/11/6/064004

Shaw, T. A., Baldwin, M., Barnes, E. A., Caballero, R., Garfinkel, C. I., Hwang, Y. T., … Voigt, A. (2016). Storm track processes and the opposing influences of climate change. *Nature Geosciences 9*(9), 656–664. doi: 10.1038/ngeo2783

Shaw, T. A. & Voigt, A. (2015). Tug of war on summertime circulation between radiative forcing and sea surface warming. *Nature Geoscience 8*(7), 560–566. doi: 10.1038/ngeo2449

Sherwood, S. C., & Huber, M. (2010). An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences 107*(21), 9552–9555. doi: 10.1073/pnas.0913352107

Sherwood, S. C., Ingram, W., Tsushima, Y., Satoh, M., Roberts, M., Vidale, P. L., … O'Gorman, P. A. (2010). Relative humidity changes in a warmer climate. *Journal of Geophysical Research: Atmospheres 115*, 1–11. doi: 10.1029/2009jd012585

Siebert, S., Webber, H., Zhao, G., & Ewert, F. (2017). Heat stress is overestimated in climate impact studies for irrigated agriculture. *Environmental Research Letters 12*(5). doi: 10.1088/1748-9326/aa702f. Retrieved from: **http://iopscience.iop.org/article/10.1088/1748-9326/aa702f/pdf**

Sigmond, M., Kushner, P. J., & Scinocca, J. F. (2007). Discriminating robust and non-robust atmospheric circulation responses to global warming. *Journal of Geophysical Research Atmospheres 112*(20), 1–13. doi: 10.1029/2006JD008270

Sillmann, J., Kharin, V. V., Zhang, X., Zwiers, F. W., & Bronaugh, D. (2013). Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *Journal of Geophysical Research: Atmospheres 118*, 2473–2493. doi: 10.1002/jgrd.50188

Simpson, I. R., Shaw, T. A., & Seager, R. (2014). A diagnosis of the seasonally and longitudinally varying midlatitude circulation response to global warming. *Journal of the Atmospheric Sciences 71*(7), 2489–2515. doi: 10.1175/JAS-D-13-0325.1

Skinner, C. B., Poulsen, C. J., & Mankin, J. S. (2018). Amplification of heat extremes by plant CO2 physiological forcing. *Nature Communications 9*(1), 1–11. doi: 10.1038/s41467-018-03472-w

Sousa, P. M., Trigo, R. M., Barriopedro, D., Soares, P. M., & Santos, J. A. (2018). European temperature responses to blocking and ridge regional patterns. *Climate Dynamics 50*(1–2), 457–477. doi: 10.1007/s00382-017-3620-2

Stone, B., Hess, J. J., & Frumkin, H. (2010). Urban form and extreme heat events: Are sprawling cities more vulnerable to climate change than compact cities? *Environmental Health Perspectives 118*(10), 1425–1428. doi: 10.1289/ehp.0901879

Stott, P. A., Christidis, N., Otto, Friederike E. L., Sun, Y., Vanderlinden, J-. P., van Oldenborgh, G. J., … Zwiers, F. W. (2016). Attribution of extreme weather and climate-related events. *WIREs Climate Change 7*(1), 23–41. doi: 10.1002/wcc.380

Stott, P. A., Stone, D. A., & Allen, M. R. (2004). Human contribution to the European heatwave of 2003. *Nature 432*, 610–614. doi:10.1038/nature03089

Sultan, B., Guan, K., Kouressy, M., Biasutti, M., Piani, C., Hammer, G. L., … Lobell, D. B. (2014). Robust features of future climate change impacts on sorghum yields in West Africa. *Environmental Research Letters 9*(10). doi: 10.1088/1748-9326/9/10/104006. Retrieved from: **http://iopscience.iop.org/article/10.1088/1748-9326/9/10/104006/pdf**.

Tack, J., Barkley, A., & Hendricks, N. (2017). Irrigation offsets wheat yield reductions from warming temperatures. *Environmental Research Letters 12*(11). doi: 10.1088/1748-9326/aa8d27. Retrieved from: **http://iopscience.iop.org/article/10.1088/1748-9326/aa8d27/pdf**

Tashiro, T., & Wardlaw, I. F. (1990). The effect of high temperature at different stages of ripening on grain set, grain weight and grain dimensions in the semi-dwarf wheat "Banks." *Annals Botany 65*(1), 51–61

Teng, H., Branstator, G., Wang, H., Meehl, G. A., & Washington, W. M. (2013). Probability of US heat waves affected by a subseasonal planetary wave pattern. *Nature Geoscience 6*(12), 1056–1061. doi: 10.1038/ngeo1988

Totz, S., Petri, S., Lehmann, J., Peukert, E., and Coumou, D. (2019). Exploring the sensitivity of Northern Hemisphere atmospheric circulation to different surface temperature forcing using a statistical-dynamical atmospheric model. *Nonlinear Processes in Geophysics 26*(1), 1-12. doi: 10.5194/npg-26-1-2019

Troy, T. J., Kipgen, C., & Pal, I. (2015). The impact of climate extremes and irrigation on US crop yields. *Environmental Research Letters 10*(5). doi: 10.1088/1748-9326/10/5/054013. Retrieved from **http://iopscience.iop.org/article/10.1088/1748-9326/10/5/054013/pdf**

Uejio, C. K., Wilhelmi, O. V., Golden, J. S., Mills, D. M., Gulino, S. P., & Samenow, J. P. (2011). Intra-urban societal vulnerability to extreme heat: The role of heat exposure and the built environment, socioeconomics, and neighborhood stability. *Health and Place 17*(2), 498–507. doi: 10.1016/j.healthplace.2010.12.005

van der Velde, M., Wriedt, G., & Bouraoui, F. (2010). Estimating irrigation use and effects on maize yield during the 2003 heatwave in France. *Agriculture, Ecosystems, and Environment 135*(1–2), 90–97. doi: 10.1016/j.agee.2009.08.017

Varghese, G., John, G., Thomas, K., Abraham, O. & Mathai, D. (2005). Predictors of multi-organ dysfunction in heatstroke. *Emergency Medical Journal 22*(3), 185–187. doi: 10.1136/emj.2003.009365

Vautard, R., Yiou, P., D'Andrea, F., de Noblet, N., Viovy, N., Cassou, C., … Fan, Y. (2007). Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit. *Geophysical Research Letters 34*, L07711. doi: 10.1029/2006gl028001. Retrieved from **https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2006GL028001**.

Vavrus, S. J., Wang, F., Martin, J. E., Francis, J. A., Peings, Y., & Cattiaux, J. (2017). Changes in North American atmospheric circulation and extreme weather: Influence of Arctic Amplification and Northern Hemisphere snow cover. *Journal of Climate 30*(11), 4317–4333. doi: 10.1175/JCLI-D-16-0762.1

Wahid, A., Gelani, S., Ashraf, M., & Foolad, M. R. (2007). Heat tolerance in plants: An overview. *Environmental and Experimental Botany 61*(3), 199–223. doi: 10.1016/j.envexpbot.2007.05.011

Wang, M. & Overland, J. E. (2012). A sea ice free summer Arctic within 30 years: An update from CMIP5 models. *Geophysical Research Letters 39*(17), 6–11. doi: 10.1029/2012GL052868

Wegren, S. K. (2013). Food security and Russia's 2010 drought. *Eurasian Geography and Economics 52*(1), 140–156. doi: 10.2747/1539-7216.52.1.140

Welton, G. (2011). The impact of Russia's 2010 grain export ban. *Oxfam Research Reports* 32. Retrieved from **https://www.oxfam.org/sites/www.oxfam.org/files/rr-impact-russias-grain-export-ban-280611-en.pdf**

West, J. W. (2003). Effects of heat-stress on production in dairy cattle. *Journal of Dairy Science 86*(6), 2131–2144. doi: 10.3168/jds.S0022-0302(03)73803-X

Wolf, S., Olesinski, A. A., Rudich, J., & Marani, A. (1990). Effect of high temperature on photosynthesis in potatoes. *Annals Botany 65*, 179–185.

Woollings, T. (2010). Dynamical influences on European climate: An uncertain future. *Philosophical Transactions of the Royal Society A, 368*(1924), 3733–3756. doi: 10.1098/rsta.2010.0040

Zappa, G., Shaffrey, L. C., Hodges, K. I., Sansom, P. G., & Stephenson, D. B. (2013). A multimodel assessment of future projections of North Atlantic and European extratropical cyclones in the CMIP5 climate models. *Journal of Climate 26*(16), 5846–5862. doi: 10.1175/JCLI-D-12-00573.1

Zhang, T., Lin, X., & Sassenrath, G. F. (2015). Current irrigation practices in the central United States reduce drought and extreme heat impacts for maize and soybean, but not for wheat. *Science of the Total Environment 508*, 331–342. doi. /10.1016/j.scitotenv.2014.12.004

Zhao, C., Piao, S., Wang, X., Huang, Y., Ciais, P., Elliott, J., … Peñuelas, J. (2016). Plausible rice yield losses under future climate warming. *Nature Plants 3*(Dec.), 1–5. doi: 10.1038/nplants.2016.202

Zhao, L., Oppenheimer, M., Zhu, Q., Baldwin, J. W., Ebi, K. L., Bou-Zeid, E., … Liu, X. (2018). Interactions between urban heat islands and heat waves. *Environmental Research Letters 13*(3), 034003. doi: 10.1088/1748-9326/aa9f73

Zhou, D., Zhao, S., Liu, S., Zhang, L., & Zhu, C. (2014). Surface urban heat island in China's 32 major cities: Spatial patterns and drivers. *Remote Sensing of Environment 152*, 51–61. doi: 10.1016/j.rse.2014.05.017

Zivin, J. G., & Neidell, M. (2014). Temperature and the allocation of time: Implications for climate change. *Journal of Labor Economics 32*(1), 1–26. doi: 10.1086/671766

Zscheischler, J., & Seneviratne, S. I. (2017). Dependence of drivers affects risks associated with compound events. *Science Advances 3*(6), e1700263. doi: 10.1126/sciadv.1700263. Retrieved from **http://advances.sciencemag.org/content/3/6/e1700263**

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