

TOPICAL REVIEW • OPEN ACCESS

Extreme weather impacts of climate change: an attribution perspective

To cite this article: Ben Clarke *et al* 2022 *Environ. Res.: Climate* 1 012001

View the [article online](#) for updates and enhancements.

ENVIRONMENTAL RESEARCH CLIMATE



TOPICAL REVIEW

Extreme weather impacts of climate change: an attribution perspective




OPEN ACCESS

RECEIVED
14 January 2022

REVISED
29 April 2022

ACCEPTED FOR PUBLICATION
11 May 2022

PUBLISHED
28 June 2022

Ben Clarke^{1,*} , Friederike Otto² , Rupert Stuart-Smith^{1,3} and Luke Harrington⁴ 

¹ Environmental Change Institute, University of Oxford, Oxford OX1 3QY, United Kingdom

² Grantham Institute, Imperial College London, London SW7 2AZ, United Kingdom

³ Oxford Sustainable Law Programme, University of Oxford, Oxford OX1 3QY, United Kingdom

⁴ New Zealand Climate Change Research Institute, Victoria University of Wellington, Wellington 6012, New Zealand

* Author to whom any correspondence should be addressed.

E-mail: ben.clarke@jesus.ox.ac.uk

Keywords: extreme weather, extreme event attribution, disaster risk reduction, climate change impacts

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Abstract

Extreme event attribution aims to elucidate the link between global climate change, extreme weather events, and the harms experienced on the ground by people, property, and nature. It therefore allows the disentangling of different drivers of extreme weather from human-induced climate change and hence provides valuable information to adapt to climate change and to assess loss and damage. However, providing such assessments systematically is currently out of reach. This is due to limitations in attribution science, including the capacity for studying different types of events, as well as the geographical heterogeneity of both climate and impact data availability. Here, we review current knowledge of the influences of climate change on five different extreme weather hazards (extreme temperatures, heavy rainfall, drought, wildfire, tropical cyclones), the impacts of recent extreme weather events of each type, and thus the degree to which various impacts are attributable to climate change. For instance, heat extremes have increased in likelihood and intensity worldwide due to climate change, with tens of thousands of deaths directly attributable. This is likely a significant underestimate due to the limited availability of impact information in lower- and middle-income countries. Meanwhile, tropical cyclone rainfall and storm surge height have increased for individual events and across all basins. In the North Atlantic basin, climate change amplified the rainfall of events that, combined, caused half a trillion USD in damages. At the same time, severe droughts in many parts of the world are not attributable to climate change. To advance our understanding of present-day extreme weather impacts due to climate change developments on several levels are required. These include improving the recording of extreme weather impacts around the world, improving the coverage of attribution studies across different events and regions, and using attribution studies to explore the contributions of both climate and non-climate drivers of impacts.

1. Introduction

Every year, climate change manifests through more intense extreme weather events, including heatwaves, droughts and heavy rainfall. This leads to impacts upon people, property and nature that would not have occurred in the absence of these increases in events' likelihood and intensity. Unlike some other impacts of climate change, extreme weather events are manifesting on immediate timescales and changes in extremes are poorly described by the climatological means studied in many projections. Unfortunately, there is currently no standardised way of, or effort towards, documenting climate change related harms systematically. As a result, there is no systematic basis to quantify the major contribution of human influence on extreme weather to the costs of climate change. This contributes to the challenge that measures taken to

mitigate and adapt to current (of ~ 1.20 °C at the time of writing (Masson-Delmotte *et al* 2021)) and future levels of global warming are not based on what could be the best available evidence.

Extreme event attribution is the method through which the role of climate change in an individual event can be assessed and quantified (Allen 2003, Philip *et al* 2020, van Oldenborgh *et al* 2021). Over the past two decades, more than 350 studies have quantified the role of climate change in over 400 extreme events (Carbon Brief 2021). This growing body of evidence is complementary to other analysis, such as work documenting observed and modelled trends in extremes due to climate change, and projections of future risk. The evidence from attribution studies adds value by highlighting the role of climate as a risk driver in experienced events, which in turn is useful for building future resilience (Raju *et al* 2022), and it enables the attribution of impacts, which is useful for cost-benefit analysis of mitigation and is a potential avenue for the exploration of drivers of loss and damage from climate-related extremes (James *et al* 2019). There is currently very little discussion of the role of science in determining loss and damage from anthropogenic climate change.

However, the number of events that have been studied using attribution methods is just a small fraction of all impactful extreme weather events that occurred over the same period. It is almost impossible to document this comprehensively due to data, time and resource constraints (Harrington and Otto 2020, van Oldenborgh *et al* 2021). Furthermore, these studies overwhelmingly focus on events that occurred in the global north (Otto *et al* 2020a). This pattern is mirrored in the unequal recording of impacts from extreme events, although nations in the global south are experiencing the most rapid changes in risk (Byers *et al* 2018) and often have high levels of underlying exposure and vulnerability to climate-related events.

The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) provides a synthesis of attributable changes in extremes in regions across the world (Masson-Delmotte *et al* 2021). This forms a core part of the evidence base in this literature review. However, in order to link regional assessments of attributable risk to impacts that have occurred, it is necessary to compile attribution statements for individual events. In doing so this review builds on the IPCC assessment, linking broad changes in hazards to the ways in which these manifest and interact with exposure and vulnerability, and result in tangible impacts, with a bottom-up methodology, in which we develop insight into human influence on assessed extreme weather event categories based on literature on individual events. Further, the distinction between regional assessment and individual events is particularly important in adding evidence for more complex events, such as droughts, and at smaller spatial scales than the IPCC's regional aggregations, at which other phenomena may affect the influence of climate change.

Overall, the review brings together the best evidence we have on changes in extreme weather hazards and the impacts of past events, covering five key hazards: heatwaves, rainfall-based flooding, droughts, wildfires, and tropical cyclones. It is important to note that several of these hazards fall along different parts of the causative chain that stretches from anthropogenic climate change to impacts; each was selected as an appropriate intersection between attribution science and impact-relevance. As such, for each hazard, we assess the degree to which past impacts can be attributed to anthropogenic climate change, and the limiting factors associated with this. In doing so, we also build a picture of where evidence is most lacking, and therefore most urgent, for both attribution science and the documenting of impacts.

Each hazard section is laid out as follows. First, we describe attributed changes in extremes on global and regional scales, then how individual event attribution fits within this. Second, we discuss why it matters, describing the causative chain that results in key impacts arising due to such hazards. Finally, we discuss the 'attributable impacts' for each hazard. The intent of this subsection is not to suggest that the impacts of an event with any degree of anthropogenic influence, no matter the scale, are all attributable to climate change. Instead, these sections contain individual attribution statements alongside the impacts of those events, in the context of their connections as described previously. This should be interpreted as a snapshot, constrained by the body of existing attribution statements and to date, of the types and magnitude of impacts that have manifested to some degree by anthropogenic climate change. We posit that this is currently the most we can know based on existing evidence. And, in the absence of science to accurately attribute impacts using an end-to-end system for every event (and understanding that a fractional attributable risk (FAR)-based attribution of impacts is most applicable to classes of event (Perkins-Kirkpatrick *et al* 2022)) this is nonetheless more useful than neglecting to combine such information at all. Tables 1 and 2 summarise this information on a global scale.

This is not a review of risk, because that is impossible without also discussing vulnerability and exposure to changing hazards. However, it provides a platform on which to begin such a discussion. Further, it is a basis for placing a price tag on the diverse impacts of climate change, with implications for mitigation and adaptation considerations at all levels of decision-making. It concludes with several key areas in which further work will improve upon quantification of climate-related impacts, and the applications of this to address the inequity at the heart of the climate crisis (Pelling and Garschagen 2019, Stone *et al* 2021, Raju *et al* 2022).

Table 1. Direct physical health impacts of different types of disaster between 2000 and 2020, as recorded by EMDAT, and the attributable influence of climate change on each hazard (EMDAT 2019).

Hazard	Observed direct impacts			Attributable influence of climate change on hazard severity/likelihood (confidence level)
	Deaths	Injured	Total affected	
Heatwaves	157 000	193 000	320 000	Increase (high)
Cold waves and severe winter conditions	14 900	1.86 million	96.1 million	Decrease (high)
Floods	111 000	304 000	1.66 billion	Increase (medium)
Droughts	21 300	N/A	1.44 billion	Increase (medium)
Wildfires	1570	7260	3.38 million	Increase (medium)
Storms	201 000	337 000	773 million	Rainfall increase (high) Other impacts no change (low)

Table 2. Direct damages of different types of disaster between 2000 and 2020, as recorded by EMDAT, and the attributable influence of climate change on each hazard (EMDAT 2019). Note that these values are likely to be substantial underestimates of the true magnitude of damages.

Hazard	Observed direct impacts		Attributable influence of climate change on hazard severity/likelihood (confidence level)
	Insured damages (USD)	Total damages (USD)	
Heatwaves	10 000	13.4 bn	Increase (high)
Cold waves and severe winter conditions	4.63 bn	31.3 bn	Decrease (high)
Floods	74.1 bn	610 bn	Increase (medium)
Droughts	21 bn	119 bn	Increase (medium)
Wildfires	51.3 bn	94.3 bn	Increase (medium)
Storms	499 bn	1.30 trillion	Rainfall Increase (high) Other impacts no change (low)

2. Climate change and extreme weather impacts

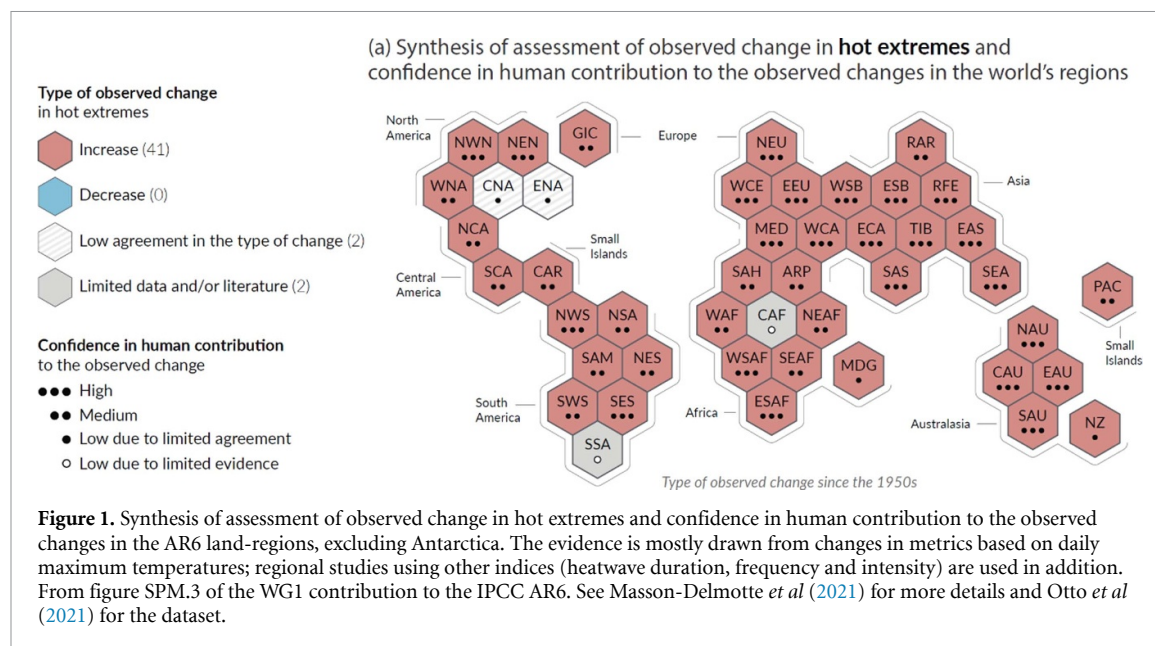
2.1. Heat

2.1.1. Changes in extremes

The most dramatic changes in extreme weather induced by climate change are in the rate and intensity of heat and cold extremes. The rate and intensity of cold extremes are declining while heat extremes are increasing, with dire consequences for communities around the world. By 2015, the chance of the most extreme daily maximum temperatures (above the 99.9th percentile) averaged over land had increased fivefold (Fischer and Knutti 2015). Globally, as a direct result of climate change, previously very rare heat is now just unusual (Donat *et al* 2016, King 2017, Dunn *et al* 2020, Seong *et al* 2021), while, in some cases, events now considered ‘extreme’ reach temperatures that were formerly all but impossible (Rahmstorf and Coumou 2011, Imada *et al* 2019, Sippel *et al* 2020, Robinson *et al* 2021). The 2021 IPCC report is unequivocal in stating that average and extreme heat are increasing on every continent and that this is due to human-caused climate change (Masson-Delmotte *et al* 2021):

- A heatwave that would once have had a chance of **1 in 10 to occur in any given year** in the pre-industrial climate will now occur 2.8 (1.8–3.2) times more frequently and be 1.2 °C hotter. At 2 °C of global warming, it will occur 5.6 (3.8–6.0) times more frequently and be 2.6 °C hotter.
- A heatwave that would have had a **1 in 50 chance to occur in any given year** in the pre-industrial climate will now occur 4.8 (2.3–6.4) times more frequently and be 1.2 °C hotter. At 2 °C of global warming, it will occur 13.9 (6.9–16.6) times more frequently and be 2.7 °C hotter.

For even rarer events and on local scales the changes are even more dramatic. The increasing regularity of formerly rare events is particularly consequential: societies tend not to prepare for events that were historically so unlikely that they have never occurred (Woo 2016). Societies are especially vulnerable to the exceptionally extreme events that are now possible in a changing climate (Ciavarella *et al* 2021). In addition to this global picture, regional trends in heat extremes are attributed to climate change in Asia (Dong *et al* 2018, Yin *et al* 2019, Chen and Sun 2021), Africa (Stott *et al* 2011), Australia (Alexander and Arblaster 2017), Europe (Christidis and Stott 2016) and South America (Rusticucci and Zazulie 2021). A synthesis of current regional changes due to human influence are shown in figure 1. We reproduce this figure and others from



Working Group 1 (WG1) contribution to the IPCC AR6 (Masson-Delmotte *et al* 2021) to give context for our discussion of where attribution can add value to these global and regional pictures.

2.1.2. Why it matters

The impact of increased temperatures on mortality is widely established in the epidemiological literature. As climate change intensifies heatwaves around the world, the risk of heat-related deaths increases unless exposed populations' vulnerability is reduced. The fraction of the burden of heat-related mortality that is due to climate change is large and growing, with 37% of heat-related deaths attributed to climate change worldwide (Vicedo-Cabrera *et al* 2021), equivalent to tens of thousands of deaths per year. Increases in the number of hot days, and intensity of heatwaves results in a range of heat-related illnesses. Such illnesses include cardiovascular and respiratory complications, renal failure, electrolyte imbalance, and harm to foetal health (Moyce *et al* 2016, Ebi *et al* 2018, Parsons *et al* 2021). Increasing temperatures and heatwaves have also increased the prevalence and range of temperature-sensitive pathogens, such as *Vibrio*, which can cause cholera and gastroenteritis (Ebi *et al* 2017).

Increases in the occurrence of heat extremes result in substantial increases in mortality, and this effect is particularly pronounced the higher the temperatures. Climate change increases the likelihood of reaching very high temperatures, at which point the human body may no longer be able to cool itself. The theoretical limit for human survival is a 'wet bulb' temperature of 35 °C, at which point even the healthiest human in shade and with water would die from severe heat stroke in a matter of hours (Raymond *et al* 2020). Both mortality and morbidity rise significantly at far lower temperatures than this upper limit, affecting the elderly, very young and those with pre-existing medical conditions, such as respiratory and cardiovascular illness (Michelozzi *et al* 2009, Sugg *et al* 2016, Watts *et al* 2018, Green *et al* 2019). Heatwaves are also strongly associated with rises in harmful pollutants such as ozone, particulate matter, sulphur dioxide, carbon monoxide and nitrogen dioxide, which further contribute to respiratory health impacts (Garcia-Herrera *et al* 2010, Analitis *et al* 2014, Li *et al* 2017, Kalisa *et al* 2018).

A direct consequence of the health impacts of heat is a loss of labour productivity during hot periods, as workers must slow down, take more breaks, and hydrate to remain safe (Sahu *et al* 2013, Kjellstrom *et al* 2016, Spector *et al* 2019, Borg *et al* 2021). In the US alone, labour productivity losses due to extreme heat cost around USD 2 bn annually (Zhang and Shindell 2021), while across the world total losses amount to USD 280–311 bn (Borg *et al* 2021). These are concentrated in lower- and middle-income countries, in tropical and subtropical areas, and in heavy manual labour and outdoor industries such as agriculture and construction (Kjellstrom *et al* 2016, Borg *et al* 2021, Parsons *et al* 2021). Across the world, the labour capacity of rural populations during summer months fell by 5.3% between 2000 and 2016 due to rising heat—in tropical regions capacity fell by up to 30% (Watts *et al* 2018). While some adaptation policies have already been put into place, such as moving work hours earlier in the day, these measures may come with unintended consequences, and decrease in effectiveness as warming continues (Masuda *et al* 2019, Parsons *et al* 2021).

While there have been very few observations of wet bulb temperatures over the critical 35 °C threshold, the occurrence of dangerous humid heat extremes, exceeding wet bulb temperatures of at least 27 °C, has

more than doubled since 1979 (Raymond *et al* 2020). By another measure, 40% of the total land surface has already entered an ‘unusual’ climate in the warmest months—that is, temperatures exceed a signal-to-noise ratio of 1 (Frame *et al* 2017, Hawkins *et al* 2020). Increases in severe heat hazards cause a disproportionate increase in the associated health risks because a disproportionately large fraction of the global population lives in hotter regions (Watts *et al* 2018). On top of that, between 2000 and 2016, the number of vulnerable people (over 65 years) exposed to extreme heat increased by 125 million, reaching 175 million in 2015 (Watts *et al* 2018).

2.1.3. Attributable impacts

Climate change amplifies the temperature of most heat extremes (Otto *et al* 2016). Attribution research has found that the most extreme heatwaves have become substantially more likely, or even only possible at all (Imada *et al* 2019), due to climate change. This includes, but is not limited to, events in Europe in 2003 (Stott *et al* 2004, Christidis *et al* 2015) and 2018 (Leach *et al* 2020), Russia 2010 (Rahmstorf and Coumou 2011, Otto *et al* 2012), the US (Shiogama *et al* 2014), China (Sparrow *et al* 2018, Zhou *et al* 2019), Argentina (Hannart *et al* 2015), North Africa (Mitchell 2016), Australasia (Hope *et al* 2016), South and Southeast Asia (Azhar *et al* 2014, Wehner *et al* 2016, Mazdiyasi *et al* 2017, Imada *et al* 2018, Christidis *et al* 2018b), and across the world (Peterson *et al* 2012, 2015, Herring *et al* 2014, 2015, 2016, 2018, 2019, 2020). In some cases, events were effectively impossible in the absence of climate change (Herring *et al* 2019, 2020, 2021, Imada *et al* 2019, Fischer *et al* 2021, World Weather Attribution 2021a), including the emerging possibility of simultaneous heat extremes across regions and continents (Kornhuber *et al* 2019, Vogel *et al* 2019).

Between the years 2000 and 2020, the disaster database EMDAT recorded approximately 157 000 deaths from heatwaves across the planet (table 2, EMDAT 2019), although it is acknowledged that this is likely to be a substantial underestimate due to reporting limitations and because deaths due to heat occur outside of officially-declared events (Otto *et al* 2020a, see below). Around 125 000 of these deaths occurred during just two events, the European heatwave of 2003 and Russian heatwave of 2010, which resulted in 70 000 and 55 000 deaths, respectively. Both of these events were made substantially more likely by climate change, as noted above (Stott *et al* 2004, Rahmstorf and Coumou 2011, Otto *et al* 2012). In the case of the 2003 heatwave, this was made at least twice as likely to occur, due to climate change, and has since become 10 times more likely again (Christidis *et al* 2015). The Russian heatwave, meanwhile, was found to have been made 5 times more likely to occur by the climate change observed since 1960 (Rahmstorf and Coumou 2011). In the UK, estimates using simple hazard-based FAR methodology link around 1,500 excess deaths from three heatwaves directly to climate change (Clarke *et al* 2021). And another study on the 2003 heatwave used an end-to-end approach, combining meteorological attribution with the effect of temperatures on mortality, to directly attribute deaths in Greater London and Central Paris; 64 additional Londoners (~20% of the total) and 506 Parisians (~70% of the total) died due to the influence of climate change (Mitchell *et al* 2016).

2.1.3.1. CASE STUDY: Western Russia, 2010

From early July until mid-August 2010, an intense high-pressure system over Eastern Europe and Western Russia caused temperatures to soar above 30 °C throughout the region, breaking 40 °C in many major cities. An event of this magnitude was made approximately 3–5 times more likely by climate change (Rahmstorf and Coumou 2011, Otto *et al* 2012).

This extreme heat led to widespread drought conditions that decimated 25% of the entire annual crop yield and also amplified wildfires across more than 10 million hectares of dried-out forests, steppe and peat regions (Barriopedro *et al* 2011, Bondur 2011). *This compounded an already growing fire hazard in rural Western Russia, resulting from changes in land use and sustainable management, among other factors* (Goldammer 2010). *The destruction of grain crops and subsequent export ban led to rising food prices domestically and abroad. Pakistan was Russia’s fourth largest customer and experienced a 16% rise in the price of wheat, linked with a 1.6% rise in poverty* (Welton 2010). *The destruction of thousands of properties left over 3500 people homeless. Harmful gases and aerosols from the fires became trapped in the stagnant high-pressure system, resulting in poor air quality in many major cities. This exacerbated the already-unprecedented public health crisis, particularly affecting those with severe asthma and heart problems. In the city of Moscow alone, around 5000 more deaths were recorded than for the same period in the previous year, and across the whole country this was closer to 55 000 from a combination of heat and poor air quality* (Barriopedro *et al* 2011).

2.1.4. Underestimation of impacts

These Europe-focused results are far from a complete tally of climate change-amplified heatwave impacts. This is largely due to data limitations. Both assessments of health associated with extreme heat (Green *et al* 2019) and weather observations, crucial for assessing the link to climate change (Otto *et al* 2020a), are concentrated within higher income countries. EMDAT lists 147 instances of impactful heat events from

individual countries for the period 2000–2020, only an improbably low 58 of which are from all of Asia, Africa, South and Central America and the Caribbean combined (EMDAT 2019). Of the 157 000 total deaths recorded, only 10 000—or 6.3%—were recorded in these regions, which together constitute almost 85% of the world's population, over 60% of the land mass, and many of the hottest and most humid climates. These data are subject to recording biases that limit the number of heatwaves registered to EMDAT to those that are officially declared by national meteorological services, many of which do not currently have formal heatwave definitions, and recorded locally as exceeding one of several impact thresholds; thus, they are limited by the capacity of governments or NGOs to attribute heat-related impacts. Further, this dataset focuses only on heatwaves, periods of relatively extreme temperatures, whereas many heat-related deaths in fact occur outside of heatwaves, when temperatures are also increased by climate change, but are not captured within these data (Gasparrini *et al* 2015).

In the two most impactful European heatwaves recorded, the maximum recorded wet-bulb temperature peaked at 28 °C; temperatures frequently exceed this in other regions of the world such as south Asia (Raymond *et al* 2020), with many more lethal heat events likely already occurring than are reported (Mora *et al* 2017).

In addition to the attributable trends in exposure to extreme heat, we can elicit evidence from the few attribution studies that exist. For instance, in 2015 in the Indian city of Hyderabad, heat extremes over a 5 day period were made more than 30 times more likely by climate change (Wehner *et al* 2016). Including this event, three devastating heatwaves in India in 2010, 2013 and 2015 resulted in the deaths of at least 5000 people (Azhar *et al* 2014, Mazdiyasi *et al* 2017). Meanwhile in neighbouring Pakistan, also in 2015, the city of Karachi experienced an extreme heat event which by the same measure would have been effectively impossible without climate change (Wehner *et al* 2016).

The impacts from heatwaves in hotter climates may be somewhat mitigated by factors such as the natural acclimatisation of populations—which might also be considered as longer-term impacts upon behaviour, culture and architecture—and age demographics (Gasparrini *et al* 2015, Green *et al* 2019). However, these mitigating factors are more than likely offset by greater population density, higher frequency of more intense extremes, and greater vulnerability in many of the regions with few reported impacts (Harrington and Otto 2018, Rohat *et al* 2019). We are therefore confident that the reported deaths from heatwaves and extreme heat, and thus those linked to climate change, are a vast underestimate.

2.1.5. *Is increased heatwave-related mortality offset by a reduction in cold extremes?*

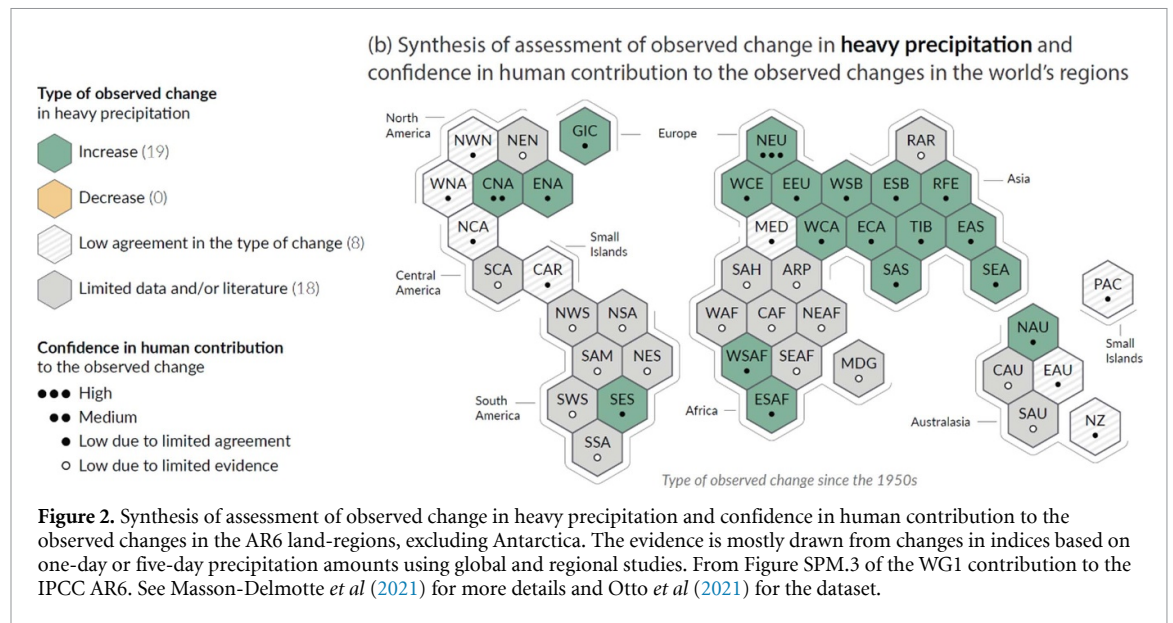
Cold extremes are decreasing in frequency and intensity across most of the world and at continental and subcontinental scales (Christidis and Stott 2016, King 2017, Dunn *et al* 2020, Hu *et al* 2020). In the Arctic, the rise in heat extremes (Sui *et al* 2017, Dobricic *et al* 2020) and decrease in cold extremes (Sui *et al* 2017) is especially pronounced, in line with its rapid warming (Box *et al* 2019). Specific cold spells of recent years have displayed this decreased probability due to climate change, including in the UK (Christidis and Stott 2020), US (Bellprat *et al* 2016), Europe (Peterson *et al* 2012, Christiansen *et al* 2018) and China (Sun *et al* 2018).

On average, mortality and morbidity rates are higher in winter than summer months in temperate regions (Conlon *et al* 2011, Ebi and Mills 2013, Gronlund *et al* 2018), with a more complex relationship in locations across the tropics and subtropics (McMichael *et al* 2008, Singh *et al* 2019). The direct effect of cold on health remains obscured by the wide array of seasonal factors at play (Staddon *et al* 2014, Kinney *et al* 2015, Hajat 2017), including cardiovascular disease which is only weakly linked to cold temperatures (Ebi and Mills 2013). For the effect of extremes specifically, there are two key factors to consider. First, temperature-mortality relationships are generally far steeper for extreme heat than extreme cold (Gronlund *et al* 2018). Second, the most severe winter cold spells contribute little to overall winter mortality, and even in some temperate regions there is evidence that climate change will not decrease winter mortality (Staddon *et al* 2014). Thus the reduction in frequency and intensity of cold extremes has likely not affected overall changes in mortality substantially, nor offset those from hot extremes (Ebi and Mills 2013) and the impact of increasing heat-related mortality are assessed to far exceed any reductions in cold-related mortality as a result of climate change (Gasparrini *et al* 2017, Huber *et al* 2017, Vicedo-Cabrera *et al* 2018).

2.2. Rainfall and flooding

2.2.1. *Changes in high rainfall extremes*

By 2015, climate change increased the likelihood of daily precipitation extremes exceeding the 99.9th percentile of pre-industrial events by 18%, averaged over all land regions (Fischer and Knutti 2015). A warmer atmosphere holds more moisture at a given pressure: the Clausius–Clapeyron relation states that the increase in moisture held at a given pressure is 6%–7% per 1 °C. Extra water in the atmosphere combines with changes in weather patterns to affect rainfall extremes in a given region (O’Gorman 2015, Pfahl *et al* 2017). In contrast to heat, these changes vary greatly across regions and seasons. For example, extreme



rainfall is increasing in Northern Europe in winter but decreasing in the Southern part of the continent in summer.

Nonetheless, since the 1950s, heavy rainfall has become more frequent and intense across most parts of the world, which is now known to be mainly due to human climate change (Fischer and Knutti 2015). It has not strongly decreased in likelihood anywhere. A synthesis of current regional changes due to human influence are shown in figure 2. Globally, the IPCC reports that, in a given location, what would once have been a one-in-10 year rainfall event currently occurs 1.3 (1.2–1.4) times every 10 years and is 6.7% wetter. At 2 °C of global warming, this will be 1.7 (1.6–2.0) times per 10 years and 14% wetter (Masson-Delmotte *et al* 2021). Sub-daily extreme rainfall events are intensifying at a rate at or exceeding Clausius–Clapeyron scaling (Fowler *et al* 2021), while regional attribution shows that deluges generally are becoming more frequent and intense especially across North America, Asia and Europe (Chen and Sun 2017a, 2021, Paik *et al* 2020, Dong *et al* 2021, Sun *et al* 2021), though this may also be true in other regions with a lower availability of observational data.

2.2.2. Link with flooding

Flooding is a major source of the impacts that extreme rainfall has upon human societies. In general, changes in the risk of flooding due to heavy precipitation also depend on changes in other factors including the susceptibility of areas to flooding, land use change and river management (Ji *et al* 2020), as well as other climate-related factors such as soil moisture, storm extent and snowmelt (Sharma *et al* 2018, Wasko and Nathan 2019). As a result, there is high regional and sub-regional variation in trends in streamflow (Do *et al* 2017, Gudmundsson *et al* 2019), but many of the observed changes can only be explained by human influence on the climate (Gudmundsson *et al* 2021). Evidence from attribution-science literature shows that growing numbers of floods have been made more intense by the effect of climate change on precipitation (Cho *et al* 2016, Pall *et al* 2017, van der Wiel *et al* 2017, Philip *et al* 2018a, Teufel *et al* 2019).

2.2.3. Why it matters

Flooding damages property and infrastructure, as evidenced by disaster data for the years 2000–2020 in which floods globally caused USD 610 bn in damage (table 2). It also places people in direct danger of injury and death. The flood events recorded in the EM-DAT database led to 111 000 deaths and affected 1.66 bn people over the period 2000–2020 (table 1, EM-DAT 2019). Indeed, flooding is the disaster that is recorded as affecting the greatest number of people—though this may be due to a bias arising from the variable ease of recording impacts for different disasters; heatwaves are more pervasive but ill-defined than flood extent, for example. One further study that considered only ‘large floods’ found that 255–290 million people were directly affected by flooding between 2000 and 2018, the population in areas affected by inundation grew by 58–86 million between 2000 and 2015, and the number of people affected by flooding continues to increase due to population increases and climate change (Tellman *et al* 2021).

Floods impact both physical and mental health. Physical impacts result directly from dangerous water flows and inundation, as well as ‘cascading impacts’, in which the destruction of infrastructure limits access

to services and utilities including clean water and sanitation, resulting in ill health (Ramana Dhara *et al* 2013). In turn, this enhances the spread of and vulnerability to water-borne disease, including leptospirosis, cholera and other diarrhoeal diseases such as giardiasis, salmonellosis, and cryptosporidiosis (Marcheggiani *et al* 2010, Ramana Dhara *et al* 2013). This occurrence of such outbreaks following floods is well documented. This evidence includes an inventory of 87 extreme events between 1910 and 2010 (Cann *et al* 2013), known associations between flood events and gastrointestinal illness in the US (Patz *et al* 2008, Uejio *et al* 2014) and India (Bush *et al* 2014), and has been observed in the aftermath of floods in Pakistan (Baqir *et al* 2012), Mozambique (Devi 2019), China (Zhang *et al* 2019), Ecuador (Carlton *et al* 2014), the Solomon Islands (Jones *et al* 2016) and many others (Fredrick *et al* 2015, Levy *et al* 2016). This is especially impactful in areas of pre-existing high vulnerability, such as those without access to improved sanitation and water sources, on top of other poverty- and conflict-related factors such as access to healthcare, education and early warning systems (Cann *et al* 2013, Davies *et al* 2015).

In addition, vector-borne diseases such as malaria, dengue and West Nile Fever may spread further following flooding, as more widespread stagnant water bodies provide breeding grounds for mosquitoes (Ramana Dhara *et al* 2013, Hinz *et al* 2019). Finally, many diseases are also enhanced by the effect of warmth and high humidity, because this increases the longevity of many pathogens and mosquitoes (Moors *et al* 2013, Levy *et al* 2016, Hinz *et al* 2019). The combination of climate change impacts on precipitation, temperature, and yet other factors that amplify the resulting impacts, such as societal capacity to deal with health impacts, create compound risks.

Other compound risks are also associated with flooding. For example, low-lying coastal areas are increasingly affected by high sea levels, due to storm surges and sea-level rise, which combine with heavy rainfall to amplify flood damages (Moftakhari *et al* 2017, Bevacqua *et al* 2019, Marsooli and Lin 2020). Similarly, tropical cyclones result in damage to infrastructure including power lines, water supplies and roads, increasing vulnerability to high temperatures as air conditioning is disabled, and access to clean water and healthcare are restricted (Lin 2019; Matthews *et al* 2019, Mejia Manrique *et al* 2021, Yu *et al* 2020).

The mental health impacts of disasters are also becoming documented and understood more widely, with an emerging literature (Hayes *et al* 2018, Watts *et al* 2018, Cianconi *et al* 2020), especially on the impacts of floods (Tunstall *et al* 2006, Stanke *et al* 2012, Alderman *et al* 2013, Azuma *et al* 2014, Fernandez *et al* 2015, Burton *et al* 2016, Waite *et al* 2017). These impacts include post-traumatic stress disorder (PTSD), anxiety, depression and suicidal thoughts, among other conditions (Dodgen *et al* 2016) and persist long after the disaster itself. First responders are severely impacted by the mental health effects of working in the aftermath of disasters, with local first responders most heavily affected (Osofsky *et al* 2011, Rusiecki *et al* 2014). These effects are more likely to occur in those with pre-existing mental health conditions (Dodgen *et al* 2016, Hayes *et al* 2018). Quantitative attribution of mental health impacts to climate change remains challenging. This is due to the diverse nature of such impacts, and because attribution studies typically consider one aspect of the causal chain (climate-meteorological event or meteorological event-mental health impacts), not both (Hayes *et al* 2018). However, a few cases exist in which mental health impacts are attributed to an event and the event itself is attributed to climate change. For example, the 2013/14 UK floods were made more likely by climate change (Huntingford *et al* 2014, Christidis and Stott 2015, van Oldenborgh *et al* 2015, Schaller *et al* 2016, Kay *et al* 2018) and caused increased psychological morbidity among those both flooded and disrupted (Waite *et al* 2017).

2.2.4. Attributable impacts

Annual monsoons are a critical source of rainfall for at least 60% of the world's population in areas including south and east Asia, Australia, and east and west Africa (Li *et al* 2016). The south Asian monsoon is of particular societal importance, providing 80% of the water to the subcontinent, which contains nearly a fifth of the world's population and is heavily reliant upon agriculture (Katzenberger *et al* 2021). In the 20th Century, a decline in the East Asian summer monsoon rains was observed, with the most intense rains becoming shorter but more intense, including flooding and droughts (Burke and Stott 2017). Since 2000, the strength of south Asian monsoon rains has increased, with the most pronounced increases occurring in the most intense events (Katzenberger *et al* 2021). This pattern covers all monsoon regions, to varying degrees, and crucially an associated increase in both drought and flooding (Burke and Stott 2017, Wang *et al* 2021). In response to future warming, and if aerosol emissions are reduced, significant and substantial increases in monsoon rains are expected, resulting in growing flash flooding risks (Masson-Delmotte *et al* 2021), especially in East Asia (Samset *et al* 2018). However, as increased precipitation is expected to occur over fewer days of more intense rainfall, worsening of droughts also becomes more likely (Burke and Stott 2017).

According to EM-DAT, around 49 000 deaths due to flooding occurred in south Asia from 2000 to 2020, almost half of recorded global flood mortality (EM-DAT 2019). The region has also suffered damages of

around USD 104 bn, only around USD 4 bn of which is recorded as insured damages. Many of the deadliest and most destructive floods in this subset occurred during the monsoon season, including in 2000 (India and Bangladesh), 2007 (across south Asia), 2010 (Pakistan), 2017 (Bangladesh), and 2005, 2008, 2013, 2019 and 2020 (India). However, even outside of the monsoon season, rainfall extremes have been amplified by climate change (Rimi *et al* 2018).

Outside of south Asia, the most impactful flood events in terms of both mortality and numbers of people affected by flooding also occurred primarily in low- and middle-income countries in Africa, including Sudan, Ethiopia, and Nigeria; South America, including Peru, Colombia and Brazil; and the Caribbean, including Haiti and the Dominican Republic. While few attribution assessments on specific events are available in these regions, there is nonetheless evidence of links between these types of events and climate change as described above. Further, trends in increased flooding have been identified in regions including parts of Brazil (Bartiko *et al* 2019) and Ethiopia (Mamo *et al* 2019), which combine with other factors to pose greater danger to people. For example, the Metropolitan Region of São Paulo has simultaneously undergone rapid urban expansion and an increase in the number of extremely heavy precipitation days. Such events were exceedingly rare in the 1950s, but by the 2010s occurred 2–5 times per year. This has placed people at a rapidly rising risk of flash flooding.

Not including tropical cyclones, extreme rainfall events with detected anthropogenic influence have occurred in Europe (Pall *et al* 2011, Schaller *et al* 2016, van Oldenborgh *et al* 2016, Otto *et al* 2018a), the Mediterranean (Vautard *et al* 2015), US (Herring *et al* 2014, Eden *et al* 2016, van der Wiel *et al* 2017), parts of South America (De Abreu *et al* 2018, Christidis *et al* 2018a), New Zealand (Rosier *et al* 2015), southeast Asia (Yun *et al* 2020), Japan (Imada *et al* 2020, Kawase *et al* 2020) and China (Burke *et al* 2016, Sun and Miao 2018, Zhou *et al* 2018, Yuan *et al* 2018b). Collectively, these events represent financial losses and destruction of property of more than USD 60 bn.

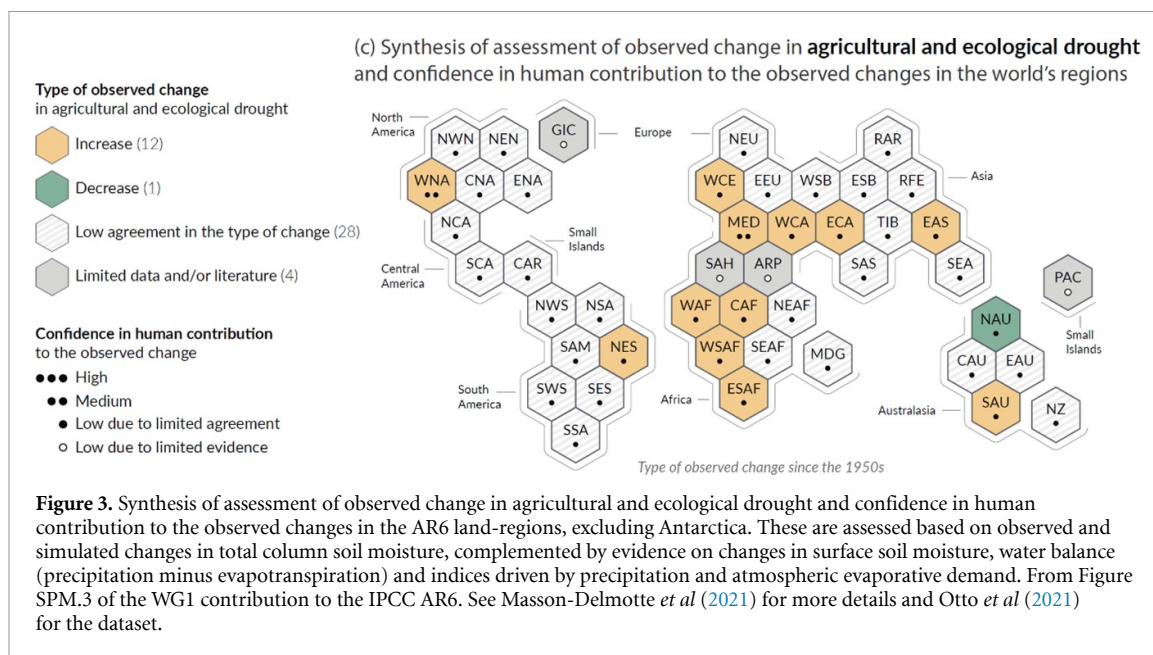
In certain areas, attribution studies on rainfall have directly estimated the fraction of damages incurred due to climate change. For example, in the UK between 2000 and 2020 approximately USD 9 bn in flood damages have been attributed to climate change (Clarke *et al* 2021). In New Zealand, USD 140 million in insured damages attributable to climate change occurred over 2007–2017, although this is likely a significant underestimate of overall costs (Frame *et al* 2020a). These studies provide broad estimates using a simple hazard-based FAR methodology. End-to-end attribution using hydrological models and taking account of exposure and vulnerability remains challenging (Schaller *et al* 2016), though research using modelling chains (Kay *et al* 2018) and a storyline approach (Schaller *et al* 2020) is ongoing. While changing weather patterns can be complex in a given area, the general trend is increasingly extreme rainfall resulting in destructive flooding over a large portion of the world's surface.

2.3. Drought

2.3.1. Changes in extremes

Droughts are complex but extremely impactful events that affect billions of people worldwide (table 1). There are many different types of drought with varying impacts. The main categories include meteorological, agricultural and hydrological drought. All are connected, and each simply refers to an anomalous moisture deficit in part of the hydrological system relative to some baseline, be it in precipitation, soil moisture, or groundwater reservoirs, respectively (Cook *et al* 2018). The fingerprint of climate change on increasing drought has been observed in several drought-prone regions of the world, including California, the Pacific Northwest, parts of China, western North America, and the Mediterranean (Gudmundsson and Seneviratne 2016, Chen and Sun 2017b, Cook *et al* 2018), as well as globally (Marvel *et al* 2019). With the exception of the Mediterranean, which is already receiving markedly less precipitation, this is largely due to amplified temperatures driving evaporation and melting snowpack, reducing the meltwater contribution to river flows (Cook *et al* 2018). Other smaller Mediterranean-like regions such as central Chile, the far southwest tip of southern Africa and southwest Australia have also dried due to climate change, and are now more prone to drought (Seager *et al* 2019). A synthesis of current regional changes due to human influence are shown in figure 3.

'Flash droughts' are a type of soil moisture, or agricultural, drought that occurs extremely rapidly, with little warning (Yuan *et al* 2019) and can have severe consequences for agricultural productivity. In recent years, there has been a notable rise in such events in the US, China and South Africa (Cook *et al* 2018). Meanwhile, some of the most catastrophic droughts in the world continue to occur in East Africa (Gebremeskel *et al* 2019). No single drought there has been linked directly to climate change, partly due to a relatively short observational record, high uncertainties and high natural variability, especially for precipitation (Uhe *et al* 2018, Philip *et al* 2018b, Kew *et al* 2021). There is limited evidence that anthropogenic warming of Western Pacific sea surface temperatures may contribute to more frequent drought (Funk 2012,



Funk *et al* 2019). More generally, the drying of the major rainy season in the region, the ‘long rains’ (Lyon and Dewitt 2012), is likely connected to climate change (Tierney *et al* 2015, Hoell *et al* 2017).

2.3.2. Why it matters

In 2019, there were approximately 690 million undernourished people. Food insecurity is linked to conflict, alongside climate-related shocks such as drought (FAO 2020). The least food secure regions of the world are the most vulnerable to drought, and thus any increase in drought severity due to climate change. In Brazil, an ongoing drought since 2019 has led to water scarcity, severe crop losses including corn and coffee, and amplified fire activity in the Amazon (Marengo *et al* 2021). In south Asia, the changing patterns of monsoon rainfall as well as rising temperatures and other types of extreme weather have already caused a decline in food security (Bandara and Cai 2014). In East Africa, the major drought in 1984/85 led to a famine that caused the deaths of around 450 000 people. More recently, a drought in 2008–10 affected 13 million people, another in 2010–11 affected 12 million and caused the deaths of 250 000 people in Somalia alone. Since 2005, droughts have increased in frequency in East Africa and caused substantial livestock death, disruption of livelihoods and rising food prices (Nicholson 2017, Gebremeskel *et al* 2019). In turn, this has contributed to internal migration and further socio-economic instabilities in the region (Gebremeskel *et al* 2019). From South Asia across the middle east and most of Africa, hunger is a growing challenge that drought is exacerbating. More broadly, extension of drought across water-scarce regions is exceptionally costly through its impact on ecosystems, agriculture and wider society (Cook *et al* 2018).

2.3.3. Attributable impacts

The fingerprint of climate change has manifested very clearly on several recent droughts. California provides an exemplary case. From 2011 to 2017, it suffered an extended drought, possibly the worst in a thousand years (Osaka and Bellamy 2020). Even as this event unfolded, scientists demonstrated that various contributing factors were attributable to climate change, including reduced snowpack (Mote *et al* 2016, Berg and Hall 2017) and warm dry years (Diffenbaugh *et al* 2015, Williams *et al* 2015). This drought was then alleviated by incredibly intense seasonal rainfall that led to destructive flooding, with damages of at least USD 1 bn (The Weather Channel 2017), in a compound event that has been linked to climate change (Simon Wang *et al* 2017). Similar compound droughts and floods have occurred in the UK (Parry *et al* 2013) and East Africa (Gebremeskel *et al* 2019). Not only that, new research shows that the California drought was a smaller part of a larger mega-drought stretching from 2000 to 2018, which itself was pushed from a moderate event to the worst in 1200 years by climate change (Williams *et al* 2020). From 2014 to 2016, economic losses in the agriculture industry amounted to at least USD 5.5 bn, and the loss of 42 000 jobs (Howitt *et al* 2014, 2015, Medellín-Azuara *et al* 2016). Furthermore, during the first three years of the drought, hundreds of millions of trees perished due to water stress, wildfires and proliferating bark beetles; in parts of the Sierra Nevada almost half of all trees died (Fettig *et al* 2019).

There are several other cases of drought across the world that have been shown to have been intensified by climate change. This includes South Africa 2015–17 (Yuan *et al* 2018a, Otto *et al* 2018b), Europe 2016–17

(García-Herrera *et al* 2019), Indonesia 2015 (King *et al* 2016), New Zealand (Harrington *et al* 2016) and Canada (Szeto *et al* 2016).

The impacts of these droughts vary greatly in severity and form, being acutely related to exposure and vulnerability in the affected region. In Canada, drought conditions led to forest fires that created a serious public health risk. In New Zealand, economic costs of the 2013 drought totalled at least USD 1.3 bn. In Europe, drought costs an average of €6.8 bn per year (García-Herrera *et al* 2019). Against this backdrop, the extreme 2016–17 event caused loss of many types of crops, including cereals, olives, tomatoes, wine grapes, and almonds, with losses of at least €2 bn in Italy alone (García-Herrera *et al* 2019). Episodic drought is becoming more common in Brazil, and though the number of fatalities has fallen drastically, the number of people affected is still increasing; since 1990, hundreds of droughts affected over a billion people (Sena *et al* 2014). In South Africa, economic losses totalled USD 400 million, cost tens of thousands of jobs and months of extreme water restrictions for citizens in late 2017 (Stanford University 2020). Cape Town also narrowly avoided ‘day zero’, when there would have been no water remaining in city pipes. Attribution research has demonstrated that climate change amplified all of these impacts.

2.3.3.1. CASE STUDY: Indonesia, 2015

In the dry season of July–October 2015, Indonesia experienced a combination of severe heat and extremely low precipitation that created drought conditions. This was partly due to the occurrence of a strong El Niño, which is linked to high temperatures and strongly linked to lower-than-normal precipitation rates in the dry season in Indonesia. In addition, the resulting land surface temperatures were also amplified significantly by anthropogenic warming (King et al 2016).

The impacts of this drought were myriad and severe. Farmland drought affected over 111 000 hectares of crops (DMCDD 2015), which led to widespread loss of income, rises in food prices (Webb and Wadhwa 2016) and poverty (Reuters 2015). It triggered the worst fire season since 1997, resulting in air pollution that detrimentally affected the health of millions and caused in the deaths of over 100 300 people across Indonesia, Malaysia and Singapore (Huijnen et al 2016, Koplitz et al 2016). The impact on vegetation more widely disrupted local wildlife, causing thousands of long-tailed monkeys to attack and steal from villages in search of food (Rohmah 2015).

2.4. Wildfire

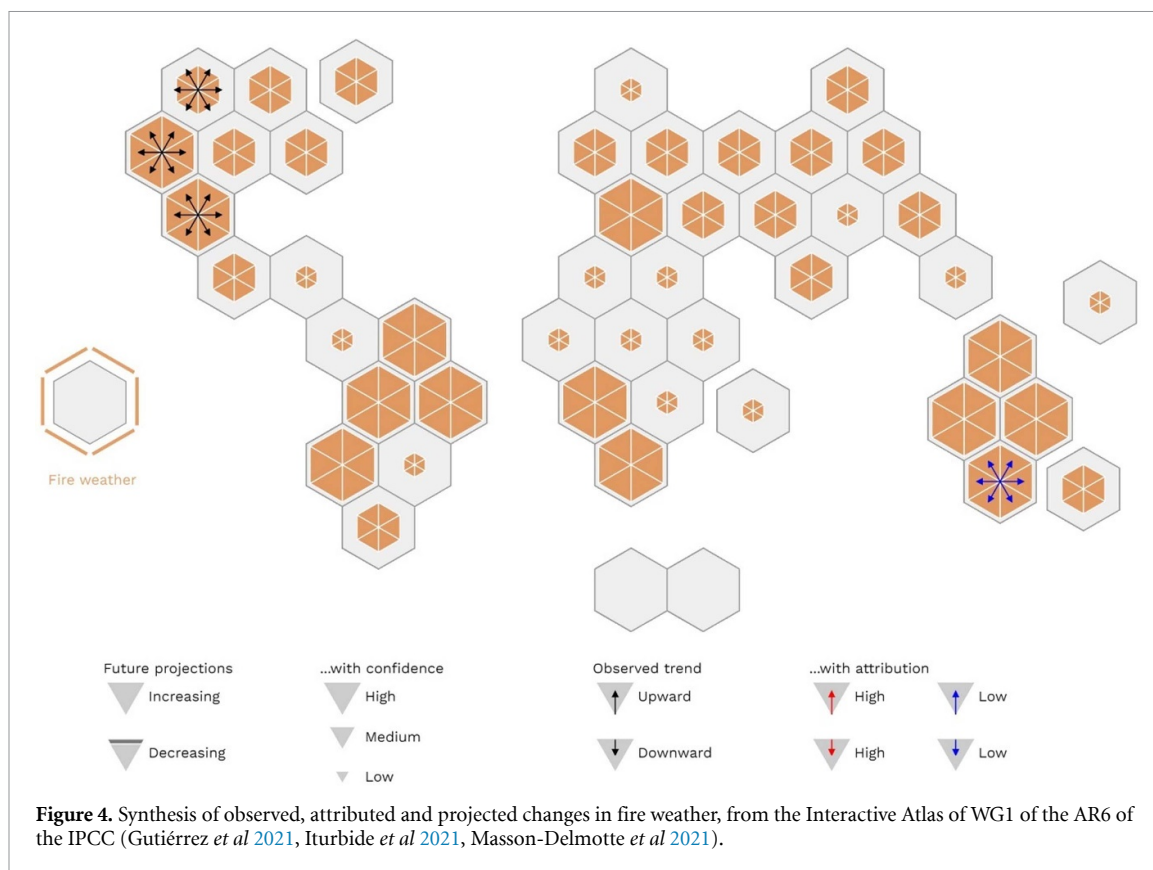
2.4.1. Changes in extremes

Wildfire risk is inextricably tied to dry and hot conditions, and is greatest during periods of ‘Fire weather’, classified using various metrics as some combination of high temperature, low humidity, lack of rain, fuel availability and high wind speed (Van Wagner 1987, Dowdy *et al* 2009). The risk of wildfire has already substantially increased in many regions, including the western US, Alaska and Canada (Jarraud and Steiner 2012, Dennison *et al* 2014, Balch *et al* 2018, Goss *et al* 2020), the Mediterranean (Abatzoglou *et al* 2019, Barbero *et al* 2020, Touma *et al* 2021), Amazonia (Alencar *et al* 2011, 2015, Abatzoglou *et al* 2019, Touma *et al* 2021), southeast Asia (Touma *et al* 2021) and Australia (Dowdy 2018, Dowdy and Pepler 2018, Harris and Lucas 2019). A synthesis of current regional changes due to human influence are shown in figure 4.

Recent blazes across the world have proved to be violent manifestations of this. For instance, in British Columbia in 2017 and 2021 severe hot and dry summers led to unprecedented forest fires. In 2017, the burned area was made 7–11 times larger by climate change and, equivalently, the event was made 2–4 times more likely (Kirchmeier-Young *et al* 2019). Similar results were found in an analysis of fire risk in Western Canada, where fires as large as those that burned almost 600 000 ha near Fort McMurray, Alberta, in 2016, were found to have become 1.5–6 times more likely to occur as a result of climate change (Kirchmeier-Young *et al* 2017). In Sweden in 2018, extensive forest fires were made 10% more likely by climate change (Krikken *et al* 2019). And using the same method, the record-breaking Australian bushfire season of 2019/20 was made at least 30% more likely by climate change (van Oldenborgh *et al* 2020). From 1984 to 2015, over 4 million ha of burned area in the western US is directly attributed to climate change (Abatzoglou and Williams 2016). And in southern China, extreme wildfires of 2019 were made over seven times more likely by climate change (Du *et al* 2021).

2.4.2. Why it matters

Wildfires can cause direct mortality, although the total number of direct deaths are typically lower than for other extreme events (table 1). However, wildfire smoke consists of fine particulate matter (known as PM_{2.5} and PM₁₀) that reaches deep into the lungs when inhaled, can reach the bloodstream, and is likely more toxic than ambient particulates of the same scale (Aguilera *et al* 2021). The hazardous air pollutants that constitute the smoke aggravate existing respiratory health issues, trigger new conditions and may also have links to cardiovascular health impacts (Reid *et al* 2016, Matz *et al* 2020, Chen *et al* 2021), as well as adverse effects on



pregnancy outcomes (Abdo *et al* 2019). In Canada, short term effects of wildfire smoke include 54–240 premature deaths and USD 0.41–1.8 bn annually, while long-term chronic issues are responsible for 570–2500 premature deaths and costs of USD 4.3–19 bn annually (Matz *et al* 2020). A similar study for the US from 2008 to 2012 showed that short-term effects cost thousands of lives and additional hospital admissions for respiratory and cardiovascular illness annually, while long-term exposure cost tens of thousands of lives annually—the economic costs of these health burdens was estimated as USD 11–20 bn (2010\$) per year for short-term, and USD 76–130 bn per year for long-term effects (Fann *et al* 2018). Finally, across the world total attributable deaths to landscape fire smoke are in the hundreds of thousands (262 000 in La Niña years, compared with 532 000 during El Niño), with the worst affected areas being sub-Saharan Africa and southeast Asia (Johnston *et al* 2012).

2.4.3. Attributable impacts

Severe impacts have also been recorded for attributed weather and fire events. For instance, during the anthropogenically amplified European heatwave of 2003, the central and Algarve regions of Portugal experienced the worst mega-fires in history (Tedim *et al* 2013). The resultant smoke dispersed across Europe, increasing the concentrations of PM_{2.5} by 20%–200% in many places (Hodzic *et al* 2007), where several hundred deaths were linked to air pollution in the UK and Netherlands alone (Solberg *et al* 2008). Fires across Indonesia in 2015 led to over 100 000 excess deaths. Similarly, in Russia in 2010 smoke from burning forests and peatlands became trapped over population centres, exacerbating the public health crisis and causing up to 2000 excess deaths in Moscow alone (Shaposhnikov *et al* 2014). The Black Saturday bushfires in Victoria, Australia in 2009 were made more likely by climate change (Black 2016), and resulted in PTSD in a significant minority of the most affected groups (Bryant *et al* 2014). Finally, the 2016 Alberta wildfires displaced over 80 000 people and caused over CAD 3.5 bn in insured losses. As noted above, these fires were made substantially more likely due to climate change. Across Canada, wildfires burn 2.1 million ha per year, approximately the area of Wales (Kirchmeier-Young *et al* 2017).

2.4.3.1. CASE STUDY: Australia, 2019/20

In the summer of 2019/20, New South Wales experienced the worst fire season on record, since dubbed the ‘Black Summer fires’. In the 2019 fire year, the burned area totalled almost three times that in any of the previous 32 years (Canadell *et al* 2021). This event was made at least 30% more likely by climate change (van

Oldenborgh *et al* 2020), which adds further evidence that dangerous fire weather in southeast Australia has emerged outside of the range of historical experience (Abram *et al* 2021). Not only that, the sheer scale of the fires went beyond anything either simulated in CMIP6 models or widely discussed even within the large uncertainties associated with wildfire hazards; this led to calls for urgent improvement of both risk modelling and uncertainty interpretation for accurately informing society of such unprecedented risks going forwards (Sanderson and Fisher 2020). This case study thus illustrates a broader point about the urgent need to provide risk guidance acknowledging both known and unknown unknowns, especially in a changing climate (Sanderson and Fisher 2020, Clarke *et al* 2021).

These fires burned a record 19 million hectares of forest and woodland (Khan 2021), resulting in the direct destruction of 5900 buildings and tens of thousands of livestock being killed. An estimated 3 bn mammals, reptiles, birds and frogs were killed or displaced, making it 'one of the worst wildlife disasters in modern history.' (WWF Australia 2020), with fears of possible extinctions of endangered species (Filkov *et al* 2020, Ward *et al* 2020).

Across the region, levels of PM_{2.5} exceeded the WHO guideline levels fourfold (Yu *et al* 2020). Smoke from the fires was responsible for '417 excess deaths, 1124 hospitalisations for cardiovascular problems and 2027 for respiratory problems, and 1305 presentations to emergency departments with asthma' (Borchers Arriagada *et al* 2020, Filkov *et al* 2020). The costs associated with this totalled AUD 1.95 bn, approximately 10 times the annual health burden due to fire smoke (Johnston *et al* 2021).

2.5. Tropical cyclones

2.5.1. Changes in extremes

Trends indicate no significant change in the frequency of tropical cyclones globally, but a greater fraction of those that do occur are the most intense Saffir-Simpson category 4 and 5 superstorms (Walsh *et al* 2019, Kossin *et al* 2020), which usually dominate the societal impacts (Christensen *et al* 2013). Tropical cyclones are also shifting poleward in most regions, affecting the areas impacted (Kossin *et al* 2016). Further, a slowing in tropical cyclone movement has been observed (Kossin 2018, Yamaguchi and Maeda 2020), accompanied by deposition of higher rainfall intensities (Patricola and Wehner 2018), affecting the severity of impacts.

There is substantial variability between basins. Increasing trends in the number of storms are most significant in the central Pacific, Arabia Sea and North Atlantic, and decreases are observed in the Bay of Bengal, the southern Indian Ocean and western North Pacific. This spatial distribution change is too large to be explained by natural variability alone and is linked to climate change (Murakami *et al* 2020). In the North Atlantic, an observed increase in intensification rate is likely too large for natural variability (Bhatia *et al* 2019), likewise for the significant slowing of translation speed over the US (Kossin 2018), while the observed increase in overall activity is significant yet not attributable to climate change (Ting *et al* 2015). In the Bay of Bengal, despite the decreasing numbers, there is a clear increasing trend in the fraction of high intensity storms and overall cyclone energy (Balaji *et al* 2018). Changes in overall activity are less certain in the west Pacific due to high variability, but northward shift in storm tracks since the 1980s is significant (Kossin *et al* 2016, Lee *et al* 2020), as is a slowdown of translation speed (Yamaguchi and Maeda 2020).

There have also been several notable events amplified by climate change in recent years, including Hurricanes Irma, Maria, Katrina, Harvey, Florence, Sandy, Typhoons Haiyan and Morakot, and others. Additionally, notable recent seasons of high cyclone activity could not be explained without anthropogenic influence, including in the Arabian sea in 2015 (Murakami *et al* 2017), in the western North Pacific in 2015 (Zhang *et al* 2016, Yang *et al* 2018, Yamada *et al* 2019), and in the North Atlantic in 2017 (Murakami *et al* 2018).

2.5.2. Why it matters

Tropical cyclones often cause flooding, including due to storm surges affecting coastal areas. In addition, storms generate high winds that fell trees, and destroy property and power lines, thus creating further disruption. For instance, in the wake of Hurricane Irma in 2017, services on Puerto Rico were hindered by blackouts after a partial collapse of the power system (Zorrilla 2017). When Hurricane Maria struck just two weeks later it caused devastation exacerbated by this additional vulnerability. Further, it extended the spatial and temporal aspects of disruption to services and the power grid across the island and for months into the future (Kishore *et al* 2018, Kwasinski *et al* 2019). The subsequent reliance on generators led to worsening air quality in San Juan (Subramanian *et al* 2018). The extreme rainfall also triggered over 40 000 landslides across the island, wiping out other power lines, roads and other structures (Bessette-Kirton *et al* 2019). The storm's passage also severely damaged vegetation across the island, which took months to fully recover (Hu and Smith 2018). There were also more long-term impacts. For example, in 2017 in Puerto Rico, in the context of an already-struggling economy, the severity of the 2017 hurricane season may have led between 129 000 and 477 000 Puerto Ricans to migrate away from the island (Acosta *et al* 2020).

2.5.3. Attributable impacts

Rainfall from Hurricanes Katrina, Maria and Irma was amplified by climate change (Patricola and Wehner 2018). In Puerto Rico, Maria and Irma resulted in widespread anxiety-mood disorders (Ferré *et al* 2019, Galea *et al* 2007, Scaramutti *et al* 2019, Whaley 2009), as in Hurricane Katrina (Galea *et al* 2007, Whaley 2009), especially prevalent among the most marginalised groups (Rhodes *et al* 2010) and the young (Orengo-Aguayo *et al* 2019). Additionally, at least 1000, and potentially as many as 4645, people died (Kishore *et al* 2018, Santos-Burgoa *et al* 2018). We note an illustrative pair of case studies is provided by the relative impacts of Hurricane Maria in Puerto Rico and Hurricane Irma in Cuba; both islands experienced devastating landfall which caused mass destruction of property and infrastructure that affected the entire population. However, in Cuba the loss of life was far lower and the recovery was much swifter, which in turn reduced longer-term impacts. This is due to an array of factors, including engaging the public in disaster preparation and incorporating science into risk planning (Zakrison *et al* 2020), which are crucial to consider in any direct end-to-end attribution of impacts.

Other high-mortality tropical cyclones include Typhoon Haiyan (Lagmay *et al* 2015) and Cyclone Idoi (Devi 2019), which are estimated to have led to over 7000 and 1300 deaths in southeast Asia and across south-eastern Africa, respectively. Typhoon Haiyan was shown to have been strengthened by climate change, increasing the height of the resulting storm surge by 20% (Takayabu *et al* 2015). During Cyclone Idoi, flooding destroyed over 800 000 hectares of croplands belonging to half a million households (Club of Mozambique, 2019). In the Philippines, Haiyan severely impacted the livelihoods of 3.4 million coconut farmers and thus disrupted a major component of the nation's agriculture industry (Seriño *et al* 2021). The deadliest cyclone in the global record in the 21st Century, representing nearly 70% of all recorded mortality for storms in the period, was Cyclone Nargis, which struck Myanmar in 2008 and caused over 138 000 fatalities (Fritz *et al* 2009). This cyclone formed due to anomalously warm waters in the Bay of Bengal (Lin *et al* 2009), where such storms are becoming less frequent but more intense due to climate change (Balaji *et al* 2018).

In early 2022 in Malawi, Mozambique and Madagascar, tropical cyclones Ana and Batsirai triggered widespread flooding after causing extreme rainfall in the midst of a heavy rainy season. This led to a range of impacts, including destruction of thousands of homes and classrooms, as well as water supply systems, crops, roads, bridges, healthcare facilities and churches, and overall affecting hundreds of thousands of people. Rainfall from each was amplified by climate change, and the impacts were further compounded by high exposure and ongoing vulnerabilities in the region, including from recent flooding, conflict in northern Mozambique, and severe food insecurity in Madagascar (Otto *et al* 2022).

The extreme rainfall from Hurricanes Katrina, Irma, Maria, Harvey, Dorian, and Florence and Typhoon Morakot were each individually amplified by climate change (Van Oldenborgh *et al* 2017, Patricola and Wehner 2018, Wang *et al* 2018, 2019, Reed *et al* 2020, 2021, Frame *et al* 2020b). Furthermore, analysis of specific drivers of Hurricane Harvey showed that such an event was linked with anomalously high ocean temperatures (both in the Gulf of Mexico and globally), therefore suggesting direct causality to global warming (Trenberth *et al* 2018). Together, the six storms listed above caused almost half a trillion dollars in damage to property and infrastructure.

In the North Atlantic basin alone, it is likely that other hurricanes constituting damages in excess of USD 200 bn follow a similar pattern (EMDAT 2019). Furthermore, while Hurricane Sandy was not significantly intensified by climate change (Lackmann 2015), the probability of storm surges as high have more than tripled due to sea level rise (Lin *et al* 2016). The added effect of climate change on this storm surge resulted in an extra USD 8 bn in damage and affected a further 71 000 people (Strauss *et al* 2021). It is reasonable to conclude that both storm surge and rainfall totals from all tropical cyclones are being amplified by climate change, while other aspects of such events vary between basins.

3. Discussion and conclusions

Developments in climate change attribution, improved understanding of the myriad impacts of extreme weather, and documenting its harms, have meant that an increasingly diverse and societally-relevant range of impacts can be assessed for their connection to anthropogenic climate change. This includes those occurring on local and regional scales beyond those assessed in the recent IPCC AR6.

However, both the impacts of climate change and the current degree of understanding of these vary across hazards and regions. In order to adapt to changing risks effectively, and to optimise mitigation of further warming, it is crucial that understanding continues to develop and does so equitably. This review and other work (Otto *et al* 2020b, Clarke *et al* 2021) provides a starting point for more systematic documenting of

the costs (monetary and non-monetary) of human-caused climate change today and the losses and damages caused. In order to build on this, there are three areas in which scientific developments will add great value.

First, recording the impacts of extreme weather far more systematically around the world. A lack of data on past impacts of extreme events is a major barrier to mitigating future damages, simply because there is no direct evidence upon which to base the necessary measures. In particular, the impacts of extreme heat are chronically under-recorded in the global south. As explored by Harrington and Otto (2020) for heat in sub-Saharan Africa, this is likely due to institutional differences in the way impacts are recorded (government agencies vs NGOs), and would benefit from a collaborative effort to create databases for documenting mortality, morbidity and impacts on transport and power infrastructure, especially in cities. Furthermore, developing official heatwave definitions for nations currently lacking them would improve the chance that they are recorded in international disaster databases such as EMDAT.

Second, improve the coverage of attribution for more regions around the world, for a more diverse range of hazards, and with a focus on event definitions that are most pertinent to the impacts upon people. Attribution allows us to identify whether and to what degree climate change influenced a given event, as well as a trajectory of change over time. This is just part of the full picture of risk, as explored below. However, it remains useful to link between lived impacts and global climate change for the purposes of communication, adaptation and mitigation. It is therefore important everywhere.

Attribution studies on individual events are currently lacking for a number of regions and hazards. This includes key flood events highlighted earlier in this review as some of the most impactful, in South Asia; in Africa, including Sudan, Ethiopia, and Nigeria; in South America, including Peru, Colombia and Brazil; and the Caribbean, including Haiti and the Dominican Republic. Attribution of extreme heat is limited across South America and Africa largely due to a lack of research capacity across the world. For tropical cyclones, while rainfall and storm surge heights are increasingly well understood, especially in the North Atlantic, changes in intensity are not. Further, basins with some of the most devastating storms of the past, such as Cyclone Nargis in the Bay of Bengal and Cyclone Idai in the southwestern Indian Ocean, remain understudied. Finally, for wildfires, the IPCC AR6 documents regional observed changes. However, these are large spatial averages that may dampen the signal of individual attribution studies if they only apply to smaller subregions. Further, additional attribution work would add value in vulnerable and drought-prone regions such as Amazonia, the Mediterranean and Southern Africa.

Going forwards, the coverage of attribution studies can be improved in several ways: operationalising attribution and recording impact information as part of national weather services; incorporating local experts into any attribution analysis; building capacity for local experts to conduct such analyses in the future; improving understanding of compound event attribution, especially for drought; utilising the existing body of attribution literature to make statements without requiring new analysis in regions that are already well understood; creating a standardised language for impacts and risk.

The third and final area for future work involves a broader consideration of risk, rather than simply hazards and impacts. The context of a disaster, in the form of the exposure and vulnerability of affected individuals, infrastructure, agricultural systems and property, is crucial to a more complete understanding, whether this is included in quantitative analysis (e.g. Otto *et al* 2015, Ebi *et al* 2017), or provides a way to frame a study and define an event that is suitable for a particular use (Stone *et al* 2021). For instance, East Africa is frequently subjected to droughts with devastating humanitarian consequences. Despite substantial research into these events, no significant connection to climate change is detectable. In part, this is due to a dearth of observational data. However, the reality in the region is that high levels of vulnerability due to poverty and socio-cultural factors, and very high regional exposure are already significant drivers of disasters.

One consequence of this is that even a relatively small climate change signal would lead to vastly-amplified impacts in the region—this framing tells part of the story. Most importantly, however, it also shows that to reduce risks it is more pertinent to tackle these non-climate drivers head-on, rather than blaming the external forces of ‘nature’ or ‘climate’ (Raju *et al* 2022).

Therefore, in the illustrative case of East Africa, expending additional resources purely to identify a climate-related signal from the noise is relatively unimportant, and headlines about climate change driving drought in the region are actively unhelpful. Instead, in order to mitigate impacts, the focus of research and resources ought to be the development of reliable seasonal forecasting, the effective distribution of this information, and other measures to reduce vulnerability (Coughlan de Perez *et al* 2019, Gebremeskel *et al* 2019). In this situation, attribution provides a crucial source of information if it is framed in such a way to identify all key drivers of impacts, not simply answering the climate question or considering meteorological extremes (Stone *et al* 2021, Raju *et al* 2022).

A recent study on famine in Madagascar exemplifies this approach (World Weather Attribution 2021b). Analysis found that low precipitation totals, which contributed to the crisis, were not significantly changed in

likelihood by human-caused climate change. Instead, the main drivers of the famine were food insecurity due to poverty, compounded by outbreaks of pests and COVID-19 restrictions. This information has great utility for risk reduction, which promises significant near-term co-benefits yet may be overlooked in analysis focused solely on climate change. Building on this, the study also notes an emerging future connection to climate change, which will likely only amplify such droughts significantly at global warming levels of greater than 2 °C. This could be important information for mitigation going forwards.

This work is in line with other analyses in which climate change is found to be the single most important driver of an event. For example, in Siberia in 2020, the extreme heat would have been all but impossible without human-caused climate change (World Weather Attribution 2021c). In essence, to address climate change appropriately, it is important to understand all of the key drivers of an event that may be hidden behind the headlines—neither ignoring climate change nor focusing solely upon it.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This work was supported by a NERC Doctoral Training Partnership Grant NE/L002612/1 and the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 101003469. R F S-S acknowledges support from the Natural Environment Research Council Grant NE/S007474/1, Climate Analytics and the Oxford Martin Programme on the Post-Carbon Transition. L J H acknowledges funding from the New Zealand MBIE Endeavour Fund Whakahura programme (Grant ID: RTVU1906). This work was also supported by the Austrian non-profit organisation AllRise (Reg. No. 1958321055). These funding bodies had no direct involvement in the conduct of the research or production of the article.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID iDs

Ben Clarke  <https://orcid.org/0000-0002-9498-6266>

Friederike Otto  <https://orcid.org/0000-0001-8166-5917>

Luke Harrington  <https://orcid.org/0000-0002-1699-6119>

References

- Abatzoglou J T and Williams A P 2016 Impact of anthropogenic climate change on wildfire across western US forests *Proc. Natl Acad. Sci. USA* **113** 11770–5
- Abatzoglou J T, Williams A P and Barbero R 2019 Global emergence of anthropogenic climate change in fire weather indices *Geophys. Res. Lett.* **46** 326–36
- Abdo M, Ward I, O'Dell K, Ford B, Pierce J, Fischer E and Crooks J 2019 Impact of wildfire smoke on adverse pregnancy outcomes in Colorado, 2007–2015 *Int. J. Environ. Res. Public Health* **16** 3720
- Abram N J et al 2021 Connections of climate change and variability to large and extreme forest fires in southeast Australia *Commun. Earth Environ.* **2** 1–17
- Acosta R J, Kishore N, Irizarry R A and Buckee C O 2020 Quantifying the dynamics of migration after Hurricane Maria in Puerto Rico *Proc. Natl Acad. Sci. USA* **117** 32772–8
- Aguilera R, Corringham T, Gershunov A and Benmarhnia T 2021 Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California *Nat. Commun.* **12** 1493
- Alderman K, Turner L R and Tong S 2013 Assessment of the health impacts of the 2011 summer floods in Brisbane *Disaster Med. Public Health Prep.* **7** 380–6
- Alencar A A, Brando P M, Asner G P and Putz F E 2015 Landscape fragmentation, severe drought, and the new Amazon forest fire regime *Ecol. Appl.* **25** 1493–505
- Alencar A, Asner G P, Knapp D and Zarin D 2011 Temporal variability of forest fires in eastern Amazonia *Ecol. Appl.* **21** 2397–412
- Alexander L V and Arblaster J M 2017 Historical and projected trends in temperature and precipitation extremes in Australia in observations and CMIP5 *Weather Clim. Extremes* **15** 34–56
- Allen M 2003 Liability for climate change *Nature* **421** 891–2
- Analitis A et al 2014 Effects of heat waves on mortality *Epidemiology* **25** 15–22
- Azhar G S, Mavalankar D, Nori-Sarma A, Rajiva A, Dutta P, Jaiswal A, Sheffield P, Knowlton K and Hess J J 2014 Heat-related mortality in India: excess all-cause mortality associated with the 2010 Ahmedabad heat wave *PLoS One* **9** e91831
- Azuma K, Ikeda K, Kagi N, Yanagi U, Hasegawa K and Osawa H 2014 Effects of water-damaged homes after flooding: health status of the residents and the environmental risk factors *Int. J. Environ. Health Res.* **24** 158–75

- Balaji M, Chakraborty A and Mandal M 2018 Changes in tropical cyclone activity in north Indian Ocean during satellite era (1981–2014) *Int. J. Climatol.* **38** 2819–37
- Balch J K, Schoennagel T, Williams A P, Abatzoglou J T, Cattau M E, Mietkiewicz N P and Denis L A S 2018 Switching on the big burn of 2017 *Fire* **1** 17
- Bandara J S and Cai Y 2014 The impact of climate change on food crop productivity, food prices and food security in South Asia *Econ. Anal. Policy* **44** 451–65
- Baqir M, Sobani Z A, Bhamani A, Bham N S, Abid S, Farook J and Beg M A 2012 Infectious diseases in the aftermath of monsoon flooding in Pakistan *Asian Pac. J. Trop. Biomed.* **2** 76–79
- Barbero R, Abatzoglou J T, Pimont F, Ruffault J and Curt T 2020 Attributing increases in fire weather to anthropogenic climate change over France *Front. Earth Sci.* **8** 104
- Barriopedro D, Fischer E M, Luterbacher J, Trigo R M and García-Herrera R 2011 The hot summer of 2010: redrawing the temperature record map of Europe *Science* **332** 220–4
- Bartiko D, Oliveira D Y, Bonumá N B and Chaffe P L B 2019 Spatial and seasonal patterns of flood change across Brazil *Hydrol. Sci. J.* **64** 1071–9
- Bellprat O, Fučkar N S, García-Serrano J, Fučkar N S, Guemas V and Doblas-Reyes F J 2016 8. The role of Arctic sea ice and sea surface temperatures on the cold 2015 February over North America *Bull. Am. Meteorol. Soc.* **97** S36–S41
- Berg N and Hall A 2017 Anthropogenic warming impacts on California snowpack during drought *Geophys. Res. Lett.* **44** 2511–8
- Bessette-Kirton E K, Cerovski-Darriau C, Schulz W H, Coe J A, Kean J W, Godt J W, Thomas M A and Stephen Hughes K 2019 Landslides triggered by Hurricane Maria: assessment of an extreme event in Puerto Rico *GSA Today* **29** 4–10
- Bevacqua E, Maraun D, Voudoukas M I, Voukouvalas E, Vrac M, Mentaschi L and Widmann M 2019 Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change *Sci. Adv.* **5** eaaw5531
- Bhatia K T, Vecchi G A, Knutson T R, Murakami H, Kossin J, Dixon K W and Whitlock C E 2019 Recent increases in tropical cyclone intensification rates *Nat. Commun.* **10** 635
- Black M T 2016 An attribution study of southeast Australian wildfire risk
- Bondur V G 2011 Satellite monitoring of wildfires during the anomalous heat wave of 2010 in Russia *Izv.-Atmos. Ocean Phys.* **47** 1039–48
- Borchers Arriagada N, Palmer A J, Bowman D M, Morgan G G, Jalaludin B B and Johnston F H 2020 Unprecedented smoke-related health burden associated with the 2019–20 bushfires in eastern Australia *Med. J. Aust.* **213** 282–3
- Borg M A, Xiang J, Anikeeva O, Pisaniello D, Hansen A, Zander K, Dear K, Sim M R and Bi P 2021 Occupational heat stress and economic burden: a review of global evidence *Environ. Res.* **195** 110781
- Box J E et al 2019 Key indicators of Arctic climate change: 1971–2017 *Environ. Res. Lett.* **14** 045010
- Bryant R A et al 2014 Psychological outcomes following the Victorian Black Saturday bushfires *Aust. N. Z. J. Psychiatry* **48** 634–43
- Burke C and Stott P 2017 Impact of anthropogenic climate change on the East Asian summer monsoon *J. Clim.* **30** 5205–20
- Burke C, Stott P, Ciavarella A and Ciavarella A 2016 Attribution of extreme rainfall in Southeast China during May 2015 *Bull. Am. Meteorol. Soc.* **97** S92–S96
- Burton H, Rabito F, Danielson L and Takaro T K 2016 Health effects of flooding in Canada: a 2015 review and description of gaps in research *Can. Water Resour. J.* **41** 238–49
- Bush K F, O'Neill M S, Li S, Mukherjee B, Hu H, Ghosh S and Balakrishnan K 2014 Associations between extreme precipitation and gastrointestinal-related hospital admissions in Chennai, India *Environ. Health Perspect.* **122** 249–54
- Byers E et al 2018 Global exposure and vulnerability to multi-sector development and climate change hotspots *Environ. Res. Lett.* (<https://doi.org/10.1088/1748-9326/aabf45>)
- Canadell J G, Meyer C P, Cook G D, Dowdy A, Briggs P R, Knauer J, Pepler A and Haverd V 2021 Multi-decadal increase of forest burned area in Australia is linked to climate change *Nat. Commun.* **12** 1–11
- Cann K F, Thomas D R, Salmon R L, Wyn-Jones A P and Kay D 2013 Extreme water-related weather events and waterborne disease *Epidemiol. Infect.* **141** 671–86
- Carbon Brief 2021 Mapped: how climate change affects extreme weather around the world (available at: www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world) (Accessed 1 January 2022)
- Carlton E J, Eisenberg J N S, Goldstick J, Cevallos W, Trostle J and Levy K 2014 Heavy rainfall events and diarrhea incidence: the role of social and environmental factors *Am. J. Epidemiol.* **179** 344–52
- Chen H, Samet J M, Bromberg P A and Tong H 2021 Cardiovascular health impacts of wildfire smoke exposure *Part. Fibre Toxicol.* **18** 2
- Chen H and Sun J 2017a Contribution of human influence to increased daily precipitation extremes over China *Geophys. Res. Lett.* **44** 2436–44
- Chen H and Sun J 2017b Anthropogenic warming has caused hot droughts more frequently in China *J. Hydrol.* **544** 306–18
- Chen H and Sun J 2021 Anthropogenic influence has increased climate extreme occurrence over China *Sci. Bull.* **66** 749–52
- Cho C, Li R, Wang S Y, Yoon J H and Gillies R R 2016 Anthropogenic footprint of climate change in the June 2013 northern India flood *Clim. Dyn.* **46** 797–805
- Christensen J H et al 2013 Climate phenomena and their relevance for future regional climate change *Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (<https://doi.org/10.1017/CBO9781107415324.028>)
- Christiansen B et al 2018 Was the cold European winter of 2009/10 modified by anthropogenic climate change? An attribution study *J. Clim.* **31** 3387–410
- Christidis N, Betts R A and Stott P A, 2018a The extremely wet March of 2017 in Peru (<https://doi.org/10.1175/BAMS-D-18-0110.1>)
- Christidis N, Jones G S and Stott P A 2015 Dramatically increasing chance of extremely hot summers since the 2003 European heatwave *Nat. Clim. Change* **5** 46–50
- Christidis N, Manomaiphiboon K, Ciavarella A and Stott P A 2018b The hot and dry April of 2016 in Thailand *Bull. Am. Meteorol. Soc.* **99** S128–S132
- Christidis N and Stott P A 2015 Extreme rainfall in the United Kingdom during winter 2013/14: the role of atmospheric circulation and climate change *Bull. Am. Meteorol. Soc.* **96** S46–S50
- Christidis N and Stott P A 2016 Attribution analyses of temperature extremes using a set of 16 indices *Weather Clim. Extremes* **14** 24–35
- Christidis N and Stott P A 2020 The extremely cold start of the spring of 2018 in the United Kingdom *Bull. Am. Meteorol. Soc.* **101** S23–S28
- Cianconi P, Betrò S and Janiri L 2020 The impact of climate change on mental health: a systematic descriptive review *Front. Psychiatry* **11** 1
- Ciavarella A et al 2021 Prolonged Siberian heat of 2020 almost impossible without human influence *Clim. Change* **166** 1–18

- Clarke B J, Otto F E L and Jones R G 2021 Inventories of extreme weather events and impacts: implications for loss and damage from and adaptation to climate extremes *Clim. Risk Manage.* **32** 100285
- Club of Mozambique 2019 Idai wiped out over 800,000 hectares of crops, in 5 Mozambican provinces—AIM report (available at: <https://clubofmozambique.com/news/idai-wiped-out-over-800000-hectares-of-crops-in-5-mozambican-provinces-aim-report/>) (Accessed 18 June 2021)
- Conlon K C, Rajkovich N B, White-Newsome J L, Larsen L and O'Neill M S 2011 Preventing cold-related morbidity and mortality in a changing climate *Maturitas* **69** 197–202
- Cook B I, Mankin J S and Anchukaitis K J 2018 Climate change and drought: from past to future *Curr. Clim. Change Rep.* **4** 164–79
- Coughlan D P, van Aalst E, Choularton M, van den Hurk R, Mason B, Nissan S and Schwager H 2019 From rain to famine: assessing the utility of rainfall observations and seasonal forecasts to anticipate food insecurity in East Africa *Food Secur.* **11** 57–68
- Davies G I, McIver L, Kim Y, Hashizume M, Iddings S and Chan V 2015 Water-borne diseases and extreme weather events in Cambodia: review of impacts and implications of climate change *Int. J. Environ. Res. Public Health* **12** 191–213
- De Abreu R C, Cunningham C, Rudorff C M, Rudorff N and Abatan A A 2018 Contribution of anthropogenic climate change to April–May 2017 heavy precipitation over the Uruguay River Basin *Bull. Am. Meteorol. Soc.* **100** S37–S41
- Dennison P E, Brewer S C, Arnold J D and Moritz M A 2014 Large wildfire trends in the western United States, 1984–2011 *Geophys. Res. Lett.* **41** 2928–33
- Devi S 2019 Cyclone Idai: 1 month later, devastation persists *Lancet* **393** 1585
- Diffenbaugh N S, Swain D L and Touma D 2015 Anthropogenic warming has increased drought risk in California *Proc. Natl Acad. Sci.* **112** 3931–6
- DMCDD 2015 Drought in Indonesia 2015 situation report (Disaster Management Center Dompét Dhuafa—Siaga Bencana)
- Do H X, Westra S and Leonard M 2017 A global-scale investigation of trends in annual maximum streamflow *J. Hydrol.* **552** 28–43
- Dobricic S, Russo S, Pozzoli L, Wilson J and Vignati E 2020 Increasing occurrence of heat waves in the terrestrial Arctic *Environ. Res. Lett.* **15** 024022
- Dodgen D et al 2016 Mental health and well-being *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (Washington, DC: U.S. Global Change Research Program) ch 8 (<https://doi.org/10.7930/J0TX3C9H>)
- Donat M G, Alexander L V, Herold N and Dittus A J 2016 Temperature and precipitation extremes in century-long gridded observations, reanalyses, and atmospheric model simulations *J. Geophys. Res.* **121** 11174–11189
- Dong S, Sun Y, Aguilar E, Zhang X, Peterson T C, Song L and Zhang Y 2018 Observed changes in temperature extremes over Asia and their attribution *Clim. Dyn.* **51** 339–53
- Dong S, Sun Y, Li C, Zhang X, Min S K and Kim Y H 2021 Attribution of extreme precipitation with updated observations and CMIP6 simulations *J. Clim.* **34** 871–81
- Dowdy A J 2018 Climatological variability of fire weather in Australia *J. Appl. Meteorol. Climatol.* **57** 221–34
- Dowdy A J, Mills G A, Finkle K and de Groot W 2009 *Australian Fire Weather as Represented by the McArthur Forest Fire Danger Index and the Canadian Forest Fire Weather Index* (The Centre for Australian Weather and Climate Research)
- Dowdy A J and Pepler A 2018 Pyroconvection risk in Australia: climatological changes in atmospheric stability and surface fire weather conditions *Geophys. Res. Lett.* **45** 2005–13
- Du J, Wang K and Cui B 2021 Attribution of the extreme drought-related risk of wildfires in spring 2019 over Southwest China *Bull. Am. Meteorol. Soc.* **102** S83–S90
- Dunn R J H et al 2020 Development of an updated global land *in situ*-based data set of temperature and precipitation extremes: HadEX3 *J. Geophys. Res. Atmos.* **125** e2019JD032263
- Ebi K L, Balbus J, Luber G, Bole A, Crimmins A R, Glass G E, Saha S, Shimamoto M M, Trtanj J M and White-Newsome J L 2018 Human health *Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II* (Washington, DC: U.S. Global Change Research Program) pp 572–603
- Ebi K L and Mills D 2013 Winter mortality in a warming climate: a reassessment *Wiley Interdiscip. Rev. Clim. Change* **4** 203–12
- Ebi K L, Ogden N H, Semenza J C and Woodward A 2017 Detecting and attributing health burdens to climate change *Environ. Health Perspect.* **125** 085004
- Eden J M, Wolter K, Otto F E L and Jan van Oldenborgh G 2016 Multi-method attribution analysis of extreme precipitation in Boulder, Colorado *Environ. Res. Lett.* **11** 124009
- EMDAT 2019 The emergency events database ed D Guha-Sapir (Univ. Cathol. Louvain—CRED)
- Fann N, Alman B, Broome R A, Morgan G G, Johnston F H, Pouliot G and Rappold A G 2018 The health impacts and economic value of wildland fire episodes in the U.S.: 2008–2012 *Sci. Total Environ.* **610–611** 802–9
- FAO 2020 The state of food security and nutrition in the world 2020 FAO, IFAD, UNICEF, WFP and WHO (<https://doi.org/10.4060/ca9692en>)
- Ferré I M, Negrón S, Shultz J M, Schwartz S J, Kossin J P and Pantin H 2019 Hurricane Maria's impact on Punta Santiago, Puerto Rico: community needs and mental health assessment six months postimpact *Disaster Med. Public Health Prep.* **13** 18–23
- Fernandez A, Black J, Jones M, Wilson L, Salvador-Carulla L, Astell-Burt T and Black D 2015 Flooding and mental health: a systematic mapping review *PLoS One* **10** e0119929
- Fettig C J, Mortenson L A, Bulaon B M and Foulk P B 2019 Tree mortality following drought in the central and southern Sierra Nevada, California, U.S. *For. Ecol. Manage.* **432** 164–78
- Filkov A I, Ngo T, Matthews S, Telfer S and Penman T D 2020 Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends *J. Saf. Sci. Resilience* **1** 44–56
- Fischer E M and Knutti R 2015 Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes *Nat. Clim. Change* **5** 560–4
- Fischer E M, Sippel S and Knutti R 2021 Increasing probability of record-shattering climate extremes *Nat. Clim. Change* **11** 689–95
- Fowler H J et al 2021 Anthropogenic intensification of short-duration rainfall extremes *Nat. Rev. Earth Environ.* **2** 107–22
- Frame D J, Rosier S M, Noy I, Harrington L J, Carey-Smith T, Sparrow S N, Stone D A and Dean S M 2020a Climate change attribution and the economic costs of extreme weather events: a study on damages from extreme rainfall and drought *Clim. Change* **162** 781–97
- Frame D J, Wehner M F, Noy I and Rosier S M 2020b The economic costs of Hurricane Harvey attributable to climate change *Clim. Change* **160** 271–81
- Frame D, Joshi M, Hawkins E, Harrington L J and de Roiste M 2017 Population-based emergence of unfamiliar climates *Nat. Clim. Change* **7** 407–11

- Fredrick T, Ponnaiah M, Murhekar M V, Jayaraman Y, David J K, Vadivoo S and Joshua V 2015 Cholera outbreak linked with lack of safe water supply following a tropical cyclone in Pondicherry, India, 2012 *J. Health Popul. Nutr.* **33** 31–38
- Fritz H M, Blount C D, Thwin S, Thu M K and Chan N 2009 Cyclone Nargis storm surge in Myanmar *Nat. Geosci.* **2** 448–9
- Funk C C 2012 Exceptional warming in the Western Pacific–Indian Ocean warm pool has contributed to more frequent droughts in Eastern Africa *Bull. Am. Meteorol. Soc.* **93** 1049–51
- Funk C et al 2019 Examining the potential contributions of extreme ‘Western V’ sea surface temperatures to the 2017 March–June East African Drought *Bull. Am. Meteorol. Soc.* **100** S55–S60
- Galea S, Brewin C R, Gruber M, Jones R T, King D W, King L A, McNally R J, Ursano R J, Petukhova M and Kessler R C 2007 Exposure to hurricane-related stressors and mental illness after Hurricane Katrina *Arch. Gen. Psychiatry* **64** 1427–34
- García-Herrera R, Díaz J, Trigo R M, Luterbacher J and Fischer E M 2010 A review of the European summer heat wave of 2003 *Crit. Rev. Environ. Sci. Technol.* **40** 267–306
- García-Herrera R, Garrido-Perez J M, Barriopedro D, Ordóñez C, Vicente-Serrano S M, Nieto R, Gimeno L, Sorí R and Yiou P 2019 The European 2016/17 drought *J. Clim.* **32** 3169–87
- Gasparrini A et al 2015 Mortality risk attributable to high and low ambient temperature: a multicountry observational study *Lancet* **386** 369–75
- Gasparrini A et al 2017 Projections of temperature-related excess mortality under climate change scenarios *Lancet Planet. Health* **1** e360–e367
- Gebremeskel G, Tang Q, Sun S, Huang Z, Zhang X and Liu X 2019 Droughts in East Africa: causes, impacts and resilience *Earth Sci. Rev.* **193** 146–61
- Goldammer J 2010 Preliminary assessment of the fire situation in Western Russia pp 2–23
- Goss M, Swain D L, Abatzoglou J T, Sarhadi A, Kolden C A, Williams A P and Duffenbaugh N S 2020 Climate change is increasing the likelihood of extreme autumn wildfire conditions across California *Environ. Res. Lett.* **15** 094016
- Green H, Bailey J, Schwarz L, Vanos J, Ebi K and Benmarhnia T 2019 Impact of heat on mortality and morbidity in low and middle income countries: a review of the epidemiological evidence and considerations for future research *Environ. Res.* **171** 80–91
- Gronlund C J, Sullivan K P, Keefelegn Y, Cameron L and O’Neill M S 2018 Climate change and temperature extremes: a review of heat- and cold-related morbidity and mortality concerns of municipalities *Maturitas* **114** 54–59
- Gudmundsson L et al 2021 Globally observed trends in mean and extreme river flow attributed to climate change *Science* **371** 1159–62
- Gudmundsson L, Leonard M, Do H X, Westra S and Seneviratne S I 2019 Observed trends in global indicators of mean and extreme streamflow *Geophys. Res. Lett.* **46** 756–66
- Gudmundsson L and Seneviratne S I 2016 Anthropogenic climate change affects meteorological drought risk in Europe *Environ. Res. Lett.* **11** 044005
- Gutiérrez J M et al 2021 Climate change 2021: the physical science basis *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte, P Zhai, A Pirani, S L Connors, C Péan, S Berger, N Caud and Y Chen (Cambridge: Cambridge University Press)
- Hajat S 2017 Health effects of milder winters: a review of evidence from the United Kingdom *Environ. Health* **16** 109
- Hannart A, Vera C, Otto F E L and Cerne B 2015 Causal influence of anthropogenic forcings on the Argentinian heat wave of December 2013 *Bull. Am. Meteorol. Soc.* **96** S41–S45
- Harrington L J, Gibson P B, Dean S M, Mitchell D, Rosier S M and Frame D J 2016 Investigating event-specific drought attribution using self-organizing maps *J. Geophys. Res. Atmos.* **121** 12,766–12,780
- Harrington L J and Otto F E L 2018 Changing population dynamics and uneven temperature emergence combine to exacerbate regional exposure to heat extremes under 1.5 °C and 2 °C of warming *Environ. Res. Lett.* **13** 034011
- Harrington L J and Otto F E L 2020 Reconciling theory with the reality of African heatwaves *Nat. Clim. Change* **10** 796–8
- Harris S and Lucas C 2019 Understanding the variability of Australian fire weather between 1973 and 2017 *PLoS One* **14** e0222328
- Hawkins E, Frame D, Harrington L, Joshi M, King A, Rojas M and Sutton R 2020 Observed emergence of the climate change signal: from the familiar to the unknown *Geophys. Res. Lett.* **47** e2019GL086259
- Hayes K, Blashki G, Wiseman J, Burke S and Reifels L 2018 Climate change and mental health: risks, impacts and priority actions *Int. J. Ment. Health Syst.* **12** 28
- Herring S C, Christidis N, Hoell A, Hoerling M P and Stott P A 2019 Explaining extreme events of 2017 from a climate perspective *Bull. Am. Meteorol. Soc.* **100** S1–S117
- Herring S C, Christidis N, Hoell A, Hoerling M P and Stott P A 2020 Explaining extreme events of 2018 from a climate perspective *Bull. Am. Meteorol. Soc.* **101** S1–S140
- Herring S C, Christidis N, Hoell A, Hoerling M P and Stott P A 2021 Explaining extreme events of 2019 from a climate perspective *Bull. Am. Meteorol. Soc.* **102** S1–S116
- Herring S C, Christidis N, Hoell A, Kossin J P, Schreck C J and Stott P A 2018 Explaining extreme events of 2016 from a climate perspective *Bull. Am. Meteorol. Soc.* **99** S1–S157
- Herring S C, Hoell A, Hoerling M P, Kossin J P, Schreck C J and Stott P A 2016 Explaining extreme events of 2015 from a climate perspective *Bull. Am. Meteorol. Soc.* **97** S1–S145
- Herring S C, Hoerling M P, Kossin J P, Peterson T C and Stott P A 2015 Explaining extreme events of 2014 explaining extreme events of 2014 from a *Bull. Am. Meteorol. Soc.* **96** S1–S172
- Herring S C, Hoerling M P, Peterson T C and Stott P A 2014 Explaining extreme events of 2013 from a climate perspective *Bull. Am. Meteorol. Soc.* **95** S1–S104
- Hinz R, Frickmann H and Krüger A 2019 Climate change and infectious diseases *International Climate Protection* (Cham: Springer International Publishing) pp 269–76
- Hodzic A, Madronich S, Bohn B, Massie S, Menut L and Wiedinmyer C 2007 Wildfire particulate matter in Europe during summer 2003: meso-scale modeling of smoke emissions, transport and radiative effects *Atmos. Chem. Phys.* **7** 4043–64
- Hoell A, Hoerling M, Eischeid J, Quan X W and Liebmann B 2017 Reconciling theories for human and natural attribution of recent East Africa drying *J. Clim.* **30** 1939–57
- Hope P, Wang G, Lim E-P, Hendon H H and Arblaster J M 2016 What caused the record-breaking heat across Australia in October 2015? *Bull. Am. Meteorol. Soc.* **97** S122–S126
- Howitt R, Medellín-Azuara J and Macewan D 2014 *Economic Analysis of the 2014 Drought for California Agriculture* (Davis, CA: University of California—Center for Watershed Sciences)
- Howitt R, Medellín-Azuara J, MacEwan D, Lund J and Sumner D 2015 *Economic Analysis of the 2015 Drought for California Agriculture, Center for Watershed Sciences* (Davis, CA: University of California)

- Hu T and Smith R B 2018 The impact of Hurricane Maria on the vegetation of Dominica and Puerto Rico using multispectral remote sensing *Remote Sens.* **10** 827
- Hu T, Sun Y, Zhang X, Min S K and Kim Y H 2020 Human influence on frequency of temperature extremes *Environ. Res. Lett.* **15** 064014
- Huber V, Ibarreta D and Frieler K 2017 Cold- and heat-related mortality: a cautionary note on current damage functions with net benefits from climate change *Clim. Change* **142** 407–18
- Huijnen V, Wooster M J, Kaiser J W, Gaveau D L A, Flemming J, Parrington M, Inness A, Murdiyarto D, Main B and van Weele M 2016 Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997 *Sci. Rep.* **6** 1–8
- Huntingford C et al 2014 Potential influences on the United Kingdom's floods of winter 2013/14 *Nat. Clim. Change* **4** 769–77
- Imada Y, Kawase H, Watanabe M, Arai M, Shiogama H and Takayabu I 2020 Advanced risk-based event attribution for heavy regional rainfall events *npj Clim. Atmos. Sci.* **3** 1–8
- Imada Y, Shiogama H, Takahashi C, Watanabe M, Mori M, Kamae Y and Maeda S 2018 Climate change increased the likelihood of the 2016 heat extremes in Asia *Bull. Am. Meteorol. Soc.* **99** S97–S101
- Imada Y, Watanabe M, Kawase H, Shiogama H and Arai M 2019 The July 2018 high temperature event in Japan could not have happened without human-induced global warming *Sci. Online Lett. Atmos.* **15A** 8–12
- Iturbide M et al 2021 Repository supporting the implementation of FAIR principles in the IPCC-WG1 Atlas (<https://doi.org/10.5281/zenodo.3691645>)
- James R A, Jones R G, Boyd E, Young H R, Otto F E L, Huggel C and Fuglestedt J S 2019 Attribution: how is it relevant for loss and damage policy and practice? *Loss and Damage from Climate Change: Concepts, Methods and Policy Options* ed R Mechler, L M Bouwer, T Schinko, S Surminski and J Linnerooth-Bayer (Cham: Springer International Publishing) pp 113–54
- Jarraud M and Steiner A 2012 Summary for policymakers. Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change (<https://doi.org/10.1017/CBO9781139177245.003>)
- Ji P, Yuan X, Jiao Y, Wang C, Han S and Shi C 2020 Anthropogenic contributions to the 2018 extreme flooding over the upper Yellow River basin in China *Bull. Am. Meteorol. Soc.* **101** S89–S94
- Johnston F H, Borchers-Arriagada N, Morgan G G, Jalaludin B, Palmer A J, Williamson G J and Bowman D M J S 2021 Unprecedented health costs of smoke-related PM2.5 from the 2019–20 Australian megafires *Nat. Sustain.* **4** 42–47
- Johnston F H, Henderson S B, Chen Y, Randerson J T, Marlier M, DeFries R S, Kinney P, Bowman D M J S and Brauer M 2012 Estimated global mortality attributable to smoke from landscape fires *Environ. Health Perspect.* **120** 695–701
- Jones F K et al 2016 Increased rotavirus prevalence in diarrheal outbreak precipitated by localized flooding, Solomon Islands, 2014 *Emerg. Infect. Dis.* **22** 875–9
- Kalisa E, Fadlallah S, Amani M, Nahayo L and Habiyaemye G 2018 Temperature and air pollution relationship during heatwaves in Birmingham, UK *Sustain. Cities Soc.* **43** 111–20
- Katzenberger A, Schewe J, Pongratz J and Levermann A 2021 Robust increase of Indian monsoon rainfall and its variability under future warming in CMIP-6 models *Earth Syst. Dyn. Discuss.* **12** 367–386
- Kawase H, Imada Y, Tsuguti H, Nakaegawa T, Seino N, Murata A and Takayabu I 2020 The heavy rain event of July 2018 in Japan enhanced by historical warming *Bull. Am. Meteorol. Soc.* **101** S109–S114
- Kay A L, Booth N, Lamb R, Raven E, Schaller N and Sparrow S 2018 Flood event attribution and damage estimation using national-scale grid-based modelling: winter 2013/2014 in Great Britain *Int. J. Climatol.* **38** 5205–19
- Kew S F et al 2021 Impact of precipitation and increasing temperatures on drought trends in eastern Africa *Earth Syst. Dyn.* **12** 17–35
- Khan S J 2021 Ecological consequences of Australian 'Black Summer' (2019/20) fires *Integr. Environ. Assess. Manage.* **17** 1136–40
- King A D 2017 Attributing changing rates of temperature record breaking to anthropogenic influences *Earth's Future* **5** 1156–68
- King A, Karoly D and van Oldenborgh G J 2016 Climate change and El Niño increase likelihood of Indonesian heat and drought *Bull. Am. Meteorol. Soc.* **97** S113–S117
- Kinney P L, Schwartz J, Pascal M, Petkova E, Tertre A L, Medina S and Vautard R 2015 Winter season mortality: will climate warming bring benefits? *Environ. Res. Lett.* **10** 064016
- Kirchmeier-Young M C, Zwiers F W, Gillett N P and Cannon A J 2017 Attributing extreme fire risk in Western Canada to human emissions *Clim. Change* **144** 365–79
- Kirchmeier-Young M C, Gillett N P, Zwiers F W, Cannon A J and Anslow F S 2019 Attribution of the influence of human-induced climate change on an extreme fire season *Earth's Future* **7** 2–10
- Kishore N et al 2018 Mortality in Puerto Rico after Hurricane Maria *New Engl. J. Med.* **379** 162–70
- Kjellstrom T, Briggs D, Freyberg C, Lemke B, Otto M and Hyatt O 2016 Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts *Annu. Rev. Public Health* **37** 97–112
- Kopitz S N et al 2016 Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure *Environ. Res. Lett.* **11** 94023
- Kornhuber K, Coumou D, Vogel E, Lesk C, Donges J F, Lehmann J and Horton R M 2019 Amplified Rossby waves enhance risk of concurrent heatwaves in major breadbasket regions *Nat. Clim. Change* **10** 48–53
- Kossin J P 2018 A global slowdown of tropical-cyclone translation speed *Nature* **558** 104–7
- Kossin J P, Emanuel K A and Camargo S J 2016 Past and projected changes in western north pacific tropical cyclone exposure *J. Clim.* **29** 5725–39
- Kossin J P, Knapp K R, Olander T L and Velden C S 2020 Global increase in major tropical cyclone exceedance probability over the past four decades *Proc. Natl Acad. Sci. USA* **117** 11975–80
- Krikken F, Lehner F, Hausteiner K, Drobyshev I and van Oldenborgh G J 2019 Attribution of the role of climate change in the forest fires in Sweden 2018 *Nat. Hazards Earth Syst. Sci.* **21** 2169–79
- Kwasinski A, Andrade F, Castro-Sitiriche M J and O'Neill-Carrillo E 2019 Hurricane Maria effects on Puerto rice electric power infrastructure *IEEE Power Energy Technol. Syst. J.* **6** 85–94
- Lackmann G M 2015 Hurricane Sandy before 1900 and after 2100 *Bull. Am. Meteorol. Soc.* **96** 547–60
- Lagmay A M F et al 2015 Devastating storm surges of Typhoon Haiyan *Int. J. Disaster Risk Reduct.* **11** 1–12
- Leach N J, Li S, Sparrow S, van Oldenborgh G J, Lott F C, Weisheimer A and Allen M R 2020 Anthropogenic influence on the 2018 summer warm spell in Europe: the impact of different spatio-temporal scales *Bull. Am. Meteorol. Soc.* **101** S41–S46
- Lee T-C, Knutson T R, Nakaegawa T, Ying M and Cha E J 2020 Third assessment on impacts of climate change on tropical cyclones in the Typhoon committee region—part I: observed changes, detection and attribution *Trop. Cyclone Res. Rev.* **9** 1–22
- Levy K, Woster A P, Goldstein R S and Carlton E J 2016 Untangling the impacts of climate change on waterborne diseases: a systematic review of relationships between diarrheal diseases and temperature, rainfall, flooding, and drought *Environ. Sci. Technol.* **50** 4905–22

- Li J *et al* 2017 Modification of the effects of air pollutants on mortality by temperature: a systematic review and meta-analysis *Sci. Total Environ.* **575** 1556–70
- Li Z *et al* 2016 Aerosol and monsoon climate interactions over Asia *Rev. Geophys.* **54** 866–929
- Lin I-I, Chen C-H, Pun I-F, Liu W T and Wu C-C 2009 Warm ocean anomaly, air sea fluxes, and the rapid intensification of tropical cyclone Nargis (2008) *Geophys. Res. Lett.* **36** n/a
- Lin N 2019 Tropical cyclones and heatwaves *Nat. Clim. Change* **9** 579–80
- Lin N, Kopp R E, Horton B P and Donnelly J P 2016 Hurricane Sandy's flood frequency increasing from year 1800–2100 *Proc. Natl Acad. Sci. USA* **113** 12071–5
- Lyon B and Dewitt D G 2012 A recent and abrupt decline in the East African long rains *Geophys. Res. Lett.* **39** 1–5
- Mamo S, Berhanu B and Melesse A M 2019 Historical flood events and hydrological extremes in Ethiopia *Extreme Hydrology and Climate Variability: Monitoring, Modelling, Adaptation and Mitigation* (Amsterdam: Elsevier) pp 379–84
- Marcheggiani S, Puccinelli C, Ciadamidaro S, Della B V, Carere M, Francesca B M, Pacini N, Funari E and Mancini L 2010 Risks of water-borne disease outbreaks after extreme events *Toxicol. Environ. Chem.* **92** 593–9
- Marengo J A *et al* 2021 Extreme drought in the Brazilian Pantanal in 2019–2020: characterization, causes, and impacts *Front. Water* **3** 13
- Marsooli R and Lin N 2020 Impacts of climate change on hurricane flood hazards in Jamaica Bay, New York *Clim. Change* **163** 2153–71
- Marvel K, Cook B I, Bonfils C J W, Durack P J, Smerdon J E and Williams A P 2019 Twentieth-century hydroclimate changes consistent with human influence *Nature* **569** 59–65
- Masson-Delmotte V *et al* 2021 IPCC, 2021: climate change 2021: the physical science basis *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press)
- Masuda Y J, Castro B, Aggraeni I, Wolff N H, Ebi K, Garg T, Game E T, Krenz J and Spector J 2019 How are healthy, working populations affected by increasing temperatures in the tropics? Implications for climate change adaptation policies *Glob. Environ. Change* **56** 29–40
- Matthews T, Wilby R L and Murphy C 2019 An emerging tropical cyclone–deadly heat compound hazard *Nat. Clim. Change* **9** 602–6
- Matz C J, Egyed M, Xi G, Racine J, Pavlovic R, Rittmaster R, Henderson S B and Stieb D M 2020 Health impact analysis of PM_{2.5} from wildfire smoke in Canada (2013–2015, 2017–2018) *Sci. Total Environ.* **725** 138506
- Mazdiyasi O *et al* 2017 Increasing probability of mortality during Indian heat waves *Sci. Adv.* **3** e1700066
- McMichael A J *et al* 2008 International study of temperature, heat and urban mortality: the 'ISOTHURM' project *Int. J. Epidemiol.* **37** 1121–31
- Medellin-Azuara J *et al* 2016 Economic analysis of the 2016 California drought on agriculture *Center for Watershed Sciences* (Davis, CA: University of California)
- Mejia Manrique S A, Harmsen E W, Khanbilvardi R M and González J E 2021 Flood impacts on critical infrastructure in a coastal floodplain in Western Puerto Rico during Hurricane María *Hydrology* **8** 104
- Michelozzi P *et al* 2009 High temperature and hospitalizations for cardiovascular and respiratory causes in 12 European cities *Am. J. Respir. Crit. Care Med.* **179** 383–9
- Mitchell D 2016 Human influences on heat-related health indicators during the 2015 Egyptian heat wave *Bull. Am. Meteorol. Soc.* **97** S70–S74
- Mitchell D, Heaviside C, Vardoulakis S, Huntingford C, Masato G, Guillod B P, Frumhoff P, Bowery A, Wallom D and Allen M 2016 Attributing human mortality during extreme heat waves to anthropogenic climate change *Environ. Res. Lett.* **11** 074006
- Moftakhari H R, Salvadori G, AghaKouchak A, Sanders B F and Matthew R A 2017 Compounding effects of sea level rise and fluvial flooding *Proc. Natl Acad. Sci. USA* **114** 9785–90
- Moors E, Singh T, Siderius C, Balakrishnan S and Mishra A 2013 Climate change and waterborne diarrhoea in northern India: impacts and adaptation strategies *Sci. Total Environ.* **468–469** S139–S151
- Mora C *et al* 2017 Global risk of deadly heat *Nat. Clim. Change* **7** 501–6
- Mote P W, Rupp D E, Li S, Sharp D J, Otto F, Uhe P F, Xiao M, Lettenmaier D P, Cullen H and Allen M R 2016 Perspectives on the causes of exceptionally low 2015 snowpack in the western United States *Geophys. Res. Lett.* **43** 10980–8
- Moyce S, Mitchell D C, Armitage T, Tancredi D J, Joseph J G and Schenker M B 2016 P077 Heat strain, volume depletion and kidney function in California agricultural workers *Occup. Environ. Med.* **73** A146
- Murakami H, Delworth T L, Cooke W F, Zhao M, Xiang B and Hsu P C 2020 Detected climatic change in global distribution of tropical cyclones *Proc. Natl Acad. Sci. USA* **117** 10706–14
- Murakami H, Levin E, Delworth T L, Gudgel R and Hsu P C 2018 Dominant effect of relative tropical Atlantic warming on major hurricane occurrence *Science* **362** 794–9
- Murakami H, Vecchi G A and Underwood S 2017 Increasing frequency of extremely severe cyclonic storms over the Arabian Sea *Nat. Clim. Change* **7** 885–9
- Nicholson S E 2017 Climate and climatic variability of rainfall over eastern Africa *Rev. Geophys.* **55** 590–635
- O'Gorman P A 2015 Precipitation extremes under climate change *Curr. Clim. Change Rep.* **1** 49–59
- Orengo-Aguayo R, Stewart R W, de Arellano M A, Suárez-Kindy J L and Young J 2019 Disaster exposure and mental health among Puerto Rican youths after Hurricane Maria *JAMA Netw. Open* **2** e192619
- Osaka S and Bellamy R 2020 Natural variability or climate change? Stakeholder and citizen perceptions of extreme event attribution *Glob. Environ. Change* **62** 102070
- Osofsky H J, Osofsky J D, Arey J, Kronenberg M E, Hansel T and Many M 2011 Hurricane Katrina's first responders: the struggle to protect and serve in the aftermath of the disaster *Disaster Med. Public Health Prep.* **5** S214–S219
- Otto F E L *et al* 2015 Factors other than climate change, main drivers of 2014/15 water shortage in Southeast Brazil *Bull. Am. Meteorol. Soc.* **96** S35–S40
- Otto F E L *et al* 2018b Anthropogenic influence on the drivers of the Western Cape drought 2015–2017 *Environ. Res. Lett.* **13** 124010
- Otto F E L *et al* 2020b Towards an inventory of the impacts of human-induced climate change *Bull. Am. Meteorol. Soc.* **101** E1972–E1979
- Otto F E L *et al* 2022 Climate change increased rainfall associated with tropical cyclones hitting highly vulnerable communities in Madagascar, Mozambique & Malawi
- Otto F E L, Harrington L, Schmitt K, Philip S, Kew S, Jan van Oldenborgh G, Singh R, Kimutai J and Wolski P 2020a Challenges to understanding extreme weather changes in lower income countries *Bull. Am. Meteorol. Soc.* **101** E1851–E1860
- Otto F E L, Massey N, van Oldenborgh G J, Jones R G and Allen M R 2012 Reconciling two approaches to attribution of the 2010 Russian heat wave *Geophys. Res. Lett.* **39** L04702

- Otto F E L, van der Wiel K, van Oldenborgh G J, Philip S, Kew S F, Uhe P and Cullen H 2018a Climate change increases the probability of heavy rains in Northern England/Southern Scotland like those of storm Desmond—a real-time event attribution revisited *Environ. Res. Lett.* **13** 024006
- Otto F E L, van Oldenborgh G J, Eden J, Stott P A, Karoly D J and Allen M R 2016 The attribution question *Nat. Clim. Change* **6** 813–16
- Otto F E, Zhang X and Seneviratne S 2021 Summary for Policymakers of the Working Group I contribution to the IPCC Sixth Assessment Report—data for figure SPM.3 *NERC EDS Cent. Environ. Data Anal.*
- Paik S, Min S K, Zhang X, Donat M G, King A D and Sun Q 2020 Determining the anthropogenic greenhouse gas contribution to the observed intensification of extreme precipitation *Geophys. Res. Lett.* **47** e2019GL086875
- Pall P, Aina T, Stone D A, Stott P A, Nozawa T, Hilberts A G J, Lohmann D and Allen M R 2011 Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000 *Nature* **470** 382–5
- Pall P, Patricola C M, Wehner M F, Stone D A, Paciorek C J and Collins W D 2017 Diagnosing conditional anthropogenic contributions to heavy Colorado rainfall in September 2013 *Weather Clim. Extremes* **17** 1–6
- Parry S, Marsh T and Kendon M 2013 2012: from drought to floods in England and Wales *Weather* **68** 268–74
- Parsons L A, Masuda Y J, Kroeger T, Shindell D, Wolff N H and Spector J T 2021 Global labor loss due to humid heat exposure underestimated for outdoor workers *Environ. Res. Lett.* **014050**
- Patricola C M and Wehner M F 2018 Anthropogenic influences on major tropical cyclone events *Nature* **563** 339–46
- Patz J A, Vavrus S J, Uejio C K and McLellan S L 2008 Climate change and waterborne disease risk in the great lakes region of the U.S. *Am. J. Prev. Med.* **35** 451–8
- Pelling M and Garschagen M 2019 Put equity first in climate adaptation *Nat.* **327–9**
- Perkins-Kirkpatrick S E, Stone D A, Mitchell D M, Rosier S, King A D, Lo Y T E, Pastor-Paz J, Frame D and Wehner M 2022 On the attribution of the impacts of extreme weather events to anthropogenic climate change *Environ. Res. Lett.* **17** 024009
- Peterson T C et al 2015 Explaining extreme events of 2012 from a climate perspective *Bull. Am. Meteorol. Soc.* (<https://doi.org/10.1175/BAMS-D-13-00085.1>)
- Peterson T C, Stott P A and Herring S 2012 Explaining extreme events of 2011 from a climate perspective *Bull. Am. Meteorol. Soc.* **93** 1041–67
- Pfahl S, O’Gorman P A and Fischer E M 2017 Understanding the regional pattern of projected future changes in extreme precipitation *Nat. Clim. Change* **7** 423–7
- Philip S et al 2018b Attribution analysis of the Ethiopian drought of 2015 *J. Clim.* **31** 2465–86
- Philip S et al 2020 A protocol for probabilistic extreme event attribution analyses *Adv. Stat. Climatol. Meteorol. Oceanogr.* **6** 177–203
- Philip S, Kew S F, van Oldenborgh G J, Aalbers E, Vautard R, Otto F, Hausteine K, Habets F and Singh R 2018a Validation of a rapid attribution of the May/June 2016 flood-inducing precipitation in France to climate change *J. Hydrometeorol.* **19** 1881–98
- Rahmstorf S and Coumou D 2011 Increase of extreme events in a warming world *Proc. Natl Acad. Sci. USA* **108** 17905–9
- Raju E, Boyd E and Otto F 2022 Stop blaming the climate for disasters *Commun. Earth Environ.* **3** 1–2
- Ramana Dhara V, Schramm P J and Lubner G 2013 Climate change & infectious diseases in India: implications for health care providers *Indian J. Med. Res.* **138** 847–52
- Raymond C, Matthews T and Horton R M 2020 The emergence of heat and humidity too severe for human tolerance *Sci. Adv.* **6** eaaw1838
- Reed K A, Stansfield A M, Wehner M F and Zarzycki C M 2020 Forecasted attribution of the human influence on Hurricane Florence *Sci. Adv.* **6** eaaw9253
- Reed K A, Wehner M F, Stansfield A M and Zarzycki C M 2021 Anthropogenic influence on Hurricane Dorian’s extreme rainfall *Bull. Am. Meteorol. Soc.* **102** S9–S15
- Reid C E, Brauer M, Johnston F H, Jerrett M, Balmes J R and Elliott C T 2016 Critical review of health impacts of wildfire smoke exposure *Environ. Health Perspect.* **124** 1334–43
- Reuters 2015 Beyond haze, El Nino drought poses poverty challenge for Indonesia (available at: www.reuters.com/article/us-indonesia-elnino-idUSKCN0SM2SK20151029) (Accessed 18 June 2021)
- Rhodes J, Chan C, Paxson C, Rouse C E, Waters M and Fussell E 2010 The impact of Hurricane Katrina on the mental and physical health of low-income parents in New Orleans *Am. J. Orthopsychiatry* **80** 237–47
- Rimi R H, Hausteine K, Barbour E J and Allen M R 2018 Risks of pre-monsoon extreme rainfall events of Bangladesh: is anthropogenic climate change playing a role? *Bull. Am. Meteorol. Soc.* **100** S61–S65
- Robinson A, Lehmann J, Barriopedro D, Rahmstorf S and Coumou D 2021 Increasing heat and rainfall extremes now far outside the historical climate *npj Clim. Atmos. Sci.* **4** 1–4
- Rohat G, Flacke J, Dosio A, Pedde S, Dao H and van Maarseveen M 2019 Influence of changes in socioeconomic and climatic conditions on future heat-related health challenges in Europe *Glob. Planet. Change* **172** 45–59
- Rohmah A 2015 Drought hits most Indonesian provinces due to El Nino (available at: www.aa.com.tr/en/world/drought-hits-most-indonesian-provinces-due-to-el-nino/22867) (Accessed 18 June 2021)
- Rosier S, Dean S, Stuart S, Carey-Smith T, Black M T and Massey N 2015 Extreme rainfall in early July 2014 in northland, New Zealand—was there an anthropogenic influence? *Bull. Am. Meteorol. Soc.* **96** S136–S140
- Rusiecki J A, Thomas D L, Chen L, Funk R, McKibben J and Dayton M R 2014 Disaster-related exposures and health effects among US coast guard responders to Hurricanes Katrina and Rita: a cross-sectional study *J. Occup. Environ. Med.* **56** 820–33
- Rusticucci M and Zazulie N 2021 Attribution and projections of temperature extreme trends in South America based on CMIP5 models *Ann. New York Acad. Sci.* **1504** 154–66
- Sahu S, Sett M and Kjellstrom T 2013 heat exposure, cardiovascular stress and work productivity in rice harvesters in India: implications for a climate change future *Ind. Health* **51** 2013–6
- Samset B H, Sand M, Smith C J, Bauer S E, Forster P M, Fuglestedt J S, Osprey S and Schlessner C F 2018 Climate impacts from a removal of anthropogenic aerosol emissions *Geophys. Res. Lett.* **45** 1020–9
- Sanderson B M and Fisher R A 2020 A fiery wake-up call for climate science *Nat. Clim. Change* **10** 175–7
- Santos-Burgoa C et al 2018 Differential and persistent risk of excess mortality from Hurricane Maria in Puerto Rico: a time-series analysis *Lancet Planet. Health* **2** e478–e488
- Scaramutti C, Salas-Wright C P, Vos S R and Schwartz S J 2019 The mental health impact of Hurricane Maria on Puerto Ricans in Puerto Rico and Florida *Disaster Med. Public Health Prep.* **13** 24–27
- Schaller N et al 2016 Human influence on climate in the 2014 southern England winter floods and their impacts *Nat. Clim. Change* **6** 627–34

- Schaller N, Sillmann J, Müller M, Haarsma R, Hazeleger W, Hegdahl T J, Kelder T, van den Oord G, Weerts A and Whan K 2020 The role of spatial and temporal model resolution in a flood event storyline approach in western Norway *Weather Clim. Extremes* **29** 100259
- Seager R, Osborn T J, Kushnir Y, Simpson I R, Nakamura J and Liu H 2019 Climate variability and change of Mediterranean-type climates *J. Clim.* **32** 2887–915
- Sena A, Barcellos C, Freitas C and Corvalan C 2014 Managing the health impacts of drought in Brazil *Int. J. Environ. Res. Public Health* **11** 10737
- Seong M-G, Min S-K, Kim Y-H, Zhang X and Sun Y 2021 Anthropogenic greenhouse gas and aerosol contributions to extreme temperature changes during 1951–2015 *J. Clim.* **34** 857–70
- Seriño M N V, Cavero J A, Cuizon J, Ratilla T C, Ramoneda B M, Bellezas M H I and Ceniza M J C 2021 Impact of the 2013 super Typhoon Haiyan on the livelihood of small-scale coconut farmers in Leyte island, Philippines *Int. J. Disaster Risk Reduct.* **52** 101939
- Shaposhnikov D et al 2014 Mortality related to air pollution with the Moscow heat wave and wildfire of 2010 *Epidemiology* **25** 359–64
- Sharma A, Wasko C and Lettenmaier D P 2018 If precipitation extremes are increasing, why aren't floods? *Water Resour. Res.* **54** 8545–51
- Shiogama H, Watanabe M, Imada Y, Mori M, Kamae Y, Ishii M and Kimoto M 2014 Attribution of the June–July 2013 heat wave in the southwestern United States *Sci. Online Lett. Atmos.* **10** 122–26
- Simon Wang S Y, Yoon J H, Becker E and Gillies R 2017 California from drought to deluge *Nat. Clim. Change* **7** 465–68
- Singh N, Mhawish A, Ghosh S, Banerjee T and Mall R K 2019 Attributing mortality from temperature extremes: a time series analysis in Varanasi, India *Sci. Total Environ.* **665** 453–64
- Sippel S, Meinshausen N, Fischer E M, Székely E and Knutti R 2020 Climate change now detectable from any single day of weather at global scale *Nat. Clim. Change* **10** 35–41
- Solberg S, Hov Ø, Søvde A, Isaksen I S, Coddeville P, de Backer H, Forster C, Orsolini Y and Uhse K 2008 European surface ozone in the extreme summer 2003 *J. Geophys. Res. Atmos.* **113** D07307
- Sparrow S et al 2018 Attributing human influence on the July 2017 Chinese heatwave: the influence of sea-surface temperatures *Environ. Res. Lett.* **13** 114004
- Spector J T, Masuda Y J, Wolff N H, Calkins M and Seixas N 2019 Heat exposure and occupational injuries: review of the literature and implications *Curr. Environ. Health Rep.* **6** 286–96
- Staddon P L, Montgomery H E and Depledge M H 2014 Climate warming will not decrease winter mortality *Nat. Clim. Change* **4** 190–4
- Stanford University 2020 In a warming world, Cape Town's 'Day Zero' drought won't be an anomaly (available at: <https://phys.org/news/2020-11-world-cape-town-day-drought.html>) (Accessed 18 June 2021)
- Stanke C, Murray V, Amlöt R, Nurse J and Williams R 2012 The effects of flooding on mental health: outcomes and recommendations from a review of the literature *PLoS Curr.* **4** 1–25
- Stone D A, Rosier S M and Frame D J 2021 The question of life, the universe and event attribution *Nat. Clim. Change* **11** 276–8
- Stott P A, Jones G S, Christidis N, Zwiers F W, Hegerl G and Shiogama H 2011 Single-step attribution of increasing frequencies of very warm regional temperatures to human influence *Atmos. Sci. Lett.* **12** 220–7
- Stott P A, Stone D A and Allen M R 2004 Human contribution to the European heatwave of 2003 *Nature* **432** 610–4
- Strauss B H, Orton P M, Bittermann K, Buchanan M K, Gilford D M, Kopp R E, Massey C, Moel H D and Vinogradov S 2021 Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change *Nat. Commun.* **12** 2720
- Subramanian R, Ellis A, Torres-Delgado E, Tanzer R, Malings C, Rivera F, Morales M, Baumgardner D, Presto A and Mayol-Bracero O L 2018 Air quality in Puerto Rico in the aftermath of Hurricane Maria: a case study on the use of lower cost air quality monitors *ACS Earth Space Chem.* **2** 1179–86
- Sugg M M, Konrad C E and Fuhrmann C M 2016 Relationships between maximum temperature and heat-related illness across North Carolina, USA *Int. J. Biometeorol.* **60** 663–75
- Sui C, Zhang Z, Yu L, Li Y and Song M 2017 Investigation of Arctic air temperature extremes at north of 60°N in winter *Acta Oceanol. Sin.* **36** 51–60
- Sun Q and Miao C 2018 20. Extreme rainfall (R20MM, RX5day) in Yangtze–Huai, China, in June–July 2016: the role of ENSO and anthropogenic climate change *Bull. Am. Meteorol. Soc.* **99** S102–S106
- Sun Q, Zhang X, Zwiers F, Westra S and Alexander L V 2021 A global, continental, and regional analysis of changes in extreme precipitation *J. Clim.* **34** 243–58
- Sun Y, Hu T, Zhang X, Wan H, Stott P and Lu C 2018 24. Anthropogenic influence on the eastern China 2016 super cold surge *Bull. Am. Meteorol. Soc.* **99** S123–S127
- Szeto K, Zhang X, White R E and Brimelow J 2016 The 2015 extreme drought in Western Canada *Bull. Am. Meteorol. Soc.* **97** S42–S46
- Takayabu I, Hibino K, Sasaki H, Shiogama H, Mori N, Shibutani Y and Takemi T 2015 Climate change effects on the worst-case storm surge: a case study of Typhoon Haiyan *Environ. Res. Lett.* **10** 064011
- Tedim F, Remelgado R, Borges C, Carvalho S and Martins J 2013 Exploring the occurrence of mega-fires in Portugal *For. Ecol. Manage.* **294** 86–96
- Tellman B, Sullivan J A, Kuhn C, Kettner A J, Doyle C S, Brakenridge G R, Erickson T A and Slayback D A 2021 Satellite imaging reveals increased proportion of population exposed to floods *Nature* **596** 80–86
- Teufel B et al 2019 Investigation of the mechanisms leading to the 2017 Montreal flood *Clim. Dyn.* **52** 4193–206
- The Weather Channel 2017 16 billion-dollar disasters have impacted the U.S. this year, tying an all-time record, thanks to the California Wildfires (available at: <https://weather.com/news/weather/news/2017-10-20-billion-dollar-weather-disasters-united-states-record-tied>) (Accessed 18 June 2021)
- Tierney J E, Ummenhofer C C and DeMenocal P B 2015 Past and future rainfall in the Horn of Africa *Sci. Adv.* **1** 1–8
- Ting M, Camargo S J, Li C and Kushnir Y 2015 Natural and forced North Atlantic Hurricane potential intensity change in CMIP5 models* *J. Clim.* **28** 3926–42
- Touma D, Stevenson S, Lehner F and Coats S 2021 Human-driven greenhouse gas and aerosol emissions cause distinct regional impacts on extreme fire weather *Nat. Commun.* **12** 212
- Trenberth K E, Cheng L, Jacobs P, Zhang Y and Fasullo J 2018 Hurricane Harvey links to ocean heat content and climate change adaptation *Earth's Future* **6** 730–44
- Tunstall S, Tapsell S, Green C, Floyd P and George C 2006 The health effects of flooding: social research results from England and Wales *J. Water Health* **4** 365–80
- Uejio C K, Yale S H, Malecki K, Borchardt M A, Anderson H A and Patz J A 2014 Drinking water systems, hydrology, and childhood gastrointestinal illness in central and northern Wisconsin *Am. J. Public Health* **104** 639–46
- Uhe P et al 2018 Attributing drivers of the 2016 Kenyan drought *Int. J. Climatol.* **38** e554–e568

- van der Wiel K, Kapnick S B, van Oldenborgh G J, Whan K, Philip S, Vecchi G A, Singh R K, Arrighi J and Cullen H 2017 Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change *Hydrol. Earth Syst. Sci.* **21** 897–921
- van Oldenborgh G J et al 2020 Attribution of the Australian bushfire risk to anthropogenic climate change *Nat. Hazards Earth Syst. Sci.* **21** 941–60
- van Oldenborgh G J et al 2021 Pathways and pitfalls in extreme event attribution *Clim. Change* **166** 1–27
- van Oldenborgh G J, Otto F E L, Hausteijn K and Cullen H 2015 Climate change increases the probability of heavy rains like those of storm Desmond in the UK—an event attribution study in near-real time *Hydrol. Earth Syst. Sci. Discuss.* **12** 13197–216
- van Oldenborgh G J, Philip S, Aalbers E, Vautard R, Otto F, Hausteijn K, Habets F, Singh R and Cullen H 2016 Rapid attribution of the May/June 2016 flood-inducing precipitation in France and Germany to climate change *Hydrol. Earth Syst. Sci. Discuss.* (<https://doi.org/10.5194/hess-2016-308>)
- van Oldenborgh G J, van der Wiel K, Sebastian A, Singh R, Arrighi J, Otto F, Hausteijn K, Li S, Vecchi G and Cullen H 2017 Attribution of extreme rainfall from Hurricane Harvey, August 2017 *Environ. Res. Lett.* **12** 124009
- Van Wagner C E 1987 Development and structure of the Canadian forest fire weather index system *Forestry* **35**
- Vautard R, Yiou P, van Oldenborgh G-J, Lenderink G, Thao S, Ribes A, Planton S, Dubuisson B and Soubeyroux J-M 2015 Extreme fall 2014 precipitation in the Cévennes mountains *Bull. Am. Meteorol. Soc.* **96** S56–S60
- Vicedo-Cabrera A M et al 2018 Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios *Clim. Change* **150** 391–402
- Vicedo-Cabrera A M et al 2021 The burden of heat-related mortality attributable to recent human-induced climate change *Nat. Clim. Change* **11** 492–500
- Vogel M M, Zscheischler J, Wartenburger R, Dee D and Seneviratne S I 2019 Concurrent 2018 hot extremes across northern hemisphere due to human-induced climate change *Earth's Future* **7** 692–703
- Waite T D et al 2017 The English national cohort study of flooding and health: cross-sectional analysis of mental health outcomes at year one *BMC Public Health* **17** 1–9
- Walsh K J E, Camargo S J, Knutson T R, Kossin J, Lee T-C, Murakami H and Patricola C 2019 Tropical cyclones and climate change *Trop. Cyclone Res. Rev.* **8** 240–50
- Wang B et al 2021 Monsoons climate change assessment *Bull. Am. Meteorol. Soc.* **102** E1–E19
- Wang C C, Tseng L S, Huang C C, Lo S H, Chen C T, Chuang P Y, Su N C and Tsuboki K 2019 How much of Typhoon Morakot's extreme rainfall is attributable to anthropogenic climate change? *Int. J. Climatol.* **39** 3454–64
- Wang S Y S, Zhao L, Yoon J H, Klotzbach P and Gillies R R 2018 Quantitative attribution of climate effects on Hurricane Harvey's extreme rainfall in Texas *Environ. Res. Lett.* **13** 054014
- Ward M et al 2020 Impact of 2019–2020 mega-fires on Australian fauna habitat *Nat. Ecol. Evol.* **4** 1321–6
- Wasko C and Nathan R 2019 Influence of changes in rainfall and soil moisture on trends in flooding *J. Hydrol.* **575** 432–41
- Watts N et al 2018 The Lancet Countdown on health and climate change: from 25 years of inaction to a global transformation for public health *Lancet* **392** 2479–514
- Webb A and Wadhwa A 2016 The impact of drought on households in four provinces in Eastern Indonesia
- Wehner M, Stone D, Krishnan H, Achutarao K and Castillo F 2016 16. The deadly combination of heat and humidity in India and Pakistan in summer 2015 *Bull. Am. Meteorol. Soc.* **97** S81–S86
- Welton G 2010 The impact of Russia's 2010 grain export ban
- Whaley A L 2009 Trauma among survivors of Hurricane Katrina: considerations and recommendations for mental health care *J. Loss Trauma* **14** 459–76
- Williams A P, Cook E R, Smerdon J E, Cook B I, Abatzoglou J T, Bolles K, Baek S H, Badger A M and Livneh B 2020 Large contribution from anthropogenic warming to an emerging North American megadrought *Science* **368** 314–8
- Williams A P, Seager R, Abatzoglou J T, Cook B I, Smerdon J E and Cook E R 2015 Contribution of anthropogenic warming to California drought during 2012–2014 *Geophys. Res. Lett.* **42** 6819–28
- Woo G 2016 Counterfactual disaster risk analysis variance pp 1–30
- World Weather Attribution 2021a Western North American extreme heat virtually impossible without human-caused climate change (available at: www.worldweatherattribution.org/western-north-american-extreme-heat-virtually-impossible-without-human-caused-climate-change/) (Accessed 9 November 2021)
- World Weather Attribution 2021b Factors other than climate change are the main drivers of recent food insecurity in Southern Madagascar
- World Weather Attribution 2021c Siberian heatwave of 2020 almost impossible without climate change
- WWF Australia 2020. Australia's 2019–2020 bushfires: the wildlife toll—WWF-Australia—WWF-Australia (available at: www.wwf.org.au/what-we-do/bushfire-recovery/in-depth/resources/australia-s-2019-2020-bushfires-the-wildlife-toll#gs.2a0x3v) (Accessed 1 June 2021)
- Yamada Y, Kodama C, Satoh M, Nakano M, Nasuno T and Sugi M 2019 High-resolution ensemble simulations of intense tropical cyclones and their internal variability during the El Niños of 1997 and 2015 *Geophys. Res. Lett.* **46** 7592–601
- Yamaguchi M and Maeda S 2020 Slowdown of typhoon translation speeds in mid-latitudes in September influenced by the Pacific decadal oscillation and global warming *J. Meteorol. Soc. Jpn.* **98** 1321–34
- Yang S-H, Kang N-Y, Elsner J B and Chun Y 2018 Influence of global warming on western North Pacific tropical cyclone intensities during 2015 *J. Clim.* **31** 919–25
- Yin H, Sun Y and Donat M G 2019 Changes in temperature extremes on the Tibetan Plateau and their attribution *Environ. Res. Lett.* **14** 124015
- Yu D et al 2020a Disruption of emergency response to vulnerable populations during floods *Nat. Sustain.* **3** 728–36
- Yu P, Xu R, Abramson M J, Li S and Guo Y 2020b Bushfires in Australia: a serious health emergency under climate change *Lancet Planet. Health* **30267–0**
- Yuan X, Wang L and Wood E F 2018a 17. Anthropogenic intensification of southern African flash droughts as exemplified by the 2015/16 season *Bull. Am. Meteorol. Soc.* **99** S86–S90
- Yuan X, Wang L, Wu P, Ji P, Sheffield J and Zhang M 2019 Anthropogenic shift towards higher risk of flash drought over China *Nat. Commun.* **10** 4661
- Yuan X, Wang S and Hu Z Z 2018b 22. Do climate change and El Niño increase likelihood of Yangtze River extreme rainfall? *Bull. Am. Meteorol. Soc.* **99** S113–S117

- Yun X, Tang Q, Wang J, Liu X, Zhang Y, Lu H, Wang Y, Zhang L and Chen D 2020 Impacts of climate change and reservoir operation on streamflow and flood characteristics in the Lancang-Mekong River Basin *J. Hydrol.* **590** 125472
- Zakrisson T L, Valdés D M and Shultz J M 2020 The medical, public health, and emergency response to the impact of 2017 Hurricane Irma in Cuba *Disaster Med. Public Health Prep.* **14** 10–17
- Zhang N, Song D, Zhang J, Liao W, Miao K, Zhong S, Lin S, Hajat S, Yang L and Huang C 2019 The impact of the 2016 flood event in Anhui Province, China on infectious diarrhea disease: an interrupted time-series study *Environ. Int.* **127** 801–9
- Zhang W, Vecchi G A, Murakami H, Jia L, Delworth T L, Paffendorf K, Jia L, Jia L, Zeng F and Yang X 2016 26. Influences of natural variability and anthropogenic forcing on the extreme 2015 accumulated cyclone energy in the Western North Pacific *Bull. Am. Meteorol. Soc.* **97** S131–S135
- Zhang Y and Shindell D T 2021 Costs from labor losses due to extreme heat in the USA attributable to climate change *Clim. Change* **164** 1–18
- Zhou C, Wang K and Qi D 2018 21. Attribution of the July 2016 extreme precipitation event over China's Wuhan *Bull. Am. Meteorol. Soc.* **99** S107–S112
- Zhou C, Wang K, Qi D and Tan J 2019 Attribution of a record-breaking heatwave event in summer 2017 over the Yangtze River delta *Bull. Am. Meteorol. Soc.* **100** S97–S103
- Zorrilla C D 2017 The view from Puerto Rico—Hurricane Maria and its aftermath *New Engl. J. Med.* **377** 1801–3