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VIEWPOINT

Extreme weather in a changing climate

Giorgia Di Capua[1,2,*] and Stefan Rahmstorf[2]

[1] Magdeburg-Stendal University of Applied Sciences, 39114 Magdeburg, Germany
[2] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, PO Box 6012 03, D-14412 Potsdam, Germany
[*] Author to whom any correspondence should be addressed.

E-mail: dicapua@pik-potsdam.de

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Abstract

Extreme weather events are rising at a pace which exceeds expectations based on thermodynamic arguments only, changing the way we perceive our climate system and climate change issues. Every year, heatwaves, floods and wildfires, bring death and devastation worldwide, increasing the evidence about the role of anthropogenic climate change in the increase of extremes. In this viewpoint article, we summarize some of the most recent extremes and put them in the context of the most recent research on atmospheric and climate sciences, especially focusing on changes in thermodynamics and dynamics of the atmosphere. While some changes in extremes are to be expected and are clearly attributable to rising greenhouse gas emissions, other seem counterintuitive, highlighting the need for further research in the field. In this context, research on changes in atmospheric dynamics plays a crucial role in explaining some of these extremes and more needs to be done to improve our understanding of the physical mechanisms involved.

A rise in weather extremes is probably the most severe early impact of rising global temperatures. Extreme weather events have a high impact on both human activities and natural ecosystems. In recent decades the world has seen an increase in heatwaves, droughts, flooding events and fire weather conditions, as expected in a warming climate. 2022 has been no exception, with record-breaking high temperatures registered across large portions of Western Europe, China and Pakistan (Hausfather 2023). In Pakistan, extreme monsoon rains and Himalayan glaciers melting away in a heat wave have flooded approximately 85 000 km^2 (USAID 2022), killing more than 1700 people and causing $15 billion of damage (World Bank), while the Horn of Africa has seen an unprecedented drought that has pushed more than three million people into emergency food insecurity (NASA Earth Observatory 2022). Many of these events have been made more likely by anthropogenic warming and represent a serious threat to human society, with effects ranging from health and mortality to economy and national security issues.

Even for lay persons it will be obvious that heat extremes will increase in a warming world. But it may be unexpected by how much: monthly heat extremes that were three standard deviations above average during the baseline period 1951–1980 have already increased over 90-fold in frequency over the global land area, while the formerly near-unprecedented 4-sigma events have increased 1000-fold to affect 3% of the land area in any given month, data show (Robinson *et al* 2021). July 2023 was the hottest month on record on Earth by a large margin (Copernicus 2023a), and likely the hottest for at least 10 000 years. Marine heatwaves have also doubled in the last few decades, and they are expected to see a 23-fold increase under a 2 °C warming scenario (Frölicher *et al* 2018)—the off-the charts sea surface temperatures in the North Atlantic in summer 2023 are a stern foretaste of this (Copernicus 2023b), while in Florida the marine heatwave caused wide spread bleaching turning into one of the worst events in the region on record (Dennis *et al* 2023).

Part of this is as expected simply by shifting a Gaussian normal distribution towards warmer values; the more extreme an event, the larger is the factor by which its likelihood increases. However, explaining the full extent of the global increase in extreme heat requires additional, dynamical effects (which we will discuss below).

And heat—especially lasting heat—is a silent killer. The death toll of the 2003 European heat wave has been estimated as ∼70 000 (Robine *et al* 2008), with a mortality peak in France higher than during any Covid19 wave (Ferrer and Breteau 2020). A first estimate for summer 2022 came in at ∼62 000 (Ballester *et al* 2023), when even in Britain temperatures soared above 40 °C for the first time in history. Temperature-related excess mortality is expected to increase with unmitigated global warming, even when accounting for a decrease in cold-related deaths (Gasparrini *et al* 2017).

Since early 2012, the fingerprint of climate change can be detected in any single day in the observed record. There are no more days on Earth where global weather is not significantly different from what it would be without human influence—on nearly all days even when just considering the weather *patterns* without the increase in global-mean temperature (Sippel *et al* 2020). Observations show that nearly the entire Earth surface has warmed since the late 19th century (except for the prominent 'warming hole' south of Greenland and Iceland, Rahmstorf *et al* 2015) and the annual global mean temperature has increased by 1.2 °C since the late 19th Century (Intergovernmental Panel on Climate Change 2021). The intensity and speed of warming differ by region, with land areas warming twice as much as the ocean surface since 1970 (Intergovernmental Panel on Climate Change 2021). Warming is more prominent in the Arctic, Eastern Europe, North Africa, the Middle East, East Asia and western North America. Key heatwave characteristics, such as frequency, duration and cumulative heat (i.e. the heat produced by heatwaves days inside a season), show increasing trends since 1950 at global scale, with stronger trends in tropical and northern latitudes. Trends for these key variables have been accelerating in the past few decades (Perkins-Kirkpatrick and Lewis 2020). Summer 2023 was no exception, with record breaking temperature recorded in Southeastern US, China, Spain, Morocco, rendered more likely by current climate change (Zachariah *et al* 2023).

While the world-wide rise in heat extremes is easily understood given the rise in global mean temperature, mean global rainfall and extreme precipitation trends depict a more complex relationship. Global rainfall is expected to increase as evaporation from warmer oceans increases. Indeed, the IPCC AR6 WGI (2021) reports an increase in globally averaged land precipitation since 1950, though with medium confidence given the large variability and spatial heterogeneity of precipitation. However, extreme rainfall events have shown a steep increase in the last few decades (especially in tropical regions), with 1 in 4 record breaking rainfall events being attributable to climate change (Robinson *et al* 2021). In August 2023, the region surrounding Beijing was hit by a severe flood event which saw the highest rainfall record of the last 140 years (744.8 mm in less the 4 d) (Hawkins 2023) Perhaps counterintuitively, some areas even show opposite trends in mean precipitation rates and extreme rainfall events. One such example is the Indian summer monsoon system, which shows a slight decrease in its mean seasonal precipitation rates together with a three-fold increase in extreme rainfall events during the 1950–2015 period (Roxy *et al* 2017). Therefore, when considering the effect of climate change on extremes, it is not enough to look at trends in mean values.

Another example of that is that despite the global-mean (and often also local) rainfall increase, the frequency and severity of droughts has also increased in some regions, for a number of reasons. One overall reason is that with approximately constant relative humidity, air will contain (and at some point rain out) 7% more moisture per degree of warming, while the resupply of water via evaporation increases only by 2%–3% per degree (Allan *et al* 2020). The additional evaporation and rainfall tends to end up in heavy rain rather than alleviating drought: Half of it comes down in the wettest 6 d each year (Pendergrass and Knutti 2018), and the heaviest rainfall events increase most strongly (Fischer and Knutti 2015). Also, increasing agricultural and ecological droughts (i.e. loss of soil moisture and drying vegetation) can be caused not just by declining precipitation but also by rising temperatures causing faster evapotranspiration. In different regions, either of these effects can be the more important one (Cook *et al* 2018). Major droughts can also result from natural climate variability and are rare events (compared to the length of available observational data). Thus, studying their trend and, more importantly, attributing them to anthropogenic global warming is not an easy task (Cook *et al* 2018). Several regions in the world have shown an increase in drought risk, such as Western North America, the Mediterranean, East Southern Africa, East Asia and South Australia, at least partly attributable to anthropogenic warming, with the Mediterranean and the North-Western North America showing the highest confidence (Intergovernmental Panel on Climate Change 2021).

In the past decade, wildfire activity has produced some new extreme fires that are unprecedented regarding propagation speed, intensity, location, timing and burnt area (Descals *et al* 2022, Senande-Rivera *et al* 2022). For example, the Australian 'Black Summer' wildfire disaster in 2019/2020 followed Australia's hottest and driest year on record, burned more than half of the habitat for over 1600 native species and directly caused 33 human deaths and almost 450 more from smoke inhalation (Himbrechts 2021). An increase in extreme fire weather conditions can already be detected at global scale, although trend magnitude and spatial patterns vary at regional scale (Jain *et al* 2022). Globally, anthropogenic global warming is projected to cause unprecedented increases in extreme fire weather risk in the 21st century (Touma *et al* 2021). Model experiments estimate that anthropogenic induced changes in fire weather indices have already emerged from natural variability for 22% of the burnable land area globally by 2019, while by the mid twenty-first century the emergence will reach 30%–60% (Abatzoglou *et al* 2019). Meanwhile, in August 2023, Hawaii has experienced its worst wildfire on record, and one of the worst in US history, where dry conditions and hurricane-force winds fueled the flames bringing utter devastation to the town of Lahaina, killing at least 93 people and thus surpassing the death toll of the Camp fire in California in 2018 (Gabbat and Anguiano 2023).

While warm extremes are to be expected due to anthropogenic global warming, cold extreme are projected to decrease in this century. Nevertheless, despite the general increase in global surface temperatures, a few regions show a cooling trend in the historical record. One such example is central Siberia, which features a cooling trend during boreal winter (Inoue *et al* 2012). While both natural variability and anthropogenic forcing are debated as causes of this trend (Inoue *et al* 2012), the cooling trend is mainly associated with an increase in cold extremes over the region. Cold air outbreaks in central Siberia and North America have been shown to result from sudden stratospheric warming events and a disruption of the stratospheric Polar vortex (Kretschmer *et al* 2018).

Detecting climate change signals can be challenging depending on the region and the variable selected, and attributing trends in temperature or precipitation fields to changes in thermodynamic or dynamic features of the atmosphere represent an even greater challenge (Shepherd 2014). In general, the largest portion of the change is to be attributed to thermodynamic effects. However, dynamic changes can further exacerbate thermodynamic driven changes and atmosphere dynamics and changes in weather patterns play an important role at regional scale (Rousi *et al* 2022). Amplified Rossby waves with preferred phase position, in particular waves with wave numbers 5 and 7, can lead to concurrent heatwaves (and crop failures) in the mid-latitudes (Kornhuber *et al* 2020), raising concerns about future food security. Arctic amplification, despite being more prominent in winter than summer, may also affect westerly winds, storm tracks and wave-guides in the mid-latitudes (Coumou *et al* 2018). Analyzing the ability of models to reproduce amplified waves 5 and 7 shows that even a small bias in upper tropospheric circulation features can have a strong impact on surface temperature and rainfall patterns (Luo *et al* 2022), highlighting that it is difficult for global climate models to simulate all mechanisms that contribute to making weather more extreme.

Europe has emerged as a hot-spot of heat extremes: it has seen a stronger increase in summer heat than other regions in the northern mid-latitudes. This enhanced warming has been related to dynamical changes such as an increase of double jet patterns, which could explain all of the additional rise in heat waves beyond what is expected simply by thermodynamics (Rousi *et al* 2022). Both observation and model experiment support the hypothesis that shrinking Arctic sea ice and reduced snow cover over northern Eurasia in spring can also contribute to increased blocking over Europe and consequent frequency of heatwaves (Zhang *et al* 2020). Sea surface temperature anomalies (in particular the northern Atlantic 'warming hole' mentioned earlier) can also reinforce heatwaves in central Europe, such as in 2015 (Duchez *et al* 2015).

In summary, it is now clear that global warming is already greatly increasing the number and intensity of many types of weather extremes, as has been predicted by climate science for decades. Much of this is due to thermodynamics. With that we mean that the atmosphere is warmer, which means it holds more energy and water to power extreme weather. The ocean is also warmer and can provide more energy and moisture as fuel to tropical cyclones. However, increasingly the attention of researchers has turned to dynamic effects. With that we refer to changes in circulation and stability of atmosphere and ocean. It includes changes to the jet stream, polar vortex, atmospheric planetary waves or to the Atlantic meridional overturning circulation.

Obtaining robust conclusions about changes in weather extremes requires long time series, given that extreme events are by definition rare events and are not easy to model. Nevertheless, the signal of climate change has now clearly emerged from the noise for many types of extremes. Disentangling the dynamic mechanisms is harder again and represents a current frontline of research. Driving forces behind dynamic changes are often regionally diverse temperature changes, such as Arctic amplification, enhanced land warming and sea surface temperature anomalies. Many facets of the dynamic mechanisms are still being debated in the scientific literature. Even if not everything is fully understood, researchers and journalists should not be shy to use every opportunity to educate the public about the fact that human-caused global warming is making weather extremes worse, already causing serious harm to many millions of people.

Even once global warming is stopped, we will see unprecedented extremes for a long time to come. Just think of a former once-in-5000 year event which at 1.5 °C warming may have become a once-in-50 year event. Thus, it will take many decades until we have seen all the possible extreme events a 1.5 °C warmer world has in store for us.

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