Reporting extreme weather and climate change

A guide for journalists

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world weather attribution

The authors would like to thank Wolfgang Blau and Rose Andreatta for their useful comments and suggestions.

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Foreword

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Sarah Sands is a British journalist. She has edited two newspapers and BBC Radio 4's Today programme. She is also a trustee of Index on Censorship and runs the annual Braemar Science Summit.

The British have always liked to turn the conversation to the weather as a way of avoiding contentious subjects. Unfortunately, by the time I joined the BBC Today programme in 2017, a show reaching some seven million listeners every week, even the weather — particularly the weather — was freighted with political overtones.

There were complaints if presenters mentioned that it was a sunny day. Sunny where, exactly? Not here in Newcastle, it isn't. Were we being London centric? If, to use a phrase that was to become popular with the government, we were to "level up" the country, then all regions must feel they had a stake in the weather. We needed multiple geographical perspectives. For a while, Sarah Smith, broadcasting from Glasgow, extended our meteorological reach by looking out of the studio window to announce whether it was raining.

My editorship of the programme coincided with a fractious period in British politics when the BBC's impartiality came under scrutiny. Why, critics asked, did we allow dissenting voices to speak on issues that were settled. Surely we should come down clearly on one side of those matters where there was no longer room for rational dispute.

Several took to quoting an old saw about journalism: "If one person says it is raining and another says that the sun is shining, it is your job to look out of the window and tell us which it is." It was a superficially attractive maxim with no practical application. Those who supported the UK's departure from the EU said it was so obviously a triumph that we should say so. Those who had wanted to remain said it was so clearly a disaster that we should report that. The problem was we were dealing with forecasts rather than things proved, so it was not so straightforward. People staring out of the same window were seeing vastly different weather.

Moving from metaphorical storms to real ones, we have seen similar arguments used again in the UK. There is now widespread acceptance of the science of climate change but even the well intentioned can be hazy about causes of extreme weather. The Today programme did a terrible job when we invited the former UK chancellor Nigel Lawson to discuss green subsidies. He adroitly moved the subject on to one of his pet themes, challenging the view that there had been an increase in extreme weather.

I wish we had had this guide for journalists to help us mount a more effective challenge to his claim. It begins by explaining that extreme weather events are becoming "more frequent and stronger in many parts of the world" but follows that with a very important point: "Crucially though, not all events are becoming more likely and changes are uneven across the world." There is no blanket explanation for extreme weather, although human caused global warming is a major underlying factor.

Happily, our data is getting better. We have increasingly scientific guides to reporting the real weather. This is important for accuracy in journalism. The next time the contentious commentator rolls his eyes and questions global warming after a snowfall in November, we can produce weather event attribution data to explain more precisely the cause and effect.

The first extreme event attribution study, using models, was published in 2004 after a heatwave in western Europe in the summer of 2003. Since then, attribution studies have been used throughout the world, although the global north has been documented more fully than the global south, an indictment of our tendency to overlook the unjust fact that climate change most affects the areas that have contributed the least emissions. The studies have given us significant insight into those horsemen of the climate apocalypse: heatwaves, floods, cyclones and wildfires. Where the trends in frequency are unproven or causes are multiple, the studies will say so.

In this way we are able to move from anecdote and conjecture, from superstition and wishful thinking, to science. We have evidence and we have facts. They are a secure foundation for news.

Introduction

Extreme weather events, such as heatwaves, heavy rainfall, storms and droughts, are becoming more frequent and stronger in many parts of the world as a result of human-caused climate change. However, not all events are becoming more likely, and changes are uneven across the world. These events often have widespread impacts on society, including the loss of crops and farmland, destruction of property, severe economic disruption and loss of life. Following an extreme event with severe impacts, a great deal of public interest is generated in its causes. Increasingly, the dominant question is: "Was this event caused by climate change?"

This guide is intended to help journalists navigate this question. First, it introduces the science of 'extreme event attribution' — the method of attributing (or not) the degree to which the weather event was influenced by climate change. Second, it lays out the statements that can reliably be made about some of the extreme weather types of greatest public interest, even when no specific scientific study is being performed. This is based on current state-of-the-art knowledge using studies of recent extreme events and the latest IPCC report. Further down, you will find an easy-to-read checklist for each type of extreme weather event.

There are three common mistakes made by news organisations when covering extreme weather events: ignoring climate change as a cause of the event, attributing the event to climate change without providing any evidence for that claim, and attributing an extreme weather event to climate change as the sole cause.

This happens partly because the question of whether climate change caused an event, while seemingly reasonable, is poorly posed. For instance, if a heavy smoker develops lung cancer, we would not say the cigarettes caused the cancer — but we might say the damage caused by the cigarettes made it more likely. In the same way, climate change cannot cause an event (in a binary use of the term 'cause') because all weather events have multiple causes, which includes chance due to the chaotic nature of day-to-day weather. But climate change can affect how likely and how intense an event was. And it can therefore affect how much impact a specific event had on people, property and nature. Journalists tasked with fulfilling the public interest in the wake of a disaster need to know how climate change affected the individual weather event. Extreme event attribution is a way that scientists can provide an answer.

Until recently, scientists largely avoided connecting any individual event with climate change, instead pointing towards the trend and saying that an event might reflect the sort of thing we can expect to see more of in the future. However, climate change is already having a profound influence on the weather we are experiencing, and has done so for decades. The science is finally becoming commensurate with this fact. In recent years, methods have been developed that enable scientists to work out the link between global climate change and an individual extreme weather event, calculating how much more or less likely, and how much more or less intense, an event has become because of global warming.

The answer varies from event to event, based on the type of weather, the location, time of year, and how severe, widespread and long it is. Not all extreme weather events are made more common and worse by climate change. Some may be decreased in chance by climate change, or may not be changed much. Journalists are therefore justified in being wary about making a connection that may not exist.

The aim of this guide is to help journalists to accurately report extreme weather events in the context of a warming planet: how can you best inform your audiences about the effects of climate change on the extreme events we are increasingly experiencing, without overstating (or, indeed, understating) the link?

Event attribution studies

An overview

The idea for attributing individual weather events came from a climate scientist whose house was in the process of being flooded. As he watched the waters rise, he began to contemplate the question of liability — who was to blame for the local-scale impacts of global-scale climate change? And was it possible to make this connection in a rigorous scientific way?

Event attribution studies calculate if, and the degree to which, a specific extreme event was made more (or less) likely and/or intense because of climate change.

The first extreme event attribution study was published in 2004, relating to a heatwave the previous year. The summer of 2003 was exceptionally hot in western Europe, an unprecedented extended heatwave in which 70,000 people died. Following this regionwide catastrophe, researchers used climate models to work out the role that climate change played.

They took the following steps:

- **First**, they simulated the modern climate — warmed by human activities — thousands of times. In simple terms, this means running climate model simulations again and again with the same conditions, essentially producing thousands of years of weather in the current climate. This is useful for studying extreme weather because it is rare by definition. Within these simulations, they counted the number of times that a heatwave as extreme as the 2003 event occurred. They found that it was a very rare occurrence, even in a warmed world.

- **Second**, they simulated the climate as it would be without any emissions from humans, including greenhouse gases and aerosols, effectively removing the human-caused climate change. It is clearly known how much greenhouse gas is in the atmosphere due to the burning of fossil fuels, so this can be done relatively straightforwardly. Then they counted the number of times such an extreme heatwave occurred. It was far rarer again. In fact, so rare that the event would have been almost impossible without human influence.

- **Finally,** they compared the numbers with and without global warming and concluded that the effect of human-caused climate change had made events like the European summer twice as likely, at the very minimum, and probably far more likely.

Since 2004, attribution studies have been performed for different weather events all over the world by researchers from many different countries — though the balance, of both studies and researchers, is heavily tipped towards the global north. Nonetheless, there is now a well established method that has grown beyond the three steps described above, documented here, for attributing many types of extreme weather event.

In the first instance, scientists define the extreme event. This is not trivial, because the same event — say a heatwave over the UK — might be described in several ways, such as three days over 30°C in London, or ten days over 25°C across England and Wales. This choice affects the results of the attribution study. The modern approach is to use several definitions and calculate results for each. This gives scientists an idea of how event definition affects the results, and enables them to tailor the study towards an aspect of the event that is most linked to the impacts. In the case above, the London-specific heatwave may have been more impactful despite being over a smaller area, because it was far more severe.

Current attribution analysis now consists of three separate but related methods. The steps listed above describe one part of the modern methodology: simulating and comparing the modern and pre-industrial climates with climate models. Lots of different climate models are used to ensure that The second part uses a method that incorporates observations of weather data from the present and the past to

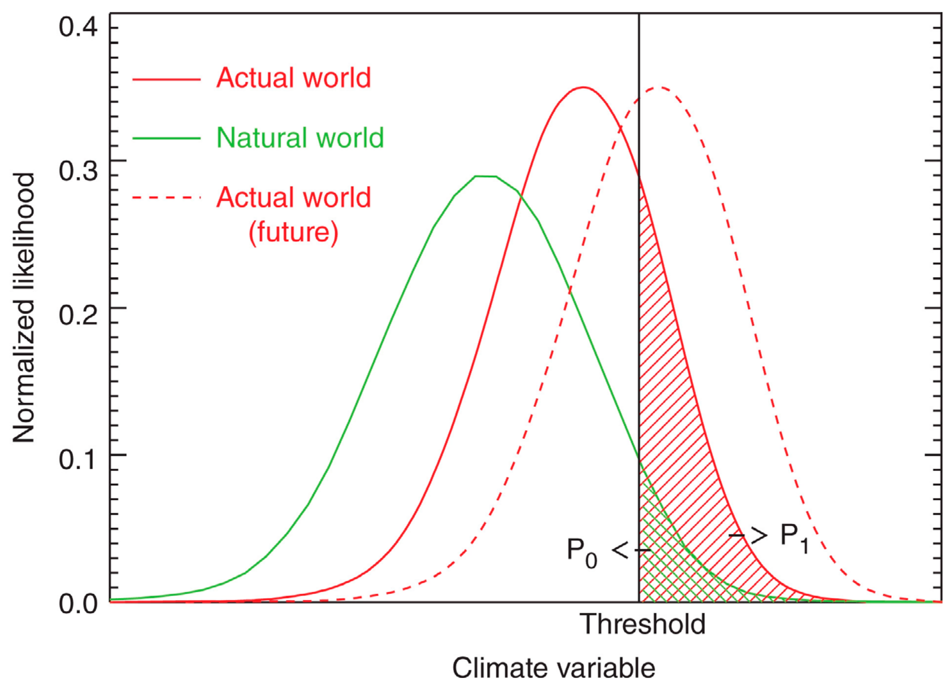

Figure 1 | Extreme event attribution in practice, from Stott et al., 2016. The two curves represent a climate variable, such as daily temperature. Average temperatures are the most likely (the peak of the curve), while extreme temperatures (hot and cold, at the edges) are the least likely. The green curve represents how likely those temperatures were in the pre-industrial world that was not warmed by human influence, red is the modern world. The threshold line is what we select when an extreme event (in this example a very hot day) occurs. Then, the relative size of the shaded areas shows how much more likely an event has become in the modern world. The dashed line shows how weather may change again in the future — in this case suggesting that the very hot day in the current climate could become a relatively cool day in the future climate.

see how the probability of similar events have changed. The final part uses climate models in the same way as observations. Rather than simulating the world with and without human influence, it simulates the climate from a historical date — say 1900 — to the modern day, with slowly rising human emissions. This enables scientists to detect trends in the extreme as well as calculating an overall probability change. Using several attribution methods, as well as different climate models, to assess the influence of climate change increases the reliability of the results.

The results of these studies allow scientists to make statements about weather events in the form of: “This event was made at least twice as likely by human-caused climate change” or “This heatwave was made 3 degrees hotter than it would have been in a world without global warming.” We may also be able to say that an event was effectively impossible without climate change, as such an event has no historical precedent and is not simulated in models without climate change.

A database of the results of the event attribution studies that have been conducted on extreme events worldwide — more than 400 to date — is published at Carbon Brief. Since 2014, an initiative led by a pan-European collaboration of attribution scientists, World Weather Attribution, has performed a number of rapid attribution studies. They aim to produce a result about the role of climate change as quickly as possible — in some cases even as the event is still unfolding. Due to the short timescale involved in this work, they publish the results ahead of peer review, but using methods that have themselves undergone peer review.

More recently, attribution studies have seen uptake by a variety of users. For example, as evidence in landmark climate litigation cases, such as Juliana vs United States, Pabai Pabai and Guy Paul Kabai vs Commonwealth of Australia, and Lluiya vs RWE, and a claim against Jair Bolsonaro at the International Criminal Court. Utilising attribution effectively in legal cases is a rapidly developing area of research. Further, research into attribution as a climate change communication tool suggests that “it shows promise […] because of its ability to connect novel, attention-grabbing, and event-specific scientific information to personal experiences and observations of extreme events.”

Event attribution studies

Examples

Flooding in Bangladesh

August 2017

- **The event**: In August 2017, Bangladesh experienced heavy rainfall, with further water flows from upstream in India joining the large river basins. The Brahmaputra river basin collected most of this water and burst its banks, causing record inundation levels and widespread flooding, particularly in the north of the country. The floods affected the homes and livelihoods of nearly seven million people.
- **The link to climate change**: The attribution study undertaken for this event was unable to conclude whether the extreme rainfall had become more intense due to climate change. This is partly because the rainfall records are short, and partly because sulphate aerosols around South Asia cause a local cooling effect, thus partially offsetting global warming. However, in the future, at 2°C of global warming, extreme rainfall events like this will become about 70% more likely.

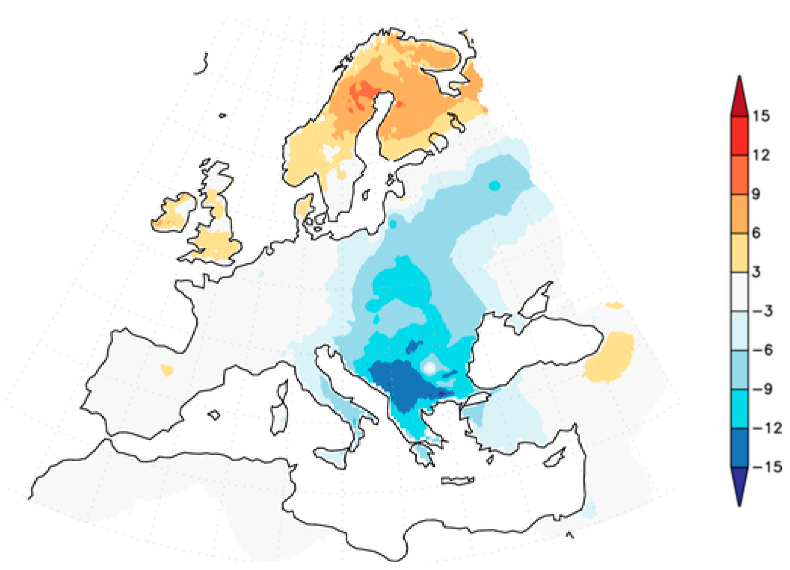

Figure 2 | Deviation from normal of the daily mean temperature over five days from January 7-11, 2017 in Europe. Source: World Weather Attribution (accessed 27/10/2021)

Extreme cold in southeast Europe January 2017 | Figure 2

- **The event**: In January 2017, a high-pressure system brought extreme cold temperatures and snow to Italy, the Balkans and Turkey. Affected areas ranged from 5-12°C below the average for that time of year and the extreme conditions caused school closures, road accidents and cancelled flights.
- **The link to climate change**: Such an event was not totally unprecedented, occurring roughly once per 35 years. Temperatures in the region are very variable, so it was not possible to put a number on the effect of global warming. However, it is unequivocal that a cold snap event like this one would have been colder before human-caused climate change.

Heatwave in western Europe

July 2019 | Figure 3

- **The event**: At the end of July 2019, temperatures soared across western Europe and Scandinavia for 3-4 days, breaking previous records from the summer of 2003. In the Netherlands and Belgium, temperatures reached 40°C for the first time.
- **The link to climate change**: In France and the Netherlands, an event at least as hot as this heatwave has become around 100 times more likely due to climate change. In Germany and the UK, it was about 10 times more likely. Across all affected regions, the heat experienced was roughly 1.5-3°C hotter than it would have been.

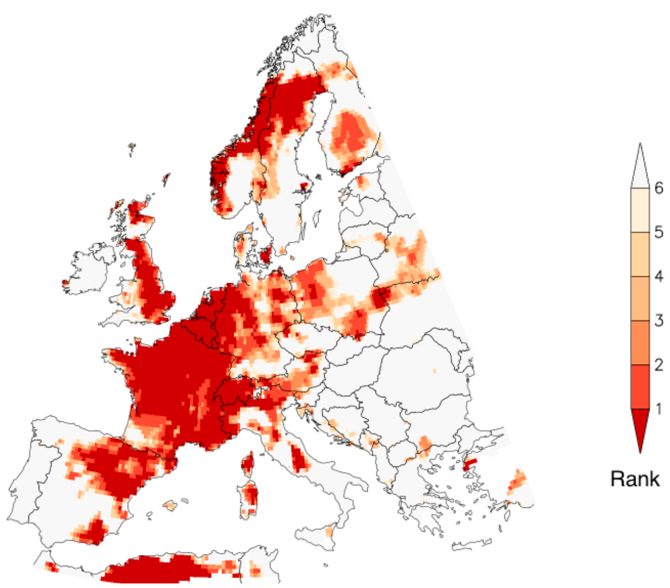

Figure 3 | Rank of annual maximum temperatures observed in Europe in 2019 compared to 1950 –2018. Source: World Weather Attribution (accessed 27/10/2021)

Drought in Cape Town

2015-2017 | Figure 4

- **The event**: From 2015 to 2017, the Western Cape province of South Africa suffered below average rainfall for each consecutive year. Reservoir stocks across the region became severely depleted. Cape Town, reliant upon water from these reservoirs, came within days of ‘Day Zero’ when the city pipes would have run dry. The water management system consisting of 14 dams and pipelines was designed to mitigate 1-in-50-year droughts. However, water management in the region is mired in accusations of politicking and corruption.

- **The link to climate change**: While an event such as this remains rare in the current climate — roughly once in a hundred years — the probability has been increased by climate change three-fold.

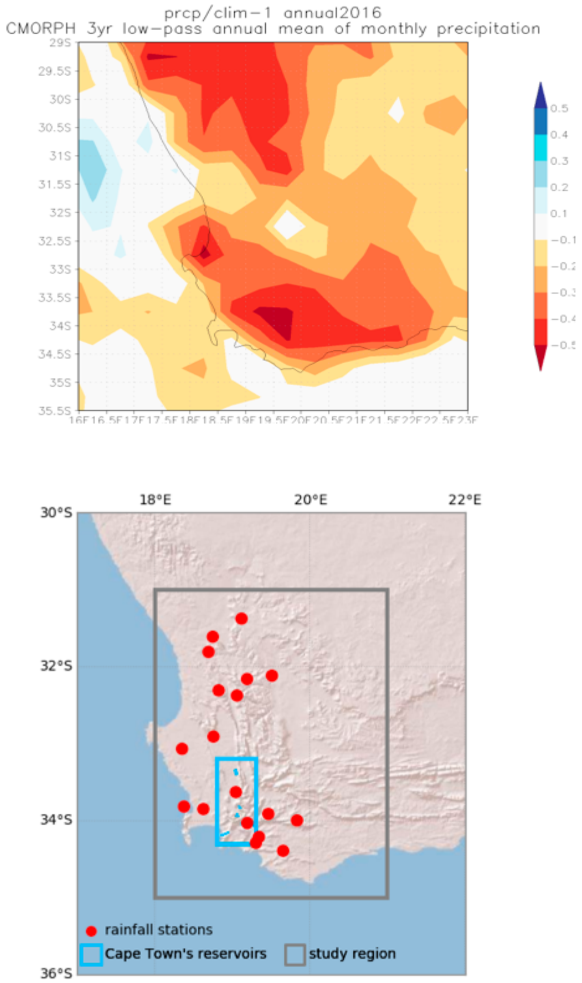

Figure 4 | (Top) Anomalies of the 2015–2017 precipitation in this region relative to 1998–2014. (Bottom) The study region (grey square) and the location of the reservoirs (blue square). Source: World Weather Attribution (accessed 03/11/2021)

How to report on extreme events when there is no attribution study

How to report on extreme events when there is no attribution study

Why there might not be an attribution study

While over 400 extreme weather events have been studied using attribution since the first study was published in 2004, this covers only a tiny fraction of the total number of extreme events that have caused impacts to society over that time.

Even rapid attribution studies require the attention of several researchers working flat out over several days, at the very minimum — it is not currently possible to do this for every major weather event. The World Weather Attribution service, for instance, is still run entirely voluntarily.

Which events are studied is also limited by the type of event. Some weather events have a more complicated relationship to global warming than others. Heatwaves are the simplest case. If there is more heat in the atmosphere, hot weather is more likely. Rainfall is also relatively straightforward, as more moisture tends to exist in warmer air. These events are therefore studied most frequently.

However, droughts, snowstorms, tropical storms and wildfires are more complicated. For instance, droughts often occur due to varied combinations of low rainfall, high temperatures and interactions between the atmosphere and the land surface. They also extend over longer time periods. This presents several challenges. In order to study these events effectively, the observations of past weather must be consistent and of a high quality, and climate models must be able to simulate these more complex phenomena.

What we can say anyway

It is still possible to report on the links between weather events and climate change, even in the absence of an attribution study. This comes from two lines of evidence. Firstly, because the field of attribution is approaching 20 years of age, for many new events attribution studies of previous similar events already exist. These can hint at the influence of climate change on the new events. Secondly, there is a relatively deep theoretical understanding of the important processes in many regions, and Working Group 1 of the Sixth Assessment report of the IPCC, published in 2021, provides an overview of the changes we're already seeing in the weather.

The remainder of this guide sets out what climate science allows us to say — and what it does not allow us to say — about the link between extreme events and climate change when there is no attribution study.

In some cases, the picture is clear and it is possible to make statements rapidly and with high confidence for any region across the world. In others, the level of confidence is lower for making certain statements in certain parts of the world, or for certain aspects of an extreme event. This nuance is important in order to provide accurate information to audiences.

Disasters are more than extreme weather

When reporting about extreme weather events it is important to highlight that, independent of climate change, natural hazards such as floods, droughts and heatwaves become disasters as a result of societal vulnerability. Who and what is in harm's way determines whether weather becomes a disaster and it is most often people's social and economic status that determines the nature of differential and disproportionate impacts.

Heatwaves

Every heatwave in the world is now made stronger and more likely to happen because of human-caused climate change

Global warming is measured as an average over the entire world, which is not what people experience. As the average temperature increases, the range of possible temperatures in any given place at a given time changes too. This means that, in every location, mildly warm days have become slightly more likely, and mildly cooler days slightly less likely. The temperatures that formerly constituted 'extreme' are now just unusual. And temperatures which were previously all but impossible are the new definition of extreme. Crucially, the change of likelihood happens fastest for the most extreme temperatures. This is clear from looking at Figure 1 (see page 7), in which the chance of a given temperature near the middle of the curves rises slightly, but those at the 'tail' of the distribution have a chance several times larger in a warmer world. An increase of 1°C in global temperature therefore makes heatwaves more than 1°C hotter.

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:

- A heatwave that would have occurred **once in 10 years** in the pre-industrial climate will now occur 2.8 times over ten years and be 1.2°C hotter. At 2°C of global warming, it will occur 5.6 times and be 2.6°C hotter.
- A heatwave that would have occurred **once in 50 years** in the pre-industrial climate will now occur 4.8 times over 50 years and be 1.2°C hotter. At 2°C of global warming, it will occur 13.9 times and be 2.7°C hotter.

These are globally averaged numbers for moderate heatwaves. But extreme heatwaves in a specific location can be as much as several hundred times more likely because of climate change. This is seen in attribution studies for individual events. The record-smashing heatwave of 2021 in Western Canada and the US would have been all but impossible without human-caused climate change, as would the Siberian heatwave of 2020. In 2015, deadly hot and humid events in northern India and Pakistan were each dramatically increased in likelihood by climate change. Other studies have shown similar results in China, Argentina, all parts of Europe and North America, North and Central Africa, Australasia and Southeast Asia. The linked examples are just a subset of the full literature. Attribution has consistently shown that the trends in heat are indeed manifesting as hotter, more common heatwaves, each of which may affect millions of people.

Limitations and points of note

The connection between global warming and more intense and frequent heatwaves is incredibly strong in every part of the world; there is little to be cautious of in making these statements. This holds true for destructive large-scale heatwaves declared by national meteorological services as well as local-scale warm days. Minor points of note are listed below:

- **'Causes' of the heatwave** — Heatwaves form due to the behaviour of the atmosphere. For example, enormous meanders of the jet streams, known as planetary waves, can lead to persistent extreme heat — particularly notable examples include Europe 2003 and Russia 2010, in which 70,000 and 55,000 people died, respectively. The exceptional heat in Siberia in winter and spring 2020 was caused in part by different atmospheric dynamics near the north pole — a very strong jet stream created clouded skies (and thus milder weather) and pulled warmer air northwards. Debate continues on the extent to which climate change is affecting these planetary waves and 'dynamic' effects. Some studies show effects, and these tend to be widely publicised studies, but others do not. The jury is still out. It may make heatwaves slightly more or less probable, or more or less severe in the future. However, any effect of this type is currently far smaller than the direct effect of global heating on extreme heatwaves.
- **Contradictory reports of heatwave attribution?** — In general, heatwaves over an entire region or large nation, such as western Europe or Brazil, or over a long timescale, such as an entire summer, have a stronger direct connection to global warming. For example, a heatwave over a summer in western Europe will likely display a greater global warming effect than a three-day heatwave in England. In the past, this has given rise to apparently contradictory reports in the media, when several studies each define an event differently. For instance, in 2018, the heatwave over the UK was reported as both "at least twice as likely" and "thirty times as likely" — the former was a three-day heatwave in Oxford, the latter was the average temperature for the entire summer over the whole of southeast England. Regardless, journalists should be confident of attributing any extreme heat to human-caused climate change.
- **Being overly cautious** — There is a danger of being journalistically inaccurate by being too cautious with respect to heat. More and more, heatwaves are smashing records, which is a direct consequence of a rapidly warming world. It has also become orders of magnitude more likely that there are heatwaves across many parts of the world at once, which can have much greater impacts on people, agriculture and food systems than an isolated event. Research shows that these 'compound events' were all but impossible without climate change.

Floods

Extreme rainfall is more common and more intense because of human-caused climate change across most of the world, specifically in Europe, most of Asia, central and eastern North America, and parts of South America, Africa and Australia. Elsewhere it is not yet possible to be confident about the changes. Flooding has likely become more frequent and severe in these locations as a result, though it is also affected by other human factors.

There are two ways in which climate change can affect heavy rainfall. First, a warmer atmosphere 'holds' more moisture. This is because water molecules move around more rapidly when warmer, and so are more likely to be in a gas phase — as vapour in the air — than a liquid phase. Scientists describe this simply using the 'Clausius-Clapeyron' relation, which tells us that in 1°C warmer air there is 7% more moisture — thus, there is more rainfall in a given downpour. This mostly accounts for why climate change has caused a global increase in extreme rain.

Second, climate change affects how often we see the conditions in which heavy rainfall occurs, such as storms and sudden outbursts, which in turn emerge from complex weather phenomena and certain atmospheric circulation patterns. This is more challenging to simulate in models, so attribution studies ensure that the models they use can accurately reflect these weather conditions. This aspect may be relatively less important, anyway: an attribution study in northern Europe found that human influence has so far had little effect on the atmospheric circulation that caused a severe rainfall event.

Flooding is the most frequently reported form of disaster associated with extreme weather (though flooding is not necessarily the most frequent to take place; other extreme events, such as heatwaves, however, are not always reported, particularly in the global south). There are many types of flooding, including river, groundwater, coastal and flash floods. All but coastal flooding are caused to some degree by heavy rainfall, in which climate change plays a significant role. We therefore touch briefly on coastal flooding in the 'Limitations' section, but otherwise we refer here to rainfall-based floods.

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-caused climate change. It has not strongly decreased in likelihood anywhere.

Globally, the IPCC reports state that, in a given place, what would once have been a one-in-ten-year rainfall event currently occurs 1.3 times every ten years and is 6.7% wetter. At 2°C of global warming, this will be 1.7 times per ten years and 14% wetter.

Attribution studies show stronger results in some areas but weaker changes elsewhere. For example, Storm Desmond led to severe flooding across northern England and southern Scotland in 2015. The rainfall total from this storm was made about 59% more likely by human-caused climate change. In contrast, greenhouse gases had a very small influence (if any) on the devastating flooding seen in Bangladesh in 2017.

Overall, from a combination of trends and attribution, there is confidence of increases in rainfall-based flooding due to climate change in Europe, most of Asia, central and eastern North America, northern Australia, northeast South America, and southern Africa. Meanwhile, changes are uncertain in wider parts of Africa, Australasia and South and Central America, where it is not possible to confidently make a statement.

Limitations and points of note

- **Uncertainty in some areas** — Any statement made about climate change and heavy rainfall is less certain than for heat and varies across the world. This is for several reasons: rainfall emerges from complex phenomena which are often difficult to simulate in climate models, and observations for rainfall are often sporadic historically and less consistent across the world, which makes it more challenging to observe trends. In practical terms, this means that we are only confident of attributing individual rainfall events to climate change in the regions where there is more confidence in the trend, and only then by acknowledging that there are wide uncertainties involved. Exceptions are northern Europe and central North America, where there is most confidence of attribution with comparably small scientific uncertainties.

- **Rainfall is not equal to flooding** — Our statements here are for heavy rainfall. For this to become flooding, other factors are relevant and these can include other human-related issues, such as how land is used (e.g. agriculture, deforestation, urbanisation), and the quality of water management and flood defences. For example, just moderate rainfall could cause severe flooding in a city with very poor drainage and a high population density. In every case of flooding, factors that relate to vulnerability and exposure of people are also highly relevant.

- **Coastal flooding** — This is driven by high winds and high tides, and therefore two key factors: the strength of storms and sea levels. Wind-driven increases in coastal flooding show little trend. However, there is an ever-increasing contribution of climate change to coastal flooding through sea level rise: every single coastal flood is higher than it would otherwise have been. This effect alone will cause once-in-a-century tides to occur once per year at many locations by 2100, with more locations affected under high-emissions scenarios.

- **Compound flooding** — A combination of high rain and intense storm surges can have catastrophic impacts on coastal cities and communities. Climate change is known to have increased the chances of these double-whammy events in North American cities and locations across northern Europe, and likely elsewhere.

Tropical cyclones
(Hurricanes, typhoons and cyclones)

The overall number of tropical cyclones per year has not changed globally, but climate change has increased the occurrence of the most intense and destructive storms. Extreme rainfall from tropical cyclones has increased substantially, in line with rainfall from other sources. Storm surges are higher due to climate change-driven sea level rise.

Climate change affects tropical cyclones in three main ways. Firstly, increased rainfall: tropical cyclones are the most extreme rainfall events on the planet. Just as with all extreme rainfall events, since the atmosphere is warmer, more moisture is present to fall as rain. This works on a percentage basis and — since rainfall totals are already so extreme for these events — the greatest absolute increases in rainfall amounts are seen in tropical cyclones.

Secondly, more heat in the oceans. Warm ocean water drives tropical cyclones, giving them their fuel. Climate change therefore creates the conditions in which more powerful storms can form, intensify rapidly and persist to reach land, while carrying more water. The amount of rainfall produced by Hurricane Harvey in Texas would have been all but impossible without the influence of record-warm ocean water in the Gulf of Mexico. This also means that tropical cyclones now occur further north and south, where sea surface temperature would not have been high enough to generate cyclones before climate change warmed the oceans. Scientists do not see nor expect more tropical cyclones overall, but they do expect to see more powerful ones, plus tropical cyclones in places that have not seen them before.

Thirdly, sea level rise. Storm surge is a major component of damage from tropical cyclones that, as seen under the 'Floods' section, is increased by climate change.

Past records of tropical cyclones are fairly limited, making it difficult to clearly identify trends. However, it is now clear that in all parts of the world in which they occur, major tropical cyclones (categories 3-5 on the Saffir-Simpson scale) have become more frequent, even though the absolute number of tropical cyclones has not changed. These cyclones are responsible for the overwhelming majority of damage from all tropical storms.

Attribution statements now exist for events in some of the major cyclone basins, showing how individual events are changing. In the North Atlantic, total rainfall from Hurricanes Katrina, Irma, Maria, Harvey, Dorian and Florence were all made more intense (by 4%, 6%, 9%, 15%, 7.5%, and 5%, respectively) by climate change. Collectively these storms caused over US$500 billion in damage. Meanwhile, in the North Pacific, Typhoon Morakot's rainfall was increased by 2.5-3.6%, and recent extreme cyclone seasons around Hawaii, in the eastern Pacific and in the Arabian sea, were made more likely by climate change.

Furthermore, individual storm surges are attributed to climate change. For example, the area flooded by Hurricane Sandy was made larger by climate change, affecting 71,000 more homes and causing an additional US$8.1 billion in damage. The devastating storm surge from Typhoon Haiyan was heightened by roughly 20% compared to a similar event without climate change.

Limitations and points of note

- **No trend in frequency** — While climate change is increasing overall tropical cyclone activity, as the most intense storms occur more often, it is not increasing the total number of cyclones.
- **Intensity cannot be attributed for a single cyclone** — The focus of attribution studies on tropical cyclones is amplified rainfall and storm surge. While there has been a broad increase in the most intense storms over time we cannot yet say whether an individual storm was intensified overall by climate change as only a single study to that effect using a single model has been conducted. However, there is growing evidence that warmer oceans do cause intensification that would not have occurred without climate change.
- **Rapid intensification** — Climate change is causing an increase in the number of cyclones that intensify rapidly, due to the presence of extremely warm ocean waters. A cyclone that intensifies rapidly is potentially far more dangerous than one that does so more gradually because it provides less warning for emergency preparations, especially if it intensifies immediately prior to landfall. Hurricanes Michael and Harvey are examples of recent rapidly intensifying cyclones.
- **Storm track poleward migration** — As ocean waters warm, it is reasonable to speculate that storms will shift further away from the equator. So far, we can only attribute a northward shift in cyclones in the western North Pacific, striking East and Southeast Asia, as a direct consequence of global warming. As a result, they may strike relatively unprepared locations without a historical reason to expect such an event.

Heavy snow

Every instance of extreme cold across the world has decreased in likelihood and intensity due to climate change. It is unclear how heavy snowfall events have changed in most places, but it may have increased in intensity in parts of East and North Asia, North America and Greenland.

The dramatic increase in warmth across the planet's land surface means that more precipitation is falling, but most of this increase is in the form of rain rather than snow. Exceptions to this rule may exist in parts of North America, North and East Asia and Greenland. These exceptions may exist because, where it remains cold enough to snow, the added warmth results in more moisture in the atmosphere that can fall as snow. In these places, snowfall is occurring over a shorter period of the year and less often, but sometimes with greater intensity.

There is low confidence on how heavy snowfall has changed so far because of climate change. This is a result of sparse observational records of heavy snowfall in many locations, and because these events are difficult to simulate in climate models.

Attribution studies have been undertaken for only a few recent heavy snowfall events, which have either found evidence of no link to climate change or been unable to state any conclusion with confidence. For example, climate change may have decreased the chance of early autumn snowfall in South Dakota as occurred in 2013, but this cannot be stated with scientific confidence. That same year, in the Spanish Pyrenees, extremely heavy snow accumulation was purely due to natural variability rather than any influence of climate change. And in 2016, climate change did not affect winter snowstorm Jonas, which struck the eastern mid-Atlantic US.

However, in high-latitude areas of the northern hemisphere, such as parts of East and North Asia, parts of North America and Greenland, heavy snowfall may have become more severe due to climate change since the 1950s. In North America, this is likely true for high-elevation areas during winter, but less so at other times of the year and in low-lying areas.

Limitations and points of note

- **The polar vortices** — There are two polar vortices in winter, one in the troposphere — the jet stream — and one in the stratosphere — the stratospheric polar vortex (SPV). When these vortices weaken, they are linked with extreme winter weather across Eurasia and North America: a weaker jet stream tends to meander, which can pull cold air from the Arctic, while a weak SPV is prone to collapse in a 'sudden stratospheric warming' event, which causes extremely cold air to spill south. This is linked to climate change because each vortex is a consequence of the temperature differences between the Arctic and areas further south. Since the Arctic is warming more rapidly than land further south, climate change may weaken each of these. However, so far, while there is some evidence of a weakening jet stream and SPV, it is not yet conclusive that this is outside the realm of natural climate variations.

- **No clear statement** — There is currently very limited possibility of attributing a given heavy snowfall event to climate change (either as an increase or decrease in probability). For a given severe snowfall event in North America, North and East Asia and Greenland, it is possible to speculate that there may be a connection, but with low confidence.

- **Snow (and extreme cold) in a warming world** — Weather and climate are not the same thing. The climate is the average of the weather over a long time — often several decades — and over a large area — typically a nation or region. By the old maxim, climate is what you expect, weather is what you get. Even in a world that on average is warming, the natural variability of the weather makes extreme cold and snow possible on any given day. Several attribution studies show that extreme cold events are becoming less likely in a warming world, but that does not make them impossible — just as living a healthy active lifestyle reduces one's chance of illness, but does not mean that it is impossible for a fitter and healthier person to fall ill.

Droughts

Droughts are becoming more common and more severe due to climate change only in some areas, including Europe, the Mediterranean, southern Africa, central and eastern Asia, southern Australia, and western North America. There is some evidence of increases in western and central Africa, northeast South America, and New Zealand.

Climate change affects drought in several ways, but two in particular. Firstly, through evaporation: as the atmosphere warms, more evaporation from the land occurs. Secondly, through rainfall: individual rainfall events are becoming heavier across the world, falling in shorter and more intense bursts. This is important because heavier rain is more likely to saturate the ground and run directly into rivers. In comparison, the same volume of moderate rain spread over a longer time is more likely to sustain soil moisture and groundwater reserves. Therefore, even if overall rainfall remains constant, drought can be exacerbated in some places. In some regions, overall rainfall is increasing, which offsets this to make drought generally less likely, although there is currently only sufficient evidence of this occurring in northern Australia. However, in some other regions, while the heaviest rainfall is becoming more frequent, the average rainfall is still dropping. This is where the clearest changes in drought are seen. Overall, the combination of more evaporation, more sporadic, heavier rainfall and less average rainfall makes drought more common in drought-prone regions and seasons.

Drought is complex. There are many forms of drought and there is no simple answer for the connection to climate change. Agricultural and ecological droughts are a lack of soil moisture, while meteorological, hydrological and groundwater droughts are a lack of rainfall, low river and groundwater levels, respectively. Agricultural and ecological droughts show the clearest signal of climate change, are detailed extensively in the most recent IPCC report, and are directly related to impacts on the food system and wider natural systems.

Regions with growing risks of these droughts include western North America, central and eastern Asia, the Mediterranean, parts of central, western and southern Africa, northeast South America, and southern Australia. To describe how severe a given drought is, scientists use units of standard deviation — a measure of how unusual the conditions are compared to normal — for a given place. This allows us to compare drying trends across areas with very different levels of annual rainfall and soil moisture. Across the drying regions listed above, the IPCC reports that, in a given place, what would once have been a one-in-ten-year drought currently occurs 1.7 times every ten years and is 0.3 standard deviations drier. At 2°C of global warming, this will be 2.4 times every ten years and 0.6 standard deviations drier.

Attribution studies of many recent droughts show stronger connections than the trends, but also examples of no connection. However, these are for all forms of drought, including agricultural and ecological. The results are therefore only partially comparable with the trends above highlighted in the IPCC. For example, from 2015-2017 a drought around Cape Town nearly resulted by a 'Day Zero' of no water — this was made 3-6 times more likely by climate change. Similarly, in China, the extreme dryness of May-June 2019 was increased in likelihood sixfold by climate change. And in the Netherlands, at least half of the observed increase in agricultural drought is due to climate change. Other droughts, in particular several in eastern Africa that had huge humanitarian impacts, were not made more likely by climate change.

Overall, from a combination of trends and event attribution statements, we can attribute an increase in drought severity and chance:

- **With high confidence** in the Mediterranean, southern Africa, central and eastern Asia, southern Australia, and western North America.
- **With low confidence** in western and central Africa, western and central Europe, northeast South America, and New Zealand.

Limitations and points of note

- **IPCC numbers apply only where drying is occurring** — The IPCC results for changes in drought rates and severity only apply to changes in drought conditions in parts of the world that are becoming drier overall. Thus, they should only be quoted relating to the areas listed above those results: western North America, central and eastern Asia, the Mediterranean, large parts of central, western and southern Africa, northeast South America, and southern Australia.
- **Drought types and uncertainty** — As explained, there are different types of drought. Each varies by region, and knowledge of each type also varies greatly. Reporting on any given drought therefore requires caution. In this guide, all types of drought are synthesised under a single banner in order to enhance usability. However, this means that we sacrifice our level of confidence from a scientific point of view, and it is important to communicate this. Here, it is possible to give high confidence only for the regions in which there are clear signals for multiple different forms of drought. There is low confidence for the regions in which there is only evidence for one type of drought. Everywhere else, we cannot clearly infer how a given drought has been affected by climate change. In East Africa, impactful droughts regularly occur, but records are too limited and climate models inadequate to make attribution statements.
- **Other factors** — Like flooding, drought is heavily reliant on how humans change the land and manage water. It is therefore important to report the other key contributing factors, such as how well people are adapting (or are able to adapt, in some places) to climate change. In particular, when discussing the impacts that such an event has had, it is fundamental to consider the vulnerability

and exposure of people — this could make the difference between a temporary hosepipe ban and a regionwide famine, regardless of the effect of climate change.

- **Concurrent drought and heat** — As with heat and flooding, the probability of multiple extremes occurring at the same time has risen rapidly — more so than individual hazards. Concurrent extreme heat and drought can result in more severe impacts than either event alone, including fires (see next section).

Fires

Fire weather is increasing in parts of all continents, with clear attributable increases in both probability and total burned area in southern Europe, northern Eurasia, the US and Australia, and some evidence in southern China.

'Fire weather' is a perfect storm combination of heat, drought and strong wind. This weather provides the highest likelihood that a fire will start, that there will be fuel for the fire, and that it will spread rapidly. Trends in fire activity are therefore closely related to trends in both drought and heat in combination. This makes fire risks rise rapidly in those areas in which both heat and drought risk are rising simultaneously. However, since heat is increasing across the planet, fire risk increases even if drought risk only remains constant.

Globally, the trend in fires shows a decrease in burned areas between 1998 and 2015 but this is largely due to human influences, such as changes in land use. The actual hazard of wildfires is still increasing in many parts of the world.

The length of seasons in which the weather creates the conditions for fire or 'fire weather' is increasing and the areas that experience such weather are expanding. As a result, in locations on every continent, there have been clear increases in the chance of fire weather due to climate change.

Attribution studies strongly reinforce the trends. In Australia, fires in both Queensland and New South Wales (NSW) were amplified by climate change — the conditions leading to the 2019/20 bushfires in NSW were made at least 30% more likely. Along the western coast of North America, from Alaska down to California, recent wildfires were made more likely and their burned area increased. From 1984-2015, over 4 million hectares of burned area in the western US is directly attributed to climate change. And in southern China, extreme wildfires of 2019 were made over seven times more likely by climate change.

Overall, we can confidently attribute a rise in the likelihood of fire weather in southern Europe, northern Eurasia, the US and Australia, with evidence of a signal also emerging in southern China. These conditions are likely to increase further across the land surface as global warming increases.

Limitations and points of note

- **Limited data** — So far, fire risks are only attributable to climate change in parts of the global north. For other regions, confidence is severely limited by data records of historical fires, observations of weather conditions and the ability of climate models to simulate fire weather. It is likely that many other parts of the world are seeing an increase in fire risk due to its strong link with rising heat extremes and drying trends. Unfortunately, we cannot quantify this increasing risk at the moment.

- **Management** — Controlled burning of forests to prevent the build-up of fuel has been a common practice for millennia in some areas, but not always consistently. A level of fire risk can be attributed to the level of planning and execution of controlled burning; if insufficient, risk is greatly amplified.

- **Ignition sources** — Human activities, such as starting casual fires, can be the trigger for forest-wide disasters. According to the US Forest Service, 85% of forest fires in the US are started by human negligence or intention. This has tripled the length of the wildfire season — an absolute increase of around three months — compared to the natural state in which ignition is caused by lightning. When reporting on the causes of impactful wildfires, it is important to report on these factors, as well as the level of exposure and vulnerability of the affected people and structures. Nonetheless, the fact that other factors are increasing wildfire risk does not minimise the role of climate change. Climate change has increased the wildfire season by roughly two weeks on average across the globe, mostly by enhancing the availability of fuel through heat and drying. However, comparing these numbers does not give the full picture: climate change also increases the intensity of the fire season in a way that a rise in human-caused ignitions does not. This is because it also affects the degree to which a given fire will take hold, spread and persist. This therefore operates in tandem with the rise in ignition by humans, making the fire season both longer and more intense.

Extreme events and climate change

One-page checklist!

The following is a very basic overview for each extreme weather type covered in this guide. Further information on each type is given in the guide, including the best current science, descriptions of how it works and important points to note to ensure accurate reporting.

Extreme weather	Key messages	Points of note and caution
Heatwave	Every heatwave in the world is now made stronger and more likely to happen because of human-caused climate change.	• Don't be too cautious — heatwaves are unilaterally linked to global warming.
Floods	Extreme rainfall is more common and more intense because of human-caused climate change across most of the world. Flooding has likely become more frequent and severe in some locations as a result, though it is also affected by other human factors.	• Flooding is linked to heavy rain but is also caused by human factors, such as water management and defences. • Coastal flooding is generally on the rise due to sea level rise, but is unrelated to rainfall-based floods.
Tropical cyclones	The overall number of tropical cyclones per year has not changed, but climate change has increased the occurrence of the most intense and destructive storms. Extreme rainfall from tropical cyclones has increased substantially, in line with rainfall from other sources. Storm surges are higher due to climate change-driven sea level rise.	• There is no increase of cyclones overall. • Individual cyclone intensities and wind speeds are not currently higher because of global warming
Heavy snow	Every instance of extreme cold across the world has decreased in likelihood and intensity due to climate change. It is unclear how heavy snowfall events have changed in most places, but they may have increased in intensity in parts of East and North Asia, North America and Greenland.	• There is very high confidence of fewer cold extremes, though these are still possible. • Snowfall changes are extremely uncertain. • Polar vortices changes are not yet clear.
Droughts	Droughts are becoming more common and more severe due to climate change in some areas only, including Europe, the Mediterranean, southern Africa, central and eastern Asia, southern Australia, and western North America - there is some evidence of increases in western and central Africa, northeast South America, and New Zealand.	• Droughts are very complex and diverse, making it difficult to acknowledge certainty. • There are many factors to consider other than climate change in the case of impactful droughts, particularly regarding water management.
Wildfires	Fire weather is increasing in parts of all continents, with clear attributable increases in both probability and total burned area in southern Europe, northern Eurasia, the US, and Australia, and some evidence in southern China.	• Data records of fires are very limited in some areas, making attribution very challenging. • Human activities, such as forest management and ignition sources, are also important factors.

Extreme events and climate change: one-page checklist

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