As extreme weather events from heatwaves to hurricanes increasingly dominate the headlines, scientists are getting better at linking them to climate change. **Isabella Kaminski** explores the growing field of attribution science.

IS CLIMATE CHANGE TO BLAME?

IN JULY, the world watched as record levels of rain fell on parts of Germany and Belgium, causing widespread flooding. More than 200 people died after rivers burst their banks, many homes and livelihoods were destroyed, and the long-term economic impacts are expected to run into many billions of euros.

As well as its devastation, the event was notable because local officials were quick to blame the extreme weather on global warming. During a visit to one of the worst-affected areas, the premier of North Rhine-Westphalia, Armin Laschet, said the region would be "faced with such events over and over, and that means we need to speed up climate-protection measures".

Just two months later his strong words were vindicated. A team of 39 scientists at international network World Weather Attribution produced a 'rapid attribution study' showing that climate change had increased the risk of the heavy rain by between 1.2 and 9 times and made the rain itself between 3 and 9 per cent stronger than it would otherwise have been.

Studies such as these are becoming more common because scientists can now calculate the extent to which a specific extreme weather event was made more likely or worse by climate change. It is part of a flourishing field called attribution science, which links meteorology, atmospheric physics, and statistics.

The first attribution study was published in *Nature* in 2004, a year after record-breaking temperatures across much of Europe caused more than 70,000 deaths.

The paper's authors said it was "an ill-posed question" whether the heatwave was caused by a modification of the external influences on climate – for example, increasing concentrations of greenhouse gases in the atmosphere – "because almost any such weather event might have occurred by chance in an unmodified climate".

Instead, inspired by the idea of one author, Professor Myles Allen, head of the climate dynamics group at the University of Oxford's atmospheric, oceanic and planetary physics department, they decided to take a probabilistic approach. Armed with the latest climate model called HadCM3 and the best set of real-life temperature records anywhere in the world, they sought to calculate how much more likely such an extreme heatwave had been made by human activity.

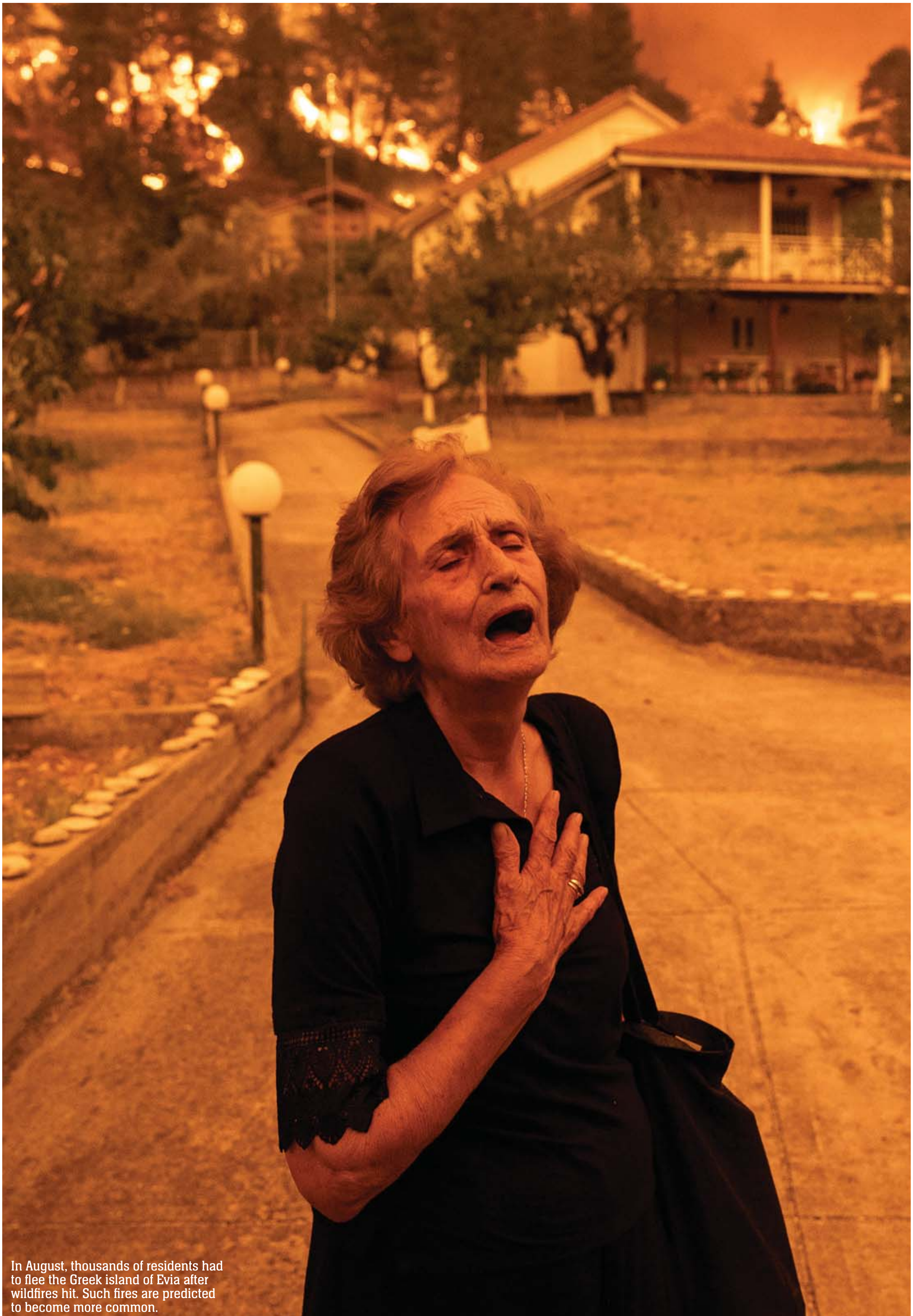
The authors ran the model from the middle of the 19th century – when coal, oil and gas began being burned in industrial quantities – until the present day, both with and without the additional greenhouse gases generated by those fossil fuels. This enabled them to compare human influence on the climate and see what potential variations in summer temperatures it might have caused in Europe.

They also ran the model from 1,000 years in the past with no greenhouse gas emissions. "That was important because we could see how [temperatures] vary from year to year to work out the one-in-1,000-year temperature extreme and see whether the model captures that," says lead author Professor Peter Stott, science fellow in climate attribution at the UK's Met Office.

It was a novel approach. "As a climate scientist I had to do some rapid learning on extreme value statistics," says Stott. The authors ultimately concluded that climate change had "at least doubled" the risk of such an extreme heatwave.

The paper opened the floodgates and hundreds of other attribution studies have since been published.

These showed, among other things, that >



In August, thousands of residents had to flee the Greek island of Evia after wildfires hit. Such fires are predicted to become more common.

Mud cracks at Thirlmere reservoir in the Lake District, UK. Climate change is expected to make long dry spells more intense in some areas due to lower regional rainfall, increased evaporation, and a reduction in snowpack during warm winters.

< climate change tripled the risk of extreme heat in a record-breaking hot period over north-west China in July 2015, boosted rainfall during Hurricane Harvey in Texas and Louisiana in 2017 by a factor of 3.5, and increased the chance of devastating bushfires in Australia in 2019 and 2020 by at least 30 per cent. They even found that the Siberian heatwave of 2020 would never have happened without climate change.

Not all studies find a connection between particular extreme events and global warming. One by the Dutch national weather institute KNMI could not conclude climate change was to blame for heavy summer rains that flooded central Europe in 2013.

Yet overall, the papers show a clear pattern. Earlier this year, experts producing the Intergovernmental Panel on Climate Change's (IPCC) sixth assessment report (AR6) analysed hundreds of attribution studies to conclude that anthropogenic greenhouse gas emissions have "led to an increased frequency and/or intensity of some weather and climate extremes".

Scientific credibility

Dr Friederike Otto, associate director of the Environmental Change Institute at the University of Oxford and co-lead of World Weather Attribution, says its inclusion in AR6 had made attribution science much more credible in the eyes of the public and the wider scientific community. "They are now seen as a really important part of the scientific literature," she says. "Not something new or special but something that you assess alongside observation studies and projections to understand what does climate change mean with respect to extreme events in every region of the world."

The field has matured considerably since Stott's original study.

For one thing, climate models have become much more advanced and there are more of them, developed in academic centres across the world from the US to China. While HadCM3 could simulate how the ocean and clouds interact and respond to rising temperatures and map rainfall patterns and temperatures over broad regions, modern models such as CMIP6 can simulate what happens in much smaller areas with greater accuracy by taking into account land surface, hydrology and ocean dynamics. "We can represent the particularities of weather much better now," says Stott.

All these models use common information such as observational temperature records but diverge in other ways. For example, they might represent clouds differently or the dynamics of how the ocean and atmosphere interact. "I think it's important that you have a diversity of models to represent those different choices," says Stott. "If the range of answers are all very definitively showing a significant effect due to human activities, then we can be very confident of it."

Power of citizen scientists

Computer power has also hugely grown, with supercomputers becoming increasingly accessible to crunch the vast amount of data needed to run complex long-term climate models.

Alternatively, climateprediction.net at the Oxford e-Research Centre relies on the processing power of thousands of citizen scientists to run computer simulations of many different possible versions of the climate system, each with very slight variations, to see what extreme events might happen under different scenarios. "It's like SETI@home – the search for extra-terrestrial life – in that we use idle time on their computers to run climate model simulations," says programme co-ordinator Sarah Sparrow.

Benefitting from cooperation between scientists in different countries and institutions, as well as well-established methodologies, individual studies can now be produced more quickly. In the case of the recent German floods, a team at World Weather Attribution published its results before they had been peer reviewed to capitalise on interest in the event before media attention drifted away.

"The evidence from those studies is that when they are repeated slowly you get the same answers, so they seem to be pretty robust," says Stott, who has been involved in World Weather Attribution. "But having said that, we've got to have careful protocols in place to check whether you can do it well."

However, as the field has grown, it has also led to a divergence of approaches. Most attribution studies, modelled on that pioneered by Stott, seek to put figures on the increased likelihood of an extreme event due to climate change or how much more intense it has become (or both), although they can do this with different models and methodologies that try to take account of the uncertainties involved.

Another way of considering extreme events, championed by Ted Shepherd, Grantham Professor of Climate Science at the University of Reading, is called the 'storyline' approach. Instead of looking at the likelihood that climate change caused a particular event, it takes a specific event and analyses how climate change affected it from a physical point of view.

Shepherd, whose background is in atmospheric dynamics, is sceptical that even the best models can accurately represent whether climate change influenced a particular weather event, because the system is so chaotic. "The nice thing about the probabilistic event is they give a 'yes or no' answer. Yet while I don't think that any of the claims that this was climate change are somehow wrong, the idea of a number is a false precision to me."

Robert Vautard, director of the Institut Pierre-Simon Laplace in France and a member of the World Weather Attribution group, came to attribution science with a background in statistics. He says these are open questions in the field, and there is always a degree of uncertainty, but remains confident in the numbers.

"We try to use several approaches, observations, models, so we try to cover all the possibilities and then average them. So quantitatively speaking it's more reliable."

Otto says most modern studies include an element of both approaches. "I think, and I think most of the rest of the community is very much with me on that, that it is useful to provide the numbers, but of course that's not the whole story."

Shepherd is also critical of the way in which attribution studies must define particular extreme events, describing these as too rigid since individual events unfold in very particular ways. It certainly is not a precise science. Sparrow says there are many ways to describe an extreme event, depending on the specific question you are trying to answer, such as whether the meteorology or atmospheric circulation were extreme or whether the event had serious impacts on humans – and deciding how to do it often requires expert judgment.

What all agree on is there is room for improvement.

For a start, not every country has datasets as good as those in Europe. Particularly Africa, which lacks a good set of observational records. Even in areas with better records, there are limits. For the

> ‘What makes an extreme event or disaster is, to a very large degree, driven by vulnerability and exposure... We need to find a way to communicate more of this within these studies.’
> **Dr Friederike Otto** World Weather Attribution

German floods, for example, there simply was not enough historical data about the specific affected region, so World Weather Attribution had to combine data from different river catchments in other areas.

Climate models also still struggle to accurately simulate details in such small areas. “The tension is always between the resolution of the model you can get, how fine a scale, how many physical processes you can include, and how many ensemble members you can get,” says Sparrow. “You can’t run these really big models on your standard laptop – you really need a supercomputer to run it and then it becomes very resource-hungry and financially hungry.”

“We can’t necessarily robustly do attribution studies for everything right now,” warns Stott. “So, we’ve got to be a bit careful that we can’t necessarily answer all the questions that people have.”

Climate change fatalities

However, attribution science does have plenty of real-world applications, from public communication of climate science and the actual impacts of global warming to the premiums offered by insurance companies.

Studies are also increasingly going beyond the likelihood that an event will happen and how extreme it is, to looking at its societal impacts. A 2016 study into the 2003 Paris heatwave, for example, concluded that most of its fatalities were a result of climate change.

They can also be used to examine economic impacts. Climateprediction.net recently held a workshop for early-career scientists in Brazil following devastating floods in Minas Gerais state in early 2020. “We were able to get access to their disaster database so we are really able to catalogue the impacts of this particular event, and then start to say how much we think of those impacts could be attributed to climate change. So, when you’re seeing financial losses or people displaced from their houses, you know how much worse that was because of climate change.”

Attribution science can also support the burgeoning legal field of climate litigation. A recent paper published in *Nature Climate Change* concludes that better use of the latest studies could improve the chances of lawsuits seeking compensation for climate-related losses, regulatory action, and emission cuts. It could also help lawyers decide when a case is weak and not worth pursuing.

Increasingly, attribution science is being used to calculate the risk of extreme events that have not yet happened.

The future becomes less certain because there are no observational records to check the models against, and there is uncertainty about what level of emissions the world will end up producing over the next few decades. But mathematically, says Vautard, the method is the same. “The numbers we give actually allow us to calculate risks for today. Once we have trust in the models, then we can apply the same statistics, and give numbers for the present as well as calculating future risk.”

These approaches could help identify critical areas at risk, like ‘breadbasket’ regions, which feed millions of people but are vulnerable to drought.

They can also help communities prepare for extreme weather events. A US city, for example, might benefit from knowing if there is an increased likelihood of a hurricane hitting it and how much more intense it might be – and allocate funds to help it plan and adapt. At present, those risk assessments tend to examine a particular country or region, but there is potential for them to go into more specific detail over smaller areas.

Otto would like to see more emphasis in future on the real risks an extreme event poses. “What makes an extreme event or disaster is, to a very large degree, driven by vulnerability and exposure and has nothing to do with the hazard. We need to find a way to communicate more of this within these attribution studies.”

“Attribution science in a sense has a practical outcome,” concludes Vautard, “which is to emphasise the need of urgent adaptation – not in the future, but today.” *

CHALLENGES

TRACING THE CAUSE OF EXTREME EVENTS

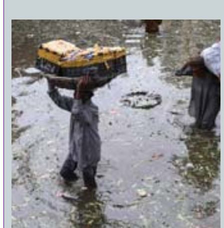
Climate change is already affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes, but some types of event are easier to connect than others.

Heatwaves

The easiest extreme weather event to connect with climate change because they are much more directly connected to the increase in global median temperatures. There have already been clear observed changes in hot extremes across the world, and a recent study found there would be much more intense heatwaves in the next few decades.

Wildfires

These are predicted to become more common as global temperatures rise and spring comes earlier, increasing the number of months in the year where fires are likely. They are also likely to be more intense as climate change induces periods of drought and stronger winds. However, wildfires also depend on a variety of other factors such as land use, so predicting them becomes more complicated.

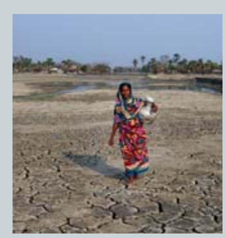


Rainfall

In general, climate change will lead to more extreme rainfall in some places. The hotter it is, the more water the atmosphere can hold, increasing the risk of heavy downpours. However, there is a lot of local variability, which makes it difficult to predict which areas will be affected. Flooding is even more challenging as it is affected by local river catchments and hydrological systems, soil type and land use.

Hurricanes

Hurricanes are tricky to analyse because they are so rare, variable, and depend on complex interactions between ocean and atmospheric conditions. We do know that the development of tropical cyclones is fuelled by rising ocean temperatures so climate change could affect intensity and path, although researchers disagree on whether they will become more frequent. One study suggested climate change would substantially increase the incidence of storms that intensify rapidly just before landfall, making them even more difficult to predict.



Drought

This is particularly difficult to define because it is the cumulation of a lack of rain over an extended period and affects wildlife and people at different points. However, climate change is expected to make these long dry spells more intense in some areas due to lower regional rainfall, increased evaporation, and a reduction in snowpack during warm winters.