Attributing Weather Extremes to 'Climate Change': a Review

For *Progress in Physical Geography*

Mike Hulme, Department of Geography, King's College London, UK

Original Submitted Version, 14 March 2014

Introduction

Humans and the societies in which they live have always sought to establish the causes of their daily weather. Many cultural beliefs and practices throughout human history have been inspired by this desire. And when weather 'misbehaves', or delivers meteorological devastation through windstorm, torrent, blizzard, drought or intense heat, the psychological need to attach blame to such events becomes overwhelming. Wolfgang Behringer's (2010) cultural history of climate offers one account of early-modern European blame narratives of deviant weather, which included the trickery of witches and the moral deviancy of human behaviour. And from the perspective of Pacific cultures, Simon Donner (2007; 2011) argues that the performance of weather has traditionally been understood as 'the domain of the gods'. The search for culpability for weather, especially adverse weather (e.g. Grattan & Brayshay, 1995), seems to be an enduring quest across all human cultures. This is especially true in the new and confusing world in which climate, in a discursive sense, seems to be changing daily (Rudiak-Gould, 2014).

Over the last 30 years scientific research has increasingly implicated human activities in contemporary regional- to global-scale climatic change. It is hardly surprising then that interest has risen in the possibility of detecting the fingerprint of human activities, not just on such broad-scale changes in climate, but on individual extreme weather (and short-term climate) events. Yet this possibility raises many difficult philosophical, epistemological and political questions. What does it mean for something to be caused by something else – especially in complex systems? Is the sought-after cause of extreme weather deterministic ('this caused that') or stochastic ('this made that more likely')? And in what ways are answers to the question of causation shaped by political or moral considerations rather than by scientific inquiry?

The difficulties involved in extreme weather event attribution were very well illustrated in the early weeks of 2014 in the UK, following a series of tempestuous and rain-laden winter storms. Extensive flooding ensued across southern England and claim and counter-claim, from scientists and politicians alike, filled broadcast and online media (Shukman, 2014). As stated by the Intergovernmental Panel on Climate Change (IPCC) in their 2012 report into extreme weather events and climate adaptation: "… it is very difficult to attribute an individual [weather] event to external forcing" (IPCC, 2012: 128).

My two previous reviews of climate change published in this journal were concerned with the nature and status of the IPCC (Hulme & Mahony, 2010) and with the possibility of global climate engineering through stratospheric aerosol injection (Hulme, 2012). In this third and final review I survey the nascent science of extreme weather event attribution. The article proceeds by examining the field in four stages: motivations for extreme weather attribution, methods of attribution, some example case studies and the politics of weather event attribution.

Motivations for Attribution

As many climate scientists can attest, following the latest meteorological extreme one of the most frequent questions asked by media journalists and other interested parties is: 'Was this weather event caused by climate change?' (Stott & Walton, 2013). I refer to this as the 'extreme weather blame' question. The question, though ubiquitous, is also ambiguous because it is not clear what exactly is meant by the causal agent 'climate change'. As explained by Fleming and Jankovic (2011), in recent decades the meaning of climate change in popular western discourse has changed from being a descriptive index of a change in climate (as in 'evidence that a climatic change has occurred') to becoming an independent causative agent (as in 'climate change caused this event to happen'). Rather than being a descriptive outcome of a chain of causal events affecting how weather is generated, climate change has been granted power to change worlds: political and social worlds as much as physical and ecological ones.

To be more precise then, what people mean when they ask the 'extreme weather blame' question is: 'Was this particular weather event caused by greenhouse gases emitted from human activities and/or by other human perturbations to the environment?' In other words, can this meteorological event be attributed to human agency as opposed to some other form of agency? - for example, purely natural processes, such as volcanic eruptions or ocean variability, or (for some) the actions of the gods or spirits (Donner 2007).

From a human psychological perspective the 'extreme weather blame' question seems a reasonable one to ask. Knowing the cause of some adversity or personal affliction is often the first step towards living with it or overcoming it; it helps reconcile an undesirable lived reality with an alternative reality we might desire (Jankovic, 2006). But why would climate scientists then be interested in developing an answer to the question? Why have climate scientists over the last ten years embarked upon research to provide an answer beyond the stock phrase 'no individual weather event can directly be attributed to greenhouse gas emissions'? There seem to be four possible motives.

The first is because the question piques the scientific mind; it acts as a spur to develop new rational understanding of physical processes and new analytic methods for studying them.

As stated by the World Climate Research Programme in 2013, attributing extreme weather events is one of the six grand challenges in climate science (cited in Peterson et al., 2013). Most climate system modelling has been driven by the desire to understand past and future large-scale changes in climate parameters and the relative influences of human and natural influences on such changes (Edwards, 2010). Extreme weather attribution asks a different set of questions however and requires climate system models to be reconfigured and deployed in different ways (Stone & Allen, 2005; Hegerl & Zwiers, 2011). The 'extreme weather blame' question therefore tests scientific understanding and the veracity of climate simulation modelling in new ways. And as models have gained in complexity, and especially as their animating computers have increased in computational power, so it has become possible to use them to answer reductive questions about the causes of specific extreme weather events.

A second argument, put forward by some, is that it is important to know whether or not specific instances of extreme weather are human-caused in order to improve the justification, planning and execution of climate adaptation. For example, Stott et al. (2013) in their overview paper of weather attribution science for the World Climate Research Programme argued that failure to accurately attribute extreme weather to human causes could lead to poor adaptation decisions (see also Allen, 2011; Stott & Walton, 2013, p.279). Conversely, Pall et al (2011) contend that the ability to quantify the contribution of human-based emissions to the risk of damaging weather events "could prove a useful tool for evidence-based climate change adaptation policy" (p.385). As another apologist for extreme weather attribution expressed it, such knowledge is simply part of 'evidence-based planning and informed decision-making' and hence self-evidently necessary (Washington, 2014). If climate adaptation is understood through the paradigm of optimisation then such claims seem logical. But as others have argued, there are alternative ways of thinking about adaptation practices (Dessai & Hulme, 2004; Dessai et al., 2009; Barnett & O'Neill, 2010; Weaver et al., 2013).

A third argument for pursuing an answer to the 'extreme weather blame' question is inspired by the possibility of pursuing legal liability for damages caused. An early example of this case was laid out by Myles Allen in 2003 in the context of flood damage caused by a meteorological extreme: "If insurance premiums rise as insurers factor in the increased risk of flooding due to climate change, and house prices consequently fall, some of this loss can straightforwardly be blamed on past greenhouse-gas emissions" (Allen, 2003; 891). This argument then drives the desire to calculate what fractional increase in probability of an extreme weather event can be attributed to a specific cause, in this case to greenhouse gas emissions (Allen et al., 2007). This motivation connects with wider arguments about litigation for climate change damages (Grossman, 2003; Masson, 2010). If specific loss and damage from extreme weather can be attributed to greenhouse gas emissions – even if expressed in terms of increased risk rather than deterministically – then lawyers might get interested (Adam, 2011). A counter-argument to this conjecture has been expressed by others; the diversity of attribution methods and the questionable credibility of climate models used for extreme weather attribution suggests to some that such evidence would unlikely hold sway in court cases (Stott & Walton, 2013, p.278; see also Anon, 2012).

The liability motivation for research into weather event attribution also bisects the new international political agenda of 'loss and damage' which has emerged in the last two years. Although the notion of loss and damage due to climate change has been on the political agenda for some years (Warner & Zakieldeen, 2012), it was first given a formal place in the ongoing UN Framework Convention on Climate Change (FCCC) negotiations at the 18th Conference of the Parties (COP18) held in Doha in 2012 and then carried forward at COP19 in Warsaw in 2013. The basic idea is to give recognition that loss and damage caused by climate change is legitimate ground for less developed countries to gain access to new international climate adaptation funds. Although the details of this arrangement are a long way from being agreed, including resolution of the definitional questions about what constitutes 'climate change' and what constitutes 'loss and damage' (Warner et al., 2012), there is an intersection here with the putative claim from climate scientists to be able to attribute specific extreme weather events to greenhouse gas emissions.

A final reason for scientists to be investing in this area of climate science – a reason stated explicitly less often than the ones above and yet one which underlies much of the public interest in the 'extreme weather blame' question - is frustration with and argument about the invisibility of climate change. Rudiak-Gould (2013) explains the problems involved in making climate change visible – and by implication 'real' – to assorted groups in society. He quotes the American Psychological Association's Taskforce on the Interface between Psychology and Climate Change:

> Because climate change is so hard to detect from personal experience, it makes sense to leave this task to climate scientists. This makes climate change a phenomenon where people have to rely on scientific models and expert judgment, and/or on reports in the mass media, and where their own personal experience does not provide a trustworthy way to confirm the reports (Swim et al. 2009, p.22).

If this is believed to be true – that only scientists can make climate change visible and real – then there is extra onus on scientists to answer the 'extreme weather blame' question as part of an effort to convince citizens of the reality of human-caused climate change. The issues involved here, including the complex human psychology of beliefs and perceptions, are nicely summarised by Doyle (2011), Kerr (2013) and Rudiak-Gould (2013).

So there are mixed and multiple motives at work in the community of scientists who have engaged in and promoted the nascent science of weather attribution. In the next section I turn to survey some of the reasoning and analytical methods underpinning weather extreme attribution.

Attribution Methods

There is a long history of detection and attribution (D&A) studies in the science of climate change and this field is well-reviewed by Allen et al. (2007), Stott et al. (2010), Hegerl and Zwiers (2011) and Bindoff and Stott (2013). Typically these studies seek, first, to detect a change in the spatio-temporal mean monthly or seasonal statistics of some climatic variable on either global, continental or regional scales and, then, to attribute such a change to a specific causal factor (e.g. volcanic eruption, elevated greenhouse gas concentration) with the aid of one or more climate simulation models. Such studies underpin the successive statements on climate change attribution that have been made by the IPCC in their 1st to 5th Assessment Reports between 1990 and 2013.

Attributing extreme weather events to human influences requires different approaches, however, of which four broad categories can be identified. The first and most general approach to attributing extreme weather phenomena to rising greenhouse gas concentrations is to use simple physical reasoning. For example, thermodynamic arguments would suggest more intense precipitation events are to be expected in an atmosphere which holds more water vapour (O'Gorman & Schneider, 2009); an upward shift in mean monthly temperature would lead to a disproportionate increase in the frequency of extreme hot daily temperatures (Trenberth, 2011). This approach has also been used recently to attribute colder winters and wetter summers in Europe to greenhouse gas forcing. It is reasoned that reduced Arctic summer sea-ice – brought about by a greenhouse-gas warmed atmosphere -- would lead to increased planetary-wave amplitudes and so to more frequent mid-latitude atmospheric blocking patterns. Such reasoning from first principles can only be approximate however; with respect to the Arctic sea-ice, for example, Screen and Simmonds (2013) show why caution should be exercised.

General physical reasoning can only lead to broad qualitative statements such as 'this extreme weather is consistent with' what is known about the human-enhanced greenhouse effect. Such statements offer neither deterministic nor stochastic answers and clearly underdetermine the 'weather blame question.' It has given rise to a number of analogies to try to communicate the non-deterministic nature of extreme event attribution. The three most widely used ones concern a loaded die (the chance of rolling a '6' has increased, but no single '6' can be attributed to the biased die), the baseball player on steroids (the number of home runs hit increases, but no single home run can be attributed to the steroids) and the speeding car-driver (the chance of an accident increases in dangerous conditions, but no specific accident can be attributed to the fast-driving) (Peterson et al., 2013: S64).

A second approach is to use classical statistical analysis of meteorological time series data to determine whether a particular weather (or climatic) extreme falls outside the range of what a 'normal' unperturbed climate might have delivered. Such analysis estimates the likelihood of a specific observed meteorological extreme occurring given no external human forcing. This was the approach used in the study of the 2003 European heatwave by Luterbacher et al. (2004) in which they concluded that “the late 20th- and early 21st-century [European] warmth very likely exceeds that of any time during at least the past 500 years” (p.1503) and that 2003 was by far the hottest summer in this period. The difficulties of such an approach are revealed in a later study of the 2003 heatwave by Charpentier (2011) and the subsequent commentary by Stott et al. (2011). All such extreme event analyses of meteorological time series are at best able to detect outliers, but can never be decisive about possible cause(s). A different time series approach therefore combines observational data with model simulations and seeks to determine whether trends in extreme weather predicted by climate models have been observed in meteorological statistics (e.g. Zwiers et al., 2011, for temperature extremes and Min et al., 2011, for precipitation extremes). This approach is able to attribute statistically a *trend* in extreme weather to human influence, but not a specific weather event. Again, the ‘weather blame question’ remains underdetermined.

To move beyond both qualitative physical reasoning and the limitations of observed trend analysis, a third method has been developed in recent years. Originally proposed by Allen (2003), and first applied to an extreme climatic event by Stott et al. (2004), the approach was outlined theoretically in Stone and Allan (2005). Taking inspiration from the field of epidemiology, this method seeks to establish the Fractional Attributable Risk (FAR) of an extreme weather (or short-term climate) event. It asks the counterfactual question, ‘How might the risk of a weather event be different in the presence of a specific causal agent in the climate system?’

The single observational record available to us, and which is analysed in the statistical methods described above, is inadequate for this task. The solution is to use multiple model-simulations of the climate system, first of all without the forcing agent(s) accused of ‘causing’ the weather event and then again with that external forcing introduced into the model. If P_0 is the probability of the specified weather extreme in the unforced (simulated) climate and P_1 the probability of the same event in the forced (simulated) climate, then FAR is simply $1-P_0/P_1$. FAR may vary between 0 and 1 and expresses the fraction of a weather risk (e.g. a rainfall intensity above a given threshold) that can be attributed to a specified influence. The credibility of this method of weather attribution can be no greater than the overall credibility of the climate model(s) used – and may be less, depending on the ability of the model in question to simulate accurately the precise weather event under consideration at a given scale (e.g. a heatwave in continental Europe, a rain event in northern Thailand) (see Christidis et al., 2013a).

A fourth, more philosophical, approach to weather event attribution should also be mentioned. This is the argument that since human influences on the climate system as a whole are now clearly established – through changing atmospheric composition, altered land surface characteristics, and so on - there can no longer be such a thing as a purely natural weather event. All weather -- whether it be a raging tempest or a still summer afternoon -- is now attributable to human influence, at least to some extent. Weather is the local and momentary expression of a complex system whose functioning *as a system* is now different to what it would otherwise have been had humans not been active. This was an argument made originally by Bill McKibbin in his book *The End of Nature* (McKibbin, 1990), where he lamented that a child born today would "never know a natural summer … Summer is becoming extinct, replaced by something else which will be called 'summer'" (p.55). This argument was also alluded to by Hulme (2000) in his commentary on the consequences of flooding in Mozambique in March of that year and resonates with the much larger literature about the hybrid nature of all of today's ecosystems (e.g. Marris, 2011).

This position is also adopted by the climate scientist Kevin Trenberth in some of his work. Trenberth's argument is that in weather and climate attribution studies, analytical techniques should be called on to refute the hull hypothesis of 'humans have influenced this weather extreme' rather than one of 'there is no human influence on this weather extreme' (Trenberth, 2011). As he says: "All storms develop in [a] changed environment. However, most of the time, the resulting weather is within the realm of previous experience. Yet all storms are different than they would have been … the question should not be is there a human component; but what is [the human component]?" (Trenberth, 2011: 929). The counter-argument to this stance from an analytical position is developed by Curry (2011) and Allen (2011), although they do not take on the philosophical dimension of the argument.

Some Example Cases of Extreme Weather Attribution

Table 1 shows a list of weather attribution studies drawn largely from the two collections published by Peterson et al. (2012; 2013). The first application of the FAR method for attributing a specific climatic extreme to human influence was conducted by Stott et al. (2004) in their study of the European summer heatwave of 2003. They concluded that "… human influence has at least doubled the risk of a heatwave exceeding this threshold magnitude" (p.610). This was consistent with results from the Luterbacher et al. (2004) and Schär et al. (2004) studies which used statistical methods alone. However in the case of other weather extremes, multiple attribution studies of the same event do not necessarily lead to convergent answers.

Dole et al. (2011) used a FAR methodology to investigate the exceptional heat over western Russia during July 2010 and concluded that it was 'due mainly' to natural internal atmospheric variability rather than to human-caused climate forcings. In contrast, Rahmstorf and Coumou (2011) using a statistical methodology concluded that there was a probability of only 20% that 'the 2010 July heat record would have occurred naturally', without the observed regional warming since 1980 which they largely attributed to anthropogenic greenhouse gas forcing. A third attribution study of this Russian heatwave then sought to understand the reason for these apparently contradictory findings (Otto et al. 2012). Also using a FAR methodology with large ensemble simulations, these authors concluded that *both* the above-mentioned studies were correct, but were answering different questions: Dole et al. (2011) whether the *magnitude* of the extreme heat could be attributed and Rahmstof and Coumou (2011) whether its *probability of occurrence* could be attributed. This demonstrates the importance when designing weather attribution studies of being clear about which precise question is being addressed and also being clear in any subsequent communication of the findings.

Date of Extreme	Location	Nature of Extreme	Source	Method
2000 autumn	UK	Floods	Pall et al. (2011)	FAR
2003 summer	Western Europe	Heatwave	Stott et al. (2004)	FAR
2010 summer	Western Russia	Heatwave	Dole et al. (2011) Rahmstorf & Coumou (2011) Christidis et al (2013a)	FAR Statistical FAR
2010 summer	Pakistan	Heavy rains	Christidis et al (2013a)	FAR
2010/11 winter	UK	Cold	Christidis & Stott (2012)	FAR
2011 December	New Zealand	48hr rainfall	Dean et al. (2013)	Models & observations
2011 summer	Texas	Drought	Rupp et al. (2012)	Modelling
2011 summer	Thailand	Heavy rains	Van Oldenborgh et al. (2012)	Statistical
2011/12 winter	Iberia	Drought	Trigo et al. (2013)	Modelling
2012 spring	East Africa	Drought	Funk et al. (2013)	FAR
2012 March	Eastern Australia	Heavy rains	Christidis et al. (2013b)	FAR
2012 October	USA	Coastal inundation	Sweet et al. (2013)	Statistical
2012 July	Southwest Japan	Heavy rains	Imada et al. (2013)	FAR
2013 summer	Australia	Heatwave	Lewis & Karoly (2013)	FAR

Table 1: Some examples of weather and short-term climate extremes to which different analytic weather attribution methods have been applied and results published.

The weather attribution studies listed in Table 1 adopt a number of different methods, but it will not always be possible for attribution studies to be applied to all or to any specific extreme weather event or short-term climate anomaly. For statistical methods to be effective long homogenous meteorological time series data are required; for some regions of the world these will not be available through instrumental measurements alone nor through combined series of instrumental and proxy measurements. For modelling attribution studies – whether combined modelling and observation studies or FAR studies based on multi-model ensembles – there are different conditions and constraints. Not only do the necessary model simulation experiments need to be conducted (constrained by the high computational demands they entail), but it needs to be demonstrated that the models used can adequately represent, at the appropriate spatial scale, the characteristics of the weather extreme under study.

In their FAR study of three high-impact events -- the 2009/10 cold winter in the UK, the heat wave in Moscow in July 2010 and the floods in Pakistan in July 2010 – Christidis et al. (2013a) concluded that no reliable attribution of the intense-rainfall events in Pakistan could be made since the model's simulation of intense rainfall in that region was inadequate. This was in contrast to the temperature extremes in the UK (winter cold) and in western Russian (summer heat) where the model performed better. It is likely that attribution of temperature-related extremes using FAR methods will always be more attainable than for other meteorological extremes such as rainfall and wind, which climate models generally find harder to simulate faithfully at the spatial scales involved. As discussed below, this limitation on which weather events and in which regions attribution studies can be conducted will place important constraints on any operational extreme weather attribution system.

Political Dimensions of Weather Attribution

The new science of extreme weather attribution is developing in the context of politically-charged debates about the causes and consequences of climate change and about appropriate responses. How weather event attribution science is framed, who funds the research, and for what reason, have unavoidable political dimensions. For example, whichever of the four motivations mentioned above is used to justify investment in this science - scientific curiousity, adaptation guidance, liability for damages, 'visualising' climate change – influences different potential research funders and also how scientific outcomes might subsequently be interpreted and used. As observed by *Nature's* editorial in 2012, "… designers of [such weather attribution] services must think very clearly about how others might want to use the knowledge that climate scientists produce" (Anon, 2012: 336).

Consider the case where weather attribution science is framed as a contribution to 'guiding adaptation decisions'. Some argue that there is an urgent need to develop this science to assist with decisions about the allocation of new international adaptation funds. For example, Myles Allen claims that "… because [adaptation] money is on the table, it is suddenly going to be in everyone's interest to be a victim of climate change […] so we need urgently to develop the science base to be able to distinguish genuine impacts of climate change from unfortunate consequences of bad weather" (Gillis, 2011). This is a view echoed by others: "Quantifying the impacts of anthropogenic climate change in this way is [...] important in guiding the allocation of resources available for adaptation" (Hoegh-Guldberg et al., 2011:72).

But Hulme et al. (2011) show why such ambitious claims are unlikely to be realised. Investment in climate adaptation, they claim, is most needed "… where vulnerability to meteorological hazard is high, not where meteorological hazards are most attributable to human influence" (p.765). Extreme weather attribution says nothing about how damages are attributable to meteorological hazard as opposed to exposure to risk; it says nothing about the complex political, social and economic structures which mediate physical hazards. And separating weather into two categories -- 'human-caused' weather and 'tough-luck' weather – raises practical and ethical concerns about any subsequent investment allocation guidelines which excluded the victims of 'tough-luck weather' from benefitting from adaptation funds.

Contrary to the claims of some weather attribution scientists, the loss and damage agenda of the UNFCCC, as it is currently emerging, makes no distinction between 'human-caused' and 'tough-luck' weather. "Loss and damage impacts fall along a continuum, ranging from 'events' associated with variability around current climatic norms (e.g., weather-related natural hazards) to [slow-onset] 'processes' associated with future anticipated changes in climatic norms" (Warner et al., 2012:21). Although definitions and protocols have not yet been formally ratified, it seems unlikely that there will be a role for the sort of forensic science being offered by extreme weather attribution science.

So consider the Thailand floods of 2011 which caused about $48 billion worth of damage. The weather attribution study of Van Oldenborgh et al. (2012) concluded that the amount of rain falling was not unusual and could not therefore be attributed to human agency. One can see why asking – and then answering - the 'extreme weather blame' question with regard to the heavy precursor rains which triggered the high river flows through Bangkok is of some interest. But it is unlikely that van Oldenborgh's conclusion would alter the rhetorical or practical use of such events as justification for funding improvements in flood defence or enhancing adaptive capacity. Policies to address loss and damage are far more likely to be influenced by the prospects for reducing vulnerability and increasing coping capacities than by whether or not the meteorological component of a disaster can be attributed to human agency (Klein & Möhner, 2011).

Then there is the obvious question about *which* extreme weather events should be investigated: the cases where human influence on meteorological extremes is easiest to detect or the cases where the political, economic or ethical consequences of extreme weather attribution are greatest (or perhaps where they are least!)? The list in Table is indicative of the range of weather/climate events and their locations that have currently been studied. But as Peterson et al. (2013) recognise, there are strong biases at work in case selection. These include researcher interest and subjective estimation of which weather extremes might be tractable: "We also see a natural [sic] bias towards scientists addressing local events … impacting themselves, their friends and neighbours" (p.S64).

The choice of which potential causal agent(s) are to be implicated in the attribution study also has political significance. Although nearly all cases investigated thus far have sought to isolate the effect on extreme weather of elevated carbon dioxide (or greenhouse gas) concentrations, the logic of weather event attribution opens up a wider range of possible causal agents. For example, if such work is motivated by the desire to support liability claims for damage caused, then distinguishing between FAR due to greenhouse gas emissions originating from fossil fuels versus those originating from land use change becomes important. Different political actors, institutional entities and social practices lie behind different emissions sources and so liability would be distributed differently. There is also the possibility of even finer causal attribution: distributing the fractional risk of an extreme and damaging weather event between fossil fuel, land use, black carbon and sulphate aerosol emissions is in principle possible using this methodology. The political significance of these choices is great and likely to be contested if such attribution claims reach parliaments or courts.

A final example of the political dimensions of this nascent science concerns the possibility of future ventures to intentional manipulate the global climate through solar engineering (Keith, 2013; Hulme, 2014). Should planetary-scale injection of sulphate aerosols into the stratosphere ever take place then weather attribution capabilities may well be drawn into adjudicating rival political claims about the cause of subsequent hazardous meteorological events. For example, interested parties might ask the question, 'Was this devastating typhoon caused by artificially injected aerosols, or by elevated concentrations of greenhouse gases or was it a naturally-occurring tropical storm?' As argued by Sarewitz (2004) more generally about the role of science in environmental controversies, deploying extreme weather attribution science in such circumstances might simply further aggravate the political and ethical conflicts that aerosol injection technology will have unleashed. The historical analogy of seeking definitive attribution of local rainfall to precursor cloud seeding interventions is not propitious (see Fleming, 2010).

What Future for Extreme Weather Attribution?

A series of international workshops organised by the informal Attribution of Climate-Related Events (ACE) group (Met Office, undated), starting in 2009, have already led to two coordinated 'annual reports' on weather attribution being published in the *Bulletin of the American Meteorological Society* (Peterson et al., 2012; 2013). There are plans for this to be an ongoing annual report series complementing the annual State of the Climate report from the World Meteorological Organisation (WMO). But as the science of extreme weather attribution moves from proof-of-concept to a more developmental stage, outlines for how an operational international extreme weather attribution service might be designed have already been proposed. In their review for the World Climate Research Programme, Stott et al. (2013) suggest how an international operational weather attribution service might be incorporated into the WMO's new Global Framework for Climate Services initiative (Hewitt et al., 2012). And in the UK, a system for configuring the Hadley Centre climate model to be used in more routine attribution of extreme weather and climate events has been demonstrated (Christidis et al., 2013a).

But questions remain (Schiermeier, 2011). Who would pay for such a real-time attribution service? The computational resource required for operational FAR analysis of extreme weather using multiple ensemble modelling methods is intimidating. And who exactly would be the stakeholders who would champion such a service? As reported by *Nature* following the 2012 ACE workshop, "none of the industry and government experts at the ACE workshop could think of any concrete example in which an attribution might inform business or political decision-making" (Anon, 2012: 336).

The idea of extreme weather attribution is of undoubted scientific interest. It can be used to drive climate model development and can be linked to improvement in, for example, seasonal forecasting capabilities (Stott et al., 2013). And it may also have some limited potential public value in sharpening pronouncements from scientists in answer to the 'extreme weather blame' question, avoiding overly glib or over-precise answers. But there remain outstanding political dangers and obstacles for extreme weather attribution if it is to be used for guiding climate adaptation investments, for servicing the putative loss and damage agenda of the UNFCCC or for underpinning legal claims for liability for damages caused by extreme weather. Climate adaptation is not about optimising society to withstand attributable physical hazards, but an exercise in hedging against a wide variety of unknown and poorly known future events. Any investments made under the UNFCCC's loss and damage agenda are more likely to be driven by the politics of vulnerability rather than by the sort of forensic science which weather attribution scientists are offering. And the courts are a long way from accepting FAR evidence as the basis for awarding damages to plaintiffs. Meteorological hazards are always mediated through complex political, social and economic structures; establishing liability for meteorological hazard falls a long way short of establishing liability for subsequent risk to society.

Acknowledgements

The author acknowledges the remarks of Martin Mahony who commented on an early draft of this review. The author declares no conflicting interests in the completing of this article.

References

Adam,D. (2011) Climate change in court *Nature Climate Change* 1(3), 127-130

Allen,M.R. (2003) Liability for climate change *Nature*, 421, 891-892

Allen,M.R. (2011) In defense of the traditional null hypothesis: remarks on the Trenberth and Curry WIREs opinion articles *WIREs Climate Change* 2(5), 767-766

Allen,M.R., Pall.P., Stone,D.A., Stott,P., Frame,D., Min,S-K., Nozawa,T. and Yukimoto,S. (2007) Scientific challenges in the attribution of harm to human influence on climate *University of Pennsylvania Law Review* 155(6), 1353-1400

Anon (2012) Extreme weather *Nature* 489, 335-336

Barnett,J. and O'Neill,S.J. (2010) Maladaptation *Global Environmental Change* 20, 211-213

Behringer,W. (2010) *A cultural history of climate* [translated from German] Polity Press, Cambridge, 295pp.

Bindoff,N.L. and Stott,P.A. (2013) Detection and attribution of climate change: from global to regional Chapter 10 (pp.867-952) in: *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535pp.

Charpentier,A. (2011) On the return period of the 2003 heatwave *Climatic Change* 109(3/4), 245-260

Christidis,N. and Stott,P.A. (2012) Lengthened odds of the cold UK winter of 2010/11 attributable to human influence *Bulletin of the American Meteorological Society* 93(7), 1060-1062

Christidis,N., Stott,P.A., Scaife,A.A., Arribas,A., Jones,G.S., Copsey,D., Knight,J.R. and Tennant,W.J. (2013a) A new HadGEM3-A-based system for attribution of weather- and climate-related extreme events *Journal of Climate* 26, 2756–2783

Christidis,N., Stott,P.A., Karoly,D.J. and Ciavarella,A. (2013b) An attribution study of the heavy rainfall over eastern Australia in march 2012 *Bulletin of the American Meteorological Society* 94(9), Suppl., S58-S61

Curry,J. (2011) Nullifying the climate null hypothesis *WIREs Climate Change* 2(6), 919-924

Dean,S.M., Rosier,S., Carey-Smith,T. and Stott,P.A. (2013) The role of climate change in the two-day extreme rainfall in Golden Bay, New Zealand, December 2011 *Bulletin of the American Meteorological Society* 94(9), Suppl., S61-S63

Dessai,S. and Hulme,M. (2004) Does climate adaptation policy need probabilities? *Climate Policy* 4, 107-128

Dessai,S., Hulme,M., Lempert,R. and Pielke,R. jr. (2009) Do we need better predictions to adapt to a changing climate? *EOS* 90(13), 111-112

Dole,R. et al. (2011) Was there a basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters* 38, L06702

Donner,S.D. (2007) Domain of the Gods: an editorial essay *Climatic Change* 85, 231-236

Donner,S.D. (2011) Making the climate a part of the human world *Bulletin of the American Meteorological Society* 92(10), 1297-1302

Doyle,J. (2011) *Mediating climate change* Ashgate Publishing Limited, Farnham, UK, 183pp.

Edwards,P.N. (2010) *A vast machine: computer models, climate data and the politics of global warming* MIT Press, Cambridge MA, 528pp.

Fleming,J.R. (2010) *Fixing the sky: the checkered history of weather and climate control* Columbia University Press, New York NY, 352pp.

Fleming,J.R. and Jankovic,V. (2011) Revisiting *Klima Osiris* 26(1), 1-6

Funk,C., Husak,G., Michaelsen,J., Shukla,S., Hoell,A., Lyon,B., Hoerling,M.P., Liebmann,B., Zhang,T., Verdin,J., Galu,G., Eilerts,G. and Rowland,J. (2013) Attribution of 2012 and 2003-12 rainfall deficits in eastern Kenya and southern Somalia *Bulletin of the American Meteorological Society* 94(9), Suppl., S45-S48

Gillis,J. (2011) *New York Times*, 16 February 2011, p. A4 http://www.nytimes.com/2011/02/17/science/earth/17extreme.html?_r=1 [accessed 6 March 2014]

Grattan,J. and Brayshay,M. (1995) An amazing and portentous summer: environmental and social responses in Britain to the 1783 eruption of an Iceland volcano *The Geographical Journal* 161 125–34

Grossman,D.A. (2003) Warming up to a not-so-radical idea: tort-based climate change litigation *Columbian Journal of Environmental Law* 28, 1-61

Hegerl,G. and Zwiers,F. (2011) Use of models in the detection and attribution of climate change *WIREs Climate Change* 2, 570-591

Hewitt,C., Mason,S. and Walland,D. (2012) The Global Framework for Climate Services *Nature Climate Change* 2(12), 831–832

Hoegh-Guldberg,O. et al. (2011) Difficult but not impossible *Nature Climate Change* 1, 72

Hulme,M. (2000) ‘There is no such thing as a purely natural weather event’ *The Guardian* newspaper, 15 March Reproduced as pp.45-46 in *Exploring climate change through science and in society: an anthology of Mike Hulme’s essays, interviews and speeches* Routledge, Abingdon, UK, 330pp.

Hulme,M. (2012) Climate change: Climate engineering through stratospheric aerosol injection *Progress in Physical Geography* 36(5), 694-705

Hulme,M. (2014) *Can science fix climate change? A case against climate engineering* Polity, Cambridge, UK

Hulme,M. and Mahony,M. (2010) Climate change: what do we know about the IPCC? *Progress in Physical Geography* 34(5), 705-718

Hulme,M., O'Neill,S.J. and Dessai,S. (2011) Is weather event attribution necessary for adaptation funding? *Science* 334, 764-765

Imada,Y., Watanabe,M., Mori,M., Kimoto,M. Shiogama,H. and Ishii,M. (2013) Contribution of atmospheric circulation change to the 2012 heavy rainfall in southwestern Japan *Bulletin of the American Meteorological Society* 94(9), Suppl., S52-S54

IPCC (2012) *Managing the risks of extreme events and disasters to advance climate change adaptation* Cambridge University Press, Cambridge, UK, 582pp.

Jankovic,V. (2006) Change in the weather *Bookforum* Feb/Mar, 39-40.

Keith,D. (2013) *A case for climate engineering* MIT Press, Cambridge MA, 194pp.

Kerr,R. (2013) In the hot seat *Science* 342, 688-689

Klein,R.J.T. and Möhner,A. (2011) The political dimension of vulnerability: implications for the Green Climate Fund *IDS Bulletin* 42, 15-22

Lewis,S.C. and Karoly,D.J. (2013) Anthropogenic contributions to Australia's record summer temperatures of 2013 *Geophysical Research Letters* 40(14), 3705-3709

Lott,F.C., Christidis,N. and Stott,P.A. (2013) Can the 2011 East African drought be attributed to human-induced climate change? *Geophysical Research Letters* 1-5

Luterbacher,J., Dietrich,D., Xoplaki,E., Grosjean,M. And Wanner,H. (2004) European seasonal and annual temperature variability, trends and extremes since 1500 *Science*, 303, 1499-1503

Marris,E. (2011) *Rumbunctious garden: saving nature in a post-wild world* Bloomsbury, London, 224pp.

Masson,J-F. (ed.) (2010) *Climate change litigation and law* Nova Science Publishers, Hauppauge NY, 151pp.

McKibbin,B, (1990) *The end of Nature* Viking Books, London, 212pp.

Met Office (undated) Attribution of climate-related events http://www.metoffice.gov.uk/research/climate/climate-monitoring/attribution/ace [accessed 7 March 2014]

Min,S-K., Zhang,X., Zwiers,F.W. and Hegerl,G.C. (2011) Human contribution to more intense precipitation extremes *Nature* 470, 378–381

O'Gorman,P.A. and Schneider,T. (2009) The physical basis for increases in precipitation extremes in simulations of 21st century climate change *Proceedings of the National Academy of Sciences* 106, 14773-14777

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 *Geophysical Research Letters* 39, L04702

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, 382-385

Peterson,T.C., Hoerling,M.P., Stott,P.A. and Herring,S.C. (eds.) (2013) Explaining extreme events of 2012 from a climate perspective *Bulletin of the American Meteorological Society* 94(9), Suppl., S1-S74

Peterson,T.C., Stott,P.A. and Herring,S. (eds.) (2012) Explaining extreme events of 2011 from a climate perspective *Bulletin of the American Meteorological Society* 93(7), 1041-1067

Rahmstorf,S. and Coumou,D. (2011) Increase of extreme events in a warming world *Proceedings of the National Academy of Sciences*, 108, 17,905-17,909

Rudiak-Gould (2014, press) Climate change and accusation: Global warming and local blame in a small island state *Current Anthropology*

Rudiak-Gould,P. (2013) 'We have seen it with our own eyes': why we disagree about climate change visibility *Weather, Climate & Society* 5(2), 120-132

Rupp,D.E., Mote,P.W., Massey,M., Rye,C.J., Jones,R. and Allen,M.R. (2012) Did human influence on climate make the 2011 Texas drought more probable? *Bulletin of the American Meteorological Society* 93(7), 1052-1054

Sarewitz,D. (2004) How science makes environmental controversies worse *Environmental Science and Policy* 7, 385-403

Schär,C, Vidale,P.L., Lüthi,D., Frei,C., Häberli,C., Liniger,M.A. and Appenzeller,C. (2004) The role of increasing temperature variability in European summer heat waves *Nature* 427, 332–336

Schiermeier,Q. (2011) Climate and weather: extreme measures *Nature* 477, 148-149

Screen,J.A. and Simmonds,I. (2013) Exploring links between Arctic amplification and mid-latitude weather *Geophysical Research Letters* 40(5), 959–964

Shukman,D. (2014) Barrage over climate change link to floods *BBC News On-line* http://www.bbc.co.uk/news/science-environment-26242253 [accessed 5 March 2014]

Stone,D.A. and Allen,M.R. (2005) The end-to-end attribution problem: from emissions to impacts *Climatic Change*, 71, 303-318

Stott,P.A. and Walton,P. (2013) Attribution of climate-related events: understanding stakeholder needs *Weather* 68(10), 274-279

Stott,P.A. et al. (2013) Attribution of weather and climate-related extreme events pp.307-337 in: *Climate science for serving society: research, modeling and prediction priorities* Hurrell,J.W. and Asrar,G.R. (eds.), Springer, Dordrecht, Germany, 484pp.

Stott,P.A., Stone,D.A. and Allen,M.R. (2004) Human contribution to the European heatwave of 2003 *Nature* 432, 61-614

Stott,P.A., Christidis,N. and Betts,R.A. (2011) Changing return periods of weather-related impacts: the attribution challenge *Climatic Change* 109(3/4), 263-268

Stott,P.A., Gillett,N.P., Hegerl,G.C., Karoly,D.J., Stone,D.A., Zhang,X. and Zwiers,F. (2010) Detection and attribution of climate change: a regional perspective *WIREs Climate Change* 1, 192–211

Sweet,W., Zervas,C., Gill,S. and Park,J. (2013) Hurricane Sandy inundation probabilities today and tomorrow *Bulletin of the American Meteorological Society* 94(9), Suppl., S17-S20

Swim,J., Clayton,S., Doherty,T., Gifford,R., Howard,G., Reser,J., Stern,P. and Weber,E.U. (2009) *Psychology and global climate change: addressing a multifaceted phenomenon and set of challenges* Report of APA Task Force on the Interface between Psychology and Global Climate Change, 108pp. [Available online at www.apa.org/science/about/publications/climate-change-booklet.pdf.]

Trenberth,K.E. (2011) Attribution of climate variations and trends to human influences and natural variability *WIREs Climate Change* 2(6), 925-930

Trigo,R.M., Anel,J.A., Barriopedro,D., Garcia-Herrara,R., Gimeno,L., Nieto,R., Castillo,R., Allen,M.R. and Massey,N. (2013) The record winter drought of 2011-12 in the Iberian peninsula *Bulletin of the American Meteorological Society* 94(9), Suppl., S41-S45

Van Oldenborgh,G-J., van Urk,A. and Allen,M. (2012) The absence of a role of climate change in the 2011 Thailand floods *Bulletin of the American Meteorological Society* 93(7), 1047-1049

Warner,K. and Zakieldeen,S.A. (2012) *Loss and damage due to climate change: an overview of the UNFCCC negotiations* European Capacity Building Initiative, Oxford, 12pp.

Warner,K., Van der Geest,K., Kreft,S., Huq,S., Harmeling,S., Kusters,K. and de Sherbinin,A. (2012) *Evidence from the front lines of climate change: loss and damage to communities despite coping and adaptation* United Nations University, Policy Report No. 9. http://unu.edu/publications/policy-briefs/evidence-from-the-frontlines-of-climate-change-loss-and-damage-to-communities-despite-coping-and-adaptation.html [accessed 28 February 2014]

Washington,R. (2014) 1852 or 2014? http://www.keble-oxford-geography.info/?p=1335 [accessed 28 February 2014]

Weaver,C.P., Lempert,R.J., Brown,C., Hall,J.A., Revell,D. and Sarewitz,D. (2013) Improving the contribution of climate model information to decision-making: the value and demands of robust decision frameworks *WIREs Climate Change* 4(1), 39-60

Zwiers,F., Zhang,X. and Feng,Y. (2011) Anthropogenic influence on long return period daily temperature extremes at regional scales *Journal of Climate* 24, 881-892