# Framing the question of attribution of extreme weather events

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**Understanding how the overall risks of extreme events are changing in a warming world requires both a thermodynamic perspective and an understanding of changes in the atmospheric circulation.**

Whenever an extreme weather or climate-related event occurs the extent to which human-induced climate change has played a role is routinely asked. Increasingly scientists are able to give robust quantitative answers to this question. In 2012, the Bulletin of the American Meteorological Society published the first annual special issue looking at how climate change may have affected the strength and likelihood of individual extreme events that took place during the previous year. This first issue contained just six papers [1]. Since then the science of event attribution has developed rapidly with an increasing number of research groups applying a wider range of methodologies (e.g., [2]), and the US National Academy of Sciences has recently completed a report into the issue, concluding "in many cases, it is now often possible to make and defend quantitative statements about the extent to which human-induced climate change (or another causal factor, such as a specific mode of natural variability) has influenced either the magnitude or the probability of occurrence of specific types of events or event classes."[3]

While the thermodynamic consequences of a warming world, namely an increased likelihood of more heat and high-precipitation extremes, are predictable (e.g. [4]) on average, in any specific location or circumstances, thermodynamic influences may be either amplified or counteracted by anthropogenically induced changes in circulation (e.g [5]; [6]; [7]) and or other local forcings [8]. As far as impacts are concerned, the mechanism whereby human influence on global climate is manifest in a particular weather event is immaterial, so to understand how the risks of extreme events are changing requires both a thermodynamic and a dynamic perspective. The emerging science of probabilistic event attribution provides tools needed to assess such risks at the spatial scales people care about.

**Multiple Approaches**

Overall, there is great strength in using different approaches to assess the role of anthropogenic climate change in extreme weather events as it allows estimates of the uncertainty in attribution statements beyond sampling uncertainty [9] thereby increasing confidence in the result. However, differences in how the attribution question is framed can lead to apparently contradictory answers to attribution questions that provide a challenge in communication, often reinforced by high media attention. An example where seemingly contradictory results are in fact complementary is provided by the studies of the Russian heat wave in 2010, where the magnitude of the event was mainly due to natural variability [10] while the likelihood of occurrence of an event of this magnitude had changed considerably due to anthropogenic drivers [11]. More subtle differences in analysing changes in the likelihood of occurrence can still lead to large discrepancies in results ([12]; [2]).

Other approaches to attribution have been suggested that allow improvements to our understanding of the event itself, but do not allow for an assessment of whether or how the risk of such an event has changed [13]. Such studies ask the question: conditional on the large-scale circulation patterns, what was the role of anthropogenic climate change in this event (e.g. [7])? Such studies allow for assessing whether climate change altered known relationships between large-scale drivers and local events. One such example [14] investigated whether anthropogenic climate change affected the relationship between ENSO and extreme rainfall in South-East Australia. While not analysing the overall change in risk of an event occurring, isolating specific drivers can still be invaluable in improving understanding and in turn our ability to simulate extreme events. It is however important for such analyses to communicate their conditional nature.

**Event Definition**

Apart from different ways of framing the attribution question, the second crucial step in extreme event attribution is the definition of the actual extreme event to analyse. Any definition involves an element of convention, but it is important for conventions to be consistent, transparent and above all relevant to the questions that stakeholders are asking. Every extreme weather event is ultimately caused by a unique combination of external drivers and internal chaotic variability. For those affected, however whether they are asking if human-induced climate change is in any sense "to blame" or making planning decisions in disaster recovery, the defining characteristic is the harm caused, not the details of the meteorological precursors. Suppose anthropogenic changes in atmospheric circulation patterns are reducing the overall risk of storms in a particular region such that, despite the thermodynamic impact of warming contributing to the intensity of individual storms, overall risk of pluvial flooding is declining. It would be confusing, to blame anthropogenic climate change, even partially, for an observed pluvial flood if the actual impact is to make such flood events in that region less likely to occur. Likewise, in rebuilding decisions, what matters is the overall impact on risk, not the role of individual drivers in the specific event.

Hence in order to assess whether and to what extent the risk of an individual event occurring has been altered due to changes in the external drivers, such as an increase in greenhouse gases in the atmosphere, the event needs to be defined in terms of a class of events that have similar or larger impacts. If only the observed event is studied, as suggested in [15] for example, it will by definition never happen again [16]. Adopting too narrow a definition of the event as the basis for an attribution study may therefore bias attribution studies, irrespective of the role of anthropogenic climate change in overall risk. It is perfectly possible that removing an anthropogenic warming signal may reduce the magnitude of an event in a simulation in which all other factors, including the initial conditions and large-scale flow, are held constant, even if the net impact of anthropogenic climate change is to reduce the probability of occurrence of similar events, even with a very restrictive definition of similarity. Indeed, this result is more likely with the most extreme weather events, which occur, almost by definition, because both natural and anthropogenic drivers work together to generate the event in question. If any single driver is removed, the result may well be to weaken the event, regardless of the impact of that driver on overall risk.

Following early simplified scenario approaches [17], Trenberth et al. [15] suggest framing the attribution question: “given the atmospheric circulation that brought about the event, how did climate change alter its impacts?” They do not intend assessing the absolute probability for the event to occur, but only investigate the change in severity of the event given that it occurred. Although undoubtedly helpful in understanding the factors behind and event and guiding research into improving predictability, it must be understood that this way of framing the attribution question is intrinsically biased towards an outcome that may not be relevant to either the assignation of blame nor planning decisions in disaster recovery.

Figure 1 illustrates this using a simple chaotic system in which a constant external forcing is added to the Lorenz ‘63 model following Palmer (2003) [18]. The forcing acts in the X-Y plane, and its overall impact is to reduce the probability of a “high-X” extreme event, as shown by the difference between the blue (no forcing) and red (forced) distributions on the X axis. If, however, the initial conditions are set to approximately one “Lorenz day” before a “high-X” event occurs, sufficiently close that the large-scale flow is unchanged, the impact of removing the forcing (blue versus red trajectories) is to reduce the magnitude of these individual “high-X” events. In this case, while it is true that the external forcing is acting to increase the magnitude of an individual “high-X” event in the immediate build-up to the event occurring, it would be misleading either to blame the forcing for the occurrence of a “high-X” event when the forcing has actually acted to make such an event less likely to occur, or to suggest we should prepared for more such events as the forcing increases. In a non-linear system, there will always be cases where the impact of the forcing conditioned on the initial conditions can be in the opposite direction to the unconditioned impact of the forcing.  Only a probabilistic approach guards against over- or under-confidence in attribution of events to human influence.

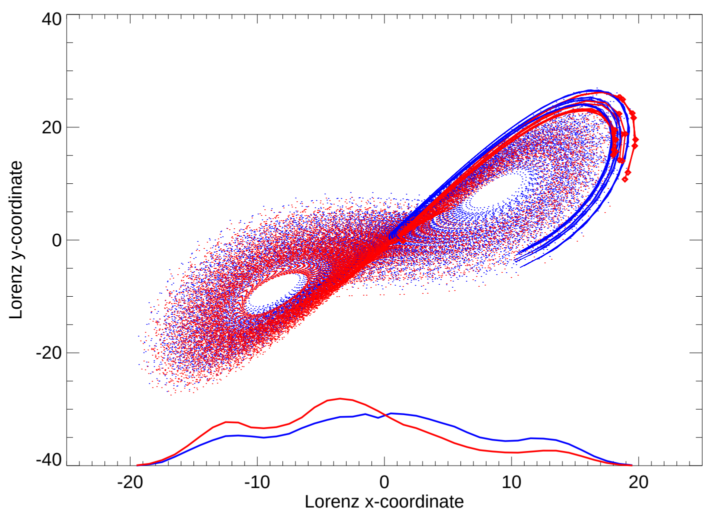


*Figure 1: Simple chaotic Lorenz 63 system with added forcing. The main figure shows the Lorenz-attractor of a Lorenz system with a forcing symbolising the current climate forcing in blue and, a weaker or natural forcing in red. The bottom of the figure shows the distribution of x for both forcings for the most extreme events with the y-axis giving the occurrence probability and the x-axis the strength of the event. The blue line is above the red line for all events with a positive x.*

**Framing attribution/ real world examples**

While the thermodynamic response of the climate system is often linear, the dynamic response can be highly non-linear and may be in the opposite direction to the thermodynamic response. Hence limiting attribution studies to the thermodynamic response alone as exemplified in [7, 15] does not allow for an assessment of the actual risk of the event occurring as the large-scale dynamics can counteract or enhance the thermodynamics. In practice the dynamic contribution is often of a similar magnitude to the thermodynamic response (e.g. [5]; [6]). In the summer of 2013 heavy flooding occurred in the Danube and Elbe basins in South East Germany resulting from extreme precipitation, with some parts of the region receiving a month's worth of precipitation in the 3 days between the 30th May and 2nd June. In a warming climate where the vapour capacity of the atmosphere increases with warming, we would expect the likelihood of such rains to occur to increase by approximately 6%, as the temperature in this region and season has risen about 0.9 K. In figure 2 we show the attribution analysis for the Elbe catchment as published in [5]. Analysis of the observation gives a return time of the event of roughly 200 years. An increase of 6% would render a 1 in 200 year event in a pre-industrial climate a 1 in 120 year event in a warmer climate. However, the two independent methodologies used to analyse the overall change in risk show no change in the likelihood of the event occurring. A 1 in 200 year event stays a 1 in 200 year event according to the model analysis (with the 90% uncertainty ranging from 1 in 144 to 1 in 413) and becomes a more than 1 in 100 in the statistical analysis (a result in the trend in the observations being negative). The model results exclude a 7%/K increase. This implies there is an important role of the circulation.

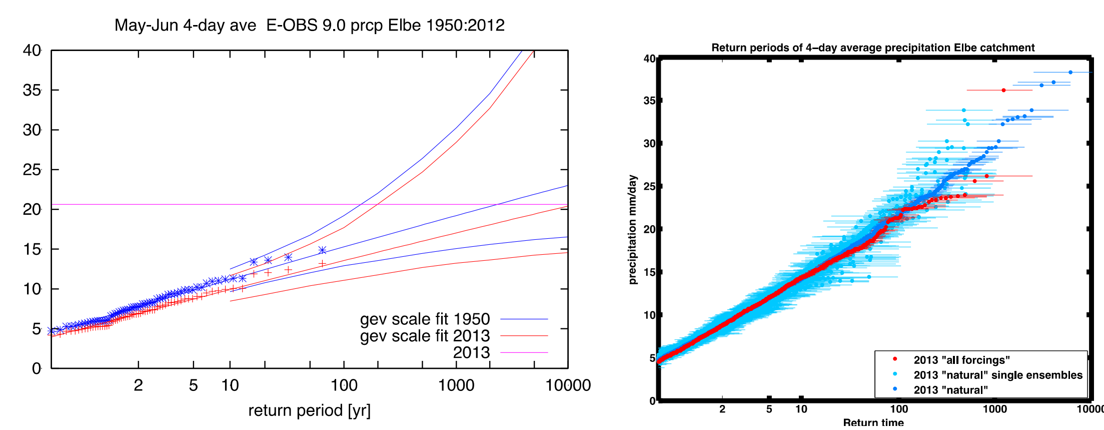


*Figure 2: Return time plots for the maximum four-day precipitation average during May–Jun for the upper Elbe catchment. Panel (a) shows the return times calculated from the E-OBS dataset, and (b) from HadRM3P. For the E-OBS dataset, red crosses indicate years from 1950 to 2012 after correction for the fitted trend to the year 2013 and the red lines correspond to the 95% confidence interval estimated with a non-parametric bootstrap. Blue crosses and lines represent the same as the red but in the climate of 1950, and the horizontal purple line represents the observed value for May–Jun 2013. For the HadRM3P datasets, the red dots indicate May–Jun possible four-day maximum precipitation events in a large ensemble of HadRM3P simulations of the year 2013, while the light blue dots indicate possible May–Jun four-day maximum precipitation events in 25 different*

*ensemble simulations of the year 2013 as it might have been without climate change. The blue dots represent the 25 natural ensembles aggregated together. The error-bars correspond to the 5%–95% confidence interval estimated with a non-parametric bootstrap.*

Another example, where the dynamical component of any changes acts in the same way as the thermodynamic is given in ref [21]. The authors identify an increase in the occurrence probability of heavy winter precipitation in Southern England of 42% as the best guess (with a 0-160% range), corresponding to an increase in intensity of about 4%(+/- 1%). In addition to this the study explicitly analyses the change in the circulation, finding an increase in the zonal regime structure of the atmosphere.

In a study on the influence of anthropogenic greenhouse gas forcing on exceptional mean sea level pressure (MSLP) in southern Australia in the winter season, [22] found that the risk of extremely high MSLP has increased by at least 70%. Such high sea level pressure precludes low pressure systems from coming inland to bring rainfall in Southern Australia, contributing to the decline in rainfall in that region. These findings corroborate earlier studies (e.g., [23]) and highlight again the importance of dynamical changes due to anthropogenic forcings in the overall risk assessment. A closely related example is the decline in winter rainfall in the southwest of Western Australia, mainly associated with circulation changes due to anthropogenic forcing [5], while the sea surface temperatures have increased and the thermodynamic response would suggest increased rainfall.

All three examples demonstrate that limiting the analysis to thermodynamic responses would give a misleading impression of the role of climate change. There are many more examples for a dominating role of the circulation (e.g., [5]; [6]; [8]) highlighting that a holistic assessment of the role of human-induced climate change can be rather complex. Robust attribution statements are only possible if the modelling approach is able to reliably reproduce the event in question as highlighted by Trenberth et al. [15]. However, in numerous studies scientists have demonstrated that models are capturing the relevant processes in a reliable way and also hold off from conducting attribution studies if the models prove unreliable (e.g., [24]). This underlines that model evaluation and bias correction deserve close attention in attribution studies. In particular applying multiple methods to answer the same question allows for model dependent results to be identified and the uncertainty to be better quantified. Attribution assessments are more likely to be reliable where they are based on a solid foundation of physical understanding. Combining multiple methods and basing findings on physical principles is thus the recommended approach for all event attribution studies.

**Conclusion**

It is often stated that it is not possible to make an attribution statement about an individual weather or climate event [25]. To the extent that an attribution statement might refer to the particular unique circumstances of any event this still holds in the sense that any attribution statement would be uninformative. However, due to the considerable progress made in the last decade there is an informative alternative. Scientists can now provide reliable answers to the question of whether anthropogenic climate change has altered the probability of occurrence of classes of individual extreme weather events, which often is a relevant question. The emergence of a set of complementary approaches deepens our confidence in these results and paves the way to provide robust answers to questions from stakeholders and the public in the immediate aftermath of an extreme weather event. When communicating these results, it is important to clearly state the probabilistic framing of the attribution question, how the event is defined and the level of confidence in the findings based on physical understanding. If the attribution question is being asked to provide guidance from the present on what the future may hold, in general approaches accounting for the full change in probability provide useful answers. This does not imply that for specific stakeholder questions a conditional framing of the attribution question would not be desirable, e.g., given a regional typical convective situation will the magnitude of rainfall increase? However, from the perspective of a stakeholder seeking information to inform disaster risk reduction strategies, it can be unhelpful to ask the question of how the probability has changed given the large-scale circumstances, as the risk crucially depends on these circumstances and their likelihood of occurring. As evidenced above, dynamical factors and thermodynamic aspects can interact in complex ways and there are many examples where the circulation is as important as the thermodynamics. Furthermore, if the event definition is too narrowly dependent on the exact atmospheric state and sea surface temperature patterns, the event may only occur if all factors are just right. This implies that all aspects of the external drivers, including human-induced climate change, are necessarily essential ingredients to reproduce the event.

In light of these facts it is important for every extreme event attribution study to clearly state the framing of the attribution question being asked. This should include whether conditional probabilities are being assessed or whether instead overall probabilities are being assessed, independent of sea surface temperatures, the atmospheric circulation state or other factors constraining the evolution of the particular event in question.

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