(global) to very high (local) resolution. We present the climate community with the capacity to take into account these new planetary-scale observation abilities. ❐

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Additional information

Supplementary information is available in the online version of the paper.

COMMENTARY:

The attribution question

Friederike E. L. Otto, Geert Jan van Oldenborgh, Jonathan Eden, Peter A. Stott, David J. Karoly and Myles R. Allen

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 questioned. Increasingly, scientists are able to give robust quantitative answers. In 2012, the *Bulletin of the American Meteorological Society* published the first of an annual series of special issues looking at how climate change may have affected the strength and likelihood of individual extreme events that took place during the previous year — with this first issue containing 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 (for example, ref. 2). The US National Academy of Sciences has recently completed a report into the issue, concluding that "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 probability of occurrence of specific types of events or event classes"[3].

Although the thermodynamic consequences of a warming world, namely an increased likelihood of more heat and high-precipitation extremes are predictable, on average, in any specific location or circumstances, thermodynamic influences may be either amplified or counteracted by anthropogenically induced changes in circulation[4–7] and/or other local forcings. 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 dynamic perspective. The emerging science of probabilistic event attribution provides the 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, thereby increasing confidence in the result[3]. However, differences in how the attribution question is framed can lead to apparently contradictory attribution statements 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[8], whereas the likelihood of occurrence of an event of this magnitude had changed considerably due to anthropogenic drivers[9]. More subtle differences in analysing changes in the likelihood of occurrence can still lead to large discrepancies in results[2,10].

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[11]. Such studies ask the following question: conditional on the large-scale circulation patterns, what was the role of anthropogenic climate change in, for example, the solar dimming observed over India?[7] Such studies allow for assessing whether climate change altered known relationships between large-scale drivers and local events. One such example investigated whether anthropogenic climate change affected the relationship between the El Niño–Southern Oscillation and extreme rainfall in Southeast Australia[12]. Although this method does not analyse the overall change in risk of an event occurring, isolating specific drivers can still be invaluable in improving understanding

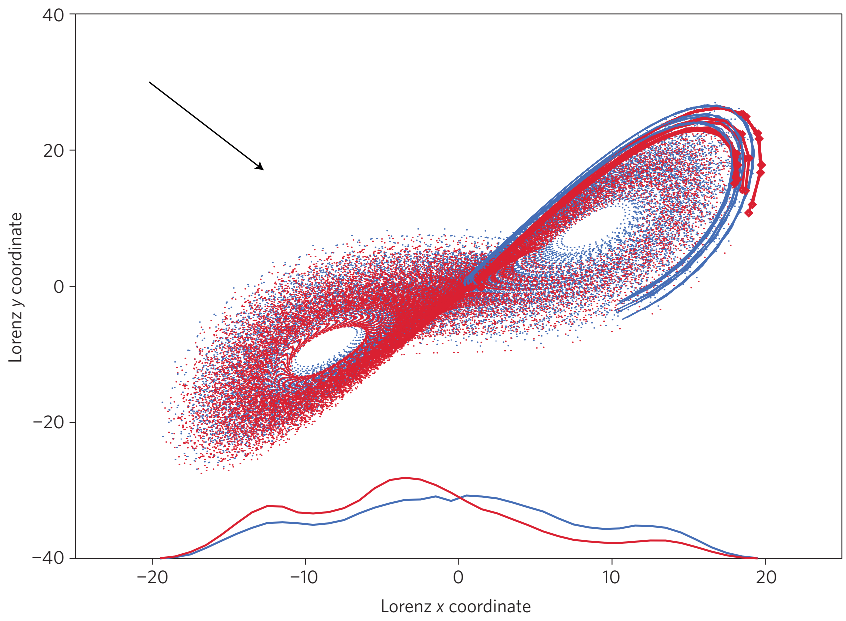

Figure 1 | Simple chaotic Lorenz 1963 model with added forcing. The main figure shows the Lorenz attractor of a Lorenz system with a forcing symbolizing the current climate forcing (red), and a weaker or natural forcing (blue). The bottom of the figure shows the distribution of x for both forcings for 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. The black arrow indicates orientation of forcing, and blue trajectories indicate impact of removing this forcing on the red trajectories shown, with identical initial conditions.

and in turn our ability to simulate extreme events. However, it is 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 being analysed. 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 and 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, the 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 and 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 ref. 13, for example, it will by definition never happen again[14]. 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, and 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[15], one group of authors[13] 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 to assess the absolute probability for the event to occur, but only investigate the change in severity of the event given that it had occurred. Although undoubtedly helpful in understanding the factors behind an 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 1963 model[16]. 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, although 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 nonlinear 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.

Real-world examples

Although the thermodynamic response of the climate system is often linear, the dynamic response can be highly nonlinear

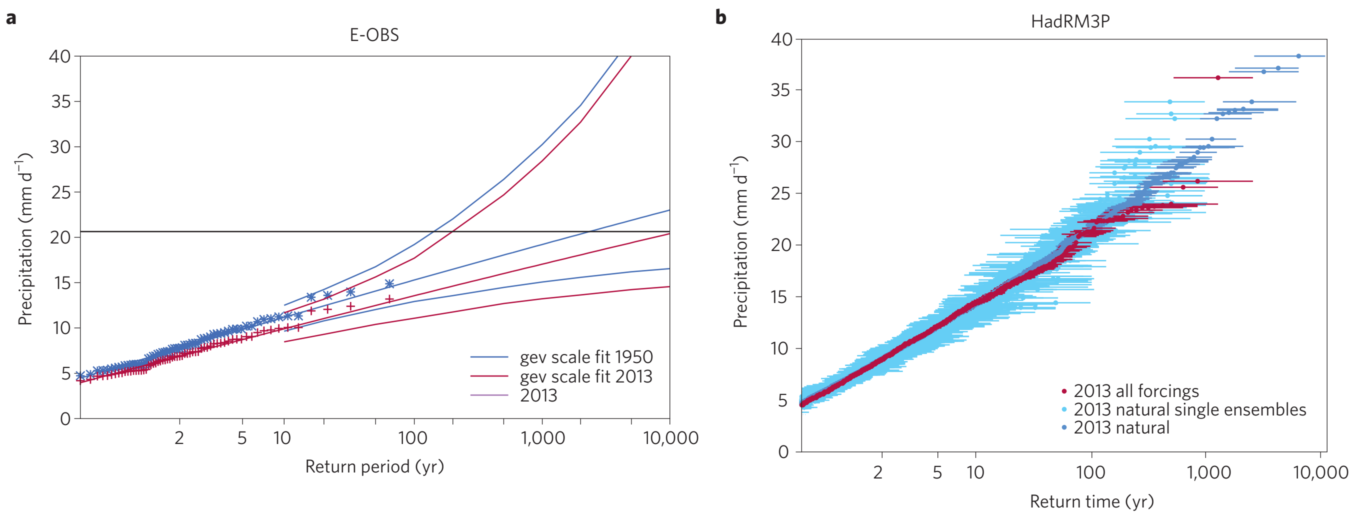

Figure 2 | Return time plots for the maximum four-day precipitation average during May–Jun for the upper Elbe catchment. **a**, Return times calculated for the E-OBS dataset, red crosses indicate years from 1950 to 2012 after correction for the fitted trend to the year 2013, and the red lines correspond to the 95% confidence interval estimated with a non-parametric bootstrap. Blue crosses and lines represent the same as the red but for the climate of 1950. The horizontal black line represents the observed value for May–Jun 2013. GEV, general extreme value distribution. **b**, As with **a** but calculated from 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, whereas the light blue dots these 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.

and may be in the opposite direction to the thermodynamic response. Hence, limiting attribution studies to the thermodynamic response alone (as exemplified in refs 6,13) does not allow for an assessment of the actual risk of the event occurring[17] 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[4,5]. In the summer of 2013 heavy flooding occurred in the Danube and Elbe basins in southeast Germany, resulting from extreme precipitation, with some parts of the region receiving a month's worth of precipitation in the three days between the 30th May and 2nd June[4]. In a warming climate where the vapour capacity of the atmosphere increases with warming, we would expect the likelihood of the occurence of such rains to increase by approximately 6%, as the temperature in this region and season has risen about 0.9 K. In Fig. 2 we show the attribution analysis for the Elbe catchment as published in ref. 4. 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-1000 year event in the statistical analysis (a result in the trend in the observations being negative). The model results exclude a 7% K^{-1} increase. This implies there is an important role of the circulation.

Another example where the dynamical component of any changes acts in the same way as the thermodynamic is given in ref. 18. The authors identify an increase in the occurrence probability of heavy winter precipitation in southern England of 42% as the best estimate (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[19], it was 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 (for example, ref. 20) 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], whereas 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 (for example refs 4,5) 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 in ref. 13. However, in numerous studies scientists have demonstrated that models are capturing the relevant processes in a reliable way[21] and also hold off from conducting attribution studies if the models prove unreliable (for example, ref. 22). This underlines that model evaluation and bias correction deserve close attention in attribution studies[23]. 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-related event[24]. To the extent that an attribution statement might refer to the particular unique circumstances of any event, this idea 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, for example, 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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