Attribution of Weather and Climate-Related Extreme Events

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Abstract

Unusual or extreme weather and climate-related events are of great public concern and interest, yet there are often conflicting messages from scientists about whether such events can be linked to climate change. There is clear evidence that climate has changed as a result of human-induced greenhouse gas emissions, and that across the globe some aspects of extremes have changed as a result. But this does not imply that the probability of occurrence (or, given a fixed damage, risk) of a specific type of recently observed weather or climate event has changed significantly as a result of human influence or that it is likely to become more or less frequent in the future. Conversely, it

is sometimes stated that it isn't possible to attribute any individual weather or climate event to a particular cause. Such statements can be interpreted to mean that human induced climate change could never be shown to be at least partly responsible for any specific event.

In this paper we propose a way forward through the development of carefully calibrated physically-based assessments of observed weather and climate-related events and identification of any changed risk of such events attributable to particular factors. Although such event-specific assessments have so far only been attempted for a relatively small number of specific cases, we describe research under way, coordinated as part of the international Attribution of Climate-related Events (ACE) initiative, to develop the science needed to better respond to the demand for timely, objective, and authoritative explanations of extreme events. The paper considers the necessary components of a successful attribution system, reviews some specific case studies made to date (2000 UK floods, 2003 European heatwave, 2008 cool US, 2010 Moscow heatwave) and discusses the challenges involved in developing systems to provide regularly updated and reliable attribution assessments of extreme weather and climate-related events.

Introduction

Extreme weather and climate events, such as the extreme heatwave in Moscow of summer 2010, the exceptionally cold December in the UK later that year, or the devastating floods in Queensland early in 2011, often cause major economic and human losses. Yet scientists are faced with a daunting challenge in generating and

communicating scientifically robust and timely information on the causes of such events, quantifying their links to human-induced climate change, and evaluating the prospects for early warning of such events.

The demand for information is often at its greatest in an event's immediate aftermath, requiring a rapid response from the scientific community. But apparently conflicting views, for example that all weather and climate events are to some extent tainted by human influence under a changed climate, or that no single event can ever be attributed unequivocally to a particular cause, serve to confuse the public. Decision makers, keenly aware of the need to protect life and property from the impacts of extreme weather and climate, wish to know whether such events could have been anticipated and whether they are likely to become more or less frequent in the future. Because some potentially damaging weather events will occur less frequently as a result of human influence on climate, a comprehensive inventory of the net cost of climate change presents substantial challenges, including the difficulty of quantifying the hypothetical cost of weather events that are prevented from occurring as a result of human influence.

However, reliable assessments of current extreme event probabilities and how those are changing in time ---- key information for informing any adaptation strategy--- are often lacking or incomplete. Furthermore, mistakenly attributing an increased risk of an extreme event to climate change could, if natural variability is playing the major role, lead to poor adaptation decisions; for example, through allocating expensive resources toward preparing for a greater frequency of such events when they are set to become less likely.

This paper provides the context for current attempts to attribute the causes of individual weather and climate-related events . The development of climate science is first described that has linked with increasing confidence observed changes in global climate to human induced drivers of climate, principally increases in well mixed greenhouse gas concentrations. While the focus of previous IPCC reports has been on identifying in observations the externally forced components of detected changes, for extreme weather and climate-related events the practical consideration of early warning leads to a pursuit of the causes of such events, whether or not a detected change in the occurrence of such extremes has occurred. Potential stakeholders are identified who could benefit from timely and authoritative assessments that go beyond changes in global climate to consider specific weather and climate events. The development of the science of event attribution is summarized and illustrated via examples of specific case studies that have been carried out so far. A key challenge for the community is to move beyond research-mode case studies to develop systems that can deliver regular and timely assessments in the immediate aftermath of extreme events. Progress in developing such systems is described. Finally, we draw lessons from the research work to date and propose some future research needs.

Development of Attribution Science

Successive assessment reports of the Intergovernmental Panel on Climate Change (IPCC) have come to increasingly confident conclusions about the causes of globally averaged temperature change over the last century, with the Fourth Assessment Report (AR4) concluding that "most of the observed increase in global average temperatures

since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations"(IPCC, 2007). In addition there has been increasing interest in understanding the causes of regional climate changes. AR4 concluded that "It is likely that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica". Since then, evidence has been published showing a detectable human influence on temperature changes over Antarctica as well (Gillett et al., 2008), and further evidence has accumulated attributing a wider range of climate changes to human activities. These changes have been judged to be inconsistent with internal climate variability alone, and are only consistent with theoretical understanding, encapsulated in climate model simulations, of how the climate system would be expected to respond to anthropogenic influence. The paper by Stott et al, 2010 reviews the evidence showing significant human-induced changes in regional temperatures and aspects of the hydrological cycle, the cryosphere, circulation changes, ocean changes and changes in extremes. Thus there is strong, robust evidence that human influence, dominated by emissions of greenhouse gases, has altered the climate system.

In addition to changes in mean climate, the AR4 report assesses that human influences have *likely* increased temperatures of the most extreme hot nights, cold nights, and cold days, and that it is more likely than not that anthropogenic forcing has increased the risk of heat waves. Subsequent detection and attribution studies have further confirmed the detection of a human influence on very cold days and nights and very warm days and nights (Zwiers et al, 2011, Christidis et al, 2011), and also on an intensification of heavy

precipitation events over a large fraction of northern hemisphere continents (Min et al, 2011).

However, evidence for a significant human influence on such large scale observed changes does not imply that a specific weather or climate extreme can necessarily be attributed unambiguously to human influence, since many types of weather extremes, including heatwaves, extreme rainfall and drought can happen in an unaltered climate and indeed have happened in pre-industrial times. On the other hand this does not mean event attribution is impossible. Instead, by careful consideration of the physical factors underlying the event and by asking how external anthropogenic and natural drivers have contributed to the probability of the event occurring, quantitative statements can be made about the role of different factors in contributing to the magnitude of and the probability of occurrence of individual events. Clearly any such studies need to carefully consider the relevant processes involved in causing the particular event in question, and need to ensure such processes are captured in the modelling used to analyse the event. While such event attribution studies have been carried out for only a few cases so far, they demonstrate the potential for quantifying the role of human and natural influences on specific weather and climate-related events, and also provide a framework for developing improved early warning capabilities. The next section discusses the potential relevance of such attribution assessments.

Relevance of attribution assessments of individual weather and climate events
There are a variety of stakeholders who for different reasons could be interested in attribution of individual weather and climate events. In this section we discuss the needs

for better attribution information for general understanding, in legal contexts, to inform adaptation strategies and for geo-engineering.

Public Interest

Given climate model projections for changes in some extremes, including in some parts of the world more frequent and intense heatwaves and heavy daily rainfall, and in places less frequent and intense cold spells and snowfall, there is often considerable public interest in the possible link between a particular extreme weather or climate event and climate change. This interest is often at its greatest during or in the immediate aftermath of such events. In such circumstances all too often the public receives contradictory messages from reputable experts. If the public hears that a particular weather event is consistent with climate change they may conclude that it is further proof of the immediate consequences of human induced global warming; on the other hand if the public hears that it is not possible to attribute an individual event, they may conclude that the uncertainties are such that nothing can be said authoritatively about the effects of climate change as actually experienced.

A particularly cold spell, as happened in the UK in December 2010, the coldest December in the UK national temperature record from 1910, with considerable adverse consequences including closed airports and schools and large economic losses, caused many people to question how such an extreme can be consistent with a warming world. On the other hand, an extreme weather event that appears to be consistent with long-term projections of climate change, such as a particularly hot spell as was seen during the warmest April in the Central England temperature record stretching back to 1659,

may lead people to ask whether such events are expected to happen much more often in the future and whether this particular extreme event should be seen as a sign of a changing climate rather than as simply an unusual occurrence of natural unforced variability.

What is often lacking is a fully informed and timely response based on the best available science that enables the public and decision makers to put such events into the context of both natural variability and climate change. Ideally one would wish such assessments to be issued regularly as in the case of weather forecasting, although some extreme events, which are often unanticipated, could demand a targeted and immediate response so as to inform discussions and considerations that frequently occur in the immediate aftermath of extremes. While such rapid attribution assessments may be superseded by later more detailed analyses, there is nonetheless potentially great value in rendering prompt appraisals, even given the uncertainty that must necessarily accompany them. Just as the timely, routine and systematic nature of weather forecasts has offered great user value despite the remaining inherent forecast errors, timely probabilistic attribution assessments should not necessarily be embargoed barring definitive conclusions, but instead could be produced routinely providing appropriate validation procedures are put in place and there is careful communication of the remaining uncertainties. As with weather forecasting, a regular attribution process would potentially lead to a continued improvement in reliability and could enhance the prospects for early warning of extreme events through enhanced understanding of predictability.

It is important to be proactive in the attribution activity and not solely reactive to specific events, which may give an unwarranted impression of selectivity and bias. If only exceptional observed cases were studied then assessments could be biased toward events made more frequent now in relation to the historical baseline because of anthropogenic emissions.

Litigation

The extent to which a specific damaging weather event could be blamed on greenhouse gas emissions is of relevance in legal contexts, since attempts to seek redress for harm caused by emissions or, as in the case of six states before the US Supreme Court, to force power companies to cut their emissions of greenhouse gases under environmental protection legislation (Adam, Nature Climate Change, 2011), would require evidence presented on the extent to which emissions can be linked to harmful effects (Grossman 2003). Allen et al (2007) argue that an objective operationalised attribution approach would be of considerable benefit to the courts since it would reduce the extent to which courts rely on expert judgement in legal contexts where the outcome often depends delicately on the exact question being asked. For example, even the same expert might agree that "human influence on climate played a substantial role in causing the European heatwave of 2003" and that "it is impossible to attribute any single weather event to human influence on climate", positions that could appear to be contradictory to a court. Therefore Allen et al (2007) argue the need for agreed objective operational assessments that could, like routine operational weather forecasts, be used by courts as objective, relatively uncontentious testimony, requiring a much more minor role for expert judgement in interpretation. A number of questions need to be considered by the

legal community including what a court might consider as natural climate, over what time scales are damages relevant, and what levels of reliability, neutrality and acceptability are required for attribution assessments to be successfully used in legal contexts.

Adaptation

The character of societal responses to extreme climate events often reveals details of the society's resilience and vulnerability, potentially exposing major "adapatability gaps". Activities designed for adaptation to climate change can be concerned with time frames ranging from the present through to many decades into the future, while those designed to better adapt to the rare extremes associated with natural variability may have a different character. Attribution studies can thus be usefully tailored to inform adaptation strategies encompassing both natural hazard mitigation and reduction of the consequences of human induced climate change.

Such investigations can reveal changes in the risk of various damaging events, thus contributing to decisions over which attribution activities require priority and which, perhaps, are no longer a top concern. By determining the causes of extreme weather events being observed now, robust information can also be provided on the extent to which a specific extreme event is a harbinger of the future, and therefore an impact against which a society, which the recent event has shown to be vulnerable to, may want to develop further resilience. Similarly, if scientific assessment concludes that an event is either likely to remain extremely rare or become less likely in the future, societies

may adjust policies; for instance, by judging that such events and their impacts do not constitute a long-term adaptation priority (Hoegh-Guldberg et al., 2011).

Geoengineering

Geo-engineering is an issue rising up the climate change agenda and attribution should be an important component of any research and development of such technologies. A recent report by the Royal Society provides a comprehensive assessment of all geo-engineering options that are actively being considered (Royal Society, 2009). Geo-engineering could be implemented to reduce the risks of crossing dangerous thresholds of climate change were society unable to constrain emissions, or in an attempt to return to a safer climatic state were dangerous levels of climate change to be reached anyway.

In the event of geo-engineering being applied, attribution assessments would be needed to determine whether the intervention is working as expected in delivering the associated benefits. Additionally attribution assessments would be needed to determine whether there are any deleterious consequences attributable to the intervention, assessments that would be of interest to stakeholders seeking compensation for any price they might be paying for delivering collective planetary benefits. Such attribution activities will force the collection of "appropriate observations" recommended by the Royal Society report, which might include those beyond the more traditional quantities such as temperature and precipitation, such as for example surface radiation fluxes in the event of Solar Radiation Management (SRM) techniques being employed. Attribution analyses, including into the potential ability to detect and attribute the consequences of proposed geoengineering interventions, will also inform the

development of climate models to include geoengineering options, thereby fulfilling another recommendation from the Royal Society report, that the climate modeling community should start to carry out predictions of the different options, and can inform the design of experiments to test geoengineering options at a local scale before planetary scale implementation.

Geoengineering should only be considered if armed with the best possible understanding of potential options, and having the tools in place to carry out verification, should geoengineering options be implemented in practice. Attribution has a major role to play in such endeavours.

Development of the science of Event Attribution

In recent years the science of event attribution has developed considerably, with a number of studies having been published that quantify the role of human and natural influences on specific weather and climate events. Whereas observations are key to describing an event and placing it into a meaningful historical context, given the complexity of the climate system any attribution analysis will inevitably involve models as well as observations in order to elucidate competing mechanisms.

The approach of using model experiments to calculate how a particular climate driver has changed the probability of an event occurring as proposed by Allen (2003), has been applied to a number of different cases (eg Stott et al, 2004, Stone and Allen, 2005, Christidis et al, 2010, Pall et al, 2011). The probability of a particular event happening in an ensemble of model simulations representing current conditions is compared with a

parallel ensemble of model simulations representing an alternative world that might have occurred had the particular driver or drivers of interest been absent.

This is illustrated schematically in Fig 1. The distribution shown in red represents the current probability distribution of a particular climate variable, and that in green, the equivalent probability distribution of that variable in the world that might have been had human influences on climate been absent. Then for a particular threshold, the probabilities, P1 of exceeding that threshold currently and P0 of exceeding the threshold were there no human influence on climate, can be calculated.

INSERT FIG 1

From these two probabilities the Fraction Attributable Risk (FAR) can be calculated, where FAR = 1-P0/P1 (Allen, 2003). FAR expresses the fraction of risk of a particular threshold being exceeded (e.g., a positive temperature departure associated with a heat wave) that can be attributed to a particular influence. For example if the probability that a particular threshold being exceeded has increased by a factor of 4 as a result of human influence on climate, FAR=0.75, and three quarters of the risk of that event is attributable to human influence. In this case, under the current climate, on average ¾ of such events could be blamed on human influence. Such a result does not indicate that human influences were responsible for 75% of the observed event magnitude, however, nor does it discriminate which specific events would not have happened, but rather that the probability of exceeding a particular threshold has increased.

The very nature of most extreme events means that their probabilities need to be estimated by statistical extrapolation or modelling unless they occur sufficiently commonly that their probabilities can be estimated directly from their observed frequencies. If events are sufficiently frequent it can be possible to carry out a "single-step" attribution analysis (Hegerl et al, 2010), in which observed and modelled changes are compared directly. In this way, Stott et al (2011) detected a significant increase in the observed frequencies of warm seasonal temperatures in many regions that were attributable to human influence. However such an approach is not feasible in the case of rare events in which case it is necessary to employ a "multi-step" attribution procedure (Hegerl et al, 2010). For such an analysis, the trend in occurrence frequency of more frequent events is attributed to human influence (as in the example given above) and extrapolation used to calculate the attributable risk of the event in question. Alternatively, an attributable trend in a related variable is calculated, such as sea surface temperature, and a model is used to calculate the implied fraction of attributable risk of the event.

Given the lack of an observed realisation, it is always necessary to use models to generate simulations of the counter-factual world needed to estimate P0, the probability of the event in the absence of a particular climate driver. Because modelling uncertainty must therefore be estimated, in addition to observational uncertainty, it is helpful to express findings in statements that are robust to these uncertainties. A number of studies (eg Stott et al, 2004; Pall et al, 2011) have employed a particular formulation,

which, in the face of uncertainty in the precise value of FAR, provides a minimum value

that FAR is expected to exceed at some level of likelihood. Thus in the case of

European summer temperatures, Stott et al (2004) concluded that despite uncertainty in

the precise value of FAR for the threshold chosen in that study as being relevant to the

2003 European heatwave, it was "very likely" (using the IPCC definition of a >90%

chance of the statement being correct) that FAR was greater than 0.5, ie that the

probability of the threshold being exceeded had more than doubled as a result of human

influence. While such a statement reflects remaining uncertainty in the change in FAR

,fortunately, it is also generally of greater interest to know whether such iconic

thresholds, such as an increase or a halving of the probability, have been passed, and, it

may be just as helpful to determine whether the probability of the event has likely not

changed substantially.

Characterising changes in the shape of tails of extreme event distributions is

challenging, particularly when factors like thermodynamic constraints are acting to limit

absolute changes, so it is important not to read too much into heuristic examples based

on idealized distributions such as Fig 1. In some cases (eg Stott et al, 2004; Pall et al,

2011), the change in the distribution of a particular climate variable can be consistent

with a constant ratio of exceedance probabilities, $P0/P1$, over a broad range of

thresholds, a point that is important for the robustness of results from such analyses

where there is ambiguity about the actual threshold that was exceeded during the event

in question.

The predictability of an event and therefore the potential for early warning (including both its amplitude and temporal characteristics) are also investigated in some attribution studies. Diagnosing whether a model is capable of capturing the physical and statistical properties of a particular event is an important test of its capabilities if it is to be used for attribution. While attribution is possible in the absence of predictability, confidence in an attribution assessment can only be justified if the models used are capable of capturing the relevant processes and if there is a clear understanding of the role of atmospheric circulation, oceanic, and land surface anomalies in causing the event in question, since anomalous atmospheric flow and other boundary conditions are often associated with extreme weather (Perlwitz et al, 2009; Dole et al. 2011).

To illustrate further the challenges involved in event attribution and to describe the main progress made so far in this area, published studies carrying out attribution of specific events are outlined in the next section.

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Examples of Event Attribution for specific cases

2003 central European Heatwave

In their study of the 2003 European heatwave, Stott et al (2004) (and later Christidis et al, 2010a, using additional data) analysed the temperature changes over a large part of continental Europe and the Mediterranean and showed, using an optimal detection analysis on simulations of the HadCM3 coupled climate model with and without anthropgenic forcings, that there had been a significant anthropogenic contribution to the observed warming of regional summer mean temperatures. They then used the model to infer the probabilities in the current world (P1) and the world without human

influence on climate (P0) of exceeding a particular seasonal mean temperature threshold associated with the 2003 event. The threshold they chose was the summer mean temperature that was exceeded in 2003 but in no other year (before that) since the start of the instrumental temperature record in 1851, a formulation designed to minimise the selection effect of choosing a threshold too closely associated with what actaully occurred (eg by choosing the threshold exceeded in 2003). This multi-step attribution approach yielded an estimate for the Fraction Attributable Risk (FAR) of 2003 European mean summer temperatures where in the first step, a change in the decadal background summer temperature was attributed to human influence, and then in the second step the relationship between year-to-year variability and the decadal background variability in summer temperatures was attributed to processes simulated in a climate model, allowing an inference of the probability of exceeding the threshold in that particular summer to be made. Figure 2a shows the calculated distributions of P0 (green) and P1 (red) expressed as number of occurrences per thousand years where the likelihood distribution represents their uncertainty. The derived distribution of FAR is shown in Fig 2b with the median value also shown. Based on the result that the 10th percentile of the distribution (as shown by the left most grey band in Fig 2b) is greater than 0.5, Stott et al (2004) concluded that the probability of seasonal mean temperatures as warm as those observed in Europe in 2003 had very likely at least doubled as a result of human influence. The conclusion that FAR is very likely greater than 0.5 serves as an example of how to make a scientifically robust assessment about a change in attributable risk despite considerable remaining uncertainty.

INSERT FIGURE 2

2000 UK floods

Pall et al. (2011) considered the extensive floods that occurred during the record-wet autumn of 2000 in England and Wales, and estimated the change in probability of such floods occurring at that time as a result of twentieth-century anthropogenic greenhouse gas emissions. This study followed a multi-step approach, with the first step attributing the bulk of warming in global sea surface temperatures to anthropogenic greenhouse gas emissions through the use of an established "optimal fingerprinting" regression analysis (Stott et al. 2006, Nozawa et al. 2005). Because of the lack of observations of events this rare and recognising the largely atmospheric seasonal-timescale nature of the event, the second step used a seasonal-forecast-resolution atmospheric climate model to generate simulations of possible autumn 2000 weather. These simulations were conducted both under conditions observed at that time and under parallel conditions that might have been obtained at that time in the absence of increased greenhouse gases, as determined from the first attribution step. The observed event was relatively rare and unpredictable, so ensembles of several thousand weather simulations were generated under these two conditions (via climate*prediction*.net public volunteer distributed computing) to sufficiently capture such unusual flood-producing weather and its change. Results were fed into a precipitation-runoff model for England and Wales to then simulate a measure of flooding, with the probability of floods of a specific magnitude counted directly from the simulations. The atmospheric model simulations acted as pseudo-observations for investigating the role of various mechanisms that could lead to changes in flood frequency between the two climates, noting that the reliability of the model in delineating mechanisms therefore become critical to the

correctness of the findings of such a study. It was found that almost all differences were due to a simple thermodynamic increase in precipitable water, a mechanism that is well understood, although this conclusion is dependent on the reliability of the model in discounting non-thermodynamic changes as major factors. Quite a large uncertainty was found in the magnitude by which the greenhouse gases increased flood risk at the threshold relevant to autumn 2000 (Fig 3). This mainly reflected uncertainty in estimating the autumn 2000 sea surface temperature (SST) conditions that would have been obtained in the absence of the greenhouse gases, as determined from the first step. Pall et al (2011) found that the precise magnitude of the anthropogenic contribution was uncertain but in nine out of ten cases their model results indicated that twentieth-century anthropogenic greenhouse gas emissions increased the risk of floods occurring in England and Wales in autumn 2000 by more than 20%, and in two out of three cases by more than 90%.

INSERT FIG 3

2008 Cool US (Perlwitz et al)

Perlwitz et al studied the nature of the very cool 2008 climate conditions in North America that diverted strongly from the long term warming trend observed over previous years. Based on a suite of model experiments their study showed that an anthropogenic warming of North American temperature was overwhelmed by a particularly strong bout of naturally induced cooling resulting from the continent's sensitivity to widespread coolness of the tropical and northeastern Pacific sea surface temperatures. Fig 4 shows North American surface temperature change for 1970-2007

(left) and departures for 2008 (right) as observed and as simulated by coupled models

(CMIP) and atmosphere only models (AMIP) forced with the observed 2008 sea surface

temperatures. While the observed pattern of temperatures in 2008 (Fig 4b) does not fit

in with the observed or modelled trends over recent decades or the 2008 departure as

simulated by the mean of the CMIP models (which by averaging will have eliminated

most natural internal variability components), it does fit broadly with the pattern

simulated by the AMIP models when forced with the observed SSTs. A conclusion is

that the departure from the long term trend during 2008 could be attributed to a

particular anomalous state of SST conditions in 2008. Further, it was found that such a

strong ocean state and its North American impacts are well simulated by models,

indicating their potential for skillful predictions of fluctuations in large scale

temperature anomalies over North America. The implication of their study was that the

cool year in 2008 did not indicate that the climate was likely to embark upon a

prolonged period of cooling and, on the contrary, the pace of North American warming

was more likely to resume in coming years.

INSERT FIGURE 4

2010 Moscow heatwave

Dole et al (2011) considered the relative importance of various physical factors

contributing to the extreme heat wave affecting Moscow and adjacent regions, using

both observational analyses and model experiments.   They showed that, in contrast to

the region affected by the 2003 European heat wave, the primary region affected by the

2010 heat wave had not experienced significant long-term warming in summer over the

prior 130-year period. CMIP-3 models forced by increasing greenhouse gases and other external forcings showed a small mean warming over the same period, but no significant change in variability. Ensemble model simulations forced by observed global sea surface temperatures and sea ice conditions also showed no statistically significant response over the heat wave region. Dole et al. concluded that the extreme magnitude of the 2010 Russian heat wave was caused primarily by internal dynamical processes that led to a very strong and persistent blocking pattern over the heat wave region, and suggested that regional land surface feedbacks were also likely important in explaining the heat wave's intensity. While these results indicated that it was very unlikely that increasing greenhouse gases contributed substantially to the magnitude of the 2010 Russian heat wave, they also showed that the western Russia appears to be on the cusp of a period in which the probability of such extreme heatwaves will increase rapidly. Many regions around the world are already experiencing a rapid increase in the frequency of more moderate extreme temperatures (Jones et al, 2008).

INSERT FIGURE 5

Attribution of Climate-related Events Group

The studies outlined above indicate the potential for event attribution, but the remaining uncertainties, even for the very small number of specific events so far considered, demonstrate that there are many scientific challenges to be faced in developing a robust assessment process for extreme events. It should also be noted that there is often an appreciable delay between the occurrence of the event in question and the appearance of

the peer-reviewed studies. Meanwhile scientists continue to face demands for more rapid reaction on the links between climate change and unusual weather events, and the number of climate litigation cases is increasing (Adam, 2011). As a result of this demand for attribution science, interested scientists from around the world have recently joined together to coordinate their efforts and consider research needs as part of the Attribution of Climate-related Events activity (ACE). The first full meeting was held in August, 2010 (hosted by NOAA and supported by funding from the UK FCO).

In the run up to the meeting, nature itself provided no shortage of illustrations regarding the question of who cares about the causes for climate conditions and extreme events. There was a deluge of media stories regarding the Russian heat wave, Pakistani floods, and China floods and of the concerns about the implications such events held for the immediate future, for example, on food supplies and commodity prices. The events impressed upon the attendees of this workshop the need for rapid, yet accurate, attribution information.   The "teaching opportunity" that such extremes offer to educate the public about future climate change was appreciated by all, though the danger of premature attribution and "misattribution" were also recognized. The attendees also concurred about the relevance of the attribution information to the prediction enterprise and early warning systems.

The meeting attendees agreed that a comprehensive and authoritative attribution activity will demand enhanced collaboration and coordination of numerous partners in order to provide a test bed for evaluating and applying data, theories, and computational methods. In this regard, the underpinning of a strong and sustained research enterprise

to provide the best possible operational systems for attribution was emphasized. The foundations of an authoritative explanation of extreme events begin with a real-time monitoring and climate analysis capability, and availability of historical data sets, such that current events can be placed into a reliable and physically consistent historical context. Model simulations and experimentation were likewise seen as core elements that provide an essential tool in "connecting the dots" so as to establish plausible cause-effect relationships. The workshop attendees also emphasized that society and decision makers also need to be provided with a clear statement of the meaning and implications of the scientific findings.

A concrete outcome of the meeting was a proposal for modelling centres to carry out a coordinated set of experiments in order to explore the importance of the experimental design, climate model design, event location and timing, and the inclusion of various anthropogenic factors to increase the robustness of attribution assessments. The experiment was also endorsed by the CLIVAR C20C group at their meeting in Beijing in October, 2010. Under this project, several modelling centres around the world will perform time-slice experiments with atmospheric modelling, following the method developed by Pall et al. (2011) except with more tractable ensemble sizes. These experiments will cover the full 1960-present period and probably into the near-future, allowing an evaluation of how anthropogenic contributions have been changing and also how estimation of these contributions depends on various aspects of the experimental setup.

Development of near-real time weather and climate event attribution

Coupled model approaches

The analysis of the 2003 European heatwave by Stott et al. (2004) provided a template for how a multi-step attribution analysis using coupled models could be carried out in which changes in the frequency of a specific event under human influences can be inferred based on an attribution analysis of mean temperatures over a region, together with an analysis of the expected change in frequency of exceeding thresholds of extreme temperature due to internal variability around the baseline of attributable large scale mean temperatures. This same approach can be applied using regularly updated data to provide assessments of attributable risk immediately following a particular season. Such an approach using coupled models has also been used to estimate the change in the probabilities of exceeding a pre-defined temperature threshold for every season in Europe (Chrisitidis et al, 2010a) and extended to sub-continental scale regions throughout the world (Christidis et al, 2010b, Christidis et al, 2011b). Unlike previous studies that carried out an optimal fingerprinting analysis over the region of interest, these studies employed constraints from a global analysis to estimate the regional temperature distributions. Look-up tables, as shown in Fig 6, of the FAR of a threshold exceedence can be computed for each region over a range of thresholds thereby providing the potential for regularly updated attribution information to be provided alongside monitoring information about the season just finished and seasonal forecasting information of the season to come.

INSERT FIGURE 6

Very large ensembles using distributed computing experiments

Attribution approaches that are appropriate for regional precipitation are being developed that use larger ensembles of higher resolution models. In particular the use of atmosphere-only models in which sea surface temperatures are prescribed allows a better discrimination between ensembles of models with each being tied to a particular evolution of SSTs. An important consideration here is that such an experimental design investigates the change in risk conditional on certain aspects of variability being tied to those observed (eg the state of ENSO) whereas ensembles of coupled models with different climate forcings are able to estimate the overall change in risk associated with the presence of a particular forcing.

In many cases interest may be in weather extremes that are extremely rare and therefore for which either very large ensembles of model simulations need to be made in order to capture the occurrence of such events or else statistical extrapolation techniques need to be used to make inferences about changes in such extremes based on changes in that part of the distribution that can be modelled. An important aspect of research therefore is to understand the benefits of the very large ensembles made possible by distributed computing and as well as the limitations of smaller ensembles that could be run more regularly as part of a near-real time attribution service. The climateprediction.net project which has pioneered the use of large ensembles for attribution and prediction has recently included a regional modelling component (the weatherathome.org project) to downscale global models for the Western US, Southern African and European regions.

A near-real time attribution capability linked to seasonal forecasting

Stone et al. (2011) have implemented a pilot version of an attribution forecast system that runs in parallel with an existing seasonal forecasting service, following a simplified version of the Pall et al. (2011) experimental design (http://www.csag.uct.ac.za/~daithi/forecast). Along with the real seasonal forecast, a parallel forecast is run of a non-greenhouse gas world in which human activities had never released greenhouse gases to the atmosphere and the ocean had not warmed in response to those emissions. Currently this simple implementation mainly serves as an apparatus for learning about how such a linked system can function when using multiple models and as a demonstration to aid in ascertaining the requirements and characteristics that potential users of such a system might demand. It has however revealed seasonal and regional variations in attributable risk, as well as some apparently robust similarities and differences with seasonal forecasting products, for instance in that the relative predictability of temperature versus precipitation events is very different in an attribution statement than in a standard seasonal forecast. This system has also provided insights into the advantages and limitations of a pro-active approach. Pre-defined event definitions have inevitably not conformed to more obvious definitions one might make after the fact, revealing the need to refine definitions in a balance between relevance and systematic objectivity. The use of confidence statements involving thresholds of attributable risk, such as that the chance of the event has at least doubled or halved, have provided a clear framework in communication sessions with potential users of such information. Just as important for such users, though, is the provision of statements of when we can say that any influence is less than a certain threshold.

The development of a more rigorous near-real time attribution capability is underway at the Met Office Hadley Centre with a focus on system evaluation and validation, and based on ensembles of simulations of the atmosphere version of the seasonal forecasting model with atmosphere-only GCMs and prescribed SSTs, also similar to the experimental design of Pall et al (2011). The ensembles using the HadGEM3-A atmospheric model are generated using a) random perturbations that represent the uncertainty in a number of parameters (Murphy et al., 2004; Collins et al., 2006) and b) vorticity perturbations that counteract the damping of small scale features introduced by the semi-Lagrangian advection scheme (Bowler et al., 2009). Simulations of the 'actual' world employ the anthropogenic and natural forcings used in previous experiments with the HadGEM1 model (Stott et al., 2006) and sea surface temperature (SST) and sea-ice data from the HadISST dataset (Rayner et al., 2003). Simulations for the climate without human influences include natural forcings only and remove an estimate of the anthropogenic change in the SSTs and sea-ice from the prescribed HadISST data. Experiments to date have been carried out using an estimate of SST change from the HadGEM1 model, while the change in the sea-ice is computed based on empirical relationships derived with HadISST data, a similar approach to Pall et al. (2011). Notably, the setup of this real-time system is closely aligned to the design of the ACE and C20C experiments.

A useful tool in the validation of ensembles for seasonal forecasting is the reliability diagram which plots the observed frequency of an event against the forecast probabilities. Reliability is indicated by the proximity of the plotted curve to the diagonal. Points above/below the diagonal indicate that the forecast model is

under/over-forecasting at the respective probability threshold. Reliability diagrams can be constructed for a number of regions to examine the model skill in simulating high and low temperature and precipitation events. An illustrative example is shown in Fig. 7 for forecasts of upper tercile temperature and precipitation events in Europe. The results suggest that the model has much better skill in capturing the predictability of temperature than of precipitation in the chosen region. Such reliability diagrams, supplemented by comparisons of observed and modeled distributions of the variable being attributed, can be used to inform the confidence that can be placed in attribution assessments. In situations where there is a high degree of predictability, for example in the case of the large scale pattern of North American temperatures in 2008 as analysed by Perlwitz (2010) and discussed above, a necessary component of model fidelity is that it is able to capture the predictable features of the weather or climate event in question. Where there is little predictability, the model should be able to capture the main impacts that attributable changes in climate could have on the statistics of the event in question.

Lessons learned and future research needs

In this section we outline the main lessons learned from research efforts to date and the principal research questions that need to be addressed for the production of timely and scientifically robust attribution assessments of extreme weather and climate events.

Definition of user requirements

It is clear that attribution forms a key part of any climate service, the essential bridge between monitoring and prediction services, that puts recent weather and climate conditions into a longer term context and relates what has just happened to likely future

changes. But there are many different potential users for such attribution information, including as discussed above for the public, in legal contexts, and to inform adaptation responses. While there may be many common requirements, different groups of users are likely to have different requirements concerning the specific questions they wish to see addressed.

Clarity about questions being asked

Many apparent discrepancies between attribution analyses of a particular weather or climate event can result from such analyses answering different questions. Attribution experiments using coupled models seek to determine the changed risk of an event overall, whereas attribution experiments using atmosphere only models and prescribed sea surface temperatures seek to determine the changed risk of an event given certain conditions of the oceanic state. The answer to the question of whether the Queensland flood of 2011 has become more or less likely as a result of anthrpogenic greenhouse gas emissions when there are La Nina conditions in the Pacific Ocean could be different than the answer to the question of whether it has become more or less likely overall irrespective of the ENSO state. The attributable change in risk as a result of the combined human influence on climate could be very different from the change in risk as a result of greenhouse increases alone. A finding that human influence has not contributed substantially to the magnitude of a particular extreme weather event may not be incompatible with a finding that human influences substantially altered the odds of such an event happening (especially a particular threshold exceedence). Therefore it is crucial to have clarity about the question being asked in event attribution.

Importance of a timely and scientifically rigorous assessment

Public and policy demands reliable information about the causes of extreme events in their immediate aftermath and yet there are no obvious authorities providing such information as a dedicated service. Further, what is available from a variety of sources often appears contradictory due to subtleties in interpretation, and is often poorly informed. For some purposes, for example to inform litigation, information would be required at a later date, although almost certainly also at a higher level of robustness. The tolerance of potential decision-making processes to uncertainties and errors in attribution assessments are uncertain and will be important to identify.

Relevance of objective assessments

Pre-determined thresholds for defining extreme weather and climate events, and pre-defined observational datasets and experimental protocols minimize the influence of subjective post-hoc reasoning and the attendant risks of cherry picking and selective use of evidence. Crucially, such definitions should be based on impact criteria and not on expectations of climate change. Some extreme situations of known high impact are amenable for *a prior* analysis of their probability of occurrence (for instance, droughts and heat waves), given expectations of near-term changes in boundary (e.g., ENSO, PDO) and/or external radiative forcings. This may thus involve assessments for the coming season, year, to decade, and could be conducted for regional scales with suitable methods.

Requirement for accurate and lengthy historical records

Observational records of sufficient length and quality are required to define extreme

events in relevant contexts. They are also needed to characterise the range of variability

in the particular climate variable and region of interest. In many regions observational

data are not available over multi-decadal timescales or the data contains unphysical

jumps or trends (inhomogeneities) related to measurement errors, changes in

observational systems, or other non-physical factors (eg Stott and Thorne, 2010).

Improvements in the robustness of the climate observing system, including

improvements in in-situ observations, supported by remote observations and weather-

forecast-related products (e.g. reanalyses), will be required to develop more reliable

monitoring and attribution systems.

Physical understanding of climate events is essential

Physical understanding complements a statistical modelling approach and is essential

for developing confidence in modelling and statistically based approaches. The 2010

Russian heat wave was an example of a climate extreme in which dynamical processes

played a dominant role in the event's origin, with its extreme intensity likely aided by

land surface feedbacks (Dole et al. 2011). Many extremes are likely to involve strong

regional processes. Rigorous assessments will therefore require validation that similar

physical and dynamical processes are represented in the process-based models being

used to the degree that reliable statistical inferences of event probabilities can be

inferred.

Event attribution requires modelling

Models are required in order to generate the counterfactual worlds and the possible

realities consistent with the current boundary conditions. Multiple models help assess structural modelling uncertainty and large ensembles help sample the tails of distributions, with statistical models being useful in many circumstances. Ensemble sizes need to be tailored for the application recognising that not all event attribution requires very large ensembles; for example Perlwitz et al (2009) find that 50 member ensembles are adequate to attribute the cool conditions in North America in 2008.

Event attribution is intimately linked to prediction

The process of assessing the cause(s) for climate events and extremes also addresses the question whether such events can be adequately simulated using current models and whether such events could have been anticipated. Attribution puts recent events into their historical context, both in the past and for the future. To the extent that causal factors can be identified and model deficiencies addressed, such understanding could lead to improved predictions of such events in the future.

Concluding remarks

Human influences have increased the risk of some extreme weather- and climate-related events, reduced the risk of others and, for some may not have affected the risk substantially. A few published studies have made assessments of particular events, reporting an attributable human influence on the probability of some (including the Autumn 2000 flooding in the UK, the 2003 European heatwave), no substantial human influence on the magnitude of others (the Moscow heatwave of 2010) and showing that some cold events are consistent with the interplay of on-going global warming and internal variability (eg the cold North American temperatures in 2008). It is important to

recognize that different questions have been addressed in such studies, such as whether human influence has altered the probability of occurrence of a particular event or its magnitude. While such initial studies demonstrate the potential for event attribution they also highlight many of the challenges still to be faced, as discussed in this article. In particular it will be interesting to see whether further research supports the conclusions of these first studies for the specific events they considered. An important consideration is that regional attribution resulting from one region is not necessarily portable to another region even when the two regions are relatively close geographically. Therefore future research will need to consider a wider range of regions and event types as well as investigate the robustness of attribution results for events already considered.

Despite the persuasive argument in favour of pre-agreed procedures and regular assessments so as to favour largely objective results not distorted by selection effects, some level of expert judgement will always be necessary for defining those procedures and in interpreting the robustness of and confidence in results. Any such judgement can only be based on a careful consideration of the reliability of an attribution assessment and therefore on the extent to which there is a good physical understanding of the causal links behind the event in question, and whether the relevant processes are captured adequately in the models used. Since anomalous atmospheric flow is often associated with extreme weather, assessments must capture such features and be able to reliably diagnose whether flow characteristics have changed as a result of human influence, or if not, be able to demonstrate that any attributable change in risk of the event in question is independent of possible changes in flow characteristics. Finally, reliable attribution

depends also on adequate monitoring and the generation of a reliable characterisation of the climate variability of the region in question.

While there are many possible users interested in event attribution, given the considerable uncertainties that remain, the potential of such information to societies can only be realised with the further underpinning research needed to develop physical understanding, and improve the observational and modelling basis. As the science develops, there is no substitute for testing our current capabilities against past and current events. The Attribution of Climate-related Events group seeks to do just that in order to develop the methodological basis of an authoritative attribution service. In the interim it will be important to manage expectations. While it is possible for an attribution service to provide quantitative results, it is much harder to provide carefully validated results that include sufficient well calibrated information that would enable a user to fully understand the capabilities and limitations of the information provided. Future progress in serving the needs of the public, policy makers and other stakeholders depends on further development of the underpinning science and effective communication of attribution results, including remaining uncertainties.

Acknowledgements

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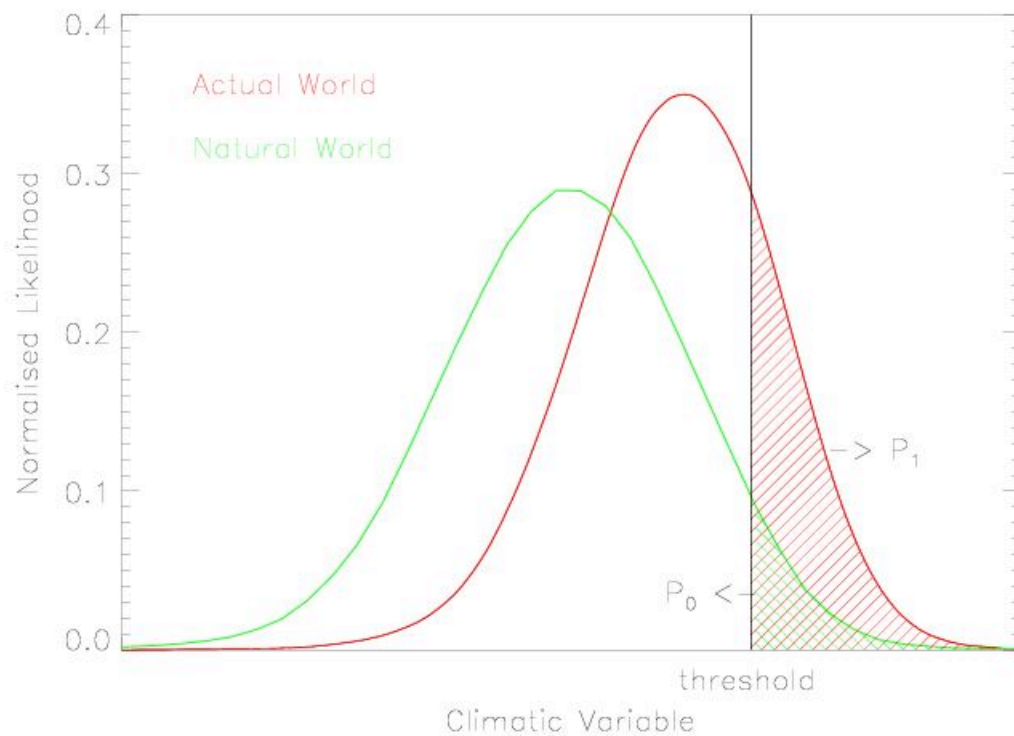
Figures

Fig. 1 A schematic illustration of the distributions of a climatic variable with (red) and without (green) the effect of anthropogenic forcings. The hatched areas mark the probability of exceeding a threshold value in the two climates. The FAR is the fractional change in the probability 1 - (P_0 / P_1).
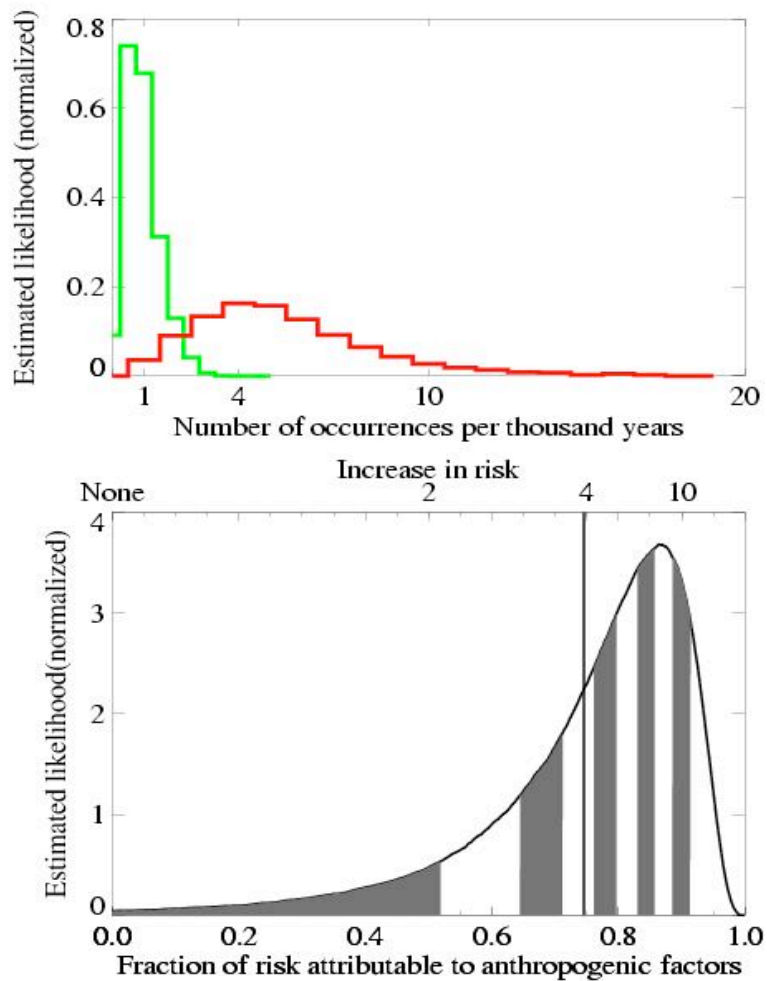
Fig 2: Change in risk of mean European summer temperatures exceeding the 1.6 K threshold. a, Histograms of instantaneous return periods under late-twentieth-century conditions in the absence of anthropogenic climate change (green line) and with anthropogenic climate change (red line). b, Fraction attributable risk (FAR). Also shown, as the vertical line, is the 'best estimate' FAR, the mean risk attributable to anthropogenic factors averaged over the distribution. From Stott et al (2004). Bands of white and shade underneath the curve represent ten percent bands of the distribution (ie 0 to 10%, 10-20% etc).
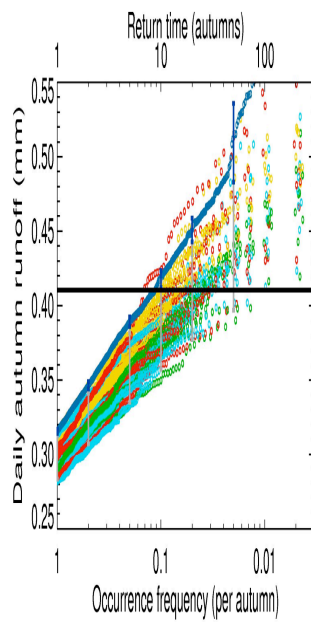
Figure 3. Return times for precipitation-induced floods aggregated over England and Wales for conditions corresponding to October-December 2000 with boundary conditions as observed (blue) and under a range of simulations of the conditions that would have obtained in the absence of anthropogenic greenhouse warming over the 20th century – colours correspond to different AOGCMs used to define the greenhouse signal, black horizontal line to the threshold exceeded in autumn 2000 – from Pall et al(2011).
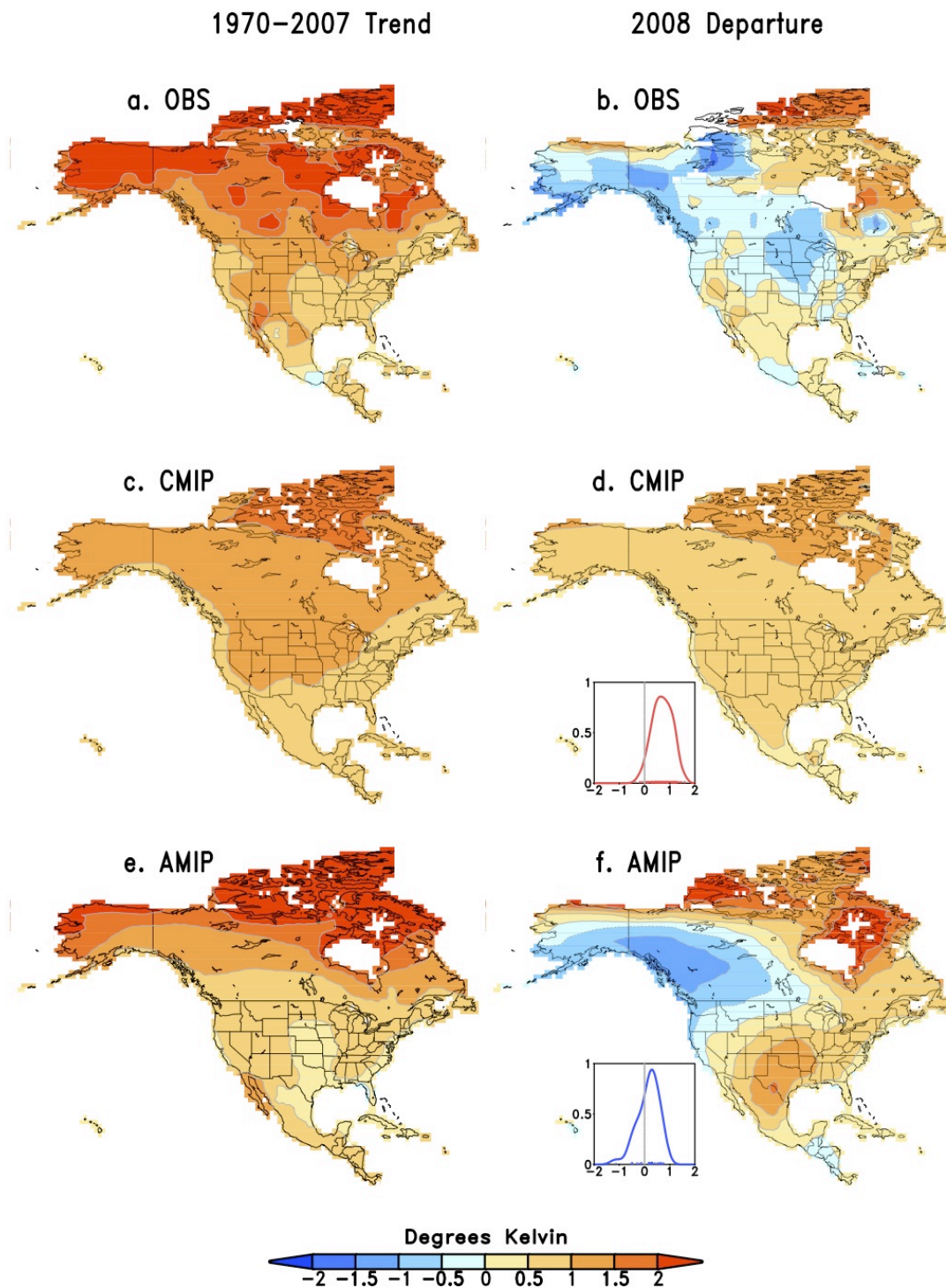
Fig 4 : (left) North American surface temperature change for 1970–2007 [K/38 yr] and (right) departures for 2008 (in [K] relative to 1971–2000 mean) based on (a and b) observations, (c and d) ensemble CMIP simulations, and (e and f) ensemble AMIP simulations. Inset in Figures 1d and 1f are probability distribution functions of the individual simulated annual 2008 surface temperature departures area-averaged over North America. The observed 2008 departure was near zero. (Figure 1 from Perlwitz et al. 2009)
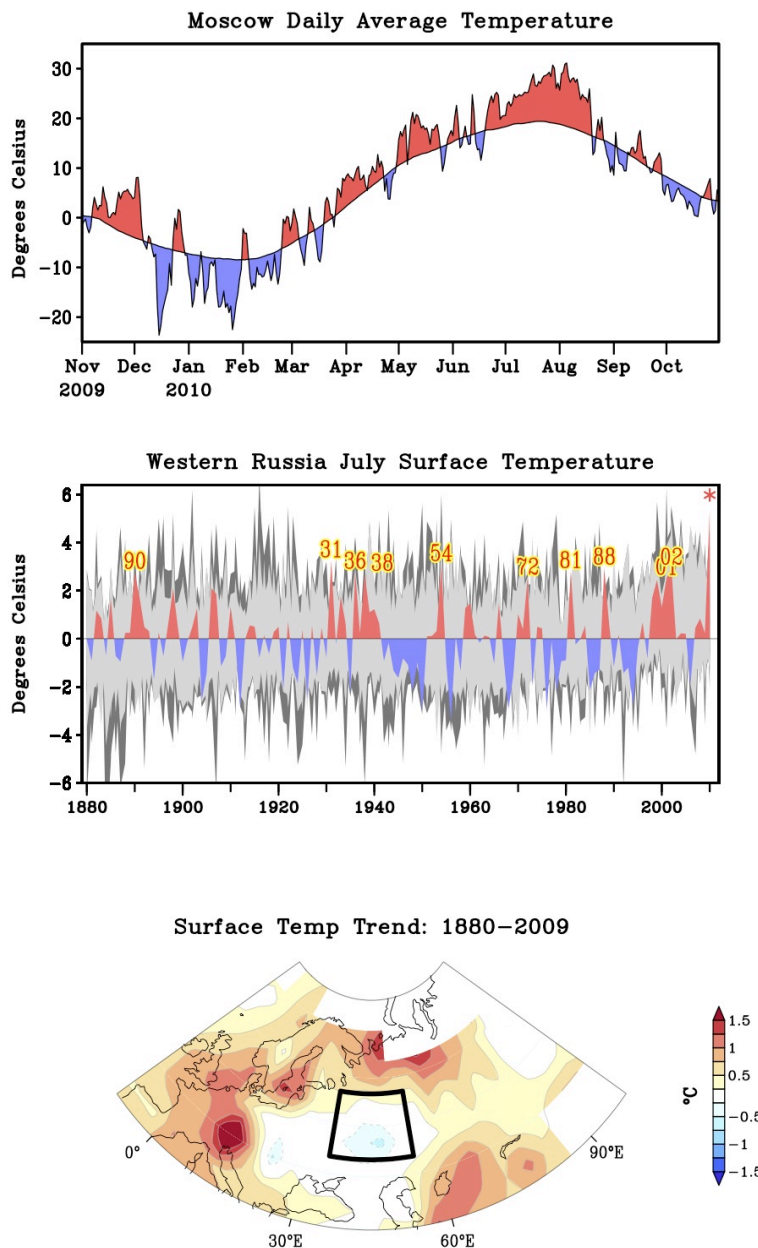
Fig 5 : (top) Daily Moscow temperature record from November 1 2009 to October 31 2010, with daily departures computed with respect to the climatological seasonal cycle. Data are from the Global Summary of the Day produced by National Climatic Data Center. (middle) Observed time series of western Russia July temperature anomalies for the period 1880 to 2010 indicated as positive (red) and negative (blue) temperature anomalies relative to the base period from 1880 to 2009. Numbers indicate the years of the ten most extreme positive anomalies. The red asterisk indicates year 2010. The light and dark shaded areas represents the envelopes of positive and negative monthly mean temperature extremes based on 22 CMIP3 model simulations for normalized and non   normalized anomaly time series respectively. (bottom) Map of observed July temperature trend [。C/130yrs] for July 1880– 2009. Box shows the area used to define " western Russia" surface temperatures.
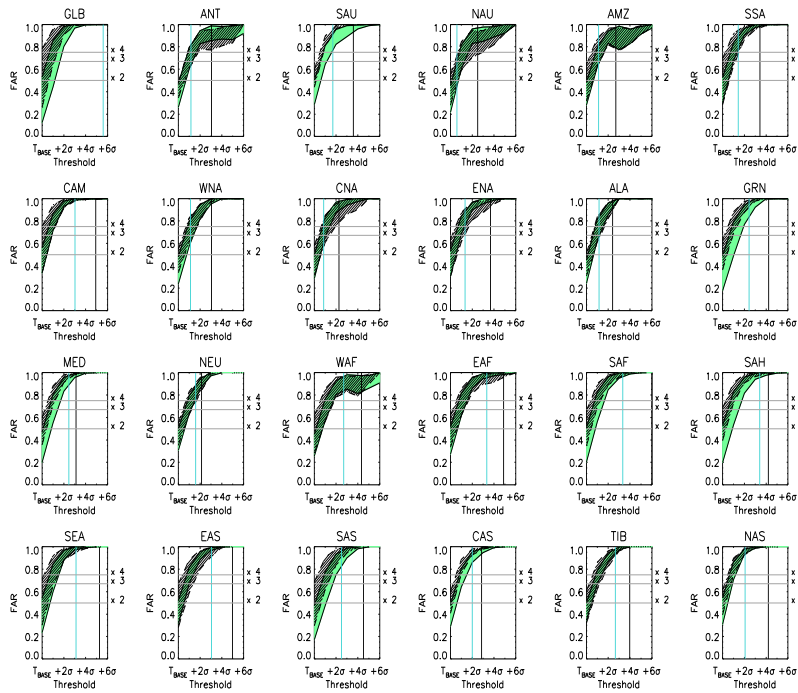
Fig. 6 Estimates of the FAR in different regions measuring how much anthropogenic forcings have increased the likelihood of exceeding a pre-specified annual mean temperature anomaly threshold during 2000-2009. Results are shown for a range of thresholds increasing from zero by multiples of the standard deviation which represents the effect of internal climate variability. The green and the black hatched areas illustrate the 5-95% range of the FAR computed with HadGEM1 and MIROC fingerprints respectively. The vertical blue line marks the annual mean temperature anomaly in 2000-2009. The vertical black line corresponds to the maximum annual mean temperature anomaly since 1900. The horizontal grey lines mark the FAR values which correspond to an increase in the likelihood of exceeding a threshold by a factor of 2, 3 and 4. From Christidis et al, 2011b.
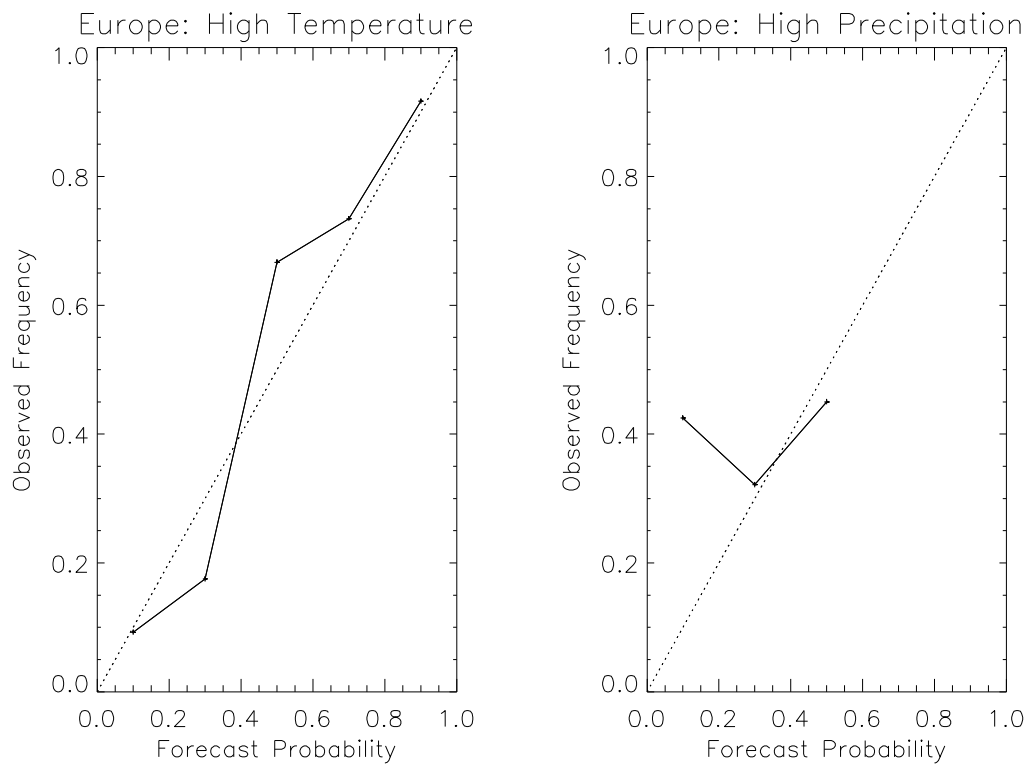
Fig 7: Reliability diagrams that assess the forecast skill of the model in predicting seasonal mean temperature (left panel) and precipitation (right panel) values averaged over Europe above the upper tercile of the 1971-2000 climatology. The NCEP/NCAR reanalysis was used to compute the observed frequency (*Kalnay et al.*, 1996).