Overview

Attribution of extreme weather and climate-related events

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Extreme weather and climate-related events occur in a particular place, by definition, infrequently. It is therefore challenging to detect systematic changes in their occurrence given the relative shortness of observational records. However, there is a clear interest from outside the climate science community in the extent to which recent damaging extreme events can be linked to human-induced climate change or natural climate variability. Event attribution studies seek to determine to what extent anthropogenic climate change has altered the probability or magnitude of particular events. They have shown clear evidence for human influence having increased the probability of many extremely warm seasonal temperatures and reduced the probability of extremely cold seasonal temperatures in many parts of the world. The evidence for human influence on the probability of extreme precipitation events, droughts, and storms is more mixed. Although the science of event attribution has developed rapidly in recent years, geographical coverage of events remains patchy and based on the interests and capabilities of individual research groups. The development of operational event attribution would allow a more timely and methodical production of attribution assessments than currently obtained on an *ad hoc* basis. For event attribution assessments to be most useful, remaining scientific uncertainties need to be robustly assessed and the results clearly communicated. This requires the continuing development of methodologies to assess the reliability of event attribution results and further work to understand the potential utility of event attribution for stakeholder groups and decision makers. © 2015 The Authors. *WIREs Climate Change* published by Wiley Periodicals, Inc.

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INTRODUCTION

Anthropogenic climate change provides a key challenge for mankind. The Fifth Assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) concluded that 'human influence on the climate system is clear' and that 'changes in many extreme weather and climate events have been observed since about 1950'.[1] Societies around the world are faced with increasing climate change risks. Reducing such risks, which requires a consideration of vulnerability and exposure to climate-related hazards, can be achieved through a combination of adaptation to those hazards that are unavoidable and climate change mitigation by reduction of greenhouse gas emissions.

Attribution of climate change has been defined as 'the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence.'[2] Therefore attribution is a key aspect of the understanding of climate change risks, many of which are associated with the occurrence of extreme weather or climate events. Such events have been defined as 'discrete episodes of extreme weather or unusual climate conditions, often associated with deleterious impacts on society or natural systems, defined using some metric to characterize either the meteorological characteristics of the event or the consequent impacts.'[3] Events can occur on a wide range of timescales from minutes to seasons or longer and on a wide range of spatial scales from a few kilometers to the size of continents. Therefore attribution can be applied to an extreme that could be classed as a weather extreme, such as a very high daily rainfall total, or an extreme that could be classed as a climate-related extreme, such as a very high seasonal mean temperature.

Often in the immediate aftermath of extreme events, there is great media and public interest in what caused them. There can be a tendency in some quarters to want to confidently attribute extremes to anthropogenic climate change in the absence of scientific consensus or to argue that it isn't possible to link individual extreme events with anthropogenic climate change, neither of which is correct. Given that many extreme weather and climate events have occurred before substantial anthropogenic modification of the climate system has been clearly detected in many regions, an over simplistic attribution to human causes could be costly. For example, based on the occurrence of a particularly damaging extreme event, plans could made to adapt to an increasing frequency of such events in future when in fact this is not what is expected.

There is a basic expectation that climate change will alter the occurrence of some extremes. Extremely hot temperatures are expected to become more frequent where mean temperatures increase. A simple shift in the mean without any change in the distribution will suffice although changes in the distribution can enhance or reverse this tendency.[4] For example, land surface feedbacks can exacerbate temperature extremes as soils dry out and fail to provide evaporative cooling to moderate temperatures, thereby broadening the distribution of summer maximum daily temperatures in continental interiors.[5] Atmospheric warming increases the moisture holding capacity of the atmosphere potentially increasing the prevalence of extreme rainfall events. These changes in temperature and rainfall extremes expected from thermodynamic considerations have been detected in the observed record[6,7] and climate models show that an increased occurrence of extreme temperature and rainfall events worldwide can be attributed to anthropogenic forcings.[7–9]

At regional scales and for individual extreme events, global statistics and thermodynamic arguments may no longer apply if the occurrence and evolution of climate extremes in a particular place is influenced by the atmospheric or oceanic circulation or when there are large external forcings on regional climate such as from tropospheric aerosols. While climate models appear to capture thermodynamic changes well, they may struggle to simulate circulation changes[10] and questions remain about what controls convection, changes in which can affect extremes,[11] and the position of the storm tracks and the tropical rain belts.[12] In the light of these difficulties, it could be decided to ignore dynamical changes and concentrate instead on how human-induced thermodynamic changes have affected extremes.[13] However, many event attribution studies consider how the probability of an event is changing. This forces consideration of both dynamical and thermodynamic influences because both can play a role in the changing probability of an event. Taking account of dynamical changes requires physical understanding to support attribution assessments and climate models used in such analyses need to be able to capture the salient physical features. Testing our understanding and our models against observed events helps to improve predictions of future changes through improved models and a deeper appreciation of why changes are occurring. The science of event attribution has developed considerably in recent years in response to a growing demand to explain recent extreme events from a climate perspective. Event attribution studies have sought to determine whether

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anthropogenic climate change has altered the probability or the magnitude of a particular event. Early examples include the European summer heat wave of 2003 that killed many thousands of people[14,15] and the flooding in the UK in autumn, 2000.[16]

A position paper presented to the World Climate Research Programme (WCRP) Open Science Conference in 2011 argued that there was a need to further develop carefully calibrated physically based assessments of observed weather and climate events.[3] Since then many other extreme events from around the world have been investigated including in an annual report explaining extreme events of the previous year from a climate perspective.[17–20] Such events are often selected for their severe and widespread impacts and the interest and capability of scientific groups in investigating them. Studies show clear evidence for human influence on some events and little evidence for human influence on others[19,20] and in some cases draw seemingly conflicting conclusions due to differences in the way the attribution question has been framed.[21]

This article discusses the challenges facing this newly emerging science of event attribution. Many of the current studies have focused on the meteorological nature of events, which we focus on here, rather than their impacts.

Methodologies section reviews the event attribution and *Evaluation* section considers the evaluation of attribution results in order to ensure they are reliable. The following section considers the influence of framing on attribution results. Over time, the regional coverage of event attribution studies has increased and this is discussed in the fifth section. Operational weather services have long provided current weather and weather forecasts to a variety of customers. More recently the operational provision of seasonal forecasts providing probabilistic predictions of future seasonal climate anomalies has become established. In a similar way there is the potential to deliver routine assessments of climate risks in an operational attribution system,[3] which is discussed in the sixth section. *Stakeholder Perspectives* section provides details of some stakeholder perspectives whereas the following section concludes with a brief summary.

METHODOLOGIES

Event attribution assessments seek to quantify to what extent anthropogenic or natural influences have altered the probability or magnitude of a particular type of event having occurred. Any climate event under consideration, for example, a heat wave, drought, or flood, has evolved in its own unique way and is therefore, in principle, attributable to a unique set of causes that is not applicable to any other event. However, event attribution assessments typically have wider applicability by considering some metric to characterize the extreme nature of the event in question. Therefore, event attribution assessments typically have relevance for the occurrence of similar types of events in future.

The concept of fraction attributable risk (FAR)[22] was first applied in 2004 in an analysis of the European heat wave of 2003.[14] This was the first instance of an event attribution study providing a direct link between anthropogenic climate change and an individual extreme climate event. To achieve this result, the probability (P_1) of a record warm summer in a particular European region was compared with its probability (P_0) had anthropogenic influences on climate been absent. This approach is shown schematically in Figure 1. These probabilities were determined from coupled climate model simulations calibrated to observations using optimal detection techniques.[14] The study concluded that human influence had very likely (probability >90%) more than doubled the probability of a record warm summer. Therefore, having calculated the probabilities of the event in the presence and absence of anthropogenic climate change, P_1 and P_0, the results can be expressed as a probability ratio, P_1/P_0, i.e., in this case a doubling of probability. Alternatively they can be expressed as a FAR, calculated as $1\text{-}P_0/P_1$ where a

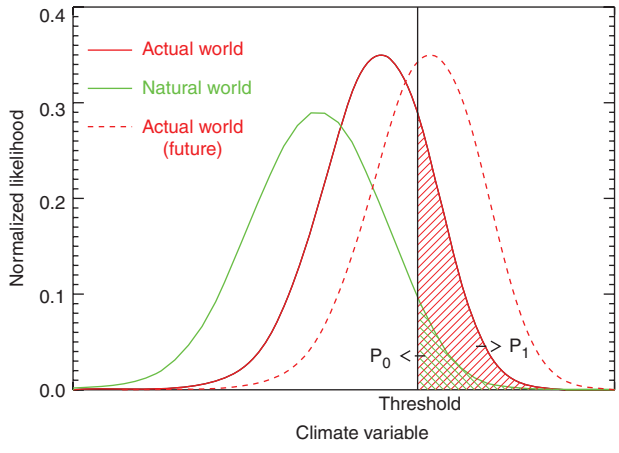

FIGURE 1 | An illustration of the Probability Density Functions (PDFs) of a climatic variable with (solid red line) and without (green line) the effect of human influence on the climate. The corresponding probabilities of exceeding a prespecified threshold (P_1 and P_0) are represented by the hatched areas of the same color. The red-dashed line illustrates how the PDF of the actual world may change in a changing climate.

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FAR of more than 0.5, as in this case, indicates its probability has more than doubled. This is equivalent to half of the instances of such events being attributable to anthropogenic climate change. An analogy is with a loaded die in which throwing a six is twice as likely as for an unloaded die. On repeated throws, a FAR of 0.5 corresponds to half the sixes being attributed to the loading of the die rather than to chance.

Subsequent research has shown that continued warming in Europe has increased the probability of such an extreme seasonal temperature event as seen in 2003 further (dashed line in Figure 1) and demonstrated the robustness of the earlier findings.[23]

Despite this reaffirmation of the robustness of the result, this early attribution finding shares with later studies using climate models a reliance on the fidelity of the models used. Climate models have errors that could invalidate attribution results. For example, tropospheric aerosol concentrations, which in recent years have reduced in Europe and increased in Asia, are potentially very important for regional climate change but also highly uncertain. There is further discussion of the evaluation of attribution results in *Evaluation* section. Clearly, all attribution assessments are contingent on our current understanding and are therefore liable to be updated as scientific understanding develops.

Confidence in attribution results can be enhanced where independent methods lead to similar conclusions. A variety of approaches have been taken to event attribution, differing in their use of observations and models, and in their framing of the attribution question being asked. We now describe the main methods used in event attribution.

Coupled Model Approaches

Coupled general circulation models (GCMs) of increasing complexity, which often include not only atmosphere, ocean, and land but also biological and chemical processes, provide the most comprehensive simulations of the climate system. Data from model experiments with different forcing combinations are readily available from the archive of the World Climate Research Programme's Coupled Model Intercomparison Project phase 5 (CMIP5)[24] and can be utilized in analyses of extreme events. This typically involves pooling data from multimodel ensembles of simulations with and without anthropogenic influences and so generating large samples of the relevant climatic variable (e.g. temperature, if investigating a heat-wave event). The distribution of the variable in the 'actual' world and the counterfactual 'natural' world without human influence on climate can thus be constructed, from which estimates of the FAR for the event under investigation are obtained. A number of studies of recent temperature and rainfall extreme events in Australia have employed this approach[25–28] and have shown that anthropogenic forcings have led to manifold increases in the likelihood of Australian heat waves, although their influence on rainfall extremes is less robustly identified. For such attribution assessments, it is important that the models employed in studies are rigorously evaluated against observations[29] (see *Evaluation* section).

Coupled model approaches have been employed to provide fast-track assessments, available as soon as an extreme event is observed. The changing likelihood of extremes is estimated with reference to prespecified thresholds, e.g., the temperature associated with a heat-wave event. By precomputing such estimates over a range of thresholds, attribution information becomes readily available when a new event occurs. This approach has been applied to annual and seasonal mean temperature extremes in subcontinental regions around the world by using an improved representation of the regional temperature distributions and introducing observational constraints from a global optimal fingerprinting analysis.[30]

An application of such a fast-track attribution methodology enabled the Met Office to issue an attribution statement on the record temperatures seen in 2014 in the UK (back to 1910) and Central England (back to 1659). Precomputed estimates of the FAR measuring the human-induced change in the likelihood of getting annual-mean temperatures in the UK above certain thresholds from the climatological mean to five standard deviations above it are illustrated in Figure 2. It is estimated that human influence has increased the likelihood of record-breaking temperatures in the UK by a factor of about 10 (best estimate of the FAR ~0.9). In a complementary study, the chances of the smaller region of England experiencing a record-breaking warm year, as seen in 2014, were found to have been made more than 13 times more likely as a result of anthropogenic climate change.[31]

In some cases, investigations are carried out into the attribution of events conditional on particular features of the climatic conditions present at the time of the event. For example, event attribution studies have investigated how anthropogenic influence under La Niña conditions has affected the likelihood of extreme rainfall seen in 2011–2012 over south-Eastern Australia[32] and the likelihood of extreme drought seen in 2011 over Texas.[33]

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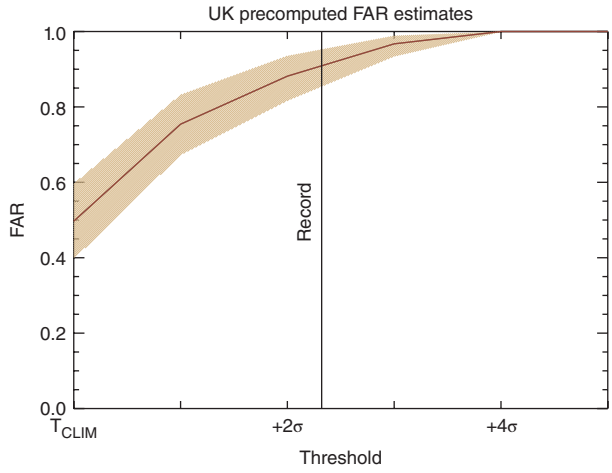

FIGURE 2 | Estimates of the fraction attributable risk (FAR) in the UK region (10°W–5°E, 48–60°N) over a range of temperature thresholds in units of standard deviation above the climatological (1961–1990) annual mean temperature. The colored area marks the 5–95% uncertainty range of the estimated FAR. The black vertical line corresponds to the UK record temperature.

Sea Surface Temperature Forced Atmosphere Only Model Approaches

Another way of conditioning results on aspects of the climatic conditions present at the time of the event is to prescribe observed sea surface temperature (SST) anomalies into an atmosphere only climate model. Thus, many event attribution studies contrast atmosphere-only general circulation model (AGCM) simulations representing the 'actual' world including the observed evolution of SSTs with simulations of the counterfactual 'natural' world, a 'world that might have been,' had there been no human influence on climate.[16,34]

As with coupled model approaches, this methodology also requires the availability of sufficiently large model datasets to simulate the statistics of the events in question, and relies on the model's ability to reliably simulate the climate conditions generating the extreme event. Prescribing SSTs in an AGCM rather than using coupled models can reduce model biases and enables more ensemble members to be simulated because they are cheaper to run, potentially resulting in a better representation of extreme events, and improved signal-to-noise ratio. However, this approach does not represent atmosphere–ocean coupling and so could lead to a worse representation of extreme events strongly affected by such coupling.

While removing the anthropogenic greenhouse gas forcing from the modeled atmosphere is straightforward, estimating the pattern of warming to be removed from the observed SSTs and sea ice is not. In the majority of studies, the warming patterns to be removed are obtained from coupled GCM simulations by subtracting 'Historical' SST simulations which include both anthropogenic and natural forcings (e.g., volcanoes and solar fluctuations) and the 'Natural' simulations which include only natural forcings. Figure 3 shows an example in which the assessment of the anthropogenic influence on the event is sensitive to differences in these patterns, hence in this case, it is important to use more than one counterfactual SST pattern. This can be a major uncertainty in attribution assessments and an alternative is to use SST patterns based on observations rather than models.[36]

Further experiments can be made using AGCMs to diagnose in more detail the anthropogenic influence on extreme events. For example, diagnostic simulations have been carried out in which SSTs and anthropogenic forcings from greenhouse gases and tropospheric aerosols have been varied separately to show that the hot dry summer in western Europe in 2013 was influenced substantially by anthropogenic forcing, whereas North Atlantic SSTs were shown to be an important factor explaining the contrast between the very dry summer of 2013 and the very wet summer of 2012.[37]

Analogue-Based Approaches

A further way of conditioning results on aspects of the climatic conditions present at the time of the event is to consider the observed circulation characteristics. Circulation analogs[38] have been designed to estimate climatic conditions in previous times under the same large-scale circulation as today.[39,40] Potentially it is one way to investigate how secular climate change has affected unusual climatic events.[13] An illustration of this approach is applied here to the Fall/Winter of 2006/2007, which was one of the warmest in Europe since 1500,[41] and the second warmest in France since the beginning of the 20th century. Euro-Atlantic sea-level pressure (SLP) anomalies from the 20CR reanalysis[42] for the 1900–2011 period and over the (80°W–60°E; 30°–70°N) domain are used to characterize the circulation type for each day starting from the beginning of the 20th century. The 'analogues' are found from the 20 days over the observed record which have similar circulation characteristics and the temperatures over these analogues are averaged. From a statistical perspective, the analogue temperatures are random 'replicates' of the temperature at the day conditioned by the atmospheric circulation. This allows a

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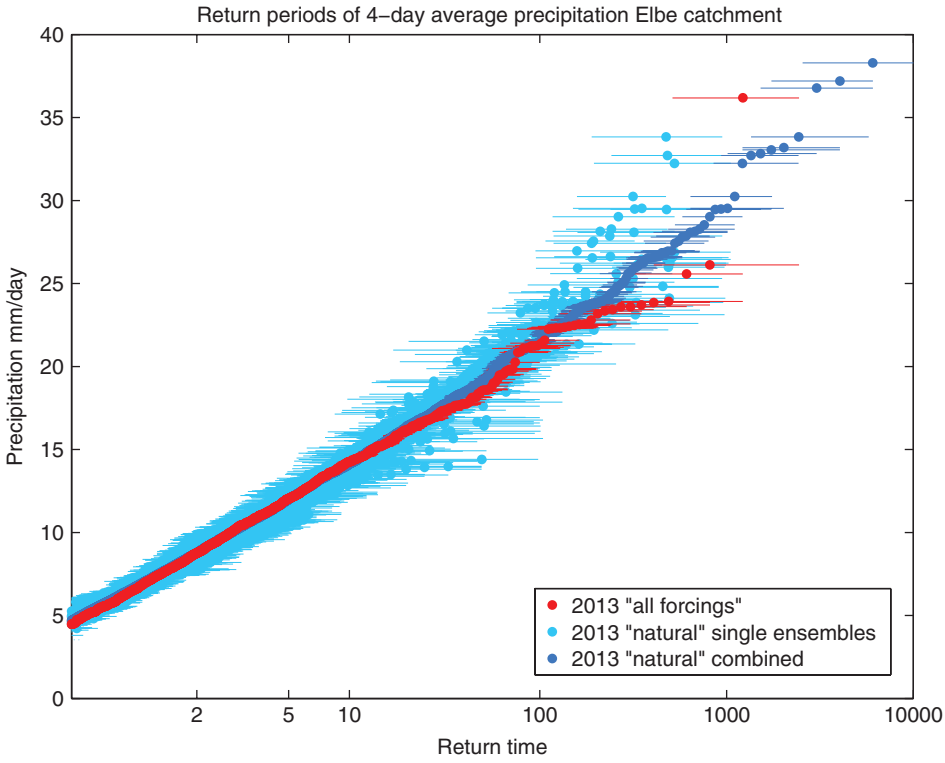

FIGURE 3 | Return time (years) for the maximum 4-day precipitation average during May to June in the HadRM3P model for the upper Elbe catchment. The red dots indicate May to June possible 4-day maximum precipitation events in a large ensemble of HadRM3P simulations of the year 2013, while the light blue dots indicate possible May to June 4-day maximum precipitation events in 25 different large ensembles of simulations of the year 2013 as it might have been without climate change where each of the 25 ensembles has a different sea surface temperature (SST) pattern to represent the anthropogenic change in SSTs. The dark blue dots represent the 25 natural ensembles aggregated together. The error bars correspond to the 5–95% confidence interval estimated with a nonparametric bootstrap. (Reprinted with permission from Ref 35. Copyright 2014 American Meteorological Society)

determination of the probability distributions of temperature variability driven by the atmospheric circulation.

Having derived circulation-dependent temperature distributions one can calculate the probability of the event in question, as measured in this illustration by the frequency of days within the cold season for which the observed temperature is above all analogue temperatures. This statistic was a record in 2006–2007 (Figure 4).

The probability P_0 of observing the record during the period 1900–1960 is estimated to be about 0.0007 compared to a probability P_1 during the period 1970–2011 of about 0.03, which indicates a more than 40-fold increase in probability between the two periods, implying a FAR of about 0.97 (estimated to be between 0.87 and 0.98 with a bootstrap estimate of uncertainty). Unlike the methods described in *Coupled Model Approaches* section and the following section, which explicitly model the world that might have been absent anthropogenic forcings, these analogue-based approaches provide a probabilistic attribution of an extreme event to the overall climate change over the period considered, howsoever caused, with the assumption that periods considered are long enough to cancel any low-frequency natural climate variability.

Empirical Approaches

Empirical approaches applied to observations directly have been used to estimate how climate change is affecting the probability or return times of particular classes of events. The odds of record-breaking temperatures can be related to increasing mean temperatures[43,44] and the odds of record-breaking daily rainfall events can be related to atmospheric warming and the associated increased water holding capacity.[45] Resultant estimates that long-term warming has caused a fivefold increase in the number of local record-breaking monthly temperature extremes worldwide[43,44] and has led to 12% more record-breaking rainfall events[45] are broadly consistent with estimates using climate models that about 18% of

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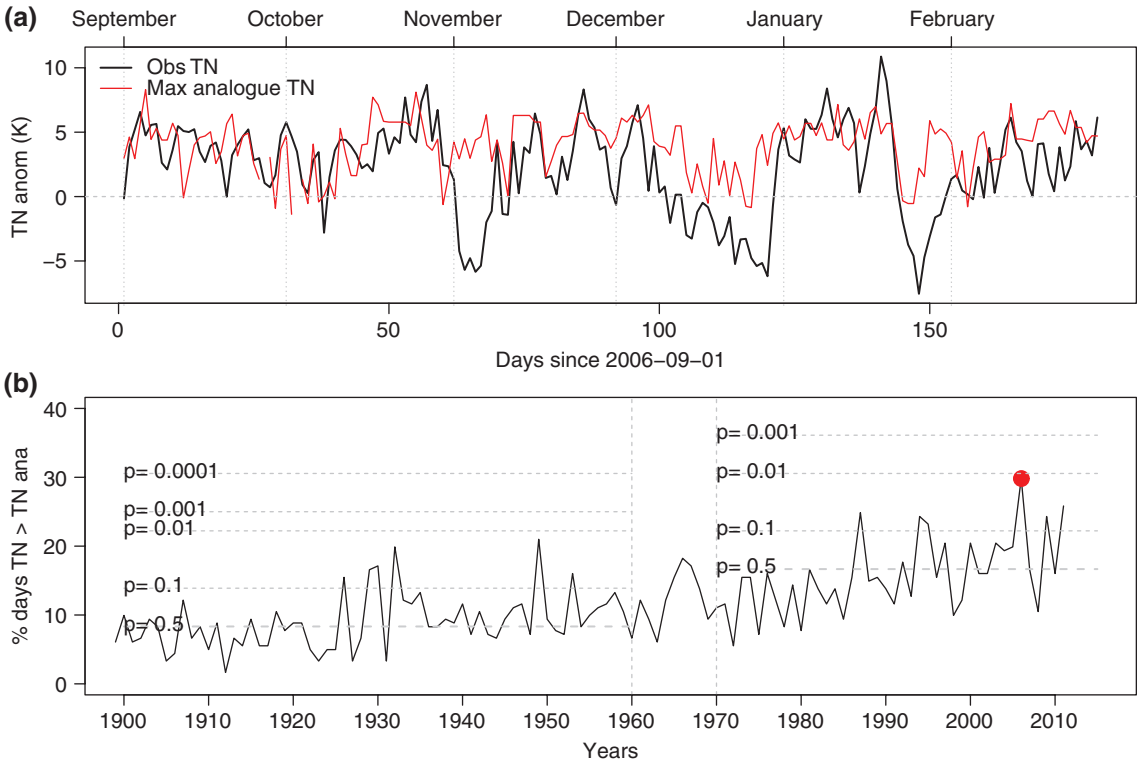

FIGURE 4 | Example of an analogue-based approach. (a) Temperature mean anomalies of minimum daily temperature (Paris, Toulouse, and Besançon) between September 2006 and February 2007 (black line). Maxima of analogue temperatures (red line). (b) variations of the fraction of observed temperatures above all analogue temperatures between September and February. The red circle indicates the record of 2006/2007. The horizontal-dashed lines indicate the quantile values of a binomial distribution that is fitted to an unperturbed period (1900–1960) and perturbed period (1970–2011).

moderate daily precipitation extremes, and about 75% of moderate daily hot extremes, currently occurring over land, are attributable to warming.[9,46] Empirical approaches can thus serve as a check on model results and are often appreciated by the users who are skeptical of the veracity of climate models, even though it necessarily also makes assumptions. They can also be employed for events that cannot yet be represented well by climate models used for attribution, such as extreme summer convective events.

An empirical approach to event attribution by fitting observed data to statistical distributions has been used to show that climate change did not play a major role in the 2011 floods in Thailand.[47] A non-significant downward trend in rainfall in the upper Chao Praya basin in Thailand found in this analysis, agreed with a similar lack of increasing trends in climate models.

Other such analyses show positive results. For example, the cold waves in the United States observed in early 2014 are found to be significantly less likely[48] although they are still not uncommon, with a return time in 2014 of about 12 years compared to a return time in 1950 of about every 4 years (Figure 5). For spatially small events such as summer thunderstorms data from stations that are close enough to be identically distributed and far enough apart to be reasonably independent can be pooled. The methods used to derive the results shown in Figure 5 have been incorporated into the public climate analysis website KNMI Climate Explorer.

Broad-Scale Approaches

While the analogue and statistical methods described in sections *Analogue-Based Approaches* and *Empirical Approaches* consider the overall effects of climate trends, attributing such changes to anthropogenic or natural causes requires the use of a climate model as described in the section *Coupled Model Approaches* and the following section.

Climate models additionally come into their own in describing the global statistics of similarly defined events over the globe. Several studies have adapted detection and attribution methods[49] used to attribute changes in the mean state of the climate

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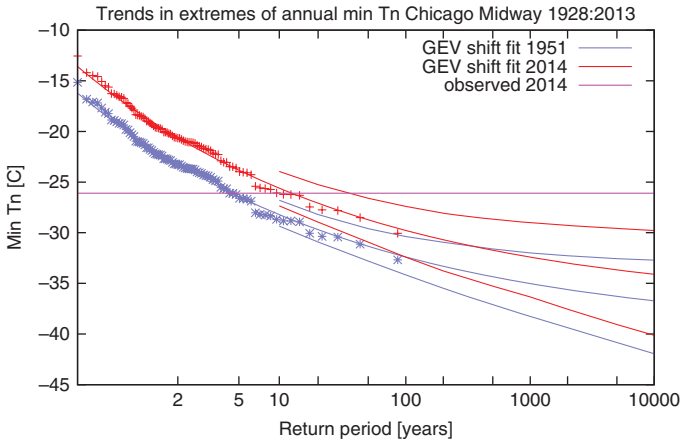

FIGURE 5 | Generalized extreme value (GEV) distribution fit to the coldest temperature of the year at Chicago Midway station 1928–2013 compared to the value observed in 2014. The distribution of the temperature is assumed to shift with the smoothed global mean temperature. The red lines indicate the fit for the climate of 2014, the blue lines indicate the fit for an earlier climate. The observations have been drawn twice, once shifted up with the fitted trend to the current climate, once down to the climate of 1951.

system[50] to analyses of changes in the frequency or intensity of specific types of extreme events. Such studies are sometimes able to provide information that is relevant to event attribution, particularly for predefined events and on larger spatial scales.

One such example considered observed changes in the annual minimum and maximum extremes of daily minimum and maximum temperature over 1961–2000 to show that, globally, extreme annual minimum daily minimum and maximum temperatures (i.e., the temperatures of the coldest night and coldest day annually) that would have been expected to recur once every 20 years on average in the 1960's had become substantially more unlikely to occur due to human influence on the climate system.[6] Expected recurrence times were estimated to have increased to 35 and 30 years, respectively, in the 1990s. In contrast, anthropogenic forcing was estimated to have increased the likelihood of extreme warm events (hottest night and hottest day of the year) by a similar factor, with expected recurrence times having decreased to 10 and 15 years, respectively.

Changes in the extremes of annual maximum 1-day and 5-day precipitation accumulations have also been shown to have been caused by human influence.[7,8] Over the period 1950–2005 for a Northern Hemisphere land domain, the increase in the intensity of annual extreme 1-day precipitation attributed to human influence has a sensitivity of change per degree of warming in global mean temperature that is consistent with the Clausius–Clapeyron relation (that expresses how moisture increases in a warming atmosphere when relative humidity stays constant). By interpreting the attributed change in terms of a reduction in the waiting time for a 20-year extreme event in the 1950s to approximately 15-years now, the FAR of such extreme events is 0.25. In contrast, for annual and seasonal mean regional temperatures that would have been 1-in-10-year events in an unperturbed climate, estimates of FAR have been found that are often well in excess of 0.75 or higher, both for annual and JJA mean temperatures.[30] For comparison, an analysis of extreme thresholds of daily temperatures and daily rainfall totals in models including those expected to occur once in 1000 days (about once every 3 years) in an unperturbed climate, finds that about 75% of these moderate daily hot extremes and about 18% of moderate daily precipitation extremes over land are attributable to warming.[9]

These approaches demonstrate the strong link between conventional detection and attribution and event attribution. They avoid selection bias since event definitions are not driven by impacts that have just been experienced (and may have received high media profiles). Being based on detection and attribution methods, they also allow projections of future risk to be observationally constrained.[51] However, they also have a number of limitations. Detection and attribution techniques for extremes are not yet fully developed, and detection and attribution remains difficult on regional and smaller scales, particularly for variables other than temperature, such as precipitation, for which evidence of a human influence is only just beginning to accumulate.

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EVALUATION

As many of the methods for attribution of extreme events rely largely on climate model simulations, providing evidence that the models employed in a study are fit for purpose is essential in order to demonstrate the degree of confidence one can have in the results. A model is likely to have different skill in reproducing different types of extremes in different regions and therefore its evaluation assessment needs to be tailored to the event under consideration. The synoptic circulation prevalent at the time of an extreme event may play a key role in its development and models need to be able to reproduce the same kind of circulation patterns with a realistic frequency to be suitable for an attribution study. For example, the heat wave in Russia in July 2010 was associated with a quasi-stationary anticyclonic circulation which needs to be reproduced by models used in an attribution analysis of the heat wave.[34] The ability of models to accurately simulate the physical processes and mechanisms linked to extremes is also crucial. For example, attribution studies of the summer heat wave of 2012 in the United States, needs to account for the effect of the stable atmosphere on the surface energy budget, which led to a decrease in soil moisture and surface evapotranspiration and an increase in temperature.[52] Finally, models need to be assessed in terms of their representation of modes of internal variability that are known to be primary drivers of regional extremes.

Evaluation assessments are typically based on comparisons between model data from a small ensemble of multidecadal simulations of the actual climate during a recent climatological period and observations or reanalysis data. Figure 6 illustrates some common tests[34] to examine whether HadGEM3-A would be a suitable model for studies

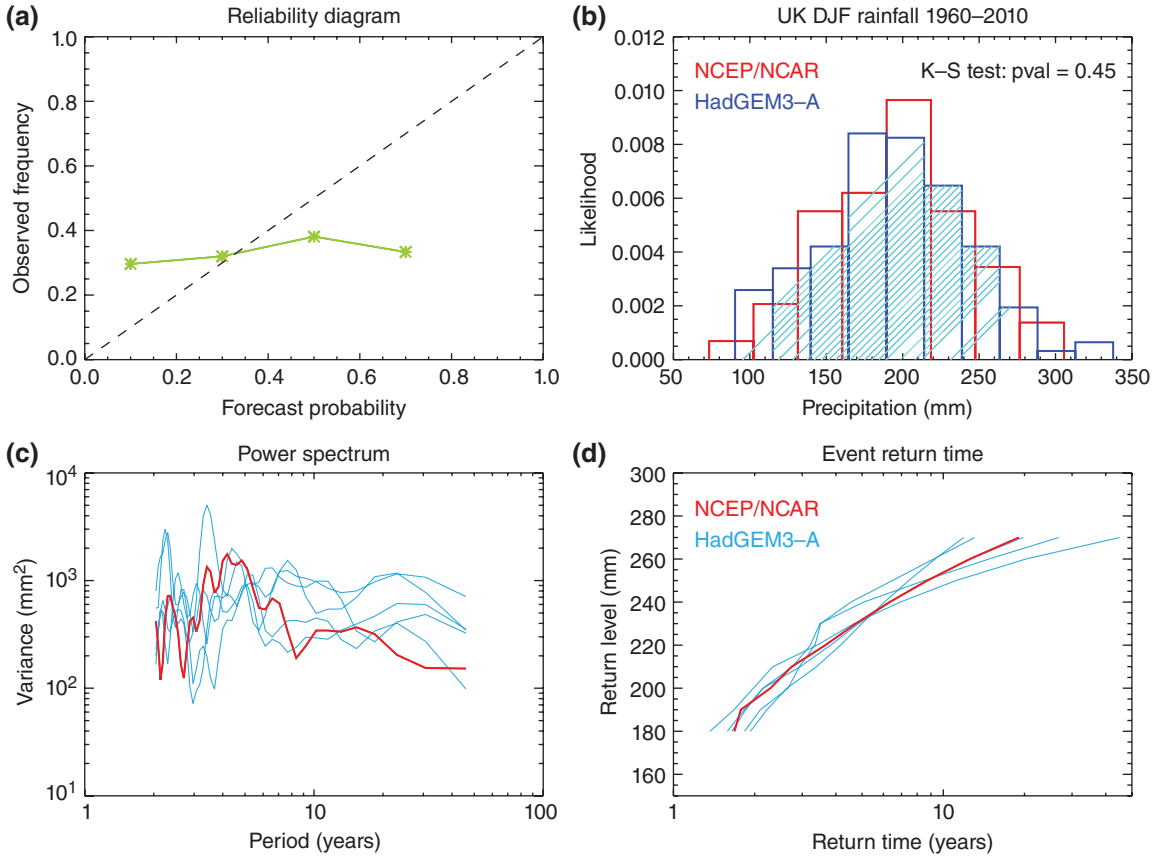

FIGURE 6 | Evaluation assessments of HadGEM3-A to determine whether the model is suitable for attribution studies of extreme winter rainfall events in the UK. (a) Reliability diagram for wet events in the UK, defined relative to terciles of the 1960–2010 climatology. (b) Normalized distributions of the winter rainfall in the UK during 1960–2010 produced with data from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (red) and five HadGEM3-A experiments (blue). (c) Power spectra corresponding to winter rainfall time series based on data from reanalysis (red) and five model simulations (blue). (d) Return time of winter rainfall events in the UK estimated with order statistics, or, for extreme thresholds, with the generalized Pareto distribution. Results plotted in red correspond to the NCEP/NCAR reanalysis and results plotted in blue to the five model simulations.

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of extreme winter rainfall in the UK region, similar to the recent extreme event during the catastrophic storms and floods of 2013/2014.[53] Five model simulations of the climate in 1960–2010 are used for this assessment which were run with observed SST and sea-ice data as boundary conditions and include all (both natural and anthropogenic) major external forcings. A seasonal forecast reliability diagram[54] indicates whether the model is able to capture the predictable features of the event under consideration (Figure 6(a)). Although the use of reliability is well established for forecasting, its meaning for attribution is less clear[55] given that reliable attribution is still possible when there is no inherent real-world predictability.

For the example of extreme winter rainfall in the UK, further tests can be undertaken to establish whether the modeled statistics for this kind of event are reliably reproduced with HadGEM3-A. Figure 6 (b)–(d) illustrates different aspects of the winter rainfall distribution and show how the model compares with the reanalysis. A Kolmogorov–Smirnov test indicates that there is no significant difference between the distributions constructed with HadGEM3-A and reanalysis data over period 1960–2010 (Figure 6(b)). The power spectra of rainfall timeseries over the same period (Figure 6(c)) also suggest that the simulated variability is generally consistent with the observations, albeit possibly higher at multidecadal timescales. Focussing on the warm tail of the distributions, the return time of high rainfall events has been estimated with a generalized-Pareto distribution (Figure 6(d)) and again the model is found to agree well with the reanalysis. Although the length of the simulations does not allow extrapolations to rarer events, the above assessments provide some evidence that HadGEM3-A would be suitable for attribution studies of extreme rainfall events in the UK region.

Model evaluation is subject to the availability and quality of observations. Identification of a clear signal of change in the observations often requires long time series of homogenous data but an evaluation of a model's representation of the most relevant processes for a particular event may be achieved with high spatial resolution data that are not available over long time frames. Thus, homogenized multidecadal datasets may be needed for some applications such as signal detection whereas reanalyses or satellite data may be appropriate for others such as model verification.

Clear evidence for human influence on extreme temperature events seen in many studies[20] benefits from robust observational support, whereas mixed evidence for human influence on extreme precipitation events[20] can be affected by inadequacies in observations in many parts of the world,[56] as well as limitations in models' representation of cloud processes.[57]

Evaluation methodologies similar to those discussed in this section have been routinely employed in studies of extremes. In some cases, bias corrections methods need to be applied to adjust modeled distributions although such corrections can strongly influence the attribution assessment and hence should be applied with caution.[58] Further development of evaluation methodologies will support additional evidence to stakeholders of the value of attribution products.

FRAMING OF THE ATTRIBUTION QUESTION

The various approaches described in *Methodologies* section are scientifically legitimate methods of framing attribution questions. But applying different methods can lead to very different assessments of change in risk even if the event considered is the same. Hence, it is paramount to clearly state the exact framing of the research question being asked.[59]

Attribution results can depend strongly on the definition of the event. Any particular event will never occur exactly the same way again so for an attribution statement to say something relevant to the future it has to be constructed for a class of events of which the one that occurred is a representative. Typical definitions of an event are for temperatures or rainfall averaged over a certain area and time to be above or below a particular threshold. Defining an event over a large area and long timescale reduces the natural variability and therefore tends to give larger FARs than more impact-based definitions focusing on small-scale extremes that may be more closely related to damage. Defining a class of events very close to the observed one tends to gives very low probabilities of occurrence. For more generalizable statements, a wider class of events needs to be considered for which details such as exact location or timing can differ.

Attribution results can also differ depending on whether an event is attributed to the overall climate change as in *Analogue-Based Approaches* and *Empirical Approaches* sections or to the change attributable to anthropogenic factors (sections *Coupled Model Approaches* and *SST Forced Atmosphere*).

The attribution of an anthropogenic contribution can be conditioned on the natural variability being in a certain state. If the probability of this

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condition is itself changing, then the overall probability of the event could be very different than the conditional probability. For example, a study of the extreme flooding in Colorado in September, 2013 concluded that the probability of such an extreme 5-day September rainfall event had likely decreased due to climate change as a result of changes in atmospheric circulation and vertical stability[60] in apparent contradiction to an analysis focusing on the effects of human influence (via increased SSTs and increased atmospheric moisture) conditioned on the atmospheric circulation regime during the event[13]

Some attribution assessments that link events to dynamically driven changes in circulation have been criticized on the grounds that small signal-to-noise ratios, modeling deficiencies, and uncertainties in the effects of climate forcings on circulation render conclusions unreliable and prone to downplaying the role of anthropogenic climate change.[13] Instead, it is argued, it is more useful to consider how changes in the climate's thermodynamic state have affected the impact of a particular event.[13] The analogue-based approaches are consistent with this approach in considering how climate change has affected events given particular circulation characteristics. But a wider variety of approaches as described in the rest of *Methodologies* section are needed to tackle the whole attribution problem which is important given that changes in global SLP patterns and corresponding circulations have been detected.[61] By always finding a role for human-induced effects, attribution assessments that only consider thermodynamics could overstate the role of anthropogenic climate change, when its role may be small in comparison with that of natural variability, and do not say anything about how the risk of such events has changed.

The importance of such framing issues mean that clear communication of results from such attribution studies is vital else apparently contradictory findings can result. For example, whereas the Russian heat wave of 2010 has been found to have been made much more likely by anthropogenic climate change,[43] its magnitude has been found to be largely attributable to natural variability[62] an apparent contradiction that can be resolved by considering the changing distribution of temperature extremes under a warming climate[21] as shown in Figure 7.

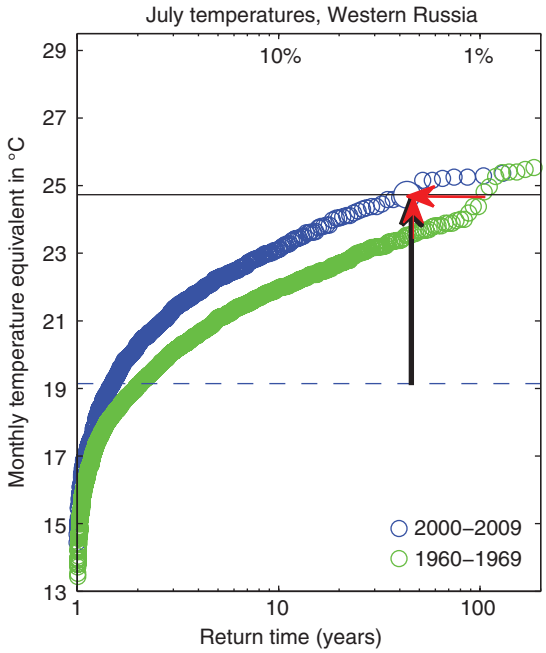

FIGURE 7 | Return periods of temperature-geopotential height conditions in the model for the 1960s (green) and the 2000s (blue) and in ERA-Interim for 1979–2010 (black). The vertical black arrow shows the anomaly of the Russian heat wave 2010 (black horizontal line) compared to the July mean temperatures of the 1960s (dashed line). The vertical red arrow gives the increase in the magnitude of the heat wave due to the shift of the distribution whereas the horizontal red arrow shows the change in the return period.

REGIONAL PERSPECTIVE

As the science of event attribution has developed, there has been an increase in the geographical coverage of such studies. This is important for the development of the field, not only in applying such science in new areas but also in developing scientific understanding by considering regions with different dominant modes of internal variability and different responses to external climate forcings.

Since 2012, a series of annual reports have been published in the Bulletin of the American Meteorological Society (BAMS) explaining extreme events of the previous year from a climate perspective.[17–20] They provide an early example of how the development of the underpinning science of event attribution is being applied to answer topical questions about real-life events around the world. Geographical coverage in the first three reports was far from uniform (Figure 8) with a greater concentration of studies into events in Europe and North America and some gaps in South America and much of Africa. However, the latest report explaining extreme events of 2014 includes a much wider geographical spread in its 32 studies with events from South America and Africa being considered in additional to events from Europe, North America, Australasia, and Asia.[20]

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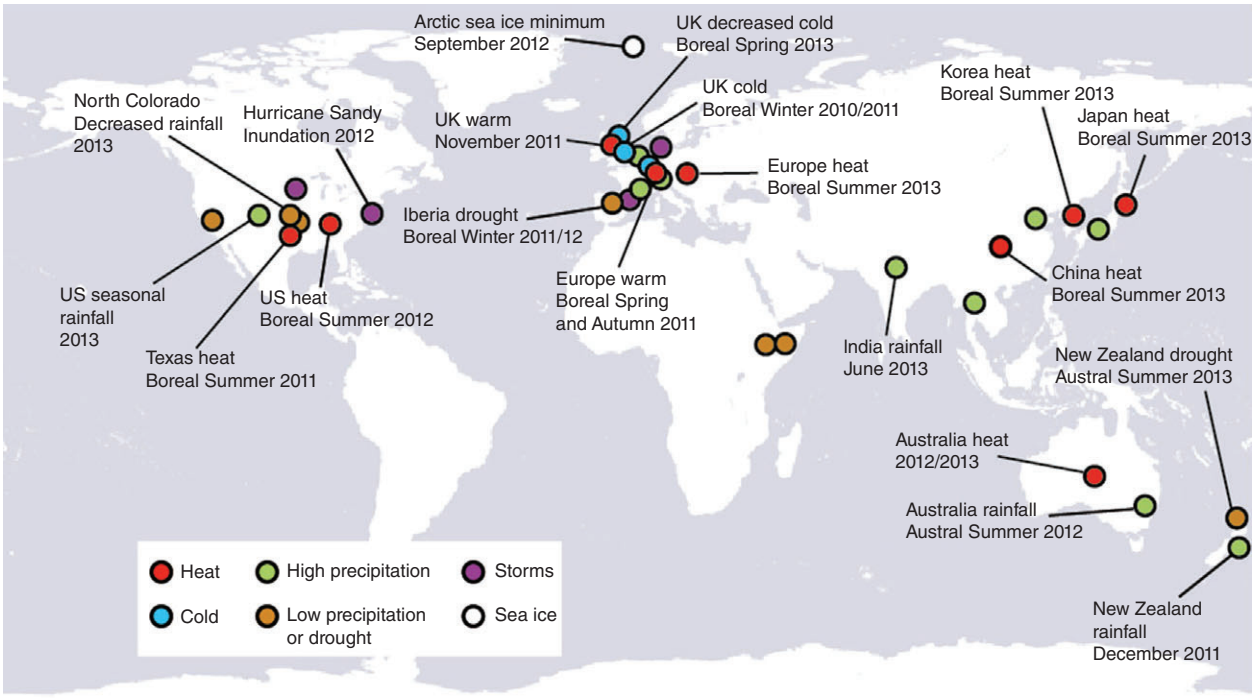

FIGURE 8 | Events considered in the three reports explaining extreme events of 2011, 2012, 2013 (Ref 17–19) indicating whether they are heat, cold, high precipitation, low precipitation or drought, storms, or sea-ice events.

Asia is one region where there has been a strong growth in interest in event attribution.

As an example, the 2013 summer saw extraordinarily high temperatures in the region with record warm temperatures observed over an extended region including Eastern China, Korea, and Japan. There was interest therefore in placing this event in the context of climate variability and change given that anthropogenic influence has been detected in changes in annual extremes of daily maximum and minimum temperatures in China.[6,63] An event attribution study of the hot summer of 2013 in Eastern China found that anthropogenic influence caused a more than 60-fold increase in its probability.[51] This result indicates that the increasing frequency of extreme summer heat in Eastern China is primarily attributable to the anthropogenic emission of greenhouse gases with rapid urbanization and the expansion of urban heat islands contributing as a secondary factor. With continued emissions 50% of summers could be hotter than the 2013 summer in only two decades (Figure 9).

Complementary studies have analyzed this event from different perspectives using different approaches and focusing on different countries. Results show consistent and clear anthropogenic

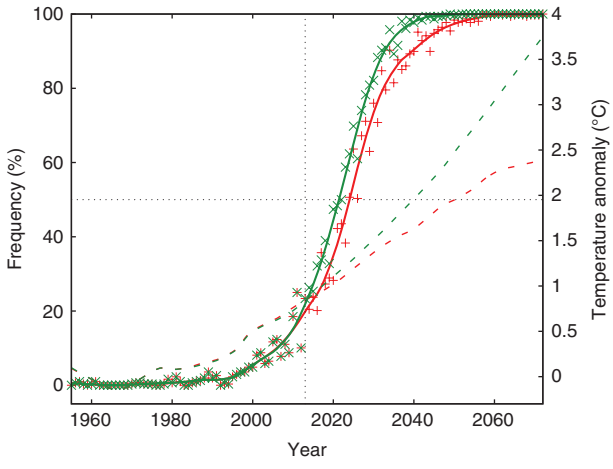

FIGURE 9 | Time evolution of the frequency of summer temperature anomalies above 1.1°C, relative to the 1955–1984 mean, in the reconstructed observations (1955–2013) and in the observationally constrained projections (2014–2072) under RCP4.5 (plus) and RCP8.5 (cross) emission scenarios (left-hand scale). The solid smooth curves are LOESS (local regression) fitting. The dashed curves represent projected ensemble mean temperature changes under the relevant emission scenarios (right-hand scale) and are shown here for reference. Results for RCP4.5 and RCP8.5 are represented by red and green, respectively. (Reprinted with permission from 51. Copyright 2014 Nature Publishing Group)

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influence on the probability of extreme temperatures in Korea[64] and Japan[65] associated with this very large-sale high temperature event, as well as also highlighting the role of natural variability in contributing to the magnitude of the extreme temperatures recorded.

DEVELOPMENT OF OPERATIONAL EVENT ATTRIBUTION

Given that there are often conflicting messages given by scientists in the immediate aftermath of damaging climate events about whether there is a link to climate change, well communicated assessments based on carefully calibrated operational attribution systems have been proposed as a way forward to address this confusion.[3] As well as providing more timely assessments of events, operational systems could address the selection effects inherent in the current *ad hoc* nature of attribution studies, events often being chosen based on scientists' individual preferences rather than any more objective criteria which has resulted in uneven geographical coverage and which has limited the potential to draw widespread conclusions from the current collection of *ad hoc* studies.

An operational event attribution service would provide regular updates using predetermined selection criteria for events and previously established methodologies. It could provide assessments on a range of timescales, during and immediately following an event, monthly or seasonally, and for publication in annual assessments.[17–20] Operational attribution assessments should aim to synthesize the available information including results from a range of methods and incorporating physical understanding in addition to models and statistics. A fast-track capability for assessment on media timescales would require the use of empirical statistical methods as described in *Empirical Approaches* section, ensembles of AGCMs with forecast SSTs or precomputed results from coupled models[30] (see *Coupled Model Approaches* section). More detailed assessments, conditioned on details of the observed climate evolution, and seeking to determine how aspects of the event in question have been affected by particular components of natural and anthropogenic influence, could be made monthly based on operational modeling systems that prescribe relevant features, such as observed SSTs[34] (see *SST Forced Atmosphere* section). Studies that adopt more tailored approaches could be published in the annual reports explaining extreme events from a climate perspective[17–20] or the general literature.

An important requirement for any operational attribution system is a clear communication of the robustness of results and of how attribution questions have been framed (*Attribution Question* section). Evidence with potential users of such information has shown that clear communication of scientific uncertainties supports rather than impedes the credibility of assessments for decision making.[66] Furthermore the comprehensive approach of an operational system, no longer dependent on *ad hoc* choices of research teams and subject to accusations of selectivity in choice of events to study, is attractive to users in enabling them to see how individual events fit in to a wider picture of climate change.[66] While human influence on the climate system is clear, carefully designed operational attribution systems should help societies understand how they are being affected by climate change and how to avoid the worst outcomes.[46]

STAKEHOLDER PERSPECTIVES

The high volume of media enquiries received by climate scientists in the aftermath of many extreme climate events shows that there is a demand for event attribution but that the whole range of possible uses for such information is not yet fully understood.[66,67] Better information about climate risks could be of potential use to the insurance industry, to regional managers developing climate adaptation strategies, to litigators, to policy makers and for disaster risk reduction.[3] But profitable use of such information requires a dialogue between stakeholders and scientists that allows the development of trust as a way to develop the credibility, saliency, and legitimacy of scientific findings.[66,68]

The credibility of event attribution is aided by objective communication of the links between climatic changes and the impacts of extreme events.[66] Successful communication of scientific findings requires the use of language adapted to lay understanding, noting that some terms such as extreme event may not be widely understood or such as 'attribution' may not translate easily into other languages such as German.[69,70] The legitimacy of event attribution for stakeholders is affected by their values and beliefs,[66,71] which may be influenced by vested interests in welcoming or rejecting climate of anthropogenic climate change and may reflect different risk cultures. The saliency of event attribution assessments for users depends on whether they provide knowledge that is relevant to them.[66] If the statistical rarity of attaining a threshold for a specific physical

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measure makes a specific event salient to a climate scientist, saliency for a stakeholder may be associated with impact-related dimensions as well. A shift of the probability of extremes in terms of casualties, economic losses, or redistribution of wealth, could be 'attributed' to multiple factors associated with climate, vulnerability, and exposure. Extreme event identification by stakeholders may therefore be dependent upon the causal chain they are mobilizing (see Figure 10).

When stakeholders consider that attribution is multifactorial, this potentially complicates the 'attribution statement.' Human influence may be perceived as a nested set of behaviors, some originating locally (e.g., land use plans), some nationally (e.g., health policy), and some internationally (e.g., anthropogenic climate change, private financing of reconstruction efforts). The interest in extreme event attribution is not solely a climatic enquiry and attribution assessments need to take this into account. Nevertheless an attribution methodology that identifies changes in the meteorologically related hazard component of climate risk can be regarded as highly useful by stakeholders who may have extensive understanding of exposure and vulnerability but little information on changes in hazard.[66]

Experience of meetings between attribution scientists and stakeholders representing sectors faced with decision making in the context of climate variability and change have demonstrated a keen interest from stakeholders in understanding how information gleaned from event attribution science could be applied.[66,67] But there is no simple recipe for user engagement. Each sector potentially has different uses for such information and therefore has different requirements.[66,67] Whatever challenges attribution science may pose to potential users, it appears clear that such science should not be ignored or seen as a distraction, but rather scientists and stakeholders should work together to ensure the science supports stakeholder needs.[72] The robust link of only a small fraction of excessive deaths in a heat wave to human-made climate change could have widespread implications for such discussions. The recognition of such losses in the broader context of climate justice has an ethical dimension.[73] A continuous dialogue between scientists and stakeholders is required to facilitate the pull through of knowledge into informed decision making.[66–68] This should include an ongoing discussion of the merits and risks of application of such knowledge in particular contexts.[74,75]

DISCUSSION AND CONCLUSIONS

This article has reviewed the current status of research into the attribution of extreme weather and

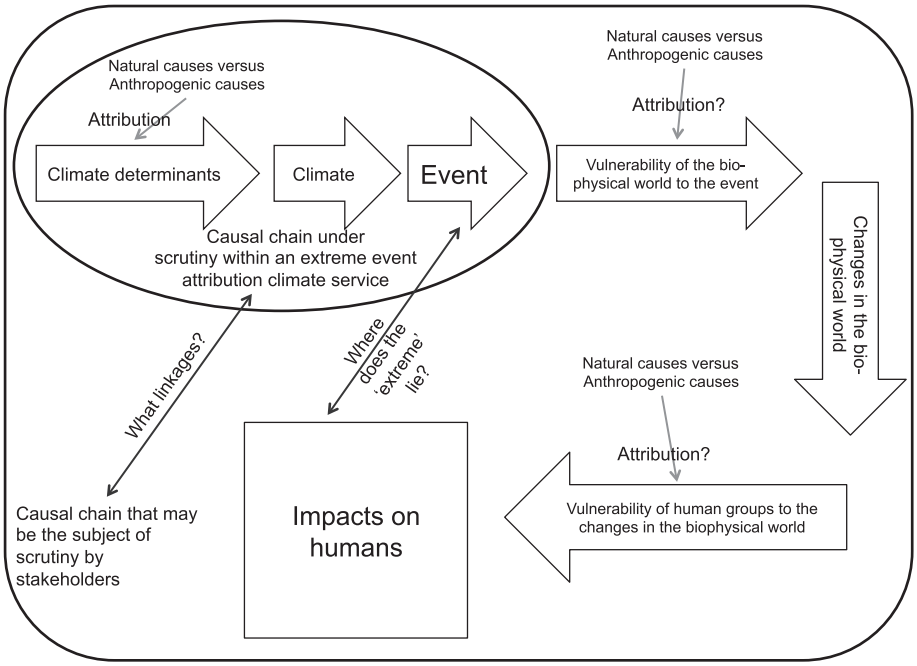

FIGURE 10 | Representation of a grounded theory of attribution in terms of causal chain and the potential interest in attribution by stakeholders.

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climate-related events and discussed the variety of different methodological approaches that have been taken. This diversity of approaches represents the strength of this field of research. No one particular approach provides the best answer for all purposes. The robustness of findings is enhanced when different approaches provide consistent results which are supported by a firm basis in physical understanding. But when assessments synthesize current evidence based on a multiplicity of approaches, it is important that the framing of those approaches is clearly articulated. Otherwise, users of such information may be confused by apparently contradictory conclusions resulting from the different framing of attribution questions.

In an emerging field of research, there remain many challenges in communicating clearly findings of event attribution studies in a way that facilitates effective decision making by stakeholders. The annual reports in BAMS explaining extreme events of the previous year provide one means for disseminating results of attribution studies.[17–20] An advantage of initiatives like this is that they encourage the development of the underpinning science while also prompting developments in the translational science needed to communicate findings to a wider audience than the specialist scientific community. Other such initiatives include the European research project EUCLEIA (European Climate and Weather Events: Interpretation and Attribution; www.eucleia.eu) which is developing an operational attribution system for Europe, and the World Weather Attribution project (http://www.climatecentral.org/wwa) which aims to provide early, science-based assessments of the extent to which global warming caused by greenhouse gas emissions played a role in a weather or climate event's probability. A continuous dialogue between stakeholders and scientists is required to enable effective decision making based on such information.

Research to date has shown much clearer evidence for human influence on extreme temperature events than extreme precipitation events, droughts, and storms. High confidence in attribution of extreme temperature events results from a robust observational basis, the ability of climate models to represent the relevant processes and confirmatory studies replicating results. The FAR for many continental and subcontinental scale temperature extreme events exceeds 0.75 consistent with findings that the majority of daily hot extremes occurring around the world can be attributed to anthropogenic climate change.[9,30,46] For extreme precipitation events, droughts, and storms, the evidence is much more mixed. The observational basis is less secure, climate models can struggle to capture relevant features of the events, and different methods of framing attribution questions can produce contrasting results. However, both thermodynamic and dynamical changes need to be considered in event attribution studies because both can influence the probability and magnitude of extreme events. As climate modeling capability improves and our understanding of the dynamical causes of extreme events develops, the potential for making holistic event attribution statements that consider all facets of the event in question will improve. In turn, developing the scientific understanding of extreme events and testing the ability of climate models to represent them, will help to improve predictions of future changes in extreme events and thereby inform adaptation planning.

The annual BAMS reports explaining extreme events provide an early example of how underpinning science is being applied to answer topical questions about real-life events. But even though the production of peer-reviewed reports for publication in September of the following year places considerable demands on authors, reviewers, and editors, these reports appear too late to be relevant on the timescales when the media are asking questions about the causality of damaging weather and climate events. Also attribution assessments included in the report have so far been carried out on a largely *ad hoc* basis, motivated largely by scientific teams' capacity and interest in analyzing particular impactful events. As a result, geographical coverage has been far from uniform and the *ad hoc* selection of events limits the ability to draw wider conclusions for the year in question.

For event attribution to fulfill its potential to inform a wider group of stakeholders throughout the world, there needs to be the development of the capability to carry out operational attribution. This would provide regularly updated attribution assessments based on predefined and tested methodologies and event selection criteria. It would include the capability to carry out event attribution studies on a range of timescales including very quickly so as being able to inform the public during the course of extreme events. This requires the continuing development of methodologies to assess the reliability of event attribution results and further work to understand the potential utility of event attribution for stakeholder groups and decision makers. There needs to be the development of regional capacity to carry out such studies throughout the globe building on local knowledge. And there needs to be a greater

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capability to incorporate the impacts of extreme weather into event attribution studies so that the risks of such events can be better understood, by including the effects of exposure and vulnerability in addition to meteorological hazard.

Event attribution science is still relatively young. Many questions still remain as to current capabilities to robustly attribute the contribution of anthropogenic climate change to the risk of many extreme weather and climate events. Further progress needs to be made in understanding how best to communicate the findings of event attribution studies to a wide range of possible users. But there has been rapid progress of this science in the last few years. For example, the first annual BAMS reports into events of 2011 contained analyses of six events restricted to heat waves, cold spells, flood, and droughts. The fourth report 3 years later contained 32 contributions and in addition to heat waves, floods, and droughts in 2014 included tropical cyclones, snow storms, and unusual sea ice extent.

It is important that climate models continue to be assessed and improved and, that, methods for assessing the reliability of attribution results continue to be developed. In particular, where attribution assessments are based on a solid foundation of physical understanding, they are more likely to be robust. As the science continues to mature, event attribution should be seen as an integral component of climate services to inform adaptation and mitigation programs around the world and to support climate risk management.

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