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Behind the veil of extreme event attribution

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Abstract

Since 2015, the community of extreme event attribution (EEA) has witnessed a scientific controversy between what is called a “risk-based approach” — estimating how the probability of event occurrence correlates with climate change — and a “storyline approach” — evaluating the influence of climate change on thermodynamic processes leading to the event. We confront those two approaches to the methodologies used in a collection of 105 case studies from 5 BAMS special issues on extreme events. We find that the controversy fails to describe the

various ways to perform EEA. In order to go beyond the controversy, we define EEA, based on corpus of interviews conducted with researchers working in the field. EEA is the ensemble of scientific ways to interpret the question “is this event caused by climate change?” and answer it. In order to break down the subtleties of EEA, we decompose this initial question into three main problems a researcher has to deal with when framing an EEA case study. First, one needs to define the event of interest. Then, one has to determine the chain of causality behind the attribution, and the subsequent level of conditioning to parameters of interest. Finally, one has to determine how to represent climate change. We conjecture that the apparent dispute on EEA is connected to its perceived potential use by stakeholders outside of academia, and not to actual scientific practice.

1 Introduction

Extreme event attribution (EEA) is a relatively new field of climate science. It started with Allen [2003] after an episode of extreme precipitation that struck southern UK in January 2003. Since 2015 several articles tend to sort EEA into two different approaches [e.g. Trenberth et al., 2015, Otto et al., 2016, Mann et al., 2017]. There is no common agreement about the best way to go, which has created a controversy. In the rest of the article, we will specifically use the term approach to describe the two sides of this controversy.

According to Venturini [2010], “controversies remain the best available occasions to observe social world and its making of”. They also give a good window on the making of science [e.g. Collins, 1985]. Understanding the mechanisms of a scientific controversy could help scientists to better adjust their practices within their own communities and their exchanges with the social world outside of their laboratories.

We first aim at clarifying the current state of EEA, and at confronting theoretical considerations and case studies. Our goal is to propose a sound basis for future debates within the climate science community and with relevant stakeholders. In order to do so, we draw on two sets of semi-structured interviews. The first one was conducted in the European project EUCLEIA (called

hereafter the EUCLEIA corpus) and the second one was done among a larger panel of researchers who did not participate in the first series of interviews (called hereafter the A2C2 corpus). The corpuses are named after the grants that funded the surveys (see Acknowledgements). The questions of both corpuses are different, although they share common points. Both grids of questions are provided in the supplementary material; the questions may have varied a little in the flow of the interviews. We also rely on the five issues of the Bulletin of American Meteorological Society (BAMS) annual reports explaining the extremes of the previous year, from 2011 to 2015, which aim at attributing specific events [Peterson et al., 2012, 2013, Herring et al., 2014, 2015, 2016]. They provide a collection of 105 case studies covering a large spectrum of established methodologies. Those reports give an overview of relatively mature, longstanding methods, which are most relevant for the scope of the present article. We will use the terms methods and methodology to describe the different technical ways to do EEA.

The scientific debate on EEA is interwoven with a debate on “which methodological approach would be more useful”. Allen [2003] goes as far as arguing that the transposition of EEA to some sort of market-based mechanism could be the best solution to cope with the alarmingly slow pace of international climate negotiations. Trenberth et al. [2015] claim that their change of framing would “better serve societal needs” and would “provide a better basis for communication of climate change to the public”. Otto et al. [2016] argue that “from the perspective of a stakeholder seeking information to inform disaster risk reduction strategies, it can be unhelpful to ask the question of how the probability has changed given the large-scale circumstances”. A few studies explore who could be potential users of EEA [see Schwab et al., 2017, James et al., 2014]. This relationship between EEA and social use is one of the keys to understand the controversy. However, this is not the only one and we will not tackle here the usefulness of EEA as this will be the topic of a second step of analysis. We will also avoid taking a position on which approaches and methodologies are best, as they all serve different goals.

Another one of the main challenges of EEA that we will not treat in this paper is the attribution of impacts. There is a gap between our capacity to attribute to climate change extreme meteorolog-

ical variables, and extreme impacts. Although more than half of the articles of the BAMS justify the choice of an event because of its impacts, very few actually calculate the influence of climate change on alleged impacts. Indeed, modeling impacts is trickier than studying meteorological variables, as impacts are always the result of an ensemble of factors that are not all weather-related.

We will first explain in detail what are the scientific arguments of the controversy. We will then show that this controversy is not effectively translated into the BAMS case studies. In order to give a proper picture of EEA, we will go back to its very definition, inferred from the ensemble of interviews. We deduce from this definition an ensemble of questions compulsory to answer in order to frame a case study, and show how the BAMS case studies give a range of answers to those questions.

2 The controversy

2.1 Conventional approach

The first approach corresponds to the historical approach to EEA. It starts in early 2003 with the Myles Allen publication in *Nature*, titled “Liability of Climate Change”. Myles Allen was personally involved in the flooding of Thames occurring in this period. He asks the question of what caused this event? He subtitles his article: “Will it ever be possible to sue anyone for damaging the climate?” The approach proposed by Myles Allen takes its roots in a liability perspective. The idea was to compensate the “negative equity” individuals will face when they are confronted to natural events linked to anthropogenic emissions. For example, if their house loses value due to being more likely flooded because of climate change, they could sue the biggest greenhouse gas emitters. The main road block identified in this article is the scientific challenge of calculating the change in probabilities. The methodology proposed is to compare the probability of occurrence of an event in both a factual world — i.e. the world as it is with anthropogenic climate change — and a counterfactual world — i.e. the world that would have been without climate change.

A year later, the same team in Oxford published the first application of this first approach adapted to singular events [Stott et al., 2004]. The authors studied the European heatwave of 2003. They proposed an estimation of “how much human activities may have increased the risk of occurrence of such a heatwave”. This article introduces the concept of fraction of attributable risk (FAR). The FAR is the ratio of the difference between the factual and counterfactual probabilities and the factual probability. A FAR value of 1 means that without climate change the event is impossible. A FAR value of 0 means that climate change had no influence on the event probability. It corresponds to a necessary causation [Hannart et al., 2016].

This first attribution methodology has been refined in more recent articles, facing one of the main problems of attribution, which is the need to have long enough datasets to make robust statements on extremes. Pall et al. [2011] rely on very large ensembles of simulations of an atmospheric model for both factual and counterfactual worlds. Those large ensembles have since been used in many studies and there are current developments to use them for an operational near real-time attribution system, called weather@home [e.g. Massey et al., 2015, Haustein et al., 2016].

2.2 Alternative approach

On the other hand, Trenberth et al. [2015] propose to use the concept of EEA as a tool to give a concrete measure of the influence of climate change on extreme events. Their approach is to describe how climate change influenced the physical processes leading to the event, rather than comparing probabilities in the factual and counterfactual worlds. According to our interviews, one of the factors that led to this approach is the political context in the US, and specifically the policy makers who do not believe in climate change: “the only way to get through to these [deniers] is through the general public. And so it’s important to communicate with the general public, and tell them that climate has changed and in fact there are tens of billions of dollars of damages that are caused by climate change every year.” In this context, which is quite different to the context in which Myles Allen introduced the concept of EEA, Trenberth et al. [2015] find it much more important to highlight any way in which climate change had an effect than to calculate a ratio of

probabilities.

Trenberth et al. [2015] highlight that for the events mainly driven by dynamics, i.e. that will not happen if not for an extreme atmospheric pattern, like extreme precipitations or storms, the conventional approach usually cannot conclude to any influence of climate change. It is rare to find a FAR significantly different from 0 for those kind of events. However, this does not imply that climate change did not play any role in the physical thermodynamic-related processes leading to the event. For example, in the case of Hurricane Sandy in October 2012, even if it is difficult to attribute the hurricane to climate change, the rise of sea level combined with the hurricane increased the subsequent floods [De Vries et al., 2013]. As a consequence, Trenberth et al. [2015] propose to distinguish thermodynamic and dynamical processes leading to a given event. The influence of climate change on thermodynamics has been established and is out of the natural variability of the climate system [see chapter 10 of Bindoff et al., 2013]. As a consequence, EEA gives an accurate notion of the role of climate change for thermodynamical events — i.e. mainly temperature extremes. However, the influence of climate change on the dynamics is still widely debated in the climate community and the models are not yet up for this task in most cases [e.g. Francis and Vavrus, 2012, Barnes, 2013]. The reason for this is that the signal-to-noise ratio is small due to the internal variability of the atmosphere.

Trenberth et al. [2015] hence propose to evaluate the changes induced by anthropogenic emissions given a circulation pattern. Given the assumption that the dynamics are not modified by climate change, one can then show how climate change influenced the event. The authors put this approach in the perspective of a world that is necessarily different because of climate change: a “new normal”. They point out that “all storms, without exception, are different” and argue that the failure to prove that climate change modified the probability of occurrence of an event does not mean that climate change did not play any role.

2.3 The current state of the controversy

In the defence of the conventional approach, Otto et al. [2016] give several examples for which the dynamics are different in the factual and counterfactual worlds, which leads them to state that “limiting attribution studies to the thermodynamic response alone does not allow for an assessment of the actual risk of the event occurring as the large-scale dynamics can counteract or enhance the thermodynamics.”.

Two recent articles (Mann et al. [2017] and Stott et al. [2017]) entered the controversy. Mann et al. [2017] go in the sense of Trenberth et al. [2015] and argue for the use of a Bayesian — rather than frequentist — statistical approach, which would account for information we already have on the physics of both the event and climate change. They mix this argument with ethical considerations regarding the choice of the null hypothesis (prove that climate change had an influence on the event or prove that climate change had no influence on the event). Stott et al. [2017] however point out that the choice of the null hypothesis is independent of the statistical framework and that there are as many biases in Bayesian than in frequentist framings. Curry [2011] also argues that there is no straightforward ethical choice of the null hypothesis in a climate change context.

A few articles have proposed ways to combine both approaches [Shepherd, 2016, Vautard et al., 2016, Yiou et al., 2017]. The alternative approach can be completed by an assessment of the influence of climate change on the circulation in which case, the whole event is accounted for. Stott et al. [2017] point out that “different approaches to event attribution may choose to occupy different places on the conditioning spectrum”. It hence appears that a part of the community does not see the use for any controversy between different approaches.

Shepherd [2016] qualifies the first approach as a “risk-based approach”, “where the change in the likelihood of the effect arising from the presence of that factor is estimated”. The choice of the word risk probably relates to concepts such as the risk ratio which is the ratio of the probability of occurrence of an event. However, in a user oriented context, it is overstated as the conventional approach really treats probabilities of events, and do not tackle the vulnerability and exposure

components of risk, with which any user will have to deal. Shepherd [2016] names the second approach, the “storyline approach”, “where the causal chain of factors leading to the event is identified, and the role of each assessed”. The name storyline comes from a paper by Hazeleger et al. [2015], which proposes to build transdisciplinary storylines — or tales— of future weather events in collaboration with users, which is closer to the creation of scenario and to storytelling than what Shepherd [2016] proposes. We will keep this terminology in the remainder of the article.

3 Confronting the controversy to case studies

The purpose of this section is to show whether the controversy we exposed in the second part is relevant when put under the light of actual case studies. We failed to classify the BAMS papers between storyline and risk based approach. This proved difficult because a lot of articles do not fall into either categories, or fall into both. We thus analyzed the genealogy of each article, in order to identify common methodologies. Stott et al. [2016] presented a review of the different methodologies to do EEA. They distinguish methodologies between coupled model methods, sea surface temperature (SST) forced atmosphere only model methods, analogue-based methods, empirical methods and broad-scale methods (they use the word “approaches” instead of “methods”, but we changed it to “methods” in order to avoid a confusion with risk-based and storyline approaches).

Our BAMS analysis shows that those different methods do not have the same popularity. The coupled model methods cover a large spread of methodologies, so we do not consider that all articles using coupled models should be part of the same category. The most used methodology, also described as the SST forced method by Stott et al. [2016], stems from Pall et al. [2011], and has been refined by Massey et al. [2015] and Schaller et al. [2014]. 27 BAMS articles cite at least one of those articles. This methodology is the one which fits best the risk-based approach. 4 articles (all from the same team) use the analogue methodology to perform a conditional attribution. They all cite Cattiaux et al. [2010] as the first article to study a specific event in the context of climate through the use of analogues. We found 7 articles with a methodology similar to what Stott et al. [2016] call empirical methods but it is almost never the only methodology in those articles and the

referencing is not as clear than for the other methodologies described here (Van Oldenborgh et al. [2012] are possibly the first to use that kind of methods to perform EEA). The broad-scale methods [e.g. Zwiers et al., 2011, Min et al., 2011] are more detection and attribution of trends on extremes than EEA. They are not fit for BAMS studies, which focus on particular case studies.

We found two other methodologies in the BAMS used in more than 3 different articles which are not presented in Stott et al. [2016] and for which we hence give more details. Knutson et al. [2013] question whether the models are able to reproduce the observed event with pre-industrial runs and with historical runs. They plot the evolution of the observed trend of the variable of interest (e.g. the mean spring temperature in the Eastern United States) with the starting year of the trend. They compare those observed trends with the ensemble of trends for both natural and anthropogenic forcings from CMIP5 models to see if the observed trends are consistent with climate variability alone. This approach lies in between detection and attribution of trends and EEA. We found 7 articles using this methodology in the BAMS.

The strategy of Arblaster et al. [2014] is to determine which parameters — among which climate change — are necessary to reproduce the observed anomaly — of temperature in this case. The coupling of a seasonal forecast system and of a multiple linear regression allows the authors to reconstitute the temperature and consider which physical processes were the most important predictors for the extreme event to happen. One of these predictors is the global mean temperature, the change of which has been attributed to climate change. The authors refer to this as a “multi-step attribution process”. 3 BAMS articles from the same team use this methodology.

Apart from the analogues, none of the methodologies described above follow a storyline approach. A few individual papers could also fit into a storyline frame [e.g. De Vries et al., 2013, Sweet et al., 2013]. However, the storyline approach lacks at the moment a widespread methodology like the one of Pall et al. [2011] is for the risk-based approach. This could be due to the fact that the storyline approach as proposed by Trenberth et al. [2015] emerged after a few of the BAMS reports were already published. This does not mean that no article use this kind of approach.

Outside of the BAMS, Hoerling et al. [2013], Meredith et al. [2015], and Pall et al. [2017] are three examples of storyline approaches.

The most important result of this genealogical sorting is that most of the BAMS papers follow their own methodology, specific to the case study or to a given framing. Our goal in describing different types of methodologies was to show that the controversy we explained in the introduction and which takes a lot of place in the community is not so relevant when put under the light of real case studies using methodologies which do not fit in both the risk-based and the storyline approaches. We hence agree with Stott et al. [2017] and Shepherd [2016] regarding the need to move on from the controversy. We propose hereafter a way to move on while describing all the potential framings of EEA.

4 Defining EEA

We have found that sorting the case studies between methodologies excludes most of the BAMS articles. This means that trying to categorize the case studies into different approaches or methodologies does not suffice to give a proper overview of EEA. However, the framing of EEA has a clear impact on the results of any given case studies. Angélil et al. [2017] have shown how the results of all the BAMS articles from year 2011 to 2014 would differ using a different method than the one used by the original authors. Dole et al. [2011] and Rahmstorf and Coumou [2011] find apparently contradictory results regarding the attribution of the 2010 Russian heatwave due to different framings [Otto et al., 2012].

We propose hereafter to differentiate the ways to frame EEA based on several criteria. In order to do so, we first need to go back to the definition of EEA. We build it from the definitions of the relevant actors : the researchers working on EEA. We select the elements common to all of their definitions and we do not keep those which do not apply to every point of view in order to get the biggest picture possible.

From both corpuses of interviews we have asked 19 climatologists who have published papers on the subject to define EEA (question 2 in SM.1 and 3bis in SM.2). The most relevant excerpts of their interviews on that question are listed in the SM.3. Through the analysis of the lexical fields used in those answers we found a few elements that come back frequently when a researcher defines what is EEA. We have sorted them in the following categories:

1. the notion of causation
2. the study of one specific extreme event
3. the relationship with anthropogenic climate change and natural variability
4. the use of statistics
5. the understanding of physical processes explaining the extreme
6. the detection of a change

The three first points seem to relate to almost all the answers. When they do not appear explicitly they are implied. EEA deals with what causes a specific extreme event, in relation with climate change. The fourth and fifth categories clearly refer to the controversy we exposed in section 2, which seems to be internalized by a part of the community. However, because we have shown that this controversy is not essential to define EEA (in agreement with Shepherd [2016] and Stott et al. [2017]), we will not keep those elements as parts of our working definition of EEA.

The 6th category is probably an artifact related to the fact that the word “detection” was used in the A2C2 corpus and not in the EUCLEIA corpus. We find it best not to consider it for our definition although there are arguments for the inclusion of the detection of a change in EEA.

Our working definition has to adopt the widest possible scope so as to include every acceptations of EEA in this article and to discuss their differences. Building on the three first categories, we propose to define EEA as the ensemble of scientific ways to interpret the question “is this event caused by climate change ?” and answer it. The attribution community agrees that this question is ill-posed (see chapter 2 of NAS2016), however we can use it as a starting point to define whether a

study can be considered as EEA. Indeed, questions like “how the probability of an event is affected by climate change?”, or “how climate change modified the physics of an event?” are different reformulations of the question “is this event caused by climate change?” in a suitable way to make it possible to answer through a scientific study.

5 Framing EEA

Now that we have a definition, we can use it to show all the possible framings of an EEA study. In order to do so, we decompose the original question “is this event caused by climate change?” into three separate issues. First, how does one define the event to study? Second, what does one mean by “caused by”? Third, how does one represent climate change? This partition and the variation of answers to those three questions allow us to give a better picture of the subtleties of EEA and to detail the choices one has to do to propose a methodology to study a given event.

5.1 The event

5.1.1 Class of events and singular event

Before explaining the different ways to define the event to study, we go back to the question “what is the meaning of the word event?”. There is a matter of whether we really consider a singular event or a class of event. In the first case, it would mean answering whether the exact event is caused by climate change. In the second case, it would mean answering whether all the events within a class (e.g. all the heatwaves above a certain threshold of temperature for a given number of consecutive days) are becoming more likely because of climate change. Harrington [2017] has shown how those two different choices can lead to different results.

The attribution of a singular event is contingent upon the idea that somehow, the causal chains leading to this event may be reproduced in whole or in part. The idea is to recreate the same event and to evaluate how this event fares with and without climate change. Until now, this has been done

in 2 different ways. Meredith et al. [2015] condition strictly the circulation of their model to the one observed during the very high precipitations they are interested in. Then, they run their model for 2 different level of GHG emissions and SST corresponding to a factual and a counterfactual world. Arblaster et al. [2014] try to recreate the precise pattern of temperature anomaly observed during a heatwave by modeling several physical processes.

The attribution of a class of event is probabilistic. The goal is to evaluate if there is a change of the risk that any extreme event which shares its extreme feature with the event of interest happens due to climate change. This is mainly done by considering all the events above a certain threshold. Many studies use the observed extreme anomaly of the variable of interest as this threshold. Others choose a lower threshold, especially when the event is so extreme that it would be difficult to trust statistical tests too far in the tail of the distribution (as was done in Stott et al. [2004]). In that case, there is no need for the event to actually happen to do an EEA study. One just needs to choose a threshold, a duration and a region [Christidis et al., 2015]. However a few methodologies rely on different ways to define a class of event, e.g. the ones based on analogues of circulation.

5.1.2 Choice of the event

Apart from those general considerations on the meaning of the word event, the first step in any EEA study is to choose the event of interest. There are different reasons to consider an event to be interesting enough to study. It can be because of its impacts, its rarity, or both. In the BAMS reports, out of 105 articles, 31 explain their interest in an event based solely on its rarity, 28 based solely on its impacts and 42 based on both. This does not mean that there are no other implicit reasons involved in the choice of a specific event. 4 articles advance different reasons. For example, King et al. [2015] chose an event because it raised the media attention. We also stress that the impacts can go from very serious (e.g. “a tragic food crisis that led to famine conditions” in Funk [2012]) to rather harmless, (e.g. the well-being of tennis players during the Australian Open [King et al., 2015]).

There is also the matter of the selection of the region where the event happened. Most of the time, researchers study events happening in the region where they live. Out of the 105 case studies in the BAMS, 77 focus on the region of the first author's laboratory. 72 study events happening in Annex I countries, as defined by the UNFCCC, 28 focus on Annex II countries and the rest (5 out of 105) look at polar regions or the ocean. Hence there is a disproportion of case studies in favour of developed countries (this was also pinpointed by Stott et al. [2016] and Angélil et al. [2017]). This selection bias is heightened by the fact that climatologists are aware of the events happening in their own countries because they see them happening, while they might not pay attention to extreme events happening on the other side of the world otherwise than through media reports of their impacts.

Sometimes, local stakeholders play a part in motivating researchers to study a particular event. One of our interviewees told us that "policy makers [...] had questions about [an] event because they are of course concerned about whether or not the same kind of event might happen [again]". Regional projects also mainly finance studies about local events. For example, the EUCLEIA consortium produced 6 case studies about European extreme events [e.g. Hauser et al., 2017, Wilcox et al., 2017], and the French project Extremoscope financed research focused on extreme events affecting France [e.g. Ouzeau et al., 2016]. A few stakeholders, like the Red Cross or UK's National Environment Research Council which funded the ACE (Attributing Impacts of External Climate Drivers on Extreme Weather) Africa project, also support research studying developing countries which do not have research infrastructures in capacity to lead such studies.

Another reason for this bias is the lack of observational data in the countries where meteorological infrastructures are not well developed, so that it may be impossible to do consistent EEA in those countries. This selection bias has societal impacts. Huggel et al. [2016] argue that the countries which would most benefit from EEA, especially in the context of loss and damage, are also those where there are no EEA case studies. The number of studies of extreme events happening in under-represented countries, which are also the most vulnerable, nonetheless keeps increasing with each BAMS issue [Stott et al., 2016].

5.1.3 Precise definition of the event

Once one has chosen an event, like a heatwave, a drought or a storm, there are three choices left to do : the precise definition of the region affected, and the time period to study, and the variable that will best represent the event. For the same event, different studies address those questions differently. For example in the BAMS report on 2013 extreme events, 3 articles deal with extreme heat in Australia. Swain et al. [2014] consider a yearly event, Wang and Schubert [2014] focus on January and February, while Funk et al. [2014] study the winter season from November to February. Most of (if not all) the time, those choices are subjective, meaning that they do not arise from scientific considerations, but rather from political frontiers, or from regions defined in earlier articles that might not be relevant for the specific event of interest. Cattiaux and Ribes [submitted] propose to optimize both of those choices by selecting the region and period for which the event has the lowest probability of occurrence. This could be a way to study the most extreme events, and to objectify the choice of a region and a time period.

5.2 The causation

The second part of the decomposition of the question “is this event caused by climate change ?” is to show all the different ways to express causation. This question has been widely investigated inside and outside climate sciences. For example, Parascandola and Weed [2001] describe several ways to define causation in epidemiology : necessary causes, sufficient-component causes, probabilistic causation, and counterfactuals. Here we explore how researchers working in EEA deal with causation, and how they sort the different ways to frame causation.

One of the distinctions is the difference between necessary and/or sufficient causations. In most cases, it is not possible to exclude the possibility that the event could have happened without climate change (necessary causation), even if its probability of occurrence would have been close to 0. A possible exception would be the annual Arctic sea ice minimum [e.g. Kirchmeier-Young

et al., 2017]. Because EEA is about extreme events, it is even less likely to find sufficient causation (i.e. because of climate change, the event was bound to happen). Hannart et al. [2016] explore the semantics of causation applied to EEA. They interpret the FAR as a probability of necessary causation and propose complementary formulas to calculate the probability of sufficient causation, and the probability of necessary and sufficient causation. Hannart et al. [2015] provide an application of this with a case study of the Argentinian heatwave of December 2013. However, apart from the work of Hannart and colleagues, the factor that has been the most used to define causation in the context of EEA is the level of conditioning.

Indeed, NAS2016 and Shepherd [2016] divide EEA between two types of methodologies : unconditional and conditional attribution. We have classified all the BAMS articles between different nuances of conditioning. This sorting does not include references to physical mechanisms possibly explaining the event when there is no specific study to evaluate the causation. There are numerous unconditional attribution case studies in the BAMS reports (38 out of 105 articles). In order to do unconditional attribution, the definition of climate change must stem directly from anthropogenic external forcings. That can only happen in studies using either only observations or coupled models (CMIP5 or studies focused on a particular model) with a comparison between pre-industrial (or natural-forcings only) and historical runs. Examples of unconditional attribution in the BAMS are the papers of Lewis and Karoly [2014] or Knutson et al. [2013]. The unconditional causation chain links climate change to an extreme observable or to impacts, although we found no examples of the latter in the BAMS. This could be explained by the complex nature of impacts modeling which necessitates a physical and a social understanding of the different processes at play.

The conditional causation chain links climate change combined to a precursor to either an extreme observable, or its impacts. This precursor is an internal element of the climate system which played a role in the occurrence of the event. Many studies, especially the ones based on the most widely used methodology proposed by Pall et al. [2011] study the influence of a thermodynamical precursor combined with green house gases (GHG) concentrations on an extreme observable (e.g. temperature, or precipitation). A thermodynamical precursor is a precursor which is directly linked

to the increase of temperatures and for which the influence of climate change is already clear. Most of the time the thermodynamical precursor is the sea-surface temperature (SST). Because of the computational costs of coupled models, the idea is to rely on atmospheric-only models, for which the SST is a boundary condition. 30 articles from the BAMS use SSTs combined with anthropogenic emissions as a proxy of climate change.

This type of conditional attribution could also be considered as implicit unconditional attribution. Indeed, it is a multi-step attribution that considers the step between climate change and the rise of SST as a given. This approach is defensible, considering the amount of proofs in the literature for that first step. This implicit unconditional attribution should however be explicit in articles using this approach which is not always the case [Otto et al., 2016]. One of the matters related to the conditioning of SSTs is that it ignores the decadal variability of SST patterns, and the influence of El Nio. The influence of SST conditioning, which is massively used in the EEA literature has not been enough documented to make the assumption that the probabilities calculated are equivalent to unconditional probabilities. Dong et al. [2017] have shown that this assumption is globally correct for temperature extremes but that the air-sea coupling significantly changes the results for precipitations and in certain regions for the circulation. Another possible thermodynamical precursor is the global temperature, e.g. in Hope et al. [2015].

Conditioning can also combine climate change to a precursor not clearly related to climate change through thermodynamics, a dynamical precursor. This type of conditional attribution is the one presented in Trenberth et al. [2015], which Shepherd [2016] called “storyline approach”. The idea is that for events heavily conditioned by the dynamics, the climate change signal will be drowned in the internal variability. This does not mean that there is no effect of climate change. The relevant question would rather be “Given the change in atmospheric circulation that brought about the event, how did climate change alter its impacts ?” [Trenberth et al., 2015] or “What is the best estimate of the contribution of climate change to the observed event ?” [Shepherd, 2016]. 8 case studies from the BAMS use a conditioning to circulation.

There are examples of other types of conditioning dealing with other scales of internal variability. There are 6 articles in the BAMS studying the influence of El Nio (or La Nia) on an event combined with the influence of climate change on El Nio [e.g. King et al., 2013].

7 case studies focus on the role of climate change on a specific precursor of the event without attributing the event itself to climate change. For example, Funk [2012] calculate the Indian-Pacific warm pool (IPWP) enhancement by climate change. They rely on the literature to link the IPWP warming to droughts in Eastern Africa, which were their event of interest. 9 case studies compare multiple precursors, in order to determine which ones have the most impact. The methodology of Arblaster et al. [2014] summarized in the third section gives an example of that kind of approach. 2 articles evaluate the impact of sea level rise on flooding. De Vries et al. [2013] look at the influence of climate change on ice thickness conditioned to the snow cover. Von Storch et al. [2014] and Feser et al. [2015] only detect changes without any attribution step so we could not sort them.

Those different ways to define a chain of causation highlight that the EEA framing can subtly vary from one study to another. It is not so easy to distinguish a multi-step unconditional study from a conditional study and the limit between both is blurry. A lot of BAMS articles explore different approaches, which makes the whole picture even more complex to map and to understand.

5.3 Climate change

EEA usually relies on the comparison of a factual and a counterfactual world. The difference between these worlds is the key to calculate the role of climate change. Their buildings vary from one study to the other. To build a counterfactual world, one has to decide how far back to anthropogenic emissions one needs to go to represent a world without climate change. There are several ways to compare worlds with and without climate change. The simplest way is to compare a past period to a most recent period (23 articles in the BAMS). This will not give a complete account of the effects of climate change, as the world of the past might already be affected by anthropogenic emissions. The main advantage of this technique is that it allows to rely on observations only [e.g.

Van Oldenborgh et al., 2012].

Other studies use pre-industrial runs from coupled models as counterfactual worlds (27 articles in the BAMS). There is a thin line between a definition of the counterfactual based on the past and the counterfactual based on pre-industrial conditions. Indeed, the pre-industrial climate is the climate of 1870. Sometimes the word pre-industrial is not explicitly stated but when the reference is a past climate of before 1900 we sorted it as pre-industrial [e.g. Barlow, 2015].

An alternative option to pre-industrial for coupled models users is to use historical runs with natural forcings only, which are available for CMIP5 models. 16 articles use that kind of counterfactual world. 6 articles use both and compare the results obtained for pre-industrial and natural counterfactual worlds.

For methodologies based on atmospheric models, the factual world is built using the observed SST as input. The tricky step is to create counterfactual SSTs. 17 articles use preindustrial SSTs, sea ice cover and anthropogenic emissions, 8 use historical ones and 9 use natural ones. There is an evolution from historical (which was the counterfactual world used in Pall et al. [2011]) towards preindustrial through the BAMS issues.

The problem of the definition of climate change in the context of EEA has been mostly overlooked. This lack of interest is puzzling given that a lot of scientists working on EEA have come from the detection and attribution community, which has done a lot of work on this problem. Hauser et al. [2017] show that the choice of different counterfactual worlds has a big impact on the results.

Another overlooked topic is the evaluation of contributions from differentiated external forcings, like GHG and aerosols, or land-use. In contrast with the detection and attribution of trends, one of the interviewees states that “EEA is very very predominantly envisioned in an anthropogenic vs natural perspective, and only with this reading grid”. There are very few studies differentiating the role of those different anthropogenic forcings in the BAMS. As an exception to that rule, Wilcox

et al. [2015] and Miao et al. [2016] make a distinction between aerosols and GHG emissions effects on the extreme event.

We note that for a few articles, the definition of a counterfactual world is not necessary. Those articles use methodologies based on the reconstitution of an observed anomaly [e.g. Arblaster et al., 2014] or only do trend detection without any comparison to trends in a counterfactual world [e.g. Feser et al., 2015].

6 Conclusion

We have shown that the storyline vs risk-based controversy often does not apply to the actual EEA case studies, which use more and more frequently different types of methodologies, compare different datasets, and explore different conditionings in order to give a better picture of the diverse causes of an extreme event. Instead, we propose to define EEA as the ensemble of scientific ways to interpret the question “is this event caused by climate change ?” and answer it. It allows us to describe the differences between framings through three main axes : how does one define the event of interest? how does one express causation? what does one mean by a world without climate change? It is clear that the answer to those three questions has an influence on the results of the case studies [e.g. Otto et al., 2012, Hauser et al., 2017, Angélil et al., 2017]. It is likely that the failure of the storyline vs risk-based controversy to describe the richness of EEA has implications on its ability to describe the different social uses of EEA that we introduced in section 2.

Shepherd [2016] makes the point that the risk-based approach is anchored in a statistical framing, while the storyline approach is grounded in physics. In the case of the latter, Shepherd [2016] defines it as a “physical investigation of how the event unfolded”, and as a “dynamically conditioned attribution”. The storyline approach can also be associated with a way to tell the story of an event as some sort of tale rather than only explaining it through probabilities. One of the interviewees explained that : “these conditioned attribution events are stories, they are real stories that have implications for the future.”. There are three elements behind the current definition which are not

equivalent : the dynamical conditional attribution, a physical approach (by opposition to a statistical approach) and a communication matter. There are many examples of BAMS articles studying the physics of the event without any dynamical conditional attribution, whether it is through multi-step attribution or attribution conditional to something else than circulation (e.g. ENSO conditioning in Funk et al. [2016]). On the other hand, the idea that the risk-based approach only leads to the calculation of a FAR is restrictive. It is possible to quantify a change in probabilities conditional to the circulation and it has been done [e.g. Yiou et al., 2017]. A few BAMS articles calculate different types of FAR attributing the event to different causes [e.g. Karoly et al., 2016]. The comparison of those different FAR could also fit in a storyline approach. Rather than a purely scientific disagreement, we believe that the controversy takes its roots in the divergences between researchers regarding the right way to communicate their results and to engage with potential stakeholders. The way researchers in EEA comprehend societal needs, and the link between their motivations and their way to frame their studies will be the topic of another article.

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