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► **To cite this version:**

Aglaé Jézéquel, Vivian Dépoues, Hélène Guillemot, Mélodie Trolliet, Jean-Paul Vanderlinden, et al..  
Behind the veil of extreme event attribution. 2018. hal-01653499v2

**HAL Id: hal-01653499**

**<https://hal.science/hal-01653499v2>**

Preprint submitted on 14 May 2018

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# Behind the veil of extreme event attribution

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April 12, 2018

## Abstract

Since [Allen, 2003]'s seminal article, the community of extreme event attribution (EEA) has grown. Several approaches have been developed: the main ones being the “risk-based approach” — estimating how the probability of event occurrence correlates with climate change — and the “storyline approach” — evaluating the influence of climate change on thermodynamic processes leading to the event. In this article, we map the different ways to frame attribution used in a collection of 105 case studies from 5 BAMS (Bulletin of American Meteorology)

logical Society) special issues on extreme events. In order to do so, we propose to define EEA, based on corpora of interviews conducted with researchers working in the field as follows: EEA is the ensemble of scientific ways to interpret the question “was this event influenced 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 propose a way to link the extreme event with climate change, and the subsequent level of conditioning to parameters of interest. Finally, one has to determine how to represent climate change. We provide a complete classification of BAMS case studies regarding those three problems.

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# 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 then, EEA has grown, and many methodologies have been developed [Stott et al., 2016]. With the growth of the field, different ways to frame EEA have emerged [e.g. Stott et al., 2016, Shepherd, 2016]. The question of framing has been the root of debates among the community [e.g. Trenberth et al., 2015, Otto et al., 2016, Mann et al., 2017, Stott et al., 2017].

The aim of this article is to confront theoretical considerations to actual data, and to discuss the framing of EEA based on case studies to describe and understand what the community is actually doing. In order to do so, we draw on two sets of semi-structured interviews. The first one was conducted among 10 researchers participating to the European project EUCLEIA (called hereafter the EUCLEIA corpus). The second one was done with 9 researchers who did not participate in the first series of interviews (called hereafter the A2C2 corpus) and are mostly (with one exception) researchers who did not participate to EUCLEIA. The corpora are named after the grants that funded the surveys (see Acknowledgements). Although they share common points, the questions posed to both corpora differ as they were done for different purposes. The EUCLEIA corpus was the first step towards the creation of a European EEA climate service. The A2C2 corpus aimed at investigating what is EEA, and why researchers engage in it. 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 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, 2016a]. We do not analyse the latest BAMS issue [Herring et al., 2018]. 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.

We will first lay out the history and introduce the different framing approaches of EEA. We will

1 then explain how we tackled the classification of the case studies and how it led us to propose a  
2 working definition, inferred from the ensemble of interviews. We then deduce from this definition  
3 an ensemble of questions compulsory to answer in order to frame a case study, and show how the  
4 BAMS case studies give a range of answers to those questions.  
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## 13 **2 Framing EEA : an history**

### 14 15 16 17 **2.1 The beginning of EEA**

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20 Myles Allen was the first to explicitly frame EEA in a publication in *Nature* in 2003, titled “Li-  
21 ability of Climate Change”. He personally experienced the flooding of the Thames occurring in this  
22 period. He asks the question of what caused this event. He subtitled his article: “Will it ever be  
23 possible to sue anyone for damaging the climate?” The approach proposed by Allen [2003] takes  
24 its roots in a liability perspective. The idea was to compensate the “negative equity” individuals  
25 will face when they are confronted to weather-related events linked to anthropogenic emissions.  
26 For example, if their house loses value due to being more likely flooded because of climate change,  
27 they could sue the biggest greenhouse gas emitters. The main road block identified in this article is  
28 the scientific challenge of calculating the change in probabilities. The proposed methodology is to  
29 compare the probability of occurrence of an event in both a factual world — i.e. the world as it is  
30 with anthropogenic climate change — and a counterfactual world — i.e. the world that would have  
31 been without climate change.  
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47 A year later, Stott et al. [2004] published the first implementation of this approach. The authors  
48 studied the European heatwave of 2003. They proposed an estimation of “how much human activ-  
49 ities may have increased the risk of occurrence of such a heatwave”. This article uses the concept  
50 of fraction of attributable risk (FAR), where risk means probability of occurrence. The FAR is the  
51 ratio of the difference between the factual and counterfactual probabilities and the factual proba-  
52 bility. A FAR value of 1 means that without anthropogenic climate change the event is impossible.  
53 A FAR value of 0 means that anthropogenic climate change had no influence on the event prob-  
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1 ability. A negative FAR means that the event became less likely with anthropogenic climate change.

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4 This first attribution methodology has been refined in more recent articles, facing one of the  
5 main problems of attribution, which is the need to have large enough ensembles of simulations to  
6 adequately sample all possible weather states for given time period. Pall et al. [2011] rely on very  
7 large ensembles of simulations of an atmospheric model for both factual and counterfactual worlds.  
8 Those large ensembles have since been used in many studies and there have been developments to  
9 use them for operational near real-time attribution systems[e.g. Wolski et al., 2014, Massey et al.,  
10 2015, Haustein et al., 2016]. In the rest of the article, this approach will be referred as risk-based  
11 approach, following the nomenclature of Shepherd [2016].  
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## 25 **2.2 Later developments of EEA**

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27 A few years later, other ways to put an extreme event in the perspective of anthropogenic climate  
28 change have emerged. For example, without explicitly calling it attribution, Perlwitz et al. [2009]  
29 showed how the unusual SST pattern of winter 2008 in the Pacific were responsible for the drop in  
30 North American temperatures, and that without anthropogenic emissions, the cold would even have  
31 been stronger. Similarly, Cattiaux et al. [2010] showed that the cold European winter of 2009/2010  
32 was caused by the atmospheric circulation, and that for the same atmospheric pattern, the tempera-  
33 tures would have been even lower in the past.  
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45 In 2015, Trenberth et al. proposed to move the focus of EEA from the risk-based approach —  
46 i.e. the comparison of probabilities in the factual and counterfactual worlds — to what Shepherd  
47 [2016] calls the storyline approach, which seeks to describe how climate change influenced the  
48 physical processes leading to the event. Their reasoning is that for some events the signal-to-noise  
49 ratio is small due to the internal variability of the atmosphere, so that the risk-based approach usu-  
50 ally cannot conclude to any change of probabilities of climate change. It is especially the case for  
51 the events mainly driven by dynamics, i.e. that will not happen if not for an extreme atmospheric  
52 pattern, like extreme precipitations or storms. Furthermore, the influence of anthropogenic forcing  
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1 on the dynamics is still widely debated in the climate community and the models are not yet up for  
2 this task in most cases [e.g. Francis and Vavrus, 2012, Barnes, 2013].  
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6       Trenberth et al. [2015] hence propose to evaluate the changes induced by anthropogenic emis-  
7 sions given a circulation pattern. Given the assumption that the influence of climate on dynamics  
8 is not detectable, one can then show how climate change influenced the event. The authors put this  
9 approach in the perspective of a world that is necessarily different because of climate change: a  
10 “new normal”. They point out that “all storms, without exception, are different” and argue that the  
11 failure to prove that climate change modified the probability of occurrence of an event does not  
12 mean that climate change did not play any role.  
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23       According to our interviews, one of the factors that led to the storyline approach is the political  
24 context in the US, and specifically the policy makers who do not believe in climate change: “the  
25 only way to get through to these [deniers] is through the general public. And so it’s important to  
26 communicate with the general public, and tell them that climate has changed and in fact there are  
27 tens of billions of dollars of damages that are caused by climate change every year.” In this context  
28 Trenberth et al. [2015] find it more important to highlight any way in which climate change had  
29 an effect than to calculate a ratio of probabilities. This means that the risk-based approach focuses  
30 on quantifying the role of anthropogenic climate change on the probabilities of the event, while the  
31 storyline approach aims at unveiling the qualitative ways in which anthropogenic climate change  
32 affects the processes leading to the event.  
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46       Otto [2017] also introduces a third approach, that she calls the Boulder approach, since it was  
47 developed by a group of scientists working at the National Oceanic and Atmosphere Administration  
48 (NOAA), in Colorado. She explains that the goal of this approach is to “disentangle different causal  
49 factors leading to the event without necessarily quantifying the influence of these causal factors on  
50 the likelihood of occurrence”. Shepherd [2016] cites papers of this group as examples of storyline  
51 approach, so depending on the authors, the storyline approach includes only the circulation con-  
52 ditional framing [Otto, 2017] or is large enough to integrate any study that dissects the physical  
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1 processes leading to an extreme and analyze how anthropogenic climate change influences those  
2 processes.  
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### 8 **2.3 Debates regarding the advantages of different framing approaches** 9

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11 Trenberth et al. [2015]’s paper criticizes heavily the risk-based approach stating that it is “is severely  
12 challenged [...] when it comes to climate extremes that are strongly governed by atmospheric cir-  
13 culation, including local aspects of precipitation”, that it “is rather ineffectual in cases that are  
14 strongly governed by the changed circulation, with generally an inconclusive outcome” and that  
15 “even when a detectable anthropogenic influence is found in a model, the reliability of that finding  
16 cannot carry much weight”. On the other hand, the circulation conditional framing is not without  
17 its own critics. Otto et al. [2016] give several examples for which the dynamics are different in  
18 the factual and counterfactual worlds, which leads them to state that “limiting attribution studies to  
19 the thermodynamic response alone does not allow for an assessment of the actual risk of the event  
20 occurring as the large-scale dynamics can counteract or enhance the thermodynamics.”.  
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34 Mann et al. [2017] go in the sense of Trenberth et al. [2015] and argue for the use of a Bayesian  
35 — rather than frequentist — statistical approach, which would account for information we already  
36 have on the physics of both the event and climate change (Risser et al. [2017] also use a Bayesian  
37 framework in a risk-based approach article). They mix this argument with ethical considerations  
38 regarding the choice of the null hypothesis (prove that climate change had an influence on the event  
39 or prove that climate change had no influence on the event). Stott et al. [2017] however point out  
40 that the choice of the null hypothesis is independent of the statistical framework and that there are  
41 as many biases in Bayesian than in frequentist framings. Curry [2011] also argues that there is  
42 no straightforward ethical choice of the null hypothesis in a climate change context (see also the  
43 response of Allen [2011] to Curry [2011] on that matter).  
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58 This debate is interwoven with a social concern on “which methodological approach would be  
59 more useful”. Allen [2003] goes as far as arguing that the transposition of EEA to some sort of  
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1 market-based mechanism could be the best solution to cope with the alarmingly slow pace of inter-  
2 national climate negotiations. Trenberth et al. [2015] claim that their change of framing would “bet-  
3 ter serve societal needs” and would “provide a better basis for communication of climate change  
4 to the public”. Otto et al. [2016] argue that “from the perspective of a stakeholder seeking infor-  
5 mation to inform disaster risk reduction strategies, it can be unhelpful to ask the question of how  
6 the probability has changed given the large-scale circumstances”. A few studies explore who could  
7 be potential users of EEA [see Schwab et al., 2017, Parker et al., 2017, Sippel et al., 2015, James  
8 et al., 2014, Stott and Walton, 2013]. In a second article, we will explore in depth the reasons why  
9 scientists do EEA, based on our two corpora of interviews. For the rest of the present article, we  
10 will avoid considerations regarding the use of EEA.  
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23 Although a part of community hence engages in a debate opposing risk-based and storyline  
24 approaches, it is not the case of the whole community. We found almost no mention of it in our  
25 interviews. Moreover, a few articles have already proposed ways to combine both approaches  
26 [Shepherd, 2016, Vautard et al., 2016, Yiou et al., 2017]. The storyline approach can be completed  
27 by an assessment of the influence of climate change on the circulation in which case, the whole  
28 event is accounted for. Stott et al. [2017] point out that “different approaches to event attribution  
29 may choose to occupy different places on the conditioning spectrum”. Furthermore, authors like  
30 Pardeep Pall and Dáithí Stone have engaged in the two types of approaches [Pall et al., 2011, 2017].  
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### 44 **3 The classification of the BAMS**

45 This section explains how we approached the classification of the 105 case studies from the BAMS.  
46 We first tried to sort them between risk-based and storyline approach (in the sense of Shepherd  
47 [2016], which includes Otto [2017]’s Boulder approach). This proved difficult because a lot of  
48 articles do not fall into either categories, or fall into both.  
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58 We then analyzed the genealogy of each article, in order to identify common methodologies.  
59 In supplementary table S4, we list all the case studies. We put an article in the genealogy column  
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1 when the authors explicitly state their method is based on another article. The supplementary table  
2 S5.1 sums up our findings regarding this explicit genealogy of BAMS articles.  
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6 Stott et al. [2016] present a review of the different methodologies to do EEA. They distinguish  
7 methodologies between coupled model methods, sea surface temperature (SST) forced atmosphere  
8 only model methods, analogue-based methods, empirical methods and broad-scale methods (they  
9 use the word “approaches” instead of “methods”, but we changed it to “methods” in order to avoid  
10 a confusion with risk-based and storyline approaches).  
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18 Our BAMS analysis shows that those different methods do not have the same popularity. The  
19 coupled model methods cover a large spread of methodologies, so we do not consider that all ar-  
20 ticles using coupled models should be part of the same category. Lewis and Karoly [2013, 2014],  
21 Sun et al. [2014], King et al. [2015] have been cited several times by BAMS articles relying on the  
22 comparison of probabilities for different CMIP5 experiments for their analysis. Many other articles  
23 use this methodology without explicitly referring to a former article.  
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32 The most used methodology, also described as the SST forced method by Stott et al. [2016],  
33 stems from Pall et al. [2011], and has been refined by Massey et al. [2015], Schaller et al. [2014],  
34 Black et al. [2015] and Schaller et al. [2016]. 21 BAMS articles cite at least one of those articles.  
35 This methodology is the one that fits best the risk-based approach. 5 BAMS articles cite Christidis  
36 et al. [2013] which also use a large ensemble of an atmospheric model with different SST forcings  
37 for a part of their analysis.  
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48 4 articles (all from the same team) use the analogue methodology to perform a conditional attri-  
49 bution. They all cite Cattiaux et al. [2010] as the first article to study a specific event in the context  
50 of climate through the use of analogues. Articles with a methodology similar to what Stott et al.  
51 [2016] call empirical methods cite either Van Oldenborgh et al. [2012], Coles et al. [2001] or do not  
52 reference a former article using this methodology [e.g. Siswanto et al., 2015]. It is almost never the  
53 only methodology used in those articles [e.g. Sippel et al., 2016]. The broad-scale methods [e.g.  
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Zwiers et al., 2011, Min et al., 2011] are more detection and attribution of trends on extremes than EEA. We did not find references to those articles in BAMS case studies.

Four other methodologies in the BAMS are used in at least 3 different articles which are not presented in Stott et al. [2016] and for which we hence give more details. Knutson et al. [2013b] 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 (including Arblaster et al. [2014]) use this methodology.

Guemas et al. [2013], Massonnet et al. [2015] and Fučkar et al. [2016] are case studies dealing with anomalies of sea ice extent. They rely on the reconstitution of anomalies with different initializations using a sea ice model. Murakami et al. [2015], Yang et al. [2015] and Zhang et al. [2016] examine tropical storms. They use forecast-oriented model simulations with different initializations to analyze the influence of climate change on those events.

Apart from the analogues, the papers based on Christidis et al. [2013] also analyze the events

1 with a circulation conditional framing. Those articles could fit in both a storyline and a risk-based  
2 approach. A few individual papers could also fit into a storyline framing [e.g. De Vries et al., 2013,  
3 Sweet et al., 2013]. However, the storyline approach lacks at the moment a widespread method-  
4 ology like the one of Pall et al. [2011] is for the risk-based approach. This could be due to the  
5 fact that the storyline approach as proposed by Trenberth et al. [2015] emerged after a few of the  
6 BAMS reports were already published. This under-representation may also be related to the very  
7 short length of BAMS articles, which does not fit as well the storyline approach than the risk-based  
8 approach. This does not mean that no article use this kind of approach. Outside of the BAMS,  
9 Hoerling et al. [2013], Meredith et al. [2015], and Pall et al. [2017] are three examples of storyline  
10 approaches.  
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23 The most important result of this genealogical sorting is that most of the BAMS papers follow  
24 their own methodology, specific to the case study or to a given framing. Indeed, only 51 out of 105  
25 BAMS articles explicitly mention a genealogical link, which is mentioned in another BAMS case  
26 study. We hence propose hereafter a way to describe all the potential framings of EEA, without  
27 relying on a sorting of different methodologies.  
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## 38 **4 Defining EEA**

39 We have found that sorting the case studies between methodologies excludes most of the BAMS  
40 articles. This means that trying to categorize the case studies into different approaches or method-  
41 ologies does not suffice to give a proper overview of EEA. However, the framing of EEA has a clear  
42 impact on the results of any given case studies. Angéilil et al. [2017] have shown how the results of  
43 all the BAMS articles from year 2011 to 2014 would differ using a different method than the one  
44 used by the original authors. Dole et al. [2011] and Rahmstorf and Coumou [2011] find apparently  
45 contradictory results regarding the attribution of the 2010 Russian heatwave due to different fram-  
46 ings [Otto et al., 2012].  
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We propose hereafter to differentiate the ways to frame EEA based on several criteria. In order

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to do so, we first need a definition EEA that captures all the different possible framings. 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 most consensual picture.

From both corpora 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 could be considered as references to the debate between risk-based and storyline approach we exposed in section 2, which seems to be ingrained in a part of the community. However, because we have shown that this debate 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. This may be related to the fact that we asked researchers to define detection and attribution of extreme events in the A2C2 corpus, rather than

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EEA, as done in the EUCLEIA corpus. We hence find it best not to consider it for our definition, since detection (in the sense of Hegerl et al. [2010]) is rarely a part of EEA studies.

Our working definition has to adopt the widest possible scope so as to include every acceptance of EEA 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 “was this event influenced by climate change?” and answer it. We avoid references to causality, as advised in chapter 2 of NAS2016. We choose to refer to *climate change* and not *anthropogenic climate change*, as EEA could be applied to changes not related to anthropogenic activities (e.g. volcanic eruptions). 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 “was this event influenced by climate change?” in a suitable way to make it possible to answer through a scientific study.

## 5 Framing EEA

We can use this definition to show all the possible framings of an EEA study. In order to do so, we decompose the original question “was this event influenced by climate change?” into three separate issues. First, how does one define the event to study? Second, what does one mean by “influenced 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

1 influenced by climate change. In the second case, it would mean answering whether all the events  
2 within a class (e.g. all the heatwaves above a certain threshold of temperature for a given number  
3 of consecutive days) become more likely because of climate change. Harrington [2017] has shown  
4 how those two different choices can lead to different results.  
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10 The attribution of a singular event is contingent upon the idea that somehow, the causal chains  
11 leading to this event may be reproduced in whole or in part. The idea is to recreate the same event  
12 and to evaluate how this event fares with and without climate change. Until now, this has been  
13 done in 3 different ways. Hannart et al. use data assimilation that allows them to constrain the  
14 event to its observed trajectory in a model. Meredith et al. [2015] condition strictly the circulation  
15 of their model to the one observed during the very high precipitations they are interested in. Then,  
16 they run their model for 2 different level of GHG emissions and SST corresponding to a factual  
17 and a counterfactual world. Arblaster et al. [2014] try to recreate the precise pattern of temperature  
18 anomaly observed during a heatwave by modeling several physical processes.  
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31 The attribution of a class of event is probabilistic. The goal is to evaluate if there is a change  
32 of the probability that any extreme event that shares its extreme feature with the event of interest  
33 happens due to climate change. This is mainly done by considering all the events above a cer-  
34 tain threshold. Many studies use the observed extreme anomaly of the variable of interest as this  
35 threshold. Others choose a lower threshold, especially when the event is so extreme that it would  
36 be difficult to trust statistical tests too far in the tail of the distribution (as was done in Stott et al.  
37 [2004]). In that case, there is no need for the event to actually happen to do an EEA study. One  
38 just needs to choose a threshold, a duration and a region [Christidis et al., 2015]. A few methodolo-  
39 gies rely on different ways to define a class of event, e.g. the ones based on analogues of circulation.  
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### 54 **5.1.2 Choice of the event**

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57 Apart from those general considerations on the meaning an “event”, before starting an EEA study  
58 one has to choose the event of interest. There are different reasons to consider an event to be inter-  
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1 esting enough to study. It can be because of its impacts, its rarity, or both. We provide an overview  
2 of those motivations in supplementary Table S5.2.1. In the BAMS reports, out of 105 articles, 33  
3 explain their interest in an event based solely on its rarity, 27 based solely on its impacts and 42  
4 based on both. This does not mean that there are no other implicit reasons involved in the choice of  
5 a specific event. 11 articles advance different reasons (for a more comprehensive list of those rea-  
6 sons, consult the supplementary Table S4). For example, King et al. [2015] chose an event because  
7 it raised the media attention. We also stress that the impacts can go from very serious (e.g. “a tragic  
8 food crisis that led to famine conditions” in Funk [2012]) to rather harmless (e.g. the well-being of  
9 tennis players during the Australian Open [King et al., 2015]).  
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21 There is also the matter of the selection of the region where the event happened, which we sum  
22 up in supplementary Table S5.2.2. Most of the time, researchers study events happening in the  
23 region where they live. Out of the 105 case studies in the BAMS, 80 focus on the region of the first  
24 author’s laboratory. 69 study events happening in Annex I countries, as defined by the UNFCCC,  
25 29 focus on non Annex I countries and the rest (7 out of 105) look at polar regions or the ocean.  
26 Hence there is a disproportion of case studies in favour of developed countries (this was also pin-  
27 pointed by Stott et al. [2016] and Angélil et al. [2017]). This selection bias is heightened by the  
28 fact that climatologists are aware of the events happening in their own countries because they see  
29 them happening, while they might not pay attention to extreme events happening on the other side  
30 of the world otherwise than through media reports of their impacts.  
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44 Sometimes, local stakeholders play a part in motivating researchers to study a particular event.  
45 One of our interviewees told us that “policy makers [...] had questions about [an] event because  
46 they are of course concerned about whether or not the same kind of event might happen [again]”.  
47 Regional projects also mainly finance studies about local events. For example, the EUCLEIA con-  
48 sortium produced 6 case studies about European extreme events [e.g. Hauser et al., 2017, Wilcox  
49 et al., 2017], and the French project Extremoscope financed research focused on extreme events  
50 affecting France [e.g. Ouzeau et al., 2016]. A few stakeholders, like the Red Cross which worked  
51 with the World Weather Attribution project [Herring et al., 2016b] or UK’s National Environment  
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Research Council which funded the ACE (Attributing Impacts of External Climate Drivers on Extreme Weather) Africa project (e.g. see the acknowledgment of Bergaoui et al. [2015]), also support research studying developing countries which do not have research infrastructures that can lead such studies.

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, there are three choices left: the precise definition of the region affected, 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 the Californian drought. 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 arbitrary, meaning that they do not arise from scientific considerations, but rather from political borders, or from regions defined in earlier articles that might not be relevant for the specific event of interest. Cattiaux and Ribes [2018] 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 Influence of climate change: level of conditioning

The second part of the decomposition of the question “was this event influenced by climate change?” is to show all the different ways to analyze the role of climate change. In order to sort them,

1 we follow NAS2016, which divides EEA between two types of methodologies: unconditional and  
2 conditional attribution. We have classified all the BAMS articles between different nuances of  
3 conditioning. We divided the articles into the following categories (see supplementary table S5.3  
4 for an overview):  
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- 7 • Unconditional – 42
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- 9 • Conditional to SST/SIC (sea ice cover) – 40
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- 12 • Conditional to circulation – 9
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- 15 • Conditional to El Niño/La Niña – 9
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- 18 • Conditional to sea level rise – 2
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- 21 • Effects of anthropogenic climate change on a precursor – 13
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- 24 • Effect of other precursors than anthropogenic climate change –29
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32 We say that attribution is unconditional when the study directly links anthropogenic climate  
33 change to an extreme observable, or its impacts. That can only happen in studies using either only  
34 observations or coupled models (CMIP5 or studies focused on a particular model) with a compar-  
35 ison between pre-industrial (or natural-forcings only) and historical runs. This does not mean that  
36 those studies are not conditional to the biases of the models they rely on. Examples of uncondi-  
37 tional attribution in the BAMS are the papers of Lewis and Karoly [2014] or Knutson et al. [2013a].  
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40 Conditional attribution links anthropogenic climate change combined to a precursor to either  
41 an extreme observable, or its impacts. This precursor is an internal element of the climate sys-  
42 tem which played a role in the occurrence of the event. Many studies, especially the ones based  
43 on the most widely used methodology proposed by Pall et al. [2011] evaluate the influence of a  
44 thermodynamical precursor combined with greenhouse gases (GHG) concentrations on an extreme  
45 observable (e.g. temperature, or precipitation). A thermodynamical precursor is a precursor that  
46 is directly linked to the increase of temperatures and for which the influence of climate change  
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1 is already clear. Most of the time the thermodynamical precursor is the sea-surface temperature  
2 (SST). Because of the computational costs of coupled models, the idea is to rely on atmospheric-  
3 only models, for which the SST is a boundary condition. They allow to better represent processes  
4 like dynamics or land-surface interactions which become more trustworthy at high resolutions.  
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10 According to Risser et al. [2017], the SST conditioning methods rely on three assumptions: (i)  
11 the effect of anthropogenic climate change does not depend on the state of the ocean, (ii) the ocean  
12 variability is not affected by anthropogenic climate change, and (iii) the effect of the atmosphere  
13 on the coupling between atmosphere and ocean is unimportant at the temporal scale of the event.  
14 The influence of SST conditioning, which is massively used in the EEA literature has not been  
15 enough documented to make the assumption that the probabilities calculated are equivalent to un-  
16 conditional probabilities. Dong et al. [2017] have shown that this assumption is globally correct  
17 for temperature extremes but that the air-sea coupling significantly changes the results for precip-  
18 itations and in certain regions for the circulation. Risser et al. [2017] also provide a methodology  
19 to evaluate the influence of the SST conditioning on EEA results. Other possible thermodynamical  
20 precursor are the global temperature [e.g. Hope et al., 2015] or sea level rise [e.g. Sweet et al., 2013].  
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35 Conditioning can also combine climate change to a precursor not clearly related to climate  
36 change through thermodynamics, a dynamical precursor. This type of conditional attribution is  
37 the one presented in Trenberth et al. [2015], which Shepherd [2016] called “storyline approach”.  
38 The idea is that for events heavily conditioned by the dynamics, the climate change signal will be  
39 drowned in the internal variability. This does not mean that there is no effect of climate change.  
40 The question asked in this case would rather be “Given the change in atmospheric circulation that  
41 brought about the event, how did climate change alter its impacts ?” [Trenberth et al., 2015] or  
42 “What is the best estimate of the contribution of climate change to the observed event ?” [Shep-  
43 herd, 2016].  
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57 There are examples of other types of conditioning dealing with other scales of internal variabil-  
58 ity. 9 BAMS articles study the influence of El Niño (or La Niña) on an event combined with the  
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4 influence of climate change on El Niño [e.g. King et al., 2013].  
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13 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.

29 case studies also consider the impacts of other precursors than anthropogenic climate change. Most of these studies (22) are combined with a part discussing the role of climate change. The methodology of Arblaster et al. [2014] summarized in the third section gives an example of such an approach. The fact that 7 BAMS studies analyse only the effect of other precursors than anthropogenic climate change shows that EEA can encompass attribution to climate change more generally than just anthropogenic climate change.

Lastly, Von Storch et al. [2014] and Feser et al. [2015] only detect changes without any attribution step so we could not sort them.

An interesting result of sorting BAMS studies into different levels of conditioning is that each issue of the BAMS increases the sampling of uses of different methods and the comparison of their results. Those studies are highlighted in boldface in the supplementary table S5.3. This is consistent with the recommendations of NAS2016 [2016]. The EUCLEIA project has also devoted one work package to multi-method case studies [e.g. Hauser et al., 2017, Wilcox et al., 2017].

### 5.3 Climate change: Definition of a counterfactual world

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 definitions 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. We have sorted the different ways to create a counterfactual world in the following categories (supplementary table S5.4 gives the detail of how we classified each BAMS article):

- Past/Historical – 24
- SST/SIC/GHG Preindustrial – 21
- SST/SIC/GHG Natural – 9
- SST/SIC/GHG Historical – 13
- Natural forcings only – 17
- Preindustrial – 22
- Not relevant – 15

The simplest way to proceed is to compare a past period to a most recent period, whether it is in observational datasets, or in the historical period of a climate model. 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 (and disadvantage, given the length and availability of the observational datasets) of this technique is that it allows to rely on observations only [e.g. Van Oldenborgh et al., 2012]. In this context, climate change accounts for both anthropogenic and natural forcings.

Other studies use pre-industrial runs from coupled models as counterfactual worlds. There is a thin line between a definition of the counterfactual based on the past and the counterfactual based on pre-industrial conditions. 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]. This arbitrary choice can be challenged, as Hawkins et al. [2017] have shown that 1870 does not necessarily equal preindustrial. We however choose to keep it to make the classification simpler.

1 An alternative option to pre-industrial for coupled models users is to use historical runs with natural  
2 forcings only, which are available for CMIP5 models. 5 articles use both pre-industrial and natural  
3 counterfactual worlds.  
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8 For methodologies based on atmospheric models, the factual world is built using the observed  
9 SST as input. The tricky step is to create counterfactual SSTs [Schaller et al., 2016]. There is an  
10 evolution from historical (which was the counterfactual world used in Pall et al. [2011]) towards  
11 preindustrial through the BAMS issues. Otto [2017] also discusses the consequences of the differ-  
12 ences between counterfactual worlds in the context of SST conditional attribution.  
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21 The use and comparison of several counterfactual worlds does not occur as frequently in the  
22 BAMS as the use of multiple levels of conditioning, although it does happen in the three latest  
23 issues studies here. However, there is a case for testing the influence of the choice of counterfactual  
24 on the results, since Hauser et al. [2017] have shown that it has an impact on the result.  
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31 In the BAMS, the evaluation of contributions from differentiated external forcings, like GHG  
32 and aerosols, or land-use is rarely done. In contrast with the detection and attribution of trends, one  
33 of the interviewees states that “EEA is very very predominantly envisioned in an anthropogenic vs  
34 natural perspective, and only with this reading grid”. There are very few studies differentiating the  
35 role of those different anthropogenic forcings in the BAMS. As an exception to that rule, Wilcox  
36 et al. [2015] and Miao et al. [2016] make a distinction between aerosols and GHG emissions ef-  
37 fects on the extreme event. We also point out that Pall et al. [2011] define their counterfactual by  
38 removing only the GHG part of the anthropogenic forcing, not the aerosols.  
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50 We note that for a few articles, the explicit definition of a counterfactual world is not necessary.  
51 We sorted them as not relevant. Those articles use methodologies based on the reconstitution of an  
52 observed anomaly [e.g. Arblaster et al., 2014] or only do trend detection without any comparison  
53 to trends in a counterfactual world [e.g. Feser et al., 2015].  
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## 6 Conclusion

We have shown that the BAMS case studies use 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. We propose a definition of EEA that encompasses the different approaches used by the community described in section 2. EEA is the ensemble of scientific ways to interpret the question “was this event influenced 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? We have described the diversity of ways to answer these questions used in the BAMS and provide a complete classification in the supplementary material.

Although the BAMS issues are a very practical database due to the common strict guidelines, they also have limitations. Indeed, a few methods (especially those following the storyline approach) have not yet been used in the BAMS [e.g. Meredith et al., 2015, Hoerling et al., 2013, Pall et al., 2017] and may never be due to the limited space allowed for each case study. This entails that while the BAMS is informative of a large part of the work of EEA, it cannot be considered as an unbiased sample.

The next step of our unveiling of EEA will be to better understand its use, as it seems to be a point of contention between the different approaches we described in section 2. A few articles have already started to tackle this question [e.g. Sippel et al., 2015, Hulme, 2014]. A second article will analyze in detail the two corpora of interviews to answer the question : “why do we do EEA?”

## 7 Acknowledgements

This work was supported by ERC grant No. 338965-A2C2 and the European Union's Seventh Framework Programme grant No. 607085-EUCLEIA. We thank Dáithí Stone, and three anonymous reviewers for their helpful comments.

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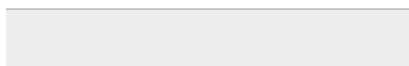
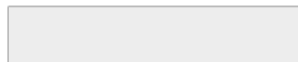
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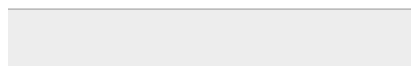
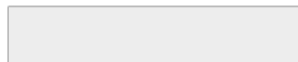


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