ATTRIBUTION OF CLIMATE EXTREMES: A THEORETICAL REVIEW AND POTENTIAL APPLICATIONS

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RESUMEN

Los estudios de atribución de causas a eventos climáticos extremos se pueden llevar a cabo empleando diferentes metodologías. Dichas metodologías no son excluyentes, sino que se complementan y contribuyen a obtener resultados más fiables.
Algunos de los aspectos más importantes a la hora de realizar un estudio de atribución son: cómo se plantea la cuestión inicial, la definición del evento a analizar y una comunicación clara de los resultados que evite contradicciones aparentes en las conclusiones obtenidas.
En el enfoque basado en el riesgo se obtienen ensambles de modelos climáticos para dos escenarios diferentes. Uno de estos escenarios representa el mundo actual, tal y como lo conocemos hoy en día. El escenario alternativo es un mundo sin influencia humana, es decir, un mundo sin emisiones humanas de gases de efecto invernadero o con niveles pre-industriales. El siguiente paso es el cálculo de las probabilidades del evento extremo analizado en ambos escenarios, el actual y el alternativo. Una vez obtenidas esas probabilidades, es posible calcular la fracción o porcentaje del evento que se puede atribuir a un forzamiento específico.
La ciencia de la atribución de eventos extremos es un sub-campo de las ciencias del clima relativamente nuevo, por lo que existe un amplio potencial para nuevas aplicaciones. Tal es el caso del estudio del impacto de las emisiones antropogénicas de gases de efecto invernadero en el sistema sanitario, cambios en la distribución de enfermedades, la influencia humana en los ecosistemas, cambios en la distribución de especies animales y vegetales o los impactos del cambio climático antropogénico en el mercado de seguros o legislación internacional.

Keywords: atribución, eventos extremos, escenario actual, escenario alternativo, fracción de riesgo atribuible.

ABSTRACT

Different approaches can be applied in order to perform an attribution study of extreme weather and climate events. Far from being exclusive, all of these approaches are complementary and contribute to more robust results. Special care has to be taken when framing the initial question, when defining the event, and in the communication of the results in order to avoid apparent contradictions.
In a risk-based approach, ensembles from climate models are obtained for two scenarios. One of those scenarios represents the factual world, a world as we know it

today. The counterfactual scenario is a world without human influence, that is to say, a world as it would be without the human emissions of greenhouse gases or with pre-industrial levels. The next step is to calculate the probabilities of an extreme event to happen in both the factual and counterfactual scenario. Once they are obtained, it is possible to analyze the fraction or percentage of the event attributable to a specific forcing.
Given the fact that attribution science is a relatively new subfield of climate science, there is still plenty of room for new applications. For example, to study the impact of anthropogenic GHG emissions in the health system, changes in the distribution of diseases, the human influence in ecosystems, changes in the distribution of species or the impacts in the insurance market or international law.

Key words: attribution, extreme events, factual scenario, counterfactual scenario, FAR.

1. INTRODUCCION

Human influence on the warming of the climate system since the 1950s has been continuously increasing (e.g.: IPCC, 2001; IPCC, 2014). In the Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC, 2007), the warming was already described as "unequivocal" and "very likely due to observed increase in anthropogenic greenhouse gas (GHG) concentrations". Furthermore, these GHG concentrations and other anthropogenic drivers are "extremely likely to have been the dominant cause of the observed warming since the mid-20th century" (IPCC, 2014). Also since that time, "changes in many extreme weather and climate events have been observed" (IPCC, 2013). In other words, anthropogenic climate change is not only altering long-term trends in the climate system, but also the frequency and magnitude of extreme weather and climate events (hereafter climate extremes (IPCC, 2012)). Furthermore, in comparison to any change in the mean values, climate extremes have a more immediate and direct impact, and so they capture great media and public attention.

Not long ago, it was not possible to assert that a particular climate extreme was caused by climate change. However, in 2003, Allen pioneered the methodology for attribution studies of climate extremes. The first published attribution study was on the 2003 European heatwave (Stott et al., 2004), and it demonstrated that human influence had at least doubled the probability of temperatures similar to those recorded during that event. Since then, attribution science has become a new subfield of the climate science in its own right. Moreover, since 2012, the Bulletin of American Meteorological Society (BAMS) (e.g.: Peterson et al., 2012; Herring et al., 2014; Herring et al., 2018), publishes a yearly report dedicated to explain extreme events from a climate perspective.

The innate curiosity of scientists, the improvements in models, the urgent necessity of public awareness and engagement, the increase of knowledge of future impacts and the adoption of the best adaptation and mitigation strategies possible, as well as the desire of legal responsibility for losses and damages, are some of the aspects that have fuelled the rapid development of attribution of climate-related evets (ACE) (Hulme, 2014).

The concepts of detection and attribution have evolved through time. In the IPCC 1 (WGI) (Wigley et al., 1990), the concept of detection is not made clear or separate from attribution. These concepts started to be differentiated with Santer et al., 1996, but it was not until the Fourth IPCC when detection and attribution were considered as two clear and specific, although inseparable, concepts (Hegerl et al,. 2007). Hegerl et al., (2010) defined attribution as "the process of evaluating the relative contributions of multiple causal factors to a change or event with assignment of statistical confidence".
Nowadays, ACE allows us to probabilistically determine to what extent anthropogenic climate change has influenced the frequency and magnitude of a climate extreme.

2. DATA AND METHODOLOGY

There are different methodologies to perform an attribution study of a climate extreme. Regardless of the approach chosen, different datasets can be used, from observations or reanalysis data to outputs of climate model simulations.
The attribution forcing can follow a single or multi-step scheme, depending on the aspect of the climate, natural or human system being studied and the driver of the change (Stone et al., 2013). But in any case, there are some common guidelines to analyse the influence of the anthropogenic climate change, or another forcing, in a climate extreme (figure 1).
Extreme weather and climate events are highly difficult to study given their particular characteristics. They are usually rare at any point and are the result of a unique combination of external factors (anthropogenic or natural) and the internal variability of the climate system (AMO, NAO, ENSO,...) (Otto et al., 2016), which determine their occurrence and magnitude. These characteristics of climate extremes hinder the availability of long and homogeneous observational data, in particular when dealing with variables other than temperature or precipitation.
Historical observations (when available), reanalysis and climate outputs, can be used to compare two different periods in time, a pre-industrial or less human-influenced, and a more recent period impacted by the emissions of greenhouse gases of human nature. The end of the 19th century to almost the end of the 20th century, has been considered an appropriate period of low human influence (Otto, 2017). Otherwise, the outputs from climate models for specific experiments, such as historical and natural simulations, commonly termed "HIST" or "ALL and "NAT" in the methodology, allow a comparison between two different worlds.
Another approach is based on the detection of changes along time in the dominant circulation pattern, similar to the one prevailing during the extreme event (Stott et al., 2016). However, this historical analogues approach assumes that the relationship and interactions between the configuration of the atmosphere and the resultant event are kept constant through time.

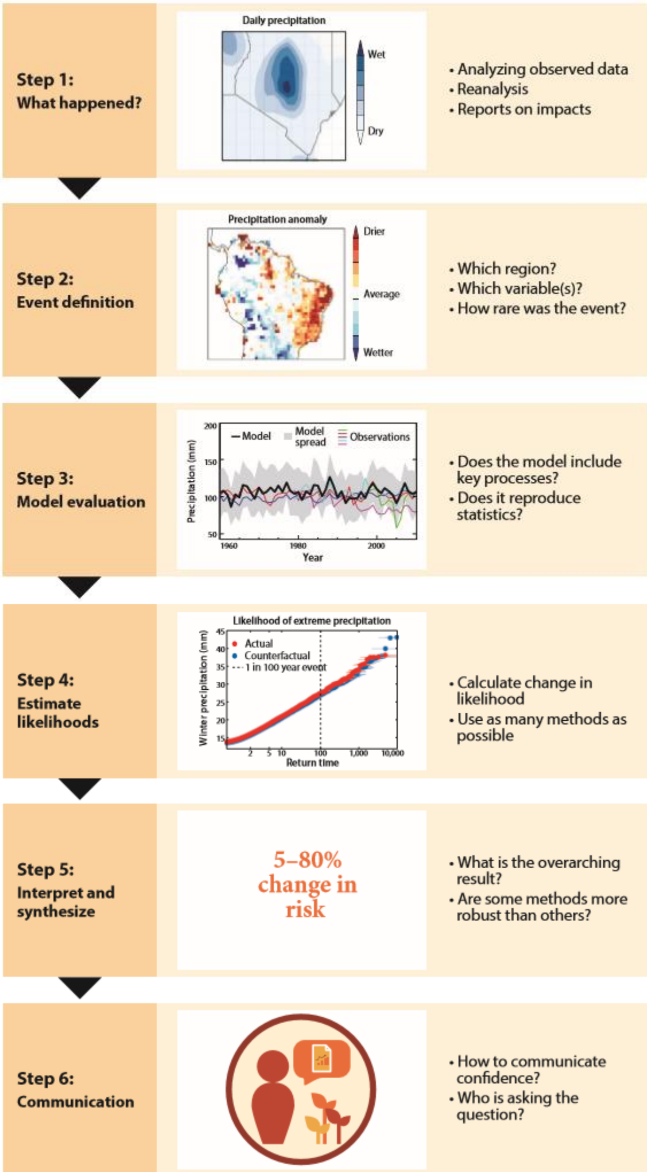

Fig. 1: Steps for a complete attribution study of climate extremes. Source: Otto, 2017 and the Raising Risk Awareness project (https://cdkn.org/climaterisk).

The other main cluster of methodologies for attribution studies of climate extremes resort to climatic models: coupled atmosphere-ocean or atmosphere only models. In any case, uncertainties are apparent when a unique model is employed in a study.
In order to use the model-based approaches, the performance of the models is usually evaluated with observations or reanalysis data in order to ensure that the event is well-captured by the model. The model assessment can be done with reliability diagrams,

Q-Q plots, a Kolmogorov-Smirnov test of the distributions, power spectra, or the return times with an extreme value analysis (EVA). In any case, and given the results, a bias correction could be applied (Stott et al., 2016).

The bias is almost impossible to avoid given the non-stationary nature of the climate and the limitations of the models (National Academies of Sciences, Engineering, and Medicine, 2016). However, if the number of ensemble members is large, the bias correction, or even the fact of making assumptions about the distribution of the data, might not be necessary (van Oldenborgh et al., 2016). Also, bias correction is avoided in simple cases by using anomalies or even using the return times instead of the magnitudes of the event (Otto, 2017).

General Circulation Models (GCMs) such as the ones from the Coupled Model Intercomparison Project phase 5 (CMIP5) from the World Climate Research Programme (WCRP), are extensively used in event attribution of climate extremes. The CMIP5 project offers the possibility of obtaining ensembles for different experiments and from different models. However, these models are quite demanding in terms of time and computation, since the simulations include the atmosphere, ocean, land and some biological and chemical processes. Even more, the CMIP5 outputs stopped in 2005, although different scenarios of greenhouse gases emissions (Representative Concentration Pathways, RCPs) can be used, if available, to span the simulations to the present. The RCP chosen has little impact on the result though, since negligible differences between them are shown up to later in the 21st century (National Academies of Sciences, Engineering, and Medicine, 2016). The counterfactual or the most natural world, is taken from the control (pre-industrial) simulations or the NAT simulations (National Academies of Sciences, Engineering, and Medicine, 2016).

The atmosphere only models (AGCMs) can run simulations as short as a year or a decade, taking into account only the land and the atmosphere, which takes less computational effort and less time, resulting in a larger number of simulations (National Academies of Sciences, Engineering, and Medicine, 2016).

Atmosphere only models are forced with observed sea surface temperatures (SSTs) or with SSTs obtained from GCMs for the actual world. However, it must be taken into account that the choice of the SST can influence the counterfactual world. Also, that we are assuming that the relationship between the model and the observations in the factual world are maintained in the counterfactual. It is possible to compare the model outputs for a climate extreme according to the different selection of the SST and Ice Concentration (IC), to assess the impact of the selection in the results (Christidis et al., 2013).

One of the most well-known atmosphere climate models is the HadAM3P model from the UK Met Office Hadley Centre, that is being run by volunteers through *weather@home*, launched by climateprediction.net (CPDN) as the largest climate model experiment. It consists of a computing infrastructure that allows thousands of ensembles of climate models to be run without the need of a supercomputer, by using the computational time from volunteers.

In some studies it is also important that the model captures and accurately reproduces the dynamics of the atmosphere and some modes of natural variability. The phenomena of natural variability usually have low frequencies that hinder the detection of human influence in the atmospheric circulation of a climate extreme (National Academies of Sciences, Engineering, and Medicine, 2016). But a low signal-to-noise ratio can also hinder the attribution, in particular at small scales, where the ratio is even lower (Trenberth, 2011).

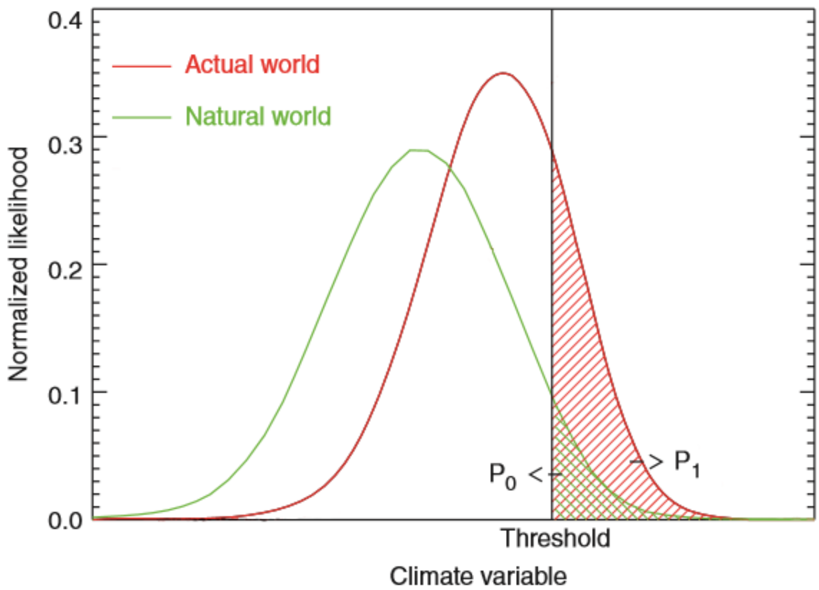

Fig. 2: Probability density function of a variable in the factual and counterfactual world. Source: modified from Stott et al., 2016.

There are two conventional approaches in event attribution: the risk-based approach and the storyline approach.
In a risk-based approach, an attribution study of an extreme weather event is performed using different groups of ensembles for two scenarios. One of those scenarios represents the factual world, a world as we know it today, whose conditions are defined by the anthropogenic and natural forcings together. The counterfactual scenario is a world without human influence, that is, a world as it would be without the human emissions of greenhouse gases which has led to the global warming and so, it is more similar to a pre-industrial atmospheric composition, leaving other aspects such as volcanic aerosols the same as the factual conditions.
Then the distribution and the likelihood of the event to occur under both scenarios is obtained. The next step is the calculation of the probabilities of the extreme event to occur in the factual and counterfactual scenario. The probability of such an event to happen due to the anthropogenic climate change, the factual world, is designated as P_1 (figure 2). Similarly, the probability of that extreme event in the counterfactual world, an unforced climate, is P_0. Once those probabilities are calculated, the fraction or percentage of the event that is attributable to a specific forcing or cause, such as the

anthropogenic climate change, is finally calculated. That is, how more probable the risk of an event is to occur due to the specific forcing.
This Fraction of Attributable Risk (FAR) used for necessary causation (Hannart et al., 2016), is defined as

$$FAR = \frac{(P_1 - P_0)}{P_1} = 1 - \left(\frac{P_0}{P_1}\right)$$

The FAR values range from 0 to 1. The closer those values are to 1, the higher the possibility of occurrence of the event under the human GHGs emissions (Kay et al., 2011). Positive values of FAR means that an extreme event is more likely to happen in a human influenced world, while negative values imply that the event is less common in the counterfactual than in the actual world (Kay et al., 2011; Christidis et al., 2013).
The fraction $\left(\frac{P_1}{P_0}\right)$ is called Probability Ratio (PR) or Risk Ratio (RR), so the higher the value of the fraction, the lesser the influence of the natural forcings.
The storyline approach does not evaluate the changes in the overall risk. This approach considers all the causal factors involved in the occurrence of the event and the thermodynamic impact of global warming in those factors.
Attribution studies can be carried out conditioned for example to a particular atmospheric circulation observed during a climate extreme, to a specific observed SST anomaly and IC, or to determine the state of a mode of natural variability such as the ENSO (Stott et al., 2016). Usually the conditioning increases the signal-to-noise ratio since it decreases the dynamical variability (Sheperd, 2016). Nevertheless, conditional statements do not allow assessment of the overall change in the risk of a climate extreme (Otto et al., 2016). This methodology can go further when firstly conditioning the results to a specific atmospheric circulation and then studying the role of the thermodynamics (Otto, 2017).
All the different approaches are not exclusive but complementary. Even more, the combination of various approaches can provide more robust results about the event being studied, provided that the event definition and framing of the question are made clear in order to avoid possible apparent contradictions (Otto et al., 2012).

3. FRAMING THE ATTRIBUTION QUESTION AND DEFINING THE EVENT

The results of an attribution study will depend on how the question to be answered is posed, the type of event being studied and how the climate extreme event is defined.
Given the chaotic nature of the atmosphere, we cannot assume that an extreme event would not have happened without the anthropogenic climate change (Otto, 2016). However, in the current scenario, neither can we deny that any extreme event is already going to be affected by human influence (Hulme, 2014). Then, the initial question to pose in an attribution study should not be if a climate event was caused by the anthropogenic influence of greenhouse gas emissions, but to which extent the magnitude or occurrence of the event is impacted by the human influence. Even more,

a null hypothesis where the non-human influence in an extreme event is tested, would be underestimating the anthropogenic climate change (Trenberth, 2011), and it does not necessarily mean that there is no effect at all (National Academies of Sciences, Engineering, and Medicine, 2016).

It is not uncommon to find a selection bias of the climate event analysed. Inevitably scientists tend to prioritize events that are registered in their more immediate environment. Also, the availability of records and their quality can determine the regions being studied. Furthermore, the availability of observations will decrease the uncertainty in the results obtained. Fortunately, this selection bias has being slowly but steadily decreasing since the publication of the first BAMS report until now, and the last report shows an increase in the number, areas and events where attribution studies are being carried out.

The approach chosen will determine how to frame the question in an attribution study of an extreme event. It will also depend on the objective of the study and the public interested in the results and their specific needs (Otto, 2017) such as decision planners, governments, etc. Besides, the framing will impact the way in which the results are communicated. The question to be answered in an attribution study has also to specify if there is some conditioning, for example, to a particular mode of the ENSO in the moment of the occurrence of the event, or another particular circulation pattern or atmospheric condition, or SST observed (Stott et al., 2016; Otto, 2017).

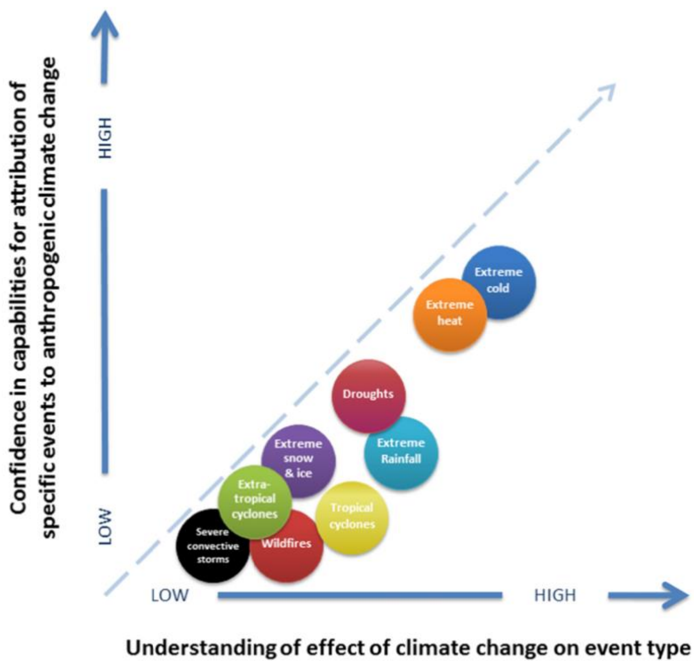

Fig. 3: Trade-off between the understanding of a climate extreme and the capabilities available for performing an attribution study of that climate extreme. Source: National Academies of Sciences, Engineering, and Medicine (2016).

Confidence of results of attribution studies varies across different climate extremes (figure 3) (National Academies of Sciences, Engineering, and Medicine, 2016). Temperature related extremes, such as extreme heat and cold events, generally offer the highest confidence in the attribution of human influence; closely followed by droughts and extreme rainfall. The least robust results are obtained in attribution of storms. The increase in the tools and capabilities for attribution studies can increase the confidence in the results for certain types of extreme events, but there is always a trade-off with the level of our understanding of the impact of climate change in the type of event being studied.
All the forcings determine the thermodynamic and dynamic environment that foster the unleashing of a climate extreme and its impacts. In general, an attribution study from a thermodynamic perspective, in particular if it is related to temperature and water vapour content, shows more confidence in the results than a dynamical approach (Shepherd, 2014). However, both, the thermodynamic and dynamic aspects of an event need to be considered, since their influence over an extreme event can be in opposite directions (Otto et al., 2016; Otto, 2017). Studies from the point of view the thermodynamics are usually easier and straightforward, and better determined and better modelled.
The type of events or particular event being studied has to be defined in detail. Some of the aspects to consider are the spatial and temporal scale, the period of time or baseline or the variable chosen, among others.
Quite often the attribution of a climate extreme is hindered by confounding factors, which are particularly difficult (if not impossible) to be captured by climate models. For example, the confounding factors in a catchment scale study of flooding can include changes in land use, soil moisture, canalization, etc. When analysing a heatwave, the effect of urban heat can impact the results; in droughts and wildfires, the land cover, the land management or deforestation are some of the aspects to consider. All the known or potential confounding factors have to be clarified at the beginning of the attribution study.
The framing of the question to answer must be as precise and clear as possible in order to avoid apparent contradictions in the results. The consideration of all these aspects improves communication of the results in an attribution study in a way oriented to the final receptor and to answer specific needs.

4. FUTURE APPLICATIONS

There is still plenty of room for improvement and new applications of the methodologies of detection and attribution of climate extremes beyond the heatwaves, cold spells, very heavy precipitation and floods, droughts, blizzards, severe frosts, extreme snow accumulation, etc.
The study of the influence of anthropogenic climate change on past and present climate extremes offers an increase of knowledge about the understanding of the behaviour of those extremes in a changing word, and so it is valuable for the design and adoption of adaptation and mitigation plans. Even more, bearing in mind that past experiences could not be applicable in the future context in which changes in the

extreme events are expected, attribution studies in the projections of future climate are even more important, since they will help to improve the understanding of the changes in the near future of extreme weather and climate events.

Thus, attribution studies of extreme events offer useful and valuable information for a great range of public and private sectors: decision makers, governments, NGOs and charities, stakeholders, and society in general. But for this to happen, effective communication between all the actors involved is needed, so efforts can be coordinate and real needs taken into account. That way inform and objective proactive actions can be accomplished, instead of a more common reactive response to an extreme event.

The future of attribution studies involves near-real time attribution of extreme events to human influence (van Oldenborgh et al., 2015; van Oldenborgh et al., 2016). Considerations about the criteria of an event to be studied, the collation of updated information or the assessment of the results communicated (National Academies of Sciences, Engineering, and Medicine, 2016) must be taken into consideration in order to develop such an operational system that could even offer information while the event is happening.

Moreover, one further step should include the study of the changes in the impacts as a result of the modification of the frequency and/or magnitude of extreme events (impact attribution). The attribution of impacts is still behind the advances in extreme weather events. An important step forward is the attribution of impacts, that is, an end-to-end attribution study. However, this is still challenging due to the different factors involved, not just meteorological influences (Otto, 2016).

Anthropogenic climate change impacts the climate system but also the human or social system, the economic, biological and physical systems (Rosenzweig and Neofotis, 2013; Stone et al., 2013).

The meteorological outputs of the models from attribution studies of extreme weather events could be useful as inputs for other models, such as the evaluation of the hydrological conditions under both world scenarios, HIST/ALL and NAT, or for agricultural models.

Detection and attribution of climate extremes could also be applied to the impact of anthropogenic GHG emissions on the health system, especially due to extremely high temperatures, and changes in the distribution and the vectors of diseases.

Ecological impacts in ecosystems, such the great barrier reef or wildfires, could be performed for ecosystems of relevant importance for a country or for their ecological value. Plant and animal species and populations are already adapting to the global warming (Root et al., 2005). The changes in the distribution and phenology of plant species are impacting the ecological systems but also the cultivation of crops for human consumption, livestock consumption, the production of biogas, or the distribution of alien species (Newton et al., 2014; Hanf et al., 2012).

Carbon dioxide is a very well mixed gas so it would be possible to attribute liability as a function of the emissions (Allen, 2003). This might be especially important in those countries with no major contribution to greenhouse gases such as the developing countries. This legal application opens the door to sue governments and companies, in combination with the GHG emissions quantification, tracking their contributions for disregarding citizens rights and influencing extreme weather and climate events.

The insurance market has to also adapt, increasing or decreasing the premiums, or even offering discounts to people who are adapting to extreme weather events in vulnerable areas. Especially vulnerable places such as developing countries, coastal areas and islands could use attribution studies of climate extremes to access financial resources and capabilities, based on the “loss and damages” principle of the Warsaw Mechanism and the Paris Agreement (UNFCCC, 2013).

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REFERENCES

Allen, M. (2003). Liability for climate change. Nature, 421(6926), 891.

Christidis, N., Stott, P. A., Scaife, A. A., Arribas, A., Jones, G. S., Copsey, D., … Tennant, W. J. (2013). A new HADGEM3-a-based system for attribution of weather- and climate-related extreme events. *Journal of Climate*. https://doi.org/10.1175/JCLI-D-12-00169.1

Hanf, F., Körper, J., Spangehl, T., & Cubasch, U. (2012). Shifts of climate zones in multi-model climate change experiments using the Köppen climate classification. Meteorologische Zeitschrift, 21(2), 111–123. https://doi.org/10.1127/0941-2948/2012/0344

Hannart, A., Pearl, J., Otto, F. E. L., Naveau, P., & Ghil, M. (2016). Causal counterfactual theory for the attribution of weather and climate-related events. *Bulletin of the American Meteorological Society*. https://doi.org/10.1175/BAMS-D-14-00034.1

Hegerl, G.C., F. W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A. Marengo Orsini, N. Nicholls, J.E. Penner and P.A. Stott, 2007: Understanding and Attributing Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hegerl, G. C., Hoegh-Guldberg, O., Casassa, G., Hoerling, M. P., Kovats, R. S., Parmesan, C., ... & Stott, P. A. (2010). Good practice guidance paper on detection and attribution related to anthropogenic climate change. In Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Detection and Attribution of Anthropogenic Climate Change. IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland.

Herring, S. C., Hoerling, M. P., Peterson, T. C., & Stott, P. A. (2014). Explaining extreme events of 2013 from a climate perspective. Bulletin of the American Meteorological Society, 95(9), S1-S104.

Herring, S. C., Christidis, N., Hoell, A., Kossin, J. P., Schreck III, C. J., & Stott, P. A. (2018). Explaining extreme events of 2016 from a climate perspective. Bulletin of the American Meteorological Society, 99(1), S1-S157.

Hulme, M. (2014). Attributing weather extremes to 'climate change': A review. *Progress in Physical Geography*. https://doi.org/10.1177/0309133314538644

IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324.

Kay, A. L., Crooks, S. M., Pall, P., & Stone, D. A. (2011). Attribution of Autumn/Winter 2000 flood risk in England to anthropogenic climate change: A catchment-based study. *Journal of Hydrology*. https://doi.org/10.1016/j.jhydrol.2011.06.006

National Academies of Sciences, Engineering, and Medicine. (2016). Attribution of extreme weather events in the context of climate change. National Academies Press.

Newton, P. C. D., Lieffering, M., Li, F. Y., Ganesh, S., & Dodd, M. (2014). Detection of historical changes in pasture growth and attribution to climate change. Climate Research, 61(3), 203–214. https://doi.org/10.3354/cr01252

Otto, F. E. L. (2017). Annual Review of Environment and Resources Attribution of Weather and Climate Events. https://doi.org/10.1146/annurev-environ

Otto, F. E. L., Massey, N., Van Oldenborgh, G. J., Jones, R. G., & Allen, M. R. (2012). Reconciling two approaches to attribution of the 2010 Russian heat wave. *Geophysical Research Letters*. https://doi.org/10.1029/2011GL050422

Otto, F. E. L., Van Oldenborgh, G. J., Eden, J., Stott, P. A., Karoly, D. J., & Allen, M. R. (2016). The attribution question. *Nature Climate Change*. https://doi.org/10.1038/nclimate3089

Peterson, T. C., Stott, P. A., & Herring, S. (2012). Explaining extreme events of 2011 from a climate perspective. Bulletin of the American Meteorological Society, 93(7), 1041-1067.

Root, T. L., MacMynowski, D. P., Mastrandrea, M. D., & Schneider, S. H. (2005). Human-modified temperatures induce species changes: Joint attribution. Proceedings of the National Academy of Sciences, 102(21), 7465–7469. https://doi.org/10.1073/pnas.0502286102

Rosenzweig, C., & Neofotis, P. (2013). Detection and attribution of anthropogenic climate change impacts. *Wiley Interdisciplinary Reviews: Climate Change*. https://doi.org/10.1002/wcc.209

Santer BD, Wigley TML, Barnett TP, Anyamba E et al (1996) Detection of climate change and attribution of causes. In: Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (eds) Climate change 1995: the science of climate change. Contribution of working group I to the second assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK, pp 407–443

Shepherd, T. G. (2014). Atmospheric circulation as a source of uncertainty in climate change projections. *Nature Geoscience*, *7*(10), 703–708. https://doi.org/10.1038/NGEO2253

Stone, D., Auffhammer, M., Carey, M., Hansen, G., Huggel, C., Cramer, W., … Yohe, G. (2013). The challenge to detect and attribute effects of climate change on human and natural systems. *Climatic Change*. https://doi.org/10.1007/s10584-013-0873-6

Stott, P. A., Stone, D. A., & Allen, M. R. (2004). Human contribution to the European heatwave of 2003. Nature, 432(7017), 610.

Stott, P. A., Christidis, N., Otto, F. E., Sun, Y., Vanderlinden, J. P., Van Oldenborgh, G. J., ... & Zwiers, F. W. (2016). Attribution of extreme weather and climate-related events. Wiley Interdisciplinary Reviews: Climate Change, 7(1), 23-41.

Trenberth, K. E. (2011). Attribution of climate variations and trends to human influences and natural variability. *Wiley Interdisciplinary Reviews: Climate Change*, *2*(6), 925–930. https://doi.org/10.1002/wcc.142

UNFCCC. (2013). Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. Assessment, (January), 1–43. https://doi.org/10.1016/j.biocon.2006.08.013

van Oldenborgh, G. J., Otto, F. E., Haustein, K., & Cullen, H. (2015). Climate change increases the probability of heavy rains like those of storm Desmond in the UK-an event attribution study in near-real time. Hydrology & Earth System Sciences Discussions, 12(12).

van Oldenborgh, G. J., Philip, S., Aalbers, E., Vautard, R., Otto, F., Haustein, K., … Cullen, H. (2016). Rapid attribution of the May/June 2016 flood-inducing precipitation in France and Germany to climate change. *Hydrology and Earth System Sciences Discussions*. https://doi.org/10.5194/hess-2016-308

Wigley TML, Barnett TP et al (1990) Detection of the greenhouse effect in the observations. In: Houghton JT, Jenkins GJ, Ephraums JJ (eds) Climate change. The IPCC scientific assessment. Cambridge University Press, Cambridge, UK, pp 241–255