Towards an inventory of the impacts of human-induced climate change

Otto, Friederike; Harrington, Luke; Frame, Dave; Boyd, Emily; Lauta, Kristian Cedervall; Wehner, Micheal; Clarke, Ben; Raju, Emmanuel; Hauser, Mathias; Bodha, Chad; James, Rachel; Jones, Richard

Toward an Inventory of the Impacts of Human-Induced Climate Change

Friederike E. L. Otto, Luke J. Harrington, David Frame, Emily Boyd, Kristian Cedervall Lauta, Michael Wehner, Ben Clarke, Emmanuel Raju, Chad Boda, Mathias Hauser, Rachel A. James, and Richard G. Jones

Corresponding author: Friederike E. L. Otto, friederike.otto@ouce.ox.ac.uk

AFFILIATIONS: Otto, Harrington, Clarke, and James—Environmental Change Institute, University of Oxford, Oxford, United Kingdom; **Frame**—Victoria University of Wellington, Wellington, New Zealand; **Boyd and Boda**—Lund University Centre for Sustainability Studies, Lund University, Lund, Sweden; **Lauta**—Faculty of Law, University of Copenhagen, Copenhagen, Denmark; **Wehner**—Lawrence Berkeley National Laboratory, Berkeley, California; **Raju**—Global Health Section, University of Copenhagen, Copenhagen, Denmark; **Hauser**—Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland; **Jones**—Environmental Change Institute, University of Oxford, Oxford, and Met Office Hadley Centre, Exeter, United Kingdom

Current levels of global warming (Haustein et al. 2017) have already intensified heat waves, droughts, and floods, with many recent events exhibiting evidence of being exacerbated by anthropogenic climate change (e.g., Herring et al. 2016, 2018). Recent improvements in understanding demonstrate that half a degree of additional warming will have further severe impacts (Masson-Delmotte et al. 2018). In the context of this rapid and damaging change, there is a clear need to quantify and address both the losses and damages from impacts we have not adapted to today, as well as to adapt to those that will emerge in the next few decades. To do this, it is essential to understand the impacts of man-made climate change on the scales that climate adaptation decisions are made. Drivers of disasters, ultimately responsible for much loss and damage, are unfolding in an ever-changing socioeconomic context, which also alters exposure and vulnerability. While various case studies exist (discussed below), there is to date no comprehensive or comparable database quantifying anthropogenic contributions to climate change loss and damage. We suggest that this needs to change.

For the first time in 2023, countries will assess their collective progress with respect to reaching the climate policy aims of the United Nations Framework Convention on Climate Change's (UNFCCC) Paris Agreement.[1] Much of the attention of this so-called global stocktake will be focused on mitigation efforts to reduce greenhouse gas emissions at the national level. At the same time, the stocktake has an important role in reporting on adaptation actions, their effectiveness and climate change–related loss. According to the Paris Agreement, this stocktake will take place every five years, and should be done in a "comprehensive and facilitative manner, considering mitigation, adaptation and the means of implementation and support, and in the light of equity and the best available science."

[1] Referred to in Article 14, Paris Agreement: https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.

Efforts to address climate change by countries and companies (Keohane and Victor 2016) draw substantially on a range of summary indicators and metrics from research at the science–policy interface. Some examples are emissions metrics (Fuglestvedt et al. 2003; Shine et al. 2007) and policy-relevant metrics of the climate response such as the transient climate response (TCR) and the transient response to cumulative emissions (Stocker et al. 2013). These play an important role in summarizing scientific information for diagnostic and prognostic purposes—they help countries and nonstate actors assess progress against mitigation goals, as well as frame current and future action.

However, at present there are serious deficiencies in this regard on the impacts and adaptation side: there is no comprehensive set of adaptation metrics. The lack of defined indicators is particularly evident with reference to the relatively new policy area of "loss and damage," which focuses on how to avert, minimize, and address the negative impacts of climate change, including those that cannot be avoided through adaptation. There is strong ambiguity about what constitutes loss and damage within the UNFCCC (Boyd et al. 2017), and therefore it is

not surprising that there is relatively little discussion of how losses and damages could be assessed under the global stocktake, and it is unlikely to be achieved within the first global stocktake comprehensively. While any definition of loss and damage within UNFCCC needs to evolve from a political process, it is crucial that the scientific community prepares the ground now, so as to truly have the best science available to feed into the process. This process requires two steps: an agreement on what the best available science constitutes in this context and subsequently a mechanism to comprehensively gather this scientific evidence.

It is also not only the UNFCCC stocktake that requires the development of metrics of climate change impacts and a clear interpretation of what available science, in the context of loss and damage, can be drawn upon. Numerous applications exist in a much broader societal context; in particular, local adaptation planning, assessments of the economic and noneconomic impacts and losses of climate change (Frame et al. 2020), insurance measures, and climate litigation would clearly benefit.

Today, groups of countries, and especially those for which loss and damage is of existential importance (Doktycz and Abkowitz 2019), want the adverse impacts of climate change to be quantified, while at the same time others inquire as to whether current measures and efforts are commensurate with the challenges of climate change. As the climate is evolving quickly into the future, alongside other socioeconomic factors relevant to human and natural systems, it is not sufficient to assess impacts in climate sensitive systems without identifying the specific role of climate change. Currently there is a gap between what is perceived or assumed by many, and what can actually be quantified and understood with sound scientific evidence as the actual adverse impacts of human-induced climate change. This gap is seen on placards of protesters for climate justice, in non-governmental organization (NGO) campaigns, and even in impact assessment studies used for adaptation planning (McSweeney and Jones 2016). In other words, we do not have an inventory of loss and damage of anthropogenic climate change today.

The remainder of this paper develops a framework for assessing the quality of evidence currently available to constitute the basis of a more comprehensive impact assessment. It is the first step toward an inventory of anthropogenic climate change impacts.

The emergence, methodological development, and maturation of the scientific field of extreme event attribution offers the evidence necessary to link impacts with anthropogenic climate change in an inventory. It is therefore critical that we assess the quality of this evidence.

Using event attribution to assess impacts

At present, the impacts of climate change mostly manifest through the changing likelihood and intensity of extreme weather events (e.g., heat waves, floods, droughts) or slow-onset events like sea level rise or changes in seasonality, e.g., the lack of frost (Pfleiderer et al. 2019).

While primarily addressing extreme weather events, the science of event attribution has been applied to all these types of climate phenomena (James et al. 2019) and allows researchers to disentangle different drivers of events from man-made climate change (Otto 2017), as well as providing end-to-end attribution of impacts on natural and human systems (e.g., Schaller et al. 2016). The emerging science thus offers the tools to develop an inventory of present-day impacts of climate change and will ultimately allow for an inventory of loss and damage to be provided. In addition, when attribution of current events is combined with projections as recent best practice suggests (Otto et al. 2018a), such an inventory would also provide a crucial basis for evidence-based adaptation planning.

Currently attribution studies are conducted ad hoc and apply a multitude of very different and not necessarily easily comparable methodologies (e.g., Jézéquel et al. 2018). Furthermore, not all event types are amenable to attribution with current technologies. And even within those classes that are, not all events can be studied with current data and tools available. For instance, Superstorm Sandy has proven very difficult to attribute while hurricanes Harvey

and Florence can be attributed with high confidence. In data-poor regions, attribution is a huge challenge (Kew et al. 2019).

There is ongoing research, prompted also by the huge public desire to have more attribution studies on current events to understand the impacts of climate change, to overcome some of these challenges, e.g., within a pilot operational attribution service in Europe.

In the long term, these developments could provide a more representative overview of the impacts of climate change, provided crucial methodological developments within science are undertaken that overcome current challenges.

However, time is something we do not have when it comes to climate change. The impacts from climate change continue to build in real time and at an accelerating rate, for example, repeated record-breaking heat waves in Europe (Kew et al. 2018) and recent bushfires in Australia accompanied by record heat (van Oldenborgh et al. 2020) following frequent hot summers (Perkins et al. 2014). This both reinforces the utility of attribution science for assessing impacts and instils a measure of urgency. Therefore, to assess loss and damage, plan adaptation and feed into the global stocktake, we need to use currently available science. Attribution, however, is a relatively young and rapidly developing field. Some of the earlier attribution studies in particular would not be considered the "best" available science today, and only provide assessments of the impacts of climate change with very low confidence. In view of the stakes, and of the centrality of event attribution to the quantification of loss and damage, it seems both important and desirable that the research community provide better guidance in terms of assessing the quality of available scientific evidence.

In the remainder of this paper we provide such guidance, by developing a set of criteria which the available evidence needs to fulfill in order to be included in an inventory as reliable evidence (next section). We will conclude with a discussion on how these criteria are not only key for assessing loss and damage, but also crucial to assess whether current efforts on adaptation are appropriate with respect to current and future impacts.

Assessing the quality of evidence from event attribution literature

A reasonable starting point for scientific standards and quality of evidence relevant to climate change monitoring activities such as the global stocktake is the Intergovernmental Panel on Climate Change (IPCC). Its guidance document (Mastrandrea et al. 2010) provides a language and framework for assessing confidence in scientific findings. Based on this detailed system of expert judgement, not all studies that in principle provide independent evidence can be equally weighted. We use this document as a starting point and present the process of expertly judging the quality of available evidence for an inventory. The main aim is to increase transparency in the assessment of evidence. In Fig. 1 we present a flowchart that illustrates seven steps and key decision points that can be used by experts to rate the quality of the available evidence for a certain type of extreme in a specific region as low, medium or high.
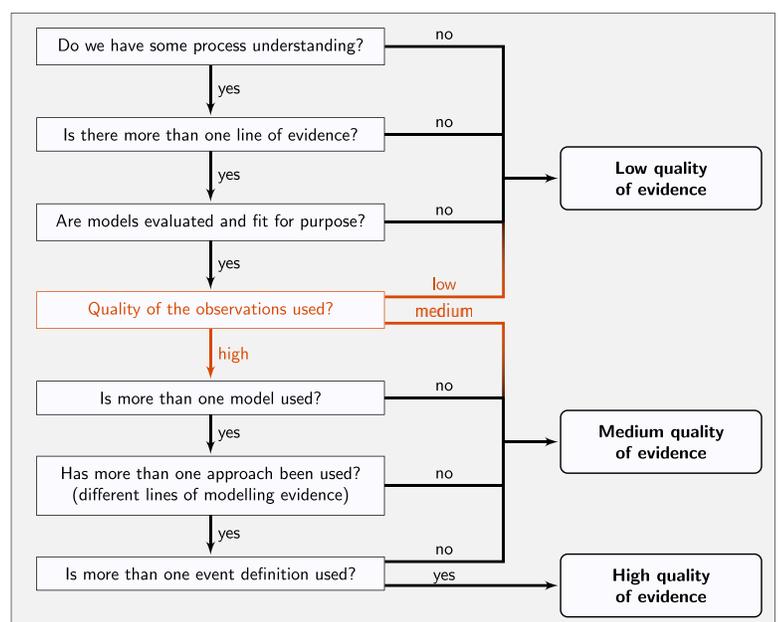

Fig. 1. Flowchart depicting the reasoning process to identify the quality of evidence in attribution studies.

The result of the quality assessment for a certain type of event in a region (and season), based on the judgement of whether or not the decision criteria have been fulfilled by the relevant studies, is depicted on the right-hand side.

The steps are as follows:

1) Process understanding: Only an attribution study that quantifies the role of climate change along with an assessment of the processes of how a changing climate leads to the attributed change can be of high quality. Without process understanding it is impossible to disentangle cancellations of errors in the models and methodologies from actual changes. In the case of heat waves, for example, the process might simply be the overall warming that leads to an increase in heat waves. In other cases the process is more complex (Vautard et al. 2016).

2) Multiple lines of evidence: Early attribution studies often use either only models or just observations. In the former case it is not possible to know whether the results are related to the observed event (e.g., Sippel and Otto 2014), while in the case of the assessments only based on observations the detected change in likelihood cannot be attributed cleanly (e.g., van Oldenborgh 2007).

3) Fitness of models evaluated: Without estimating whether the models used are fit for purpose, the quality of the evidence is obviously low.

4) Observational quality: In locations where observational data are of poor quality, the basis of the event definition as well as of model evaluation is necessarily weak and thus low-quality observations cannot lead to high-confidence impact assessments.

5) Use of multiple models: While model evaluation is essential, it does not eliminate the structural deficiencies of a single model. Using different, independent models mitigates some of the risk to overlook cancellation of errors and be overconfident.

6) Multiple approaches: Certain types of modeling approaches are prone to systematically over- or underestimating the role of climate change (Bellprat and Doblas-Reyes 2016); using different types of modeling approaches mitigates the risk of being overconfident.

7) Multiple event definitions: Last, the result of an attribution assessment strongly depends on the definition of the event (Uhe et al. 2016). No assessment can eliminate this fact, but by using more than one definition a study can test how different results pertain to different definitions and thus how much the results depend on a particular definition. In some cases results are largely independent of the definition (van Oldenborgh et al. 2017), while in others there are large differences (Sippel and Otto 2014; Leach et al. 2020).

A catalogue of available science, that could be called a pre-inventory (Table 1), could be structured very similarly to present day disaster databases like the Emergency Events Database (EM-DAT; Doktycz and Abkowitz 2019), in which different categories of events are used to organize the database. With respect to climate-related disasters these are droughts, extreme temperature events, floods, storms, and some very localized events like fog. In addition, the database lists epidemiological disasters that are highly relevant with respect to human-induced climate change, even though the evidence from attribution science is still sparse to date; the further listed geological and technical disasters are not of immediate relevance in this context. A second dimension to organize the pre-inventory database would be geographical regions. There has been much but inconclusive debate about how best to divide the world into regions. This is, however, not relevant here, as the most meaningful geographical definition of a type of climate-related event very much depends on the context in which it impacts and the scale(s) on which decisions about relocation and resilience building are made. Thus, it strongly depends on the system of interest, what is an appropriate definition of the impact and hence what individual pieces of evidence will

Table 1. Examples of quality assessment for three well researched high-impact extreme events.

Type of event	Year	Country	Total deaths	Total affected	Total damage (US$)	Result from attribution studies	Quality of evidence	References
Floods	2014	U.K.	0	540	624,000	Increase in likelihood by ~40%	High	(Schaller et al. 2016; Vautard et al. 2016; Yiou et al. 2017)
Drought	2010	Somalia	20,000	4,000,000	Not estimated	Mixed signal but very large uncertainty that does not exclude increase/ decrease by a factor of 10	Low	(Funk et al. 2013; Lott et al. 2013; Otto et al. 2018a)
Heat wave	2010	Russia	55,760	55,760+	400,000	Increase in likelihood by a factor of 1.7–10	Medium	(Dole et al. 2011; Hauser et al. 2016; Otto et al. 2012)

form the pre-inventory catalogue. In the context of this catalogue, the aim of geographical categories is just to find the information relevant for subsequently constructing an inventory.

While the assessment of the quality might seem a bit of a detour, it is essential to use evidence of the actual impacts of climate change to adapt, or to base damage assessments upon (e.g., Frame et al. 2020). Once quality criteria are established, the archiving of a wider variety of climate change induced impacts, such as environmental and cultural impacts, will be possible. This will enrich the available evidence for loss and damage that are largely missed by established disaster databases (Zaidi 2018).

The aim is not directly assigning confidence levels to the assessment as such, but only to rate the quality of evidence. The former requires the additional assessment of agreement as described in the IPCC guidance document. It might be the case that the quality of evidence is high, but the overall confidence of how a type of event has changed or will change at a certain warming level is only medium as agreement between different studies is medium.

To illustrate how the flowchart can be used in practice we consider three examples that had considerable socioeconomic impacts: a flood in the south of the United Kingdom, a drought in eastern Africa, and a heat wave in Russia. Table 1 gives an overview of the events. In the case of the U.K. floods, despite not using more than one model in the earlier studies (Schaller et al. 2016), other studies on similar events using a multimodel approach found quantitatively similar results (Otto et al. 2018b). Furthermore, several articles are dedicated to understanding the processes behind the event and evaluating the models used (Vautard et al. 2016; Yiou et al. 2017). Climate models evaluated with high-quality observational data have been found to perform well. In contrast, while equally well researched (Funk et al. 2013; Lott et al. 2013; Otto et al. 2018a), the low quality of observational data in Somalia does not allow for high-quality assessments of the role of climate change. The Russian heat wave, also very well researched, is an example where all studies use an identical event definition (Dole et al. 2011; Hauser et al. 2016; Otto et al. 2012) that is not based on the impacts of the event, thus quantitative assessments of the role of climate change are only of medium quality.

Given that for the relatively new field of event attribution no best-practice methodologies exist yet, it is particularly important to clarify the assessment process and make steps transparent. However, the process described above is not fundamentally different for projections or trend assessments. For the latter, the last step of testing the dependency of the event definition is not relevant. It is important to highlight that there are some cases where a clear "yes or no" answer cannot be given at certain steps in the flowchart, or where very different models are used (e.g., end-to-end attribution). It is thus not a strict recipe but guidance in order to increase transparency in the expert judgement process and quality of an inventory.

Conclusions

While climate change adaptation needs to be taken very seriously both at the international policy level and at national and local levels, current experience suggests that we are mal-adapted even to today's extreme events. Disentangling the complex interplay between vulnerability, exposure, and rapidly changing hazards is not a problem science alone can solve.

Nevertheless, incorporating evidence from the best-available science about the changing nature of hazards in response to a warming world is crucial. Event attribution studies do not usually form the basis of adaptation and disaster recovery strategies. Instead, those are largely based on observed changes and projected impacts. Disaster recovery can potentially be very well linked and aligned with climate change adaptation. However, stakeholders engaging with recovery and adaptation tend to be different at the local level.

Recovery in many places continues to be "building the same way" as before with little or no improvement. As different sources of evidence are usually not available on the same scale, they do not necessarily connect well. Appropriate and adequate responses to these impacts, however, require a comprehensive and detailed understanding of the nature of the impacts (type, scale, spatial and temporal distribution, etc.), how these might evolve over time, as well as what is driving the impacts. Hence, only when attributable changes in climate hazards (either those that have already occurred, or are expected to) are considered alongside observed and projected changes to exposure and vulnerability within different communities, can decision-makers begin to resolve changes in aggregate risk over the coming decades. The framework presented in this study therefore represents an important first step toward contextualizing expected changes in the physical climate against demographic and other socioeconomic changes in the future. Future adaptation pathways have a better chance of success if the risk profile associated with future climate change is understood. Identifying the highest-quality evidence to quantify these risks, particularly in a rapidly evolving scientific landscape, remains crucial.

References

Bellprat, O., and F. Doblas-Reyes, 2016: Attribution of extreme weather and climate events overestimated by unreliable climate simulations. *Geophys. Res. Lett.*, **43**, 2158–2164, https://doi.org/10.1002/2015GL067189.

Boyd, E., R. James, R. G. Jones, H. R. Young, and F. E. L. Otto, 2017: A typology of loss and damage perspectives. *Nat. Climate Change*, **7**, 723–729, https://doi.org/10.1038/nclimate3389.

Doktycz, C., and M. Abkowitz, 2019: Loss and damage estimation for extreme weather events: State of the practice. *Sustainability*, **11**, 4243, https://doi.org/10.3390/su11154243.

Dole, R., and Coauthors, 2011: Was there a basis for anticipating the 2010 Russian heat wave? *Geophys. Res. Lett.*, **38**, L06702, https://doi.org/10.1029/2010GL046582.

Frame, D. J., M. F. Wehner, I. Noy, and S. M. Rosier, 2020: The economic costs of Hurricane Harvey attributable to climate change. *Climatic Change*, **160**, 271–281, https://doi.org/10.1007/s10584-020-02692-8.

Fuglestvedt, J. S., T. K. Berntsen, O. Godal, R. Sausen, K. P. Shine, and T. Skodvin, 2003: Metrics of climate change: Assessing radiative forcing and emission indices. *Climatic Change*, **58**, 267–331, https://doi.org/10.1023/A:1023905326842.

Funk, C., G. Husak, J. Michaelsen, S. Shukla, and A. Hoell, 2013: Attribution of 2012 and 2003–12 rainfall deficits in eastern Kenya and southern Somalia [in "Explaining Extreme Events of 2012 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, **94** (9), S45–S48, https://doi.org/10.1175/BAMS-D-13-00085.1.

Hauser, M., R. Orth, and S. I. Seneviratne, 2016: Role of soil moisture versus recent climate change for the 2010 heat wave in western Russia. *Geophys. Res. Lett.*, **43**, 2819–2826, https://doi.org/10.1002/2016GL068036.

Haustein, K., M. R. Allen, P. M. Forster, F. E. L. Otto, D. M. Mitchell, H. D. Matthews, and D. J. Frame, 2017: A real-time global warming index. *Sci. Rep.*, **7**, 15417, https://doi.org/10.1038/s41598-017-14828-5.

Herring, S., A. Hoell, M. P. Hoerling, J. P. Kossin, C. J. Schreck III, and P. A. Stott, Eds., 2016: Introduction to explaining extreme events of 2015 from a climate perspective [in "Explaining Extremes of 2015 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, **97** (12), S1–S3, https://doi.org/10.1175/BAMS-D-16-0313.1.

——, N. Christidis, A. Hoell, J. P. Kossin, C. J. Schreck, and P. A. Stott, Eds., 2018: Explaining Extreme Events of 2016 from a Climate Perspective. *Bull. Amer. Meteor. Soc.*, **99** (1), S1–S157, https://doi.org/10.1175/BAMS-EXPLAININGEXTREMEEVENTS2016.1.

James, R. A., R. G. Jones, E. Boyd, H. R. Young, F. E. L. Otto, C. Huggel, and J. S. Fuglestvedt, 2019: Attribution: How is it relevant for loss and damage policy and practice? *Loss and Damage from Climate Change: Concepts, Methods and Policy Options*, R. Mechler et al., Eds., Springer, 113–154.

Jézéquel, A., V. Dépoues, H. Guillemot, M. Trolliet, J. P. Vanderlinden, and P. Yiou, 2018: Behind the veil of extreme event attribution. *Climatic Change*, **149**, 367–383, https://doi.org/10.1007/s10584-018-2252-9.

Keohane, R. O., and D. G. Victor, 2016: Cooperation and discord in global climate policy. *Nat. Climate Change*, **6**, 570–575, https://doi.org/10.1038/nclimate2937.

Kew, S. F., S. Philip, G. J. van Oldenborgh, F. E. L. Otto, R. Vautard, and G. van der Schrier, 2018: The exceptional summer heat wave in southern Europe 2017 [in "Explaining Extreme Events of 2017 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, **100** (1), S49–S53, https://doi.org/10.1175/BAMS-D-18-0109.1.

——, and Coauthors, 2019: Impact of precipitation and increasing temperatures on drought in eastern Africa. *Earth Syst. Dyn. Discuss.*, https://doi.org/10.5194/esd-2019-20.

Leach, N. J., S. Li, S. Sparrow, G. J. van Oldenborgh, F. C. Lott, A. Weisheimer, and M. R. Allen, 2020: Anthropogenic influence on the 2018 summer warm spell in Europe: The impact of different spatio-temporal scales. [in "Explaining Extremes of 2018 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, **101** (1), S17–S22, doi:10.1175/BAMS- D-19-0233.1.

Lott, F. C., N. Christidis, and P. A. Stott, 2013: Can the 2011 East African drought be attributed to human-induced climate change? *Geophys. Res. Lett.*, **40**, 1177–1181, https://doi.org/10.1002/grl.50235.

Masson-Delmotte, V., and Coauthors, 2018: Global warming of 1.5°C. IPCC Special Rep., IPCC, 32 pp., www.ipcc.ch/sr15/.

Mastrandrea, M. D., and Coauthors, 2010: Guidance note for lead authors of the IPCC Fifth Assessment report on consistent treatment of uncertainties. IPCC, 4 pp., www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf.

McSweeney, C. F., and R. G. Jones, 2016: How representative is the spread of climate projections from the 5 CMIP5 GCMs used in ISI-MIP? *Climate Serv.*, **1**, 24-29, https://doi.org/10.1016/j.cliser.2016.02.001.

Otto, F. E. L., 2017: Attribution of weather and climate events. *Annu. Rev. Environ. Resour.*, **42**, 627–646, https://doi.org/10.1146/annurev-environ-102016-060847.

——, N. Massey, G. J. van Oldenborgh, R. G. Jones, and M. R. Allen, 2012: Reconciling two approaches to attribution of the 2010 Russian heat wave. *Geophys. Res. Lett.*, **39**, L04702, https://doi.org/10.1029/2011gl050422.

——, S. Philip, S. Kew, S. Li, A. King, and H. Cullen, 2018a: Attributing high-impact extreme events across timescales—A case study of four different types of events. *Climatic Change*, **149**, 399–412, https://doi.org/10.1007/s10584-018-2258-3.

——, K. van der Wiel, G. J. van Oldenborgh, S. Philip, S. F. Kew, P. Uhe, and H. Cullen, 2018b: Climate change increases the probability of heavy rains in Northern England/Southern Scotland like those of storm Desmond—A real-time event attribution revisited. *Environ. Res. Lett.*, **13**, 024006, https://doi.org/10.1088/1748-9326/aa9663.

Perkins, S. E., S. C. Lewis, A. D. King, and L. V. Alexander, 2014: Increased simulated risk of the hot Australian summer of 2012/13 due to anthropogenic activity as measured by heatwave frequency and intensity [in "Explaining Extremes of 2013 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, **95** (9), S34–S37, https://doi.org/10.1175/1520-0477-95.9.S1.1.

Pfleiderer, P., I. Menke, and C.-F. Schleussner, 2019: Increasing risks of apple tree frost damage under climate change. *Climatic Change*, **157**, 515–525, https://doi.org/10.1007/s10584-019-02570-y.

Schaller, N., and Coauthors, 2016: Human influence on climate in the 2014 southern England winter floods and their impacts. *Nat. Climate Change*, **6**, 627–634, https://doi.org/10.1038/nclimate2927.

Shine, K. P., T. K. Berntsen, J. S. Fuglestvedt, R. B. Skeie, and N. Stuber, 2007: Comparing the climate effect of emissions of short- and long-lived climate agents. *Philos. Trans. Roy. Soc. London*, **365A**, 1903–1914, https://doi.org/10.1098/rsta.2007.2050.

Sippel, S., and F. E. L. Otto, 2014: Beyond climatological extremes - Assessing how the odds of hydrometeorological extreme events in South-East Europe change in a warming climate. *Climatic Change*, **125**, 381–398, https://doi.org/10.1007/s10584-014-1153-9.

Stocker, T., and Coauthors, 2013: Summary for policymakers. *Climate Change 2013: The Physical Science Basis*, T. F. Stocker et al., Eds., Cambridge University Press, 2–29.

Uhe, P., F. E. L. Otto, K. Haustein, G. J. van Oldenborgh, A. D. King, D. C. H. Wallom, M. R. Allen, and H. Cullen, 2016: Comparison of methods: Attributing the 2014 record European temperatures to human influences. *Geophys. Res. Lett.*, **43**, 8685–8693, https://doi.org/10.1002/2016GL069568.

van Oldenborgh, G. J., 2007: How unusual was autumn 2006 in Europe? *Climate Past*, **3**, 659–668, https://doi.org/10.5194/cp-3-659-2007.

——, and Coauthors, 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environ. Res. Lett.*, **12**, 124009, https://doi.org/10.1088/1748-9326/aa9ef2.

——, and Coauthors, 2020: Attribution of the Australian bushfire risk to anthropogenic climate change. *Nat. Hazards Earth Syst. Sci. Discuss.*, https://doi.org/10.5194/nhess-2020-69.

Vautard, R., P. Yiou, F. Otto, P. Stott, N. Christidis, G. J. van Oldenborgh, and N. Schaller, 2016: Attribution of human-induced dynamical and thermodynamical contributions in extreme weather events. *Environ. Res. Lett.*, **11**, 114009, https://doi.org/10.1088/1748-9326/11/11/114009.

Yiou, P., A. Jézéquel, P. Naveau, F. E. L. Otto, R. Vautard, and M. Vrac, 2017: A statistical framework for conditional extreme event attribution. *Adv. Stat. Climatol. Meteor. Oceanogr.*, **3**, 17–31, https://doi.org/10.5194/ascmo-3-17-2017.

Zaidi, R. Z., 2018: Beyond the Sendai indicators: Application of a cascading risk lens for the improvement of loss data indicators for slow-onset hazards and small-scale disasters. *Int. J. Disaster Risk Reduct.*, **30**, 306–314, https://doi.org/10.1016/j.ijdrr.2018.03.022.