Possible methods for the estimation of flood damages in the State of Vermont

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Summary

With this submission, we are replying to question (2) posed in the questionnaire of the Request for Information issued by the State of Vermont. We focus on economic damages from flood events as one of the most common impacts from climate change in the State.

We discuss three scientific, peer-reviewed methods which can estimate economic damages from flooding. Using these approaches, a damage quantification of the economic impacts from flooding that are attributable to human-induced climate change can be achieved for the State of Vermont.

'Event attribution' has developed as a scientific field in the past two decades and includes scientific methods that can quantify the effects of climate change on changes in the probability or intensity of a wide variety of extreme weather events, including extreme precipitation. Recent scientific developments allow these methods to be extended to assess climate change impacts on economic losses and human health. Our submission explains how these methods could be applied to support the State to develop a Climate Superfund Cost Recovery Program. Our own expertise lies in performing extreme event attribution studies and is outlined separately to the discussion of methods below.

References to relevant peer-reviewed studies can be found at the end of the submission.

The science of damage quantification for flood events

Factors influencing the development of flood events

The development of flood events depends on multiple local factors. Following, we summarise some of the factors that can determine flood severity, including antecedent conditions and meteorological regimes that lead to extreme precipitation.

- Antecedent effects in the catchment area include the **soil moisture anomaly and ground water height** which might be higher due to high rain or snowfall in the leadup to the event. This effect can be further exacerbated by **cold spells** which can freeze the water content in the upper soil layers. Freezing temperatures can thereby "lock" water in the upper soil layers and increase further runoff. This was one of the factors leading up to the 1996 north-central Pennsylvania floods[1].

- **Freezing temperatures** before the event can lead to thick ice cover on rivers which can subsequently **form ice jams on rivers** when floods break up the ice cover[2].
- Atmospheric conditions that lead to disastrous flooding events in the mid-latitudes include **atmospheric blocking** which can lead to multiple storms being steered into the same region, leading to long-lasting precipitation events[3].
- **Atmospheric rivers** are elongated regions of high water content in the atmosphere transporting large water masses into higher latitudes where they can rain out. The moisture in them is estimated to increase with climate change[4].
- In Vermont, extreme rainfall can also be associated with **remnants of hurricanes in the summer and autumn months**. It is likely (e.g. ref[5]) that these storms are able to transport more moisture as both atmosphere and sea surface temperatures warm with climate change.

The severity of floods is determined by various factors including their return time in a given location, speed of onset, velocity of water flow, and water depth[6]. Because of the inhomogeneity of flood events, it might be helpful to define them according to their impacts rather than rainfall amounts[7].

Macroeconomic approach to damage quantification

Callahan and Mankin[8] developed an approach that connects the emissions of individual actors to damages on a national level. For example, to relate heat damages to individual emitters, Callahan and Mankin[9] describe a full causal chain from emissions to impacts. First, the emissions from one emitter are

[1] Leathers, Kluck, and Kroczynski, 'The Severe Flooding Event of January 1996 across North-Central Pennsylvania'.
[2] Merz et al., 'Causes, Impacts and Patterns of Disastrous River Floods'.
[3] Merz et al.
[4] Payne et al., 'Responses and Impacts of Atmospheric Rivers to Climate Change'.
[5] Zhu, Emanuel, and Quiring, 'Elevated Risk of Tropical Cyclone Precipitation and Pluvial Flood in Houston under Global Warming'; Guzman and Jiang, 'Global Increase in Tropical Cyclone Rain Rate'.
[6] Brown and Murray, 'Examining the Relationship between Infectious Diseases and Flooding in Europe'.
[7] Delforge et al., 'EM-DAT'.
[8] Callahan and Mankin, 'National Attribution of Historical Climate Damages'.
[9] Callahan and Mankin.

linked to an increase in global mean surface temperature (GMST). This is done using a simple carbon climate model such as FaIRv1.3[10]. This change in global temperature due to one emitter's share of emissions can subsequently be linked to a local change in mean temperature or an increase in magnitude of an event such as the mean of the five hottest days in a year[11]. In a final step, Callahan and Mankin[12] use relationships between local temperature changes and economic growth to estimate the damages from the warming associated with one emitter. We are not aware of studies which extend this analysis to flooding, but it can be done in principle.

The benefit of this method is that it does not require the user to perform detailed case studies (see e.g. ref[13]). Instead, the overall cost of climate change is estimated using a damage function which is based on a regression analysis between climate inputs such as temperatures and GDP (e.g. ref[14]). The method's simplicity makes it straightforward to use.

Fraction of attributable risk (FAR) approach to damage quantification

Risk-based extreme event attribution can quantify the impact of climate change on a class of extreme events by calculating the fraction of attributable risk (FAR). This approach uses climate model simulations with anthropogenic and natural climate forcings (called "ALL") and only natural forcings ("NAT"). The probability of exceedance of an event threshold is estimated for both sets of simulations, from which the FAR can be calculated.

Studies by Frame et al.[15] use this approach on pluvial (rainfall-related) flooding events in New Zealand, as well as for Hurricane Harvey, which caused widespread flooding (also mostly pluvial) in Houston, Texas. Frame et al.[16] use existing estimates of FAR from previous studies. In cases where there are no

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[10] Millar et al., 'A Modified Impulse-Response Representation of the Global near-Surface Air Temperature and Atmospheric Concentration Response to Carbon Dioxide Emissions'; Smith et al., 'FAIR v1.3'.
[11] Eyring et al., 'Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) Experimental Design and Organization'.
[12] Callahan and Mankin, 'National Attribution of Historical Climate Damages'.
[13] Merz et al., 'Review Article "Assessment of Economic Flood Damage"'.
[14] Callahan and Mankin, 'Globally Unequal Effect of Extreme Heat on Economic Growth'.
[15] Frame et al., 'Climate Change Attribution and the Economic Costs of Extreme Weather Events'; Frame et al., 'The Economic Costs of Hurricane Harvey Attributable to Climate Change'.
[16] Frame et al., 'Climate Change Attribution and the Economic Costs of Extreme Weather Events'.

existing studies calculating FAR, climate models (e.g. ref[17]) could be used to calculate FAR for the event of interest.

Using damage estimations from multiple sources such as the US National Oceanic and Atmospheric Administration (NOAA), estimates from re-insurance datasets, and the international emergency database (EM-DAT[18]), Frame et al. calculate the fraction of the damages that can be attributed to climate change.

One limitation of this approach is that models that are typically used to calculate FAR can struggle to represent certain weather types such as extreme precipitation. Therefore, studies often focus on the probability of exceedance of an extreme event threshold[19].

Hydraulic model approach to damage quantification

Another approach is provided by Wehner and Sampson[20] and has been used to estimate climate-change-attributable flood damage from Hurricane Harvey. The authors use a hydraulic model at 30 metre resolution[21] to estimate the change in flooded area attributable to climate change. To drive simulations of the hydraulic model for Hurricane Harvey, the authors use observed precipitation over the Houston, Texas area during the event and decrease it using a best estimate of precipitation changes attributable to climate change from previous attribution studies. To calculate the damage estimate, the authors in this study assumed that assets were evenly distributed in the flooded area and that antecedent conditions would not change the event outcome. These assumptions were sensible for Hurricane Harvey due to the amount of precipitation, but this might not be the case for other case studies where urban and rural areas are considered at the same time or when climate change is assumed to have an impact on antecedent conditions such as soil moisture and river flow. In these cases, models using asset locations could be

[17] Eyring et al., 'Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) Experimental Design and Organization'.
[18] Delforge et al., 'EM-DAT'.
[19] Perkins-Kirkpatrick et al., 'On the Attribution of the Impacts of Extreme Weather Events to Anthropogenic Climate Change'.
[20] Wehner and Sampson, 'Attributable Human-Induced Changes in the Magnitude of Flooding in the Houston, Texas Region during Hurricane Harvey'.
[21] Wing et al., 'Validation of a 30 m Resolution Flood Hazard Model of the Conterminous United States.

more suitable. Using their approach, Wehner and Sampson[22] estimated damages attributable to climate change that were significantly lower than the estimate found using the FAR approach discussed above.

One limitation of the hydraulic model approach is that the perturbations in precipitation used to drive the hydraulic model depend on large-scale climate model simulations whose skill varies for extreme precipitation events. There are, however, now methods that can more reliably model changes in extreme precipitation. This includes multiple methods under what is called the “storyline approach" for event attribution. While risk-based event attribution considers an event class defined by a threshold, the aim of storyline attribution is to consider the specific dynamics of a unique event and answer the question of how the event magnitude was changed due to climate change *given* the dynamical conditions of the atmosphere. Forecast-based event attribution[23] and pseudo-global warming simulations[24] (both storyline approaches) are promising for damage attribution as they involve high-resolution, initialised datasets. The output from such simulations could then be used to drive a hydraulic flood model in much the same way as in Wehner and Sampson’s work on Harvey[25]. Forecast-based attribution might be useful because weather forecast models are often already integrated with early warning systems such as for flood warnings. This might simplify the setup of case studies and yield synergies with national agencies such as NOAA. One potential limitation of storyline attribution methods is that they are conditioned on the meteorological conditions before the event and so do not consider the potential effects of climate change on these antecedent conditions.

[22] Wehner and Sampson, ‘Attributable Human-Induced Changes in the Magnitude of Flooding in the Houston, Texas Region during Hurricane Harvey’.
[23] Leach et al., ‘Forecast-Based Attribution of a Winter Heatwave within the Limit of Predictability’; Leach et al., ‘Heatwave Attribution Based on Reliable Operational Weather Forecasts’; Ermis et al., ‘Event Attribution of a Midlatitude Windstorm Using Ensemble Weather Forecasts’.
[24] Patricola and Wehner, ‘Anthropogenic Influences on Major Tropical Cyclone Events’; Lackmann, ‘Hurricane Sandy before 1900 and after 2100’; Wehner, Zarzycki, and Patricola, ‘Estimating the Human Influence on Tropical Cyclone Intensity as the Climate Changes’.
[25] Wehner and Sampson, ‘Attributable Human-Induced Changes in the Magnitude of Flooding in the Houston, Texas Region during Hurricane Harvey’.

Expertise of our group

We are an interdisciplinary group of physical climate scientists and lawyers. Our group has experience in preparing extreme event attribution studies for publication in peer-reviewed journals and translating scientific findings for legal use. Our prior work includes studies on slow-onset events such as glacial retreat[26] and developing new methods for storyline attribution of complex events such as windstorms[27]. Our work aims to support legislation, litigation, and public policy with rigorous scientific evidence.

Contributors

Shirin Ermis is a doctoral student in Physics at the University of Oxford focusing on extreme event attribution for midlatitude storms. She has published on increased risks from extreme windstorms and worked on tropical cyclone risks in the past. Shirin is also a research assistant for the Oxford Sustainable Law Program where she studies methods for the estimation of economic damages from climate change, in particular from flood events in the United States. Shirin holds a BSc in Physics from the University of Heidelberg (Germany) and a MSc in Physics with Extended Research from Imperial College London (UK).

Dr. Rupert Stuart-Smith is a Senior Research Associate in Climate Science and the Law at the Oxford Sustainable Law Programme. In his research, Rupert advances methods in attribution science to shed new light on the impacts of climate change on health, glaciers, and extreme weather events. He studies how climate science can be leveraged to enhance legal scrutiny of corporate and state climate action and accountability for the impacts of greenhouse gas emissions. Rupert also publishes on the implications of burgeoning climate litigation on climate-related financial risk. His research has been published in leading scientific journals including Science, Nature Geoscience and Nature Climate Change.

Prof. Ben Franta is an Associate Professor of Climate Litigation at the Oxford Sustainable Law Programme and the founding head of the Climate Litigation Lab. His research focuses on applying

[26] Stuart-Smith et al., 'Increased Outburst Flood Hazard from Lake Palcacocha Due to Human-Induced Glacier Retreat'.
[27] Ermis et al., 'Event Attribution of a Midlatitude Windstorm Using Ensemble Weather Forecasts'.

rigorous methods to practical challenges presented by climate litigation worldwide and has been published in *Nature Climate Change*, *Global Environmental Change*, *The Guardian*, and more, translated into 10 languages, and cited in the US Congressional Record. Dr. Franta holds a PhD in Applied Physics from Harvard University, a separate PhD in History (History of Science) from Stanford University, a JD from Stanford Law School, an MSc in Archaeological Science from the University of Oxford, and a BA in Physics and Mathematics from Coe College in Cedar Rapids, Iowa. He is also a licensed attorney and a member of the State Bar of California.

About the Oxford Sustainable Law Program

The Oxford Sustainable Law Programme, based at the University of Oxford, is a joint initiative of the Smith School of Enterprise and the Environment and the Faculty of Law. Founded in 2021 by Prof. Thom Wetzer, we draw on wide-ranging expertise from across the University of Oxford and collaborate intensively with our international partners in the academic, public, private, and not-for-profit sectors.

Our work is multidisciplinary, rigorous, and informed by practice. We are impact-oriented thinkers who see the law as a tool to catalyse the sustainability transition.

The SLP works to:

- conduct world-leading and actionable research that facilitates the systemic changes needed to equitably address the world's biggest sustainability challenges;
- deliver impact-focused education to students at Oxford and partner organisations, and to the wider legal and scientific communities through our executive education programmes;
- engage with a wide range of partners in the public, private, and not-for-profit sectors to translate research insight into practical application.

Our ongoing research covers the following priority areas:

- **Climate science and law**: conducting scientific research that is relevant to emerging issues in climate litigation and policy, including supporting the improved use of scientific evidence in the court room, understanding the impacts of climate change on health, and evaluating mitigation consistent with legal norms and associated state and corporate obligations.

- **Strategic litigation**: supporting the development of climate lawsuits designed to effect systemic change by quantifying losses attributable to policy delays, scoping legal opportunities to bring climate-related legal actions through international courts, and developing resources to support lawyers identify attributable climate impacts and potential defendants.

- **Net zero law and governance**: address emerging legal challenges related to the net-zero transition, including management of carbon sinks and carbon markets.

- **Sustainable finance**: shaping the way the financial sector responds to the risks associated with climate change, including pioneering research into emerging climate-related legal risks.

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