



THE UNIVERSITY *of* EDINBURGH

## Edinburgh Research Explorer

### Quantifying the contribution of an individual to making extreme weather events more likely

**Citation for published version:**

Lott, F, Ciavarella, A, Kennedy, J, King, A, Stott, P, Tett, S & Wang, D 2021, 'Quantifying the contribution of an individual to making extreme weather events more likely', *Environmental Research Letters*, vol. 16, 104040. <https://doi.org/10.1088/1748-9326/abe9e9>

**Digital Object Identifier (DOI):**

[10.1088/1748-9326/abe9e9](https://doi.org/10.1088/1748-9326/abe9e9)

**Link:**

[Link to publication record in Edinburgh Research Explorer](#)

**Document Version:**

Publisher's PDF, also known as Version of record

**Published In:**

Environmental Research Letters

**Publisher Rights Statement:**

© 2021 Crown copyright & The Authors. Published by IOP Publishing Ltd

**General rights**

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

**Take down policy**

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact [openaccess@ed.ac.uk](mailto:openaccess@ed.ac.uk) providing details, and we will remove access to the work immediately and investigate your claim.



LETTER • **OPEN ACCESS**

## Quantifying the contribution of an individual to making extreme weather events more likely

To cite this article: Fraser C Lott *et al* 2021 *Environ. Res. Lett.* **16** 104040

View the [article online](#) for updates and enhancements.

ENVIRONMENTAL RESEARCH  
LETTERS

## LETTER

## OPEN ACCESS

## RECEIVED

8 October 2020

## REVISED

9 December 2020

## ACCEPTED FOR PUBLICATION

25 February 2021

## PUBLISHED

12 October 2021

Original content from  
this work may be used  
under the terms of the  
[Creative Commons  
Attribution 4.0 licence](#).

Any further distribution  
of this work must  
maintain attribution to  
the author(s) and the title  
of the work, journal  
citation and DOI.

Quantifying the contribution of an individual to making extreme  
weather events more likelyFraser C Lott<sup>1</sup> , Andrew Ciavarella<sup>1</sup>, John J Kennedy<sup>1</sup>, Andrew D King<sup>2</sup> , Peter A Stott<sup>1</sup>, Simon F B Tett<sup>3</sup>   
and Dongqian Wang<sup>4</sup><sup>1</sup> Met Office Hadley Centre, Exeter, United Kingdom<sup>2</sup> School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Parkville, Victoria, Australia<sup>3</sup> School of Geosciences, University of Edinburgh, Edinburgh, United Kingdom<sup>4</sup> National Climate Center, China Meteorological Administration, Beijing, People's Republic of ChinaE-mail: [fraser.lott@metoffice.gov.uk](mailto:fraser.lott@metoffice.gov.uk)**Keywords:** event attribution, climate impacts, loss and damage**Abstract**

Probabilistic event attribution aims to quantify the role of anthropogenic climate change in altering the intensity or probability of extreme climate and weather events. It was originally conceived to calculate the costs associated with any increased likelihood of the meteorological event in question. However, only recently have such studies attempted to divide liability between polluting nations and ascribe a cost. Recent protests indicate a perception that older generations have the greater responsibility for climate change. In this paper, we examine how a portion of the cost of an event can be attributed to any individual person, according to their age and nationality. We demonstrate that this is quantitatively feasible using the example of the 2018 summer heatwave in eastern China and its impact on aquaculture. A relatively simple technique finds sample individuals responsible for between 0.53 and 18.10 yuan, increasing with their age and their country's emissions over their adult lifetime since the first international consensus on carbon emissions was reached. This provides an illustration of the scale of such responsibilities, and how it is affected by national development and demographics. Such data can support decisions, at national and international levels, on how to fund recovery from climate impacts. It offers a simple quantitative approach for individuals to know their impact on the climate, or for governments to use in making policy decisions about how best to distribute costs of climate change.

**1. Introduction**

'The eyes of all future generations are upon you. And, if you choose to fail us, I say: "We will never forgive you."' These words, spoken by Greta Thunberg [1] at the United Nations Climate Summit in New York, 23 September 2019, express the betrayal felt by many in her generation. Emissions which have given developed nations short- and medium-term economic gains have caused long-term changes in the global climate [2]. The cost of that change must already be paid, and continue to be paid for the foreseeable future. This has long been predicted, with calculations indicating that early action would be less costly in the long term [3]. The phrasing 'choose to fail' used by Thunberg is arguably apt, since those who have profited from emissions while knowing the risks to the climate have, in essence, chosen to take a

loan that they and younger generations are now starting to pay back, and will continue to have to pay for many years to come. Given the current strength of feeling, would it be surprising if the younger generations, once in a position of power, insist that the older should pay the debt themselves?

Allen [4] first explained how to calculate human liability for extreme weather events, and the field of event attribution has grown out of that concept. While an interesting research topic in its own right, it has not joined up with efforts of the international community to address loss and damage [5], where it is often viewed as controversial and distracting from the immediate need for disaster response [6]. Nevertheless, the means to quantify the anthropogenic component of the cost of weather events through attribution studies, then subdivide it amongst nations or corporations according to the 'polluter pays'

principle [7], is already possible in theory [8–11]. Were an international framework established to produce and use such results, nations could potentially receive invoices. Younger generations may wish to see older individuals pay proportionally more of these bills, in line with their responsibility for historic emissions.

If such a choice is made, it is important to be as fair, objective and transparent as possible. Thus, in this paper we examine the data and calculations required for dividing up responsibility for (and associated cost of) an example event amongst individuals according to their personal emissions.

## 2. Method

### 2.1. Quantifying relative culpability

How can we divide up the cost of the impact of an extreme event? Event attribution studies have been doing the first stage of this for many years now. Since the question being asked is more usually, ‘How much more likely was this event after climate change?’, the risk ratio ( $R_R = \frac{P_{all}}{P_{nat}}$ ) has become the common measure of event attribution (where  $P_{all}$  is the probability of the event in worlds with all external climate forcings, both natural and anthropogenic, and  $P_{nat}$  is the probability with only natural forcings). However, the original metric used by Allen [4], the fraction of attributable risk ( $F_{AR} = 1 - \frac{P_{nat}}{P_{all}}$ ) is more applicable here, since it answers the question, ‘What fraction of the probability of this event is anthropogenic?’ Allen suggests using this as the fraction of the cost of the impact which should be charged to those responsible for the change in the climate, an idea recently revisited by Frame *et al* [10]. This is therefore our starting point for this study, while acknowledging that a full impact calculation needs to quantify exposure, vulnerability and response in addition to hazard [12].

Otto *et al* [8] divide that responsibility amongst nations according to their cumulative emissions. Their technique is contingent on the extremity of the climatic variable in the event in question being proportional to cumulative emissions (this precludes examining climatic tipping-points). This is true also in the observational attribution technique of van Oldenborgh [13], which uses either global mean surface temperature or atmospheric CO<sub>2</sub> concentration as a covariate in the distribution of the variable of interest. We adapt this technique to the problem examined by Otto *et al*, allowing the distribution to vary with cumulative anthropogenic carbon emissions, rather than physically modelling the changes to the atmosphere in the absence of a proportion of those emissions. It also enables us to extend the principle to much smaller scales, so that, by calculating an individual’s emissions, we can consider their personal  $F_{AR}$ . We then follow Frame *et al* [10] to simply estimate their financial liability by multiplying  $F_{AR}$  by the cost of the event.

Otto *et al* also show the importance of the order in which emissions by individual countries are added to the global total, and how sensitive their calculated responsibility is to this result. This is because a linear change in the extremity of an event results in a non-linear change in its probability. This effect is also present in our study, but is reduced by our framing. We examine climate change due to emissions starting from the New Year following the publication of the First Assessment Report of the IPCC [14], i.e. January 1991, so only consider emissions from 1991 onwards. By this point, governments had agreed consensus to the conclusion of the First Assessment Report, that human emissions will enhance the greenhouse effect, resulting on average in additional warming. Using this baseline is in accord with a range of policy studies, as discussed by Mittiga [7]. Because this period has a higher initial greenhouse gas concentration, it also reduces the Otto *et al* problem of the sensitivity of the national or individual  $F_{AR}$  to when emissions take place.

It is also worth noting that the approach of Otto *et al* implies the ‘polluter pays’ principle [7] for dividing up liability for events. Our move to the scale of the individual will move this framing closer to the ‘beneficiary pays’ principle or Mittiga’s related ‘consumer pays’ principle [7]. Where this is deemed inappropriate from a policy perspective, further development of the methodology will be required.

### 2.2. Determining individual contribution

For an extreme recorded temperature of  $T_{obs}$ , we can obtain the probability of all events as hot or hotter as follows:

$$P(T \geq T_{obs}) = 1 - \text{cdf}(T_{obs}, \mu(\varepsilon_{global}), \sigma, \xi)$$

where  $\text{cdf}()$  is the cumulative distribution for the event.  $\mu$  (the mean or location parameter, depending on the distribution) is chosen to vary with total global anthropogenic carbon emissions  $\varepsilon_{global}$ , while the shape ( $\xi$ ) and scale ( $\sigma$ ) parameters are assumed constant as described by van Oldenborgh [13]. Note that the start date for counting emissions is arbitrary, so long as it is consistent through all calculations. 1961 is used in this study, since this is the beginning of our observed temperature time series. The choice of distribution and covarying parameter must depend on the variable in question. For example, rainfall tends to be gamma distributed, so uses the scale parameter as covariate with  $\varepsilon_{global}$ . It is also prudent to incorporate a response time between the emissions and its effect on the climate. van Oldenborgh achieves this with a 3 year rolling average on their covariate. We adopt this, mapping the distribution in year  $Y$  to  $\varepsilon_{global}(Y - 1)$ , so that emissions later than the event do not affect the calculation. Sample uncertainty on this probability can be evaluated by bootstrap resampling the temperature data to fit a range of parameters to the data.

Once derived, these probabilities feed into  $F_{AR}$ , after which a simple multiplication by the cost of the event ( $c_{event}$ ) in question yields the anthropogenic cost ( $c_{anthro}$ ).

$$c_{anthro} = c_{event} F_{AR}.$$

Otto *et al* [8] attribute changes to a given nation by either modelling the change in  $F_{AR}$  in the absence of that country's emissions, or alternatively in the absence of all other countries' emissions. This gives a low and high estimate respectively. Here, rather than using a physical model, we model the statistical shift in the cdf with the same presence or absence of emissions, either relative to those up to the first year of responsibility (here  $\varepsilon_{1990}$ ) or relative to global emissions since then ( $\varepsilon_{global}$ ). This technique may equally be applied on the smaller scale of individuals, rather than whole nations. Because this results in a much smaller change in the climate, as well as being set against the higher baseline of 1990, the difference between the high and low estimates is less dramatic than those discussed by Otto *et al*.

Low estimate :

$$F_{AR}^{indiv} = 1 - \frac{1 - \text{cdf}(T_{obs}, \mu(\varepsilon_{global} - \varepsilon_{indiv}), \sigma, \xi)}{1 - \text{cdf}(T_{obs}, \mu(\varepsilon_{global}), \sigma, \xi)}$$

High estimate :

$$F_{AR}^{indiv} = 1 - \frac{1 - \text{cdf}(T_{obs}, \mu(\varepsilon_{1990}), \sigma, \xi)}{1 - \text{cdf}(T_{obs}, \mu(\varepsilon_{1990} + \varepsilon_{indiv}), \sigma, \xi)}$$

To calculate the individual's emissions ( $\varepsilon_{indiv}$ ), we use the annual carbon emissions of the nation whose citizenship the individual holds [15] and annual adult population total [16]. Taking the simplest assumption of equal responsibility amongst a country's adult population, we can divide emissions by the adult population, then sum over each year since the individual became responsible.

$$\varepsilon_{indiv} = \sum_{Y=Y_0}^{Y_{event}-1} \frac{\varepsilon_Y}{p_Y}.$$

$Y_0$  is the first year of responsibility of the individual;  $Y_{event}$  is the year in which the extreme event in question happened;  $\varepsilon_Y$  is the national carbon emissions total for year  $Y$ ;  $p_Y$  is the adult population of that nation in year  $Y$ .

### 3. Case study results—East China 2018 heatwave

As a case study, we examine a heatwave previously presented by Ren *et al* [17]. This example is chosen to demonstrate an approach that could be taken more widely. We make no judgement as to the importance

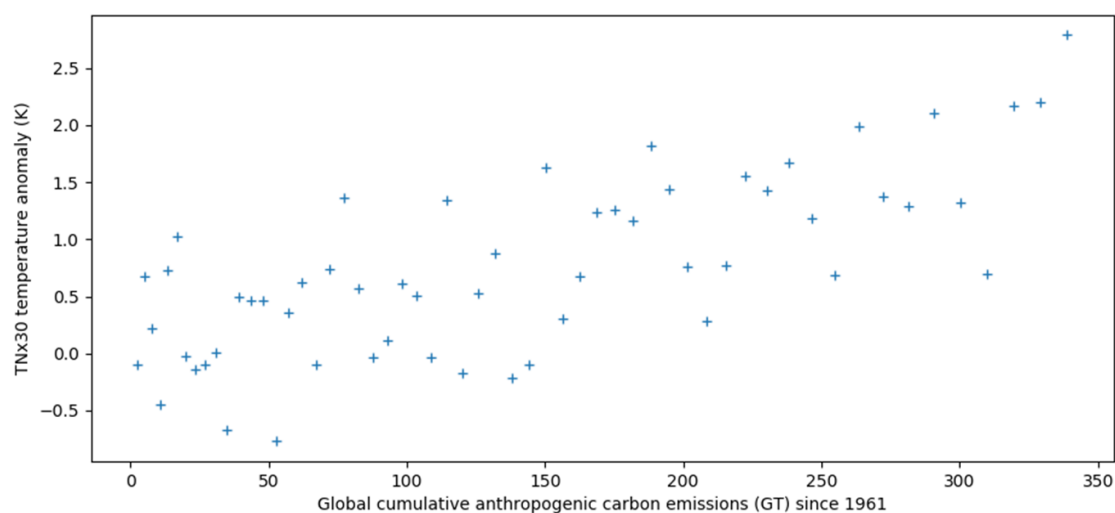
of this particular event (or its impacts) relative to other weather events. Ren *et al* report losses of 6.87 billion yuan renminbi by Chinese aquaculture alone. We also use this figure, without examining whether this loss/damage could have been avoided. This will be a crucial component in future work, but for now this cost is merely illustrative. Since other losses are not stated, our results are likely to be conservative. Based on their maximum of a 30 d running average of daily minimum temperature anomaly (referred to as TNx30) relative to 1961–2013, we adapt the covariate-based attribution technique of van Oldenborgh [13], fitting a Gumbel distribution (as we do not expect a physical upper or lower limit for such extremes) to TNx30 observations from 1961 to 2018, detrended relative from global cumulative anthropogenic carbon emissions. Figure 1 suggests that TNx30 has a linear relationship with carbon emissions, confirming the validity of the technique for this event. Once fit, the scale parameter is fixed and the location parameter scales with emissions, as shown in figure 2. This gives this heatwave a central  $F_{AR}$  estimate of 0.88 for global anthropogenic carbon emissions since 1991, thus an attributable anthropogenic cost of 6.1 billion yuan.

From here, we calculate the cost to individuals in four illustrative countries, using their age to estimate emissions by assuming equal emissions across the national adult population. Emissions are shown in table 1, with the corresponding cost ranges in table 2 allowing those emissions to have taken place at any time between 1991 and 2017. Note that in all cases here, we assume an adult 'age of responsibility' of 18 years, and only count complete emission years where the individual is older than that.

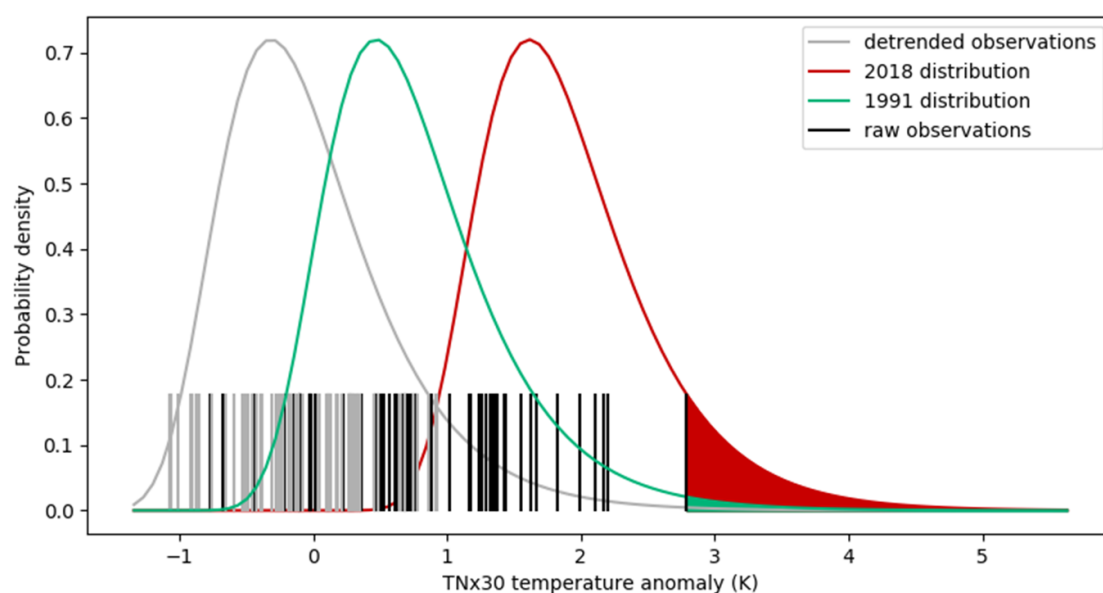
By examining the 5th to 95th bootstrap percentiles of the Gumbel fit to carbon emissions, we find that the sample uncertainty from using this observation-based technique with only 57 sample years is much larger than that produced by emission date in table 2. The  $F_{AR}$  range from global emissions determined by this technique is 0.81–0.94, corresponding to a total anthropogenic cost for this event of 5.6–6.4 billion yuan. The corresponding individual cost ranges are shown in table 3. For future studies, this uncertainty range may likely be reduced by using a large ensemble of simulations in place of observations. Uncertainties in the original financial cost of the event must also be carried through. As Frame *et al* point out [10], these are likely to be larger than uncertainties related to climate change.

### 4. Discussion

At this point, the reader may be asking the place of these calculations in the broader climate science endeavour. There are a number of ways in which such information could be used and we speculate on some of them here, without judging their desirability. One



**Figure 1.** Relationship between the maximum of the 30 day running-mean daily minimum temperature anomaly relative to 1961–2013 (TNx30) and the global cumulative anthropogenic carbon emissions since 1961, in gigatonnes.



**Figure 2.** TNx30 observations, raw (black vertical bars) and detrended with respect to carbon emissions since 1961 (grey bars). A Gumbel distribution is fitted to the detrended data, then its location parameter scaled to 1991 (green) and 2018 (red) levels of atmospheric carbon.

**Table 1.** Personal mass of carbon, to the nearest tonne, emitted from year of responsibility (the later of 1991 or the first full year aged 18 years or over) to the end of 2017 (the year before the event being studied), calculated assuming all people of the same age and nationality emit equally.

Age in 2018	25	30	35	40	46+
Nationality					
Sweden	10	19	30	41	55
China	14	24	30	36	41
Russian Federation	24	43	61	80	110
United States of America	37	71	109	147	192

possibility is to use this to enable people to assess their own impact on the climate. When an extreme event happens, for example, they might wish to contribute to charities working to improve resilience to future events. These figures could help them to decide

their contribution. Another possibility is for an over-seeing effort which sums the contributions over all events experienced in a year, expressed as the cost of a nation or individual's activities, incorporating reimbursement for any impacts felt by that country.



**Table 2.** Upper and lower bounds (based on order of emissions as per Otto *et al* 2017) for personal responsibility, in yuan renminbi, for the cost to aquaculture of the 2018 East China heatwave, shown for a selection of nationalities and ages, based on personal emissions in table 1.

Age in 2018 Nationality	25	30	35	40	46+
Sweden	0.69–0.71	1.38–1.43	2.17–2.25	3.00–3.13	4.02–4.20
China	1.05–1.07	1.75–1.81	2.22–2.30	2.59–2.70	2.99–3.13
Russian Federation	1.72–1.76	3.11–3.22	4.47–4.65	5.83–6.08	8.04–8.41
United States of America	2.66–2.72	5.18–5.36	7.93–8.24	10.71–11.17	13.95–14.59

**Table 3.** As table 2 but with uncertainties incorporating both emission date and the 5%–95% bootstrap range in fitting the Gumbel distribution to the detrended TNx30 observations.

Age in 2018 Nationality	25	30	35	40	46+
Sweden	0.53–0.87	1.05–1.78	1.65–2.84	2.28–3.91	3.09–5.16
China	0.79–1.33	1.34–2.24	1.72–2.92	1.94–3.36	2.27–3.80
Russian Federation	1.31–2.16	2.37–3.93	3.38–5.77	4.44–7.52	6.09–10.44
United States of America	2.01–3.40	3.91–6.68	6.06–10.14	8.21–13.91	10.89–18.10

We will also see events which are less likely after climate change, such as most cold waves, and thus reduced costs of events could be incorporated into the total. Note that the traditional definition of  $F_{AR}$  has little meaning in this case, and an alternative such as that discussed by Hansen *et al* [18] would need to be adapted to quantify any benefit of climate change.

Since a substantial operational attribution effort would be required to attain the  $F_{AR}$  for every event, one future option could be to incorporate this into a seasonal forecasting system. This would then also open the possibility of attributing a change in probability of an event which did not occur, but had a higher probability in the natural world, and incorporating this reduction in cost. As Frame *et al* [10] note, arriving at potential costs for unseen events is work in itself. Their discussion of economic modelling of indirect losses may indicate the direction such developments might take. We can also include the costs and benefits of mean climate change, though we might expect costs to outweigh benefits, given much infrastructure is adapted to the past climate. We must also be aware of the limits of adaptation and, in turn, the limits of our knowledge, to ensure fair treatment of countries with weather which is difficult to predict and attribute.

The calculation in this paper is an illustrative example to demonstrate feasibility. We chose the simplest method we could for such an illustration, and as such is not a policy recommendation. All individuals in a country are assumed to emit equally in any given year, so the total national emission in that year is divided equally. Summing over each year of their adulthood after 1990 would give their total responsible emission. Monetary contribution follows straightforwardly, but with some interesting political decisions to be made if this method were used for

taxation. If adult emissions are chosen in preference to lifetime emissions, are parents then to pay additionally based on having children? Are post-1990 emissions by persons now deceased absorbed by the state, or must the inheritors of their estate be charged? (This is an extension of the ‘disappearing perpetrators problem’ [19].) Many value judgements would need to be made if such approaches were implemented in practice, which are far outside the remit of this paper.

Using data from the tax system may make weaker assumptions possible, depending on the detail of historical records kept on individuals. For example, we might seek to use the link between income and energy consumption [20] by subdividing the annual contribution amongst the population by their personal income in that year. This may come closer to charging an individual for their true emissions, but because it uses historical income, it might be considered a wealth tax.

Both these assumptions arguably fail to reward the environmentally conscious individual (or penalise the negligent). One’s past actions are difficult to prove, but may not be impossible. For example, credit rating agencies might retain enough sales data to offer a personal score. Performing such calculations is beyond the scope of this paper, and future work in economics and political science can refine these options. Indeed, many would argue that corporations, rather than individuals, should pay for the impacts of climate change. One technique to calculate this has already been demonstrated by Ekwurzel *et al* [11], and the method used in our paper could also be extended to such a policy. Since we have demonstrated that calculating an individual contribution to the changing probability of extreme events is now mathematically feasible, it is even more relevant for those with policy expertise to examine all these issues.

## 5. Conclusions and future work

In this study, we have attributed a fraction of the probability of an extreme event to the carbon emissions of an individual. For simplicity, only the effect of carbon emissions is included, but aerosol emissions and land use change can also have significant impacts on a localised scale. These will be particularly important for rapidly developing nations, so this should be incorporated in future studies of this type where possible.

We used these results to examine the cost of that event incurred by the individual, including uncertainty ranges. Assessing this can be useful for the individual to understand their own impact, and for society to understand the impact of different demographics. For a broader range of policy options on a national and international level, these calculations must be adapted in future work. We have discussed building these techniques into an operational attribution system that would sum over all events in a period and give an individual's total balance. The reduction of uncertainty ranges will be key in that future system, but they can never be fully eliminated. Their handling (e.g. whether the cost to an individual is calculated from the minimum or best estimate) may ultimately be a political decision.

Assigning blame for climate change is necessarily an emotive subject, and will likely become more so as its impacts are felt increasingly widely. As Boyd notes [6], fear of paying compensation has shaped international discussions of loss and damage. Such fear is often greater when it is of an unknown potential. We hope that our example calculation on a personal scale can reduce this fear. We believe that this study offers a useful tool to help address the problem in an objective, quantitative and diplomatic manner.

## Data availability statement


The data that support the findings of this study are available upon reasonable request from the authors.

## Acknowledgments

Thanks to Stephen Belcher, Jason Lowe, Stephen P Haddad and Stuart Fox for advice and encouragement in the drafting of this manuscript. Thanks also to Rachel James, who conceived that this work might be used to suggest charitable donations, and to our editor and reviewers. This work was supported by the EUPHEME project, which is part of the ERA4CS, an ERA-NET initiated by JPI Climate and co-funded by the European Union (Grant 690462). It was also supported by the Met Office Hadley Centre Climate Programme, funded by BEIS and Defra. A D K was supported by the Australian Research Council (DE180100638) and acknowledges support from the Australian Research Council Centre

of Excellence for Climate Extremes. SFBT was supported by the U.K.–China Research and Innovation Partnership Fund through the Met Office Climate Science for Service Partnership (CSSP) China as part of the Newton Fund. D W was funded by the National R&D Program of China (2018YFC1507702).

## ORCID iDs

Fraser C Lott  <https://orcid.org/0000-0001-5184-4156>

Andrew D King  <https://orcid.org/0000-0001-9006-5745>

Simon F B Tett  <https://orcid.org/0000-0001-7526-560X>

## References

- [1] Thunberg G 2019 *No-one Is Too Small to Make a Difference* (London: Allen Lane)
- [2] 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* ed T F Stocker, D Qin, G-K Plattner, M Tignor, S K Allen, J Boschung, A Nauels, Y Xia, V Bex and P M Midgley (Cambridge: Cambridge University Press) p 1535
- [3] Stern N 2007 *The Economics of Climate Change: The Stern Review* (Cambridge: Cambridge University Press)
- [4] Allen M 2003 Liability for climate change *Nature* **421** 891–2
- [5] UNFCCC Decision 2/CP.19 2013 *Warsaw International Mechanism for Loss and Damage Associated with Climate Change Impacts* (Bonn: UNFCCC)
- [6] Boyd E *et al* 2017 A typology of loss and damage perspectives *Nat. Clim. Change* **7** 723–9
- [7] Mittiga R 2019 Allocating the burdens of climate action: consumption-based carbon accounting and the polluter-pays principle *Transformative Climates and Accountable Governance. Palgrave Studies in Environmental Transformation, Transition and Accountability* ed B Edmondson and S Levy (Cham: Palgrave Macmillan) ([https://doi.org/10.1007/978-3-319-97400-2\\_8](https://doi.org/10.1007/978-3-319-97400-2_8))
- [8] Otto F E L *et al* 2017 Assigning historic responsibility for extreme weather events *Nat. Clim. Change* **7** 757–9
- [9] Lewis S C, Perkins-Kirkpatrick S E, Althor G, King A D and Kemp L 2019 Assessing contributions of major emitters' Paris-era decisions to future temperature extremes *Geophys. Res. Lett.* **46** 3936–43
- [10] Frame D J *et al* 2020 Climate change attribution and the economic costs of extreme weather events: a study on damages from extreme rainfall and drought *Clim. Change* **162** 781–97
- [11] Ekwurzel B, Boneham J, Dalton M W, Heede R, Mera R J, Allen M R and Frumhoff P C 2017 The rise in global atmospheric CO<sub>2</sub>, surface temperature, and sea level from emissions traced to major carbon producers *Climatic Change* **144** 579–90
- [12] Simpson N P *et al* 2021 A framework for complex climate change risk assessment *One Earth* **4** 489–501
- [13] van Oldenborgh G J 2007 How unusual was autumn 2006 in Europe? *Clim. Past* **3** 659–68
- [14] Houghton J T (Intergovernmental Panel on Climate Change and World Meteorological Organization) 1990 IPCC first assessment report (Geneva: WMO)
- [15] Global Carbon Project 2018 Supplemental data of global carbon budget 2018 (Version 1.0) [Data set] Global Carbon Project (<https://doi.org/10.18160/gcp-2018>)
- [16] United Nations, Department of Economic and Social Affairs, Population Division 2019 *World Population Prospects 2019*



- Online edn (available at: <https://population.un.org/wpp/Download/Standard/Population/>)
- [17] Ren L *et al* 2020 Anthropogenic influences on the persistent night-time heat wave in summer 2018 over Northeast China *Bull. Am. Meteorol. Soc.* **101** S83–S88
- [18] Hansen G *et al* 2014 On the attribution of a single event to climate change *J. Clim.* **27** 8297–301
- [19] Page E A 2011 Climatic justice and the fair distribution of atmospheric burdens: a conjunctive account *Monist* **94** 412–32
- [20] Oswald Y, Owen A and Steinberger J K 2020 Large inequality in international and intranational energy footprints between income groups and across consumption categories *Nat. Energy* **5** 231–9