The attribution of human health outcomes to climate change: transdisciplinary practical guidance

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Abstract

For over 30 years, detection and attribution (D&A) studies have informed key conclusions in international and national assessments of climate science, providing compelling evidence for the reality and seriousness of anthropogenic effects on the global climate. In the early 21st century, D&A methods were adapted to assess the contribution of climate change to longer-term trends in earth system processes and extreme weather events. More recently, attribution research quantified the health and economic impacts of climate change. Here we provide practical guidance to inform transdisciplinary collaboration among health, climate, and other relevant scientific disciplines and interested parties in designing, conducting, interpreting, and reporting robust and policy-relevant attribution analyses of human health outcomes. This guidance resulted from discussions among experts in health and climate science. Recommended steps include co-developing the research questions across disciplines; establishing a transdisciplinary analytic team with fundamental grounding in the core disciplines; engaging meaningfully with relevant interested parties and decision-makers to define an appropriate study design and analytic process, including defining the exposure event or trend; identifying, visualizing, and describing linkages in the causal pathway from exposure to weather/climate variables to the health outcome(s) of interest; choosing appropriate counterfactual climate data, and where applicable, to evaluate the skill of the climate and health impact model(s) used in D&A research; quantifying the attributable changes in climate variables; quantifying the attributable health impacts within the context of other determinants of exposure and vulnerability; and reporting key results, including a description of how recommendations were incorporated into the analytical plan. Implementation of guidance would benefit diverse interested parties including researchers, research funders, policymakers, and climate litigation by harmonizing methods and increasing confidence in findings.

1. Introduction

Detection and attribution (D&A) analyses underpin conclusions since the mid-1990s that human activities have unequivocally warmed the atmosphere, ocean, and land (IPCC, 2021a). These analyses assess the extent to which the ‘climate or a system affected by climate has changed in some defined statistical sense’ (detection) and ‘the relevant contributions of multiple causal factors to [this] change’ (attribution; IPCC, 2021b). In essence, these attribution methods quantify the proportion of an observed change in the Earth system from a pre-industrial baseline period that may be causally attributed to specific anthropogenic forcings (e.g., well-mixed greenhouse gases and aerosols; Santer et al., 2003; Hegerl et al., 2010; Stone et al., 2013, Eyring et al., 2021). Climate scientists have applied these methods to quantify the extent to which greenhouse gas emissions and the associated increases in atmospheric concentrations of greenhouse gases have caused changes in surface temperature (e.g., Gillett et al., 2021), hydrologic cycle, glacier retreat, sea-level rise, and many other variables (e.g., Eyring et al., 2021, and references therein). For extreme weather and climate events, related methods, commonly termed ‘extreme event attribution’, assess the change in an event’s intensity and/or frequency attributable to anthropogenic climate change (Stott et al., 2004; Seneviratne et al., 2021).

Recent developments extended the application of attribution methods to assess impacts on different sectors (O’Neill et al., 2022). Examples include economic losses, food security, wildfires, agriculture, hydrological change, and health (e.g., Uhe et al., 2021, Mitchell et al., 2016, Ebi et al., 2017; Ebi et al., 2020; Dasgupta and Robinson, 2022; Romanovska et al., 2024; Burton et al., 2024; Gibb et al., 2023; Vicedo-Cabrera et al., 2021, 2023; Stuart-Smith et al., in review). However, existing health attribution studies are still limited, both in terms of the health impacts covered and their geographical scope (Carlson et al., 2024). Current understanding of the health impacts of climate change is consequently partial, biased towards types of exposures where the climate science community has conducted D&A analyses and towards regions with more abundant long-term health and weather data. D&A analyses are starting to focus on places assumed to be the most vulnerable and most affected by climate change (e.g. Carlson et al., 2024; Callaghan et al., 2021; Childs et al., 2024). In practice, most health attribution studies have concentrated on problems where the anthropogenic signal dominates the noise in the climate system, and where the health outcome is strongly associated with the climate variables (e.g. heat-mortality).

The definition of attribution can vary between and within the climate science and impact communities. Climate science typically focuses on attribution of changing weather/climate patterns to radiative forcings and sometimes to specific emitters of greenhouse gases. Impact communities focus on attribution to radiative forcings or on other metrics of climate change (e.g., extreme weather and climate events). Health attribution studies have focused on the latter.

Incomplete understanding and documentation of the impacts of climate change on health impedes decision-making and legal responses. D&A studies could be an important input for climate risk assessments to inform policy; and could provide leverage for implementing adaptation policies to support affected individuals and communities. Improved and expanded evidence on health impact attribution might also inform litigation and the program of the nascent Loss and Damage Fund established by the United Nations Framework Convention on Climate Change (UNFCCC) at COP27 (UNFCCC 2022).

To increase the robustness and relevance of D&A studies of human health outcomes, we developed a framework to promote robust D&A study design and analyses that follow best practices, based on peer-reviewed publications and expert knowledge. The framework is designed to promote transparency on analytic choices made, not to provide a rigid approach. Within this framework, we include guidance for designing, conducting, interpreting, and reporting D&A analyses. This guidance is intended to support transdisciplinary collaborations to improve methods, including new approaches where necessary, and to build the capacity for conducting empirical studies, including in low-resource settings, that, in turn, contribute to national and international assessments of the impacts of climate change on human health. In addition to researchers in health, climate, and other disciplines, the intended audiences of this framework include editors of academic journals, research funding organizations, public health organizations, experts involved in ongoing scientific assessments, decision-makers, and legal scholars. The guidance is designed so that future iterations can easily incorporate diverse knowledge systems and new scientific developments.

2. Methods

Three steps were taken to develop and refine the framework and associated guidance for conducting robust and policy-relevant health D&A analyses:

The first step involved recruitment of an international panel of scientific experts. The organizing team (K.L. Ebi, R.F. Stuart-Smith, A. Haines, J.J. Hess) identified a scientific advisory committee based on expertise across issues in health and climate attribution (C. Wright, L.A. Galvao, M. Taylor, and R.K. Kolli). The organizing and scientific advisory committees invited 65 scientists based on a systematic review of the scientific literature and snowball sampling to participate in a hybrid workshop intended to generate consensus recommendations on a framework and guidance on D&A analyses for climate change impacts on health. Selection criteria included area of expertise (health and/or climate), geographic area of research, gender, and career stage. Facility constraints meant the invitation list could not include all relevant researchers. Expert solicitation, including workshop availability, was conducted by email in August 2024 and substitutions made via mutual agreement between the organizing team and the contacted expert.

In the second step, panelists convened remotely and in person in London, U.K. in a workshop in September 2024 sponsored by the Wellcome Trust and co-convened with the University of Washington. Of the final panelist pool, 35 participated in person and 20 participated remotely. All consenting participants are included as authors. The overarching goal was to reach consensus on key recommendations for a framework and guidelines on conducting robust and policy-relevant climate and health D&A studies. Panel discussions included topics such as making D&A relevant across diverse communities, incorporating novel data sources, prioritizing different types of (qualitative and quantitative) data, loss and damage, and methodological issues. Small group discussions included climate science and public health perspectives on D&A approaches to engaging interested parties, and when and how attribution evidence might be used. The agenda and list of participants are available upon request.

In the third step, workshop volunteers formed a core writing team to draft the guidance, which was then reviewed and agreed upon by all authors.

3. Overview of pathways by which climate change affects health and well-being

Changing weather patterns can affect human health and well-being through a wide range of pathways. These include the effects of extreme weather and climate events such as heatwaves, floods, droughts, and wildfires. Long-term changes in weather variables, sometimes combined with extreme events, are altering the prevalence and distribution of water and nutrition-related health outcomes; changes in transmission and emergence of vector-borne, water-borne, food-borne and zoonotic diseases; exacerbation of chronic diseases (e.g. metabolic and allergic); and the effects on mental and physical health from population displacement and poverty (Cisse et al., 2022). Illustrative examples of the plethora of possible causal chains between weather/climate exposures and associated health outcomes are listed below. Different types of D&A analyses may require different approaches. It is important that health D&A studies clearly communicate to what the impacts are being attributed. Ideally, attribution studies should provide evidence of a causal association at each step of the causal chain (Grose et al., 2024).

- Climate hazards associated with extreme weather and climate events such as extreme heat, floods, droughts, typhoons, and wildfire can cause excess morbidity, mortality, mental ill-health and other adverse health effects
- Exposure to higher ambient temperatures can result in morbidity and mortality, including adverse maternal, neonatal and child health outcomes
- Exposure to climate-driven changes in air pollution (e.g., wildfires and aeroallergens cause premature mortality, allergic, and other respiratory diseases
- Changes in temperature, precipitation, and other weather variables can alter the spatial distribution, seasonality, and/or incidence of a range of infectious diseases, vectors, and disease organisms
- Exposure to climate-driven changes in water and food safety, availability, and security can affect associated disease outcomes

Climate change-associated impacts on access to and delivery of healthcare can also cause morbidity and mortality. Indigenous Peoples and historically minoritized peoples and communities, including displaced peoples, suffer disproportionate impacts because of systematic discrimination and injustice leading to an amplification of poor health outcomes.

Health outcomes are influenced by the intersection of exposure to a hazard, the vulnerability of the exposed populations, and the capacity of health and other relevant systems to manage. Therefore, it is important to consider factors such as changing socioeconomic and demographic circumstances, changes in upstream drivers of health outcomes, the capacity to prepare for and manage impacts, and other earth system changes that could be responsible partly or wholly for observed changes in health outcomes.

Attribution studies may span the full, or parts of, these multi-step exposure-impact pathways, assessing the influence of the range of drivers that contributed to the health outcome(s) or proxy health outcome of interest. For vector-borne diseases, for example, the outcome analyzed could be the abundance and/or seasonal activity of the vector or disease organisms, disease incidence, and/or associated morbidity or mortality (Harrington et al., 2022). Relevant considerations include the role of non-climate drivers that affect the magnitude and pattern of health outcomes, and the underlying vulnerabilities or protections that could have modified the extent of the impact (Stone et al., 2021; Jézéquel et al., 2024). Nevertheless, studies that only quantify the effect of climate change on health outcomes, 'all else being equal', are legitimate modes of inquiry, and remain informative in some settings, such as in climate lawsuits where the relevant question might be how the impacts would have differed in the absence of the actions of defendants (e.g., those responsible for greenhouse gas emissions) (Stuart-Smith et al., 2024).

Impact modeling should consider nonlinearities between a weather driver and health outcome (Mitchell, 2021) and interactions with underlying socioeconomic conditions (Lowe et al. 2021). For example, statistically linking flood-related mortality with precipitation indices given known river flood characteristics, or nutrition-related health outcomes with heat indices where a strong pathway through agricultural production is expected, will omit nonlinearities in the response of these interim impacts and the health outcomes. Modelling these interim impacts (river flood, agricultural production, etc.) as exposures for health analyses can integrate additional process understanding and knowledge of their exposure and vulnerability characteristics, including human management, and thereby strengthen the attribution finding (Cotterill et al., 2024)

4. Probabilistic and storyline approaches for climate event and trend attribution

Two broad approaches have been used in D&A studies: storyline and probabilistic (risk-based) estimates. In some cases, these approaches may be closely related; storylines can be considered a special case of some of the probabilistic analysis when, for instance, the initial condition uncertainty is fully constrained (Leach et al., 2024). Several protocols describe these methods (e.g., Philip et al., 2020 for probabilistic methods).

- Storyline-type approaches usually disaggregate the causes of a given event or trend into multiple causal processes (typically, an approximation of the thermodynamic and dynamic components) and then assess the contribution of anthropogenic climate change to one or more of these processes (see Perkins-Kirkpatrick et al., 2024 for a more detailed overview). A common approach for applying these methods is to condition the analysis on given dynamical conditions (such as a specific atmospheric pressure pattern) and then assess the effects of anthropogenically forced changes on specific variables such as ocean temperatures or atmospheric CO_2 concentrations in the build-up to the event (e.g., Ermis et al., 2024) or to quantify the changing likelihood of those dynamical conditions occurring (Faranda et al., 2023). Such an approach often (but not always) neglects changes in dynamical processes due to climate change, which can be useful for simplifying the problem, but dynamical processes can be substantially affected by anthropogenic warming and affect health outcomes.
- The probabilistic approach estimates the change in frequency or intensity of certain meteorological conditions, with and without anthropogenic climate change. These studies usually assess either or both the change in likelihood of meteorological conditions exceeding a certain value, or the change in intensity of an event of a given probability. Assessing changes in the intensity of an event with a fixed probability of occurrence could be viewed as a storyline approach.

Often, an observed outcome, the 'factual' range of outcomes produced by historical climate model simulations including all human and natural forcings, is compared with the 'counterfactual' range of outcomes that might have occurred due to natural forcings alone over the same period. To generate this counterfactual, studies may use historical-natural ('hist-nat') simulations, with the most common being from the Detection and Attribution Model Intercomparison Project (DAMIP) (Gillett et al., 2016). Studies also have used statistical regression-based counterfactuals of observations and re-analyses, for instance available through the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; Mengel et al., 2020) or generated via time series of anthropogenically-driven global temperature change, such as the Global Warming Index (Haustein et al., 2017) (see Table 1). Toolkits such as the KNMI Climate Explorer have been developed to support these analyses (https://climexp.knmi.nl/). The assessed contribution of climate change varies between events; studies have found substantial influence of climate change on heatwaves supported by a strong theoretical understanding of the processes by which climate change affects extreme heat (Domeisen et al., 2022). By contrast, for example, there is less certainty surrounding the attribution of severe convective storms to climate change because of limitations to the accuracy of precipitation in models (Perkins-Kirkpatrick et al., 2024).

Because the associations between weather or climate variables and impacts are often non-linear, it cannot generally be assumed that the proportion of climate-change attributable health impacts is equal to the proportion of a meteorological event's likelihood that is attributable to human influence (Perkins-Kirkpatrick et al., 2022). Non-linearity also arises from other drivers of the health outcome of interest, from implemented adaptation options (e.g., heatwave early warning systems) and from compounding and cascading risks. For example, a loss of housing or income source can introduce a cascade of impacts through negative feedback loops.

Care needs to be taken when impacts result from the combined effect of multiple climatic variables such as temperature and humidity, including their wider consequences, particularly when undertaking bias correction in climate model outputs. Multivariate indicators such as wet-bulb globe or apparent temperature are widely applied (see e.g. Mitchell 2016; use of Fire Weather Index: Kirchmeier-Young et al., 2017). Copula-based statistical approaches are sometimes used to assess the combined effect of multiple meteorological variables (Chiang et al., 2021; Zachariah et al., 2023). These approaches provide a flexible representation of the multivariate distribution without assuming a linear relationship between changes in each of the variables, such as in hydroclimatic analysis that combine temperature and precipitation (e.g., Tootoonchi et al., 2022). Ultimately, the choice of the variables used should be determined by knowledge of the epidemiology of the health outcome, particularly the contribution of weather/climate variables to the observed impacts, and pragmatic requirements of the impact modelling approach that might determine whether a multivariate indicator or time series of individual variables is required.

Consideration should be given to the climate forcings that are the focus of the analysis (Skeie et al., 2017), including whether the effects of local land cover change should be accounted for, and which anthropogenic greenhouse gas and aerosol emissions to include. For instance, in some regions local or remote aerosol emissions or land-use changes confound some of the impacts expected from greenhouse gas emissions (e.g. Thiery et al., 2020). Similarly, some observed recent warming due to greenhouse gas emissions resulted from reductions in sulphate aerosols that until then had temporarily masked the warming (NASA 2023).

Approaches that quantify the portion of the probability of a certain climate event occurring that is attributable to climate change (the 'Fraction of Attributable Risk' or FAR) and then apply this finding to quantify the portion of attributable health impacts do not account for any changes in the probability of a health impact occurring as the climate hazard changes in magnitude. Further, this approach is often extremely sensitive to the spatial and temporal scales chosen (Cattiaux & Ribes, 2018; Leach et al., 2018), which makes simplistic linkages problematic. This results in the entire health impact being represented as a binary phenomenon that either occurs or does not occur. However, the magnitude of many health impacts increases progressively with the magnitude of the climate hazard. For instance, higher temperatures are normally associated with higher mortality above the optimal temperature for a specific location. As such, the FAR method has important limitations. When there is a specific impact threshold in the system of interest, it may be informative to understand how climate change modified the likelihood that it was exceeded (Noy et al., 2024; Perkins-Kirkpatrick et al., 2022). For example, when the focus of the analysis is on a temperature threshold that results in 1,000 extra heat-related deaths, because that would strain public health resources, then a FAR analysis can be informative. However, if the focus of the analysis is on the mortality of a specific event, then a FAR analysis may be unintentionally misleading. For this reason, event attribution studies are gravitating towards approaches that assess changes in events' intensity (e.g., temperature, precipitation) and the associated changes in the magnitude of impacts (see, e.g., Perkins-Kirkpatrick et al., 2022).

Studies have quantified climate change impacts attributable to the greenhouse gas emissions of individual entities, such as companies or countries, including for extreme weather events (Beusch et al., 2022; Lewis et al., 2019; Lott et al., 2021; Otto et al., 2017) and sea-level rise (Ekwurzel et al., 2017). Some studies quantified changes in extreme event occurrence or intensity with the emissions of individual entities excluded, for instance using reduced-complexity earth system models (Quilcaille et al., 2024). Others used simplified statistical approaches to estimate contributions proportional to the entity's proportion of historical emissions (Stuart-Smith et al., in review).

Table 1: Climate model data that can facilitate D&A analyses[1]

Dataset name	**Institutional Source**	**Weblink / reference**
CMIP6 (historical, pre-industrial control simulations)	World Climate Research Programme	https://wcrp-cmip.org/ Eyring et al., 2016
DAMIP (natural-only historical simulations [hist-nat], well-mixed greenhouse-gas-only historical simulations [hist-GHG], anthropogenic-aerosol-only historical simulations [hist-aer])	Detection and Attribution Model Intercomparison Project	https://damip.lbl.gov Gillett et al., 2016
ATTRICI	Inter-Sectoral Impact Model Intercomparison Project	https://www.isimip.org Mengel et al., 2021
HiResMIP2 (see also HiResMIP1)	High Resolution Model Intercomparison Project phase 2	https://highresmip.org/ Roberts et al., 2024
Coordinated Regional Climate Downscaling Experiment (CORDEX; and other coordinated regional modelling experiments)	WCRP CORDEX	https://cordex.org Giorgi et al., 2009

5. Framework for conducting health D&A analyses: event attribution example

Figure 1 outlines the framework for detecting and attributing health impacts to climate change, using extreme events as an example. Similar steps would be required for a trend D&A analytical approach, e.g. detecting and attributing health impacts to increases in temperature, changes in seasonal temperatures, or changes in the frequency, intensity, and duration of other extreme weather and climate events, and alterations in precipitation patterns (e.g., Childs et al., 2024).

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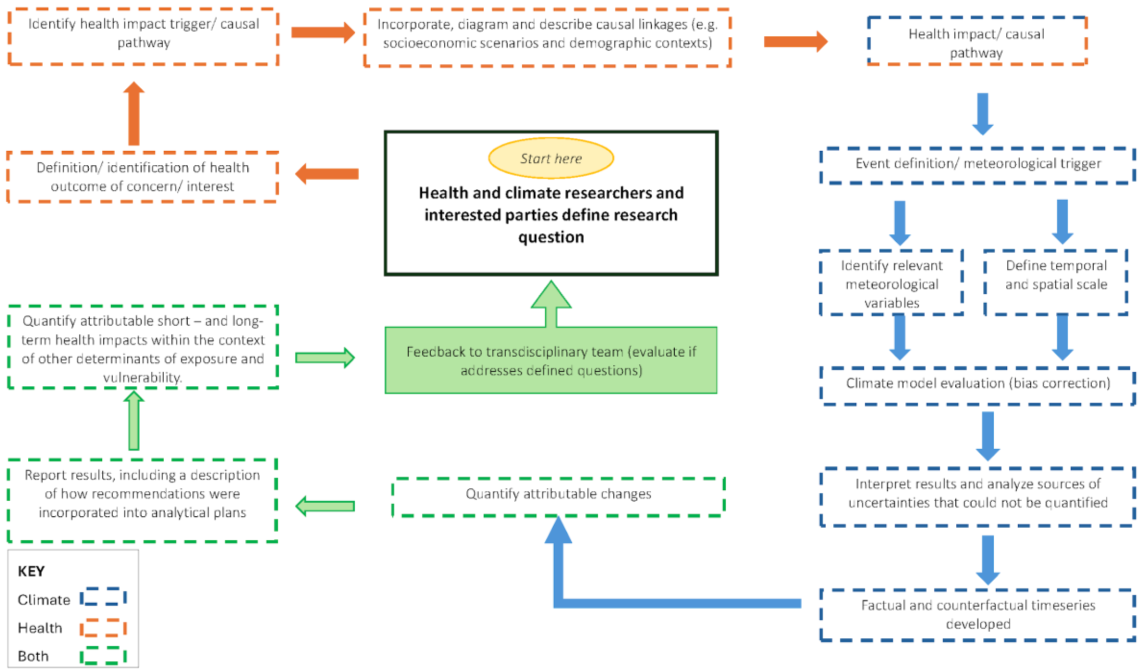
[1] Note that this table is neither intended to be complete nor representative of the model datasets used in climate change attribution studies. DAMIP is most commonly used across the literature. Region-specific semi-operational attribution tools are also being developed by national meteorological services (e.g., UK, Japan, France, Canada, Australia, New Zealand).

Figure 1: Framework for attributing impacts of extreme events to climate change. The framework is intended to be indicative of the key steps typically included in analyses rather than prescriptive. Most studies would involve similar steps and expertise.



In addition to the framework presented here, additional steps may be appropriate, for example considering whether other factors could have changed vulnerability or exposure, such as deforestation. Further experience in health D&A studies will refine the framework. This might include the development of standard approaches for incorporating adaptation and location- and population-specific vulnerabilities.

6. Guidelines

A checklist is provided for analyses to attribute human health outcomes to climate change.

6.1 Work jointly across disciplines to define the research question/ intent

The research question frames all subsequent choices made. What specifically the study is set to achieve will determine who is involved, the methods used in climate and health analyses, the data required, the causal links identified, and how the results are communicated, etc. (Otto 2017; van Oldenborgh et al., 2021).

6.2 Establish a transdisciplinary analytic team

The analytic team should include researchers with a foundational training in climate science with expertise in attribution methods, health scientists with relevant expertise, adding other disciplinary scientists or skill sets as needed to ensure the team has sufficient breadth and depth of expertise in the research disciplines and region(s) of interest (e.g., Perkins-Kirkpatrick et al. 2025). Potential candidates include statisticians or scientists trained in applying statistical approaches elsewhere such as economists for method development, agricultural scientists for climate change-health impacts relating to food production or hydrologists for climate change-health impacts mediated via water safety and security, Indigenous Knowledge holders for climate-health impacts on Indigenous Peoples, etc. (e.g., Redvers et al. 2023). An example is Perkins-Kirkpatrick et al. (2025), who developed a multi-disciplinary team to attribute heatwave-related mortality from the 2009 Victorian heatwave to climate change.

6.3 Meaningfully engage communities of practice, partners from affected communities and representative decision makers to inform study design and enhance policy relevance and uptake. Early engagement of communities and people likely affected by the event/trend and of local health authorities who will take action will ensure their perspectives are incorporated into the study design and the practical utility of the analyses maximized (e.g., Berry et al. 2018). This approach is increasingly used by some health-oriented funders in their grant-making and research priority setting processes.

6.4 Identify, illustrate, and describe causal linkages in an evidence-based causal pathway linking exposure to weather/climate variables to the health outcome(s) of interest.

The analytic team and partners should collaboratively develop a framework illustrating the drivers of the health outcome of interest, including the meteorological exposure (e.g., daily maximum temperature, or changes in the start of the heat season), and assess the evidence for detection of a climate signal for that health outcome. Causal relationships should only be assumed from exposure-response relationships with a clear theoretical basis, not just from correlational analyses between a weather variable and health outcome. Plausible mechanisms for observed results need to be described and quantified to the extent possible. The socioeconomic and demographic contexts (e.g., changes in age structure, poverty levels and the physical environment of urban and rural areas, including factors that may modify exposure-response relationships like green space or access to air conditioning) should be described, including changes over time. For example, Burden of Proof method (Zheng et al., 2022) is one of several standardized approaches that may be useful for assessing and reporting the strength of causal evidence for a disease pathway.

A key area for improvement is understanding the factors that affect the relationships between climatic stressors and observed health outcomes. A large part of the empirical literature studying climate change impacts on human health includes limited consideration of the socioeconomic and environmental factors that likely modify climate change-health pathways such as income and wealth, gender, quality of housing stock, access to electricity, and access to health care (Dasgupta and Robinson, 2024). Focusing on leverage points can help with untwining the multiple factors influencing climate change-health pathways.

Another area for improvement is incorporating multiple health outcomes that could be associated with exposure to extreme weather/climate events. For example, heatwaves can be associated with increased exposure to wildfire smoke; these joint exposures then can exacerbate health impacts (e.g. Masri et al. 2022). The co-occurrence of compound extreme temperature and air pollution events in Europe demonstrated spatial disparities, which has implications for developing targeted and effective adaptation strategies (Chen et al. 2025). Improved health D&A of joint exposures requires detailed weather and climate data, understanding of the atmospheric processes leading to the joint exposures, and appropriate health data for the independent and joint exposures.

6.5 Define the exposure event (or trend), evaluate the climate model(s) skill, and quantify attributable changes in health-relevant meteorological variables. To determine the contribution that climate change made to a health outcome, the plausible climate-related drivers of the health outcome of interest must be identified and used to define the event or trend of interest. This includes identifying the relevant meteorological variables; the geographic and temporal scales including the importance of antecedent conditions; whether changes in an event's intensity or return period will be the focus; changes in the start and end date of the event or season of interest; and the appropriate counterfactual in which the effect of climate change is excluded. Also, where possible, studies should develop additional scenarios to address the influence of other drivers that contributed to the health outcome of interest. This includes considering natural climate variability cycles such as ENSO events, monsoons, etc. and separating their influence on health outcomes from anthropogenic climate change (Haines and Lam, 2023). Health and climate data and model availability can affect the choices made.

The skill of the climate models should be evaluated in terms of their fidelity in capturing the appropriate, observed meteorological drivers. If the models are found to be biased, they should be bias adjusted (ISIMIP offers one such method; Lange et al. 2019), weighted and constrained, as appropriate. This will require evidence from relevant populations or models (e.g., physiological or epidemiological studies), with appropriate attention to generalizability and confidence intervals across the range of exposure values, to understand the relevant meteorological variables for analysis. Note that for many health outcomes, such as heat-related mortality, both events and trends are relevant, particularly when considering the distribution of potential confounders including socio-economic development patterns.

Ideally, multiple models are used to quantify attributable changes. Doing so strengthens the attribution statement. In extreme event attribution, it is now standard practice to use multiple climate models because the specific anthropogenic signal will vary across models, assessing results' robustness to model differences. Combining model results provides a robust attribution statement. A similar approach should be the aim for health D&A models, for example by combining an epidemiological model of heat-related mortality with quantification of excess deaths. These would provide different absolute numbers of deaths that, when combined qualitatively, strengthen the attribution statement.

6.6 Quantify attributable short- and long-term health impacts within the context of other determinants of exposure and vulnerability. Health data are often only available on a courser temporal and spatial scale than weather and climate data, requiring justification of necessary assumptions (Chapman et al., 2022). The burden of health outcomes changes over time as vulnerability, risk factors, and exposures change, and interventions to reduce the health burden are increasingly implemented. The ability of health models to capture the relationships between observed meteorological drivers and observed health impacts should be regularly assessed. Exposure-response relationships should be calculated and used at spatial scales representing the scale at which exposures are experienced.

Ideally, data are available on all factors that may affect vulnerability to both exposure (events and trends) or health outcomes. Where possible, data on population size and on characteristics that affect vulnerability to the exposure can inform meaningful counterfactual scenarios (e.g., age distribution to determine whether the proportion of the population above age 65 years increased over time, which would affect heat-related mortality). Data on other determinants of exposure can inform the analyses, such as air pollution data (or proxies) for analyses on heat-related or wildfire-related morbidity and mortality, particularly for socially and economically marginalized populations that could experience greater exposure or health impacts (e.g., changes in subpopulations in cities with less greenspace with more intense urban heat islands; political/social instability; or structure of or access to healthcare). The robustness of D&A studies would be improved by incorporating data on interventions implemented to reduce vulnerability, to assess the possible effects of policy measures. The effect of mitigation measures on climatic variables should be captured by attribution analyses, but the co-benefits of mitigation actions, such as reducing air pollution morbidity and mortality, would not be captured but might affect changes in vulnerability over time. Data that consider the extent to which other environmental stressors could modify climate and health relationships, such as areas where freshwater aquifers are depleted, also could improve the robustness and relevance of D&A studies.

Analyses should document the extent to which the incidence or prevalence of the health outcome of interest changed over time and any changes in the relationships between exposures and outcomes disaggregated by key population groups (e.g., gender, age, vulnerable and marginalized populations). Understanding the sensitivity of exposure-response relationships to changing vulnerability and exposure may inform appropriate adaptation approaches and indicate the consequences of a chosen adaptation approach. In instances in which exposure-outcome relationships are unavailable or cannot justifiably be applied to the exposure range being modeled, relationships can be estimated using statistical frameworks (e.g. Vicedo-

Cabrera et al., 2019; Gibb et al., 2023) if sufficient data are available for a valid assessment. Expert elicitation can be used to qualitatively estimate exposure-response relationships in some settings.

Models of relationships between weather/climate variables and health outcome are generally either empirical (statistical) or process-based (biological or mechanistic), each with strengths and weaknesses (Ebi 2022). Empirical models develop relationships between observations of exposure and response variables, often assuming a linear relationship. Challenges include data availability, accuracy, and length of time series. Further, observations of recent disease patterns implicitly incorporate the extent of effectiveness of control programs. Validated absence data are generally not available, which means these models may not accurately reflect the underlying relationship between an exposure and response. Mechanistic models use equations to describe the dynamics of disease etiology; challenges include poorly understood parameter values and the possibility of unknown processes. Describing the criteria to select one modeling approach over another would increase the transparency of the D&A analyses. Ideally, an ensemble of health impact models, employing a combination of statistical, machine learning and mechanistic modeling approaches could help capture different relationships and interactions between weather/climate and health outcomes and better quantify uncertainty around health outcome simulations.

6.6 Report the results, including a description of how the above recommendations were incorporated into the analytical plan. A synthesis document or peer-reviewed publication should describe the framework used to inform the analyses; the health, climate, and other data collected; efforts to align the data on the same spatial and temporal scales; consideration of other drivers of the health outcomes; and any counterfactual scenarios used. The analytic approaches should be described and justified. General study limitations and sources of uncertainty that could not be addressed should be described. The code developed to conduct the analysis should be published and archived in an open repository for scrutiny and reproducibility.

7.0 Discussion

Health D&A analyses can provide robust evidence to move from statements about current associations between weather variables and health outcomes to statements documenting the magnitude and pattern of current impacts of climate change on health and wellbeing. This moves the policy relevance of climate change within the health sector from a future consideration into the current mandate of ministries and departments of health. Further, D&A analyses provide a robust foundation for negotiations related to the Global Goal on Adaptation and to Loss and Damage, and for judicial adjudication in climate lawsuits.

Despite the opportunities, limited climate change and health attribution research has been conducted to date, with studies unequally spatially distributed (Carlson et al., 2024). The full range of methods from climate and health sciences have yet to be exploited. In addition, few regions and health outcomes have been analyzed in health D&A studies.

There is substantial methodological diversity and often insufficient characterization of the strength of causal evidence in pathways used for analysis. Explicit description of causal pathways and reporting of causal relationships will help address concerns related to causality, while collaborative partnerships with climate scientists would help address concerns related to situating attribution studies within continuously evolving approaches. Further, standards need to be developed for robust approaches for extrapolating data or relationships from one location to another, such as comparable climatic, demographic and socioeconomic structures, and health profiles. These standards would help scale up current analyses to provide a more comprehensive assessment of the impacts of climate change on health.

Using an equity lens to identify priority D&A analyses would ensure the results are useful to inform policies to protect people and regions at higher risk. To date, limited consultations with affected communities and people and with decision-makers reduces the application and relevance of D&A studies. Creating an expectation of, and providing support for, such consultation by funders and incorporating this consultation into timelines for proposals and analyses could begin to address this concern. For example, Dasgupta et al. (2024) note that civil society-led, city-based forums on heat and health could bring together multiple interested parties; such forums can facilitate wide-ranging consultations in a multi-disciplinary setting (also see Daly and Dessai, 2018). Important interactions between the frequency of extreme events, recovery times, depletion of resources for recovery, and changing thresholds for damage, such as compounding vulnerabilities from repeated extreme events, may be fruitful areas for exploration to inform decision-making (e.g., Young and Hsiang 2024).

Another critical need is generating best practices for incorporating adaptation into D&A analyses. Few studies have explicitly quantified the effects of adaptation. It is also valuable to assess changes in exposure-response relationships over time that may indicate the effectiveness of adaptation, particularly if linked to the implementation of associated policies. One example, not yet used in a D&A analysis, is an evaluation plan of the effectiveness of the English heatwave plan used time-varying exposure-response relationships to estimate the change in population sensitivity to heat before and after the plan was introduced (Williams et al. 2019). Although this approach does not allow for disaggregation of different causes of the changes in exposure-response relationships, it illustrates the effects of changing vulnerability and exposure over time. Incorporating such changes into a D&A analysis to account for fewer expected deaths would require quantitative evaluation of the system effectiveness to estimate the true number of climate change attributable deaths. Conducting D&A analyses at finer geographic scales can provide insights into impacts for different population groups, such as historically marginalized areas within a city (Smiley et al. 2022).

Generating insight into the impacts of climate change on health despite data limitations remains a critical challenge that must balance retaining robustness with ensuring that large knowledge gaps are not left in understudied regions (e.g., Vicedo-Cabrera et al., 2021). Limited weather/climate and health data pervades health attribution analyses in many regions that are presumed to be highly affected by climate change (Otto et al. 2020; King et al. 2023). Stable, long-term funding to ensure the continuous collation of high-quality weather/climate and health data must therefore be viewed as a necessity to improve understanding of climate-related health risks. Until then, an opportunity for further D&A analyses is developing applications to use mixed methods approaches that combine qualitative and quantitative data. In some settings, fully quantitative analyses are possible; in others, adequate and appropriate weather/climate and/or health data may be missing, permitting analyses on the climate driver alone, or on the health outcomes but not the contribution of climate change to their climate-related drivers (e.g., drought). Mixed methods approaches are being used to collect Indigenous and traditional knowledges and bridging them with Euro-western approaches to data analyses, which can provide valuable insights (Redvers et al., 2023).

Guidance is mainly of value if it is widely implemented, therefore research funders could consider following or advancing the proposed framework and guidance as a condition of funding (or in exceptional cases a strong justification for not following the guidance). Incorporation of guidance related to D&A studies and other approaches to building evidence related to climate and health in hubs such as the Equator Network (https://www.equator-network.org/) that supports reporting guidelines for health research studies could increase uptake. Journal editors, reviewers, and judges (in climate lawsuits) can also reinforce good practice by demanding high standards of evidence generation. The proposed guidance also can support good practice in doctoral training programs and short courses in research methods.

A growing understanding of the extent to which climate change is affecting health will become increasingly central to real-world decisions on investments into and prioritization of climate and health policies and programs. For example, during the one-week 2021 Pacific heat dome in the state of Washington, emergency departments were overwhelmed, with more than 440 excess deaths (Climate Impacts Group 2023) despite accurate forecasts with lead times of 10-20 days. This event that broke all-time maximum temperature records was virtually impossible without climate change (Philip et al. 2021). The resulting impacts led to a multi-agency extreme heat response plan being developed and deployed, including technical support for healthcare systems, cooling centers, and outreach to at-risk populations (Public Health, Seattle and King County, 2024). In another example, climate change is increasing extreme flooding in Africa, which interacts with conflict, poverty, and waste management to impact vulnerable communities, underscoring the need for strengthening transboundary early warning systems through data sharing and collaboration (Pinto et al., 2024).

Open science practices would support building a larger evidence base of health D&A analyses. For example, the Coupled Model Intercomparison Project (CMIP) was, from its start, committed to making climate model simulations publicly available (e.g. through the Earth System Grid Federation, ESGF). Likewise, the ISIMIP project is producing a portfolio of climate and socioeconomic data publicly available, enabling D&A studies across a range of impact sectors (Mengel et al., 2021). Climate and impact models are increasingly open source. Without such commitments to open science, scientific progress would be much slower, in terms of model evaluation, model improvement, and attribution applications. Moreover, open science facilitates reproducibility, a key component of credible impact attribution studies, which are increasingly used in high-stake applications such as global media coverage, international climate negotiations, policy development, and climate lawsuits. For example, the Working Group I contribution to the IPCC 6th Assessment Report used FAIR (Findable, Accessible, Interoperable, Reusable) data principles to facilitate open science by ensuring that the data and code used are findable and accessible and can be reused for reproducibility and for further developments using interoperable (Iturbide et al., 2022).

Fostering open science in health impact attribution studies is complicated because of national and sub-national data privacy regulations that determine who can gain access to what personal health data at what scale. These regulations are designed to protect individual privacy and have become increasingly stringent over time. The goal of these regulations is to ensure that it is not possible to identify an individual from anonymized data because of a rare condition or characteristic. Transdisciplinary research teams will need to develop strategies for merging health and weather/climate data taking these restrictions into account. Open access health data are generally annual across large geographic regions, which is generally not specific enough for D&A analyses. However, open science can be promoted by publishing articles fully open access with open-source code by researchers from high- and middle-high income countries, noting that this further disadvantages researchers from low- and middle-low-income countries. This critical bias needs to be addressed explicitly and quickly to ensure knowledge and insights gained from all sources are accessible by all, to strengthen resilience to further climatic change.

Rapid advances in D&A methods in climate and impact sectors means that guidance on conducting attribution analyses should be regularly updated by incorporating insights gained through experience, changes in data availability, modeling developments, and other advances. This would future proof the guidance and promote uptake and increase its utility. Periodic and perennial systematic reviews of attribution studies are needed to assess the changing magnitude and pattern of the health effects of climate change.

Checklist for attribution of human health outcomes to climate change

Define the research question

- Describe the event/trend of interest, including its geographic and temporal scale.
- State the study aims and objectives.
- Specify the target audience(s) including primary decisionmakers of interest.

Establish a transdisciplinary analytic team

- Include researchers with a foundational training in climate science with expertise in attribution methods, health scientists with relevant expertise at a minimum, adding other disciplinary scientists or skill sets as needed to ensure the team has sufficient breadth and depth of expertise. Provide a rationale for which disciplines should be included
- Include representatives from communities of practice, partners from affected communities, and decisionmakers, including experts on the region(s) of interest as relevant.
- Outline the causal links between the event/trend and health outcomes, including
    - Major determinants of susceptibility/vulnerability to climate change (e.g., population aging, socioeconomic status)
    - Effect modifying factors that may influence the climate-health relationship, including other environmental changes e.g. urbanization and other land use change.
- List and describe the data required and justify the analytic methods to be used.
- Establish a communication plan.
- Publishing the study protocol in advance of the analyses will improve research standards by promoting transparency, reduce publication bias, and enhance the reproducibility of study design and analysis.

Establish a plan to meaningfully engage with communities of practice, partners from affected communities and representative decision makers as the analyses are conducted

- Describe strategies to facilitate appropriate engagement with interested parties and communication with the target audience. Early engagement of communities and people likely affected with ensure their perspectives are incorporated.

Identify, diagram, and describe causal linkages in an evidence-based causal pathway linking exposure to weather/climate variables to the health outcome(s) of interest

- Develop a framework illustrating the drivers of the health outcome of interest, including the meteorological trigger where relevant and assess the evidence for detection of a climate signal for that health outcome.
    - Use causal relationships based on rigorous research describing exposure-response relationships at appropriate spatial and temporal scales, accounting for lagged effects where appropriate
- Describe and quantify plausible mechanisms for observed results, to the extent possible.
- Describe the socioeconomic and demographic contexts (e.g., changes in age structure, poverty levels) and changes in the physical environment of urban and rural areas, including changes over time that could affect the health outcomes of interest.

Define the exposure event (or trend), evaluate the climate model(s) skill, and quantify attributable changes in health-relevant meteorological variables

- Determine the contribution that climate change made to the health outcome. This includes identifying the relevant meteorological variables; the geographic and temporal scales including the importance of antecedent conditions; whether changes in an event's intensity or return period will be the focus; (changes in) the start and end date of the event or season of interest; and the appropriate counterfactual in which the effect of climate change is excluded
- Justify why the attribution approach used (for instance, probabilistic or storyline methods; presenting results as changes in intensity and/or probability) is appropriate for the impact pathway being studied.
- Where possible, develop additional scenarios to address the influence of other drivers that contributed to the health outcome of interest., such as natural climate variability exemplified by El Niño events.
- Evaluate the skill of the models in terms of their fidelity in capturing the appropriate, observed meteorological drivers. If model biases are identified, they should be bias corrected, weighted and constrained, as appropriate.
- Use multiple climate models to quantify attributable changes where possible, to strengthen the attribution statement and reduce results' sensitivity to a single model.
- Describe and analyze sources of uncertainty that could not be addressed quantitatively.

Quantify attributable short- and long-term health impacts within the context of other determinants of exposure and vulnerability

- Ideally, health data can be collected on the same temporal and spatial scales as exposure variables, although that is uncommon in practice.
  - For health data at coarser temporal and spatial scales than weather and climate data, justify necessary assumptions.
- Describe and justify exposure-response functions used.
  - Where possible, describe how these functions vary among vulnerable and marginalized populations.
- Define and justify the health metrics used, such as mortality, disability-adjusted life years lost, and years of life lost.
- Define and justify the data sources used.
- Assess the ability of the health model(s) to capture the relationships between observed meteorological drivers and observed health impacts.
- Where possible, use data on population size and on characteristics that affect vulnerability to the exposure to inform meaningful counterfactual scenarios (e.g., age distribution to determine whether the proportion of the population above age 65 years increased over time, which would affect heat-related mortality).
- Include data on other determinants of relevant exposures to inform the analyses, such as air pollution data (or proxies) for analyses on heat-related or wildfire-related morbidity and mortality.
  - Take into account the possible effects of adaptation and mitigation measures on exposure-response relationships.
- Document the extent to which the incidence or prevalence of the health outcome of interest changed over time and any other changes in the relationships between exposures and outcomes among vulnerable and marginalized populations. In instances in which exposure-outcome relationships are unavailable because of data limitations or cannot justifiably be applied to the exposure range being modeled and so need to be extrapolated, the assumptions used should be clarified and sensitivity testing employed to assess the effects of varying assumptions.
- Describe and analyze sources of uncertainty that could not be addressed quantitatively.

Report the results, including a description of how the recommendations were incorporated into the analytical plan

- A synthesis document or peer-reviewed publication should describe the framework used to inform the analyses; the health, climate, and other data collected and their sources; approaches to align the data on the same spatial and temporal scales; consideration of other drivers of the health outcomes; and any counterfactual scenarios used. The analytic approaches should be described and justified. General study limitations and sources of uncertainty that could not be addressed quantitatively should be described.

Data and Code Transparency

- Where possible, openly and publicly share data and code to facilitate open science.
    - Legal or ethical limitations to data sharing should be explicitly stated.

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