

# The need for multi-method extreme event attribution

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## Introduction

Extreme event attribution (EEA) seeks to link observed extreme weather events to specific causes, to understand and quantify the contribution of human-induced climate change. There are two key motivations behind EEA: contributing to collective knowledge, and societal applications such as climate litigation or infrastructure design (Jézéquel *et al.*, 2024).

Initially, EEA studies used a probabilistic framework, unconditioned on the dynamics of the actual event, assessing the return period of exceeding a specified threshold (in magnitude) in present and preindustrial climates (Philip *et al.*, 2020). Over the past two decades,

many complementary methods have been developed. The range of available EEA techniques enables us to address specific questions related to different characteristics of an event, as each method offers distinct benefits and limitations. It has been shown that methodological differences can lead to seemingly contradictory results (Dole *et al.*, 2011; Rahmstorf and Coumou, 2011; Otto *et al.*, 2012; Sippel *et al.*, 2024). By employing multiple approaches, we can enhance confidence in findings by providing complementary lines of evidence or investigating contradictory results. As noted by Shepherd (2016) the most useful method will depend on the specific research question, but we must also consider the confidence in results.

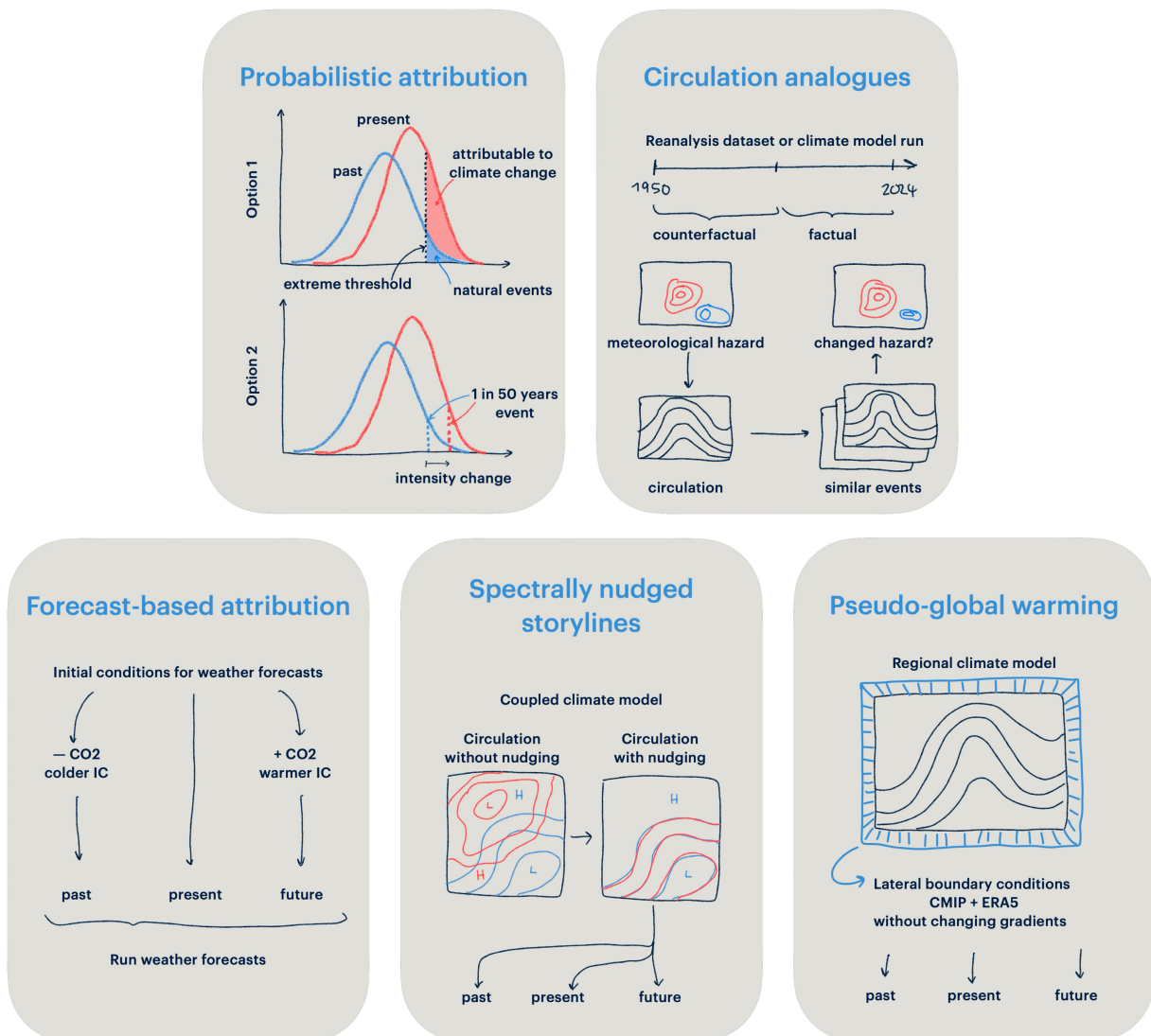


Figure 1. Outlines of the EEA methods discussed here. IC = initial conditions, CMIP = coupled model intercomparison projects, ERA5 = fifth generation ECMWF reanalysis, H/L = high/low pressure.

Here, we outline several key attribution techniques (Figure 1). We discuss their differences and highlight important considerations when combining results from such diverse methods. We provide recommendations to foster collaborative progress in the community, emphasising the complementary value of approaches as collectively informative rather than mutually exclusive.

## Existing attribution methods

EEA methods generally fall within two groups: unconditioned probabilistic and conditioned storyline methods. Probabilistic attribution considers the overall change in an event class, while storyline attribution examines how a specific extreme event would unfold in a different climate (Shepherd, 2016). We will later argue that existing methods fall within a spectrum (see ‘Considerations in Comparing Methods’ section).

We outline here a selection of the available EEA techniques (Figure 1) acknowledging that this list is not exhaustive. Notably, dynamical storylines (Zappa and Shepherd, 2017) – an early type of meteorological storyline – are designed to characterise physically plausible mean changes in selected climatic properties (e.g. precipitation or temperature over a specific region) rather than attribute particular observed extreme events. While this approach predates the nudged storylines, it is less directly targeted to EEA, and it is thus not included here. Other approaches comprise Granger-causal attribution (Risser *et al.*, 2025), and recent methods still under development, such as machine-learning-based techniques (Pérez-Aracil *et al.*, 2024) and reanalysis-based storylines (Hawkins *et al.*, 2023).

### Probabilistic

Probabilistic attribution asks how a class of events has changed in likelihood and, equivalently, how an event of fixed likelihood has changed in magnitude (Figure 1). This class of events is usually defined by the meteorological hazard – such as temperature or rainfall – over a specific region and time-

scale and often within specific months (van Oldenborgh *et al.*, 2021). It can be applied to both observational data and climate models, often utilising large ensembles. Probabilistic attribution can be performed quickly, and applied to many event types. It forms the cornerstone of rapid attribution studies published by World Weather Attribution, which provide timely assessments of high-impact extremes (Philip *et al.*, 2020).

This method does not consider how an event unfolds; thus, events that are dynamically different may be grouped together. This could be an advantage: if the hazard is equivalent, the precise dynamic pathway may seem secondary. However, it restricts the method’s ability to disentangle specific drivers of events. As a result, probabilistic methods have a tendency to falsely rule out the influence of climate change. This has helped motivate the development of additional attribution methods.

Additionally, probabilistic attribution methods can deem the most extreme events to be impossible in the current climate despite their observed occurrence (Thompson *et al.*, 2023; Zeder *et al.*, 2023), indicating limitations in the statistical methods.

### Circulation analogues

Circulation analogues assess changes in dynamically similar events over time by identifying comparable atmospheric circulation patterns (Figure 1). Characteristics of the analogues are assessed, such as intensity or spatial scale of pressure systems. This approach can be applied to observational data enabling a detection of change but cannot attribute the change (Faranda *et al.*, 2024b). Generally, reanalysis products are used, and so a key advantage of this method is the utilisation of readily available data sources. It can also be applied to large ensembles of climate models such as future projections (Thompson *et al.*, 2024), or using a single forcing large ensemble which enables attribution of change. By comparing analogues from within time slices of known warming levels, relative contributions of thermodynamic and large-scale dynamics

can be quantified. To determine the best analogues several methodological decisions must be made. Sensitivity testing the analogue domain, atmospheric variable and choice of dataset is necessary – for instance, using too large a domain will lead to analogues less representative of the observed event, increasing uncertainty.

Circulation analogues rely on the premise that the event is characterised by the atmospheric circulation itself. This is true for temperature extremes, but not always, for instance, for hydrological extremes, for which convective processes and moisture sources also influence hazard.

### Forecast-based attribution

Forecast-based attribution uses operational weather forecast systems on medium-range (Leach *et al.*, 2024; Ermis *et al.*, 2024) and seasonal (Hope *et al.*, 2016; Wang *et al.*, 2021; Abhik *et al.*, 2023; Weisheimer *et al.*, 2025) timescales to model extreme weather events. Counterfactuals for the attribution comparison are created by modifying boundary conditions such as greenhouse gas concentrations and initial conditions in the ocean, land and atmosphere (Figure 1). As not all components of the climate system are modified, there may be an underestimation of the difference in meteorological hazards between climate states. Forecast systems are routinely assessed on their reliability, and their performance on individual events can be assessed immediately. Ensemble-based systems allow for uncertainty quantification.

After initialisation, forecasts run freely, which enables varied conditioning on the observed event, that is, how closely the forecast is following observed dynamics (Figure 2). Thus, forecast-based attribution lends itself to an analysis of dynamic and thermodynamic contributions to extremes from climate change. Due to the changes in the initial conditions, simulations can initially exhibit instabilities and model drift; therefore, it is useful to compare the response of the event at multiple lead times to improve reliability in the climate change signal.

Forecast-based attribution is, in theory, applicable to all events which are well forecast. It has been applied widely for extreme heat (Leach *et al.*, 2024), midlatitude windstorms (Ermis *et al.*, 2024) and fire weather (Hope *et al.*, 2019).

### Spectrally nudged storylines

This approach enables exploration of the evolution of a specific event in different climate states (Figure 1). Building on earlier applications to tropical cyclone hindcasts (Schubert-Frisius *et al.*, 2017), dynamic conditioning in spectrally nudged storylines is achieved by

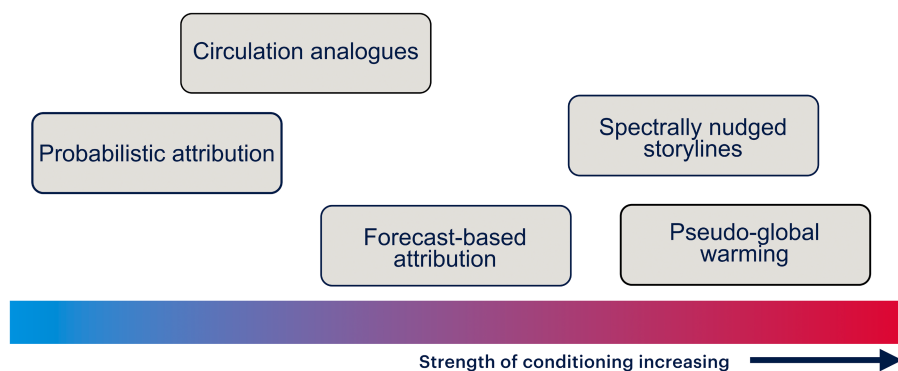


Figure 2. A spectrum of EEA approaches on a scale from low conditioning to strong conditioning.

partially imposing the observed wind evolution – typically from reanalysis data – into a climate model using spectral nudging (van Garderen *et al.*, 2020; Sánchez-Benítez *et al.*, 2022; Feser and Shepherd, 2025). Other variables, like temperature, moisture or ocean conditions, are left to evolve freely. These identical winds are imposed in both present-day and counterfactual climates, with most nudged storyline studies using initial states from CMIP-type free-running simulations to produce well-adjusted climate states at different warming levels. Holding circulation constant allows the storylines to isolate the thermodynamic effects of climate change on event characteristics such as intensity or spatial extent.

This method cannot assess changes in event likelihood or account for possible shifts in atmospheric circulation. Although thermodynamic changes usually dominate the climate change signal, uncaptured dynamic contributions may still play a role for certain regions or event types (van Garderen *et al.*, 2020). Nevertheless, for the same reasons, the nudged storyline approach is particularly well suited for extremes driven by large-scale dynamics, including heat (Sánchez-Benítez *et al.*, 2022; Athanase *et al.*, 2024a; Klimiuk *et al.*, 2025), large-scale precipitation (Athanase *et al.*, 2024b) and drought (van Garderen and Mindlin, 2022).

### Pseudo-global warming

Pseudo-global warming (PGW) explores how specific events could play out in different climates, by re-simulating present-day weather with regional climate models (RCMs) (Schär *et al.*, 1996; Brogli *et al.*, 2023) (Figure 1). The boundaries of the RCM are perturbed. This perturbation is typically derived from the future response of a climate model ensemble to include the mean circulation shift expected in a warmer climate, and constructed on a monthly scale for surface pressure, 3D temperature, humidity, and horizontal wind (de Vries *et al.*, 2024). As observed circulation changes are beginning to emerge in observational records – and often lie outside the range shown in models – deriving the circulation shift from a model ensemble invokes additional uncertainties. Within PGW, an ensemble approach can provide information on the uncertainty; the initial state can be perturbed by using different forecast realisations or lead times (Lenderink *et al.*, 2025). The initial conditions are then perturbed to alternative climate states.

During the simulation, the RCM adapts to the modified conditions, capturing part of the thermodynamic warming response (Schär *et al.*, 1996). The circulation in PGW realisations will be very similar across the different climates modelled.

## Considerations in combining methods

After an extreme weather event, climate scientists often seek to answer: What role did climate change play in this event? Had this event happened in the past, would it have been less severe? And how would it play out in a warmer future climate? This can be broken down further, into the specific characteristics of a given event, such as the following:

1. Changes in likelihood/frequency
2. Changes in intensity
3. Changes in duration
4. Drivers of these changes (long-term forcing trends and/or local processes).

No single method can address all of these, highlighting the need for multiple approaches. Combining methods can enhance confidence in conclusions and advance the collective understanding of the associated uncertainties.

Methods that are less conditioned on the dynamical set-up of the specific event, like probabilistic attribution, provide statements on changes in probabilities and thereby can address how (1) likelihood and (2) intensity of an event have changed. However, they cannot provide insights into the associated dynamics and driving processes. Because probabilistic methods are agnostic about event types, they have a tendency for falsely not attributing any climate change role – a problem that is addressed in conditioned methods.

Methods that are highly conditioned on the weather pattern of an event can assess how climate change influences the (2) intensity and (3) duration of an event – and their societal consequences when combined with impact modelling. However, as they assume fixed circulation, they cannot account for changes in likelihood or frequency, and are therefore limited to events primarily controlled by atmospheric dynamics. Many conditioned methods allow selective conditioning, such as keeping soil moisture unchanged while SSTs are altered. This not only reduces some uncertainties in the change of intensity, but can enable evaluation of (4) drivers of the identified changes in event characteristics.

Some methods allow for conditioning to be varied in other ways; for example, forecast-based attribution can be performed with a range of lead times. At longer lead times, the method may address how (1) likelihood changes, whereas at shorter lead times, the event becomes ‘locked in’, though (2) intensity changes can still occur. Similarly, analogues can be chosen with different levels of conditioning – that is, multivariate analogues will be more conditioned to the specific event than analogues based on only one atmospheric variable, or simply

using fewer analogues, which would likely be closer analogues but give reduced confidence in conclusions.

A clear understanding of user needs is essential to selecting appropriate methods – and adjustments within the methods – for each target application. For policymakers and climate litigation, it may not matter how an event unfolded, and thus probabilistic methods alone can provide useful information. To discuss adaptation to possible future climate change and advance process understanding, storylines may be more useful.

As alluded to already, EEA methods exist along a continuum of conditioning levels, rather than a binary classification (Shepherd, 2016; Coumou *et al.*, 2024). Along this spectrum, analogue methods are conditioned on circulation, as analogues are selected for their similarity in large-scale patterns. However, particularly when using observational or reanalysis data, the ‘best’ analogues exhibit a range of dynamical features. For exceptional events, few good analogues may be available, reducing the level of conditioning.

At the highly conditioned end, methods such as pseudo-global warming and spectrally nudged storylines can generate ‘near-perfect’ circulation analogues, changing only boundary conditions to simulate the same dynamical event in a different climate. These methods are thus strongly constrained – conditioned – by the imposed circulation. However, because of this fixed dynamical state, they may not represent events that are equally plausible in a warmer future climate, where mean circulation patterns may shift.

### Case Study 1: North America heatwave

In June 2021, an exceptional heatwave occurred in Western North America, leading to many environmental and societal impacts including ~500 deaths (Thompson *et al.*, 2022). The Canadian temperature record was broken by 4.6°C. The event has been extensively studied, including several attribution studies using a range of methods (Bercos-Hickey *et al.*, 2022; Philip *et al.*, 2022; Zhang *et al.*, 2023; Leach *et al.*, 2024). Here we consider how results from probabilistic, forecast-based and analogue techniques complement each other to address a range of research questions (Table 1).

Both probabilistic and forecast-based attribution were able to give an estimate of change in likelihood and intensity. However, probabilistic attribution found this event to be virtually impossible in a preindustrial climate, creating a major challenge in assessing the change in likelihood. Such extreme outliers highlight the need for multiple methods to improve our collective understanding. PGW could also estimate intensity change, finding

results consistent with forecast-based attribution (allowing for differences in preindustrial). Forecast-based attribution and PGW may provide smaller estimated attributable intensity

changes due to the model set-ups, as the models may not be fully adjusted to the new climate state. The model preindustrial perturbations in both FBA and PGW do not include

changes to all components of the climate system, and thus some non-linear interactions may not be fully realised. Both analogues and PGW explore the role of dynamics and climate

<b>Table 1</b>					
<i>Summary of the June 2021 heatwave attribution studies.</i>					
<i>Research question</i>	<i>Method</i>	<i>Event definition</i>	<i>Data</i>	<i>Counterfactuals</i>	<i>Key finding</i>
Has the likelihood changed?	Probabilistic (Philip <i>et al.</i> , 2022)	Daily maximum temp. 45–52°N, 119–123°W	ERA5	–1.2K, +2K	150× more likely
	FBA (Leach <i>et al.</i> , 2024)	Daily maximum temp. 45–52°N, 119–123°W	Global IFS model	–1.25K +2K	8× more likely
Has the intensity changed?	Probabilistic (Philip <i>et al.</i> , 2022)	Daily maximum temp. 45–52°N, 119–123°W	ERA5	–1.2K	2K hotter
	FBA (Leach <i>et al.</i> , 2024)	Daily maximum temp. 45–52°N, 119–123°W	Global IFS model	–1.25K	1.3K hotter
	PGW (Bercos-Hickey <i>et al.</i> , 2022)	Daily maximum temp. 45–52°N, 119–124°W	Regional climate model	–0.8K	0.8–1K hotter
How did dynamical processes influence the event?	Analogues (Zhang <i>et al.</i> , 2023)	7-day maximum temp. 40–65°N, 105–125°W	GHCN-D	1959–2021	50% attributable to heat dome
	PGW (Bercos-Hickey <i>et al.</i> , 2022)	Daily maximum temp. 45–52°N, 119–124°W	Regional climate model	–0.8K, +1.75K, +3.8K	Soil moisture conditions amplified event

*Note:* Counterfactual numbers refer to the difference in global temperature from present day, or the timeframe of data used.  
 FBA: forecast-based attribution; PGW: pseudo-global warming; IFS: Integrated Forecasting System; ERA5: fifth generation ECMWF reanalysis; GHCN\_D: global historical climate network daily.

<b>Table 2</b>					
<i>Summary of Storm Boris attribution studies.</i>					
<i>Research question</i>	<i>Method</i>	<i>Event definition</i>	<i>Data</i>	<i>Counterfactuals</i>	<i>Key finding</i>
Has the likelihood changed?	Probabilistic WWA (Kimutai <i>et al.</i> , 2024)	4-day accumulated rainfall over regions of Poland, Czechia, Austria, Romania, Hungary, Germany and Slovakia	Reanalysis, observations, climate models	–1.3K, +2K	Twice as likely
	Analogues WWA (Kimutai <i>et al.</i> , 2024)	–10–40°E, 30–60°N, Z500 4-day, 12–15 Sep.	Reanalysis	1950–2024	No change
Has the intensity changed?	Probabilistic WWA (Kimutai <i>et al.</i> , 2024)	4-day accumulated rainfall	Reanalysis, observations, climate models	–1.3K	7% wetter
	Analogues ClimaMeter (Faranda <i>et al.</i> , 2024a)	3–30°E, 42–55°N, SLP 2-day, 14–15 Sep.	Reanalysis	1979–2001 v 2001–2023	Up to 20% wetter
	Nudged storylines (Athanas <i>et al.</i> , 2024a)	12–16 Sep.	Global climate model	–1.3K, +4K	9% wetter
	PGW KNMI (de Vries and Lenderink, 2024)	14–15 Sep.	Regional model	–1.5K, +1.5K, +3K	7.5% wetter
Has the spatial area changed?	Nudged storylines (Athanas <i>et al.</i> , 2024a)	12–16 Sep.	Global climate model	–1.3K, +4K	Increase
	PGW KNMI (de Vries and Lenderink, 2024)	14–15 Sep.	Regional model	–1.5K, +1.5K, +3K	Increase
Has the intensity of the cut-off low changed?	Analogues ClimaMeter (Faranda <i>et al.</i> , 2024a)	3–30°E, 42–55°N, SLP 2-day, 14–15 Sep.	Reanalysis	1979–2001 v 2001–2023	Deepening

*Note:* Counterfactual numbers refer to the difference in global temperature from present day, or the timeframe of data used. In event definition, for analogues Z500 or SLP determines the variable used to identify analogues.  
 FBA: forecast-based attribution; PGW: pseudo-global warming; WWA: World Weather Attribution; KNMI: Royal Netherlands Meteorological Institute; SLP: sea-level pressure; Z500: 500 hPa geopotential height.

system interactions, enabling further insights into the event to be uncovered.

## Case Study 2: Storm Boris

Storm *Boris* hit central and eastern Europe in September 2024, bringing unprecedented rainfall magnitudes to large areas (Athanasé *et al.*, 2024b). The greatest impacts were felt across Austria, Czechia and Hungary. Rapid attribution assessments were produced by ClimaMeter (Faranda *et al.*, 2024b) World Weather Attribution (WWA) (Kimutai *et al.*, 2024) and KNMI (de Vries and Lenderink, 2024) within weeks of the event. A first peer-reviewed study estimated how the thermodynamic contribution of change affected the event, using event-based spectrally nudged storylines (Athanasé *et al.*, 2024b). Further work is still emerging, including multi-method studies (Riboldi *et al.*, 2025). Here we compare the four initial studies (Table 2).

All four studies provide an estimate for change in rainfall intensity since preindustrial, and all conclude that similar events are intensifying. Presenting multiple lines of evidence aids confidence in this finding, yet quantitative estimates differ (Table 2). Spectrally nudged storylines showed changes in vertically integrated water vapour and suggested a thermodynamically driven increase in air ascent, adding mechanistic understanding to the statistical statements from probabilistic methods. The storyline approaches (spectral nudging and PGW) assess change in spatial magnitude – finding an expansion in the spatial scale of extreme rainfall in a warmer world.

Both WWA and ClimaMeter use circulation analogues, with WWA showing no change in analogue frequency, while ClimaMeter finds an increase in the intensity of both the cut-off low-pressure system and rainfall. Without a clear statement of research questions, this could be seen as a contradiction. Yet, WWA assesses whether similar dynamical events have changed in frequency, while ClimaMeter assesses whether the intensity of dynamically similar events has changed – and so both can be consistently accurate statements.

This case study exemplifies several of the challenges of combining methods. Multiple past and future warming levels are included, and a range of event definitions is used (Table 2). Even when two studies use the same method – circulation analogues, for WWA and ClimaMeter – methodological differences such as domain size and atmospheric variable could have led to apparent contradictions in findings.

## Recommendations

During the 2025 EGU General Assembly, we hosted a splinter session bringing together experts in attribution methods to share

ideas on how to advance the field. The lively discussion, which exceeded room capacity with participants from various backgrounds and career stages, covered the strengths and challenges of both well-established and emerging approaches, opportunities for standardisation, and scope for collaboration. The popularity of the session demonstrated strong interest in developing a more connected community supporting multi-method attribution.

Strengthened exchanges between method users are fundamental to fostering multi-method understanding, intercomparisons and collaboration. Events such as this splinter meeting will support early sharing of results and discussion of challenges, enhancing productivity and impact of the attribution field.

We need more multi-method attribution studies, since few have been undertaken. Interpreting differences between methods can be complex. Managing such a study presents challenges beyond single-method assessments that can typically be carried out within one institute. Yet these efforts are worthwhile: they improve our understanding, and presenting multi-method findings within a single report can greatly aid EEA communication of robust findings to the public, reducing the possibility of apparent conflict from misunderstanding.

Clearly defining both conditioning and questions addressed for each method can help interpretation of multi-method results. Efforts should be made towards more uniform definitions of climate baselines. For instance, there is no standard definition of preindustrial: KNMI's future weather system uses 1.5°C cooler than present (Lenderink *et al.*, 2025), both World Weather Attribution and AWI storylines define preindustrial as 1.3°C cooler (Athanasé *et al.*, 2024b), and ClimaMeter defines past as 1950–1986 (Faranda *et al.*, 2024b). Similarly, warming levels for future simulations vary. Inconsistencies can occur in event definitions: assessments of the same event may use different regions or timescales, limiting the comparability of results.

A range of event types and geographical regions should be studied. Within the limited multi-method studies we are aware of, most are European events. While individual groups, such as World Weather Attribution, ensure that the event studied covers a range of event types and locations, this is also key for multi-method studies (Clarke *et al.*, 2023). Similarly, studies should not be limited to single hazard variables. Compound events, including multiple events within a season, warrant greater focus. Further exploration of how different methods perform in different contexts would be valuable.

It is essential to understand that no method is suitable for all event types. In the current, rapidly changing climate, unprec-

edented and record-smashing weather events are occurring with increasing frequency. The less heavily conditioned attribution methods are not suited for uncharted extremes: probabilistic attribution may suggest observed events are impossible, while analogue methods may not be applicable if too few dynamically similar events have occurred previously – highlighting the need for an informed decision of an appropriate method for each event.

Attribution of the impacts of extreme weather events is a rapidly expanding research area not covered here. As in the attribution of the events themselves, multiple methods are emerging – leading to a clear need for method comparison in the context of impact attribution.

In conclusion, combining methods within a single study is challenging, but essential for advancing EEA. Coproduction of multi-method assessments is key, enabling the development of event definitions that can be used across methods and consistent counterfactual baselines. Integrating conclusions from several lines of evidence has the potential to overcome limitations of individual methods, providing more comprehensive information better suited to policymakers, the public and the climate science community.

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## Author contributions

**Vikki Thompson:** Conceptualization; writing – original draft; writing – review and editing. **Shirin Ermis:** Conceptualization; writing – review and editing; writing – original draft; visualization. **Marylou Athanasé:** Conceptualization; writing – original draft; writing – review and editing.

## Conflict of interest statement

None.

## Data availability statement

No new data have been generated as part of this research.

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