COMPASS

Report on recommendations for attribution methods suitable for compound events with damaging impacts

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Executive summary

The aim of this report is to provide recommendations for attribution methods suitable for compound events with damaging impacts, with a preference for methods that are easily transferrable for a range of event types and regions. There are currently a wide range of methods for univariate extremes, many of which are used for operational attribution, but there are far fewer studies and methods for compound events such as those of a spatially compounding, temporally compounding, multivariate or pre-conditioned nature. This report draws upon on the learnings from the COMPASS Phase 1 Use Cases in Work Package 4 through *D4.1 'Hazard and Impact Synthesis and Attribution for Phase I use case'* and incorporates the collective experience of the use case authors. The use cases attribute impacts of compound events, including assessment of exposure and vulnerability in addition to the hazard. This deliverable also builds upon learnings from WP2 (Attribution frameworks in a physical context) and builds upon D2.5: 'Report documenting the developments in conditional attribution and results from initial application' (Cotterill et al., 2026).

The report finds four common themes for compound attribution methods. Firstly, the strong benefit of impact attribution for complex extremes, where many variables can be combined to produce one set of impacts. Hence bypassing many of the statistical challenges faced when going from the attribution of a single variable to multiple variables, but it is also beneficial given the difference in attribution results found in many of the use cases between when impacts are modelled and when just the hazard is modelled. Secondly, the COMPASS use cases highlight the benefit of modelling multiple hazard variables compared to just a single hazard, with the inclusion of the compounding nature of the event shown to amplify impacts in many of the use cases. Thirdly, there are challenges around the impact attribution of compound drought-heatwaves, with many different impacts all requiring different hazard models that in many cases are not openly available. This was less of a problem for compound flood-based events. The fourth theme was the importance of including exposure and vulnerability assessments and their role in how changes in the hazard due to climate change are being translated into societal impacts

Recommendations are provided for attribution methods applied to events with damaging impacts for each of the four categories of complex extremes; multivariate, temporally compounding, spatially compounding and preconditioned (Zscheischler et al., 2020) for different event types. These are based on the feedback and experience of the use case authors, the common themes identified and the transferability and ease of implementation of the methods to different event types and regions. These are general recommendations for the most suitable method; however, to improve confidence in the results a wide range of methods should ideally be used for the event in question. Furthermore, different attribution methods answer different questions about the event in question. Therefore, we encourage stakeholder engagement at an early stage in order to guide the choice of method to produce the most useful output.

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Glossary

Anthropogenic Climate Change: Long-term increase in global mean temperatures resulting from human activity

Climate Change: Long-term increase in global mean temperatures driven by human activity including natural factors

Climate Counterfactual: What the climate would have looked like without some or all human influence on the climate. Could be representative of a pre-industrial climate or a climate in the past (i.e. 1950 baseline).

Temporally compounding: A succession of hazard events leading to amplified impacts

Spatially compounding event: Co-occurrent hazard events at different locations, the combination of which leading to amplified impacts

Preconditioned event: Pre-existing climate condition in combination with a hazard leading to an amplification of the impacts of the hazard

Multivariate nature: Multiple hazards or meteorological extremes at the same location leading to amplified impacts

ERA5: Reanalysis v5 produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020)

Exposure: Population or assets exposed to an extreme event

Vulnerability: Susceptibility of people/assets exposed due to socio-economic and environmental factors

SST: Sea Surface Temperatures

1. Introduction

The main aim of the COMPASS project is to create a harmonised methodological framework for compound impact attribution. Hence bridging the gap from single-hazard drivers to multiple hazard drivers, hazard only attribution to impact attribution, and attribution of climate only to attribution of climate, exposure and vulnerability. The aim is for the flexible framework to be able to be applicable to a range of event types for a range of locations, in terms of the hazard data, the impact modelling chain and exposure/vulnerability datasets. In this report, we provide some recommendations on methods for compound extremes with damaging impacts, based on the work carried out so far. The COMPASS phase 1 use cases covering a range of complex extremes and locations such as East Africa, Honduras, France and United Kingdom were completed as part of ***D4.1 Hazard and Impact Synthesis and Attribution for Phase I use case*** (Jack et al., 2025). A second phase of use cases will be carried out in as part of ***D4.4 Storylines connecting hazard, exposure, vulnerability and impacts to decision making for Phase II***. In this report we are able to incorporate the learnings from the first set of use cases, with the leading author of each use case providing input into this report on method recommendations.

Given the range and type of complex extremes, the method recommendations for one type of compound extreme may not be suitable or applicable to other types. Hence, in this report we refer to complex events using the four categories of compound extremes introduced in the Zscheischler et al., 2020 review article, i) Multivariate, ii) Spatially Compounding, iii) Temporally Compounding, and iv) Preconditioned. Descriptions of each are given below:

- ***Multivariate:*** This occurs when multiple hazards occur at the same location lead to an amplified impact, examples of this are strong winds and extreme rainfall occurring from tropical cyclones, or compounding heatwaves and drought from atmospheric blocking (Zscheischler et al., 2020). It can also include compound flooding, such as a combination of two or more of coastal/pluvial/fluvial flooding.
- ***Spatially Compounding:*** This occurs when more than one location is impacted by hazard(s) at the same time, resulting in higher impacts than if it were to occur at only one of the locations (Zscheischler et al., 2020). Examples of this include multiple regions producing the same crop experiencing drought (hence crop shortage), or nearby regions both experiencing flooding (more challenging for emergency services/evacuation).
- ***Temporally Compounding:*** This occurs when there is a succession of events such as multiple heatwaves or storms in a row, results in increased impacts compared to the impacts from a single event occurring on its own (Zscheischler et al., 2020).
- ***Preconditioned:*** This is where a pre-existing climate driven condition, in combination with at least one hazard has led to a bigger impact, than without the initial condition (Zscheischler et al., 2020). This could be the saturation of soil before a flooding event, where high soil moisture from previous rainfall has exacerbated the flooding event during more recent extreme rainfall.

All of these categories are covered by the six Phase 1 Use Cases (P1UCs), and in many use cases multiple categories are covered. Zscheischler et al., 2020 does note that these are subjective to some extent and some compound events can fit into multiple categories.

The following section of this report summarises the methods used in each of the P1UCs, for the hazard counterfactual, impact modelling chain and attribution of exposure and vulnerability, alongside the key results and transferability/challenges of the methods to other regions/event types. Section 3 picks up the major themes found across the UCs for compound impact attribution methods, with section 4 providing specific recommendations of methods and frameworks suitable for compound event attribution with damaging impacts, and suggestions of ways forward. Finally, the lessons on attribution methods for compound event attribution with damaging impacts are summarised in section 5.

2. Methods Used in Impact Attribution Use Cases

2.1 Phase 1 Use Cases

This report covers recommendations for attribution methods suitable for compound extremes with damaging impacts. There are two main choices to be made on suitable methodology. Firstly, which method is used to produce/represent the counterfactual climate for the hazard(s), and then secondly how this is translated to impacts. As was found while carrying out the use cases, the choices can be dependent on each other, depending on the complex extreme in question. There is also a third-choice option, on the method chosen to represent changes in exposure and vulnerability, alongside changes in the hazard from climate change. The choice of methodologies used in each of the Phase 1 Use Cases are briefly summarised in Table 1.

Table 1 Summary of attribution methodologies used in each of the Phase 1 Use Cases.

Event	Hazards	Hazard Counterfactual Method	Impact Modelling Method	Exposure and Vulnerability method
UC1 – Xynthia 2010 (France)	Wind, storm surge – coastal flooding (Spatial and Multivariate)	Coastal Flooding: long term trend sea-level rise and other variables Wind: *Method 1:* Extreme value analysis detrending ERA5 *Method 2:* Climate model factual and counterfactual ensembles	Coastal Flooding: Delft3D Storm Surge Model Windstorm: Wind speed damage function	Exposure: Compared to 1950's baseline using historic data (quantitively) Vulnerability: For coastal flooding component only, using 1950 protection levels compared to now (quantitively)
UC2a – United Kingdom winter storms (2013/2014	Rainfall, wind, storm surge, flooding (fluvial, pluvial, coastal) (Temporal and Multivariate)	Climate model ensembles in factual and counterfactual climate	Deltares compound flood modelling framework	Exposure: Using exposure dataset from 1870 (quantitative)
UC2b – United Kingdom drought heatwave (2022)	Drought, Heatwave Multivariate and preconditioned	Large climate model ensembles in factual and counterfactual climate conditioned on SST patterns in 2022	Impact metric using regression model	Exposure: Data with 1980 baseline (quantitative) Vulnerability: Qualitative analysis
UC3a – East Africa Cyclones	Wind, storm surge, rainfall,	Intensity uplifts from literature for wind, rainfall	Deltares compound flood	Exposure: Building Footprints (present-day)

Idai and Kenneth (2019)	flooding (fluvial, pluvial, coastal) Multivariate and spatial	(Clausius Clapeyron). Long-term trend in sea-level rise.	modelling framework (Deltares, 2026)	Vulnerability: Depth-damage curves
UC3b – East Africa Cyclone Freddy (2023)	Wind, storm surge, rainfall, flooding (fluvial, pluvial, coastal) Multivariate	Intensity uplift based on Clausius Clapeyron relation	Deltares compound flood modelling framework	Exposure: Building Footprints (present-day) Vulnerability: Depth-damage curves
UC4 – Tropical storms Eta and Iota in Honduras 2020	Rainfall, flooding (fluvial, pluvial) Multivariate (non-climate) Temporal	Intensity uplift based on Clausius Clapeyron relation	Deltares compound flood modelling framework	Exposure: Building Footprints (present-day) Vulnerability: Stakeholder Engagement (Qualitative)
UC3a (extended) – TC Idai , Mozambique	Wind, storm surge, rainfall, flooding (fluvial, pluvial, coastal) Multivariate	Climate storylines based on spectrally nudged climate simulations	Deltares compound flood modelling framework	*Not included*

Summaries of the event, methods used and results for each of the use cases based on material from D4.1 'Hazard and Impact Synthesis and Attribution for Phase I use case' (Jack et al., 2025) are described in more detail in the following sections. We also summarise extra material from the extension of UC3a, currently being produced as part of the Phase II UCs, and Use Case 5 which is part of work package 5 (WP5: Demonstrator with steps towards operational deployment). These also provide extra insight into the discussion on best attribution methods for compound events with damaging impacts.

2.1.1 Use Case 1: Storm Xynthia 2010 in France

Event: France experienced compound impacts from both widespread windstorm damage and coastal flooding on the 28th February 2010 brought about by Storm Xynthia. There were over 2.5 billion euros in damages and 47 fatalities. The impact attribution study analyses the impacts from climate change on both the windstorm aspect and coastal flooding individually. The event was both spatially compounding and of a multivariate nature.

Hazard method*:* Two hazards were considered: coastal flooding and extreme winds. For the coastal flooding: the counterfactual was produced by estimating and removing the long-term trend in sea-level rise since 1950, and for wind-speeds detrending the reanalysis data since 1950 using a transformed-stationary extreme value analysis methodology (tsEVA). When attributing Windstorm damage, two methods were used; the tsEVA (Mentaschi et al., 2016) approach (Method 1) and climate model factual and pre-industrial counterfactual ensembles using HadGEM3-A runs (Method 2).

Impact method: The coastal flood damage impacts were calculated by inputting ERA5 into the Delft3D hydrodynamic model to reproduce storm surge heights, combined with flood inundation maps for the impacted region. The windstorm impacts were calculated through a wind-damage function.

Exposure and Vulnerability: Exposure was calculated quantitatively both for the year of the event and for a 1950s baseline using historical economical and statistical data for the region, both for windstorm damage and coastal flooding. Vulnerability was also calculated quantitatively for coastal flooding using estimated regional vulnerability through multivariate vine-copulas (Paprotny et al., 2025a).

Key Results: The impacts of coastal flooding for the event have increased by 10-14%, due to climate change, with sea level rise since 1950 being the leading factor. The two attribution approaches to analyse windstorm damage showed an increase in economic damage by 22% for Method 1 and 7% (90CI: -71 to +44) for Method 2, in a warming climate. There is strong confidence that coastal flooding impacts have increased due to climate change, however, less confidence that windstorm damage has increased due to climate change due to the large uncertainty uncertainties. Increased exposure since 1950 led to a big increase in flood damages, with a decrease in vulnerability since 1950 partially counteracting this increase.

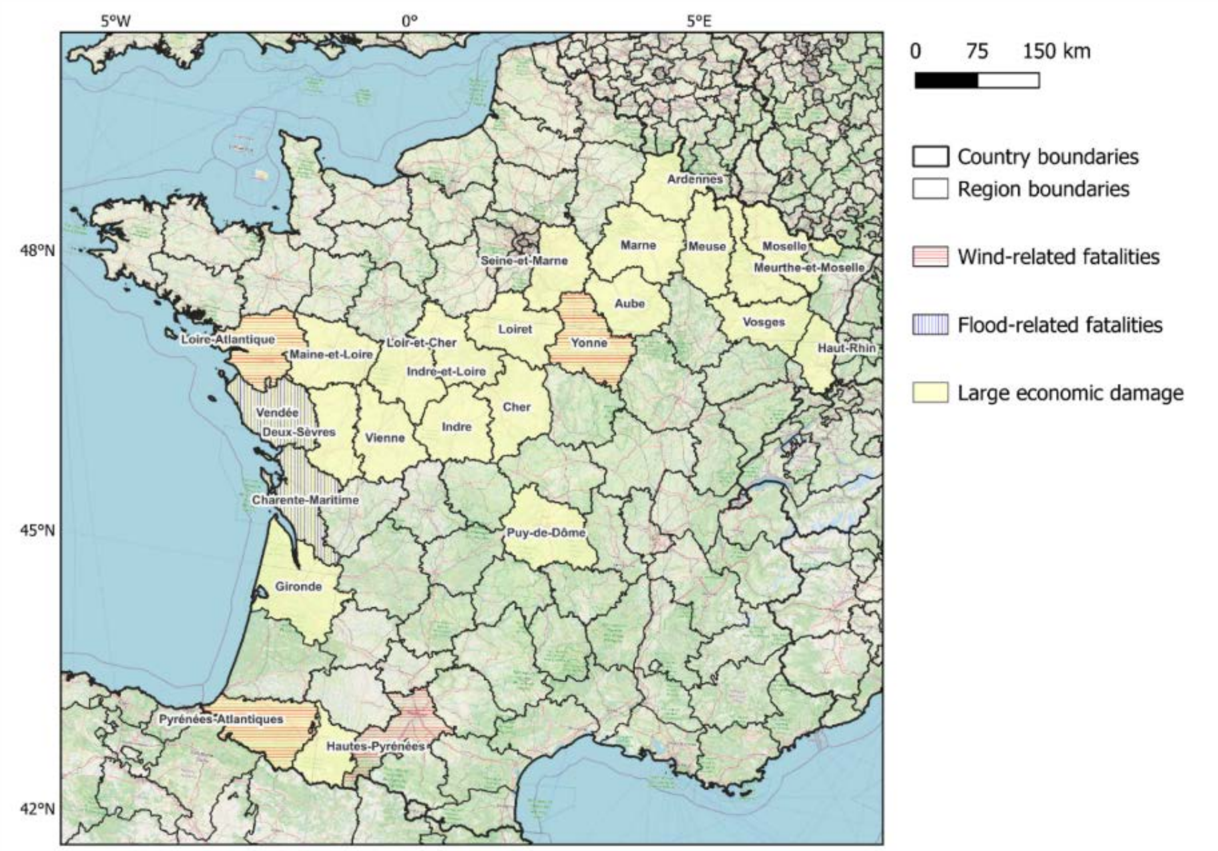

Figure 1 Map showing regions with fatalities and economic damage from Storm Xynthia in France 2010 due to both flooding and high winds (Source: Jack et al., 2025).

Transferability and challenges of method: The windstorm model relies on data from global datasets, in this case ERA5 (Hersbach et al., 2020) and/or the HadGEM3a attribution runs (Ciavarella et al., 2018) for the hazard. Similarly, global data was used for exposure combined with a generic damage modelling approach. This makes it transferable to other regions. The flood model was applied across Europe (Paprotny et al. 2025b) using mostly Europe-specific data, therefore it is well suited for European applications, but would require considerable adjustments outside the continent.

2.1.2 Use Case 2a: UK winter storms 2013-14

Event: During the winter of 2013/14 a series of at least 12 storms within a 3-month period (Kendon and McCarthy, 2015) lead to flooding of multiple types to the UK including pluvial, fluvial and coastal flooding. The economic cost from these storms reached £1.3 billion for England and Wales. The use case was focussed on the flooding of the Somerset Levels in south-west England, which included 30% of the flooded agricultural land in the UK over this time period. This event was both temporally compounding and multivariate in nature.

Hazard method*:* To simulate flooding from multiple winter events, climate model attribution runs (HadGEM3-A runs) for winter rainfall were used, for both a factual climate (2005-2024) and a counterfactual climate (pre-industrial) climate. These runs are conditioned on observed sea surface temperatures (SST), with the counterfactual ensemble members having the anthropogenic influence on SST and sea ice components removed (Ciavarella et al., 2018).

Impact method: This factual and counterfactual data were used as inputs to the Deltares compound flood modelling framework, which incorporates the wflow hydrological model for river flows and the SFINCS hydrodynamic model to model compound flooding. The initial river flows at the start of each winter are calculated using ERA5 hourly rainfall data from the year before. The output of the model contained flood depth maps at 90m resolution for each of the winters simulated.

Exposure and Vulnerability: Exposure changes due to population growth were calculated quantitatively using the HANZE v2.0 population exposure dataset. Vulnerability was not covered quantitatively for this use case.

Key Results: The magnitude of the flood extent over the Somerset Levels, was found to have marginally increased because of anthropogenic climate change, with the likelihood of exceeding that flood extent 1.21 times more likely in 2013/14 than in a pre-industrial climate. However, the results give large uncertainties (in the 95% confidence intervals between 3 times less likely and 4.5 times more likely). Increases in exposure as a result of population growth since 1870 is responsible for the biggest increase in impacts.

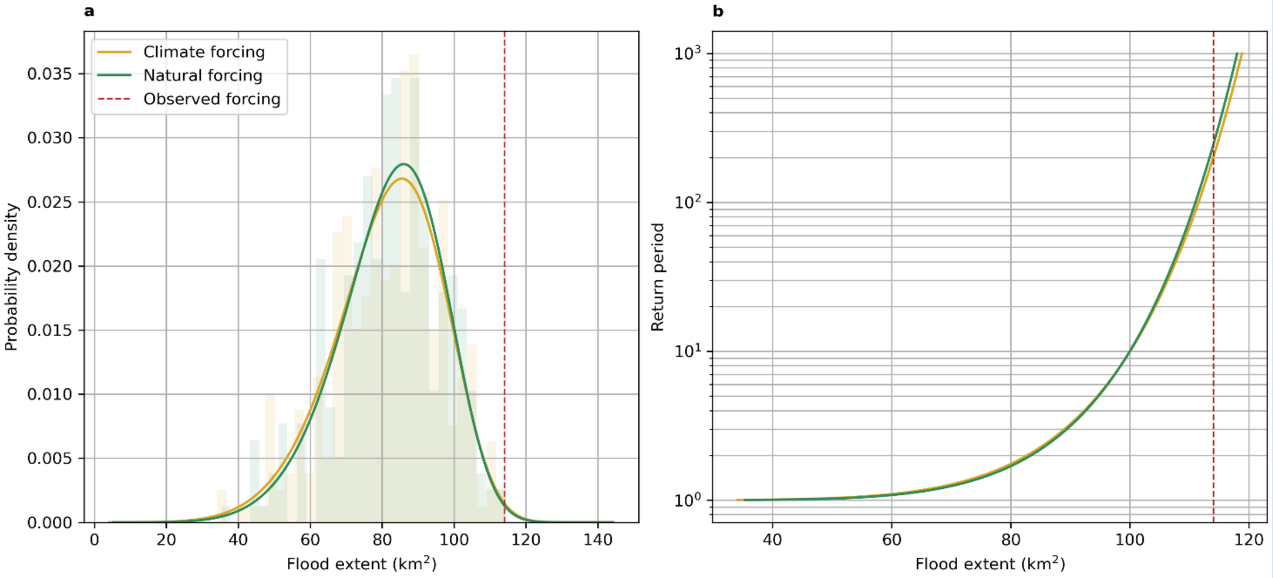

Figure 2 Impact attribution results for the 12 consecutive UK winter storms in 2013-14, showing a) the probability distributions for current (Climate forcing) and pre-industrial (Natural forcing) climates and b) the return period of the flood extent over the Somerset Levels in both climates (Source: Jack et al., 2025).

Transferability and challenges of method: These methods rely on data from global HadGEM3a attribution runs (Ciavarella et al., 2018) for the hazard. The impact attribution methodology uses the Deltares compound flood modelling framework which has been applied successfully to other locations such as Mozambique and Honduras. Therefore, both the hazard and impact modelling is transferable to other regions and types of compound flooding. There are however challenges around the resolution of the attribution runs (60km) when simulating flooding. The UK is also quite a data-rich region especially for terrain data and flood maps, but there may be more challenges when applying to regions with limited local data.

2.1.3 Use Case 2b: UK Drought-Heatwave 2022

Event: The UK experienced very dry conditions and multiple heatwaves during the summer of 2022, with temperatures exceeding 40°C for the first time. This occurred in combination with very dry conditions in the 6-months leading up to that summer. Impacts affected and included heat mortality (approximately 2227 excess deaths), wildfires, agriculture and national infrastructure. In this use case the impact of focus was the airport runway melting at Luton Airport leading to the cancellation of 100 flights. This compound event was both of a multivariate and preconditioned nature.

Hazard method*:* The hazard input data was 6-hourly average air temperatures between 7:30 am and 1:30 pm over Luton Airport. To compare factual and counterfactual (pre-industrial) climates a large ensemble (525 members) of climate model simulations (HadGEM3-A runs), conditioned on observed SST patterns from 2022 were used. The pre-industrial ensemble members have the anthropogenic influence on the sea ice components and SSTs removed based on long-term trends (Ciavarella et al., 2018).

Impact method: The impact metric and threshold were chosen through regression analysis of runway temperatures and local air temperatures over Luton Airport for a 20-year observation period.

Exposure and Vulnerability: Exposure changes since 1980 calculated quantitatively from historic passenger and flight numbers. Vulnerability examined qualitatively.

Key Results: The results show that anthropogenic climate change has increased the likelihood of the runway melting by a factor of 12, with the event as much as 32 times more likely and at least 6 times more likely. The intensity of an event with the same return period in the pre-industrial climate is unlikely to have been hot enough for the runway to melt. The results are in line with other research showing low soil moisture to be a preconditioning factor in the extremity of maximum heatwave temperatures. Increased exposure through usage of the airport; 531% increase in passengers since 1980, means that impacts were greater in 2022 than for an equivalent event in 1980.

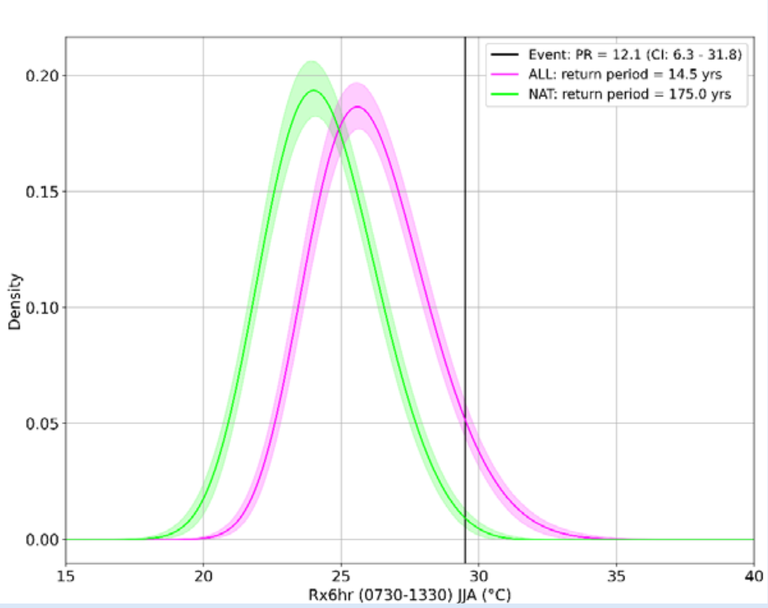

Figure 3 Distribution plot showing the probability of exceeding the impact threshold for runway melting at Luton Airport, in both the current (ALL- all forcings) and pre-industrial (NAT -natural forcings only) climate using large-ensembles (Source: Jack et al., 2025).

Transferability and challenges of method: The climate hazard factual and counterfactual large ensembles used global datasets. However, to estimate the impact threshold, local data was required and would need to be available at the location of interest and type of event to be transferrable. This method is suited for step-based impacts (above threshold = impacts, and below the impact threshold =no impacts).

2.1.4 Use Case 3a: Tropical Cyclones Idai and Kenneth 2019

Event: Two devasting Tropical Cyclones (TC), Idai and Kenneth hit Mozambique during the spring of 2019 within just 6 weeks. There were almost 1300 fatalities from TC Idai with around 3 million people impacted, as heavy precipitation and a combination of low-pressure and high winds brought about compound inland flooding and storm surges respectively. TC Kenneth also brought heavy precipitation, concentrated predominantly over coastal areas, leading to severe impacts for transport, people, and agriculture. The event was both of a multivariate (high-winds and rainfall) and temporally compounding (consecutive strong TCs) nature.

Hazard method*:* The counterfactual event was calculated by removing estimates of anthropogenic influence on each of the relevant hazard variables subtracted as a percentage from the observed event. The rainfall estimate used was reduced using the Clausius Clapeyron rate (7% increase per degree of warming), with wind speeds using the best estimate from the literature (10% reduction in max win speeds). The sea level was reduced by 0.14m in the counterfactual to take sea-level rise into account. TC Kenneth only examined inland flooding, whereas TC Idai included storm surges.

Impact method: The observed event was run through the relevant hydrological and hydrodynamic models in the Deltares compound flood modelling framework (Aleksandrova et al., 2024) using ERA5 and IBTrACS hazard data. The output of the hydrodynamic SFINCS model contained flood depth maps at 100m resolution for both the factual and counterfactual simulated event.

Exposure and Vulnerability: Exposure is calculated by using building footprints from OpenStreetMap (OSM) and population data from WorldPop. Vulnerability is calculated using depth-damage functions.

Key Results: Climate change is found to have increased damages by 29% and increased the population exposed to flood depths exceeding 20 cm by 18% for Storm Idai. The increase in damages was largely driven by sea-level rise increasing coastal flooding impacts in the city of Beira, with the increase in inland flooding contributing only a small fraction to the overall increase in impacts for TC Idai (Vertegaal et al., 2025). The study also shows that climate change increased the impacts from TC Kenneth with a 10% increase in population exposed to 20cm flood depths.

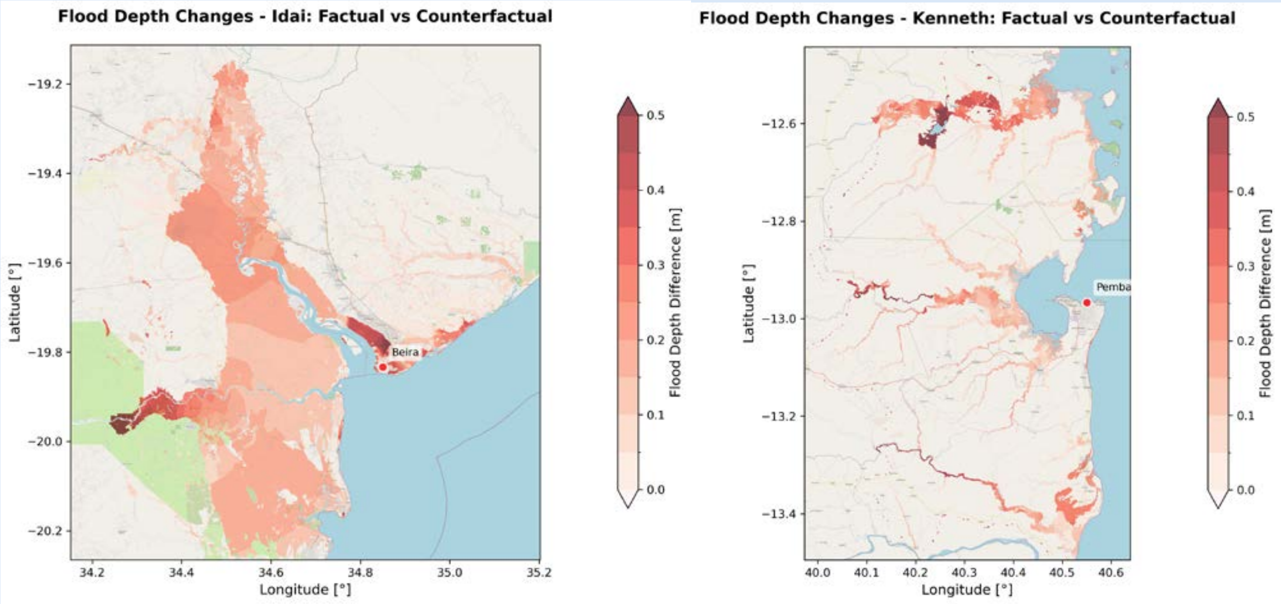

Figure 4 Flood depth maps for the difference between factual and counterfactual climate simulations for Tropical Cyclones Idai and Kenneth, where the left map shows the flood depth difference for TC Idai of the Factual – Counterfactual, and the right map showing the same but for TC Kenneth (Source: Jack et al., 2025).

Transferability and challenges of method: The method of producing the counterfactual event can be applied to any location, and the flood modelling framework has already been applied to other continents and hence is transferable. Currently, the compound flood modelling framework does not fully integrate large-scale and nearshore wave models that are needed to estimate wave dynamics on the coastal water levels (see Vertegaal et al., 2025). Wave setup can be estimated based on the ERA5 significant wave height, but this does not allow to produce a counterfactual. Therefore, care should be taken to apply the framework to a flood event where waves played a major role. Challenges lie around the quality of the input data (e.g. bathymetry and elevation) as well as the lack of validation data (e.g., rain and tide gauges), and the requirement for a detailed understanding of the local context in the choice of models used.

2.1.5 Use Case 3b: Tropical Cyclone Freddy 2023

Event: Tropical Cyclone (TC) Freddy brought extreme rainfall leading to widespread flooding in Mozambique in 2023. Freddy was one of the longest tropical cyclones on record- lasting 35 days. The resulting flooding impacted over 1.1 million people and destroyed almost 200 000 properties. TC Freddy struck Mozambique twice after regenerating in the Mozambique channel after it had already hit initially. It was of a multivariate nature with storm surges and high precipitation occurring simultaneously.

Hazard method*:* The methodology is the same as the one used in UC3a. The expected rainfall intensity change due to Clausius Clapeyron rate (7% increase per degree of warming) was applied to the observed event to produce the climate counterfactual, which was then simulated through the compound flood modelling framework.

Impact method: Both the observed and counterfactual events were run through the relevant hydrodynamic and hydrological models in the compound flood modelling framework using ERA5 hazard data (Aleksandrova et al., 2024). The output of the model contained flood depth maps at 100m resolution for both the factual and counterfactual simulated event.

Exposure and Vulnerability: Exposure is calculated by using building footprints from OpenStreetMap (OSM) and population data from WorldPop (Tatum 2017). Vulnerability is calculated using depth-damage functions.

Key Results: Climate change is found to have increased damages by 19% and increased population exposed to flood depths exceeding 20 cm by 13%. This is despite the 8% increase in rainfall intensity in the factual climate only leading to a 3% increase in flood extent simulated for TC Freddy.

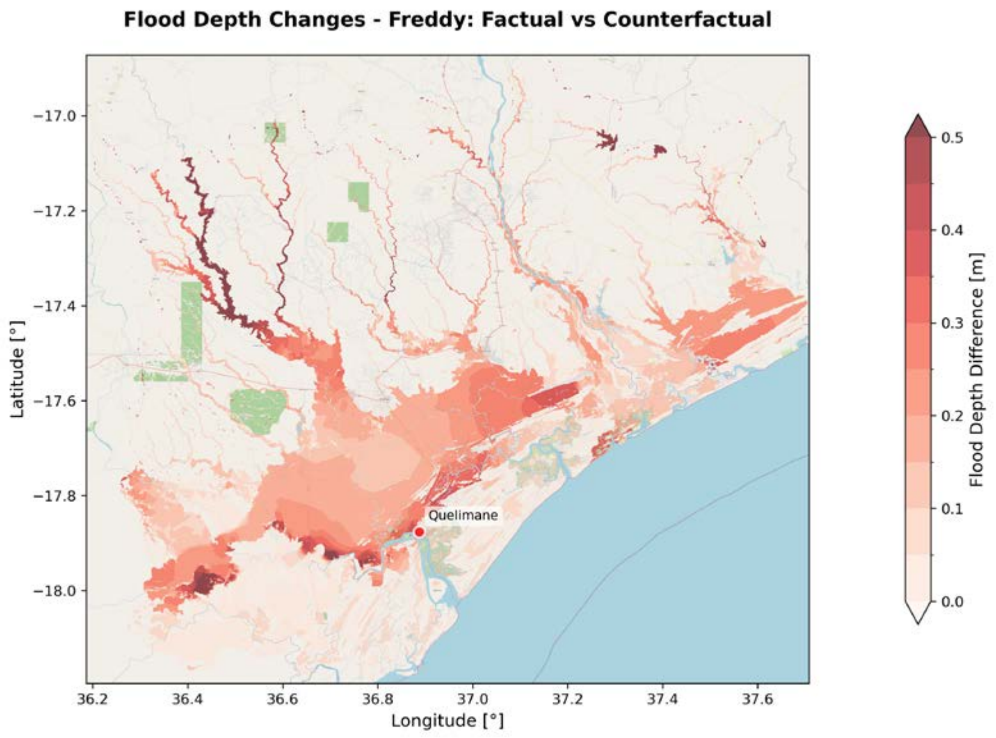

Figure 5 Flood depth maps for factual and counterfactual climate simulation for Tropical Cyclone Freddy (Source: Jack et al., 2025).

Transferability and challenges of method: The method of producing the counterfactual event can be applied to any location, and the flood modelling framework has already been applied to other continents and hence is transferable. This use case is an example of how the same method applied in UC 3a can be transferrable to another event. Challenges remain around the quality of the input data and lack of validation data, and the requirement for a detailed understanding of the local context in the choice of models used.

2.1.6 Use Case 4: Hurricanes Eta and Iota 2020

Event: Consecutive hurricanes within two weeks brought severe flooding to Honduras and other countries in the region in November of 2020, including landslides, flash flooding and riverine flooding. The hurricanes directly impacted just under half a million people, including 87 fatalities and 170 000 needing evacuation. This event was of a temporally compounding nature as Storm Iota (17th November) affected the same area, where there was extreme rainfall and consequent flood impacts from Storm Eta (4th November) 13 days earlier.

Hazard method*:* The climate counterfactual was produced using the observed event profile from ERA5, but with rainfall intensity reduced by 9% based on the Clausius Clapeyron rate (7%/degree of warming). Both hurricanes were included in the climate factual and counterfactual.

Impact method: Both the observed and counterfactual events were run through the relevant hydrodynamic and hydrological models in the compound flood modelling framework using ERA5 hazard data (Aleksandrova et al., 2024). The output of the model contained flood depth maps at 100m resolution for both the factual and counterfactual simulated event.

Exposure and Vulnerability: Exposure is calculated using population data from WorldPop and building footprint data from OpenStreetMap. Vulnerability is examined qualitatively through stakeholder engagement.

Key Results: The results showed that despite a 9% higher rainfall intensity in the event profile for the current climate, this did not result in significantly more flood impacts or a larger flood extent. The differences in population and building exposure were found to be minimal between simulations of the climate factual and counterfactual run through the flood modelling framework.

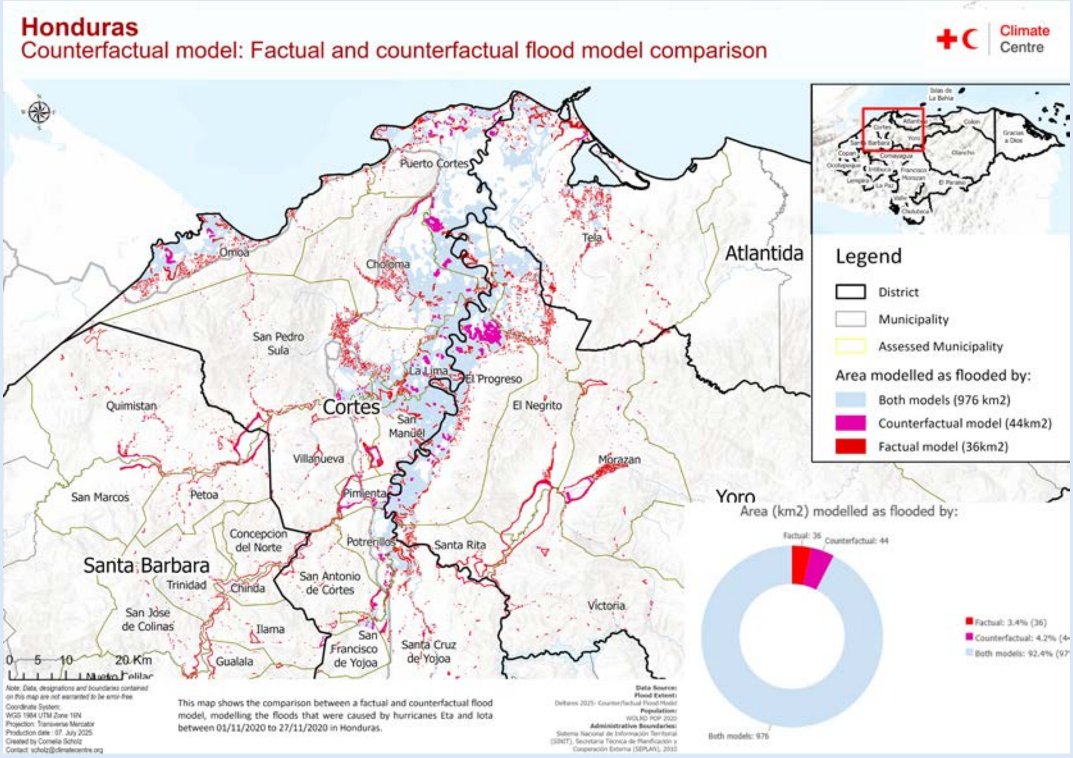

Figure 6 Flood extent comparison for factual and counterfactual climate simulations of Hurricanes Eta and Iota (Source: Jack et al., 2025).

Transferability and challenges of method: The method of producing the counterfactual event can be applied to any location, and the flood modelling framework has already been applied to other continents and hence is transferable. Challenges remain around quantifying uncertainty and the sensitivity of the assumptions made in the methodology.

2.1.7 Use Case 5: Drought-heatwave Poland

Overview and Methods: This Use Case is used as a testbed for scalable workflow developed in D5.1 Report on Integration and Datasets (Terefenko and Śledziowski, 2025) that aims to support compound impact attribution. The framework produced in this deliverable is supposed to be flexible and cover all types of hazard combinations, global datasets and approaches. The workflow will be demonstrated for Poland as an example of operational implementation. The Use Case 5 will develop an online demonstrator for compound drought and heatwave events. A model to estimate the effects of climate variability on crop yields in Poland will be performed on both the observed and counterfactual datasets. Counterfactual will be produced automatically using the data from ERA5. The report notes that although some of the process can be automated, collaboration including expert judgement and local data cannot be in some cases.

Transferability: The use case will demonstrate that attribution studies can be realized operationally on a daily basis. Proposed methodology will be transferable especially for preprocessing activities such as bias adjustment and downscaling as well as counterfactual data generation.

2.1.8 Extension of UC3a Tropical Cyclones Idai (Phase 2 Use Cases)

Event: Tropical Cyclone (TC) Idai hit Mozambique during the spring of 2019. TC Idai led to almost 1300 fatalities and impacted around 3 million people, as heavy precipitation and a combination of low-pressure and high winds led to compound flooding.

Hazard method*:* This use case is an extension of UC3a with the goal to test the climate storyline simulations provided by the Climate DT developed by Destination Earth (ECMWF, 2025). The ClimateDT provides kilometre-scale simulations of extreme events under counterfactual and factual conditions using spectral nudging. By fixing the large-scale dynamics, it is possible to replay what an extreme event would like with or without climate change.

Impact method: Using the same workflow as for UC3a, the factual and counterfactual storylines were run through the relevant hydrological and hydrodynamic models in the Deltares compound flood modelling framework (Aleksandrova et al., 2024). The output of the SFINCS model contained flood depth maps at 100m resolution for both the factual and counterfactual simulated event.

Exposure and Vulnerability: In this extension of UC3a, we did not include exposure and vulnerability.

Key Results: Results show a relatively clear large-scale climate signal with a 10% decrease in the 1-day peak rainfall in a counterfactual climate over the entire model domain when comparing the factual and counterfactual scenario (Figure 7). However, this change varies strongly depending on the temporal and spatial aggregation of rainfall. For example, the 3-day peak rainfall is decreased by only 2.4% in the counterfactual scenario. However, the change in rainfall varies spatially with some areas seeing decreasing whereas in other areas there is an increase. For tropical cyclone Idai, there were two main rivers that contributed to the flooding; the Buzi and the Pungwe. The simulations indicate that climate change drives an increase in rainfall over the Pungwe catchment, resulting in higher discharge, whereas the Buzi River catchment shows a minimal decrease. Consequently, flood depths increase in the Pungwe basin and decrease in the Buzi basin. These results therefore show differences from the method used for Phase 1 of UC3a, which shows an increase or no-change in flooding in all areas.

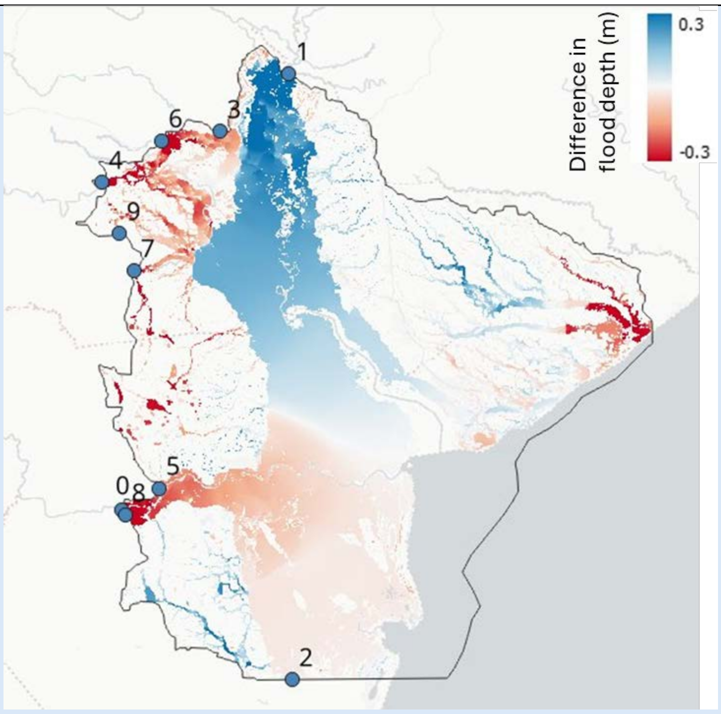

Figure 7 Map showing the difference in flood depth maps for factual and counterfactual climate simulation for Tropical Cyclone Idai, where blue represents higher flood depths and red represents lower flood depths. The black outline represents the SFINCS model extent, with the numbers indicating the discharge stations.

Transferability and challenges of method:
With respect to the compound flood modelling framework, see the text given at UC3a. With respect to use of the climate storyline provided by the ClimateDT, the global kilometre-scale simulations provide a promising new direction for impact attribution that could be applied to other regions and events. The fact that the event structure in term of tropical cyclone track hardly changes in the counterfactual simulations are beneficial for impact attribution. However, we were also faced with several challenges. The results show that the change in rainfall is not spatially uniform. When attributing the total amount of rainfall of the event, this is not a problem, however when used as input for hydrological modelling this is problematic since it alters the outcome. However, it remains unclear to what extent these differences arise from anthropogenic climate change versus internal climate variability. This could lead to spurious or contradictory results. Another limitation is that in these nudged simulations, large-scale winds are largely constrained, therefore the Climate DT cannot be used to attribute wind-driven hazards such as storm surges and waves. Methods needs be further developed to be able to provide meaningful results.

2.2 Coverage of Phase 1 Use Cases

The coverage of complex extremes included all 4 typologies of compound extremes, multivariate, spatially compounding, temporally compounding and preconditioned. A range of variables were also examined including sea-level rise, wind, soil moisture, heatwaves and extreme rainfall.

i. Multivariate:

- UC1: Storm surge from Storm Xynthia in France, includes multiple variables that can change in a warming climate including wind speeds and sea level-rise.
- UC3a Tropical cyclones are multivariate by nature, and the Use Case includes changes in rainfall, wind and sea-level rise in a warming climate for TC Idai over Mozambique. The case study also is a multivariate extreme given that it looks at a range of flooding types; coastal, pluvial and fluvial.
- UC4: Tropical Storms Eta and Iota are also of a multivariate nature given they include both pluvial and fluvial flooding.

ii. Spatially compounding:
  - UC1: Storm Xynthia was spatially compounding due to both the coastal flooding and windstorm. The windstorm made evacuation of coastal areas challenging, with both also increasing economic losses at the same time.

iii. Temporally Compounding:
  - UC2a: UK winter storms in 2013/14 were temporally compounding due to 12 consecutive storms resulting in higher flooding impacts throughout and at the end of winter. This intensity of impacts were significantly higher than if there had just been one intense rainfall event.
  - UC4: Consecutive tropical storms Eta and Iota in Honduras within the space of 2-3 weeks, led to higher combined impacts than the individual storms, with emergency services still providing support for Eta when Iota impacted.

iv. Preconditioned:
  - UC2a: UK winter storms 2013-14 the extreme rainfall from storms in the early winter left the ground heavily saturated/flooded in the later winter months exacerbating flooding impacts from storms in late January and early February.
  - UC2b: During the UK 2022 drought-heatwave the extreme sub-daily temperatures seen in south-east England were likely exacerbated by low soil moisture from low rainfall/evapotranspiration in the preceding months.

A wide range of methods were used for the hazard counterfactuals, including detrending ERA5 using extreme value analysis, large-ensembles conditioned on SSTs, long term trends in variables such as sea level rise, and using values from physics-based mechanisms such as Clausius Clapeyron or the literature. Therefore, some of these methods will measure the impact of climate change and some will measure the impacts of anthropogenic climate change. All use cases used impact modelling of a kind, including compound flood modelling chains (including hydrological, coastal and hydrodynamic models), storm surge modelling, windstorm damage functions, and impact thresholds. The COMPASS compound flood modelling framework developed by Deltares was used in four of the use cases and was shown to be transferrable for a range of regions and hydrological events. The use cases were also able to attribute changes in exposure and vulnerability either qualitatively or quantitatively in addition to changes in the climate. Methods to attribute exposure included examining changes in historical population or economic data for some of the flooding and windstorm events, for the runway closure; changes in the historical usage of the affected airport were examined. Attributing vulnerability quantitatively was more challenging with many of the methods using a qualitative approach, with the exception of UC1 which estimated regional vulnerability more quantitively through multivariate vine-copulas based on socio-economic factors.

The broad coverage within the Use Cases provides a good foundation of knowledge and learnings for recommendations of compound impact attribution methods, with some repetition of methods allowing statements on transferability to be made. The next couple of sections build strongly upon feedback and experience from the lead authors of the phase 1 Use Cases.

3. Common Themes and Learnings for Compound Attribution Methods

Theme 1: Impact attribution step even more beneficial for attribution of complex extremes than for single hazard drivers

The benefits of impact attribution over hazard attribution for single hazard-drivers have already been shown, with non-linearities and lags meaning that the influence of climate change on impacts can be different from its influence on the hazard (Perkins-Kirkpatrick et al., 2022). Multiple studies relating to flood events such as Hurricane Harvey in the US or a rainfall event in New Zealand (Perkins-Kirkpatrick et al., 2022, Wehner and Sampson, 2021) have shown this with the spatial distribution of rainfall and hence flooding found to be key in translating from the hazard to impacts. Attribution results that contain statements on specific impacts rather than the overall hazard can also be more useful for applications of attribution, such as litigation or adaption, and can make the results more tangible for public communication (Otto 2023; Noy et al., 2024).

There is an argument to be made that the advantage of impact attribution is even greater for complex extremes than single hazards. In the case of multivariate extremes, such as compound high rain-wind or drought-heatwave events the dependence between variables are ideally required to calculate probability changes in the compound hazard. This is statistically challenging given the dependence would likely be different for the most extreme events (very few datapoints in the tail) and would also likely change with climate change in some instances (Zscheischler and Seneviratne, 2017). Large ensembles could be used to overcome this (Bevacqua et al., 2023), however, they often do not have high enough temporal and spatial resolution required for impact modelling and are not suitable for certain events such as Tropical Cyclones. Therefore, an impact model that would take all the relevant variables and produce an impact directly, hence removing the need to deal with such obstacles (Zscheischler et al., 2020) and making it a univariate problem (where the variable is the impact) negates this issue significantly (van der Wiel et al., 2020).

In our use cases, we found that for many multivariate or cascading events there are also no easy ways of linking changes in hazard variables, into anything that would resemble the change in impacts. The compound flooding caused by Tropical Cyclone Idai examined in UC3a, found that sea-level rise and an increase in wind speeds due to climate change increased the damage from coastal flooding by 27% (Vertegaal et al., 2025). This is despite it resulting in a less than 1% increase of flood-extent/volume overall, compared to in-land flooding where the flood volume increased by 9% due to increased rainfall intensity due to climate change, but only resulted in 4% increase in flood damage (Vertegaal et al., 2025). The compound flood modelling framework was able to combine the hazards (sea level rise, antecedent conditions, rainfall and wind intensity) into an impact-based result where the relative contribution of the variables that are changing in a warmer climate are able to be assessed. Similarly, for the 12 consecutive UK winter storms in 2023-14 in UC2a it is challenging to find a reasonable metric that would combine these into something that would represent flood risk well, especially as each storm had different rainfall intensities. Given the importance of the high tides in this event, an impacts model also allows sea-level rise to be included.

Based on these results, we argue that for attribution of compounding hydrological extremes or variables leading to hydrological extremes, impact attribution could be considered essential. For more temperature-dominated compound extremes such as drought-heatwaves or co-occurring droughts this is not necessarily as important. Multivariate indices such as the Fire Weather Index (FWI) or Standardised Precipitation Evapotranspiration Index (SPEI), or spatially compounding indices that turns the complex extreme into a univariate problem has already been used in attribution studies for complex extremes (i.e. Barnes et al., 2025; Christidis and Stott, 2021; Qian et al., 2023). It is important to note the drought-heatwaves can result in a number of impacts, whether that is related to crop yields, vegetation, water availability or transport infrastructure, and occur over a range of timescales (Hao et al., 2022). The relative contribution of the hazard variables (i.e. drought and heat aspects) relevant to each impact, are likely to be different, and therefore hazard attribution of multiple variables including the spatial-temporal aspect leaves a fair amount of subjectivity, that can be reduced through the usage of impact models (Zscheischler et al., 2020). However, it is important to note that models for particular impacts may not so easily be available compared to open-source flood models that were used in the COMPASS use cases, a point that will be discussed more in theme 3.

Theme 2: Impacts amplified when going from single-driver to multi-driver attribution methodology

The literature states that in many cases multiple meteorological drivers contribute to the impact of extreme weather events and can often amplify them (van der Wiel et al., 2020; Zscheischler and Lehner, 2022). This is consistent with what we find in the phase 1 COMPASS use cases. In the consecutive UK winter storms study, the flood extent after the most extreme storm in terms of daily precipitation over the Somerset Levels in mid-December was 3-4 times less than the total flood extent after all the storms (end of February) over the catchments examined in the study. The increase in impacts due to climate change for Tropical Cyclone Idai in Mozambique, were amplified by including both changes in wind and sea-level-rise, and not just one of them. The change in flooding impacts was also amplified by including changes in these variables and rainfall for examination of inland flooding. In the case of consecutive Hurricanes Eta and Iota in Honduras, the study also extended to multivariate drivers including combinations of climate and non-climate drivers. These examples clearly show the added benefit of including multiple hazard variables and how they are changing in a warming climate in attribution studies.

Theme 3: Impact attribution of compound drought-heatwave related events remains a challenge

Hazard attribution of temperature-dominated extremes is generally considered to be less challenging than for precipitation related extremes. This is due to issues with data quality in models and observations for precipitation and the high natural variability of extreme rainfall events (Stott et al., 2016). However, translating impacts of temperature-dominated extremes such as drought-heatwaves to on-the-ground impacts was found to be more challenging than hydrological extremes within the first phase of Use Cases.

Impact attribution of hydrological extremes has the benefit of open-source flood models (e.g. LISFLOOD-FP (Bates and De Roo, 2000), SFINCS (Leijnse et al., 2020)) and flood damage models (e.g., CLIMADA, Delft-FIAT, GLOFRIS), which can be applied to any region. These models can simulate flood inundation, with flood depths or flood extent above a certain flood depth good estimators of local impacts. The COMPASS compound flood modelling framework developed by Deltares, was applied successfully to four of the phase 1 use cases for different locations, including Mozambique, Honduras and England, and can cover compound aspects of flooding. The challenges around hydrodynamic impact modelling lie more with the resolution and quality of the input data such as elevation data or bathymetry for the region of interest, rather than the models themselves (Bates, 2022). In the use cases there were challenges around model input data, including resolution of rainfall factuals/counterfactuals, requirement for local expertise, quality of the validation data, and missing or averaged out local details in topography/bathymetry datasets.

Compound drought-heatwaves are expected to increase in most regions in a warming climate and can result in a range of impacts such as crop failure, wildfires, human health, water shortages and cause harm to ecosystems (Hao et al., 2022). The COMPASS 2022 UK drought-heatwave use case, reported impacts including over 2000 excess deaths, wildfires, school closures, hosepipe bans, road and runway closures, agricultural impacts and high pressure on the emergency services (Jack et al., 2025). The diversity of impacts means that to attribute the overall impacts, a large number of very different impact models would be required. These would all require local data, calibration and expertise in the individual areas. Therefore, unlike for the use cases focussed on flooding, producing a compound impact modelling framework is a lot more difficult and potentially impractical. Therefore, early stakeholder engagement and a clear idea on the impacts of most interest is essential, and whether a metric that encompasses all impacts is best. Approaches could focus on one specific impact as carried out in the COMPASS use case for 2022 UK drought-heatwave, or compromise by using multiple indicators of impacts for the range of observed impacts (i.e. SPEI or FWI) at the expense of modelling the impacts specifically.

Theme 4: Use Cases highlight the key role vulnerability and exposure changes have on impacts

The severity of impacts from extreme meteorological events are influenced not by just the hazard, but also by exposure and vulnerability (Seneviratne et al., 2021). Analysis of the hazard alone, can overlook the large influence vulnerability and exposure can contribute towards impacts, with the inclusion of these additional components making attribution studies more useful and useable (Otto, 2023). Noy et al., 2024 points out that although the components can be analysed individually with the other components held constant, interaction between them such as how climate change has altered both exposure and vulnerability to the hazards of interest can be missed.

The COMPASS phase 1 use cases analyse the role of all three components for the attribution in most cases, with the choice of impact attribution over hazard attribution allowing quantitative attribution statements on exposure and vulnerability changes to be made over the same time period the hazard is analysed. The storm Xynthia use case which compared changes in economic loss due to all 3 components with a 1950 baseline, found that the effect from changes in exposure and vulnerability were far greater than that from the hazard (despite the hazard increasing impacts by 10-14%), with impacts increasing significantly due to an increase in exposure but reduced to some extent through reduced vulnerability since the 1950s. In use case 2b which focusses on the closure of a UK airport runway, found large quantitative increases in impacts due to both the hazard (since preindustrial) and exposure (since 1980s), amplifying the overall impacts. In cases where vulnerability is difficult to define quantitatively, qualitative assessments can provide useful information. Use case 4, which attributed the impacts of Hurricanes Eta and Iota in Honduras, found through analysis and causal mapping how COVID-19, violence and insecurity amplified/compounded the impacts.

Vulnerability and exposure assessments are beginning to be included more regularly in attribution studies, with recognition from within the attribution community of its importance (Otto., 2023). One of the most comprehensive attribution studies including a range of socioeconomic drivers, Paprotny et al., 2025b, examines how climate change and different socio-economic drivers has influenced flood impacts since 1950, based on over 1700 flooding events in Europe between 1950-2020, showing the strong benefits of adaption due to a decrease in vulnerability, with the counteracting large increase in impacts due to increasing exposure. Work Package 3 within the COMPASS project ‘Enabling impact attribution by multi-scale modelling of exposure and vulnerability’ has already delivered a report on Exposure Datasets at multiple scales (Paprotny, 2025) and Guidance on qualitatively assessing vulnerability factors (Singh et al., 2025). These are useful resources for attribution studies aiming to include exposure and vulnerability assessments.

4. Recommendations

This section contains recommendations for attribution methods suitable for compound extremes with damaging impacts. The recommendations are based on expertise and feedback from the lead-authors of the COMPASS use cases, the key themes identified in section 3, ease of implementation, the transferability of the methods to different regions and events, and literature in the field. It is important to note the benefits of early stakeholder engagement, which may guide the best choice of methodology used in each case. This is because different methods can answer different questions about the compound event in question, such as the intensity change, likelihood change, change in duration, or the key drivers of change (Thompson et al., 2025) and the relevant stakeholder may be interested in a particular aspect, given the impacts of the event- which may make some methods more suitable. Therefore, these should only be seen as general recommendations, not event specific recommendations. If multiple methods can be used for the same event, this is very beneficial as it will provide more strands of information, which can both increase understanding of study results and confidence in the results, especially given the extra layer of uncertainties when adding impact modelling.

The large range of complex extreme types and hazards means we will provide recommendations separately for each of the 4 complex event typologies described in Zscheischler et al., 2020. These are Multivariate, Spatially Compounding, Temporally Compounding and Pre-conditioned, with the definitions of each given in the introduction of this report.

i. Multivariate Extremes

Attribution studies for multivariate events such as compound flooding, or multiple variables (i.e. wind/rain/sea-level-rise) leading to one or more types of flooding, the recommendation is to always include some form of hydrological and hydrodynamic modelling if possible. The use cases and literature have shown the significant non-linearities between changes in the hazard and changes in the impacts. In the absence of flood modelling, changes in risk and impacts may be significantly misrepresented. Flood modelling allows important drivers such as sea-level rise to be easily integrated into the attribution study, alongside other components such as precipitation, evapotranspiration and wind. There aren't any metrics/indicators that we know of that are able to easily combine these variables and link them to impacts more generally. The compound flood modelling framework developed in COMPASS was shown to be applicable to a range of locations and event types in the use cases, showing that the capability for impact modelling of compound extremes of that type is possible currently.

The choice of attribution method to produce the hazard counterfactuals is limited for rainfall extremes, especially those associated with unusual storm tracks. Impacts are very sensitive to the storm track and hence require factual and counterfactual events with similar tracks. Large ensembles of climate data required for probabilistic attribution, can lack events similar to the extreme being attributed, or are too coarse resolution to produce similar event intensities at a local scale to simulate realistic impacts (Leach et al., 2024; Weisheimer et al., 2025). Therefore for these types of events most probabilistic methods are unsuitable currently, with more highly-conditioned approaches such as pseudo global warming experiments (Lenderink et al., 2025), spectral nudging (van Garderen et al., 2021; John et al., 2024) or forecast attribution (Leach et al., 2024) which are more likely to be able to simulate similar events in a counterfactual climate and at the higher resolution required are more suitable. An extension of UC3a tested the DestinE storyline spectral nudging approach for TC Idai, found that using this highly conditioned approach, a factual and counterfactual with similar tracks could be compared. If the multivariate attribution includes wind as variable this approach would not be suitable, given that the large-scale upper winds are constrained in the events. Initial results do however find the spatial structure of the rainfall deviated between the factual and counterfactual, making its application to impact attribution challenging, with a study of Hurricane Sandy finding similar (Goulart et al., 2024). A potential method that could address this problem, would be to use the storylines to produce delta change factors over the entire region, which could be subtracted from the ERA5 event, similar to Dullaart et al., 2024 which applied such an approach to a future climate. Wehner and Sampson 2021, used results from multiple hazard attribution studies for the delta-change factors for Hurricane Harvey, to carry out the impact attribution. One disadvantage of such a methodology is that any change in speed of the precipitation event due to climate change would not be accounted for in the results. Literature shows some evidence that climate change is playing a role in the speed of storms over Europe for example (Kahraman et al., 2021).

For multivariate extremes such as drought-heatwave events there are a range of methods that are suitable for damaging impacts. As discussed in Theme 3, the combination of hot and dry extremes can lead to a diverse range of impacts. The choice of method is strongly dependent on whether the stakeholder is interested in covering a specific impact or a method that covers the impacts more broadly. In the case of a specific impact, we would recommend simplifying it to a univariate problem either through impact modelling/damage functions, or indicators that combine the relevant variables (i.e. FWI for wildfires). If a broader overview is required, a univariate index (i.e. SPEI) that covers the relevant timescale of interest, could be used with large-ensembles of factual and counterfactual climate simulations. An alternative multivariate compound hazard attribution method that has been used successfully is bivariate FAR, which is an extension of FAR (fraction of attributable risk (Stott et al., 2004)) for multivariate extremes. This was developed in Zscheischler et al., 2022 and applied to Western Cape in South Africa for the hot and dry years 2015-2017, using large ensembles using precipitation and temperature. For all the above cases, given the timescale of the drought aspect and the requirement for extremes in both variables in most cases, large ensembles such as SMILES are recommended to model the tail of the combined extremes.

ii. Spatially Compounding

This covers events occurring at two different locations at the same time, in a way that amplifies the impacts. The best choice of method will again depend on the question being asked by the stakeholder. If the attribution question is to examine how the intensity of both events have changed due to climate change and hence the intensity of their impacts given they both happen at the same time, a highly-conditioned approach is recommended (i.e. storyline approach). If there is an interest in how the probability of there being two extreme events at the same time, that could be influenced by both changes in the large-scale dynamics and thermodynamic aspects more locally, then it is important to use large ensembles that will have enough composites in order to estimate how their co-occurrence is changing, in addition to their intensity.

For the impact modelling, if a storyline approach is used for the counterfactual hazard then the recommendation would be to use impact models that simulate impacts directly, given the non-linearity between changes in the hazard and societal impacts. This is particularly beneficial for hydrological based extremes. The Storm Xynthia study is a good example of this, where windstorm impacts across France were calculated using damage functions, and coastal flooding impacts were calculated using hydrodynamic modelling. This allows the sum of the damages from both events to be calculated in both a factual and counterfactual climate.

For a probabilistic approach where the attribution question also involves including how climate change is impacting the co-occurrence likelihood due to any changes in the large-scale dynamics, the method in Qian et al., 2023 could be used. This involves creating a compound index that uses the hazard anomalies and their standard deviations in order for the magnitude of the spatially compounding event to be quantified (Qian et al., 2023). Just like for any probabilistic attribution approach of compounding extremes, large datasets and ensembles such as SMILES are required to distinguish any climate signal from noise (Bevacqua et al., 2023). It is however important to include validation on the co-occurrence of the variables in the large-ensembles used, compared to observations.

iii. Temporally Compounding

Temporally Compounding events are complex events where successive hazard events lead to amplified impacts. Use case 2a: UK Winter Storms of 2013-14 is a good example of this where 12 successive storms in the space of 3 months lead to extreme flood impacts. For this type of compound event, early assessment of the key large-scale drivers that result in multiple consecutive events, can provide useful input for the best choice of attribution method. In the COMPASS project, Rushby et al., 2025 provides a framework to link large-scale drivers to compound impacts, using weather patterns as an intermediatory. For temporally compounding hydrological extremes-such as consecutive storms, the recommendation is to use hydrodynamic modelling, given the non-linearities found between changes in the hazard and societal impacts. The flood modelling can also capture preconditioning from the earliest events (challenging to capture in an index), which is likely to be impacting the final event in the sequence.

When choosing the attribution method for the counterfactual hazard there are a few key considerations. Firstly, how much the identified large-scale drivers of the cascading hazard are being influenced by climate change. If the literature or any initial assessment shows significant alteration of these large-scale drivers in a warming climate, a more probabilistic approach would be recommended to capture this, along with any thermodynamic changes. As described in the spatially compounding methods recommendation section, a probabilistic methodology for such an extreme would require large-ensembles to capture enough examples of consecutive extremes. The second consideration is the resolution of the counterfactual hazard data for the chosen method, often large-ensembles are of coarser resolution, which can provide challenges when converting hazard changes to impacts. Therefore, more storyline based-approaches which are likely to have higher-resolution hazard data the preferable choice, if there is no obvious climate signal identifiable in the large-scale dynamics.

iv. Preconditioned

Preconditioned extremes occur as a result of a hazard or its impacts being amplified as a result of a pre-condition. Examples of this include high soil moisture amplifying the impacts of extreme rainfall, or dry soil moisture resulting in more extreme heatwaves or amplifying the impacts of flash floods. Including impact modelling is highly recommended for preconditioned events, in order to capture the relationship between the pre-conditioning and hazard to its impacts, including any feedback processes. For hydrological extremes, hydrodynamic models often use both soil moisture and rainfall as input to examine damaging flood impacts. Impact models involving preconditioning in many cases require a long warm up period, where the compound flood modelling framework applied to the COMPASS use cases including events in East Africa, Honduras and the UK required the river-flow model to run for a year before the event. In each of these cases the preconditioning was kept constant, however if they weren't kept constant this would require more time to run the range of pre-conditions through the model. There can be a trade-off between using longer runs that capture the climate influence on the conditioning over a longer period, but be computationally more expensive, and shorter runs that capture less of the pre-conditioning but are quicker and less expensive to run.

Highly-conditioned storyline methods such as pseudo global warming experiments (Lenderink et al., 2025), spectral nudging (van Garderen et al., 2021; John et al., 2024) or forecast attribution (Leach et al., 2024), would have to be run for long enough in advance to capture any climate signal on the preconditioning. Therefore, such approaches are more suitable for events where the climate signal influence on the precondition occurs over a short period close to the event. Probabilistic or analogue approaches using large ensembles would be recommended if the preconditioning relevant to the event occurred over a long period. In the case of heatwave study use case 2b soil moisture was likely a precondition to the peak intensity of the heatwave. For such events the conditioning may already be included in the climate model factual and counterfactual data including feedbacks. In such cases, there is a much wider range of attribution methods available, due to it becoming a univariate problem.

5. Summary

In this report we provide recommendations for attribution methods suitable for compound events with damaging impacts, using the learnings of the COMPASS Use Cases. The use cases cover a range of complex extremes including multivariate, spatially compounding, temporally compounding and preconditioned, covering a range of event types and continents. The methods used and developed in the use cases aimed not only to extend hazard attribution from single to multi-driver, but also to extend hazard to impact attribution, and to include where possible quantifiable vulnerability and exposure assessments.

Our findings highlighted that the hazard-to-impact attribution step is even more beneficial for attribution of complex extremes than for single hazard drivers. The impact model approach allows the relevant hazard variables to be combined to produce one set of impacts. Hence, allowing assessment of the relative contribution of changes in each variable to the impacts and avoiding statistical challenges around extremal dependence of variables for calculating probabilities. The results highlighted that specifically for the flood use cases such as Tropical Cyclones Idai and Kenneth, there were large differences between attribution statements on the hazard (rainfall), the intermediatory (flood extent) and societal impacts (flood depth damage functions). The use cases also clearly highlighted the benefit of including changes in multiple hazard variables due to climate change in the attribution methods, where the inclusion of multiple rather than just one of the compounding factors were shown to amplify impacts in most cases.

The use cases also highlighted the challenge of impact attribution for drought- heatwave type compounding events, where there are often a range of different impacts all requiring different impact models. These tend to be less openly available and location specific. This issue was not as present for compound events of a hydrological nature as we were able to successfully apply a compound flood modelling framework developed in COMPASS to multiple regions and event types. The addition of exposure and vulnerability assessments within attribution studies is recommended, with the COMPASS use cases showing quantitatively how increases in exposure for multiple events have amplified impacts. The vulnerability aspect was found to be more challenging to assess quantitatively, however one of the use cases was able to provide a quantitative assessment on how reduced vulnerability partially negated the increase in impacts from increases in the hazards and exposure.

The attribution method recommendations, for flood-based compound extremes, such as compound flooding, coastal flooding, or spatially/temporally compounding storms and pre-conditioned flooding, would be to include impact modelling. This is due to the strong non-linearities between hazard and impact attribution results, the inclusion of important variables such as sea level-rise, and the opportunity this opens to quantitative assessments of vulnerability and exposure. The best choice of hazard attribution methodology (i.e. how the counterfactual is produced) is likely guided by the spatial-temporal scale and quality/suitability of the hazard data for the chosen method. Highly conditioned approaches such as those of a storyline nature, are often preferable due to their ability to reproduce the event (i.e. the specific track of a TC which is crucial for impacts), and their higher spatial resolution compared to the resolution of large ensembles required for a probabilistic approach. Events involving impacts from heatwaves and droughts, that rely less on the high-resolution of the hazard data, large ensembles are recommended. These can be combined with impact modelling or indices that take into account multiple variables such as the FWI and SPEI. Large ensembles will allow for enough extreme composites of the hazards contributing towards the impacts and can also capture any changes in the large-scale dynamics which could be particularly important for spatially or temporally compounding events. Storyline attribution methods could however prove more useful for very rare events, where there aren't enough similar composites in the set(s) of large ensembles.

These recommendations are a guidance only, based on the common themes found across the COMPASS use cases, with the literature, the ease of implementation and transferability also considered. It is important to reiterate that different attribution methodologies can answer different questions and provide different output, whether that is the change in intensity, likelihood, driving factors or duration of the compound event in question (Thompson et al., 2025). Noy et al., 2024 notes that events with damaging impacts are often defined by intensity, hence methods that calculate the intensity in both a factual and counterfactual climate for the equivalent event, may be more useful. If the event is defined by a probability, then a probabilistic method may be more suitable. Therefore, we recommend early stakeholder engagement, particularly with the extra choices required in impact attribution methodologies for compound extremes around conditionality and the question the study aims to answer (Cotterill et al., 2026). The studies have also highlighted the importance of local expertise for impact modelling and cross-disciplinary collaboration for exposure and vulnerability assessments. The complexities involved in impact attribution of compound extremes for damaging impacts will require close collaboration between domain users and attribution experts to best utilise study results.

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