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WCD Ideas: The transition from event-based storylines to conditional climate trajectories

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Abstract. The recent emergence of studies using multi-year storyline simulations raises questions regarding the interpretation of the climate information they provide. We argue that these simulations can be viewed as conditional climate trajectories, extending the original event-based storyline concept while preserving its fundamental philosophy of conditioning on atmospheric circulation. The transition of storylines from assessing individual events to continuous multi-year simulations changes how the associated statistics and attribution statements should be interpreted and communicated. Therefore, in this paper, we revisit the conceptual interpretation of multi-year storyline simulations and examine the implications of viewing them as conditional climate trajectories.

1 Introduction

The storyline framework offers a physically-based complement to probabilistic approaches to attribute the role of global warming in extreme events (Shepherd, 2016). Instead of estimating the probability of an event class across a broad range of possible counterfactual climates derived from large ensembles of climate models, event storyline approaches condition atmospheric circulation to a specific weather pattern shaping a historical event to ask how the thermodynamical aspects of global warming modify its features (Trenberth et al., 2015). The framework has proven to be particularly valuable for event attribution, climate impacts research, and risk communication (Baldissera Pacchetti et al., 2024).

However, there is growing attention on using constrained climate simulations extending far beyond individual events. This is an emerging trend especially for nudged storyline simulations, which constrain the large-scale circulation towards reanalysis and observed data while changing the background thermodynamics (Feser and Shepherd, 2025; Van Garderen et al., 2021; John et al., 2026; Klimiuk et al., 2025; Sánchez-Benítez et al., 2022). As such datasets get longer, and multiple continuous years are available, studies increasingly investigate how observed extreme events of such periods would systematically unfold under alternative thermodynamic conditions (Burderi et al., 2026; Kettaren et al., 2026; Klimiuk et al., 2026; León-FonFay et al., 2026b; Merz et al., 2026). The expansion of the storyline framework in time broadens the focus from individual extremes to the response of entire sequences of weather events, including both extremes and everyday weather, under alternative climates

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(Thomas et al., 2026). At this point, the object of study is no longer a single event, but a conditional climate trajectory: a continuous climate sequence following a single historical atmospheric pathway, where the chronology of weather is preserved. Consequently, the conditioning shifts from individual atmospheric states to entire atmospheric trajectories. This transition occupies a conceptual space between storylines and conventional climate models, and raises a fundamental question: *What does a multi-year storyline represent, and what climate information does it provide?*

2. When conditioning goes from events to climate

While the storyline concept implies a hypothetical thought-experiment, where a unique event is translated into an alternative climate, it remains physically interpretable, as it is conditioned on an actual weather situation leading to the event. If we relate it to probabilistic conditional attribution, where the influence of climate change on an event may be assessed conditional on a particular atmospheric circulation (National Academies of Sciences and Medicine, 2016), we have:

$$\frac{P_f(E,C)}{P_c(E,C)} = \frac{P_f(E|C)}{P_c(E|C)} \frac{P_f(C)}{P_c(C)}, \qquad (1)$$

Here, f and c denote the factual and counterfactual datasets, E is the event of study, and C is the atmospheric circulation associated with that event. The conditioned circulation could represent a blocking system, the dynamical conditions leading to an atmospheric river, or a particular teleconnection pattern. These circulations have a clear physical meaning, and in the storyline framework one asks, '*Given this atmospheric situation, how does climate change influence the resulting event?'*. The paradigm changes when C represents a multi-year circulation trajectory conditioned on the observed climate. Consider a simulation constrained to reproduce the observed atmospheric evolution between 2010 and 2019. The conditional object C is no longer a circulation state but an entire atmospheric trajectory Ω, containing the full sequence of atmospheric dynamics during that period, including blocking events, cyclone tracks, ENSO variability, and NAO fluctuations, all over the globe. Unlike an individual circulation pattern C, Ω is not, we would argue, itself physically interpretable as a storyline. Rather, it provides a common dynamical framework within which many different storylines can be identified.

Under this interpretation, *the multi-year constrained simulation should not be viewed as a single storyline analysis, but as a conditional climate trajectory containing multiple storylines.* The circulation patterns Cassociated with a particular event remain physically meaningful and retain the role of storylines, while the observed atmospheric trajectory Ω acts as the experimental framework in which they occur.

3. What do conditional climate trajectories represent?

When using these long-term simulations, the distinction from conventional climate models can get blurred. It is tempting to interpret them in the same way as climate model ensembles and to generalize their statistics as representative of a given cooler (pre-industrial), factual or warmer climate. After all, averaging over decades of constrained simulations also produces a climatology of possible climate states under a particular warming level, much like a climate model ensemble. This is the logic

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behind the Pseudo Global Warming (PGW) (Brogli et al., 2023; Kimura and Kitoh, 2007) and delta-change approaches (Hay et al., 2000). One advantage is that these possible climate states are ensured to be physically realistic: would you rather have 30 years of real climate states, or 1000 years of simulated climate states, if the latter have significant biases in the phenomena of interest, such as blocking? Another advantage is that constraining the circulation allows for a paired rather than an unpaired comparison between factual and counterfactual climates, providing a far better signal-to-noise ratio than is possible with a free-running simulation. This is shown by the fact that even a single year of storyline weather can recover many of the robust aspects of climate change (Thomas et al., 2026). It remains the case that any statistics derived from these simulations are conditional on the dynamical states represented within that trajectory and may not be representative of the full range of atmospheric variability, let alone of changes in that variability in response to climate change. However, many of the robust aspects of changes in distributional properties of extremes, such as changes in variance and skewness of surface temperature distributions, arise from changes in large-scale temperature gradients rather than from changes in large-scale dynamics (Tamarin-Brodsky et al., 2020). The same applies to distributional properties of precipitation extremes (Thomas et al., 2026). Unlike climate-model ensembles, conditional climate trajectories do not sample multiple possible atmospheric pathways. Instead, like event storylines, their value lies in quantifying the response of the climate system conditional on an observed atmospheric evolution. In this way, conditional climate trajectories prioritize causal interpretability by comparing sets of dynamically identical events across different thermodynamic climates. Consequently, conditional climate trajectories occupy an intermediate conceptual space between climate model ensembles and event-based storylines. Climate ensembles sample multiple atmospheric pathways and quantify possible futures. Event storylines quantify the response of specific events to climate change. Conditional climate trajectories quantify the response of multiple storylines contained in a historic atmospheric trajectory to different thermodynamic states (Figure 1).

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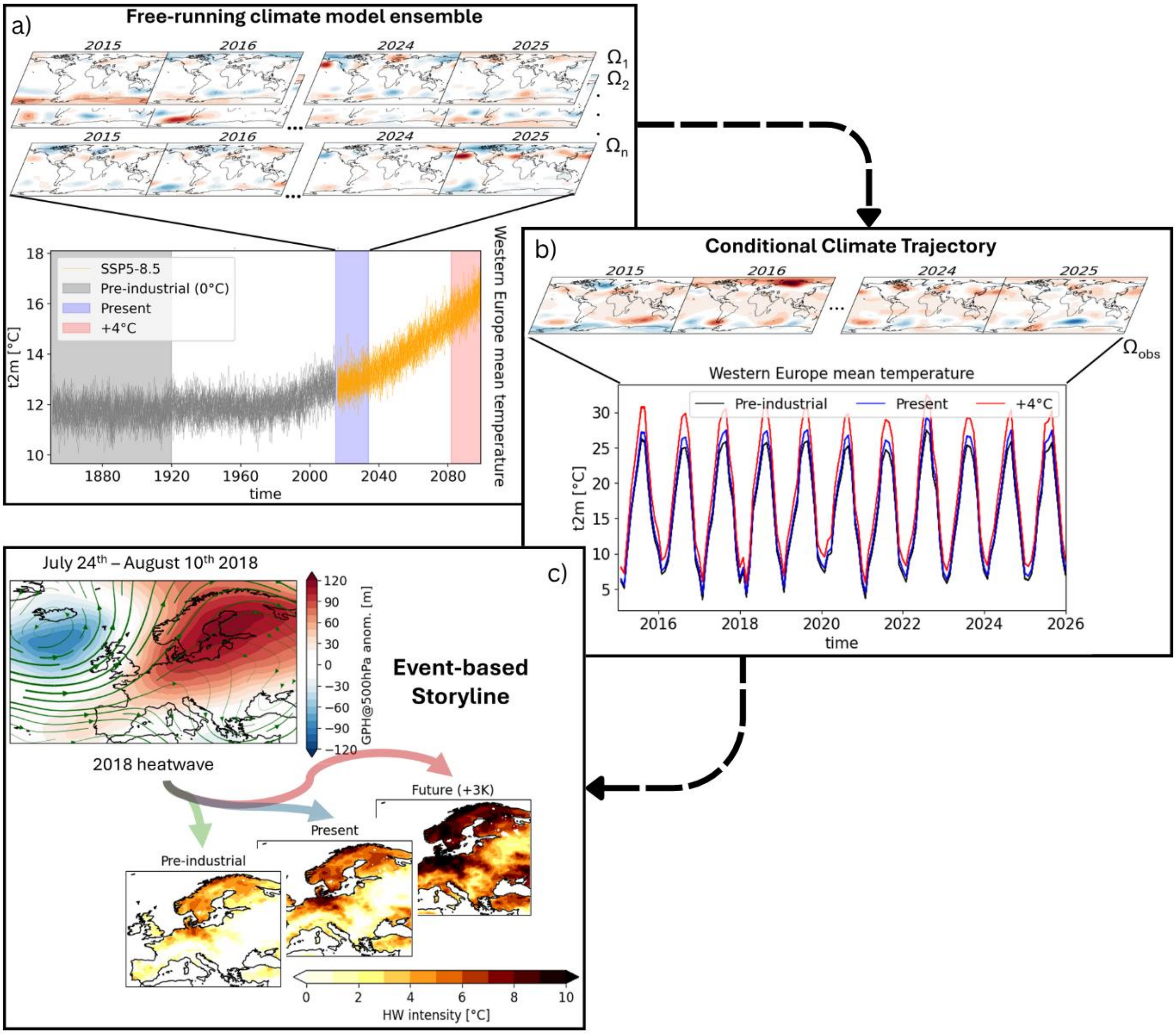

Figure 1. Conceptual difference between free-running models, conditional climate trajectories and event-based storylines. a) A free-running model (here MPI-ESM LR (Olonscheck et al., 2023)) showing the mean temperature of western Europe progresses forward in time, from which a pre-industrial, present and future dataset can be obtained. If we focus on the present period, a set of n realizations (ensemble members) are used to represent the mean climate state and its uncertainty, each following a different atmospheric pathway **Ω**, reflecting the chaotic nature of atmospheric variability. **b)** In a climate trajectory conditioned to the observed large-scale circulation, a single dynamical pathway **Ω_{obs}** is needed to simulate the same time period (and the events occurring within it) under pre-industrial, present and future warming conditions, resulting in reduced dynamical uncertainty. **c)** Individual storylines can be extracted from a conditional climate trajectory, such as the 2018 European heatwave shown here, triggered by a blocking over Scandinavia (adapted from León-FonFay et al. (2026a)). In this framework, climate ensembles sample many trajectories, conditional climate trajectories follow an observed dynamical pathway to simulate long-term trends and all historical events within it, and event storylines focus on specific events embedded within that pathway.

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4. Opportunities for Extremes Research

In a multi-year constrained simulation, the entire historical sequence of events occurring in a given period is prescribed. While the same sequence of events will never occur again in an alternative climate, the constraining ensures the presence of the events that occurred within that trajectory. In that way, it enables the study of a physically realistic dynamical pathway, capturing trends and events that free-running models struggle to represent. This provides a controlled framework for investigating how climate change systematically modifies extremes, impacts, and long-term climate responses, being useful for:

Process-based attribution: Because the same atmospheric evolution is compared across factual, counterfactual, and warmer climates, differences in event characteristics cannot arise from changes in large-scale circulation. Instead, they can be directly associated with thermodynamic drivers such as local temperature increases, moisture availability, atmospheric stability, or land-atmosphere interactions. This allows researchers to move beyond the question of whether climate change influenced a class of events and investigate the physical mechanisms through which that influence occurred, including the state dependence of the thermodynamic effects of climate change. For instance, Klimiuk et al. (2026) used nudged simulations conditioned on the 2018-2022 atmospheric trajectory to address the role of evapotranspiration regimes in amplifying hot and dry European summers of this period.

Compound events: Because conditional climate trajectories preserve the chronology of observed weather, they provide a natural framework for analyzing compound and sequential events. Unlike climate-model ensembles, where comparable sequences may be rare or absent, the same chain of events can be directly compared across multiple thermodynamic climates. Multi-year droughts, for example, can be viewed as single climate events emerging from a highly specific long-term sequence of atmospheric conditions, making them particularly well suited to analysis within conditional climate trajectories (Kettaren et al., 2026; León-FonFay et al., 2026b), see Figure 2.

Complex events: Storyline frameworks are particularly valuable for studying complex extreme events (van Garderen and León-FonFay, 2026), which might be challenging to identify statistically or to simulate, since they emerge from the interaction of multiple processes, see Figure 2. By preserving a physically consistent atmospheric evolution, attribution analyses that extend beyond individual extremes and capture dependencies across similar dynamics are enabled. For example, using storyline simulations of 2017-2024, Burderi et al. (2026) showed that the intensification of Italian precipitation extremes under global warming varies across weather types.

Thermodynamic attribution of long-term trends: This may be particularly valuable for circulation trends whose representation in climate models remains uncertain. In this sense, conditional climate trajectories complement dynamical-adjustment approaches, which attempt to statistically remove circulation influences from climate trends, with the residual interpreted as the thermodynamic response to climate change. Here, dynamical evolution is controlled explicitly, allowing the

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thermodynamic response to be estimated directly. For example, using circulation-constrained climate simulations covering 1980-2024, Dunkl et al. (2026) were able to reproduce observed European summer drying trends and found that approximately 55% of the drying could be attributed to changes in atmospheric circulation patterns.

Identifying robust thermodynamic climate change signals: If thermodynamic responses estimated from conditioned simulations are consistent with those obtained from climate model ensembles, mutual confidence in the underlying climate change signal is strengthened. Conversely, discrepancies may reveal processes that are strongly dependent on circulation changes. Conditional climate trajectories therefore provide an additional line of evidence for distinguishing robust thermodynamic responses from changes that depend critically on atmospheric dynamics. In this context, using a decade of nudged simulations, León-FonFay et al. (2026) found consistent patterns of heat-extremes in South America with those reported by ensemble simulations. Similarly, using a single year of conditioned atmospheric dynamics, Thomas et al. (2026) showed that many characteristics of everyday weather and precipitation responses in warmer climates remain consistent with expectations from climate-model projections. Together, these studies suggest that a substantial fraction of the diagnosed changes reflects robust thermodynamic responses to global warming rather than properties of a particular atmospheric trajectory.

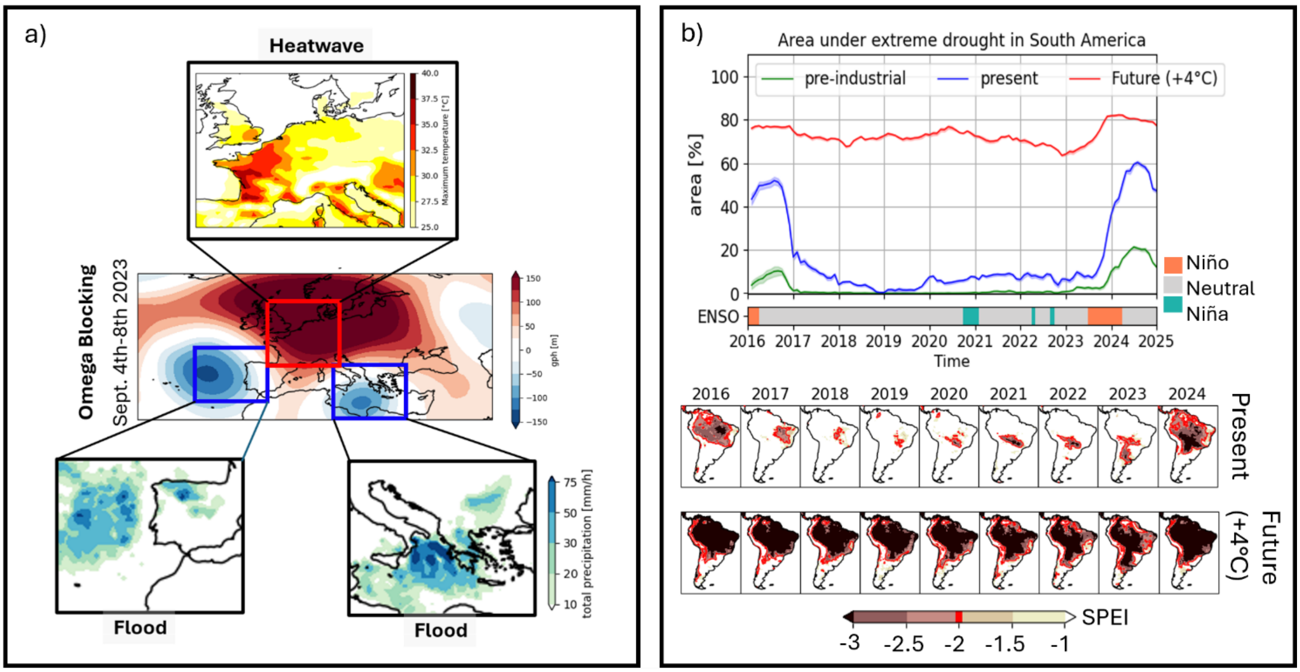

Figure 2: Examples of applications of conditional climate trajectories. a) September 2023 European blocking, which simultaneously generated a heatwave and flood events on either side of the blocking anticyclone. b) Multi-year South American droughts arising from a prolonged sequence of atmospheric and oceanic conditions (adapted from León-FonFay et al. (2026b)). Whether to identify a set of rare

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compound events that may be difficult to sample in a large ensemble (a), or to study long-lasting events requiring a highly specific sequence of atmospheric and ocean dynamics (b), a simulation conditioned to an observed atmospheric pathway ensures the presence of such events and allows their direct comparison in alternative thermodynamical backgrounds.

5. Concluding remarks

Table 1. Guidelines for interpreting Conditional Climate Trajectories	
The research question in the context of attribution	**Climate model ensembles:** How has climate change altered the likelihood and severity of a class of events across many possible climate realizations? **Conditional climate trajectory:** How does climate change affect a set of dynamically consistent events under a known atmospheric pathway? **Storylines:** How did climate change affect this event, given its atmospheric circulation?
Can climate statistics be computed?	Yes, but they remain conditional on the sampled atmospheric trajectory and should be interpreted in that context.
When are broader conclusions more defensible?	When responses arise from physically robust thermodynamic mechanisms, are supported by a sufficiently large, diverse, and representative sample of events, or are shown to be consistent with other lines of evidence (e.g. observations or climate-model ensembles).
When should we be cautious with extrapolating results beyond the conditioned trajectory?	When conclusions depend on limited time series, a small number of extremes or circulation regimes, events which are hard to simulate, or if rare events dominatie the diagnosed signal.
What are future potential applications?	As climate trajectories become longer and reach climate time scales, classes of historical events can be analysed, and more reliable statistics can be derived from dynamically consistent datasets embedded in a causal framework. Potential applications range from systematic attribution of underlying mechanisms, compound and complex events, climate-trend attribution, and robust climate-change signals across broader classes of 'real-life' observed events.
Are they climate projections?	No, they are a hypothetical experiment to represent what if the observed dynamical trajectory had happened in an alternative climate.

As storylines extend in time, an intermediate object emerges sitting between an event-based storyline and a free-running model. This intermediate object has the conditional nature of a storyline while containing multiple dynamical phenomena, long enough to represent climate, as in a conventional climate model, but along an observed dynamical pathway. This requires a new conceptual interpretation. We argue that this intermediate object can be interpreted as a conditional climate trajectory, where the atmospheric circulation follows a continuous long-term historical trajectory containing multiple storylines within it. They provide a controlled experiment, where a historical class of events can be compared through identical large-scale dynamics, under different thermodynamics.

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While their usefulness relies on providing causal insights into the influence of the thermodynamical component of global warming, careful interpretation is required. First, an experiment following a conditional climate trajectory is not a climate projection. A single realization conditioned on a historical pathway neglects possible dynamical changes also relevant for global warming. Second, the statistics derived from these datasets are conditioned to a unique trajectory, meaning that their generalization is not assured. This raises questions about the attribution statements they convey. For instance, when are the responses diagnosed from a conditional climate trajectory indicative of broader climate change signals, and when are they characteristic of the particular atmospheric pathway on which the analysis is conditioned? In Table 1, we propose a set of questions to guide the interpretation of results derived from conditional climate trajectories. While there is an emphasis on spectrally nudged storylines, these points apply to other storyline approaches extending in time.

Recent applications demonstrate both the potential and the challenges of this emerging conceptual object. Such studies illustrate how conditional climate trajectories can provide physically interpretable insights that are difficult to obtain from either individual storylines or climate-model ensembles alone. By enabling multiple events, processes, and impacts to be investigated within a common dynamical framework, they open new opportunities for attribution and climate research. We suggest that a multi-year storyline represents a conditional climate trajectory, not merely a longer form of storyline analysis, but a distinct category of climate information whose role may become increasingly important in bridging event attribution and climate-scale understanding.

Code and data availability

All custom codes are implementations of standard methods in Python. The code used to produce the figures in this paper is available from the corresponding author upon request. The MPI-ESM-LR Grand Ensemble dataset is publicly available at https://esgf-data.dkrz.de/search/cmip6-dkrz/?mip_era=CMIP6&activity_id=RFMIP&institution_id=MPI-M&source_id=MPI-ESM1-2-LR (last access: 26 August 2026). The global spectrally nudged storyline dataset is available upon request.

Author contributions

DLFF conceptualized the initial idea, wrote first draft and prepared visualization. All authors equally contributed to conceptualization and writing (review and editing).

Competing interests

Authors declare no competing interests.

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