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ADVANCED REVIEW

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# Varieties of approaches to constructing physical climate storylines: A review

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**Abstract**

The physical climate storyline (PCS) approach is increasingly recognized by the physical climate research community as a tool to produce and communicate decision-relevant climate risk information. While PCS is generally understood as a single concept, different varieties of the approach are applied according to the aims and purposes of the PCS and the scientists that build them. To unpack this diversity of detail, this article gives an overview of key practices and assumptions of the PCS approach as developed by physical climate scientists, as well as their ties to similar approaches developed by the broader climate risk and adaptation research community. We first examine varieties of PCSs according to the length of the causal chain they explore, and the type of evidence used. We then describe how they incorporate counterfactual elements and the temporal perspective. Finally, we examine how value judgments are implicitly or explicitly included in the aims and construction of PCSs. We conclude the discussion by suggesting that the PCS approach can further mature in the way it incorporates the narrative element, in the way it incorporates value judgments, and in the way that the evidence chosen to build PCSs constrains what is considered plausible.

This article is categorized under:

Assessing Impacts of Climate Change > Scenario Development and Application

Climate, History, Society, Culture > Technological Aspects and Ideas

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KEYWORDS

climate change, climate risk, counterfactual, methodology, physical climate storyline, storyline, value judgments

## 1 | INTRODUCTION

The concept of "climate storyline" is being increasingly taken up by the physical climate modeling research community and it is used to describe an approach to produce decision-relevant climate information. For example, the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) of Working Group 1 (WG1) dedicates a section to this concept in the introductory chapter (Chen et al., 2021, sect. 4.3.4), and box 10.2 mentions this concept as a tool for different purposes:

- for the exploration of low-likelihood, high-impact events (Lee et al., 2021, sect. 8), and/or of cross-scale interactions for the purpose of informing adaptation (Doblas-Reyes et al., 2021, sect. 3.4.2),
- as a particular approach to put historic events in the context of a changing climate (Doblas-Reyes et al., 2021, sect. 3.2.2),
- as an alternative approach to event attribution studies (Seneviratne et al., 2021, sect. 2.4),
- as information distillation exercises (Doblas-Reyes et al., 2021, sect. 5.3), or
- as providing climate information that is integrated with socio-economic information and delivered in the form of narratives through climate services (cross-chapter box 12.2 in Ranasinghe et al., 2021).

However, the many purposes mentioned by the IPCC AR6 WG1 and by Shepherd et al. (2018) prompt the question of how the concept is translated into scientific practice within the physical climate science community, given its particular sets of existing paradigms. The answer to this question can help establish the relation of the physical climate storyline approach as taken up by the physical climate science community to other existing approaches to developing decision-relevant information in the wider climate research community. It can also help evaluate the maturity of the approach, applications for which it is fit-for-purpose and whether it meets the needs of potential users of PCSs.

Here, we adopt the definition of "physical climate storyline" (PCS) introduced by Shepherd et al. (2018): a PCS is a "self-consistent and plausible unfolding of a physical trajectory of the climate system, or a weather or climate event, on timescales from hours to multiple decades." There are at least three components that any PCS needs to include according to this definition. First, it needs to be self-consistent and within the realm of physical plausibility, which implies that a causal element grounded in scientific understanding needs to underlie the physical trajectory of the climate system, or weather or climate event. Second, it needs to include a climate or weather component (in contrast to traditional scenarios that describe future socio-economic states not necessarily explicitly referring to climate or weather elements). Third, it needs to include a temporal element, that is, the storyline needs to unfold in time, but it is not confined to the future—it can also describe the past or present unfolding of a physical trajectory.

There is another important component of PCS that is not explicitly mentioned in the definition, and this is counterfactual ("what-if-things-had-been-different") thinking about causation. Menzies and Beebee (2020) provide a philosophical overview of this type of reasoning and Shepherd (2019) analyses it in the context of the application of causal networks to storyline constructions. Counterfactual reasoning is already used in the context of exploration of future risk associated with hypothetical alternatives to extreme events of the recent past (Woo et al., 2017). This type of reasoning can be a powerful tool to make assumptions and value choices on the part of modelers and decision-makers more explicit. For example, Weber (1996) introduces "downward" counterfactuals, which are built by considering how things could have possibly been *worse* with respect to a particular state of affairs, therefore making the value judgment that drives the counterfactual explicit. Woo (2019, 2021) extends this reasoning to extreme events. When applied to PCSs, counterfactual reasoning makes the conditional nature of PCSs explicit, can be used to introduce temporal elements of PCS (Section 3), and helps make value choices on the part of modelers and decision makers more explicit (Kunimitsu et al., 2023), an issue we address in detail in Section 4.

Several of the above components introduced as part of the PCS approach are rooted in insights developed by the broader climate research community, especially about climate change risk assessment and adaptation planning. As recognized by Shepherd et al. (2018), the definition of PCS clearly borrows from that of "scenario" which is defined as a "plausible [...] description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships" (Millennium Assessment, 2005). Similarly, "scenario storylines," described as the qualitative component of scenarios, do not seek to make predictions, but aim at exploring plausibility and uncertainties, especially in the context of human–environmental relationships (Rounsevell et al., 2021; Rounsevell & Metzger, 2010), an aim shared by PCS (Shepherd et al., 2018). The importance of exploring the evolution of a scenario has been developed and used in contexts where there is a high degree of complexity and uncertainty (O'Neill et al., 2020), such as projections of future population or technology (see, e.g., O'Neill, 2004). Furthermore, some of the problem-framing elements of PCS are rooted in the climate scenario-driven "impact approach" of the early IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations (Carter et al., 1994; see also Jones, 2001 and Carter et al., 2007, especially sect. 2.2) and climate risk assessments (Jones & Mearns, 2005).

The narrative element of climate information has also been increasingly recognized as important in adaptation planning and communication of information more generally (Fløttum & Gjerstad, 2017). Importantly, different typologies of narratives can help highlight different aspects of the information and its implications, such as environmental, personal, or social aspects of climate change adaptation (Coulter et al., 2019; Jensen, 2021). Narratives also help identify adaptation pathways in complex human–environmental systems (da Cunha et al., 2020). More recently, Baulenas et al. (2023) have explored the use of the storyline concept in climate-related research and have found that PCS is one approach alongside at least two others: discourse analytical approaches, which focus on building narratives that "share meaning [of research objects] among actors, associated practices, and the underlying discourses in relation to climate change, science, and policy" (Baulenas et al., 2023, p. 6), and scenario analysis—which is defined as above. Their analysis suggests that cross-pollination of these approaches can be fruitful. Here, we focus on the concept of PCS and explore in more depth how it has already borrowed from other climate research fields.

To establish how the physical climate science community has taken up the concept of PCS and the elements outlined above, our analysis starts by identifying key varieties of the PCS approach associated with references mentioned in the IPCC AR6 WG1 report. It broadens the analysis by looking at more recent peer-reviewed publications of physical climate scientists that adopt these different varieties of the approach, traces how the approach has borrowed concepts from the broader climate research community and how the approach has developed in recent years. Centering our analysis in the IPCC assumes that the IPCC provides a broad assessment of physical climate change research, where climate scientists can individuate a methodology as being part of a general approach. This choice assures that methodologies that physical climate scientists themselves identify as representing the PCS approach are included even if the term "storyline" is not used in individual publications, allowing for a broad evaluation of how the physical climate science community is adopting this approach.

Section 2 describes the characteristics of different ways of developing PCS and organizes the literature according to key methodological choices that exemplify different varieties of the PCS approach (i.e., how the unfolding of the physical trajectory is constructed). In Section 3 we describe how the temporal element is included in PCS. In describing key varieties of approaches to developing PCS, we highlight how these are related to other relevant approaches developed by the broader climate research community. Section 4 discusses in more detail how value judgments are implicitly or explicitly included in the aims and construction of PCS. Section 5 suggests where the PCS approach can further mature, and we provide a brief conclusion in Section 6.

## 2 | VARIETIES OF THE PCS APPROACH

Shepherd et al. (2018) argue that PCS can (i) provide a different type of framing of risk for particularly hazardous events in a way that is directly targeted at people's perception and response to risk, (ii) strengthen decision making by starting from a specific decision point or the consideration of key vulnerabilities of a target and combining climate change information with other relevant factors, (iii) provide a physical basis for partitioning uncertainty, especially when Global Climate Model (GCM) and regional model output is combined; and (iv) explore boundaries of plausibility in a way that differs from, and goes beyond, approaches that are rooted in statistical analyses of model output. It has also recently been argued that the PCS approach is an important step toward providing more meaningful, and hence usable, climate science (Shepherd & Lloyd, 2021).

These aims have long been recognized to be important in risk assessment and policy analysis. In their foundational book on the topic, for example, Morgan et al. (1990) argue that the decision-centric problem framing and explicit consideration of uncertainties (and what the uncertainties are of) are two of the "ten commandments" of good policy analysis (pp. 36–44). In general, the PCS approach, as taken up by physical climate scientists, borrows insights from the broader climate change impacts and adaptation community. In particular, the PCS approach incorporates methodological frameworks related to the development and communication of information about climate-related risks that involve high degrees of uncertainty (see, e.g., Carter et al., 2007; Jones, 2000, 2001), aiming to provide an explicit analysis of the assumptions and values involved in how this information is developed and how this affects exploration of uncertainty.

Here, we summarize and analyze the varieties of the PCS approach used to develop PCS and describe the different ways of developing PCS that are illustrated in Figure 1. While there is some overlap with the categorization of the IPCC in terms of the purposes of PCS, this overlap is not complete. The identification of variants specified here is guided by the thematic focus of the PCS. These foci are the following: (a) climate at the regional scale and related uncertainty

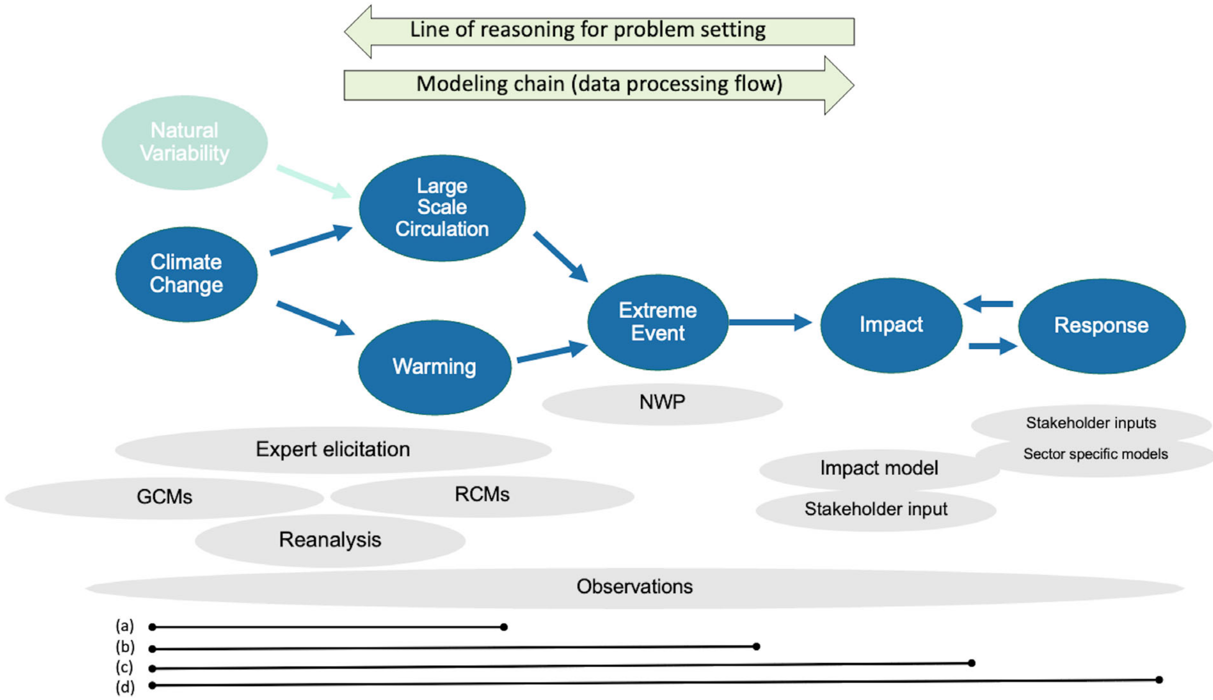


**FIGURE 1** Causal chain that represents the unfolding of a physical trajectory of the climate system, or a weather or climate event at different spatiotemporal scales. The two arrows at the top of the figure represent the starting point for problem setting, which usually starts from the extreme event or impact and then investigates its climatic context (top) and the flow of data along the modeling chain (bottom). Blue ovals show the links of the causal chain that are usually explicitly represented in PCS and light blue oval (natural variability) is what is conditionalized on. Blue arrows represent the direction of causation. Gray ovals represent different sources of evidence used to substantiate different links of the causal chain. GCM is "Global Climate Model," RCM is "Regional Climate Model," and NWP is "Numerical Weather Prediction model." Lines associated with (a), (b), (c), and (d) indicate which components of the causal chain are taken into consideration for different varieties of PCS development described in the main text. Adapted from Shepherd (2019).

(Section 2.1), (b) effects of climate change on regional hazards (Section 2.2), (c) the impact of hazards that occur under different types of climatic conditions, and (d) the consequences for impact that different adaptation strategies/options (or the lack thereof) can provide (Section 2.3).

Figure 1 shows what types of evidence are used to support the different causal elements of the PCS in relation to its focus [(a) to (d)]. PCS are predominantly constructed by using one or more of the following models at different scales: from GCMs, to regional models, to numerical weather prediction models, to societal and climate impact models. PCS can have different spatiotemporal foci, for example, climate at the regional scale, local weather events, or impact propagation. Furthermore, PCS can be produced by climate scientists or interdisciplinary groups of scientists, who either work to improve process understanding of relevant phenomena, or who analyze model output once informed by stakeholders' interests, or co-produce information with stakeholders.

Note that the top arrow in Figure 1 shows that the line of reasoning that is followed in problem setting usually starts from the right-hand side and is directed toward the left. So, depending on the length of the causal chain, the line of reasoning can start from the choice of an extreme event, an impact, or a type of adaptation response that those involved in the construction of PCS are interested in exploring. This implies that different kind of values will be driving the PCS construction process than would be if the problem were set starting from GCMs, a topic we explore in more depth in Section 4. Table 1 provides representative storylines associated with the different PCS varieties described. For a more detailed technical description of representative storylines, see the table in the Data S1.

## 2.1 | Variety (a): Climate at the regional scale and related uncertainty

One focus of PCS is regional climate change. In this case, the aim is usually to provide a physical basis for partitioning uncertainty by analyzing Global Climate Model (GCM) ensemble output, sometimes in combination with Regional

**TABLE 1** Representative examples of storylines developed with the PCS approach, including their spatial and temporal focus.

| Reference | Storylines | Spatial focus | Temporal focus |
|---|---|---|---|
| van den Hurk et al. (2014) | Variety (a): Several storylines illustrating European regional warming and strong Arctic amplification, with high-pressure anomalies in the Mediterranean for the winter and west of the British Isles in the summer. Storylines show different responses in the Rhine basin, where pressure response patterns that lead to strong temperature anomalies are different from the ones that generate large precipitation anomalies. | Regional climate | Future (Representative Concentration Pathways - RCPs) |
| Zappa and Shepherd (2017) | Variety (a): Storylines illustrate atmospheric circulation change depending on three remote drivers: tropical and polar amplification of global warming and changes in stratospheric vortex strength, and the effect of this on Mediterranean precipitation change and central European windiness change. | Regional climate | Future (RCPs and global warming levels) |
| Dessai et al. (2018) | Variety (a): Narratives describing different possible combinations of moisture availability over the Arabian Sea and strength of flow perpendicular to the Western Ghats (India) and their local effect. Depending on the dominance of either of these drivers, different precipitation changes are described over the Cauvery River Basin in Karnataka, India. | Regional climate | Near future (2050s) |
| Trenberth et al. (2015) | Variety (b): Examples of causal narratives of extreme events that connect synoptic atmospheric and ocean conditions with extreme events: "snowmaggedon" in Washington DC in February 2010 and its connection to unusually high sea surface temperature (SST) in the tropical Atlantic Ocean; Superstorm Sandy in New Jersey in October 2012 and counterfactuals of the storm with different levels of SST and their effect on storm intensity; super typhoon Hayan in the Philippines in 2013 and sea level and SST anomalies; Boulder (Colorado, USA) floods and SST in the Gulf of Mexico—this study is compared with the analysis of the same event of Hoerling et al. (2013). | Regional climate | Not specified |
| Meredith et al. (2015) | Variety (b): Two storylines, one describing the observed extreme 2012 Krymsk (Baltic region) precipitation event. The other storyline describes the same event with lower SST, showing a lower intensity event. The storylines are connected by an explanation of a physical mechanisms that links the sudden amplification of coastal convective precipitation and gradual SST increase. | Local hazard | Past (1980) |
| Hazeleger et al. (2015) | Variety (b): Storyline describing a compound event of precipitation and surge due to wind led to a large hydrological impact in the Netherlands, exposing vulnerability of the region to such events. A counterfactual "what if" storyline is explored by simulating the same event under conditions of sea-level rise. | Local hazard | Future (assumed warming scenario) |
| Pall et al. (2017) | Variety (c): Storylines describing the heavy precipitation event leading to the Colorado floods of September 2013 under observed climatic conditions and a counterfactual condition without global warming. The storylines provide a mechanistic analysis of the contributions from atmospheric dynamics and thermodynamics to the extreme event. | Local hazard | Past (no anthropogenic forcing) |
| Hegdahl et al. (2020) | Variety (c): Several storylines based on four high-precipitation events in Norway and their impact on selected catchments. | Local hazard | Future (RCP 4.5) |

(Continues)

TABLE 1 (Continued)

| Reference | Storylines | Spatial focus | Temporal focus |
|---|---|---|---|
| | Different storylines explore different combinations of event and catchment conditions, showing possible impacts under hypothetical future conditions. | | |
| Bhave et al. (2018) | Variety (d): Several climate and socioeconomic narratives of changes in key drivers of regional climate change in the Cauvery River Basin and changes in agricultural and urban water demand applied to water resources planning. The adaptation options and pathways are tested against different performance metrics under different storylines. | Regional climate | Near future (up to 2050s) |
| Jack et al. (2020) | Variety (d): Several narratives exploring possible climate risks to key systems of interest to local governing bodies: e.g., in Lusaka interest was expressed in exploring potential risks to the Kafue river flows. For Windhoek three narratives explored to represent the uncertainty in climate information, linked with "provocative" socioeconomic scenarios. Narratives varied drastically depending on the region in which they are developed. | Regional climate (determined by political boundaries) | Future (dependent on stakeholder) |

*Note*: van den Hurk et al. (2014), Zappa and Shepherd (2017), and Dessai et al. (2018), Bhave et al. (2018) are not based on observed events and only include future storylines (see Figure 2(i)). Other temporal components are based on observed events and counterfactuals of possible past or possible future (see Figure 2 (ii),(iii) as well as the discussion in Section 2.2). For more detailed descriptions of the methodological steps implemented in these storylines as well as their intended purpose, see the Data S1.

Climate Model (RCM) output, expert elicitation, or observation and reanalysis data. The aim, here, is to improve the communication of climatic information by improving the understanding of sources of uncertainty in the dynamics and thermodynamics of the projection.

An early example can be found in Risbey et al. (2002), where GCM output and synoptic–dynamical reasoning are used to develop physically consistent qualitative information about regional climate change. The importance of physical reasoning in the interpretation of uncertainty in GCM output at the regional scale has also been recognized more recently (see, e.g., Giorgi, 2020; Shepherd, 2021). Shepherd (2014) has argued that the dynamical components of general (atmospheric) circulation can be isolated when evaluating model responses to anthropogenic forcing to provide a more meaningful study of climate impacts and related uncertainties (see also Shepherd & Lloyd, 2021 and Trenberth et al., 2015 for similar arguments).

This variety of PCS approach has been used to evaluate how mean temperature and atmospheric circulation, as represented in model ensembles of the Coupled Model Inter-comparison Project phase 5 (CMIP5), drives sub-continental expression of mean temperature and precipitation (e.g., Manzini et al., 2014; van den Hurk et al., 2014). Zappa and Shepherd (2017) use elements from van den Hurk et al. (2014) and Manzini et al. (2014) to individuate remote drivers of the components of regional atmospheric circulation responsible for European weather trends during the cold season and evaluate their response to global-mean temperature increase. This method has been extended to systematically evaluate qualitatively different model responses to anthropogenic forcing at the regional scale (see, e.g., Garrido-Perez et al., 2021; Harvey et al., 2023; Mindlin et al., 2020; van der Wiel et al., 2021; Zappa, 2019).

Dessai et al. (2018) use a different type of evidence basis to explore uncertainty in regional climate change. Here, the authors use the Sheffield Expert Elicitation Framework (SHELF) (see O'Hagan, 2019) to identify a hierarchy of large-scale processes that drive the Indian Summer Monsoon and organize the possible responses of the two most relevant processes along two axes (adapting the approach of Van't Klooster & van Asselt, 2006) to construct a space of possible near future (2050s) responses to global warming of these processes. These responses were subsequently compared with reanalysis data of the recent past to corroborate the expert elicitation and provide further evidence for the PCS.

The unifying theme of variety (a) is the explicit use of a temporally extended causal chain to explore the uncertainty of future regional climate change. The plausibility of the chain is supported by model output, observations, and structured expert elicitation, but in all cases physical arguments drive the narrative element of the PCS. This variety still mostly follows the problem setting of top-down risk assessments and "predict-then-act" approaches to decision making, where the capacity to model climate change is prioritized and the cause-effect relationships are followed to provide meaningful information for systems of interest (Carter et al., 2007; Jones & Preston, 2011). Nevertheless, the prioritization of systematic physical interpretation of model output at different spatiotemporal scales aims at making the information more accessible and easier to interpret.

## 2.2 | Variety (b): Effects of climate change on regional and local hazards

Another way of developing PCS starts from extreme weather events or extreme sea level rise that can have a high impact on human and environmental systems. As such it prioritizes values related to the need to explore events that have *severe* consequences for human and environmental systems, including low-likelihood-high-impact (LLHI) events (Lee et al., 2021, sect. 8). So, it is also a way of further exploring events for which little is known due to their low likelihood, therefore promoting scientific understanding thereof.

This variety of PCS is more explicitly different from the predict-then-act approach as it aims to co-identify with key interested stakeholders high-impact events that are not well captured in model projections and observation records (Sillmann et al., 2021). This further allows for the integration of different perspectives and values. Nevertheless, model fitness remains a key priority in this approach and no impact or societal vulnerability is explicitly taken into consideration in the modeling chain.

Hoerling et al. (2013) introduced key steps of this variety by examining the climatological context of an extreme drought event by combining and analyzing present and past climatology derived from GCMs (from CMIP5) and initialized forecast model output. This strategy has been generalized to develop PCS by choosing an event of interest, identifying the large-scale atmospheric conditions of the event, and creating counterfactual storylines by scaling the thermodynamic components of large and mesoscale systems to obtain new boundary and initial conditions for (or alternatively to constrain the time evolution of the large-scale flow of) high-resolution numerical weather prediction. Thus, this strategy does not investigate whether the synoptic conditions assumed in the storyline would occur in a different climate (Shepherd, 2016, p. 34), but does explore the regional impacts of such circulation under changed climate conditions. The scaling of the thermodynamic component is substantiated by the arguments of Trenberth et al. (2015) (but note the criticism of this assumption by Otto et al. (2016)).

The aim of variety (b) is to explore the causal chain describing hazardous and/or LLHI events, such as droughts or intense rainfall events, unfolding over relatively short temporal scales and across different spatial scales under different climatic conditions, and it has been taken up extensively (see, e.g., Chen et al., 2020; Gutman et al., 2018; Hibino et al., 2018; Kanada et al., 2017; Lackmann, 2015; Lau et al., 2016; Lawal et al., 2016; Meredith et al., 2015; Pall et al., 2017; Patricola & Wehner, 2018; Sánchez-Benítez et al., 2022; van Garderen et al., 2021; Wehrli et al., 2020). This particular method to construct PCS is described as an alternative framework for extreme event attribution studies (e.g., Shepherd, 2016; van Garderen & Mindlin, 2022) or as what has been called a "pseudo global warming study" (Doblas-Reyes et al., 2021, sect. 3.2.2; Schär et al., 1996). The use of high-resolution models—such as regional climate models—allows for the explicit representation of small-scale processes such as atmospheric convection—a key component of precipitation—and it can lead to a closer analysis of how temperature and moisture increase are related during extreme precipitation events (e.g., see Pall et al., 2017).

## 2.3 | Varieties (c) and (d): Impacts and adaptation

PCS can be constructed to also include impacts of hazardous events under different physically plausible climatic conditions (Coughlan de Perez et al., 2023; Goulart et al., 2021; Hegdahl et al., 2020; Middelanis et al., 2021; Schaller et al., 2020; Sillmann et al., 2021). This variety (c) shares many methodological details with (b) and extends it by feeding NWP model output into an impact model to estimate the effects of hazards occurring under physically plausible climatic conditions (van den Hurk et al., 2023). This variety is used for exploring the extent of floods (Schaller et al., 2020) or weather-induced crop failure (Goulart et al., 2021) in counterfactual conditions. For example, Goulart et al. (2021) constructs a modeling chain to study the causal relation between climate change, severe weather, and crop failure. The chain studies the key variables of the weather event that led to a historical crop failure in the United States in 2012 (diurnal temperature range, precipitation, and temperature for growing seasons), and studies the occurrence of these variables jointly (as representative of the occurrence of the same event) or individually (as each can have an impact on crop production) in warmer climates (2 and 3 degrees global warming), to explore the occurrence of crop failures in such climates. By using different model configurations, it is also possible to explore how different features of impact models, such as spatiotemporal resolution, can affect the simulation of the impact (Hegdahl et al., 2020).

The PCS can further extend the modeling chain (see Figure 1) and combines observational datasets, GCMs, weather prediction, and impact model output to create a causal chain of events from climatic conditions to hazardous events, to impact propagation (variety (d)). The chain sometimes includes possible adaptation or policy options that may mitigate impacts (see, e.g., Bhave et al., 2018; Ciullo et al., 2021; De Bruijn, Cumiskey, et al., 2016; De Bruijn, Lips, et al., 2016; Koks et al., 2022; Yates et al., 2015). This variety can also involve the interaction of different types of scientists (e.g., physical climate scientists, environmental or social scientists) with stakeholders to define a problem space and identify hazards and impacts around which to build the storyline (e.g., Bhave et al., 2018; Ciullo et al., 2021; Sillmann et al., 2021). Nevertheless, PCS are mostly developed by scientists after information is retrieved from stakeholders, loosely following the "iterative interaction" co-production lens described in Bremer and Meisch (2017). This lens involves an iterative process where stakeholders are consulted to enhance the relevance of the modeling-based analysis (Bhave et al., 2018).

New ways of constructing PCS that explore potential socio-economic consequences of climate impacts are currently being developed (see, e.g., Ciullo et al., 2021; Mester et al., 2021; Middelanis et al., 2021). For example, Ciullo et al. (2021) combine NWP and impact model output to evaluate the impact on local infrastructure and how this propagates to financial systems in the EU, showing the explicit dependence of the financial health of the European Union Solidarity Fund on capitalization choices thereof. So, they provide alternative storylines that explore the relation between hazardous events, impact propagation, and financial cost to the European Union. This particular way of constructing PCS allows for an explicit consideration of values both in building the storyline, and in the kind of policy options that one might choose depending on one's risk aversion (Kunimitsu et al., 2023).

The common theme here is that varieties (c) and (d) are rooted in historical events and the construction of model chains that recreate the causal chain describing the event. Alternative storylines are then constructed to explore the chain in different climates or different policy contexts. The plausibility of the alternative storylines is usually argued for by evaluating the modeling chain with data of the historical event and how the causal chain would unfold under different climate or policy conditions.

Moreover, these varieties share the objectives of scenarios of integrating across different research disciplines—in particular climate/earth system modeling and the assessment of impacts, adaptation, and vulnerability—and being relevant to questions about climate change and decisions that can inform severity of impacts or adaptation decisions (van Vuuren et al., 2014). Furthermore, some iterations of these varieties are based on risk assessment models. For example, Middelanis et al. (2021) base their work on the input–output model developed by Hallegatte (2008) that links disasters with the socio-economic costs of their impacts to study the impact propagation in detail. On the other hand, Ciullo et al. (2021) use a problem framing similar to the one for exploring uncertainty for decision-making described by Lempert et al. (2004, sect. 4), where policy decisions are assessed against a range of possible scenarios.

## 3 | TEMPORAL PERSPECTIVES OF PCS

As described in Section 2, PCS represent a physically plausible causal chain of events and are usually constructed to ask about the effect of specified interventions on the causal chain (Shepherd, 2019). Here we focus on how the temporal element is introduced into PCS.

While PCS associated with variety (a) usually explore future possible chains of event (see Figure 2(i)), varieties (b)–(d) often start from an observed event in the recent past. Once the benchmark is established, counterfactual storylines are constructed to represent analog past, present or possible future conditions. This type of counterfactual reasoning has also been used generally in risk assessments where the sensitivity of key components of the system is tested against changes in climatic conditions (Jones & Mearns, 2005). These varieties take into account key elements of risk analysis, where the effects of climate and policy and the associated uncertainty on a target of interest (e.g., the intensity of a hazardous event, and/or its impact propagation) are explored. To do so, alternative storylines that represent possible past or future chains are constructed by intervening on elements of the chain that can represent possible past or future conditions. This implies that these PCS usually come in groups of two or more PCS, of which one is

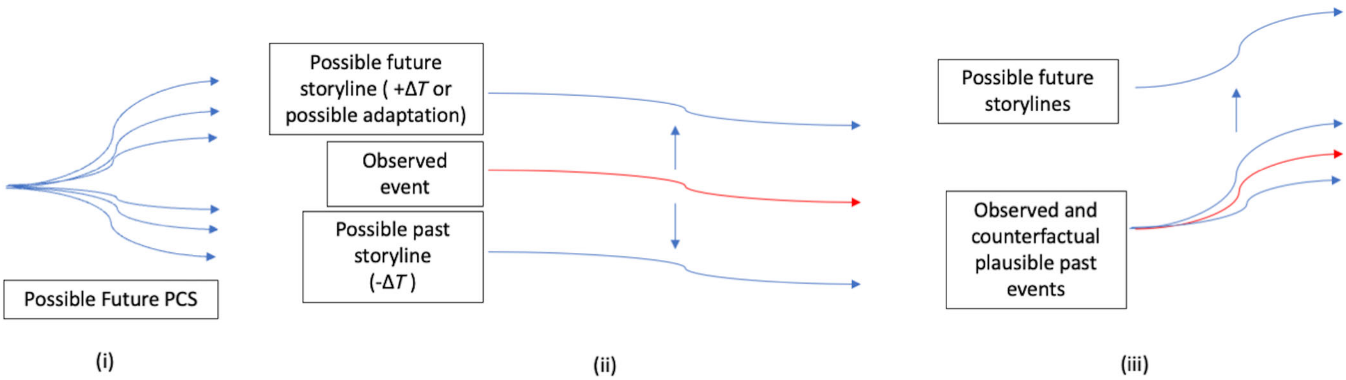


**FIGURE 2** Temporal element in the PCS approach. The red arrows represent the factual storyline based on observed event(s), and the blue arrows represent plausible counterfactual storylines. The upward and downward arrows in (ii) and (iii) indicate the intervention that links the original storyline to representations of possible past or future storylines, both in regard to the climate component and to the response to the impact (through adaptation policies or reactive measures). In (ii) counterfactual interventions on the observed event are used to construct PCS that are of the past or the future. In (iii) possible counterfactuals of observed events are considered, and then further arguments are used to construct the temporal component of PCS.

factual (i.e., based on historical events) and at least one other is counterfactual. Each counterfactual member of the group can be rooted in conditions analogous to past, present, or possible future climate.

Possible future PCS (usually associated with variety (a)), however, are composed only of counterfactual storylines (Figure 2(i)). In this case, the different counterfactuals can represent different responses of climatic drivers to different forcings. PCS that follow varieties (b)–(d) are generally developed by first identifying a causal chain for a reference weather event, from observational data or model output, forming the factual storyline. Counterfactual storylines may then be constructed to investigate, for example, how an event would have unfolded in the absence of (the thermodynamic component of) anthropogenic forcing (e.g., Meredith et al., 2015; Pall et al., 2017; Patricola & Wehner, 2018; Takayabu et al., 2015; downward arrow in Figure 2(ii)), how an event would unfold in a climate with higher global mean temperature (see, e.g., Hegdahl et al., 2020, van der Wiel et al., 2021, upward arrow in Figure 2(ii)), how a different (predicted) realization of an extreme event would impact a specified system in a warmer climate (Ciullo et al., 2021, Figure 2(iii)), or how the frequency of unrealized forecast extreme events has changed over time (Coughlan de Perez et al., 2023). Some PCS construct both analog pasts and futures (Chen et al., 2020; Lackmann, 2015).

When counterfactual storylines are explored and compared with factual storylines, there are at least two different ways in which counterfactual storylines representing possible past or future events can be developed. One way constructs a causal description of a regional climate or weather event, separating dynamic and thermodynamic components at different spatial scales, and then intervenes on the thermodynamic component to construct the counterfactual storyline (Figure 2(ii)). This way of constructing a PCS is motivated by epistemic considerations regarding uncertainty of local responses to global warming (e.g., Shepherd, 2014; Trenberth et al., 2015), the representational accuracy of models of higher resolution (e.g., Meredith et al., 2015; Pall et al., 2017), or the inability of free-running GCMs to capture the target event (Chan et al., 2022; Hazeleger et al., 2015; van Garderen et al., 2021). In other words, the approach promotes values related to scientific understanding of climatic phenomena.

Furthermore, the counterfactual storyline can be built in such a way that it shows thermodynamic conditions analogous to past or future climate conditions. Counterfactuals from the past (e.g., negative global temperature change ($\Delta T$)) are usually derived from historical or reanalysis data (Cattiaux et al., 2010). Expected future thermodynamic conditions are derived either by forcing models by scaling with positive $\Delta T$ without any specific temporal connotation, or with global positive $\Delta T$ derived from CMIP5 model output for different greenhouse gas concentration levels (see, e.g., van der Wiel et al., 2021). The last column in Table 1 shows how representative examples of approaches to PCS incorporate the temporal element when building counterfactual storylines.

The other way of tying together the temporal characteristics of climate change and counterfactuals is exemplified by Ciullo et al. (2021) (see Figure 2(iii)). Their starting point to construct PCS is the identification of possible downward counterfactuals derived from unrealized predictions of observed high-impact events (e.g., hurricanes and their impact propagation) of the recent past—weather events that might plausibly have occurred under certain synoptic conditions actually observed in the past, but on those occasions did not. The counterfactuals examine modeled realizations of situations where such events (or even more extreme cases that are recognized as plausible with increasing climate change) do indeed occur. Here, the authors adopt the counterfactual approach of Roese (1999) which has been applied in the context of climate risk management by, for example, Woo et al. (2017) and Woo (2019). In this case, downward counterfactuals are possible event realizations with a *worse* outcome, that is, a more severe hurricane with a worse outcome for the vulnerable human and natural systems impacted, and upward counterfactuals are possible event realizations with a *better* outcome. PCS are constructed by inferring the ways in which a subset of these counterfactuals (upward or downward) can be considered analogous to similar events occurring in past or future climatic conditions. This use of counterfactuals, when represented through a causal network, can be particularly useful when analyzing value attitudes of those using PCS to support decision-making (Kunimitsu et al., 2023).

## 4 | PCS AND VALUES

The analysis in Section 2 shows that, in addition to different aims, there are different varieties of approaches to develop PCS. Each variety makes explicit or implicit assumptions about what kind of values it pursues. Making assumptions explicit is an important aspect of risk assessment (Jones, 2001) and PCS (Shepherd, 2019), especially when evaluating uncertainty. It is also increasingly recognized by scientists that different types of values enter the scientific process at different stages. For example, the IPCC recognizes that methodological choices in the construction of all types of climate information involve implicit or explicit value judgments, and Undorf et al. (2022) show how values enter model-based assessments of climate sensitivity. Moreover, it has been recognized that values should be incorporated and communicated more explicitly across various branches of climate science (Pulkkinen et al., 2022). Here, we exemplify how values enter the PCS approach to facilitate an explicit analysis of value judgments in climate science.

Philosophers of science distinguish between cognitive and non-cognitive values. Cognitive (also called "epistemic") values are usually those values that are thought to be conducive to scientific knowledge, such as empirical adequacy, internal consistency, simplicity, and variety of evidence, among others (see Kuhn, 1977, Laudan, 1984, and Quine & Ullian, 1978 for foundational work on values in science; and see Elliott, 2017 for a recent introduction). Non-cognitive values range from pragmatic to social and ethical values, such as "applicability to human needs," or how one addresses the unequal distribution of risk. The distinction and interaction between cognitive and non-cognitive values have been disputed: non-cognitive values have been argued to have an influence on the key cognitive values that are preferred by groups of scientists (Longino, 1996). Nevertheless, it is useful to distinguish between them as they may reflect different types of attitudes of scientists and decision-makers. Cognitive and non-cognitive values permeate scientific processes: from the selection of research questions to selection of methodology, to the evaluation of evidence, choice of boundary conditions and metrics, and how scientific results are communicated (Douglas, 2009). In many cases, scientists need to consider trade-offs between epistemic and ethical considerations, as can be seen, for example, in cases of flood risk management (Vezér et al., 2018).

Different types of values are embodied in the aims of the PCS approach. PCS can have cognitive aims, that is, aims related to the pursuit of knowledge—and hence promote cognitive values—and non-cognitive aims, that is, the practical, social, and ethical aims of the knowledge that is produced—and hence promote non-cognitive values. In many cases, these aims and values interact and intersect in complex ways. We evaluate what and how values are embodied in the aims of PCS described in critical perspectives of the approach found in the literature and exemplify how these values drive methodological choices in some examples of PCS.

Aims of the PCS approach that explicitly incorporate non-cognitive values can be found in Shepherd et al. (2018), Shepherd and Lloyd (2021), and Sillmann et al. (2021). Here, the values are related to providing actionable knowledge, that is, what Longino (1996) calls "applicability to human needs." For the case of PCS, the human needs are related to providing meaningful and usable climate science (Shepherd & Lloyd, 2021). This involves developing what Sillmann et al. (2021) call an "actionable risk perspective," targeting the framing of risks to people's perceptions and responses, and considering key vulnerabilities of those involved in and impacted by decision-making (Shepherd et al., 2018). The narrative element is particularly important in this context. As mentioned in the introduction, narratives do shape the information that is conveyed (Coulter et al., 2019; Fløttum & Gjerstad, 2017). This implies that narratives can be a way of explicitly conveying value judgments made in constructing PCS.

Furthermore, the backgrounds of a group of researchers can influence how particular values are used to construct PCS. Skelton et al. (2017) show that values held by groups of researchers can and do shape methodological decisions. For example, they show that scientists involved in producing Dutch national climate change scenarios (KNMI 2014) prioritized stakeholder engagement activities throughout the production of the scenarios, rather than eliciting user needs and feedback at limited stages throughout the production of this information (Skelton et al., 2017, pp. 2333–2334). These methodological decisions influenced the type of product that was developed, balancing tradeoffs between pragmatic needs of users—such as having easily accessible information and a limited set of scenarios and metrics—and the desire of scientists to produce quantitative estimates of uncertainty (Skelton et al., 2017, p. 2332). So, different groups of researchers and stakeholders will let different types of value judgments influence the kind of PCS that they produce. PCS that are produced by groups of physical climate scientists usually prioritize cognitive values with the purpose of improving mechanical/process understanding of remote drivers of regional climate change or extreme events and evaluating the associated uncertainty (e.g., Pall et al., 2017; Zappa & Shepherd, 2017).

On the other hand, approaches to developing PCS *with* stakeholders aim at co-producing PCS in a way that deeply integrates knowledge and values of stakeholders, which can also shape the approach to PCS construction. In this case, storyline development is not primarily led by scientists, but by different types of experts (scientific and non-scientific). Priorities of stakeholders are taken to be of equal importance when producing storylines, following the "extended science" lens (Bremer & Meisch, 2017). This approach is exemplified by Jack et al. (2020), where, depending on the region of interest, stakeholders, and local priorities, very different PCS are constructed. In this project (FRACTAL),[1] so-called "Learning Labs" were created where climate information was introduced with the aim of not having it dominate the narrative of the local decision-making process. So, depending on local priorities which affected the types of narratives that were co-created, climate information was either derived from forward-looking GCM output, expert elicitation, or past data (Jack et al., 2020, sect. 4). Jack et al. (2020) explicitly state that the goal of their PCS is to integrate "climate science information into urban decision-making" (p. 2), which promotes the pragmatic value of "applicability". The methodological choice associated with this value is to prioritize the local needs, which also meant de-prioritizing the development of new physical climate science and the exploration of uncertainty when creating decision-relevant information and engaging with local decision-makers.

Non-cognitive values can also influence implicit methodological choices in the PCS approach. For example, Ciullo et al. (2021) (see also Kunimitsu et al., 2023) construct "downward counterfactuals" by identifying those unrealized predictions that could have had a *more devastating* impact on the target region, and therefore on the EU Solidarity Fund. In this case, social and ethical considerations about highlighting key vulnerabilities of the region impacted by a climate hazard drive the methodological choice of what kind of counterfactual to consider. Moreover, what can broadly be considered cognitive values can have consequences for the non-cognitive implications of the type of information developed by the PCS approach. For example, PCS that are based on weather events (see Hazeleger et al., 2015; Sillmann et al., 2021) have been recognized to involve an explicit value judgment insofar as they focus on avoiding false negatives (type 2 errors) rather than false positives (type 1 errors) (Lloyd & Shepherd, 2020; Trenberth et al., 2015; Winsberg et al., 2020).

To clarify, Lloyd and Shepherd note that "by aggregating over an inhomogeneous population [e.g. a group of models that are not organized according to responses to key drivers of change as done in variety (a), models that make different parametrization or structural assumptions, and/or models with different grid size], statistical approaches are prone to miss the [climate change] signal and conclude with a statement such as "no effect detected", which makes them prone to type 2 errors" (Lloyd & Shepherd, 2020, p. 107). This implies that approaches that heavily rely on statistical analysis may miss effects of climate change when in fact climate change did have an effect. Type 1 errors, on the other hand, may lead to statements such as "an effect was detected" when in fact no effect was present. While it is difficult to pinpoint exactly what values may influence the avoidance of one type of error over another, Lloyd and Oreskes (2018) have argued that cognitive values such as "rigor" promote avoiding type 1 errors—as highlighted also in the "falsificationist" approach discussed in Lloyd and Shepherd (2020). Ultimately, however, the implication is that the information produced with this approach embodies the non-cognitive attitudes of scientists toward what philosophers have called "inductive risk," that is, scientists' evaluation of the implications of possible errors in their statistical (or scientific) analysis (see Douglas, 2000, 2009; Elliott & Richards, 2017).

PCS developers also make methodological choices that are the result of explicit tradeoffs between cognitive and non-cognitive values (for an in-depth analysis of this in the context of decision theoretical modeling and flooding, see Vezér et al., 2018). Hazeleger et al. (2015, p. 108), for example, develop a methodology that emphasizes "realism" and "coherence" in the representation of weather events and their impact in a future climate to reveal local hazards. The decision to emphasize vulnerability of the EU Solidarity Fund to cyclone intensity and frequency explored by Ciullo et al. (2021) is driven by non-cognitive values, whereas the focus on realism promotes cognitive values of accuracy of representation and consistency. Nevertheless, these values are not often explicitly discussed—which suggests that a more explicit mention of values can and should be integrated in PCS development (as done, e.g., in Kunimitsu et al., 2023).

## 5 | LOOKING FORWARD

As we have seen in Section 2, while many PCS are based on observed events, and some are constructed by substantially working with observations (e.g., Cattiaux et al., 2010; Chan et al., 2022; Dessai et al., 2018; Lloyd & Shepherd, 2021), PCS are mostly built from the results of analysis of model output, be this just one model or a modeling chain. Considering this analysis and the discussion in Section 4, there are several points regarding this approach that deserve further consideration and/or are currently under development. In particular, we focus on the need to include the narrative element (Section 5.1), and on efforts to diversify evidence and expand the boundaries of plausibility (Section 5.2). These themes are related to the aims of PCS identifying by Shepherd et al. (2018) and introduced at the beginning of Section 2: strengthening decision-making by starting from a particular stakeholder decision point or vulnerability and exploring the boundaries of plausibility.

### 5.1 | Including the narrative element

Emerging guidance (see, e.g., Shenk & Gutowski, 2022) about how model output and mechanistic explanations should be translated into narrative elements of PCS should be evaluated and adopted. Further research about how these translations depend on the purposes of PCS and the values that drive their development, such as improving understanding or communicating information about climate and related impacts within and across disciplines and areas of expertise, is also needed. Some steps in exploring this relation have been made in Shepherd and Lloyd (2021), in which a particular perspective on narrative is used and its relevance to PCS is discussed.

Relatedly, philosophers of science have explored how the narrative element can have an epistemic role in the sciences by promoting creativity and organization (Otto & Rosales, 2020). Nevertheless, there are many components of a narrative that have to be actively elaborated to create a story (see Paschen & Ison, 2012; Trutnevyte et al., 2014), and these may change depending on what groups of individuals build the PCS, and the intended audience of PCS. For example, classical, structural components of a narrative are *initial situation*, *complication*, *reaction*, *resolution*, and *final situation* (Fløttum & Gjerstad, 2017, p. 3) and narratives are also usually accompanied by a moral (Fløttum & Gjerstad, 2017). These elements are explained for PCS in Box 1 as an example of how a narrative could be constructed following certain principles. Narratives can explicate the values of stakeholders and scientists involved in constructing the PCS, for instance in the process of selecting boundary conditions or (impact) metrics. So, developing guidance on how narrative elements are incorporated in the development of PCS can improve the transparency and meaningfulness of climatic information. Having stakeholders as part of the PCS process is one step in creating accessible narratives that are relevant to the target audience and incorporate their cognitive and non-cognitive values. However, co-production of PCS is still underdeveloped. More explicit guidance on how to link expertise from different scientists and stakeholder groups needs to be part of the PCS methodology.

These considerations become particularly important when PCS are intended for a non-specialist audience. As is shown by Skelton et al. (2017), different scientists at different institutions interpret their aims differently, which has an influence on what and how values are promoted and incorporated in developing decision-relevant information. Moreover, Porter and Dessai (2017) show that in some cases, scientists see their audience as having similar skills as their own, which ultimately can lead developers of information to not provide adequate translations of the complex messages and limitations of their work. Explicit guidance on how to make values and assumptions explicit in information development within and across disciplines and areas of expertise, while extremely challenging, may improve the accessibility and relevance of PCS. Moreover, this would also allow the development of a protocol to monitor and assess the fitness-for-purpose and uptake of PCS, which is currently lacking.

### 5.2 | Diversifying evidence and expanding the boundaries of plausibility

The issue of reliance on models and the development of the narrative element in PCS is related to the role of (cognitive and non-cognitive) values in the PCS construction process. As discussed in Section 4, the type of evidence that is

**BOX 1 Example of possible narrative elements of a physical climate storyline**

In this box we explore possible narrative elements of a physical climate storyline in terms of: initial situation, complication, reaction, resolution, and final situation and moral (Fløttum & Gjerstad, 2017, p. 3) for the storyline briefly described in Hazeleger et al. (Hazeleger et al., 2015, box 1) for more detail see: van den Hurk et al. (2015) and Malagon Santos et al. (2021).

*Initial situation*: The Netherlands is well known for its highly managed hydrological system, which has a sluicing capacity from the inland waterways to the North Sea of 10 mm/day.
*Complication*: In early January 2012, 20–30 mm/day of rain fell for a few consecutive days, due to the passing of a synoptic pressure system. In addition, strong northwesterly winds at the end of the period prevented the sluicing of accumulated rainfall due to a wind-induced surge.
*Reaction*: This led the local authorities to order evacuation of the region, exposing the vulnerability of the region to this type of compound event.
*Resolution and final situation*: Local authorities led a call for extra measures.

This type of narrative can be further explored in a counterfactual case in which a similar event occurs in a situation with increased sea-level. Other narratives can also be explored in which the initial situation is altered by imagining a situation in which either the hydrological system or distribution of critical infrastructure in the region is altered. Research to substantiate the quantitative component of this counterfactual "initial situation" is currently being developed: for example, Nirandjan et al. (2022) have developed a spatially explicit dataset of critical infrastructure that can be combined with hydrological modeling to explore how these types of compound events would affect critical infrastructure such as energy storage and distribution networks.

Exploring combinations of possible realizations of the compound event in different climatic conditions (e.g., increased sea-level rise) for different socio-economic scenarios with different configurations of critical infrastructure can help develop a narrative that conveys a moral about either mitigation or adaptation actions, or both. For example, if emphasis is given on high sea-level rise with "business as usual" development of critical infrastructure and hydrological management, it can be highlighted that unmitigated climate change can lead to higher impact events than those observed in the recent past. On the other hand, if sea-level rise is combined with critical infrastructure and hydrological management that follows specific adaptation pathways (see Haasnoot et al. (2013) for a description of this concept), narratives can convey the importance of implementing adaptation independently of the mitigation actions taken, as different adaptation option can lead to less severe impacts. These storylines have been recently developed by Koks et al. (2022).

considered satisfactory to construct a particular storyline is related to the epistemic values of whomever is constructing the PCS. Moreover, the type of events, and the type of counterfactuals that are considered relevant are related to the socio-political and ethical values of both scientists and stakeholders. Making both cognitive and non-cognitive values more explicit in the PCS production process, and how these influence what PCS look like, may help improve the effectiveness of PCS as a communication tool and the transparency of the PCS methodology, and is one of the key principles of risk assessments (Jones, 2001; King et al., 2015; Sutton, 2019).

The use of models as the predominant evidence base for PCS raises some questions about the extent to which PCS can explore the boundaries of plausibility. In event-based storylines, plausibility is explored starting from an observed event (see Figure 2(ii),(iii)). There are two main factors that justify why event-based PCS are rooted in observed events. First, some neurological studies substantiate the hypothesis that imagining the future requires "a system that can flexibly recombine details from past events" (Schacter et al., 2007, p. 659), which suggests that rooting PCS in observed events may improve the uptake of information about possible futures. Second, PCS focus on *plausibility*, and observations of past events/event patterns, basic theoretical considerations and numerical models can support arguments about the plausibility of any counterfactual PCS. However, in many cases, the departure from the observed event is justified using only numerical models (for an exception to the use of models as evidence see Dessai et al., 2018). This approach to building PCS may underestimate the importance of going *beyond* the conceptual boundaries of numerical models (GCMs, RCMs, NWP models, and impact models), and does not always question whether these models are needed at all (see also Jones et al., 2014, p. 200, FAQ 2.1). This worry is usually avoided in the scenario approach (Moezzi et al., 2017) but becomes particularly acute when considering the importance of pushing the boundaries of what is considered plausible when sampling uncertainty space for robust decision-making approaches. So, the PCS approach could benefit from further investigation into the assumptions that underlie PCS and how plausibility is explored by using different types of evidence to construct PCS. Clarifying the assumptions and methodological choices can also help justifying the scientific contribution of PCS: be this about furthering understanding of earth-system processes and uncertainties in their representation or temporal evolution, or the development of a new, reproducible approach to exploring climate change-driven risk to current and future societies and ecosystems.

## 6 | CONCLUSION

In this essay, we have provided an analysis of the varieties of approaches associated with the concept of PCS (Section 2), how temporal perspectives are included (Section 3), and discussed how PCS can be driven by the different values of the scientists and stakeholders that build them (Section 4). Throughout the discussion, we have also highlighted how this approach is indebted to other approaches developed by the wider risk and scenario communities (Carter et al., 1994, 2007; Jones, 2001; Jones & Mearns, 2005), and we have identified aspects of PCS that need further developments (Section 5).

We have shown that the concept of PCS provides an approach that encompasses different varieties which can be distinguished by evaluating the evidence that is used to construct the storylines, the scope of the storyline (whether it is about regional climate or local impacts and adaptation measures), and how the temporal element is incorporated in baseline and counterfactual storylines. We have also shown how the different varieties can promote different types of cognitive and non-cognitive values. We have further identified areas of improvement in the future development of the PCS approach: the way it incorporates the narrative element in different contexts; the way it incorporates value judgments; and finally the way that the evidence chosen to build PCS constrains what is considered plausible. Along with the suggestions of Baulenas et al. (2023) to further promote the interaction across different communities using storyline concepts in climate-related research, these areas will help mature the PCS approach.

### AUTHOR CONTRIBUTIONS

**Marina Baldissera Pacchetti:** Conceptualization (lead); investigation (lead); methodology (lead); resources (equal); writing – original draft (lead); writing – review and editing (lead). **Liese Coulter:** Resources (supporting); writing – review and editing (supporting). **Suraje Dessai:** Conceptualization (supporting); methodology (supporting); project administration (supporting); supervision (supporting); writing – review and editing (supporting). **Theodore Shepherd:** Methodology (supporting); project administration (supporting); resources (supporting); writing – review and editing (supporting). **Jana Sillmann:** Writing – review and editing (supporting). **Bart van den Hurk:** Funding acquisition (lead); project administration (supporting); resources (supporting); writing – review and editing (supporting).

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The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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## ENDNOTE

[1] https://www.fractal.org.za/

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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