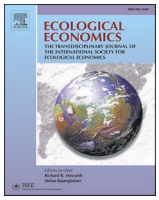
Ecological Economics 239 (2026) 108756

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon



ANALYSIS

Climate storylines to build resilience for European public and private risk finance instruments against remote events☆

Stefan Hochrainer-Stigler [a,*], Jan Brusselaers [b], Qinhan Zhu [a], Max Tesselaar [b], Alessio Ciullo [c]

[a] IIASA- International Institute for Applied Systems Analysis, Laxenburg, Austria
[b] IVM, Institute for Environmental Studies, VU Amsterdam, Amsterdam, the Netherlands
[c] CLIMADA Technologies & ETH Zurich, Switzerland

ARTICLE INFO

Keywords:
Climate storylines
Remote events
Public and private finance instruments
Cyclones
Europe

ABSTRACT

Europe is increasingly threatened by climate-induced events happening remotely from the continent. To test the resilience of selected public and private finance risk instruments against external shocks we analyse multiple hypothetical scenarios based on historic events, focusing on cyclone risks, and various alternative realisations, so-called climate storylines. We present the storyline approach as a systems approach to examine whether events outside a system can affect elements within the system. Furthermore, we provide a framework to analyse possible transmission channels of such remote events jointly as well as separately. In doing so we combine a multi-model approach within single and multi-climate storylines to better address the various vulnerabilities of risk management and adaptation options for today and in the future. We specifically focus on humanitarian emergency assistance (via the Caribbean Catastrophe Risk Insurance Facility), public sector governance help (via the European Union Solidarity Fund), macro-economic financial effects (by assessing international financial flows and investment decisions) and consequences to insurance uptake due to remote climate events (via increases in risk aversion of reinsurers). The experiences made with this approach are compared with the advantages and disadvantages of both storylines and probabilistic assessments and we provide ways forward for a unified approach.

1. Introduction

Natural hazard induced disaster events and corresponding losses, both in human and economic terms, are still increasing across the globe (Wallemacq and House, 2018) and natural variability, climate change as well as global changes will very likely exacerbate the problem in the future (IPCC, 2023). Furthermore, losses are and will not be distributed uniformly across systems, regions and sectors and resources and adaptation options to cope with disaster events differ significantly between risk bearers across the globe (IPCC, 2022). In this context, especially indirect (e.g. follow on consequences) and cascading (e.g. triggering further risks throughout the system) risks due to natural hazard events became a serious concern among scientists and policymakers as they can spread widely, eventually causing systemic risks to realize (Reichstein et al., 2021). The occurrence of compound events and the increased interdependencies between different sectors and scales further increases the intensity and therefore importance of indirect and cascading risks and its management (see, for example, in respect to Covid-19 and climate risk Dunz et al., 2023, in respect to systemic risk considerations Sillmann et al., 2022, and in respect to multi-risks Hochrainer-Stigler et al., 2023).

Generally speaking, such cascading effects can happen and stay within given system boundaries (e.g. countries or sectors), but they can also affect other systems (e.g. Helbing, 2013; Naqvi et al., 2020; Dunz et al., 2023). In that regard, the focus in this paper is on risk that is realised outside a given system boundary but affects the given system due to interdependencies, with a particular emphasis on the pivotal role of the financial sector and climate risk (Battiston et al., 2017; Monasterolo, 2020). This is an important topic as it links risk management and adaptation to threats that are usually outside the control of a given system or risk bearer. It also allows to stress test policies and instruments following such risks. Such considerations are especially important for Europe, our focal point of analysis regarding system boundaries, which faces increased threats from climate-induced events outside the

☆ This article is part of a Special issue entitled: 'Climate impacts and adaptation finance' published in Ecological Economics.

* Corresponding author.
E-mail addresses: hochrain@iiasa.ac.at (S. Hochrainer-Stigler), jan.brusselaers@vu.nl (J. Brusselaers), zhuqinhan@iiasa.ac.at (Q. Zhu), max.tesselaar@vu.nl (M. Tesselaar), alessio.ciullo@climada.tech (A. Ciullo).

https://doi.org/10.1016/j.ecolecon.2025.108756
Received 29 January 2024; Received in revised form 24 February 2025; Accepted 5 August 2025
Available online 25 August 2025

continent (Mahalingam et al., 2018). Those risks are transmitted via increased global interdependencies in socio-economic sectors, financial networks, and the escalation of natural disasters worldwide (Poledna et al., 2020). Various natural hazards can result in such interdependencies, and we pay particular attention on one hazard, namely cyclone risks. This natural hazard is chosen here because such storms cause on average the largest economic damages (Jaramillo et al., 2023). Furthermore, our emphasis will be on spillover effects, and multi-risks due to such events including an analysis of transmission channels and potential amplification effects, selected risk instruments, and adaptation options to lessen those impacts in Europe.

Innovatively, these effects will be further analysed according to different changes in climate and global settings using a so-called climate storyline approach. A climate storyline approach is quite different compared to risk-based approaches. The latter typically uses the full probabilistic information of (random) natural hazard events induced losses for assessing management options, most prominently insurance (Woo, 2011). In contrast, climate storylines are based on past events but include plausible different risk realisations under different current and future climate and socio-economic settings. Such climate storylines allow a stress test instead of an assessment of the impact of probabilistic event sets. This stress test can trigger a wake-up call and motivation to change and improve climate risk governance (Krauß and Bremer, 2020). Another argument in favour of the storyline approach mainly emerges from a key weakness of the probabilistic approach. Those probabilistic top-down approaches from global climate model ensembles simulations usually inadequately deal with uncertainties in regional climate predictions as aleatoric and epistemic uncertainties are mixed (Shepherd et al., 2018). Climate storylines do not focus on the probabilistic information of events but instead place emphasis on the consequences that can be assessed, understood and conditioned on specified climatological and socio-economic boundary conditions (van den Hurk et al., 2023). This allows risk bearers to better navigate through the complex interrelationships that could emerge, create and increase risks, and possibly result in spillover and cascading effects. As will be discussed, climate storyline as well as probabilistic approaches have their advantages as well as weaknesses in providing information for managing risk.

In this context, our analysis both considers public and private instruments, including humanitarian emergency assistance (via the Caribbean Catastrophe Risk Insurance Facility, CCRIF), public sector governance help (via the European Union Solidarity Fund, EUSF), macro-economic financial effects (by assessing international financial flows and investment decisions) and consequences to insurance uptake due to remote climate events (via increases in risk aversion of reinsurers). The climate storyline will shed light on the remote risks to Europe and the associated instruments and will therefore provide a detailed analysis of the potential impacts on public and private finance due to these plausible events and impacts due to climate change. This paper's contribution to the literature on climate risk and adaptation finance measures can be summarized as follows: First, we present the storyline approach as a systems approach to examine whether events outside a system can affect elements within the system. The impact of remote events on Europe has not been described in detail yet. Second, we provide a framework to analyse possible transmission channels of such remote events jointly as well as separately. Third, we combine a multi-model approach within single and multi-climate storylines to better address the various vulnerabilities of risk management and adaptation options for today and in the future. Fourth, we discuss and compare the advantages and disadvantages of both storylines and probabilistic assessments based on the experiences gained from the economic modelling approaches. For example, while a storyline approach can indicate the potential impacts on finance instruments due to remote events, a probabilistic approach is often needed for setting up such instruments, e.g. for insurance the risk must be quantifiable. We therefore call for a hybrid approach that take both considerations into account.

Our paper is organised as follows. Section 2 introduces the methodology employed including the storyline development, models and instruments looked at. Section 3 then presents the results, Section 4 a discussion within a broader context and finally section 5 ends with a conclusion and outlook to the future.

2. Methodology

The methodology applied in this paper consists of a series of subsequent steps (see Fig. 1) which are described in detail next. To avoid confusion, we partly refer to the case study applications in the description of the steps.

2.1. Define system boundaries and system scope (Step 1)

The first step applies a systems perspective to differentiate elements within the system and the relationship of the system to elements and systems outside that system. We define a system as a set of elements which are (partly) connected and which has clear boundaries (Hochrainer-Stigler et al., 2023). In this rationale, we define the system boundary under study to be mainland Europe, with all elements outside mainland Europe (excluding the outermost regions) considered external to the system. Furthermore, interconnectedness is defined here in financial and economic terms, and we further differentiate between public and private sector related instruments to manage risks. Hence, we define the system boundary in terms of geography or (however, partly) the political boundaries of the European Union (EU).

2.2. Selection of past events and regions (Step 2)

In this step the hazard(s) as well as possible past events to be looked at, including hotspot regions, are determined. We selected cyclones as the main hazard due to the fact that one way to carry out a counterfactual analysis of climate events, is to use past forecast data. Although cyclone forecasts were made serving a different purpose, i.e. *predicting* the development of a climate event (e.g. the final path and intensity of a tropical cyclone), the ensemble of forecasts represents, when used retrospectively, physically plausible alternative realisations of what happened in the past. In addition, such hazards were already indicated to be especially devastating and causing large scale impacts across the globe (see for example Jaramillo et al., 2023).

Regarding different regions of interest, we used the study by Mahalingam et al. (2018) as a first benchmark. They showed that natural hazards causing losses for 1 trillion USD or more can have an impact on the global financial market. Although such an event never occurred in the past, the authors identified six plausible scenarios that may lead to such a degree of damage and have relevant impacts on the market including the devaluation of investment assets, changes in interest rates, changes in currency exchange rates and sovereign credit ratings. Two of the analysed scenarios are climate driven and pertain to tropical cyclones affecting the USA. One scenario considers a superstorm which affects the New Jersey Coast including the New York Metropolitan area. The storm reaches peaks of 146 mph winds, with total losses of 1.15 trillion USD. Another scenario involves a hurricane making a first landfall in Florida with winds over 147 mph into Florida Bay and then a second landfall near Pensacola at sustained winds of 127 mph, with total losses of 1.35 trillion USD.

In addition, such events can also hit the Caribbean region where the EU is active in regard to humanitarian operations and assisting in public finance schemes such as the CCRIF. Furthermore, this area also includes some outermost regions of the European Union as well, such French Guiana, Saint Martin, Guadeloupe and Martinique in the North Atlantic Ocean, which could therefore ask for assistance through the European Union Solidarity Fund (a risk financing instrument to assist governments during the emergency phase). Finally, such large-scale losses also can trigger large insurance payouts and this can have impacts on insurance

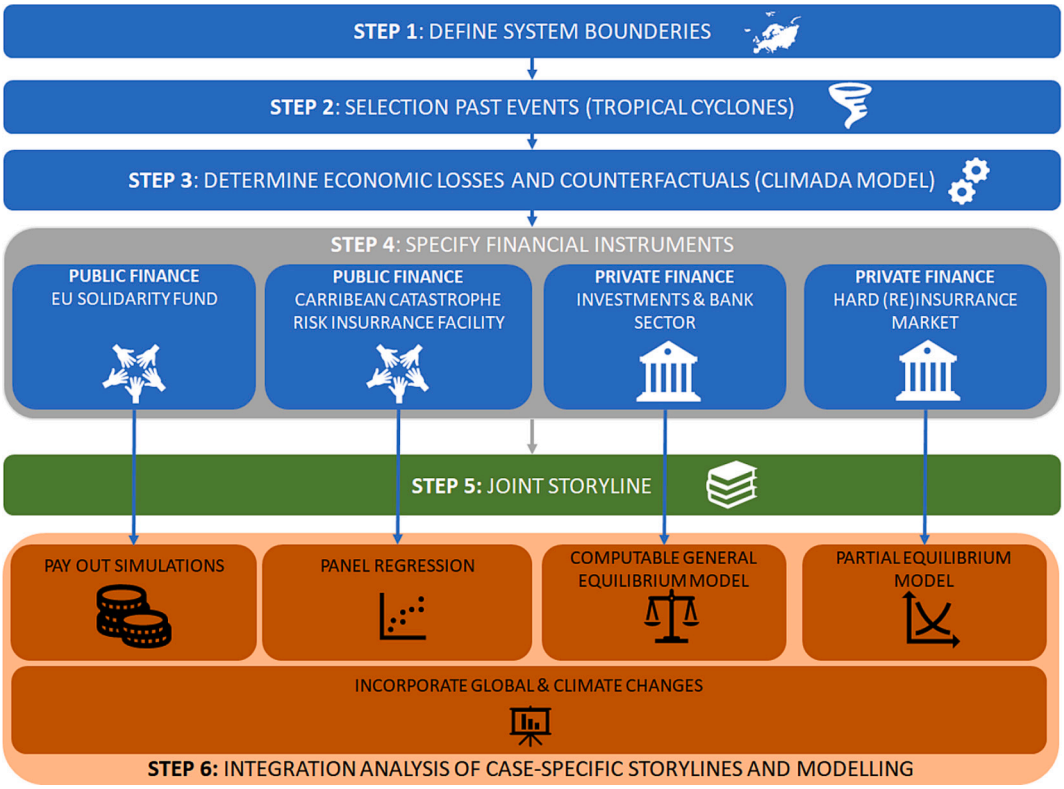


Fig. 1. Stepwise methodological approach and integration of different models.

density and affordability for Europe and international financial flows and investment levels as well. Based on these considerations past events of tropical cyclones hitting the East Coast of the USA and the Caribbean region were selected within step 2.

2.3. *Determine economic damages of past events and counterfactuals through CLIMADA (Step 3)*

After selection of the hazards and regions, counterfactuals of past events and their impact (e.g. economic damages) should be assessed. For the selection of counterfactuals, we focus on climate storylines based on downward counterfactual thinking, or in other words, aim to analyse past events that could have been worse (Ciullo et al., 2021; Shepherd et al., 2018). To do so, storylines are framed in an event-oriented manner exploring plausible "*what if*" scenarios. Thus, the development of storylines does not entail any consideration about the probability of the considered causal chain events. This leads to an increase in risk awareness, as people relate more easily to the description of actual (or fictitious yet plausible) events rather than probabilistic estimates. Quantification of the economic damages of past events and all of their

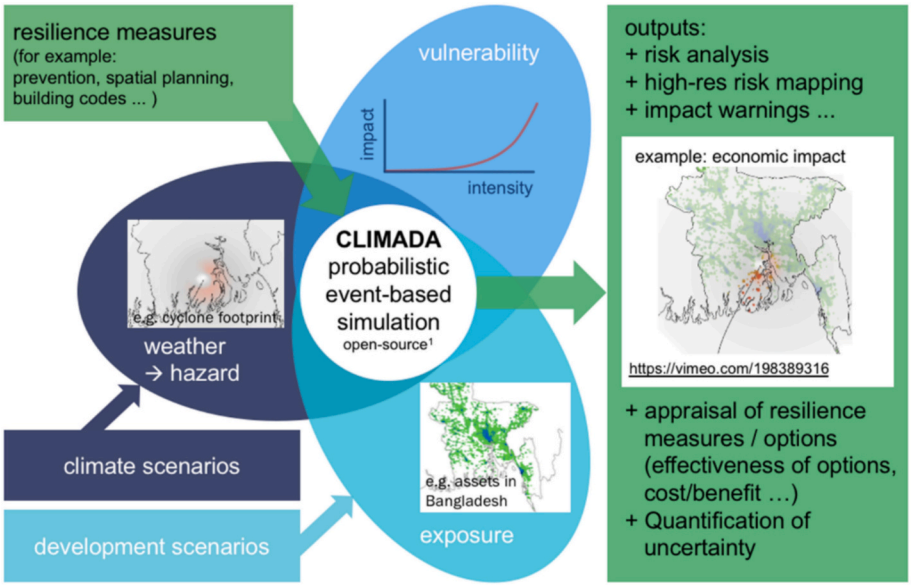


Fig. 2. Methodological approach of the CLIMADA model for modelling disaster risk. Source: Aznar-Siguan and Bresch, 2019.

possible counterfactuals is done using the open-source CLIMADA model following Aznar-Siguan and Bresch (2019). Direct damages in CLIMADA are assessed as a function of weather-related hazards, exposure of people and goods to such hazards, and vulnerability of the exposed entities (Fig. 2).

In more detail, hazard from tropical cyclones is represented in CLIMADA by a map of 1-min sustained wind gusts, modelled as the sum of two components: a static circular wind speed and a translational wind speed arising from the tropical cyclone movement. Both components are derived from information about tropical cyclone tracks such as time, location, radius of maximum winds, and central pressure (Geiger et al., 2018). CLIMADA provides various built-in methods to generate exposure (see, e.g., Aznar-Siguan and Bresch, 2019). We use the method by Gettelman et al. (2018) which determines the exposed economic value by downscaling regional Gross Domestic Products (GDP) using nighttime lights data. Vulnerability in CLIMADA is represented, as typically done in natural catastrophe modelling, via a damage function which relates hazard intensity to damage percentage in exposed value. Hazard data about historic tropical cyclone tracks are retrieved from the International Best Track Archive for Climate Stewardship (IBTrACS) dataset (Knapp et al., 2010). Counterfactual tropical cyclones are simulated by using forecast data provided by the Observing System Research and Predictability Experiment (THORPEX). THORPEX initiated in 2005 the THORPEX Interactive Grand Global Ensemble (TIGGE) program, which contains many forecasting data sets of tropical cyclone tracks from several international meteorological agencies (Swinbank et al., 2016;). The dataset contains historical tropical cyclone track data since 2008 and is updated continuously.

Changes in economic damages due to climate and global changes was done using selected future scenarios. In particular, three Paris scenarios were analysed, each corresponding to a different combination of SSPs (Shared Socioeconomic Pathways) and RCPs (Representative Concentration Pathways) scenarios including the Ambitious Paris (SSP1 - RCP2.6), Conservative Paris (SSP2 - RCP4.5) and Failed Paris (SSP5 - RCP8.5) scenarios. The corresponding changes within the parameters of the CLIMADA model were made using projections of changes in the intensity and exposure based on findings from past literature. For example, tropical cyclone intensity was adjusted based on the estimations provided by Knutson et al. (2020), according to which tropical cyclone intensity might increase between 1 % to 10 % in a 2 degrees warmer world. Socio-economic perturbations are derived from projections of Gross Domestic Product based on selected SSPs. These were used as inputs to CLIMADA and the changes in losses are used again as an input to the models.

2.4. Selection of instruments and models (Step 4)

Based on step 1 and 2, including the selection of remote areas as well as past hazards, and the economic damages of counterfactuals, the impact transmission pathways had to be determined in more detail including the selection of modelling approaches and counterfactuals that could cause a critical performance of relevant instruments for Europe. As discussed above, this selection was partially based on a literature review of remote events, but was also further advised based on a stakeholder process, including a workshop where the selection and usefulness of instruments and hazards was discussed with key stakeholders (see Ciullo et al., 2021). Table 1 presents the selected sectors and financing instruments.

We discuss some details on how these instruments are related to remote risk next. One overall question to be addressed was if and how the counterfactuals would affect Europe. To start with, the impact of remote events on the EU public sector can be twofold. First, the many overseas EU territories (e.g. Saint-Martin, Réunion (FR)) are eligible for funding from the EU Solidarity Fund. Second, the EU is one of the donors contributing to risk management instruments such as the Caribbean Catastrophe Risk Insurance Facility (CCRIF) and, as such, there are moral liabilities (e.g. helping the ones who cannot help themselves, such as the poor; usually not arising from contractual obligations) to assist in climate resilient development. In regard to private finance, the disaster insurance sector increasing claims due to large remote events may result in higher insurance premiums and reduced covering capacity. Furthermore, under a worst-case scenario, prime insurers may go bankrupt and global European re-insurers may need to relocate their business. This could lead to a hard insurance market (e.g. higher premium payments) in Europe including consequences in regard to affordability and insurance penetration rates across EU member states. In addition, regarding the investment and banking sector on the one hand, remote events can destroy physical capital (buildings, machines, transport equipment) owned by European investors and cause indirect damage to European commercial interests through supply-chain disruptions and macroeconomic feedback. On the other hand, such events increase opportunities for (recovery) investments. But as climate-risk increases in remote areas, EU investors may update their risk perception and thus be forced to reconsider and redirect their investments. Each of the consequences due to remote events for the selected instruments required an own modelling approach which are summarized within Table 1 and discussed in step 5 next.

Table 1
Instrument, storyline rationale as well as modelling approach for each storyline.

Storyline	Instruments & Storyline rationale	Methodology / Model
Public finance - EU Solidarity Fund	EUSF exposed to outermost regions due to cyclone risk	Pay-out Simulations
Public finance - Caribbean Catastrophe Risk Insurance Facility	CCRIF exposed to plausible past cyclone events that would make the CCRIF even more beneficial	Panel regressions
Private finance - Macroeconomic consequences	A cascade of extreme weather events based on historical events directly impacts remote regions and indirectly affects the EU.	Computable general equilibrium model
Private finance - Hard insurance market	Storyline combines a large remotely occurring catastrophe with unfavourable economic conditions to trigger a hard insurance market.	Partial equilibrium model

2.5. Joint storylines and individual analysis (Step 5)

After identifying the impacts and possible effects on selected instruments, the next step was to develop a joint storyline. This was done to maintain consistency regarding the applicability of counterfactuals for all instruments (Table 1), i.e. to evaluate both the instruments and the spillover effects across sectors and instruments, and for possible integration of individual case-specific analyses (Step 6). In developing the joint storyline, the approach suggested in Ciullo et al. (2021) was applied. This included the analysis of possible critical performances for the instruments looked at (Table 1) where critical performance was based on selected risk metrics (see the discussion further down below). The analysis also gave important information on plausible events and critical performances that also could have happened only for some regions and countries. Hence, based on the joint storyline results, the different instruments were assessed in more detail using additional and extended storylines. Regarding the critical performance metrics for selecting storylines the following observations can be made:

- The EUSF is assisting countries after a natural disaster event. As the EUSF budget is limited there is the risk of default (critical performance metric) which we analyse looking at outermost regions of the EU. Here a direct relation between CLIMADA outputs of losses and the EUSF payouts can be made as the criteria for payouts from the

EUSF is defined in losses experienced by a country (in monetary terms).
- For CCRIF, this allows analysis of the usefulness of the instrument to decrease fiscal risks (critical performance metric), and indirectly decrease the EU's implicit liabilities for humanitarian assistance. Through a panel regression approach in this region, the relation of losses with fiscal risk of Caribbean countries were determined and the corresponding regression used for estimating the benefits of CCRIF in case of counterfactuals, provided by CLIMADA.
- Given a remote event the risk aversion of insurers may increase and we address the question about the effects on insurance affordability (critical performance metric) and the government acting as an insurer of last resort. Rather looking at specific relations between insurance interdependencies across the globe, we assumed such effects given large events and focused on the consequences within Europe for affordability of insurance as well as insurance densities in EU countries.
- Overall macroeconomic consequences due to such events across different sectors (growth effects used as critical performance measure) were calculated using a CGE modelling approach, namely GDyn which can simulate the global economy over a long time horizon and which is basically a recursive dynamic version of the GTAP model of the global economy (Ianchovichina and McDougall, 2012).

Afterwards, different adaptation options for decreasing the risk of critical performance were looked at and compared across different climate storylines. These results were afterwards used as an input to an open-web application where the summary of results can be looked at and results presented to key stakeholders (not discussed here).

2.6. Integration of analysis of joint and individual storylines (Step 6)

While the joint storylines initiated the development of the individual storylines, the latter can be used for building additional joint storylines between each individual public and private sector related instruments. This is one benefit of a storyline approach as all models use the same input data from CLIMADA and therefore can combine the storylines and instruments. This should indicate some possible but not yet happened situations and, more importantly, fill some blind spots of possible interactions and transmission channels that have not been looked at in the joint storyline as well as within the individual storyline analysis. In this way a comprehensive picture of possible interactions and transmission channels between instruments can be gathered and used for the analysis of adaptation finance options.

3. Results

We now present the results for each step within our suggested framework. Due to space constraints, it is not possible to present the single instruments and storylines within step 5 and we refer to Ciullo et al., 2021 for the EUSF analysis, Tesselaar et al., 2020 for the insurance analysis, Kuik et al., 2022 for a macroeconomic perspective and Hochrainer-Stigler et al., 2023b for the CCRIF. Instead, the focus in the results section is on the joint storyline within step 5 and corresponding results (Section 3.1) and the integration of the separate analysis in step 6 (Section 3.2). This lays out the basis for a discussion of the advantages as well as disadvantages of a storyline approach for public and private finance including implications for policy making in regards to adaptation as well as modelling wise in regards to probabilistic assessments (discussed in Section 4).

3.1. Single climate storyline for multi-risk analysis

The selection of the system boundaries and outside regions of interest were already discussed above (Fig. 1, Step 1). Step 2 of the framework considers a selection of large scale past events which caused considerable damages in the respective region of interest. Given that our focus is on remote events that eventually cause a critical performance of a variety of EU instruments or economic and financial relevant sectors a focus on the storms Harvey, Irma and Maria was given. These recent events resulted in long-term damages amounting to billions of USD across various regions. Based on these past events, all counterfactual storm tracks (i.e. plausible ones, that could have happened but did not) using the CLIMADA model were looked at and those were chosen that caused multiple consequences in several countries at once. Fig. 3 illustrates selected tracks of counterfactuals from the three storms.

For example, storm Maria first made landfall in Martinique and Guadeloupe, which are the French overseas territories. At almost the same time, Caribbean member states such as Dominica and more countries were affected along its way until the storm hit Florida. We calculated the losses in monetary terms from this counterfactual (Fig. 1, Step 3) using the CLIMADA exposure and vulnerability model. Their direct impacts on each region is as follows, for the Caribbean region the direct damages were estimated to be around 673 million USD, for the outermost countries losses to be financed was estimated to be 237 million USD, and for the USA estimated damages were around 7410 million USD.

These counterfactuals were seen relevant to some important public and private instruments such as the EUSF, CCRIF and from macroeconomic and insurance perspectives (Fig. 1, Step 4). In the following, some important and critical impacts (in terms of performance of the instruments) for the selected instruments are examined in more detail: Counterfactual Maria cause damages to outermost countries, most of this damage is suffered by Guadeloupe (about 191 million EUR) followed by Martinique (about 45 million EUR), and the rest by Saint-Martin. The European Union Solidarity Fund is assisting Member States in case of disasters given some predefined thresholds are met. In the case of outermost countries, damages more than 1 % of the regional GDP need to occur, which is the case for Guadeloupe. While the losses are only minor, additional impacts of few other selected storylines were assessed as well (see Ciullo et al., 2021 for a full analysis). In particular, one counterfactual representation assumes that, in 2017, counterfactual Ophelia would have hit the Azores and counterfactual Enawo would have hit La Reunion. This would have made the EUSF funding shortage due to the earthquake in central Europe much larger. Furthermore, the occurrence of counterfactual Berguitta hitting La Reunion in 2018 would have prevented the recovery of the fund in the following year. Climate and global changes would only increase such risks in the future and therefore also the possibility of a default.

As for the impact on Caribbean countries, the selected counterfactuals are less damaging compared to the historical catastrophic Hurricane Irma and Maria, which caused losses of more than 12.9 billion USD in total. The sum of direct damage of these two selected counterfactuals reaches 673.4 million USD, while the counterfactual of Harvey did not hit CCRIF countries. Though the sum of losses is smaller than historical records, the impact of the storms are still significant for the region. Based on a Panel regression approach to determine a relationship between past damages and fiscal performances (including being part of the CCRIF) we found that considerable assistance from the EU can be assumed under these counterfactuals with possible spillover effects to other instruments. We also found that the CCRIF could help to reduce outside assistance needs after such large-scale events and climate change will likely increase losses to such levels that additional risk reduction options need to be considered as well (we refer to Hochrainer-Stigler et al., 2023b for a full analysis).

Regarding macroeconomic spillover effects, storm Maria's counterfactual causes damages of USD 73,103 million to the Southern US, particularly in Florida. In the same hurricane season, the Southern US was struck by hurricanes Irma and Harvey. The counterfactuals of these storms cause damages of up to USD 548 billion in total. This order of magnitude of damages has an impact on the economy of the US and beyond and on global financial markets. Because the EU and the US have

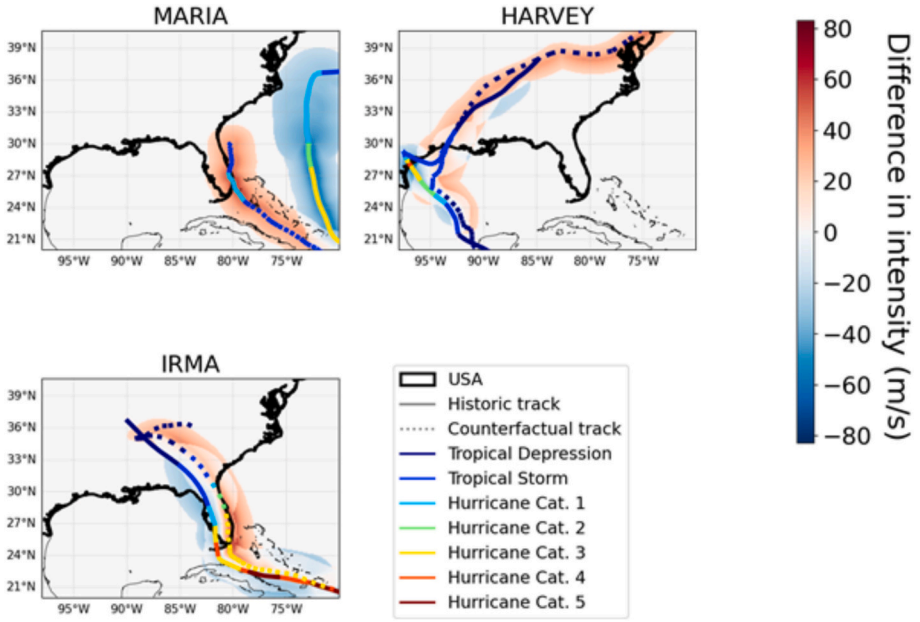


Fig. 3. The Wind Tracks of Hurricanes Maria, Harvey and Irma in 2017 (Historical and Downward Counterfactuals), produced from CLIMADA model.

strong economic and financial relationships, simulations with a global dynamic Computable General Equilibrium model indicated that three consecutive hurricanes in one season can have a considerable effect on the EU economy. In the first place, physical assets in the US that are owned by EU investors are destroyed or damaged, leading to a direct loss for EU investors, although this loss is not large in relative terms. While EU exports increase relative to baseline, overall economic activity in the EU falls below its baseline level for a number of years until the middle of the century. There are marked differences between economic sectors though, with Heavy and Light Manufacturing sectors and also Agriculture doing well because of increased export opportunities, while the Capital Goods producing sector and the Construction sector suffer losses. Also here, the counterfactuals indicated some distinguished impacts to the European macroeconomic performance in the short and long term (we refer to Hochrainer-Stigler et al., 2022 for more details).

Due to the counterfactual, the global expected rate of return on capital increases initially by 0.11 %, which in a capital constrained ("hard") market could lead to an increase in global (re)insurance premiums, also affecting EU citizens. A hard insurance market with high to unaffordable premiums, i.e. because awareness of increased risk among insurers also increases the premiums, possibly arises because of the large-scale need for (re)insurers to recapitalize after a large catastrophe, or multiple disasters in close succession. The large-scale demand for capital by (re)insurers will, through forces of supply-and-demand, raise the price of capital on financial markets. The higher costs of recapitalization will raise the price of certain insurance products, which will cause some products to no longer be competitive, causing insurance availability to decline. For other products, the increasing costs are transferred to policyholders as higher premiums. A hard capital market because of natural catastrophes has in the past occurred on several occasions, for example due to the severe tropical cyclone season in the US in 2005, as well as after the 2011 earthquakes in Japan and New Zealand. The analysis shows that the impact of hard insurance market conditions on premiums and, consequently, on the unaffordability of and low demand for insurance, is highest in certain regions of Poland, Bulgaria, and Portugal. While flood risk, and increasing flood risk due to climate change, is the major driver of these issues, risk-based premium-setting in these countries makes the impacts of hard insurance markets particularly severe there (we refer to Tesselaar et al., 2020 for a detailed analysis).

Summarizing, the joint storyline indicated significant negative effects on the instruments considered and they would get worse in the future due to climate and global changes. As indicated, for each instrument several additional climate storylines and possible consequences were constructed and analysed. While we do not incorporate the results here, we present the integration of those as suggested in our framework within step 6 in the next section.

3.2. *Multi-climate storylines for single risk analysis*

We already indicated that while the risks to public and private finance instruments are modelled differently, each of them (Table 1) applied the same approach (i.e. using estimated losses of counterfactuals through CLIMADA) to construct the respective impacts. We also indicated that step 5 conducted multi-climate storylines (e.g. looking at a variety of storylines) for each instrument separately to gather more detailed information about other past counterfactuals and possible effects under climate and global change. Here, we now discuss step 6 and the possibility to combine these different individual storylines and to cluster them according to different themes, e.g. public and private finance related dimensions (Fig. 1, Step 6). In addition, we further analyse some different combinations of storylines that indicate how different events can interact and stress the system more significantly than would be apparent from separate analysis. Fig. 4 includes a selection of possible interactions between public and private finance instruments (rows) as well as different storylines and regions (columns). Note, column 5 includes also the joint storyline approach as discussed above.

It should be stressed that while the storylines share the same methodological foundations, single storylines can also be integrated to investigate possible combinations not previously looked at within step 5. For example, columns 4–6 present different combinations of storylines that are especially interesting in case of co-occurring events, which requires the different instruments to be activated simultaneously. As a case in point, column 4 indicates an interaction between the two public finance instruments EUSF and the CCRIF. This is because the EUSF is now merged with the Emergency Aid Reserve (EAR), which, like the EUSF has limited funding and in addition shares now the same funding resource (Hochrainer-Stigler et al., 2023c). The EAR can be used to finance emergency support for non-EU countries including the

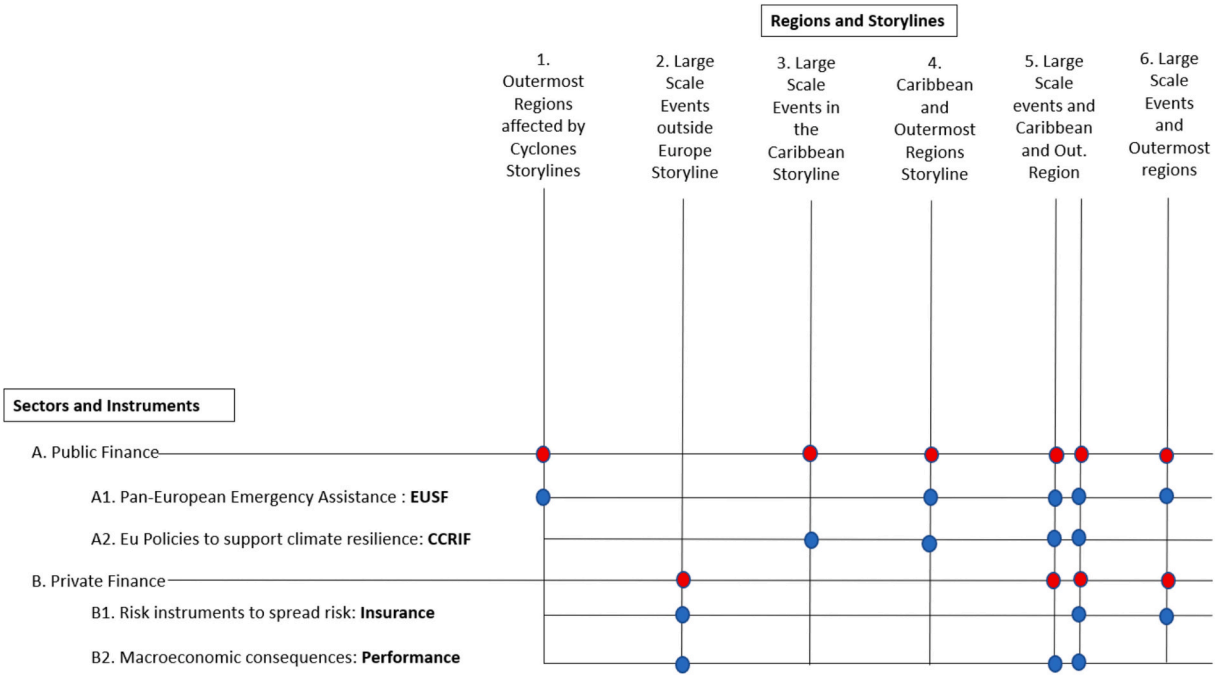


Fig. 4. Storylines, regions, and public & private finance instruments considered. Red dots indicate sectors, blue dots indicate instruments per sector. Column 1–3 and column 5 are covered in separate storylines. Columns 4 and 6 represent combinations of different storylines and their possible effects on sectors and instruments. Source: Authors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Caribbean Island states. As they are both using the same funding there is now an increased risk for depletion of the fund, either due to a) overspending because of the EAR part or b) overspending of the EUSF related EU outermost regions part. Such interactions are difficult to be detected and a storyline approach can help in analysing such interactions. In addition, such storylines and instruments can be further expanded to include compound scenarios such as in the case of a hard insurance market (column 5) which could further increase the risk of the EUSF and the CCRIF as governments have to act as an insurer of last resort. To make things worse, under climate change scenarios discussed earlier, capital requirements for the EUSF as well as the CCRIF will increase considerably, and additional adaptation options must be considered. Also, the increase in exposure and hazard intensities within Europe will increase the risk of uninsurable losses and therefore will decrease insurability within Europe given such increase in absolute levels of losses from remote events in the future. The importance of the future evolution of climate change is also demonstrated for the macroeconomic consequences of remote disasters for Europe.

The above examples should already indicate that the storylines developed separately enable also a better understanding of possible transmission channels in case of compound events and possible multi-risks and supports integration. Simultaneous occurrence of the

Table 2
Storylines, resilience and policy options and advantages and limitations compared to probabilistic approaches.

Storyline	Resilience options	Policy option 1	Policy option 2	Storyline Advantages vs Probabilistic	Storyline Limitations vs. Probabilistic	Single/ compound multi-risk
Public finance - EU Solidarity Fund (EUSF)	Increase in capitalization levels of EUSF	Multi-Hazard and Multi-Risk tool as designed in SEAR	Changes in policy processes regarding pay-outs	Clear connection of plausible past events and consequences for fund for decision makers	Assessment of capitalization needs not possible	Hybrid
Public finance - Caribbean Catastrophe Risk Insurance Facility (CCRIF)	Insurance as viable option for decreasing contingent moral obligations	Integration of emergency phase with reconstruction phase to decrease indirect risks	Risk reduction for future climate change impacts	Benefits of CCRIF for plausible past events that did not happen can be shown to decision makers	No assessment of premium payments and ruin probabilities for CCRIF possible	Hybrid
Private finance - Macroeconomic consequences	Improved investment circumstances in the EU. Safeguard access to financial resources. Identify vulnerability in terms of sectoral composition of the affected countries	Increased responsiveness to provide substitute production capacity and turn the EU into a safe destination for long term investments.	Monitor capital availability and investment levels in the EU to remediate in case of capital shifts to affected regions	Reduction of complexity of sectorial impacts and importance of spillover effects. Determination of hotspot regions important for economic functioning of EU market	No gradual changes analysed and focus on disruptive scenarios only	Storylines
Private finance - Hard insurance market	Reducing insured risk in the EU by DRR. Governmental provision of reinsurance coverage for NatCat insurance	Combine it with EUSF and SEAR into a public-private partnership	Related insurance and risk reduction through incentives and provide subsidies for most vulnerable	Qualitative analysis of possible remote effects and consequences for EU insurance market possible to be established	Risk based assessment of optimal strategies not performed, rather hard and soft insurance markets as two ends of continuum.	Storylines

different storylines can lead to severe financial shocks endangering the proper functioning of the European economy. The simultaneous occurrence of the storylines in this context can lead to an exacerbated effect, larger than the sum of the individual effects. The impact of climate change can be quite drastic and selected storylines were also analysed according to RCPs and SSP2 scenarios. As indicated, the different financial instruments can also be analysed separately in the context of climate change (Table 2). The problem setup for the different climate shocks, as well as public and private finance instruments can be manifold. A separate analysis can be conducted to explore ways to increase resilience, especially in the context of compound events (Zscheischler et al., 2018, 2020) and multi-risks (Hochrainer-Stigler et al., 2023) as exemplified here. In the next section we compare our framework and analysis to other approaches and determine key advantages as well as limitations.

4. Discussion

Natural hazard events are inherently random and therefore also the impacts (Grossi et al., 2005). To account for this randomness, probability-based approaches are usually applied to determine the whole range of possible hazard events and accompanying losses (e.g. through catastrophe modelling, see Woo, 2011). As such, they provide essential input for assessing risk management strategies to decrease losses, e.g. in the form of physical risk reduction, or through financial instruments such as insurance (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Pflug and Romisch, 2007). However, such probabilistic risk analysis becomes increasingly challenging (either from the empirical, modelling, as well as from a stakeholder perspective) when multi-risks as well as global and climate changes should be included in such assessment. Part of this is due to the sheer complexity involved in such assessments. In this context, climate storyline approaches gained interest as they i) can considerably reduce complexity, ii) are able to focus on narratives, and iii) can provide a different perspective on global and climate change dynamics and their impact on losses (Shepherd et al., 2018). However, both probabilistic as well as climate storylines have their unique advantages as well as limitations, especially with respect to climate change adaptation and event attribution. Based on our findings in Section 3 we discuss these in more detail and within a broader context now. We start our discussion by comparing for each public and finance dimension what a climate storyline can achieve and what it lacks in comparison to probabilistic approaches (Table 2).

To start with the public finance instruments, the storyline approach for the EUSF showed through an analysis of additional storylines (Ciullo et al., 2021) that the argument of no depletion in the past and therefore sufficient capitalization levels of the fund are inadequate. Especially it was possible to show that there were plausible past events which could have caused a severe stress to the EUSF. This analysis was also presented in a hearing to the European Parliament and gained considerable interest, as it is easy to grasp as it relates to past events. We therefore argue that such an approach is indeed appealing to raise awareness of possible challenges not encountered yet. The latter is more difficult to achieve through a probabilistic assessment (e.g. using corresponding risk measures such as Value at Risk) which are difficult to understand for non-experts. However, for quantifying the necessary capitalization levels, while the storyline approach can also be used for such an analysis, a full probabilistic assessment of natural disasters eligible for EUSF funding must be performed. This can only be done according to insurance principles and the quantification of risk through the use of probabilistic approaches (Hochrainer-Stigler et al., 2023c). We therefore argue that a hybrid approach is in such a case the best way forward, including compound or multi risk analysis. In accordance with the assessment of the EUSF, similar results were found for the CCRIF. Also within the CCRIF, insurance principles and related quantification techniques have to be used to estimate necessary capitalization levels and, in addition, premium payments. However, while insurance is addressing direct losses within the CCRIF analysis through the storyline approach the reduction of fiscal risk (e.g. changes of fiscal performance during the emergency phase) can be assessed for plausible past events in the past, making an argument, similar to the EUSF case, for being (even more) beneficial under hypothetical but plausible events in the past. Hence, also here a hybrid approach for targeting different policy related and quantitative related needs are necessary, again this can be expanded to a multi-risk setting as well.

Regarding private finance, the macroeconomic assessment developed a storyline of cascading events triggered by major tropical cyclones in the US, China, and Japan and effects on Europe. The storyline approach provided a useful tool to integrate plausible downward counterfactuals of the considered tropical cyclones into economic analysis. This analysis identified the European sectors most vulnerable to remote climate events as the storylines for different affected countries demonstrated that the negative (positive) indirect impact for Europe increases in case the affected region's economy is complementary (competitive) to the European economy. The analysis also allowed a distinction between short term positive impacts and long-term impacts. This in turn can be used to think about resilience and other policy options (Table 2). Usually in such large-scale economic models a probabilistic assessment either has to be done through sampling of events from the loss distribution (which is a very resource intensive task and therefore seldomly completed) or through the incorporation of average losses into the models. The storyline approach can complement such an analysis by providing information of selected extremes of interest and is especially valuable here to show the complex interrelationships across scales and sectors that are possible. This is even more so the case if multi- and compound risks have to be analysed.

Finally, the assessment of hard insurance markets resulting from remote climatic catastrophes is based on a storyline where we estimate the impact of a hard insurance market on premiums and insurance coverage in the EU. However, occurrence of hard insurance markets in the past demonstrates that remote natural disasters are not the only cause of hard insurance markets. The hard insurance market following the terrorist attack on the 11th of September 2001 serves as a schoolbook example. The approach applied in the insurance market scenario, therefore, may be interpreted as an upper and lower bound of EU insurance market conditions that depend on external capital market conditions. Here, we have a qualitative analysis of effects due to remote events based on selected storylines while providing results using a probabilistic assessment within Europe. Also in this context, one can discuss current resilience options and adaptation policy options. However, the link to insurance market cycles is complex and storyline approaches one way to think about possible relationships also quantitative wise.

In Fig. 4 we indicated that the storylines can be combined. In this setting one assumes that different climate storylines are happening in conjunction or as a sequence. Such an analysis within a joint model that brings together the different methodologies (Table 1) would require strong assumptions of external conditions, including overall economic conditions and therefore dependent on external factors. Consequently, a storyline method, as applied in these assessments, may in the end be the most prudent approach as it provides an appropriate hypothesis for the modelling framework. In the insurance case for example, the costs of reinsurance increase because of large-scale demand for capital after a natural catastrophe. Using this hypothesis is necessary because financial markets, including insurance markets, are highly complex and dependent on many external factors. Assessing the occurrence of a large climatic event in combination with less favourable economic conditions in a probabilistic way, therefore, becomes too complex and uncertain for an insightful assessment. A storyline approach allows for a simplification in this regard, while not limiting the plausibility of results. This turns the storyline approach into a viable way forward to decrease complexity and enable an analysis of different interaction channels that may have significant impacts on different regions and sectors.

Hence, a storyline approach is useful to bring multi-risk instruments together through combined probabilistic and storyline based assessments. In that regard, the storyline approach should be seen as part of a toolbox that can be used for various challenges which need tailor-fit approaches. Storylines therefore seem especially useful for events outside the system that are too complex to consider, but nevertheless are important to analyse how they may affect the performance within a given system. Performance within the system then could be analysed with probabilistic approaches given stress levels due to remote events, e.g. through storylines. The same can be said about complex changes that are not easy to be modelled. The system definition, here in terms of political boundaries of the EU, plays an important role in that regard. For example, we focused on possible adaptation options for this system but neglected feasible adaptation strategies and changes in coping capacities for the remote areas, e.g. Caribbean and the US, which also could be viewed as a system. Furthermore, based on our system definition we looked at the dependencies between the elements of the system focusing on finance dimensions, however, other sectors could be looked at as well. In that regard, the complexity can be increased through additional inclusion of climate storylines that include specific sectors as well as additional sub-systems finally leading to a system-of-systems approach often used within systemic risk research analysing network dynamics (Helbing, 2013). This relates back to a toolbox approach which can then be used to build tailor-made models and an analysis of potential interrelationships that could increase or decrease future risks across scales and sectors and corresponding systems. In our case, the CLIMADA model and its provision of losses in economic terms for different storylines enabled a joint analysis of different instruments. However, for other non-financial types of risks, such as supply chain disruptions and related consequences in the short and long term, other kind of models may be needed, e.g. focusing on the hazard that can seriously affect critical infrastructure, and consequences that have to be modelled through transportation related modelling approaches.

5. Conclusion

We assessed the role of both public and private finance instruments in Europe regarding remote natural disaster risks. In doing so, we suggested a step-by-step framework for defining the system state first and subsequently selecting counterfactuals that can cause critical performances of selected instruments. We first presented a joint storyline for multi-risks, followed by a comparative analysis for multiple-storylines and single risk instruments. We argued that the different modelling efforts can be combined within the storyline approach in a coordinated effort using CLIMADA as the main link (i.e., apply the same procedure to develop each individual storyline for each individual instrument). In this rationale, the storyline approach can be used as part of a toolbox to assess various cases which require tailor-fit approaches. In particular, the storyline approach allows flexible design of counterfactual scenarios which describe plausible different occurrences of extreme weather events or various climate change trajectories. In addition, they also can be looked at in conjunction to determine possible interrelationships.

Our research findings especially address the EU's risk perception. Looking at public finance instruments first, the storyline on the EUSF for example finds that if events had unfolded differently this could have led to depletion of the EUSF's capitalization levels. Accordingly, the analysis on the CCRIF describes how the exposure to, and intensity increase of hazards can result in an unsustainable increase in risk. These conclusions intricately link to the conclusions on the private finance instrument. The macroeconomic analysis finds that the impact of remote events on private finance in the past could have been considerably higher in case of a different, more harmful, course of events. Plausible alternative scenarios could have resulted in more considerable and long-lasting economic impacts and shocks on the financial market. Because of these more profound consequences, the perception of risk from remote events for the EU might have increased by now. Hence, the storyline approach is useful because it describes such future effects. Finally, the storyline approach unravels the impact dynamics on risk instruments which lead to hard insurance markets. As the storyline approach manages to identify critical situations, the analysis also allows identification of options to build resilience.

In relation to probabilistic approaches, we conclude that both approaches provide a specific perspective on the challenges up-ahead and therefore should not be seen in isolation. While the storyline approach is not able to provide information for analysing risk-based instruments it is useful for stakeholders and risk bearers for understanding the challenges in regards to hazard events and complete a stress test. While the risk-based approach is more difficult to be grasped and understood it does allow a full analysis of the spectrum of events that happened or will happen in the future, either under a current or specific climate change setting. The advantages and limitations from a multi-model perspective should indicate which approaches are best to be applied under which circumstances and calls for a hybrid-approach for a comprehensive assessment that includes both, quantification needs as well as appropriate ways how stakeholders can navigate through complex interrelationships that could emerge.

While we conclude that flexibility is one of the main strengths of the storyline approach, this simultaneously also raises concern on the correct use of the storylines. An unlimited number of variations are possible, hence also unrealistic scenario-design. This observation supports the call of van den Hurk et al. (2023) to design guidelines to consistently develop and interpret storyline event analyses. A clear framework ensuring realistic and widely accepted storylines could benefit the approach in the future. van den Hurk et al. (2023) and Ciullo et al. (2021) discuss ways forward for this matter in a more general context. Nevertheless, storylines assessing financial instruments will keep on facing limitations compared to risk-based methodologies, and therefore both, storylines as well as risk-based approaches should be used in conjunction, dependent on the underlying questions at hand.

CRediT authorship contribution statement

Stefan Hochrainer-Stigler: Writing – review & editing, Funding acquisition, Data curation, Investigation, Conceptualization, Writing – original draft, Methodology, Formal analysis. **Jan Brusselaers:** Writing – review & editing, Conceptualization, Writing – original draft. **Qinhan Zhu:** Conceptualization. **Max Tesselaar:** Conceptualization. **Alessio Ciullo:** Conceptualization.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was funded by the EU Horizon 2020 REmote Climate Effects and their Impact on European sustainability, Policy and Trade (RECEIPT) project, grant agreement No. 820712.

Data availability

Data will be made available on request.

References

Aznar-Siguan, G., Bresch, D.N., 2019. CLIMADA v1: a global weather and climate risk assessment platform. Geosci. Model Dev. 12 (7), 3085–3097.
Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., Visentin, G., 2017. A climate stress-test of the financial system. Nat. Clim. Chang. 7 (4), 283–288.

Ciullo, A., Martius, O., Strobl, E., Bresch, D.N., 2021. A framework for building climate storylines based on downward counterfactuals: the case of the European Union solidarity fund. Clim. Risk Manag. 33, 100349.
Dunz, N., Essenfelder, A.H., Mazzocchetti, A., Monasterolo, I., Raberto, M., 2023. Compounding COVID-19 and climate risks: the interplay of banks' lending and government's policy in the shock recovery. J. Bank. Financ. 152, 106306.
Geiger, T., Frieler, K., Bresch, D.N., 2018. A global historical data set of tropical cyclone exposure (TCE-DAT). Earth Syst. Sci. Data 10 (1), 185–194.
Gettelman, A., Callaghan, P., Larson, V.E., Zarzycki, C.M., Bacmeister, J.T., Lauritzen, P. H., Neale, R.B., 2018. Regional climate simulations with the community earth system model. J. Adv. Model. Earth Syst. 10 (6), 1245–1265.
Grossi, P., Kunreuther, H., Patel, C.C. (Eds.), 2005. Catastrophe modeling: a new approach to managing risk. Springer Science & Business Media.
Helbing, D., 2013. Globally networked risks and how to respond. Nature 497 (7447), 51–59.
Hochrainer-Stigler, et al., 2022. Storylines for Future Impacts of Climate Change on Public and Private Finance. Deliverable 4.3. Receipt Project.
Hochrainer-Stigler, S., Trogrlić, R.Š., Reiter, K., Ward, P.J., de Ruiter, M.C., Duncan, M. J., Gottardo, S., 2023. Toward a framework for systemic multi-hazard and multi-risk assessment and management. Iscience 26 (5).
Hochrainer-Stigler, S., Zhu, Q., Ciullo, A., Peisker, J., Van den Hurk, B., 2023b. Differential fiscal performances of plausible disaster events: a storyline approach for the Caribbean and Central American Governments under CCRIF. Econ. Disast. Clim. Change 7 (2), 209–229.
Hochrainer-Stigler, S., Zhu, Q., Reiter, K., Ciullo, A., 2023c. Challenges of instruments that should tackle multi-hazard and multi-risk situations: an assessment of the recent reforms of the European Solidarity Fund and the Solidarity and Emergency Aid Reserve. Mitig. Adapt. Strat. Glob. Chang. (8), 28–41.
Ianchovichina, E., McDougall, R., 2012. Theoretical Structure of Dynamic GTAP. Chapter 2 in Ianchovichina, E. and Walmsley, T. Dynamic Modelling and Applications for Global Economic Analysis. Cambridge University Press, Cambridge.
IPCC, 2022. Summary for policymakers. In: Pörtner, H.-O., Roberts, D.C., Poloczanska, E. S., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. (Eds.), Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33. https://doi.org/10.1017/9781009325844.001.
IPCC, 2023. Summary for policymakers. In: Core Writing Team, Lee, H., Romero, J. (Eds.), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, pp. 1–34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001.
Jaramillo, L., Cebotari, A., Diallo, Y., Gupta, R., Koshima, Y., Kularatne, C., Lee, J.D., Rehman, S., Tintchev, K.I., Yang, F., 2023. Climate Challenges in Fragile and Conflict-affected States. IMF Staff Climate Notes, 2023/001.
Knapp, K.R., Kruk, M.C., Levinson, D.H., Diamond, H.J., Neumann, C.J., 2010. The international best track archive for climate stewardship (IBTrACS) unifying tropical cyclone data. Bull. Am. Meteorol. Soc. 91 (3), 363–376.
Knutson, T., Camargo, S.J., Chan, J.C., Emanuel, K., Ho, C.H., Kossin, J., Wu, L., 2020. Tropical cyclones and climate change assessment: part II: projected response to anthropogenic warming. Bull. Am. Meteorol. Soc. 101 (3), E303–E322.
Krauß, W., Bremer, S., 2020. The role of place-based narratives of change in climate risk governance. Clim. Risk Manag. 28, 100221.
Kuik, O., Zhou, F., Ciullo, A., Brusselaers, J., 2022. How vulnerable is Europe to severe climate-related natural disasters abroad? A dynamic CGE analysis of the international financial and economic impacts of a large hurricane in the southern USA. GTAP Conference Paper, 25th Annual Conference on Global Economic Analysis, 2022.
Linnerooth-Bayer, J., Hochrainer-Stigler, S., 2015. Financial instruments for disaster risk management and climate change adaptation. Clim. Change 133, 85–100.
Mahalingam, A., Coburn, A., Jung, C.J., Yeo, J.Z., Cooper, G., Evan, T., 2018. Impacts of Severe Natural Catastrophes on Financial Markets. Cambridge Centre for Risk Studies.
Monasterolo, I., 2020. Climate change and the financial system. Ann. Rev. Resour. Econ. 12, 299–320.
Naqvi, A., Gaupp, F., Hochrainer-Stigler, S., 2020. The risk and consequences of multiple breadbasket failures: an integrated copula and multilayer agent-based modeling approach. OR Spectr. 42 (3), 727–754.
Pflug, G.C., Romisch, W., 2007. Modeling, Measuring and Managing Risk. World Scientific.
Poledna, S., Rovenskaya, E., Dieckmann, U., Hochrainer-Stigler, S., Linkov, I., 2020. Systemic Risk Emerging From Interconnections: The Case of Financial Systems. OECD 2020, Paris, France.
Reichstein, M., Riede, F., Frank, D., 2021. More floods, fires and cyclones—plan for domino effects on sustainability goals. Nature 592 (7854), 347–349.
Shepherd, T.G., Boyd, E., Calel, R.A., Chapman, S.C., Dessai, S., Dima-West, I.M., Zenghelis, D.A., 2018. Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. Clim. Change 151, 555–571.
Sillmann, J., Christensen, I., Hochrainer-Stigler, S., Huang-Lachmann, J., Juhola, S., Kornhuber, K., Mahecha, M., Mechler, R., et al., 2022. ISC-UNDRR-RISK KAN Briefing Note on Systemic Risk. International Science Council, Paris, France. https://doi.org/10.24948/2022.01.
Swinbank, R., Kyouda, M., Buchanan, P., Froude, L., Hamill, T.M., Hewson, T.D., Yamaguchi, M., 2016. Supplement: combination of ensemble data in the presence of correlated and uncorrelated errors. Bull. Am. Meteorol. Soc. 97 (1), ES11–ES13.
Tesselaar, M., Botzen, W.W., Aerts, J.C., 2020. Impacts of climate change and remote natural catastrophes on EU flood insurance markets: an analysis of soft and hard reinsurance markets for flood coverage. Atmosphere 11 (2), 146.
van den Hurk, B.J., Pacchetti, M.B., Boere, E., Ciullo, A., Coulter, L., Dessai, S., Witpas, K., 2023. Climate impact storylines for assessing socio-economic responses to remote events. Clim. Risk Manag. 40, 100500.
Wallemacq, P., House, R., 2018. Unisdr and Cred Report: *Economic Losses, Poverty Disasters (1998–2017)*. EMDAT/CRED. Available at https://www.preventionweb.net/files/61119_credeconomiclosses.pdf.
Woo, G., 2011. Calculating Catastrophe. World Scientific.
Zscheischler, J., Westra, S., Van Den Hurk, B.J., Seneviratne, S.I., Ward, P.J., Pitman, A., Zhang, X., 2018. Future climate risk from compound events. Nat. Clim. Change 8 (6), 469–477.
Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., Vignotto, E., 2020. A typology of compound weather and climate events. Nat. Rev. Earth Environ. 1 (7), 333–347.