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Publication date:
2021

Permanent link:
https://doi.org/10.3929/ethz-b-000501366

Originally published in:
Climate Risk Management 33, https://doi.org/10.1016/j.crm.2021.100349

Funding acknowledgement:
820712 - REmote Climate Effects and their Impact on European sustainability, Policy and Trade (EC)

Climate Risk Management 33 (2021) 100349

Contents lists available at ScienceDirect

Climate Risk Management

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

A framework for building climate storylines based on downward counterfactuals: The case of the European Union Solidarity fund

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ARTICLE INFO

Keywords:
Climate storylines
Downward counterfactuals
European Union Solidarity Fund

ABSTRACT

Recent research introduced the concept of climate storylines as an alternative approach to estimate climate impact and better deal with uncertainties. A climate storyline is an event-based approach which aims at building "*physically self-consistent unfolding of past events, or of plausible future events or pathways*". As such, climate storylines may profit from downward counterfactual thinking, which aims at analyzing how past events could have been worse. Notwithstanding the various applications of downward counterfactual thinking in the natural risk management literature, no study relates this with the climate storyline approach. The main goal of this paper is thus to introduce a framework that supports the development of climate storylines from downward counterfactuals. The framework is event-oriented, it focuses on impact, and it is designed to be applied in a participatory fashion. As a proof-of-concept application, we study the impact of tropical cyclone events on the European Union Solidarity Fund (EUSF) and do not conduct a participatory analysis. These events represent a serious threat to the European outermost regions, and their impact to the EUSF capital availability has never been studied. We find that payouts due to tropical cyclones can hamper a recovery of the fund if large payouts concurrently occur in mainland Europe. To avoid this also considering future changes, an increase in capitalization up to 90 % percent may be required.

1. Introduction

The increasing need for climate adaptation policies is raising interest within the climate research community about the most appropriate use of climate data and impact models when supporting decision-making under deep uncertainty. Within this debate, Hazeleger et al. (2015), Shepherd et al. (2018), Shepherd (2019) and Sillmann et al. (2021) challenged the conventional probabilistic approach of modeling uncertainty in regional climate that generates local climate information by downscaling results from global climate model ensembles simulations. Such probabilistic modelling approach, also referred-to as a "top-down approach", has been considered inadequate in dealing with uncertainties in regional climate predictions because it mingles together aleatoric and epistemic uncertainties (Shepherd, 2019).

As an alternative, Shepherd et al. (2018) introduced the *climate storyline* approach, where a *storyline* is defined as "*a physically self-*

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https://doi.org/10.1016/j.crm.2021.100349
Received 19 March 2021; Received in revised form 8 July 2021; Accepted 1 August 2021
Available online 5 August 2021

consistent unfolding of past events, or of plausible future events or pathways". Unlike the conventional probabilistic approach, the climate storyline approach does not aim at predicting system states nor at assigning probabilities to these states. Rather, the storyline approach focuses on identifying what *plausible* factors (i.e., climatic and socio-economic) bring the system under severe stress. Furthermore, instead of using ensembles of model simulations, climate storylines aim at describing and understanding (series of) individual regional climate events. Thus, the climate storyline approach is well-suited to study compound climate risk, namely risk rising from the interaction of several weather or climate events (Zscheischler et al. 2020; 2018).

Shepherd et al. (2018) identified four main strengths of the storyline approach. First, it improves people's risk awareness as it triggers episodic memory, i.e., it reproduces climate events that are similar to those people already experienced and can thus personally relate to. This aspect is relevant as it allows accounting for people's risk perception, based on cultural and personal values, and thus connects with the narratives of change approach to climate risk governance advocated by Krauß (2020) and Krauß and Bremer (2020). Second, it strengthens decision-making as it focuses on revealing the factors responsible for system failure, thus allowing the identification of robust decision options, i.e., options which perform satisfactorily under a wide range of system states (McPhail et al. 2018; Wilby and Dessai 2010). Third, it allows to partition uncertainties relative to thermodynamic and dynamic aspects of climate events, which are instead merged when using the conventional probabilistic approach. Last, it enables the exploration of the boundaries of plausibility, i.e., visualizing and estimating the full spectrum of plausible impacts that can arise from the considered climate events.

The first point above is most effective if storylines are event-based and hence connect to events people can relate to. Therefore, the climate storyline approach may benefit from counterfactual thinking, which refers to imagining alternative pasts by reconstructing events that could have occurred but actually did not (Roese 1999). Roese (1999) distinguishes between upward and downward counterfactuals to refer to events which may have turned better or worse than they actually did, respectively. As downward counterfactuals aim at considering plausible negative outcomes, they trigger the so-called wake-up call, i.e., a motivation to change and improvement (McMullen and Markman 2000). Woo (2019) and Woo et al. (2017) propose to adopt a downward counterfactual thinking approach to address risk analysis problems. They recognize that historical events are just one realization of many possible alternatives and show that, when considering downward counterfactuals of these historical events, many disasters that took societies by surprise could have been anticipated.

Applications of downward counterfactual thinking in the context of natural disaster risk analysis include a counterfactual analysis of the 1999 Kocaeli earthquake (Woo and Mignan, 2018) and the 1997 Montserrat Volcanic explosion (Aspinall and Woo, 2019), as well as new methods to estimate flood risk (Zischg and Bermúdez, 2020). Methods to derive plausible counterfactuals vary greatly, including historical analysis, Bayesian Networks, and perturbation of past events. Lin et al. (2020) propose a general framework on how to generate downward counterfactuals and apply this to various extreme natural events. Regardless of the adopted approach, the greatest challenge when building downward counterfactuals of past events is ensuring plausibility in the constructed counterfactuals.

As the storyline approach and risk studies using downward counterfactuals thinking have so far developed along complementary, yet very distinct, research lines, the first goal of this paper is to combine the two into a single framework. The framework is iterative and aims to foster co-production of knowledge between scientists and stakeholders when developing storylines, and, as such, resembles previously introduced approaches for creating climate risk narratives (Jack et al. 2020). In particular, the framework first allows constructing climate storylines based on an iterative analysis of what (combinations of) counterfactuals are deemed critical (i.e., downward), and it then allows analyzing the future impact of storylines using climate change and socio-economic scenarios. The value of combining counterfactuals and scenarios is also recognized by Derbyshire (2020) and Schoemaker (2020) who discuss, within a more general context, how counterfactual reasoning enhances scenario-building and thus allows for better planning. In our framework, the aforementioned challenge of plausibility when modeling downward counterfactuals is addressed by simulating counterfactual events using past ensemble forecast data, which, by their own nature, represent physically plausible alternatives of past weather and climate events.

The second goal of the paper is to apply the proposed framework on a case study. To this end, we study the implications of tropical cyclones on the financial capacity of the European Union Solidarity Fund (EUSF), a fund set-up in 2002 to provide financial relief to European Union Member States affected by large disasters following natural hazards. Tropical cyclones represent a serious threat for the European Union outermost regions, i.e., French, Portuguese and Spanish islands located outside mainland Europe. As previous studies analyzed the impact on the EUSF of other perils, e.g., flooding, which might happen in mainland Europe (Hochrainer et al., 2010), the goal of this work is to build climate storylines to assess whether, and to what extent, tropical cyclones hitting the EU's outermost regions can compromise the stability of the EUSF.

The paper is structured as follows. Section 2 illustrates the proposed framework; Section 3 is split into three subsections introducing the case study, the impact model, and data; Section 4 presents results; Section 5 critically discusses the framework and results; Section 6 provides final remarks.

2. Building climate storylines: A downward counterfactual approach

This section introduces the proposed framework for building climate storylines using downward counterfactuals. The main challenge when constructing downward counterfactuals is ensuring plausibility, which is paramount to avoid arbitrary and fictional speculations of the past and to ensure trust from the stakeholders regarding the formulated storylines. A way to ensure plausibility without resorting to new modeling nor detailed historic investigations is using past numerical weather forecast data, especially ensembles (Palmer 2019). Although these data were generated to serve a different purpose, i.e., to quantify the uncertainty of a weather prediction (Leutbecher and Palmer 2008), they do represent, when used retrospectively, physically plausible realizations of past weather events to the degree that numerical weather forecast models capture the underlying physical processes. Using numerical weather forecasts of tropical cyclones allows identifying historical near-misses that could have been catastrophic. For example, according to forecasts, Hurricane Matthew could have been one of the most destructive hurricanes in Florida had it made landfall at Palm Beach as a Category 4 hurricane in 2016, Hurricane Irma with a less westerly track would have struck Miami as Category 4 in 2017, and Hurricane Dorian could have struck Florida as a Category 4 storm in 2019 (Woo et al., 2017; Woo, 2019). These alternative tracks were all physically plausible and could have led to much higher damages than the actual events did.

The proposed framework is composed of three steps and it is illustrated in Fig. 1. The framework is iterative, and it is designed to support participation and interaction among stakeholders and interested parties in the selection of climate storylines. In Step 1, impact is assessed based on all available counterfactuals , i.e., by running an impact model with each ensemble forecast member for the period of interest. Based on the generated counterfactual impacts, Step 2 aims at building climate storylines from (combinations of) counterfactuals while making sure that each event in each storyline is represented by only one of its counterfactual representations. This step is the most crucial one and needs to be carried out iteratively and participatorily. It requires the analyst and stakeholders to work closely together to 1) visualize counterfactual events; 2) compare them with the actual events; 3) discuss what could had plausibly gone wrong; 4) build climate storylines from downward counterfactuals based on the assessment of critical system performances. Following some of the principles of co-production of climate services outlined in Bremer et al., 2019, this step is designed to be interactive, pedagogical and empowering.

The step is interactive as it requires the analyst and stakeholders to work together in determining what counterfactuals are deemed of interest out of the full set of counterfactuals. This requires the analyst to start visualizing tentative counterfactual tracks, strengths, and damages, and to update the visualization with different counterfactuals as feedback from the stakeholders on what counterfactuals are more interesting are acquired. The step is also pedagogical, as visualizing and comparing counterfactual events with the actual event triggers stakeholders' episodic memory, thus fostering engagement, participation, reasoning and learning about what could have plausibly gone wrong. The step is empowering as it is essential to involve the widest range of stakeholders, including minorities and groups embedding local values and knowledge. This is important for several reasons. First, this knowledge is crucial for interpreting modeling results generated in Step 1, which cannot typically capture the full range of impacts and are usually limited to economic damages. Second, local knowledge is important as detailed knowledge on what people and communities experienced during the actual event allows to better investigate the counterfactual impact. Third, as the selection of what counterfactuals constitute the various climate storylines relies on the assessment of critical system performances, a diversity of stakeholders is needed as such assessment cannot often be uniquely made. Indeed, critical performances differ across stakeholder's preferences and values. For example, some stakeholders may have a higher preference in avoiding damages to urban areas, some others to agricultural or rural areas. Some may focus on monetary damage, while others may value non-monetary damages more. All these different views need to be accommodated, as they might lead to the selection of different climate storylines.

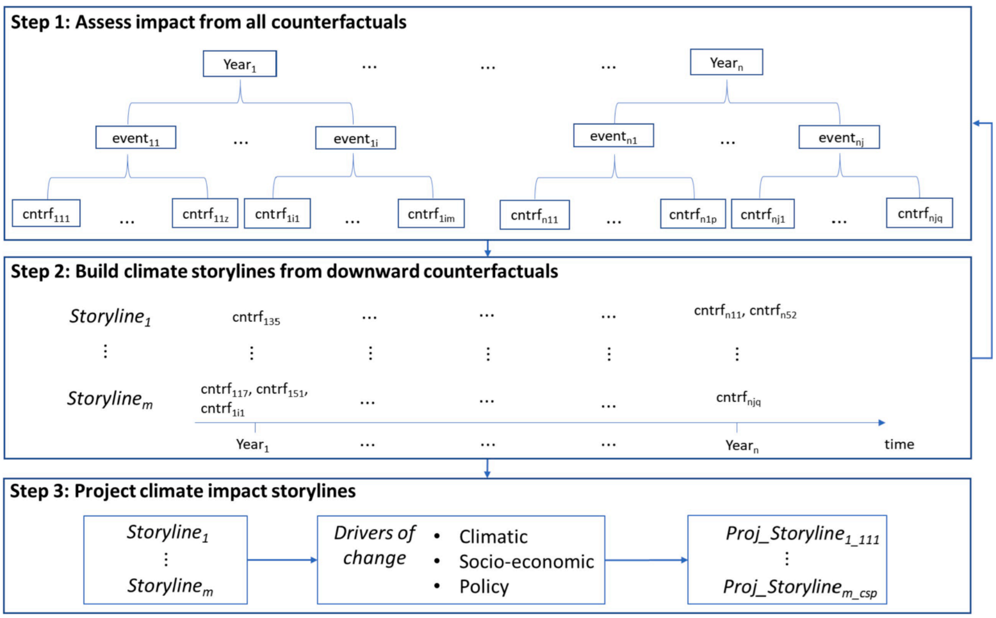

Fig. 1. The proposed framework to build climate storylines based on downward counterfactuals. The hierarchical structure reported in Step 1 resembles the one of forecast data. Each event in each given year has multiple counterfactuals (cntrf for short), with, e.g., $cntrf_{njq}$ being the q^{th} counterfactual of the j^{th} event of the n^{th} year. In Step 2 storylines are built from combining downward counterfactuals. The selected counterfactuals in the figure are mere examples. This selection should be carried out through an iterative process as indicated by the feedback arrow connecting Step 2 to Step 1. Finally, in Step 3, $Proj\_Storylines_{m\_csp}$ represents the future projection of the m^{th} storyline given the applied climatic, c, socio-economic, s, and policy, p, changes. The framework is introduced with an annual temporal resolution, but different resolutions can easily be adopted.

Step 3 aims at estimating possible future impacts of the selected climate storylines based on projections of changes of the climatic, socio-economic, and policy drivers. This step can be carried out in various ways. For example, one can use the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSP) (O'Neill et al., 2014) for projecting the climate storylines under alternative future climatic and socio-economic conditions. This approach would allow investigating when, and to what extent, could the impact from the selected climate storylines exacerbate in the future. Alternatively, one could adopt an Exploratory Modeling and Analysis approach (EMA) approach, (Bankes et al., 2013). In EMA, one runs a series of computational experiments to test the system under all possible values of the drivers. In so doing, one generates a large space of possible system states, and investigates vulnerabilities within such space, i.e., assesses what changes in the drivers may lead to states of poor system performances (Kwakkel and Pruyt, 2013). Only after, and if needed, one may assess how likely these changes in the drivers are and when they might occur in the future.

3. Case study

We applied the framework introduced in Section 2 to assess the impact of tropical cyclones on the financial sustainability of the European Union Solidarity Fund (EUSF). Tropical cyclones represent a serious threat for the EU's outermost regions, which include French territories (La Réunion and Mayotte in the South-West Indian Ocean; French Guiana, Saint Martin, Guadeloupe and Martinique in the North Atlantic Ocean) and the Macaronesian Region consisting of Portuguese (Madeira, Azores) and Spanish (Canary Islands) islands.

3.1. The European Union Solidarity fund (EUSF)

The EUSF was set up in 2002 in response to severe floods in Central Europe to provide financial relief to Member States affected by natural disasters. Although the fund's main structure and objectives have remained unchanged since 2002, the EUSF underwent several reforms in 2014 (Hochrainer-Stigler et al., 2017). Until 2013, the EUSF was capitalized with 1 billion EUR per year, payouts were triggered if damages exceeded a threshold of either 0.6% of the countries' Gross National Income (GNI) or 3 million EUR in 2002 prices, and financial aid amounted to 2.5% of the damage below the threshold, plus 6% of the damage above it. Even when the damage threshold was not met, the EUSF could still be used for smaller "extraordinary regional disasters" if the disaster were deemed to have long-lasting effects on the region's economic and social stability (Hochrainer et al., 2010). However, since no clear guidance was provided, extraordinary regional disasters were evaluated case-by-case and, as a result, 45 out of 61 requests were rejected or withdrawn (Hochrainer-Stigler et al., 2017). Consequently, one of the major changes of the 2014 reforms was a clearer definition of "extraordinary regional disasters".

To better define what constitutes a regional disasters, the 2014 reform established that payouts corresponding to 2.5% of the total damage should be made when regional damages exceed 1.5% of the regional GDP for NUTS 2 territories (from the French *Nomenclature des unités territoriales statistiques*), and 1% of the regional GDP for the EU's outermost regions. Payout rules for national disasters remained mostly unchanged, with the only change regarding the 3 million EUR threshold which was updated to 2011 prices. Capitalization rules did change after the 2014 reform, with a new annual capitalization of 500 million EUR in 2011 prices (thus about one half of the previous annual capitalization amount) with the option of carrying forward for one year any unspent capital.

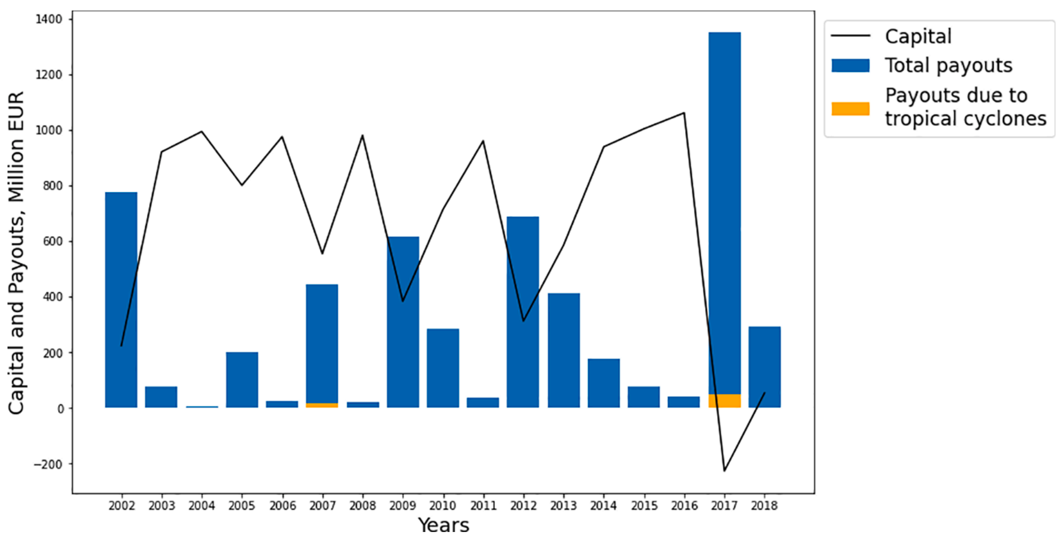

Fig. 2. Historical payouts data (bars) and calculated EUSF capital (black line) for the 2002–2018 period in million Euros. Yellow bars indicate payouts due to tropical cyclones affecting the outermost regions and blue bars all other payouts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2 shows the EUSF data of historical payouts and the calculated capital availability given these payouts for the period 2002–2018. Overall, only two payouts were made as a consequence of tropical cyclones, in 2007 and 2017. Both payouts were however very low when compared to the overall payouts made by the EUSF within these years. In 2017, capital level dropped below zero after a large earthquake that took place in Central Italy and, to cope with this, upfront payments from the year 2018 were made.

Although payments due to tropical cyclones contributed to render the overall 2017 payouts even higher, the overall absolute contribution was very low as the EUSF capital would have anyway dropped below zero. Historic evidence thus suggests that tropical cyclones cannot undermine the EUSF capital capacity. However, the available data cover a too short time frame, also considering that until 2014 there were no clear payout rules in place for regional disasters, which are those more exposed to such tropical cyclones. We thus aim to better study this aspect by building climate storylines through analyzing payouts from counterfactual tropical cyclones. Following the EUSF payout rules introduced above, estimating counterfactuals payouts is straightforward after direct damages from counterfactual tropical cyclones are estimated. This requires the use of an impact model, which is introduced in the next subsection.

3.2. The impact model

Direct economic damages from tropical cyclones are estimated using the open- source and -access CLIMADA impact model described in detail in Aznar-Siguan and Bresch (2019). Briefly, direct damages in CLIMADA are assessed as a function of weather-related hazard, exposure of people and goods to such hazards, and vulnerability of the exposed entities. Hazard from tropical cyclones is represented in CLIMADA by a map of the 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 cyclones tracks such as time, location, radius of maximum winds, and central pressure. More details can be found in Geiger, Frieler and Bresch (2018). CLIMADA provides various built-in methods to generate exposure (see, e.g., Aznar-Siguan and Bresch, 2019; and Eberenz et al., 2020). We use the one introduced in Gettelman et al. (2018) where the exposed economic value is calculated by downscaling regional Gross Domestic Products (GDP) using nighttime lights data. Vulnerability in CLIMADA is represented as typically done in natural catastrophe models, i.e., via an impact function which relates the hazard intensity to a damage percentage in exposed value.

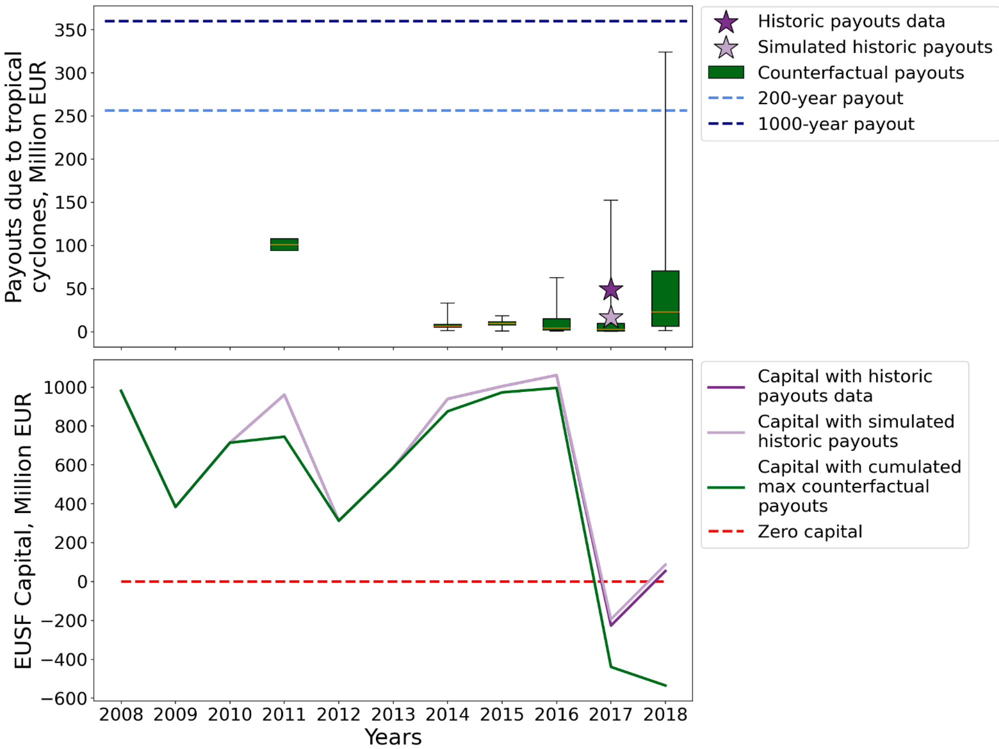

Fig. 3. Payouts due to tropical cyclones (top) and EUSF capital (bottom). The top figure reports data about historic payout (purple star), simulated historic payouts (pink star) and the distribution of counterfactual payouts (green boxplots). The boxes' dimension indicates the interquartile range and the whiskers indicate the minimum and maximum values. The lighter blue dotted line shows the 200-year payout, while the darker blue dotted line shows the 1000-year payout. The bottom figure shows (in analogy to Fig. 2) capital calculated with data of historic payouts (solid purple line), with simulated historic payouts (solid pink line), and the worst possible outcome (green line), i.e., cumulating each event's max counterfactual payout. The horizontal dashed red line indicates zero capital levels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Data

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; Park et al., 2008). The dataset contains historical tropical cyclone track data since 2008 and is updated continuously. For the sake of comparison, we also perform a probabilistic assessment and use the synthetic tropical cyclone tracks of the STORM dataset (Bloemendaal et al., 2020).

Regarding exposure, we use as nightlight data the DMSP-OLS Nighttime Lights Time Series (Lloyd, 2016) provided by NOAA until 2013 and the NASA's Black Marble data (Román et al., 2018) after 2013. Regional GDP data are taken from EUROSTAT (https://ec.europa.eu/eurostat). Finally, the adopted vulnerability function is provided by Eberenz et al. (2020) who calibrated impact functions for each tropical cyclone basin by comparing modeled and reported damages. They carried out calibrations using different methods and we here use the one they derived optimizing the total damage ratio.

4. Results

As a proof-of-concept application of the framework presented in Section 2, in this section we assess whether, and to what extent, EUSF payouts due downward counterfactual tropical cyclone events may compromise the stability of the EUSF. We present results following the same steps in the framework. As introduced in Section 2, the selection of climate storylines based on downward counterfactuals needs to be based on an iterative and participatory co-production process. However, we do not conduct a participatory analysis for this proof-of-concept case study as it is obvious what variable is of interest to identify what constitute critical performances for the EUSF, i.e., capital levels, and its assessment is straightforward since is regulated by clear and transparent rules. Climate storylines are thus built based on various (combinations of) downward counterfactuals that can lead to persistent negative capital levels.

4.1. Assess impact from the full set of counterfactuals

We present results in terms of payouts due to tropical cyclones (top panel of Fig. 3) and the resulting capital (bottom panel of Fig. 3). In particular, we compare data about historic payouts, simulated historic payouts (i.e., using the CLIMADA impact model with IBTrACS) and the counterfactuals payouts (i.e., using the CLIMADA impact model with TIGGE forecast data). Given these payouts and those registered in mainland Europe in the same years due to other perils (blue bars in Fig. 2), capital is calculated accordingly.

When comparing historic payouts data and simulated historic payouts (purple and pink stars in the top panel of Fig. 3), one can see that the model correctly simulates only one payout in 2017, therefore it does not lead to false payouts nor missed payouts, but it underestimates its extent. The historic payout amounts to 48.9 million, while the simulated historic payouts amount to 16.5 million. When comparing capital resulting from historic payouts data and simulated historic payouts (purple and pink lines in the bottom panel of Fig. 3), the latter overestimates the former of about 32,5 million EUR in 2017 (same amount as the payout difference in the same year) and 31 million EUR in 2018. This error is one order of magnitude lower than the yearly capitalization amount (i.e., 1000 million EUR before 2014 and 500 million EUR after 2014) and it thus cannot lead to a wrong identification of persistent negative capital levels, which is the goal of the analysis. Given the above, the known large uncertainties in impact modeling (Wagenaar et al., 2016; Molinari et al., 2020) and the fact that we are only simulating wind-driven damages, the underestimation (overestimation) of payouts (capital) can arguably be considered acceptable. The adopted set-up of the CLIMADA impact model is thus suited to simulate impacts from counterfactuals.

Looking at the counterfactual payouts (boxplots in the top panel of Fig. 3), it is evident that many more payouts than historically witnessed could have happened, and with higher magnitude. Maximum counterfactual payouts (upper whiskers of the boxplots) are large in the years 2011, 2017 and 2018, with this latter that could have registered a payout higher than the 200-y payout. To establish whether payouts from tropical cyclones can undermine capital availability, we calculate capital resulting from the worst possible counterfactual realizations, i.e., cumulating each event's max counterfactual payout (green line in the bottom panel of Fig. 3). It emerges that payouts due to tropical cyclones alone cannot bring EUSF capital levels below zero. For example, the counterfactual year 2011 requires large payouts, but the EUSF capital is still of about 600 million EUR. Rather, when large losses occur in mainland Europe, as in 2017 after the earthquake in Central Italy, large payouts due to tropical cyclones could exacerbate that loss and, most importantly, prevent a recovery of the capital in the following years.

By focusing on counterfactuals in the years 2017 and 2018, in the following section we identify which of these cause the missed recovery (i.e., the downward counterfactuals), compare them to the corresponding historic events and, finally, use the identified counterfactuals to build climate storylines.

4.2. Build climate storylines from downward counterfactuals

As reported in Table 1, historically, payouts due to tropical cyclones were triggered after Hurricanes Irma and Maria in 2017 and no payouts were triggered in 2018. Counterfactually, instead, there could have been more payouts in 2017 than those triggered by Hurricanes Irma and Maria, as well as payouts in 2018. To illustrate this point, we compare the historic and downward counterfactual events (Fig. 4). One can see that most of the outermost regions (islands in yellow) are within a red-shaded area, meaning that winds from the downward counterfactual are higher than the observed winds. This can be explained either by a change of the track and/or

Table 1
Payouts and damages from simulated historic and downward counterfactual events leading to EUSF payouts in 2017 and 2018. The first number in parenthesis indicate damage and the second indicates payouts, both in million EUR. The reported damages and payouts of the historic events are simulated with CLIMADA using IBTrACS.

Event type	Historic		Counterfactuals (cntfr in Fig. 1)	
Year	2017	2018	2017	2018
Name of event (damage – payouts)	Irma (320–8) Maria (335–8.4)	–	Irma (250–6.2) Maria (2′472 – 62) Harvey (95–2.3) Carlos (1′494 – 37.3) Enawo (6′090.8–152.2) Ophelia (68.7–1.7)	Berguitta (12′971 – 324) Fakir (929–23.2) Isaac (354–8.86) Helene (58.7–1.46) Kirk (144.2–3.6) Leslie (328–8.2) Ava (256–6.4)

the intensity of the tropical cyclone.

Tropical cyclone Enawo is an example where a change in track would have mattered more than a change in intensity (top-left panel of Fig. 4). Enawo was a Category 4 tropical cyclone that had a devastating impact on Madagascar but a negligible one on La Réunion, as it passed far away from it. Counterfactual Enawo, however, would have had a much lower intensity while taking a more southward

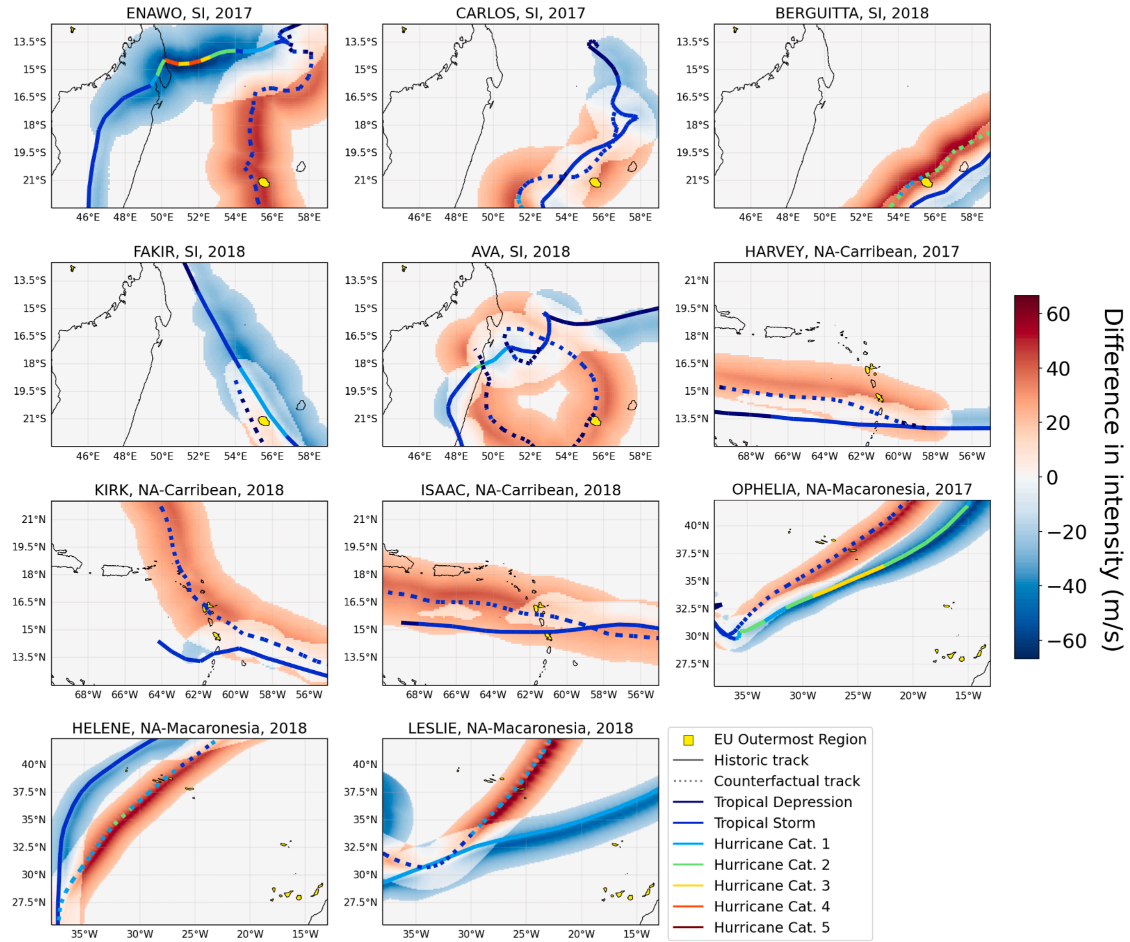

Fig. 4. Observed (solid line) and downward counterfactual (dashed line) tropical cyclone tracks and wind field difference (colour shading, m/s) between the two (counterfactual minus observed). Red (blue) areas indicate higher winds from the downward counterfactual (observed) events. Line colours indicate categories of the Saffir-Simpson scale. Each panel in the plot reports the tropical cyclone's name, basin and year. The outermost regions are indicated in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
The four identified climate storylines: the rationale behind their choice, a description of their impact on the EUSF and the involved downward counterfactuals.

Climate storylines	Rationale	Description	Counterfactuals (cntfr in Fig. 1)
$Storyline_1$	One high-impact event	A single large payout is required to La Réunion in 2018.	2018: Berguitta
$Storyline_2$	One high-impact event per year	Two large payouts are required to La Réunion in 2017 and 2018.	2017: Enawo 2018: Berguitta
$Storyline_3$	One high-impact event in one year followed by a series of events the next year	A single large payout is required to La Réunion in 2017, followed by a series of payouts to La Réunion, the Azores, Guadeloupe, Saint-Martin, and Martinique in 2018.	2017: Enawo 2018: Berguitta, Fakir, Isaac, Helene, Kirk, Leslie, Ava
$Storyline_4$	A series of events per year	A series of payouts are required to La Réunion, the Azores, Guadeloupe, Saint-Martin, and Martinique in 2017 and in 2018.	2017: Carlos, Enawo, Harvey, Irma, Maria, Ophelia 2018: Berguitta, Fakir, Isaac, Helene, Kirk, Leslie, Ava

path, thus passing very close to La Réunion leading to substantial losses. Counterfactual Enawo therefore, although weaker than historic Enawo, would have been more damaging from the perspective of the EUSF due to its change in tracks. Counterfactual Enawo leads to the highest counterfactual payout in 2017. Tropical cyclone Berguitta is an example where change in intensity could have mattered more than change in track (top right panel of Fig. 4). Berguitta was a tropical storm that affected both Mauritius and La Réunion as it passed close to these islands. Counterfactual Berguitta would have passed closer to La Réunion, almost making landfall, and with a much higher intensity. Counterfactual Berguitta leads to the highest counterfactual payout in 2018. Tropical cyclone Helene is an example were both a change in intensity and path would have made the event worse from the perspective of the outermost regions (Fig. 4 bottom left). Helene produced winds on the most western Azores as a tropical storm. Counterfactual Helene would have made landfall on many Azorean islands as as a Category 1 hurricane.

The identified downward counterfactuals serve as building blocks for climate storylines. Four climate storylines are identified and summarized in Table 2. The storylines are of increasing impact, and they are built to represent impacts from single large events and series of events (i.e., compound events). Compound events are analyzed in the form of temporal clustering, i.e., multiple weather events affecting the same territories within the same season (Zscheischler et al., 2020). In modeling event series, it is reasonable to assume that after an event hits, the damage potential of the following events decreases. This is considered by reducing each event's damage by an amount equal to the fraction of GDP lost from the preceding event.

The EUSF capital availability resulting from the four climate storylines is reported in Fig. 5. The increase in severity from the first to the fourth storyline is clear. However, there is only little difference between EUSF capital in the second and third storylines, meaning that the additional damage contribution of the event series in 2018 is not substantial. The figure also shows where the climate storylines locate with respect to the range of downward counterfactuals delimited by historic payouts (upper bound) and the worst possible scenario (lower bound), as introduced in the lower panel of Fig. 3. Although to different degrees, all storylines prevent a recovery of the EUSF capital after the payouts to the earthquake in Central Italy in 2017. The next section investigates impact from these climate storylines under climatic, socio-economic, and policy changes.

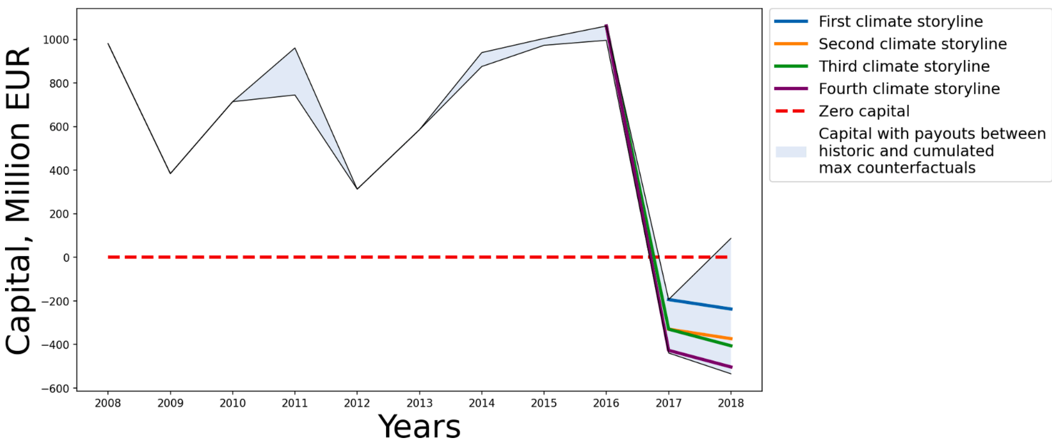

Fig. 5. Capital from the four identified climate storylines (blue, orange, green and purple solid lines), the range of counterfactual outcomes (light blue bandwidth) and the level of zero capital (dotted red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3. Projection of climate storylines into the future

Following the proposed framework, impacts of the selected climate storylines are projected into the future by evaluating the climate storylines under various assumptions of climatic, socio-economic, and policy changes. In particular, future changes are explored using an Exploratory Modeling and Analysis approach. The goal is to estimate under what plausible future states of the world the EUSF undergoes severe budget deficits without aiming to quantifying when such states may occur, nor how likely they are. In terms of climatic changes, an increase in the intensity of tropical cyclones is expected, with the the degree of such change being however uncertain. Knutson et al. (2020) estimated that the range of change of maximum surface wind speed is between 1 and 10 percent, which is the range we consider. As for socio-economic change, we assume an increase in GDP from 1 to 20 percent. As for policy changes, they are modeled as increase in the EUSF capitalization, which we assume it spans from 1 to 150 percent. As the fund was indeed capitalized with 1 billion EUR before 2013 (thus about twice as much as the current capitalization), an increment up to 150 percent is considered reasonable and affordable.

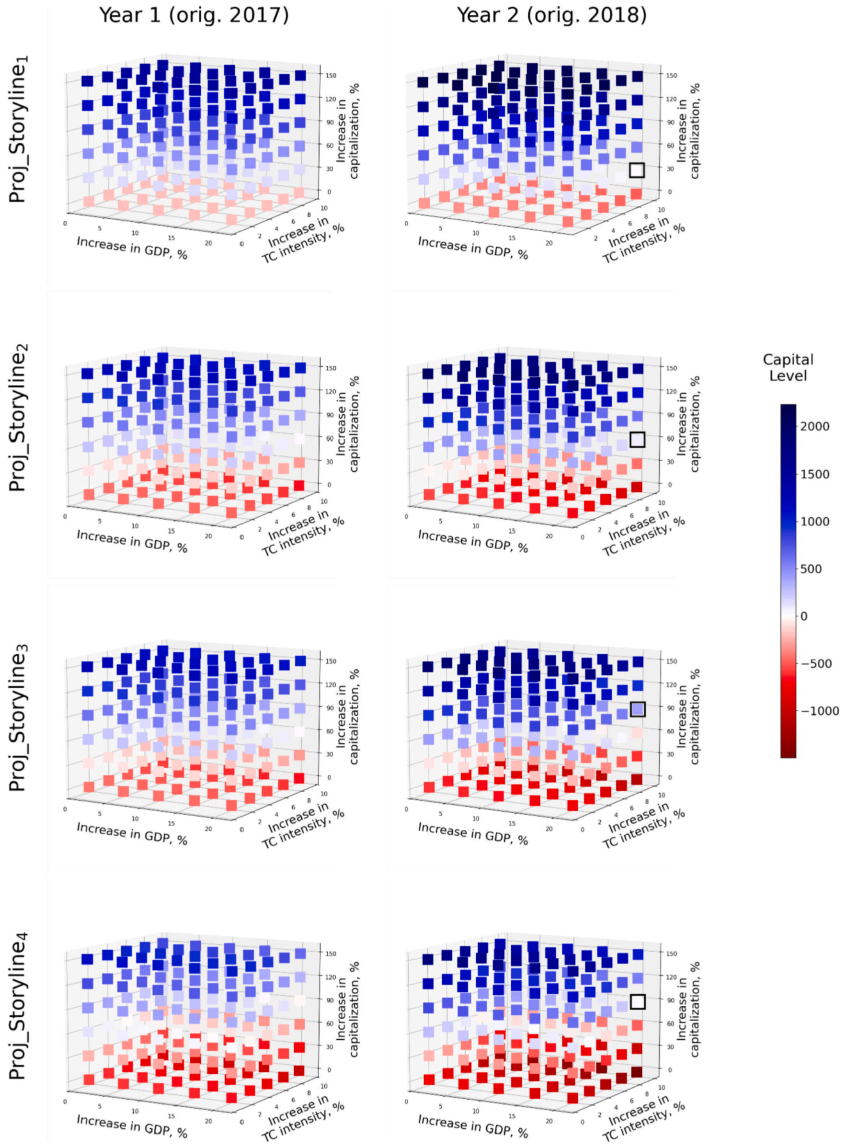

Fig. 6. 3D-heatmaps of simulated capital for the four selected climate storylines (see Table 2 for details). Panels on each row indicate the climate storylines, while panels on the two columns respectively indicate the years 2017 and 2018 projected in a hypothetical future. The axes in each panel indicate the percentage increases of tropical cyclones (TC) intensity, Gross Domestic Product (GDP), and annual EUSF capitalization levels. Blue (red) colours indicate capital above (below) zero. For each Proj_Storyline and under the highest GDP and TC intensities increases in the projected year 2018, the black square indicates what percentage increase in capitalization would be needed in order for the EUSF to have enough capital to cope with payouts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

By looking at the capitalization level indicated by the black squares, it is evident that the capitalization level which allows coping with the highest increases in GDP and TC intensities at the end of the second year differs across climate storylines. In particular, under the first climate storyline (first row of Fig. 6), a slight increase in capitalization (at about 30 %) would allow the fund to cope with the highest modeled increases in tropical cyclone intensity and GDP. As this storyline simulates a single large downward counterfactual in 2018, it seems that no single large tropical cyclone event can be of serious concern for the EUSF capital. For the second and third storylines (second and third rows of Fig. 6) an increase in capitalization of about 50 % would allow coping with high climatic hazard and socio-economic exposure increases. The fourth climate storyline (last row of Fig. 6) simulates series of downward counterfactuals for two consecutive years. The effect of the temporal cumulation is evident when looking at capital levels in the second year, where acceptable levels of capital (light blue) can be found at around 60 % increase in capitalization and a 90 % increase in capitalization is required to cope with the highest climatic and socio-economic scenarios considered. A 90 % percent increase in capitalization virtually implies re-introducing the capitalization rules in force before the 2013 reforms.

Restoring the previous capitalization rules would thus guarantee that the contribution of tropical cyclones will at most exacerbate large payouts coming from mainland Europe (Year 1) but would not prevent a recovery from such year. From a more general perspective, however, Hochrainer et al. (2010) concluded that, even before the 2013 reforms, the EUSF might have been undercapitalized against losses due to other perils like floods. Therefore, a substantial policy change in how the EUSF is capitalized would be needed to cope with payouts from both tropical cyclones hitting the outermost regions and other perils, such as flooding, concurrently occurring in continental Europe.

5. Discussion

In this section we comment upon the introduced framework, as well as discuss upon the data and model used for the analysis. Regarding the framework, we identify one challenge and one limitation. The challenge relates to the requirement of selecting a limited number of climate storylines from the many (combinations of) counterfactuals. As discussed, this entails iteratively visualizing the impact of (combinations of) downward counterfactuals and agreeing upon the ones deemed critical and relevant for the case study and by the parties involved. If, on the one hand, this aspect is indeed the strength of the approach, as it engages all stakeholders in a process of system understanding and awareness-raising about how things could have gone worse; it does, on the other hand, require more resources and efforts than a standard probabilistic analysis. The limitation regards the poor support of the proposed framework to *a posteriori* statements about the likelihood of the identified climate storylines. Although the storyline approach does not primarily aim at modeling probabilities of the derived climate storylines and rather focus on identifying chains of events which are plausible and potentially critical for the system under study, in some cases there could be the need to assign probabilities after climate storyline are built. One possible way to remedy this is by interpreting the built climate storylines as causal networks in a Bayesian framework (Shepherd, 2019), and this will be subject of future work.

Regarding the analysis, we comment upon the quality of the forecast data, the impact analysis and, finally, on alternative ways for better projecting the impact of climate change on the strength of tropical cyclones. The whole analysis relies upon the use of climate information provided by ensemble forecasts data. These data guarantee plausibility in the generated counterfactuals as they were generated by numerical models that capture fundamental physical processes and, thus, they all represent plausible alternative realizations of past events. As such, no use is made of info regarding forecasts predicting skills, nor forecasts are filtered based on their lead-times or forecasting capabilities. Nevertheless, the predictive capacity of forecast data is indicative of their quality, and therefore of the climate information used to support the generation of climate storylines.

Several authors assessed the reliability of various ensemble prediction systems. For example, Titley et al. (2020) verified all named storms in all tropical cyclones basins in 2017 and 2018 and concluded that ensembles exhibit good reliability in track probability forecasts. Furthermore, they showed the added value of combining members from different ensembles into a multi-model ensembl in terms of imrpoved forecast skills. Froude (2010) and Yamaguchi et al. (2017) analyzed the reliability of ensemble forecasts provided by TIGGE in forecasting tracks position and strength. They both concluded that the reliability of ensemble forecasts significantly increased over time, with ensemble forecasts being very reliable in predicting the track positions but less so in forecasting the track strength, which is underestimated. This latter issue is due to the still low resolution of numerical models, which does not allow to capture the titled structure essential to model cyclone's growth and decay. Therefore, although all forecasts are plausible, the quality of the information they provide is higher with respect to the track path than the track intensity, which is expected to be underestimated.

As for the impact analysis, the main limitation relates to the limited amount of payout data from the outermost regions against which we were able to compare simulations from the impact model. Indeed, the impact model rightly simulates a payout in 2017 and within the same order of magnitude, but more data would have helped to better benchmark the model. Another limitation relates to the use of GDP as a proxy of asset values. Although this was convenient as EUSF payouts for the outermost regions are triggered based on how direct damages relate to GDP, not all GDP relate to physical assets, and therefore this may be a poor proxy of asset exposure. Related to the discussed aspect of forecast data underestimating tropical cyclones intensity, it is expected that counterfactual damages and payouts, all else being equal, have been underestimated.

Finally, in Step 3, projections of future increases in tropical cyclone intensity were simulated by applying a multiplicative factor to the strength of the identified downward tropical cyclones, according to plausible values reported in the literature. Alternatively, one could employ a more comprehensive pseudo-global warming approach and assess the effect of global warming on intensity, path and evolution of individual tropical cyclone events. Such approach makes use of numerical weather prediction models to generate new tropical cyclones using the observed synoptic weather patterns, but thermodynamic conditions of a warmer climate (Lackmann, 2015; Ito et al., 2016). In this way, tropical cyclones would be projected not only by simulating an increase in intensity but by regenerating the entire event as if it happened in a warmer world, and the impact of climate storylines can be assessed accordingly. Because of the event-based nature of the pseudo global warming approach, it perfectly fits the framework proposed in the present paper.

6. Conclusions

In this paper we introduce a framework for building climate storylines based on downward counterfactuals and apply it to a proof-of-concept case study. The framework is event-oriented, focuses on impact, and is participatory-based. It entails three steps. First, impact is assessed from all counterfactuals. Second, climate storylines are built in an iterative process as a (combination of) downward counterfactuals. Last, the identified climate storylines are projected in the future based on projected climatic, socio-economic and policy changes. We apply this framework to assess the impact of tropical cyclones on the sustainability of the European Union Solidarity Fund, a fund set-up by the EU in 2002 to help Member State to cope with natural disasters.

Results of this proof-of-concept study show that the contribution of tropical cyclones alone cannot compromise the availability of the EUSF capital. However, should a major event occur in mainland Europe and large payouts due to tropical cyclones be required in the same year, the latter would hamper a recovery of the EUSF capital. Future projections show that a 30 % increase in capital would allow coping with a single large event. Should large payouts due to tropical cyclones happen in consecutive years and from event series, however, an increase in capitalization from 60 % to 90 % may be required, which would imply restoring the capitalization rules that were in force before 2013.

The adopted framework allows visualizing the (downward counterfactual) weather events responsible for critical outcomes and to investigate under what climatic, socio-economic, and policy changes these can be controlled or exacerbate further. The introduced framework explicitly avoids any probabilistic statement regarding neither the likelihood of the events deemed critical nor the applied future changes. However, in some cases it can nevertheless be relevant for decision makers to be able to assign probabilities to such events and projected future changes. Future research will focus on this aspect by, e.g., interpreting climate storylines as causal networks as well as applying the framework to a wider range of climate risk management problems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is funded by the EU Horizon 2020 *REmote Climate Effects and their Impact on European sustainability, Policy and Trade* (RECEIPT) project, grant agreement No 820712. The authors acknowledge Stefan Hochrainer-Stigler for providing feedbacks to an earlier version of this manuscript and the three anonymous reviewers whose comments substantially improved the quality of the manuscript.

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