Climate impact storylines for assessing socio-economic responses to remote events

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Quote:

"What I hear, I forget. What I see, I remember. What I do, I understand." (Xunzi, ~300 BC)

Abstract

Complex interactions involving climatic features, socio-economic vulnerability or responses, and long impact transmissions are associated with substantial uncertainty. Physical climate storylines are proposed as approach to explore complex impact transmission pathways and possible alternative unfolding of event cascades under future climate conditions. These storylines are particularly useful for climate risk assessment for complex domains, including event cascades crossing multiple disciplinary or geographical borders. For an effective role in climate risks assessments, practical guidelines are needed to consistently develop and interpret the storyline event analyses.

This paper elaborates on the suitability of physical climate storyline approaches involving climate event induced shocks propagating into societal impacts. It proposes a set of common elements to construct the event storylines. In addition, criteria for their application for climate risk assessment are given, referring to the need for storylines to be physically plausible, relevant for the specific context, and risk-informative.

Six examples of varying scope and complexity are presented, all involving the potential climate change impact on European socio-economic sectors induced by remote climate change features occurring far outside the geographical domain of the European mainland. The storyline examples illustrate the application of the proposed storyline components and evaluates the suitability criteria defined in this paper. It thereby contributes to the standardization of the design and application of event-based climate storyline approaches.

Keywords: climate change, physical climate storylines, climate risk assessment, risk transmission

1. Introduction

In the modern, highly connected and globalized world, the assessment of impacts of past and projected climate change on nature and society needs to extend beyond the local perspective in which adverse climate features are linked to immediate, localized consequences (Hedlund et al., 2018). Impacts from fast (extreme weather) and slow-onset events (van der Geest and van den Berg, 2021) at any location on the planet can be transmitted to remote areas via various physical and socio-economic pathways (Benzie et al., 2019), including trade (exchange and transportation of goods and services), finance (private and public capital), biophysical transfers (such as spatially extensive hydrological systems), and people's behavioral responses. The societal impacts are not only governed by the physical hazard and the resulting effect cascades, but are also strongly linked to the societal risk response (Simpson et al., 2021). The COVID-19 pandemic has contributed to a growing awareness of transboundary implications and considerable complexity of systemic risks (Phillips et al., 2020; Ringsmuth et al., 2022), including climate change (Challinor et al., 2017; Gaupp, 2020; IPCC, 2022).

Assessment of impacts resulting from remote climate change features requires an analysis framework that embraces a "systemic risk" approach (Hochrainer-Stigler et al., 2020) and acknowledges complex interactions between risk attributes (Simpson et al., 2021). Globalized, systemic shocks originating from extreme weather or climate conditions have been documented and analyzed for a wide range of events, for instance the 2003 and 2010 breadbasket disruption (Gaupp et al., 2020; Falkendal et al., 2021), global supply chain interruptions (Abe and Ye, 2013; Haraguchi and Lall, 2015) and financial exposure (Woo, 2019; Tesselaar et al., 2020). A systemic risk approach includes the need for a comprehensive definition of the system boundaries, relevant climate features, the risk propagation mechanism, quantitative hazard impact evaluation, and specification of alternative scenarios (Carter and et al., 2021).

However, a generalization of complex cascading events, in order to evaluate societal risk or preparedness, is not trivial (Cutter, 2018, 2021). The topic is complicated by the nearly unlimited spatial extent over which risk transmission can take place, and the numerous pathways, triggers, event cascades and dependencies on boundary conditions. A formal probabilistic assessment of the associated risk is virtually impossible: impacts of climate events propagate through a complex and dynamic network of highly conditional cause-effect chains, and quantitative analysis of signal strength and cascading probabilities is conceptually far from being straightforward (Dessai and Hulme, 2004; Stainforth and Calel, 2020).

Alternatively, the exploration of specific risk-transmission pathways can provide useful information on socio-economic sensitivities to remote and cascading climate events, especially when interactions are very complex and subject to many conditional dependencies, which is a form of deep uncertainty (also framed as "radical uncertainty"; (Kay and King, 2020)). For this, well-designed physical climate storylines triggered by specific climate events (Shepherd et al., 2018; Lloyd and Shepherd, 2020; Sillmann et al., 2021) offer a helpful framework for analyzing how impacts can be reduced and resilience to climate change can be enhanced. A description of selected historic events that have been experienced by individuals can give more meaningful insights than a quantitative uncertainty assessment across a complex chain of causes and effect (Shepherd and Lloyd, 2021). Event-oriented physical climate storylines (or in brief: climate event storylines) generate insights that can lead to better preparedness, for instance by developing stress-tests conditioned on plausible and verifiable boundary conditions, or by revealing previously unexplored risk propagation pathways or responses to emerging risks (Baldissera Pacchetti et al.; Albano et al., 2021).

However, similar to probabilistic approaches an effective application of climate event storylines requires a credible and traceable approach to construct them (Stainforth et al., 2007). The number of potential event-chains that could be chosen is infinite, and also the underlying assumptions, tools and metrics require an explicit documentation and justification in order to be useful as resource for climate risk assessments. Therefore, some standardization of storyline construction guidelines and evaluation criteria is desirable.

In this paper we outline a development protocol for climate event storylines that is designed to map impacts of global climate features on selected European socio-economic sectors. We propose a generic structure for the definition, engagement and quantitative analysis of the climate event storylines, and include examples of the use of such a protocol in various contexts. The approach is not free of ethical considerations reflecting stakeholder's perspectives and values as they refer to choices of events, impact transmission pathways and analysis protocol (Baldissera Pacchetti et al.). Stakeholder inputs are addressed here in the scoping of the climate event storylines, but a detailed analysis of the ethical aspects is out of scope of this study. However, to facilitate the societal uptake of this scientific information, a set of criteria (“realistic”, “relevant” and “risk-informative”) has been formulated and evaluated, broadly similar to those proposed by (Cash et al., 2003) for climate services.

We first outline the criteria and core ingredients of the analysis framework and processing steps, arriving at a description of case-specific storylines, the involved data and modelling approaches, and the role of alternative realizations of the storylines, referred to as “counterfactuals”. The storylines are constructed using different types of sources of evidence (e.g., models, data, expert judgement) that can be manipulated (perturbed) such that the result assesses the particular context at hand (i.e. societal risk to climate change). The collection of case studies illustrates different methodologies for selection, modelling and perturbing the specific storyline components. We conclude each storyline description with an evaluation of the criteria, and provide further outlooks to the future development of these and related event-based climate storylines.

2. Criteria for climate event storylines

In order to be a useful source of information supporting the assessment of climate change implications for a specific target domain, the criteria realism, relevance and risk-orientation are used as guidelines. The construction of “realistic” storylines is promoted by using historic event chains that demonstrated the European exposure to worldwide climatic features in practice, or events generated by models with epistemic reliability (Baldissera Pacchetti, 2021). The description of the impact transmission pathway is guided by the use of observations and witness testimonials focusing on key indicators and processes that characterize the storyline. We use or adapt fit-for-purpose modelling concepts that are evaluated for their ability to reproduce the relevant processes and interactions, and set up experiments that allow reproduction, verification and comparison (see (Baldissera Pacchetti et al., 2020) for a discussion on quality dimensions for forward looking regional climate information).

The "relevance" (or "salience") of the event storylines is promoted by a number of design principles. First, a storyline scoping and selection process is carried out involving stakeholder insights, documentation of drivers and direct and indirect sectoral impacts of historic events, and screening the relative importance of subjects in the socio-economical domain of interest. To allow analysis of the effect of remote climatic features on European sectors, we compare the outcome of multiple versions of constructed storylines with a reference configuration, and one or more "counterfactuals" with perturbed characteristics derived from predefined climate and socio-economic scenarios. A level of standardization across these scenarios is imposed by making explicit linkages to global warming levels and Shared Socio-economic Pathways (SSPs), matching the boundary conditions used in many national or European-wide climate risk assessments (see e.g. (Talebian and et al., 2021)). Finally, the representativity of the storylines for stakeholders can be enriched by adding "micro-stories", illustrating impacts by responses of specific actors related to the stakeholder community.

The climate event storylines are not designed to quantify the probability of the occurrence of impact pathways, which is duly impossible given the complexity of events and their consecutive impact cascade (Sillmann et al., 2021). Rather, the approach focuses on the plausibility (being not demonstrably inconsistent) of the event chains conditioned on specified climatological and socio-economical boundary conditions. They are still designed to be "risk-informative" by revealing or understanding the (sometimes hidden) relationships between climatic hazards and their remote impacts. Also the storylines support the discovery element in exploratory foresight studies designed for informing present day policy making on future implications (Termeer et al., 2017; Wiebe et al., 2018). The assumptions used to select the storyline components need to be documented in order to allow evaluation of the realism of the findings, and reproduction of the storyline in other contexts and by different analysts. In addition, probabilistic context can be added by quantifying the (conditional) occurrence frequency of large-scale climate features giving rise to the hazard event included in the storyline (Shepherd, 2019).

3. Construction of event-based climate storylines

We define climate event storylines as "physically self-consistent unfolding of past events, or of plausible future events or pathways" (Shepherd et al., 2018; Sillmann et al., 2021). In our context, a sequence of events with an underlying causal relationship forms a logical narrative that links climate hazards at a given location in the world with a socio-economic impact materialized in Europe. The storyline is captured in an analysis framework (using models, data or expert judgment) that can be interpreted, perturbed and explained in the context of a societal risk due to global climate change.

The climate event storylines described here connect *geographical domains* (of climate hazards and (remote) impacts), *time scales* (for precursors, events, impacts and response actions), *process cascades* (combining the physical, economic, ecological and social domains) and *actors* (including those that are directly impacted in the region of climate hazards, contributing to the impact transmission, and experiencing or responding to remote impacts). (Carter and et al., 2021) identified similar connecting elements while exploring an analysis framework for remote climate impact chains. In our study, these elements are brought together in the construction of climate event storylines in order to identify a common structure that spans the entire chain between the remote climatic hazards and the final (socio-economic) European impact. The common elements are illustrated for each of the selected storyline examples below. They consist of (see also *Figure 1*):

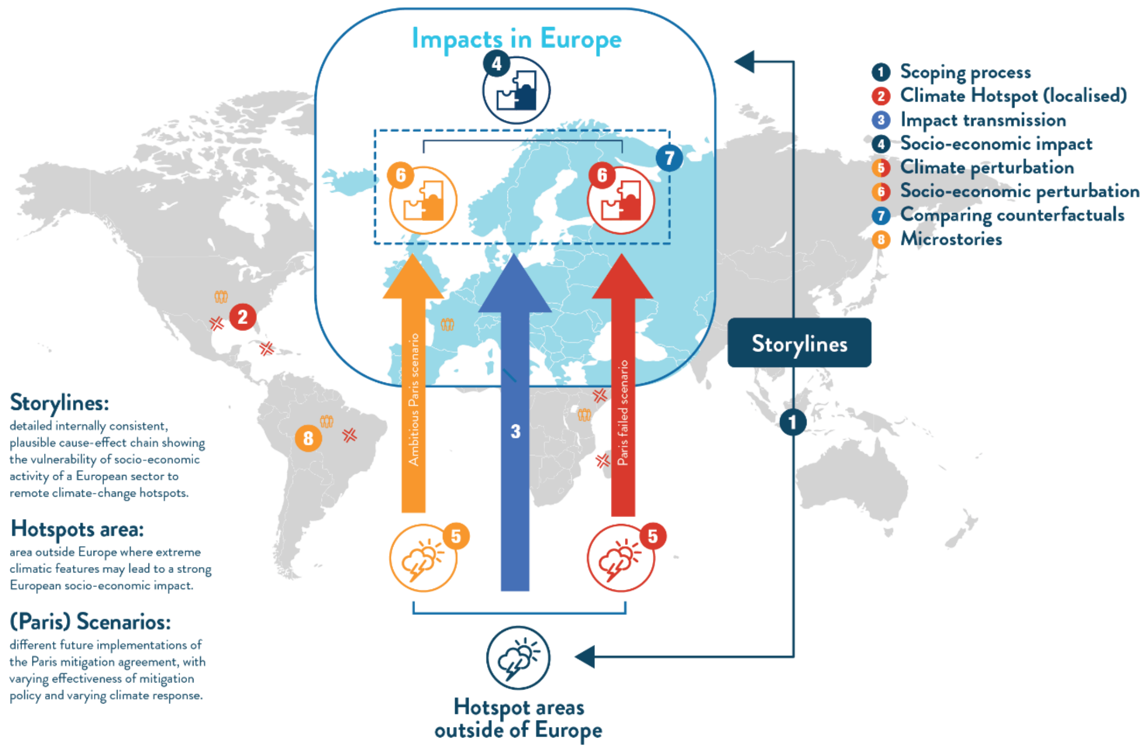

Figure 1: Design steps for climate event storylines (see text for details)

1. A *scoping process:* from the diversity of historic events, societal sectors and physical and socio-economic transmission pathways, a selection of individual storylines is made that reveal relevant and recognizable impact transmission pathways. This includes an inventory of interested societal stakeholders, analysis of macro-economic global networks and supply/demand chains, inspiration from recent climate events and evidence of shock propagation in the globalized world. Stakeholder feedback by means of interviews and workshops is sought to collect relevant information on impacts, vulnerabilities and non-climatic drivers that are of interest for climate event storylines. This feedback is subsequently analyzed in conjunction with evidence from “top-down” climate and socio-economic scenario information archives (Berkhout et al., 2013; Cairns et al., 2013);
2. The *remote climate hazard region* (also referred to as the *climate hotspot*): the geographical area where the initial triggers are manifested. The selection of climate hotspots is guided by historical evidence or extractions from model projections. Their description includes their causal drivers, hydrometeorological variables aggregated to an appropriate time and space scale, and an assessment of the level of scientific understanding (LOSU) of the link between climate change and their plausibility of occurrence. The climate hotspot can be a region where the climate hazards of interest are common features, but are expected to change in intensity/frequency, timing or domain in future climate conditions. Sometimes the assessment of the likelihood of

occurrence in the region is enriched by exploring alternative event realizations using ensemble techniques to create so-called “downward counterfactuals” (Woo, 2019). However, the hazard occurrence at that location may be unprecedented due to an uncommon hazard pathway, atmospheric circulation pattern or combination of precursors. Multiple hotspot regions can emerge simultaneously, for instance by a common large-scale driver such as ENSO or other SST anomaly patterns. The climate hazards have a locally disruptive impact that eventually affects the European impact;

3. The *impact transmission pathway* (also labeled as the *socio-economic pathway*): the process chain that links the climate hotspot to the impact on European stability, growth or resilience. This can consist of trade networks, supply/demand chains of food and commodities, financial exposure portfolios (by investors, insurance or liability configurations), or geophysical teleconnections (sea level rise induced by remote ice mass loss, or impacts cascading across transboundary watersheds) (Benzie et al., 2019). Input for this step is provided by the stakeholder feedback during the scoping phase, or statistical data on, for instance, historic trade records;
4. The *socio-economic impact* of the transmitted disturbances evolving from the remote climate hazard: this can be a qualitative description (changes in public perceptions or diplomatic relationships) or a quantitative measure of consequences for a specified set of societal actors (financial damage, anomalies in volume of trade or consumption). The overall impact is strongly conditioned on the socio-economic structure of the sector where the impact is emerging: different socio-economic boundary conditions will generally lead to (potentially very large) differences in the impact. The combination of the remote climate hazard region, the transmission pathway and the European socio-economic impact metric represents the reference configuration, in which present day (adverse) climate features can be linked to socio-economic impacts;
5. The *climate perturbation*: the purpose of our climate event storylines is to identify impacts of remote climate change. For this the comparison between different climatic background states is organized, by construction of a so-called *(climate) counterfactual* evolution of the event chain. In fact, the selection of hotspots in step 2 and the stakeholders input to this process are partly based on the perceived or expected climate anomalies in the region of interest. The comparison of different unfoldings of events is inherent to various techniques for climate event attribution (Hannart et al., 2016; van Oldenborgh et al., 2021), including the analysis of the attribution of impacts of these events (see for instance (Mengel et al., 2020)). The construction of perturbed climate event storylines is supposed to describe the change of the physical characteristics of the climate feature(s) in the climate hotspot as a plausible response to changing levels of global warming, for which a reasonable LOSU exists (Hazeleger et al., 2015). This can be an observed analogue (for instance in an historic, cooler, climate episode), or a perturbation applied to a modelled representation of the event, for instance by applying a temperature-based scaling (Te Linde et al., 2010), regional modelling (Lenderink et al., 2021), model nudging (Van Garderen et al., 2021), conditional sampling of circulation patterns (Zappa and Shepherd, 2017) or analogue hazards (Hegdahl et al., 2020; Schaller et al., 2020), statistical resampling (Ward et al., 2014; Li et al., 2018) and other techniques. The application of a perturbation to the climate feature in the event storylines is triggering a chain of responses across the impact transmission pathway up to the target socio-economic impact metric;

6. A *socio-economic perturbation:* the change of remote event-impact relationships under different climate change scenarios is not necessarily restricted to a changing physical climate. Scenarios of future climate conditions, for which impact assessments are usually carried out, also represent changes to the socio-economic background state. Shared Socio-economic Pathways (SSPs) have been constructed (O'Neill et al., 2014) that sketch the global evolution of macro-economic and social indicators (such as GDP, population, industry, land use) following a set of narratives on global cooperation, technology and energy consumption. In many national or regional assessments of future socio-economic developments these SSPs are interpreted for the local context, feeding into projections of spatial developments, employment, mobility, economic structure and other attributes (Frame et al., 2018; Talebian and et al., 2021). These downscaled projections usually don't include recursive or planned responses to environmental or socio-economic developments (Andrijevic et al., 2020; Chen et al., 2020). Responses to socio-economic impacts arising from (remote) climate pressures, such as implementing adaptation policies or changing exposure or vulnerability to high-impact shocks may be included in the socio-economic perturbation that is part of the counterfactual event-based storyline;
7. *Comparison between reference and counterfactual(s):* the comparison of the reference storyline and the counterfactual(s) in which climate features and/or socio-economic structures have been perturbed allows the formulation of the "climate change narrative", describing the implications of these changing conditions in the event-impact cascade. Quantitative and qualitative understanding can be derived from following the altered background state through the storyline components: a perturbation of the triggering climate features (an imposed link to global warming) may or may not lead to significant changes in the local impact, downstream transmission, or socio-economic impact, depending on specific properties of the causal network chain and its dynamic responses. The perturbations to create the counterfactuals can be applied without explicitly considering the probability of occurrence of the climate hazards or the climate change impact on this occurrence. This comparison thus provides insights in potential plausible *pathways* of the event-impact relationship and its details, conditional to the assumptions made to create the storyline. This requires a careful selection of data and models used, a thorough documentation of conditions and assumptions, and a targeted experimental (model) design to generate the reference and counterfactual storylines;
8. *Accompanying micro-stories:* these are complementary narrative elements to enrich the climate event storylines by providing additional detail or context. The event storylines usually contain events, transmissions and impacts whose selection is highly conditional, rendering for alternative representations, sensitivities to choices, and diversity in perspectives. "Micro-stories" can be helpful to make occasional excursions from the main storyline narrative, for instance to explore the sensitivity of the processes in the event-cascade to subtle changes in the used assumptions. Also inputs from individuals and stakeholders, for instance "witness reports" from people affected by historic event impacts, or stakeholders involved in the design in impact assessment or adaptation, may be added as micro-stories to the storyline package (see for instance (Jack et al., 2020; Coulter and et al., 2021)).

4. Overview of the illustrative storylines

In the following section we describe six different storylines and their counterfactuals. Each storyline describes sector-specific socio-economic impacts of remote climate change features (see Figure 2) and the insights derived from it. We present two storylines related to food production, three storylines featuring tropical cyclones, and one storyline addressing (extreme) sea level rise.

Each of the protocol steps is briefly presented, and the variety of storyline designs is presented and discussed (see Table 1 below). Each description concludes with an assessment of the potential application domain. Criteria for their applicability are also summarized and discussed in the next sub-section (Table 2). Methodological details on the storyline construction are found in the Annex.

Figure 2: Geographic overview of remote climate change features affecting European socio-economic sectors used in the storyline illustration.

<u>Storyline example 1: soybean production for European food supply</u>

1. Rationale of the storyline

A vast majority of all soybean consumed and processed in Europe is produced in areas concentrated in the mid-west US, Brazil and Argentina, together accounting for over 90% of the total global soybean export (Wellesley et al., 2017). These main soybean production areas are exposed to varying patterns of climate variability and trends, having pronounced impacts on regional production volume and world trade volumes (Anderson et al., 2017; Torreggiani et al., 2018).

In addition, various societal responses to climate and environmental change affect the sector strongly. Rainforest conservation policies in importing countries impose additional criteria on the spatial extent of soybean exploitation and are considered to constrain options of producers to expand or transfer production regions (Gibbs et al., 2015; Bager et al., 2021). Also changes in dietary preferences in importing countries may affect demand and hence trade volumes and prices (Willett et al., 2019; Ortiz et al., 2021).

The climate event storylines explore the potential climate change impact on temporary production declines in major soybean producing areas in the US and South America. It reconstructs a number of recent drought-induced soy yield losses and their impacts on global and European prices, trade and consumption patterns, and explores how these events could unfold in a future warmer world. In addition, counterfactual storylines are exploring impacts of diet changes towards less meat consumption and forest conservation policies. The resulting impact cascades are highly conditional on climatic and socio-economic features, and the combination of these multiple factors introduces a significant uncertainty in the ultimate socio-economic impact in Europe.

2. Storyline elements

The *scoping* process was guided by a consultation with NGOs representing local soybean producers, shaping the analysis of local climate impacts and the various counterfactuals. A survey of global *climate hotspots* for agricultural drought in major food production areas (Ercin et al., 2019) contributed to the selection of the remote target regions and identification of climatic drivers of yield losses in South America and US. We focused on the 2011/2012 growing season which displayed an unprecedented impact that resulted from a combination of low precipitation and high summertime temperature in US domains (Goulart et al., 2021). Future analogues of the 2011/2012 yield shock are used to analyse the *transmission* of yield deficits on *socio-economic impacts* in Europe and other continents. The *socio-economic impacts* include trade and economy (changes in trade patterns, imports and prices), production and consumption (of food, feed and other products, changes in calorie intake) and environment (changes in land use, production area, carbon and water footprints).

In this complex network of physical and societal processes and interactions, many stories can be told. Here a reference situation is defined as the anomaly of the 2011/2012 season relative to a 30-yr time series of selected metrics. The *climate perturbation* is applied by selecting analogues from climate projections following global warming levels of 2.5 and 3°C by 2050. Also a *socio-economic perturbation* is imposed by using indicators such as trends in population, land use and technology. The *comparison* of the SSP-counterfactual to the reference situation is expressed quantitively using metrics for soybean yield, production area and volume, trade volumes with Europe, European consumption, and price. In particular, the effect of the yield deficit shock on these metrics is quantified and visualized.

In parallel to the SSP-counterfactual, *two additional counterfactuals* are processed: one in which the meat and dairy consumption in Europe, and subsequently the demand for soy as a feedstock, is reduced by 50%, and one where in tropical forest areas conversion of primary forest into cropland is not allowed. This set of reference simulations and counterfactuals allow an insightful illustration of the resilience against temporary climate-driven anomalies in soybean yields, and the degree to which this resilience is affected by a reduced dependency on specific hotspot regions through conservation policies and/or adjusted consumption patterns.

Micro-stories can be used to describe specific implications for one of the many actors in this sector, for instance addressing conflicts on water use in soybean production areas with other sectors under sustained drying (Flach et al., 2020), shifts in employment in the agri-food business both in production areas and within Europe, drought impacts on domestic transportation (Marengo et al., 2021), risk of depreciated investments (Chain Reaction Research, 2018), trends in predictability of climatic and technological impacts on yields, the interactions between regional deforestation and increased magnitude and frequency of soybean losses (Flach et al., 2021) and the role of carbon pricing to reduce deforestation pressures.

3. Application domain

The soy market has many actors, including soybean producers, traders, food processing companies, but also consumers, policy makers, financing industry and NGOs in addressing environmental or social wellbeing aspects. The relevance of the storyline is supported by the large economic value, the contribution to food supply in Europe, evidenced exposure to climatic pressures, and societal attention to efficient land allocation and environmental impacts of soybean production and consumption. The illustration of the impact of changing characteristics of climate extremes and socio-economic interventions in well-constrained climate event storylines are used in policy simulations to support for instance development of international policies on land management or food security (van Meijl et al., 2020). It also serves as a stress-test in activities aimed at preparing for global shocks in one or more major food sectors, both for public and private company responses. And it can assist in shaping the communication and intervention policies of NGOs active in the field.

<u>Storyline 2: Concurrent drivers of disrupted food security in the Horn of Africa</u>

1. Rationale of the storyline

Beneath conflict and social instability, many countries in the Horn of Africa are facing frequent drought- or pest-induced domestic harvest failures, which, in combination with relatively small grain reserves (Laio et al., 2016), makes them dependent upon grain imports, or even food aid in crisis situations (ICPAC and WFP, 2018). Food security and humanitarian wellbeing in African (and other) countries are relevant to a wide range of European policies concerning development aid and humanitarian support (such as the formal partnership agreements with the African, Caribbean and Pacific states, ACP (Hurt 2003)). However, potential impacts of climate change are very strongly intertwined with compounding pressures and responses, and an analysis of the "net" impact of climate change on food security is far from straightforward. Therefore, a storyline is developed that analyses the food security crisis during the 2019/2021 locust outbreak in the region, jointly with counterfactuals referring to potential climate induced local and global food crises such as experienced during the 2007/08 simultaneous hikes of the world market prices for the main food crops wheat, maize, and rice, which pushed an estimated 63 to 80 millions of people into food insecurity (Tiwari and Zaman, 2010). A second counterfactual storyline is included that explores the impact of export restrictions by drought-affected export nations or precautionary buying of rich, import-dependent countries (Trostle et al., 2011; Challinor et al., 2018).

2. Storyline elements

The *scoping* process is driven by analyses of food security statistics (see Annex), revealing national and regional cereal import dependency indicators in response to major disruptions in the food production and trade chains. Long-term drivers of food crises include population growth, changing diets in emerging economies (Headey, 2011), low investments in research and development since the 1990s (von Braun, 2008), and the policy-induced demand for biofuels (Fraser et al., 2015). Year-to-year weather variability (including multi-breadbasket failures) and uncoordinated unilateral policy measures are singled out as the two main short-term drivers of these recent crises (Trostle et al., 2011). In 2019/20 desert locusts found ideal breeding conditions at both sides of the Red Sea due to three landfalling tropical cyclones bringing unusual amounts of precipitation. Additionally, response measures were delayed by the COVID-19 pandemic, and large swarms were able to form that spread not only across the Horn of Africa region but also across the Arabian Peninsula and Southeast Asian Countries. The climatic counterfactual storyline involving a global food supply failure does not have a single *climate hotspot*, but is linked to modes of climate variability with the potential to disrupt near-simultaneously cereal production in the major breadbasket regions around the world, specifically El Niño-Southern Oscillation, the Indian Ocean Dipole, Tropical Atlantic Variability, and the North Atlantic Oscillation (Anderson et al., 2019; Gaupp et al., 2020). The *impact transmission* of the regional food security crises to the EU is governed by historically grown trade dependencies (d'Amour et al., 2016) and development corporations (Langlois, 2014). For instance, in 2020 and 2021 the European Union has allocated nearly €200 million for a broad humanitarian-development approach, from which more than €20 million were mobilized to support the United Nations and partner countries in fighting the locust infestation (European Commission). The *socio-economic impact* is measured with various metrics: 1) world market price volatility (a potential precursor for insufficient accessibility to food); 2) impaired supply at the national level arising from the harvest failures and export restrictions (which urges countries to tap into their reserves or rely on international markets or humanitarian aid); and 3) the ratio of impaired supply to reserves (an indication for risk to limited food availability at the national level).

The *climate perturbation* is applied by combining the food trade and production conditions in the region where the locust infestation was dominant with the implications of the multi-breadbasket failure experienced during the 2007/08 major food crisis. (Gaupp et al., 2019) analyzed potential impacts of further global warming to 1.5 or 2°C on the likelihood of simultaneous crop failures, and found that particularly global wheat production failures are sensitive to the degree of global warming. In the current storyline set-up these future warming levels are not explicitly imposed, but the counterfactual combining a factual 2019/21 reference scenario with the 2007/08 global production failure serves as an indication of event cascades impacted by global warming. A *socio-economic perturbation* is addressed in a second counterfactual, where the impact of uncoordinated export restrictions is implemented. The *comparison of counterfactuals* allows the evaluation of the effectiveness of regulating these unilateral policy responses on the food security indicators. The analyses show that substantial mitigation potential exists in better coordinating policy responses in times of global food crises (Falkendal et al., 2021). *Micro-stories* allow assessing food security implications at the sub-national level using the INFORM severity framework (Poljanšek et al., 2020). This framework also allows analyzing the impact of compounding crisis situations such as the ongoing conflict in Ethiopia as well as the efficacy of different humanitarian response options.

3. Application domain

The storyline provides information on cascading food security triggers, including the potential implications of major climate-induced global cereal production declines. The World Food Program enriches their subnational food shock impact assessments with global drivers of these impacts. The INFORM risk framework is used by the European Commission to prioritize humanitarian and emergency assistance and anticipate, prevent and prepare for famines and food crisis, including through development agreements such as the new EU-OACPS (Organisation of African, Caribbean and Pacific States (OACPS) Partnership Agreement). Evidence on trends in risk for humanitarian crises can support policy formulation on risk management building on enhanced climate attribution of hazards and impacts (see (IPCC, 2021, 2022)), and initiatives to protect people displaced across borders in the context of disasters and climate change, such as the Platform on Disaster Displacement (PDD). Causal event pathways similar to the one explored can serve as blueprint for mapping impacts of geopolitical disruptions like the Russian-Ukraine 2022 war on African food security, as illustrated by (Gbadamosi, 2022).

<u>Storyline example 3: Impacts of tropical cyclones on the European Union Solidarity Fund (EUSF)</u>

1. Rationale of the storyline

An extraordinary active Atlantic hurricane season in 2017 (Klotzbach et al., 2018) directly affected the European Union’s outermost regions in the Caribbean. Particularly the island of St Martin (French overseas collectivity) and Guadeloupe were strongly hit by hurricanes Irma and Maria, with severe damage to human life, property and mangrove ecosystems (Walcker et al., 2019). The events in the Caribbean and mainland Europe are connected via the European Union Solidarity Fund (EUSF) (Hochrainer-Stigler et al., 2017) which arranges payouts to member states (including their overseas territories) in response to large disasters following extreme natural hazards such as floods, forest fires, earthquakes, storms and droughts. In 2017 payouts following disasters in the Caribbean and (particularly) mainland Europe led to a negative EUSF capital position, compensated by allocations from 2016 and 2018. This occasion triggered the question whether alternative, unprecedented yet plausible, realizations of past hurricane events could have compromised the EUSF. If so, this may reveal weak spots in the system impact causal chains and serve as guidance for further stress-testing under climate and socio-economic changes. This question is not readily answered by following generic probabilistic climate attribution approaches (Frame et al., 2020), but acknowledges the highly conditional problem statement required for this particular context.

2. Storyline elements

During the *scoping* process procedures for the assessment of risk for compromising the EUSF capital position were explored. Alternative hurricane trajectories (or “downward counterfactuals”, (Woo, 2019)), generated with natural catastrophe assessment models were used to develop storylines of spatial and temporal compound events (Ciullo et al., 2021). The *climate hotspots* for these storylines are the hurricane-prone territories of the Caribbean, Macaronesia and the West Indian Ocean. The annual number of hurricanes in these areas varies considerably (Knapp et al., 2010), and overall there is no clear trend in the observed frequency of hurricane development. However, an increasing trend in intensity with global warming is becoming apparent (IPCC, 2021). The *impact transmission* of the intense hurricane season in these hotspots reaches the European continent via (among others) the payout scheme of the EUSF.

For the current storyline the main *impact indicator* is the capital availability of the EUSF fund, particularly the possibility of the fund to not have enough capacity for coping with requested payouts. *Climate perturbations* are applied in two steps. First storylines of consecutive hurricane seasons are constructed by selection of tracks from the catalogue of historic events and their alternative trajectories that cause maximum damage in one of the target regions, and combine multiple high damage seasons in target regions of the EUSF. The second step addresses impacts of global warming. The level of scientific understanding of the relationship between ambient atmospheric and oceanic temperatures and hurricane intensity justifies the exploration of intensified hurricanes and their potential damage via an adopted hurricane intensity range (Knutson et al., 2021) setting up a range of climate counterfactuals. S*ocio-economic perturbations* are applied by adopting different levels of (future) GDP of any of the overseas target regions, which affects the value of exposed objects to extreme events and the calculated EUSF payouts. In addition, policy changes are explored by changing the capitalization of the EUSF.

The *comparison of counterfactuals* allows mapping the boundaries of the tolerable operating space of the EUSF. The counterfactuals incorporate a range of hurricane intensity levels (considered to be increasing with global warming), and GDP (representing varying socio-economic conditions), all applied as perturbations to a reference storyline with multiple consecutive hurricane seasons. Critical EUSF capital conditions will occur when in subsequent years rare (and high-damage) events are combined.

Large (but plausible) events would have a tremendous impact on the communities living in the affected territories, whose long-term social and economic sustainability is not reflected by whether or not the EUSF is solvent. In addition, territories can suffer longer-term impacts coming from indirect losses (such as trade interruptions, long-term employment or environmental impacts). Potential *micro-stories* can relate to the longer-term impact on these small islands of such large worst-case events, and focus on the long-term sustainability of these regions.

3. Application domain

The storyline is used to stress-test the EUSF, which is to be merged with a newly formed European emergency aid fund, the European Support Instrument. It provides support to choices regarding the fund capitalization and pay-out protocols. However, major hurricane event cascades have the potential to affect other European policies and regulations , including financial disclosure schemes, national catastrophe financial protection and solvency (e.g. stress and sensitivity tests performed by the European Insurance and Occupational Pension Authority (EIOPA, 2021)), and identification of remote climate risks in national and European climate risk assessments and adaptation strategies.

A similar storyline approach was applied to the analysis on Caribbean Catastrophe Risk Insurance Facility ((CCRIF, 2009)), an insurance framework backed by EU and other international entities. By examining the impacts of storm damages and CCRIF payout on the fiscal performance of local governments, the CCRIF study indicates that such a fast payment insurance mechanism is effective in providing urgent liquidity to target countries.

Storyline 4: Impact of TC landfalls in US on European consumption and trade

1. Rationale of the storyline

Major tropical cyclones (TCs) making landfall – besides causing devastating local damages and economic losses (direct impact) – can result in macro-economic trade shocks and ripples through trade loss propagation (indirect impact) (Lenzen et al., 2019). Earlier work on the New York/New Jersey landfall of hurricane Sandy (2012) analyzed the potential indirect impact on global (final) consumption, showing that both downstream and upstream interactions can result in losses or gains of consumption in other parts of the world that are not directly affected (Middelanis et al., 2021).

The storyline concentrates on the shock propagation in the trade network induced by the direct effects from the landfall of TC Harvey (2017) and its global indirect economic repercussions, including impacts onto the European economy. These effects are linked to climate change due to the (highly variable) response of frequency, intensity and size of TCs to global warming. Propagation and cumulative impacts of TC induced shocks are very specific to many attributes of the event cascade. Due to the large inherent uncertainty of the topic a storyline approach is chosen over probabilistic modelling. An event storyline is built using a trade network modelling framework using a selection of counterfactuals of the Harvey landfall cascade under climate change.

2. Storyline elements

A *scoping* process carried out by interviews with European trade organizations and an estimate of the business interruption of the local economy using reported unemployment claims were used to map direct and indirect impacts. Harvey disrupted the globally important and strong economy of Texas and Louisiana, which is situated in a main Atlantic TC landfall area, identified as our *climate hotspot*. The *impact transmission* was expressed by modelled distributed production declines and subsequent price anomalies in a time window of up to one year in the aftermath of the TC landfall, and downstream and upstream interactions resulting in losses or gains of consumption and production in other parts of the world that are not directly affected, including Europe (Middelanis et al., 2021), which define the *socio-economic impacts*.

Similar to the EUSF storyline *climate perturbations* are applied by changing the rainfall intensity of the TC, motivated by the attribution of climate warming as one of the drivers of unprecedented precipitation volumes (Van Oldenborgh et al., 2017). At the same time, although still uncertain (IPCC, 2021), also an expansion of the effective size of the tropical cyclone due to future global warming was investigated (Li and Chakraborty, 2020; Knutson et al., 2021), which gives rise to an increase of the regional GDP that is exposed to the damaging event. These modifications to the TC characteristics were scaled to the duration and extent of the business interruption in the affected area in counterfactual Acclimate simulations.

Specified *socio-economic perturbations* are used to explore various assumptions underlying the analysis of the shock propagation throughout the network. First, transfer of direct impacts (from local disruption) to indirect impacts (e.g. on remote consumption and production levels) is strongly dependent on the baseline economic structure. Alternative baseline characteristics of technology, GDP or distribution of trade volume over actors can be expected to modulate the transfer of direct to indirect impacts. For example, the previous work on TC Sandy (Middelanis et al., 2021) suggests a non-linear impact on consumption losses or gains as a function of the magnitude of the actor's baseline trade volume to the directly affected actors, giving unequal relative impacts for larger and smaller regions. The *comparison of counterfactuals* is using various metrics (including trade volume) to isolate the climate change impact on time-varying regional and sectoral shock impacts. Comparing the reference situation with climate counterfactuals with perturbed TC characteristics isolates the potential impact of global warming on the impact of similar events. Earlier studies with a similar structure (Kuhla et al., 2021) demonstrated that the joint occurrence of multiple hazards of different types within a given time window triggers a socio-economic feedback that leads to a resonance effect on the economic ripples that exceeds the combined effect of the separate hazards. Regions cannot produce enough to satisfy the demand as a consequence of the hazards, resulting in a subsequent overproduction and associated non-linear price increases. *Micro-stories* can isolate the dynamics of specific sectors and regions from the aggregated analysis, or highlight the role of manufacturing agents involved in transfer of production capacity from the affected area to remote regions, or industry involved with disaster recovery operations.

3. Application domain

The many regions and sectors affected, and the many expected and unexpected non-linear responses make the analysis of interest for European policies on trade (via e.g. biannual trade reviews carried out by the European branch of the World Trade Organization), access to strategic materials and technology, and disclosure of climate risks by major financial institutions (Ünüvar, 2019). The storyline approach provides an instrument to the required toolkit for stress testing major socio-economic interruptions similar to those that have been demonstrated in the COVID19 pandemic situation (Ringsmuth et al., 2022). Recent studies using the Acclimate model have proven to produce realistic and useful results in disaster impact analysis (Willner et al., 2018; Kuhla et al., 2021).

<u>Storyline example 5: Flood-induced displacement caused by Tropical Cyclone Idai</u>

1. Rationale of the storyline

(IPCC, 2022) concluded with high confidence that climate and weather extremes in all world regions are increasingly determining human displacement and contributing to humanitarian crises where hazards overlap with high vulnerability. The report projects displacement to increase in a further heating world as heavy precipitation and associated flooding, tropical cyclones, drought and, sea level rise increase in vulnerable regions. In Mozambique an average of 1.5 Tropical Cyclones (TCs) make landfall per year (JBA, 2019; Warren, 2019). TC Idai (2019) caused massive damage to housing and infrastructure, resulting in 639,000 human displacements in the countries of Mozambique, Malawi and Zimbabwe (IDMC, 2019). The costs associated with managing (internal) displacement may overwhelm national capacity and may even lead to fiscal collapse of already fragile states (Hochrainer-Stigler et al., 2019). European disaster relief funds and humanitarian aid provided by European agencies and NGOs are major tools to support affected populations and ease stress on partner countries' adaptive capacities. The European Institute for Security Studies (ISS) produces foresight reports, addressing potential conflicts to come (Commission, 2020) and consequences of stagnation of foreign aid to Africa (EUISS, 2021, 2022). Beyond financial considerations, the EU's responsibility to protect people from vital threats also requires that displacement risk, and the means to reduce it, is factored into EU policymaking. Displacement can lead to a cascade of mutually reinforcing effects, increasing urbanization stress and fueling internal or transboundary conflicts (Desai et al., 2021).

A tool to assess different drivers of humanitarian risk is the INFORM Risk Severity Index (Poljanšek et al., 2020). An analysis of the Idai crisis shows a high risk to local humanitarian threats which triggers national and international disaster relief funding and interventions of NGOs including the International Red Cross Red Crescent Movement. Apart from COVID19 and various reasons for blocking the access to humanitarian relief resources, the effect of climate change features on the specific INFORM risk assessment can be analyzed using dedicated event storylines. This example explores to what extent the associated crisis may already have been amplified by past human-induced climate change. A set of historical counterfactuals is created by removing the effects of anthropogenic climate change on storm intensity and sea level, which are main drivers of coastal flooding and its consequences.

2. Storyline elements

The *scoping process* is guided by the need to provide information on risks of humanitarian crises, and the role of climate change as driver for these crises, to European security and foreign cooperation agencies. The selected historical event is one of the largest recent disaster-induced displacement events and draws attention to the role of climate change in this type of crises. The *climate hotspot* is the region of the landfall of Idai, and impacts of TC landfall are related to climate change features by the dependence of TC intensity and frequency on ambient temperature, and by the impact of sea level rise on the exposure to storm-induced surge (Knutson et al., 2019; Walsh et al., 2019; Dube et al., 2021). The *impact transmission* consists of a response of European governmental and non-governmental organizations to the disaster relief and development aid to disasters striking in the risk-prone south-east African area with a lack of financial relief resources. The *socio-economic impact* consists of the land area affected by the flood caused by the 2019 Idai landfall, and the consecutive number of people that were displaced out of the affected region, either for a temporary shelter in a nearby region or in the form of long-term migration to other settlements. These impact metrics are calculated in a series of models and remote sensing data representing the storm surge, coastal and riverine flooding and the fraction of people that are displaced from the flooded area, dependent on flood depth.

Two *climate perturbations* were applied, separately as well as in combination. Trends in the fraction of global and regional sea level rise that is attributable to human-made climate change (Dangendorf et al., 2017; Strauss et al., 2021) and the TC intensity (derived from IBTrACKS observations, (Knapp et al., 2010)) were used to represent a counterfactual climate state without the effects of global warming. In the INFORM risk analysis framework a number of *socio-economic perturbations* were explored, such as the impact of the ongoing COVID-19 pandemic, and the limited access to humanitarian relief. A direct impact of trends in population density and exposure could in principle be included in the landfall storyline but this example focuses on the role of climate change. The *comparison of counterfactuals* is carried out by comparing the current value of the INFORM risk severity index report of the Idai landfall to situations where climate conditions were set to early 20th century conditions, by recomputing the flooded area and the corresponding number of displaced persons. Note that this is evaluating the impact of past rather than potential future climate-induced changes to TC intensity and sea level, but still allows isolating a climatic driver of the disaster extent. *Micro-stories* can be targeting different displacement routes (short/long-term migration), cost of migration, assumptions in the model configuration, or combinations with other terms in the INFORM risk index.

3. Application domain

The INFORM risk severity index operated by the European Joint Research Centre is an established risk evaluation framework in use by various policy domains of European foreign affairs, security and humanitarian divisions. A shift of a risk index value from “medium” to “high” (as resulted from comparing the early 20th century sea level and wind factors to present day conditions) implies a heightened alert level and a reprioritization of policy interventions. Exploration of different combinations of main features in the storyline allow disentangling socio-economic from climatic drivers, and even highlight the complex event-cascade in complex situations such as conflict or systemic shocks such as a the global COVID19 pandemic. Information gauged by catastrophe models or risk indices such as INFORM can inform policies that foster coherence of EU external actions (e.g. Global Strategy for the EU's foreign and security policy (EUISS, 2016)). This includes the consideration of support for policy options such as enhanced risk pooling and social protection schemes for vulnerable regions and countries as being considered by expert groups on displacement and risk management under the Warsaw Mechanism on Loss and Damage and the Platform on Disaster Displacement (Mechler et al., 2019; UNFCC, 2021b, 2021a). The ‘Joint Communication on Resilience’ specifies how a strategic approach to resilience can support EU’s development and humanitarian commitments, while better protecting it from external threats. It places emphasis on a number of pressures in partner countries including protracted crisis, environmental degradation, climate change, migration and forced displacement.

Storyline 6: Impacts of Storm Xaver on infrastructure damage in German Bight

1. Rationale of the storyline

Global warming and sea level rise will continue to increase the frequency and severity of flood hazards across European coastal regions. Together with continued development of the coastal floodplains, coastal risk is projected to grow by a factor of two by 2050 (Jongman et al., 2014). Storm Xaver made landfall in the German Bight on 6 December 2013. The coinciding surge and tide created “record breaking water levels for large parts of the southwestern German North Sea coastline” (Dangendorf et al., 2016), which boosted the estimate of the water level with a 1:200 year probability exceedance by 40 cm. Although the storm led to large direct damage in United Kingdom (UK), Netherlands, Germany and Denmark (Wadey et al., 2015; Rucińska, 2019), the considerable improvements in coastal protection and disaster risk reduction management significantly reduced the total damage and number of people affected compared to a similar storm in 1953 (Spencer et al., 2015; Wadey et al., 2015). Both the large anomaly of the storm and the complex cascade of impacts (particularly relating to the macroeconomic losses from long-term business interruption, damage to transportation networks and other critical infrastructure) create deep uncertainty that is difficult to assess using probabilistic approaches. The storyline approach used here enables the local direct physical damages to critical infrastructure and the (indirect) macroeconomic losses due to infrastructure failure to be explored. The primary counterfactual consists of Xaver reaching the coastal zone when mean sea level has risen, increasing the potential damage assuming coastal protection is left unaltered. Additional storylines are evolved by incorporating the consideration of alternative adaptation strategies and developments in the spatial extent of risk prone assets are included as additional counterfactual storylines.

2. Storyline elements

The *scoping process* was guided by a combination of event reports and analysis and engagement with national policy leads and infrastructure owners around different aspects of the storyline development. In particular, information was collected on both the implications for the local settlements and assets, and for the economic development of a wider area triggered by a range of cascading impacts resulting from the failure of service provision by critical infrastructure.

The storyline enables the assessment to move beyond standard assessments of SLR and include the influence of (remote) ice masses on Greenland and Antarctica and their potential contribution to (large) sea level rise (Le Bars et al., 2017; IPCC, 2021), which is *transmitted* to coastal regions by increasing the *impact* of storms like Xaver. The *socio-economic impact* consisted of direct damage and wider economic losses as a result of storm-induced inundation of critical infrastructure and power outages in surrounding areas of the Hamburg port area (Kettle, 2020).

The simulation of the direct and indirect impacts of the 2013 Xaver landfall is complemented with the simulation of the counterfactual occurrence of the same storm event under a *climate perturbation* represented by a mean sea level that is elevated by 2.25m; a hypothetical sea level rise for 2120 assuming a high climate forcing and substantial instability of the Greenland and Antarctica ice masses. Apart from a climate counterfactual, simulations with *socio-economic perturbations* are applied by altering the regional density of critical infrastructure – and thus the exposure to the storm damage – derived from selected Shared Socio-economic Pathways (SSPs). Also dedicated counterfactuals are designed addressing various adaptation strategies altering the potential impact of coastal flooding in Europe. The *comparison of counterfactuals* is expressed by quantitative differences in the spatial extent and inundation depth of the flooded area, the exposure of the critical infrastructure, the physical damages caused by the flood, and the consequences for the macro-economic production and substitution in the multiregional network. The wider-economic impacts quickly diminish with increasing spatial aggregation scale, revealing high absolute negative impacts for the affected region and lower (sometimes positive) impacts in connected European regions as a result of substitution possibilities between producers and consumers. *Micro-stories* are focusing on e.g. the impact of surge and winds on port operations, or the emergency management of infrastructure assets such as the electricity or road networks.

3. Application domain

The storyline allows evaluation of cascading impacts of local infrastructure disruptions, which is a relevant input to national and pan-European climate risk assessments and contingency plans in the context of the European Climate Adaptation strategy. Comparing different adaptation strategies, and climate (sea level) and socio-economic (expansion of spatial extent of exposure) conditions allows stress-testing regional infrastructure functioning and assessing of asset exposure for financial risk assessments. The evaluation of this combination exposes potential impact pathways and cascades for unprecedented extreme conditions that are within reach of the planning horizon of relatively near-term regional infrastructure design decisions (McEvoy et al., 2021). A strategic view on changing vulnerability patterns of European ports is of relevance to the prime objectives of the Trans-European Transport

Network (TEN-T), which include an improved use of infrastructure, reduced environmental impact of transport, enhanced energy efficiency and increased safety (e.g. European Commission, 2021).

Storyline overview

The overview in Table 1 lists each of the storyline development steps for the six examples. The *scope* of each of the storylines refers to historic events that had a major impact, and where an explicit or implicit connection between remote event triggers and a European impact exists. The *climate hotspots* have been identified in different ways. For the soy and African food security storylines a systematic survey of production areas under drought risk conditions was executed, while for other storylines a geographically constrained event location identified the remote hazard region. The *impact transmission* occurs via trade and supply/demand paths (storylines on soy and the Harvey landfall), financial exposure of damaged assets (EUSF and German storm) or development and humanitarian interaction (African food security and storm-induced displacement). For the trade and financial impact transmissions, network or financial risk models were used to express the impact of the remote hazard on the European sector. The humanitarian and development aid transmissions are expressed as risk categories in the INFORM risk assessment. The *socio-economic impacts* are diverse, including direct (financial) damage of events to European stakeholders, positive and negative anomalies in European productivity, and humanitarian risks associated with disrupted food security due to rapid price fluctuations or human displacement in response to remote climate disasters. *Climate perturbations* are applied to the climatic background of the remote climatic events, by relatively simple scaling procedures (for the tropical cyclone storylines EUSF, Harvey and Idai landfall), exploring climate projection archives (drought characteristics in the soy storyline; sea level rise in the European and Mozambique storm events) or combining climatically driven global breadbasket failures with non-climatic locust outbreaks (African food security storyline). The climate perturbations both serve the purpose to expand the range of plausible events under current climate conditions ("downward" counterfactuals) and the expression of the impact of global climate change on the intensity, extent or impact of the baseline events. *Socio-economic perturbations* include potential measures to reduce the potential impact of the climate hazards (for instance coastal defense infrastructure, or capitalization of the EUSF), changes in the socio-economic background state which affects the impact of shocks in trade or supply/demand networks, or compounding impacts from socio-economic response actions such as export restrictions. The *comparison between reference and counterfactuals* allows the assessment of the impact of the climate perturbation on the socio-economic metric of interest. The comparison generally includes a display of quantitative indicator values for different storyline counterfactuals, a visualization of the alternative event-impact chains, and a textual guidance to attribute the main changes to key nodes in the event-impact chain. Finally, *micro-stories* are used to elaborate on specific storyline choices for parameter settings or boundary conditions (for the soybean and the various tropical cyclone landfall cases), or to highlight impacts for specific sectors affected in the remote or European region (Harvey and European storm landfall).

Table 1: Overview of approaches followed in the climate event storylines for each of the development steps

Storyline development step	**Soybean production**	**Africa food security**	**European Solidarity Fund**	**Major TC Landfall in USA**	**Flood-induced Displacement**	**European Storm**

1. Scope	Importance of remote production declines for European food system and economy	African regions dependent on local production and import	Damage by tropical cyclones in overseas European territories	Global trade balance & consumption effects of TC landfalls in the USA	Displacement caused by coastal flooding in Mozambique	Storm damage to critical infrastructure under elevated sea level
2. Identification of climate hotspots	Overlay global production areas and drought risk maps	Crop growing conditions in main production areas	Cyclone tracks within European domain	Harvey landfall region	Intensification of tropical cyclones in the South Indian Ocean basin	Ice caps (source of sea level rise); German North Sea coast (storm conditions)
3. Impact transmission	European socio-economic metrics (trade, employment, food production)	Partnership agreement on trade, humanitarian aid and sustainable development	Payout by fund	Indirect effects of landfall on European consumption	Humanitarian aid	Global distribution of sea level rise
4. Socio-economic impacts	Food price, volume food production	Humanitarian implications of remote food insecurity, social instability	Risk of fund to be compromised	Consumption effects, trade balance	Humanitarian implications of remote people displacement	Local economy disruptions, transfer via demand/ supply network
5. Climate perturbations	Perturbation of 2011/2012 drought event using climate projections	Joint occurrence of global breadbasket failure and local locust outbreak	Construction alternative cyclone sequences, and upscaled intensity	Scaling precipitation and spatial extent with temperature	Removal of sea level rise and amplification of wind speeds	Sea level rise
6. Socio-economic perturbations	Trade and production restrictions	Food export restrictions, stock policy	Varying GDP levels	Alternative baseline socio-economic scenarios	None	Alternative socio-economic configuration and flood protection measures
7. Comparison reference/counterfactual	Value of collection of socio-economic indicators under different warming levels	Food insecurity status for different counterfactuals	Fund status for range of TC intensity and GDP levels	European production effects for different TC landfall scenarios	Number of local displacements for different counterfactuals	Direct and indirect flood damage under different adaptation and sea level scenarios
8. Micro-stories	Variety of changes in local and remote parameters	Future climate versions of locust outbreaks (tbc)	Adjacent financial facilities	Compounding effects of TC landfall; illustration of impact on specific sectors	A set of water level impact thresholds	Adaptation strategies; port and infrastructure functioning

5. Discussion and summary

This gallery of climate event storylines illustrates the wide diversity of impact-pathways of climate change features. These pathways connect locations separated by long distances via complex physical and socio-economic cause-effect chains propagating over multiple time scales. Diagnosing the impact of climate change on the impact cascades involves a methodological approach that generally involves synthetic model outcomes, and makes the (inevitably) subjective choices on assumed boundary conditions, uncertainty estimates and analysis tools explicit.

To make the construction of the storylines and its climate analyses transparent and reproducible, we have introduced a methodological protocol that distinguishes a set of predefined storyline development steps, and have applied this protocol to six examples (Table 1). The purpose of this inventory is to illustrate the practical implementation of the physical climate event storylines (Shepherd et al., 2018; Sillmann et al., 2021), and discuss concrete choices made to include stakeholder views, select analysis tools, interpret findings, represent uncertainty and provide useful information to societal actors.

For each of the storylines a number of criteria were evaluated assessing their potential to facilitate societal uptake (Table 2). All six storylines are built on historic events, and have used impact mapping tools that have either been shown to give realistic results in earlier applications, or show good correspondence with observed impacts. The counterfactuals are rooted in historic climate trends or apply well-documented climate projections or physical scaling protocols, which provides *realism* to the storylines. Apart from a broad societal interest in the topic of analysis most storylines have gained *relevance* by concrete contributions by stakeholders. An explicit analysis of potential adaptation strategies is included in a few storylines, and standard risk reporting tools are used to support *risk-assessments*. Risk-oriented information is derived from the exploration of expected future climate and/or socio-economic conditions.

Table 2: Evaluation of the criteria for societal uptake of the climate event storylines

Criterion	**Soybean production**	**Africa food security**	**European Solidarity Fund**	**Major TC Landfall in US**	**Flood-induced Displacement**	**European Storm**
Realism	Historic event and subsequent impacts; stakeholder reports; physically based climate projections; documented agronomy models	Evidence of plausible joint occurrence of multiple drivers of local food security	Historic event selection; evidence of consecutive active hurricane seasons	Based on data and model framework that have proven to be realistic in earlier disaster impact analyses	Observation-based estimates of changes in sea level and wind intensity; impact mapping tools proven to be realistic	Good reproduction of observed flood extent; well-documented sea level scenarios
Relevance	Societal attention for environmental impacts, land allocation and forest conservation	Broad concern of food security and societal instability and displacement	Stakeholder participated in storyline development	Evidence of impact cascade affecting many sectors	Meaningful effect of past climate trends on local impact detected	Considerable development of coastal area within near future
Risk-informativeness	Visualization of illustrative metrics on soy consumption, trade and prices	Exploration of future resilience and mitigation strategies	Explore different GDP and climate conditions	Exploration of future event disruptions	Physical and societal dimensions of human displacement integrated in risk assessments in humanitarian policies	Revealing potentially unexpected yet credible impact cascades; exploration of adaptation strategies

The storylines explored in this paper are intended to map risks to the European socio-economy that emerge from an immensely complex cascading set of event-impact chains (triggered by remote climate features), which cannot be analysed without a very stringent set of constraints imposed on available projection outputs from climate and impact assessment models. The concept does not rely on a standardized climate modelling toolset such as CMIP6 (Touzé-Peiffer et al., 2020), but instead combines stakeholder evidence, historic events and a mix of data analysis and model experiment techniques to arrive at evidence based narratives of “unfoldings of events and their hypothetical future counterfactuals” (Shepherd et al., 2018). As such it combines quantitative and qualitative elements

(Shepherd and Lloyd, 2021), where the quantitative information gives a meaningful contribution to the risk assessment from complex climate change processes, and the qualitative elements provide insights in relevant pathways of risk transmission. By exploring a range of present-day or future counterfactual conditions in most storylines, crucial climatic elements in the storylines are complemented with a quantification of the underlying uncertainty. However, given that the event cascades and a large number of compounding boundary conditions or contextual settings are prescribed, any probabilistic statement on the outcome of the storylines is highly conditioned on these assumptions, and thus heavily constrained. Storylines like these may serve as a stress-test for particular critical societal functions, or contribute to exploratory foresight analyses of future societal developments (Wiebe et al., 2018). However, a review of storyline applications in the climate change domain is out of scope of this paper (Baldissera Pacchetti et al.).

The prime purpose of this paper is to document a methodological protocol to construct storylines that can contribute to the exploration of potential implications of climate change for a collection of societal topics. The steps in the protocol are organized around a central narrative of the chosen storyline, which is segmented into more or less standard scripting building blocks. Surrounding this central narrative the communicative power of the storylines can be promoted by a carefully designed visual and textual language (Jack et al., 2020), application of story maps (Vollstedt et al., 2021), enhancing personal context by use of personas or actors (Moezzi et al., 2017), and other attributes.

The synthesis of a collection of storylines does allow extraction of generic principles, calibration of crucial parameters in for instance macro-economic supply-demand interaction models (Robinson and Roland-Holst, 1988; Partridge and Rickman, 2010; Otto et al., 2017), or build conceptual system dynamics or Bayesian network models (Bala et al., 2017) exploring key dynamics, vulnerabilities and adaptation options under specific sets of assumptions. Also integrated or cross-sectoral climate change assessments carried out by these approaches rely on explicit or implicit choices on scope, boundary conditions and interactions between drivers and impacts. As such, a storyline structure as described above can also be applied to this cross-sectoral climate impact assessment.

6. Conclusions

A methodological protocol is proposed to construct climate event climate storylines, designed to analyse and document complex cascading event-impact chains contributing to societal climate risk. The protocol distinguishes a number of standardized steps in the narrative, connecting a (remote) climate hotspot region to a particular socio-economic impact to be explored for a baseline and one of more alternative realizations of the storyline. It includes stakeholder input to define the scope, allows for the exploration of alternative response options, and mixes qualitative and quantitative components to construct the storyline.

Baseline versions of the storyline are usually rooted in historic events where documented hazards and consecutive impacts are captured in data analysis and modelling tools that are able to represent essential dynamics of the event evolution. Climate change perturbations and alternative societal configurations are derived from plausible projections and scenarios, and resulting impacts are mapped for one or multiple counterfactual realizations of the storyline.

A set of criteria is defined to promote the societal relevance and uptake of the storylines. They should be expected to be realistic, relevant and risk-informative. A list of six example storylines is described and explored in this paper, to illustrate the protocol and the application of the criteria.

The protocol and criteria checklist are shown to enable covering a wide range of storylines for a diverse set of sectoral applications, and help to standardize the design and application of climate event climate storylines.

Annex: Description of methodologies, data and models

The storylines described in this paper are constructed with varying tools and instruments. For *Storyline 1* (soybean yields) a combination of trade statistics, climate reanalysis archives and hydrological water resource modelling is used to generate spatial distributions of soybean production areas, water footprints (water use intensity) and agricultural drought, following (Mekonnen and Hoekstra, 2016; Ercin et al., 2019). Future analogues of yield shocks were created with a hybrid model configuration combining a large ensemble of climate projections (Van Der Wiel et al., 2020) aggregated to different levels of global warming taken as drivers for the global biosphere management model GLOBIOM (Havlík et al., 2014; Soterroni et al., 2018; Jägermeyr et al., 2021). Alternative socio-economic scenarios are imposed by driving the GLOBIOM model with SSP2-4.5 forcing scenarios.

For *Storyline 2* (Africa food security) statistics on food security and trade are released by FAOSTAT (FAOSTAT, 2021), World Bank (Worldbank, 2021) and USDA (USDA, 2021). Simulations are carried out using a combination of a global model for world market prices of staple crops accounting for trade policies and storage (Schewe et al., 2017) and a food supply network model (Falkendal et al., 2021). The World Food Program operates a subnational food shock impact model SISMOD (WFP, 2017), and is working on inclusion of shock propagation procedures.

For *Storyline 3* (EU Solidarity Fund) use is made of natural catastrophe assessment models such as CLIMADA (Aznar-Siguan and Bresch, 2019), forced by an extended present-day hurricane climatology with large numbers of synthetic storms calibrated on forecast ensembles (Bloemendaal et al., 2020). For *Storyline 4* (Harvey landfall) the trade, production and consumption model Acclimate (Otto et al., 2017) was used to simulate deviations of sectoral production and trade decisions around a baseline state in 268 regions and 27 sectors across the globe. The Acclimate trade network relies on information on agent's decisions on production, consumption and pricing, which are assumed to be governed by rational considerations and perfect yet myopic knowledge. The indirect impact of Harvey landfall on remote (European) consumption is quantified by the time-varying deviation of aggregated European regional production levels relative to baseline equilibrium values.

For *Storyline 5* (Idai landfall) a numerical wave propagation model (LeVeque and George, 2008; Berger et al., 2011) is used to simulate coastal surge resulting from a given storm intensity and underlying sea level. Observed wind speeds and present-day local sea level are used to estimate the extent and depth of coastal flooding, which serves as the baseline event. Regarding the sea level rise assumption in the counterfactual simulations, we conservatively assume a value 10cm lower without anthropogenic climate change. For maximum wind speed we adopt an increase of 0.25 knots (0.13 m/s) per year over a period of 50 years, based on local data from the IBTrACS database (Knapp et al., 2010). This results in a

10% reduction of maximum wind speeds in the counterfactual without climate change. For *Storyline 6* (European storm landfall) modelling of coastal inundation over dry land and buildings was carried out with the 2D-Hydrodynamic model ANUGA, also capable of simulating effects time-varying coastal defense infrastructure such as dam/dyke breaks (Roberts et al., 2015). Using OpenStreetMap data a spatial expression of the damage to multiple categories of critical infrastructure was generated (Nirandjan et al.). The wider economic losses and gains for 270 NUTS2 regions in the European Union (Thissen et al., 2018) are assessed using a macro-economic Multiregional Impact Assessment (MRIA) model (Koks and Thissen, 2016), including production inefficiencies resulting from damaged industries and the substitution of production in regions not affected by the direct impact.

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