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TOPICAL REVIEW

Challenges and opportunities in climate risk assessment: future directions for assessing complex climate risks

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Abstract

As climate change impacts intensify worldwide, assessing climate risks comprehensively is essential for guiding effective disaster risk management and adaptation strategies. This systematic literature review examines the latest developments in Climate Risk Assessment (CRA), focusing on how climate risks are framed and assessed. It explores advancements, ongoing challenges, and emerging opportunities to guide future generations of CRAs. Key findings highlight a more nuanced risk framework that incorporates climate responses, modulating the three risk determinants (exposure, vulnerability, and hazards), as outlined in the latest IPCC assessment. The state-of-the-art concentrates on the temporal and spatial characteristics of hazards, while exposure and vulnerability are increasingly understood as dynamic concepts influenced by socioeconomic changes. Recent developments, such as multi-hazard approaches, risk tolerance integration, and the concept of Climatic Impact-Drivers (CID), provide new perspectives on assessing climate risks. However, managing complexity and uncertainty remain the main operational challenges, underscoring the need for improved CRA methodologies and models, as well as consistent, interoperable datasets. The paper discusses avenues to advance CRA, emphasizing the importance of bridging the gap between academic advancements and practical implementation. Conceptual recommendations include adopting a systemic approach to, for example, better account for the cascading and compounding risks, hazard thresholds, adaptation limits, and risk amplifiers, as well as using storylines to improve CRA communication. Technical recommendations include leveraging emerging technologies such as artificial intelligence, machine learning methods and big data analytics to improve real-time risk prediction and modeling. To enhance the CRA practice, the study advocates for greater stakeholder involvement and inclusive governance to ensure that CRAs remain context-specific and relevant. These recommendations, together with strengthened interdisciplinary collaboration and knowledge-sharing, are expected to pave the way for more effective climate risk management, adaptation, and resilience-building strategies.

1. Introduction

As climate change increasingly impacts individuals, assets, and nature (Abbass *et al* 2022, IPCC 2023a), there is a growing need to understand the type, scale, interactions, and significance of climate risks, as well as the effective responses to them. climate risk assessment (CRA) has always been vital for the scientific, practice, and policy communities, providing stakeholders with crucial insights necessary for effective decision-making. However, the requirements and expectations placed on how the assessment

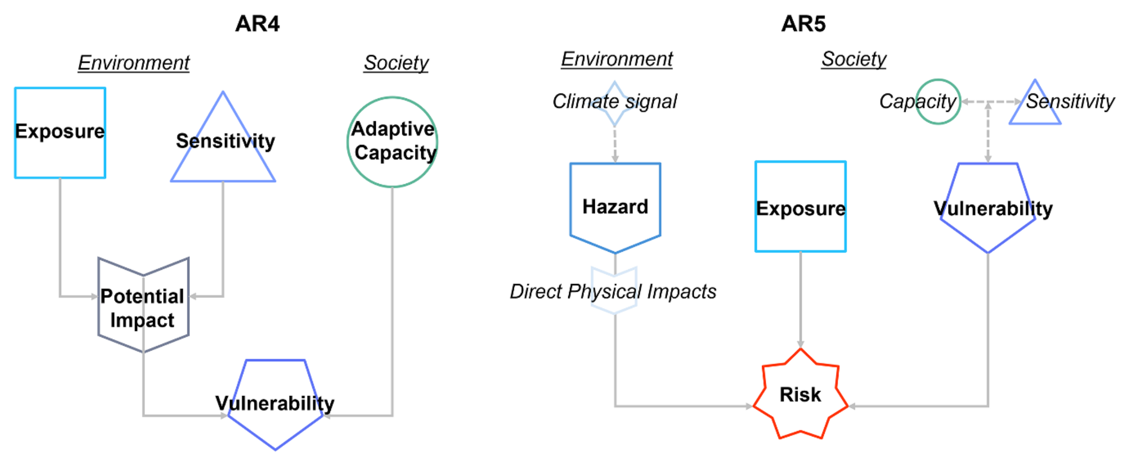

Figure 1. The shift of focus from climate vulnerability to climate risk in IPCC 4th and 5th assessments.

should identify, analyze, and evaluate current and future climate risks have evolved. Against the background of new requirements at various governance (e.g. national, regional, municipal; Warren *et al* 2018, Conway *et al* 2019) and systems levels (e.g. finance, food, critical infrastructure or health; (Challinor *et al* 2018, Estoque *et al* 2020, Battiston *et al* 2021), we review the challenges and limitations, and explore the ways to move forward.

Our understanding of climate risks, methods for assessing them, and management practices (Reisinger *et al* 2020, Simpson *et al* 2021) is reflected in the evolving concepts and frameworks employed by the Intergovernmental Panel on Climate Change (IPCC) to frame climate risks across the assessment reports (AR) 4 (IPCC 2007), 5 (IPCC 2014) and 6 (IPCC 2023b). An important conceptual shift occurred during the transition from the AR4 to AR5 (Birkmann and Mechler 2015). While AR4 focused on assessing *climate vulnerability* and understanding risk as a potential consequence of climate change impacts, AR5 adopted a new framework centered around risk factors. This shift[6] (figure 1) from consequences to risk has paved the way for a more nuanced understanding of the multifaceted interplay of risk drivers.

The AR5 has helped to portray risk as an interplay of exposure, vulnerability, and (current and future) hazards, building on decades of long research and practice in the disaster risk reduction domain. This risk-focused approach comes with greater potential to inform a wide range of decision-makers and practitioners, including those who may not have extensive experience or familiarity with the concept of risk. Since the transition from climate vulnerability to risk and with increasing impacts from climate change being felt, CRAs have gained attention and are increasingly being implemented across various scales, sectors, regions, and communities (Ara Begum *et al* 2022), including the private sector such as finance (Walenta 2020, Battiston *et al* 2021) and insurance (Golnaraghi 2018, Lyubchich *et al* 2019, Nobanee *et al* 2022).

Responding to the increasing relevance of CRA for understanding, managing, and preparing for climate-related risks, this paper comprehensively reviews the state-of-the-art regarding the current operationalization of risk assessment and its components (i.e. hazard, exposure, and vulnerability). This refers to the application of climate risk concepts into guiding frameworks and methodologies for assessing climate-related risks in real-world scenarios. It also identifies recent advancements in the field, the persistent challenges faced in assessing ongoing and future climate-related risks, and the latent opportunities that can enhance future generations of CRAs. To this effect, this systematic literature review seeks to critically analyze the current state of CRA in peer-reviewed studies, providing valuable insights for researchers, policymakers, and practitioners on four aspects: (i) Current conceptualization of risk; (ii) Recent conceptual developments; (iii) Advancements (technological and methodological) and prevailing challenges in CRA; and (iv) Emerging opportunities and new directions for future CRA.

The methodological approach for conducting this literature review is described in section 2, followed by the main findings in section 3 presenting the current conceptualization of the risk components, emerging concepts, recent advancements and challenges encountered in CRA. Section 4 gives an outlook including future directions and

[6] This shift has been well documented in IPCC's 5th assessment cycle and started with the publication of the SREX[1] report in 2012 (IPCC 2012) further feeding into the 5th assessment report (AR5) in 2014 (IPCC 2014).

opportunities for CRA, building on technical and practice recommendations, areas of future research, and conceptual advancements.

2. Methodology

We conducted a systematic review of the peer-reviewed literature to provide a comprehensive overview of key themes in the field of CRA. Focusing on both conceptualization and operationalization aspects, we qualitatively synthesized recent advancements, challenges and opportunities for this discipline. To achieve this, we utilized a specific search on keywords 'climate', 'risk', 'assessment', 'analysis', 'framework', 'tool', 'method', 'approach', 'review', and 'concept*' across a variety of databases, including Scopus, JSTOR, PubMed, and DOAJ. Articles did not need to feature all keywords simultaneously (except for 'climate' and 'risk') and the combination of the keywords ensured a broad capture of relevant literature (by using Boolean operators AND and OR). The keywords 'climate' and 'risk' were linked with the Boolean operator AND, meaning that all documents must contain these terms. The remaining terms (i.e. assessment, analysis, framework, tool, method, approach) were connected using OR, so documents may contain at least one of them. The latter allowed us to capture the plurality of terms used within the field to study climate risks. The keyword 'review' was also included using OR to capture overviews and syntheses of CRA approaches, methodologies, and frameworks, as well as the current state and other insights in a particular sub-area of CRA—aspects central to our research goals. Similarly, 'concept*' was included in the search strategy with OR to capture both, articles exploring conceptual approaches or frameworks for CRA, and articles delving into the conceptualization of climate risk and its drivers (hazard, exposure, and vulnerability). Doing so, enabled the inclusion of both, established and forward-looking articles related to CRA. Additionally, our review focused on publications in English spanning from 2010 to 2023, resulting in 656 results. This period was selected to capture relevant literature during the transition initiated by the new conceptualization of climate risk at the time of publication of IPCC SREX/AR5.

The screening of papers involved manual sorting based on title and abstract. Articles that explicitly mentioned the description, utilization, development, or review of a CRA framework, tool, method, or approach in the title or abstract were included in the review. Given that this review was conducted within the CLIMAAX project (www.climaax.eu/), our review is focused on how climate risk concepts and assessment approaches are developed and applied in the European context, hence, we concentrated the further analysis on publications from this region. Also, publications that dealt with conceptual or generic applications were included.

To ensure the included papers held significant influence within the CRA community, we implemented a citation threshold. Papers published between 2010 and 2019 required a minimum of 30 citations. This citation threshold was chosen as a pragmatic criterion to include papers that had demonstrated a minimum influence in the field. We acknowledge that citation counts can vary significantly depending on the year of publication due to differing time frames for accumulating citations. Thus, papers published from 2020 onward faced no such citation restrictions. While a formal sensitivity analysis on the chosen citation threshold could further refine our selection criteria as different thresholds might yield different sets of papers; however, this was beyond the scope of this study. Importantly, this limitation does not undermine the validity of our review or its findings.

From the initial 656 search results, 48 papers were selected for full-text review. Nevertheless, three publications were excluded from the final analysis as one did not meaningfully address CRA-related issues, while the other two were deemed inaccessible due to subscription-based access (paywalls). Figure 2 summarizes the article selection process used in this study.

Next, the selected 45 articles were subject to content analysis inspired by Berg (2006) and Bernard (2013), which consisted of classifying the text based on predetermined codes that aligned with specific guiding questions (*see* appendix). To facilitate this process, we used the open-source reference management software Zotero. Following the coding, a thematic analysis (Nowell *et al* 2017, Thompson 2022) was performed by transferring the codes into a matrix.

For instance, the following statements were classified under the code 'Challenge', and the respective thematic category as they address the question of 'Which challenges and barriers were identified regarding CRA?': '*(…) about the objectivity or replicability of qualitative assessment approaches (…) it is challenging to make the process of such an evaluation as representative as possible by including enough people, having a good mix of stakeholder and experts, and asking the right questions, as well as correctly evaluating the answers.*' (Zebisch *et al* 2021, p 52). Another example, which was coded as 'Vulnerability' and answers the research question 'How were risk and its components conceptualized and considered?' under the thematic category of 'Risk conceptualization' is: '*Overall, the approach to vulnerability 'as an outcome' seemed to be the most data and resource demanding, but simultaneously most comprehensive in terms of assessments of future risks. The approach to vulnerability as 'a pre-existing condition' was the most common, and suitable for both assessments of current and future risks. This approach is more suitable for understanding*

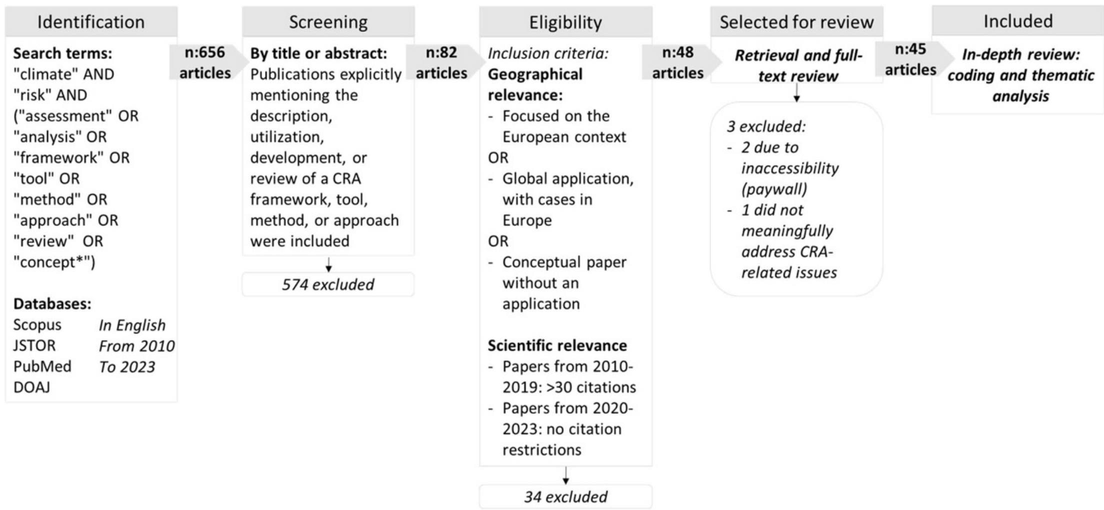

Figure 2. Process for selecting the literature.

the patterns of risk, as well as mapping risks, rather than identifying adaptation measures and their effect. 'Vulnerability as a threshold' requires modeling skills, and preferably stakeholder involvement to determine thresholds. This approach also allows to set the priorities for adaptation areas and objects.' (Jurgilevich *et al* 2017, p 10). In a similar fashion, each code was assigned to a thematic category, and each category was analyzed across all the findings according to the respective guiding question to identify patterns and trends in the specific theme.

3. Results

The results of our analysis are structured along the main categories addressed in the subsequent sections. These include the state of the art of risk and its three main drivers (*exposure, hazard, vulnerability*), operational challenges and limitations currently faced in the CRA, as well as emerging key topics and approaches to improve CRA.

3.1. Current understanding of climate risk

IPCC's most recent 6th AR has defined risk as '*the potential for adverse consequences for human or ecological systems [...]. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change*' (Reisinger *et al* 2020, p 4). The *Risk Propeller* diagram from IPCC SREX (IPCC 2012), where risk is determined by hazard, exposure, and vulnerability, has been taken up and updated in AR6 (Reisinger *et al* 2020), emphasizing complexity and the role of responses (i.e. mitigation and adaptation) in modulating each of these determinants (figure 3(a)). Although the report does not consider responses as a new risk determinant, it suggests this as a perspective for future CRAs (figure 3(b)). This underpins the need for a consistent multi-disciplinary approach to CRA, such as the one applied in the European CRA—EUCRA (European Environment Agency 2024).

Additionally, this definition better conveys the fact that risk is not static but rather constantly evolving and influenced by changes in hazards, vulnerability, and exposure caused by climatic and non-climatic factors (IPCC 2012, Reisinger *et al* 2020, Chen *et al* 2021, Ranasinghe *et al* 2021). These changes, whether they are natural, unintended, or deliberate, contribute to the dynamic nature of risk (Reisinger *et al* 2020). For instance, urban sprawl (among other factors) in Southern Europe is intensifying the extreme heat and drought risks, while more frequent storm surges due to sea level rise are heightening flood risks in Northern Europe (European Environment Agency 2024). The complex nature of climate risks becomes evident when considering how changes in one system (e.g. climate, ecosystem) can trigger responses in others (e.g. society, economy) and vice versa (i.e. feedback loops), how multiple risks can combine and escalate over time (i.e. cascading or compounding interactions), and how unpredictable changes can occur due to the non-linear behavior of the climate system, often leading to unexpected or unprecedented outcomes (surprises) that challenge existing models and knowledge (Ara Begum *et al* 2022). These surprises can have far-reaching consequences and may arise from changes in the correlation of extreme events that increase their likelihood of occurring simultaneously or in rapid sequence (compounding); from tipping elements leading to abrupt changes in stable components of the earth (e.g. glacier and ice sheets, El Niño–Southern Oscillation—ENSO, Atlantic meridional overturning circulation—AMOC, and the Amazon

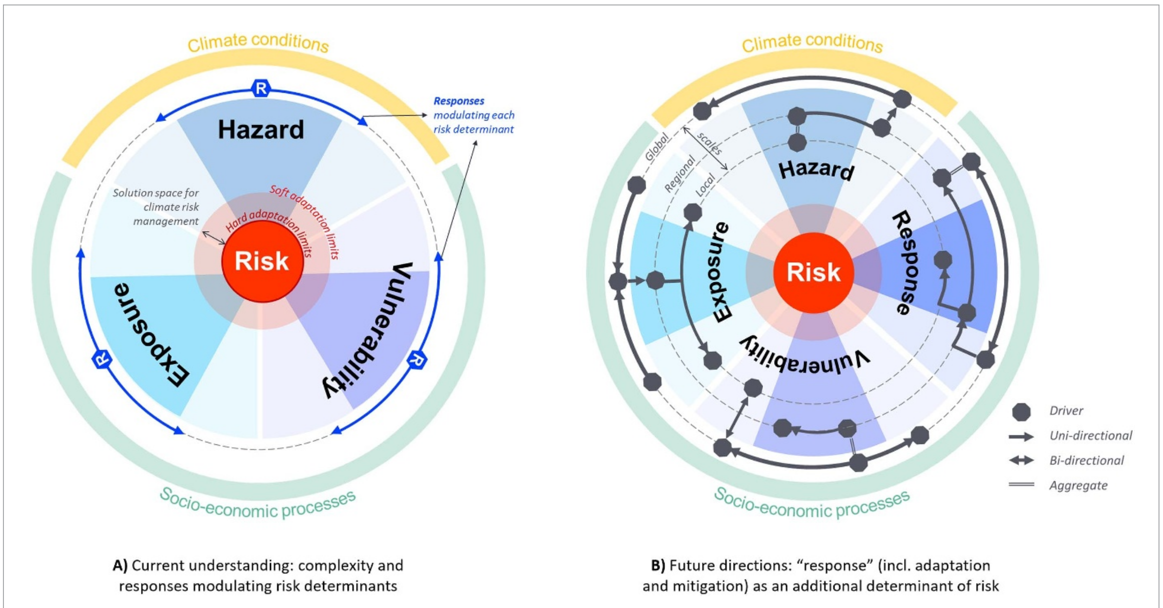

Figure 3. Modified representation of the IPCC AR6 'Risk Propeller', emphasizing complexity and the role of responses.

rainforest); or from the 'unknown unknowns' (Kopp *et al* 2017). Such complex dynamics require a more nuanced approach to assessing climate risks.

Anthropogenic climate change, natural climate variability, and socioeconomic development all play significant roles in shaping risks, exposure, and vulnerability (IPCC 2012, Field *et al* 2014); risks can thus also arise from maladaptation or side effects of some responses (Reisinger *et al* 2020). Consequently, not only does climate change generate risks that can surpass the limits of adaptation and result in significant losses and damages (IPCC 2023a); but also, poor planning and mismanagement of climate risks can have far-reaching implications. Therefore, the terminology of '*weather and climate events*' and '*disaster risks*' used in the SREX report (IPCC 2012), has evolved to a broader understanding in the AR6 (IPCC 2021) with terms referred to as '*climate hazard*' and '*risk*', respectively. Thus, in the context of the IPCC reports, risk specifically refers to potential adverse effects of climate change (Field *et al* 2014), and risks induced by shifts in physical climate phenomena that directly influence human and ecological systems (Ranasinghe *et al* 2021).

3.2. State of the art of the risk drivers hazard, exposure, and vulnerability

3.2.1. Current conceptualization of hazards

Different approaches have been taken forward to develop hazard definitions based on the phenomena characterization. Some frameworks classify hazards based on specific typologies. For instance, Oppenheimer *et al* (2014) categorized hazards into floods, droughts, heatwaves, cold spells, wind, landslides, coastal hazards, wildfire, water scarcity, and more. Another classification method groups hazards as intensive or extensive events (Lam and Lassa 2017). Extensive events are gradual changes on a broad scale, such as droughts, sea level rises, and gradual temperature increases, while intensive events are extreme occurrences of physical phenomena, such as heavy precipitation, heat waves, and storm surges. Following this logic, a categorization of hazards in their temporal manifestation distinguishes between *slow-onset processes or trends* and *sudden onset extreme events* (Cardona *et al* 2012).

Taking a more comprehensive approach to the definition of hazards[7], UNDRR and ISC (2020) compiled an extensive list of 302 hazards grouped into eight clusters. These clusters include processes, phenomena, and human activities that (i) have the potential to impact a community; (ii) have measurable spatial and temporal components; and (iii) have proactive and reactive measures available. The list excludes complex, compound, and cascading hazards, as well as underlying disaster risk drivers like climate change. Unlike other hazard categorization systems, the publication refrains from categorizing some phenomena as 'climate hazards' to avoid attributing their causes to climate change, despite acknowledging climate change as a key factor contributing to their occurrence.

In terms of hazard assessment methods, as natural hazard events exhibit natural randomness (*aleatoric uncertainty*), probabilistic approaches are considered the most appropriate for the analysis of such

[7] 'A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation' (United Nations General Assembly 2016).

processes (Hochrainer-Stigler et al 2023). This typically entails studying past occurrences through statistical analysis or developing weather generators capable of simulating hazards and categorizing those into 10-, 50-, and 100 year events (the inverse of which is the occurrence probability). Quantiles, averages, or threshold levels are commonly employed as statistical risk measures for establishing extremes (Grossi et al 2005). Recently, increasing use of Machine Learning techniques (Zennaro et al 2021), Earth Observation imagery (Kotchi et al 2019), and big data approaches (Pollard et al 2018) have been applied worldwide to improve hazard characterization and forecasting through the enhancement of real-time detection, prediction and monitoring.

3.2.2. Current conceptualization of exposure

The characterization of exposure in current CRAs and related literature varies considerably, for example depending on the analyzed hazards, impacted sectors, and the spatial scale of the assessment. The IPCC definition of exposure[8] is widely referenced in the literature (e.g. Gallina et al 2016, Adger et al 2018, Aznar-Siguan and Bresch 2019, Simpson et al 2021, O'Neill et al 2022), which alludes to the geographical location of elements relative to a climate hazard (Jurgilevich et al 2017), for example, the number of buildings or communities within a specific flood-prone river basin area. Conversely, some studies conceptualize exposure by focusing on the effects of changing hazard characteristics due to climate change (e.g. Lung et al 2013, Onyango et al 2016, Parker et al 2019, Zebisch et al 2021) and lack of timely adaptation action (Warren et al 2018). Rather than the relative location of the elements to a hazard, this perspective considers how changing climate and absence of proactive preparedness might alter the intensity or likelihood of hazards (e.g. sea-level rise or deglaciation), thereby impacting other elements over time that were not originally exposed to associated risks.

Exposure is primarily characterized as the population or socially valued (socioeconomic, cultural, infrastructures and environmental) assets at risk (e.g. Cavan and Kingston 2012, Lissner et al 2012, Gallina et al 2020, Harrington et al 2021, Simpson et al 2021, Rising et al 2022), which is also the case for the EUCRA (European Environment Agency 2024). The indicators that are used to characterize exposed elements can be hazard-dependent, such as population exposed to Malaria (Onyango et al 2016) or heat waves (Lissner et al 2012), as well as sector-dependent, for example, using crops exposed to water scarcity (Ronco et al 2017) or health services exposed to floods and landslides (Zebisch et al 2021). While not often, other elements at risk, such as supply chains and ecosystems, are also the subject of analysis in literature. For instance, Challinor et al (2018) analyze the exposure of food supply chains in Europe to climate-related impacts through changes in price spikes and volatility in the region and abroad. Similarly, Gallina et al (2020) focus their exposure assessment on environmental receptors (i.e. exposed elements) of climate impacts such as wetlands, beaches, protected areas, and river mouths. In other regional- to local-scale CRAs in Europe, studies also account for additional elements at risk such as a variety of crops (Ronco et al 2017), tourism attractiveness (Agulles et al 2022), value chains (Lückerath et al 2023), human health and socioeconomic activities (European Environment Agency 2024).

3.2.3. Current conceptualization of vulnerability

Vulnerability in most recent analyses refers to the potential harm or loss a system may suffer when exposed to a hazard. This is in line with the conceptual shift of considering vulnerability as not an analytical endpoint but a risk driver, according to IPCC AR5 terminology (Oppenheimer et al 2014). It is a function of the character, magnitude, and rate of climate change and variation to which the system is exposed, including sensitivity and adaptive capacity (Zebisch et al 2021). Sensitivity refers to how much a system is affected (positively and negatively) by a climate-related driver, and it can be influenced by natural factors (e.g. ecosystem types, land cover, slope, water holding capacity and erodibility of soils), physical factors related to human land management activities and infrastructures (e.g. existence and quality of dikes, terraces, irrigation systems, houses, roads, electrical grids) as well as societal factors like population density or age structure (Warren et al 2018, Zebisch et al 2021). Adaptive capacity, on the other hand, relates to the societal characteristics that enable a community to prepare for and cope with the consequences of a hazard, including a rapid recovery. It is determined by factors such as economic strength, human skills, education, technology, infrastructure, as well as institutional capability and preparedness (Lung et al 2013). The IPCC WGII defines adaptive capacity as '*the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences*' (IPCC 2014, p 214).

Vulnerability is usually measured in relation to the impact, e.g. through so-called fragility or damage curves (Aznar-Siguan and Bresch 2019, Kropf et al 2022). As the impacts of climate-related hazards are various and manifest in different sectors, vulnerability is multifaceted and can vary depending on the extent or intensity of the hazard and the affected sector (Oppenheimer et al 2014, Gallina

[8] 'The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected' (Oppenheimer et al 2014).

et al 2020, O'Neill *et al* 2022). Physical vulnerability focuses on the potential of a system to suffer physical damage (e.g. infrastructure damage) (Cremen *et al* 2022). Social vulnerability studies the socio-economic factors (age, income, gender, education, etc) that drive people's vulnerability to natural hazards. The level of social vulnerability is often represented by using social vulnerability indices, which combine different factors into one composite index (Cutter *et al* 2003, Oppenheimer *et al* 2014). Ecological vulnerability focuses on the susceptibility of ecosystems to damage, including impacts on biodiversity, ecosystem services, and environmental resources (Torresan *et al* 2016, Zebisch *et al* 2022). In the recent EUCRA (European Environment Agency 2024), each of these vulnerabilities are thoroughly considered.

It is well understood that vulnerability varies over time, not only as a response to the changes in hazard and exposure, but as the expression of the societal evolution of the systems (Oppenheimer *et al* 2014). For instance, implementing adaptive processes can help decrease vulnerability, however, vulnerability can also increase in the short term after damage is incurred from a hazard. Thus, when multiple hazards hit the same location in a short time interval, it is extremely important to account for vulnerability dynamics (Ward *et al* 2022) (*see* also section 3.3.4).

3.3. Emerging concepts, approaches, and frameworks

This section presents an overview of relevant concepts, approaches and frameworks reshaping CRA. It begins by describing climate responses as a component of risk, where recent frameworks and studies reflect on the dual nature of adaptation and mitigation strategies, either mitigating or driving climate risks. The section further unfolds with concepts such as *Climatic Impact-Drivers* (*CID), risk tolerance*, and *exposure and vulnerability* as dynamic components that enhance the understanding of the effects of climate change on human and ecological systems. Finally, the section highlights the significance of *multi-hazard approaches* alongside the innovative *event-based storylines* approach to better comprehend the dynamic and complex nature of climate risk landscapes.

3.3.1. Climate responses as a component of risk

The framework for complex climate risks (Simpson *et al* 2021) recognizes that risks can also arise from climate adaptation and mitigation responses, not just from the influence of climate change on the conventional risk propeller (hazard, exposure, and vulnerability) (IPCC 2012, 2014). Accordingly, the authors incorporate '*responses*' as the fourth risk component. This is also aligned with Terzi *et al* (2019) who support the idea that maladaptation practices can increase risks to other hazards. Furthermore, several studies have explored how adaptation responses can affect climate risk at local, national and international levels including the socio-economic dimension in the risk assessment framework (Oppenheimer *et al* 2014, Dawson *et al* 2018, Warren *et al* 2018, Simpson *et al* 2021). For instance, the third United Kingdom Climate Change Risk Assessment (UKCCRA) includes the effectiveness of existing and planned adaptation responses as a sub-step to determine the risk urgency (Brown and Berry 2022).

Regarding the influence of adaptation responses, Jurgilevich *et al* (2017) identified various studies in Europe (i.e. Norway, Germany, Italy, and Netherlands) that integrated the simulation and evaluation of adaptation measures and scenarios (business-as-usual, opportunistic adaptation, active adaptation) to gain understanding of risk-increasing factors. Adger *et al* (2018), building on the experience of the second UKCCRA, reviewed the CRA practice with a focus on adaptation policy development. They highlight the influence of non-rational decision-making, such as the use of heuristics, and introduce biases in risk perception (e.g. loss aversion, cognitive myopia and preference for maintaining the status quo). This can lead to varying preferences for adaptive responses and overreactions to perceived risks (*i.e. social amplification of risks)*, ultimately resulting in maladaptive responses. Terzi *et al* (2019) explored the interdependency of adaptation responses and other anthropogenic processes within a multi-hazard framework and how they can generate cascading effects.

These complexities underscore the increasing interest in analyzing a range of responses within the CRA to better understand and integrate aspects such as residual risks, risk tolerance, and societal perception of risk, which can ultimately inform more effective policy interventions (Adger *et al* 2018).

3.3.2. Climatic Impact Drivers

The concept of CID, introduced by Ruane *et al* (2022) and adopted in the IPCC AR6 (see Chen *et al* 2021), expands the evaluation of physical climate conditions (averages, events, and extremes) beyond hazards that may affect human and ecological systems. The authors argue that depending on the system's tolerance, climatic conditions can have not only negative or detrimental impacts, but may also have beneficial, neutral, or even mixed consequences, across different interacting system elements, regions, and sectors of society. The objective of this framework is to allow for a more systematic and neutral approach to assessing and identifying climatic factors that are relevant for the assessment of risk. The CID concept was applied in the latest IPCC report (Ranasinghe *et al* 2021) in a comprehensive assessment of physical climate conditions, recognizing that multiple sectors can be influenced by various CIDs, with each CID having an impact on multiple sectors that can be considered either hazards when associated with risk, or 'boons' when associated with benefits or opportunities.

3.3.3. Risk tolerance

Risk tolerance incorporates the risk preference of households, private and public sector agents towards risks they face. Assessing risk tolerance can be considered an additional step in risk evaluation from objective (modeled) to subjective (perceived) risk. For instance, Laino and Iglesias (2023) found that integrating local perspectives from ten European cities through *Living Labs* provides a more context-specific and comprehensive understanding of the impacts and risks of climate change in coastal regions. Risk tolerance assessments can be used to break down the risk space into domains where risk is considered acceptable (no further climate risk management is necessary), tolerable (risk reduction measures necessary, depending on resources), and intolerable, where no action is feasible as limits to adaptation are encountered (Mechler *et al* 2014). For example, this type of assessment has been undertaken in the national risk assessment of The United Kingdom, The Netherlands, Portugal, Switzerland, Germany, and Austria (OECD 2018). Risk tolerance is closely linked to risk perception, as people are more likely to tolerate risks that they perceive as low or manageable. Risk can be perceived differently depending on the temporal positioning (e.g. after an extreme event, people tend to perceive similar risks as higher, which may turn to lower levels over time), as well as the existing social, economic, political, cultural, technical and environmental conditions (Aerts *et al* 2018). For example, coastal regions that rely heavily on tourism may perceive risks of high erodibility and storms as more significant compared to drought or landslide risks, which primarily impact other sectors such as agriculture or ecosystems (Laino and Iglesias 2023). Besides that, the assessment of risk preferences allows for the categorization of actors, communities, regions, or sectors as risk-averse, risk-neutral, or risk-tolerant. This is important for risk evaluation as well as for tailoring adaptation investments and measures, such as insurance products. Considerations of risk preference and tolerance are not new to socio-economic analysis (Klinke and Renn 2002) but have only recently entered CRA (e.g. Kunimitsu *et al* 2023) in line with discussions regarding the limits of adaptation (Klein *et al* 2014, Masson-Delmotte *et al* 2018). Yet, to date, risk tolerance assessments have not yet reached conventional approaches to CRA and remain somewhat disconnected from climate risk management studies that ascertain the effectiveness of adaptation.

3.3.4. Dynamic exposure and vulnerability

Recent studies have acknowledged that exposure is a dynamic concept (e.g. Zscheischler *et al* 2018, Kropf *et al* 2022, Rising *et al* 2022, Ward *et al* 2022, Zebisch *et al* 2022). Many authors discuss how socioeconomic development and adaptation responses could influence future climate risks by changing exposure and vulnerability (Gallina *et al* 2016, Berrouet *et al* 2018, Cremen *et al* 2022, Rising *et al* 2022). In fact, some authors (i.e. Gallina *et al* 2016, Harrington *et al* 2021, Menk *et al* 2022) argue that exposure may be a more significant risk driver than changes in hazard characteristics due to climate change. These studies suggest the need to better account for future changes in exposure by exploring socioeconomic or land-use change scenarios (Gallina *et al* 2016, Berrouet *et al* 2018, Cremen *et al* 2022), which is still often neglected in current research due to a lack of projections data at scale (Jurgilevich *et al* 2017, Menk *et al* 2022, Zebisch *et al* 2022).

Berrouet *et al* (2018) describe the dynamic nature of vulnerability in socio-ecological systems as being influenced by various factors, such as changes in the system's adaptive capacity, recoverability after disturbances, and the degree of the dependencies of the affected components with the climate impacts. By focusing on the interconnectedness of socio-ecological systems, the authors introduce a conceptual framework that recognizes vulnerability dynamics in response to environmental, social and economic factors. Likewise, Ward *et al* (2022) highlight the importance of considering changes in vulnerability over time as vulnerability can increase after a hazard due to the suffered damage. These dynamics are particularly important in the context of multi-hazards, when more than one hazard hits the same location in a short time interval. Furthermore, future changes in climate risks are driven by socioeconomic developments that influence exposure and vulnerability such as population growth or decline, urbanization and urban sprawl and progress in human development (e.g. equality, poverty reduction) (Cardona *et al* 2012, O'Neill *et al* 2017, Thiery *et al* 2021). These future dynamics can be explored with the help of projections based on socioeconomic scenarios (Jurgilevich *et al* 2017, Cremen *et al* 2022, Kropf *et al* 2022). However, vulnerability dynamics are rarely assessed in the current literature.

3.3.5. Multi-hazard approaches

There is a growing interest in multi-hazard approaches, analyzing how different hazards coincide, amplify and cascade to generate compound risks (Aznar-Siguan and Bresch 2019, Parker *et al* 2019). Multiple hazards in the context of climate risks have been studied from two different angles: one by investigating how multiple drivers coincide to drive impacts and risks (van den Hurk *et al* 2023a), and another by analyzing natural hazards of different kinds and their interrelationships in time and space (e.g. triggering, amplifying, independent, compound; Ward *et al*

2022). In both cases, the compound impacts of the overlapping hazards have a greater impact than each hazard alone. For instance, the combination of the storm surge from cyclone *Xynthia* with the high tide, large waves, and already saturated soil led to severe damage on the coasts of France in 2010 (Tilloy *et al* 2019).

Various frameworks for assessing multi-hazard risks exist (Gallina *et al* 2016, Hochrainer-Stigler *et al* 2023). One of the first frameworks for the assessment of risk from compound hazards was proposed by Zscheischler *et al* (2018). Gallina *et al* (2020) developed a multi-risk assessment methodology, designed to evaluate cumulative climate impacts in coastal areas using a case study on the North Adriatic coast. To do so, multiple hazards are analyzed using an influence matrix to determine hazard strength interactions across spatial units and temporal scales and, later, integrated along with exposure and vulnerability of different receptors (e.g. beaches, wetlands, urban areas). Also, some studies used the impact chain approach for tracing how multiple hazards propagate and aggregate through systems to generate risk conditions (e.g. Agulles *et al* 2022, Menk *et al* 2022, Zebisch *et al* 2022). The multi-hazard approach can present a more comprehensive analysis of risks in a region (Gallina *et al* 2016, Terzi *et al* 2019, Simpson *et al* 2021). For instance, Sutanto *et al* (2020) investigated the occurrence, interaction, and cascading nature of heatwaves, droughts, and wildfires across Europe, identifying spatial and temporal patterns of these hazards, thus, areas prone to concurrent and sequential events. Such an understanding can support better risk management options that account for synergies between risk management measures for individual hazards (De Ruiter *et al* 2021). A multi-risk perspective may also consider both climatic and non-climatic factors (e.g. dynamics of vulnerability and exposure) that interact to generate risks (Lung *et al* 2013).

3.3.6. Event-based storylines approach

Unlike deterministic approaches, probabilistic approaches for CRA assess the impacts of natural hazards based on their likelihood (Sillmann *et al* 2021), providing a spectrum of possible outcomes. However, they do so by assuming a constant probability distribution over a climatic reference period—typically 30 years—implying that the statistical properties of the climate system remain unchanged during this time (Cheng and Agha-Kouchak 2014). This assumption can be misleading because climate change does not follow consistent or predictable patterns, influencing climate processes with non-linear behavior and variations across multiple scales (Hurrell *et al* 2009). For example, small changes in ocean temperatures and atmospheric circulation can result in significant, and sometimes sudden, shifts in the frequency, intensity, and spatial distribution of extreme weather events (IPCC 2012, 2023a, Masson-Delmotte *et al* 2018), such as hurricanes or storms. While probabilistic models that better account for the evolving climate and its associated risks have been developed more recently (Cheng *et al* 2014, Vanem 2015, Cancelliere 2017), they have not been taken up yet in the CRA literature. To complement probabilistic approaches, non-probabilistic approaches have been recently applied, including those building on event-based storylines (Shepherd *et al* 2018, Sillmann *et al* 2021, van den Hurk *et al* 2023b). Storylines are valuable not only because they help to integrate both quantitative (including scenario-based information) and qualitative information, providing a holistic view of potential impacts addressed, but also for understanding and exploring low likelihood but plausible outcomes (see Baldissera Pacchetti *et al* (2023) for more on climate storylines). This approach focuses on the interaction of driving factors and the resulting impacts (Shepherd *et al* 2018), rather than quantifying event probabilities, which can be difficult due to their rarity and uniqueness (Zscheischler *et al* 2018). By considering plausibility, salience, and relevance, climate risk is addressed with a combination of physical and human facets of climate change, which includes vulnerability and exposure considerations (Sillmann *et al* 2021). Additionally, analysis of past weather events under different climatic, socio-economic, or policy changes can provide valuable insights into the impacts and dynamics of hypothetical events, known as 'counterfactuals' (Ciullo *et al* 2021).

Despite both approaches having their advantages and limitations, a combination of probabilistic and storyline approaches is possible (Brusselaers *et al* 2023). While the probabilistic approach is especially useful, for example, risk financing and cost-benefit analysis, the storyline approach can reveal the complexities of natural hazard events both in terms of direct and indirect impacts of various risk bearers. van den Hurk *et al* (2023b) describe that through a storyline of the impacts on the European food supply caused by droughts in North and South America. Therefore, constructing storylines comprising uncertain events and emerging impacts can provide novel system insights that might be missed in a probabilistic approach and may give meaningful inputs to stakeholders in a decision-making process.

3.4. Progress and challenges encountered in CRA

Considering the rapidly changing climate, socio-economic inequalities and other societal and environmental challenges, the development and implementation of CRAs need to proactively take on and incorporate multiple factors. In the reviewed literature, *complexity* and *uncertainty* are dealt with as major issues for CRAs, along with other practical challenges, such as technical choices related to an increasingly rich landscape of *approaches and tools*, the need for *data enhancement,* involving and being relevant to a broad range of stakeholders and their respective needs through more *inclusive and iterative* approaches, and the need to enable a better consideration of CRA outcomes in *decision-making* related to climate risk management. These factors are discussed in the following sub-sections.

3.4.1. Handling complexity

Characterizing climate risk is challenging due to the various components and interactions of risk drivers that are not yet fully understood (Simpson *et al* 2021, Menk *et al* 2022). Climate risks can have complex ramifications of impacts that cascade through inter-related systems (e.g. sectors, ecosystems or geographical regions) (Challinor *et al* 2018). Analyzing these indirect risks and causal risk pathways, including their economic implications, is not an easy task (Challinor *et al* 2018, Cremen *et al* 2022, Rising *et al* 2022), particularly, when determining the variability of risk perceptions across different spaces, times, sectors, and cultural associations (Brown and Berry 2022). While the dynamic interplay between hazard, exposure, and vulnerability makes it difficult to estimate the occurrence and progression of risk events properly (Ward *et al* 2022), analyzing interconnected and interacting climate-related risks on multiple sectors and effects on their components, increases the assessment complexity (Terzi *et al* 2019, Menk *et al* 2022).

Distinguishing cause-effect relationships from the various interacting factors, natural variability, and threshold values can be analytically complex. This complexity often causes compartmentalization of approaches which can lead to a fragmented view of risks (Brown and Berry 2022). For example, by:

- Focusing on specific hazards overlooking other risks that may have serious consequences (Cremen *et al* 2022) and without exploring a wider variety of potential scenarios and associated outcomes and their uncertainty (Pirani *et al* 2024).
- Only considering the hazard variability as climate changes, omitting variations in exposure and vulnerability over time (Jurgilevich *et al* 2017, Brown and Berry 2022).
- Assessing multi-risk as the aggregation of individual risks from different hazards (e.g. floods and droughts) based on existing conditions or specific scenarios rather than accounting for how these risks may interact over time (Ward *et al* 2022), as seen when droughts and heatwaves increase the risk of wildfires (e.g. Sutanto *et al* 2020).
- Not considering relevant aspects such as adaptive capacity (of both nature and humans), system resilience and stability under different future climates and socio-economic pathways (Brown and Berry 2022), and system recoverability after disturbances (Berrouet *et al* 2018).
- Focusing on specific subsets of systems, such as particular sectors or communities, without considering important linkages in risk transmission (e.g. via supply chains) (Challinor *et al* 2018).

To face these limitations, recent CRA literature has approached complexity from various perspectives. To categorize this within climate risks Simpson *et al* (2021) proposed a framework which introduces *single-driver interaction, multiple-driver interaction*, and *interacting risks* as three categories contributing to increasing complexity. Additionally, Cremen *et al* (2022) conducted a review on modeling and quantifying future climate risks. Authors highlighted the framework of Bouwer (2013) to account for dynamics in hazard (due to climate change), exposure patterns (e.g. population, land use, built environment), and vulnerabilities (e.g. due to adaptation and socio-economic changes).

Also, various CRA scholars have progressed in the understanding of climate risks interconnectedness and impact transmission across the systems. Challinor *et al* (2018) propose a new approach that distinguishes between climate factors (e.g. extreme weather events) and socio-economic factors (e.g. trade, migration) in the transmission of climate risks across borders (e.g. droughts in one region triggering food insecurity in another) and sectors (e.g. droughts disrupting the energy system, affecting raw material supply chains and manufacturing sector), based on a review of various methods for assessing transmitted risks and risk amplification. Furthermore, Harris *et al* (2022) introduce a protocol that helps incorporate analysis of transboundary risks (risks crossing geographical or political borders) by leveraging principles for managing complex risks and frameworks for assessing risk ownership (who is responsible for managing the risk across different scales). Carter *et al* (2021) present a conceptual framework for assessing cross-border impacts and emerging risks by examining initial impacts and downstream consequences, including recipient risk and impact and response dynamics. Additionally, van den Hurk *et al* (2023b) propose the event-based storyline approach which tracks remote climate events that may have impacts across geographical borders and sectors, as experienced with the landfalls of hurricanes Sandy in 2012 and Harvey in 2017 in the United States that triggered global trade shocks, with indirect economic repercussions for Europe (refer to Middelanis *et al* 2021).

Furthermore, advancements in multi-risk assessment models have allowed for improved methods of assessing climate-related risks by taking into account how different hazards are interrelated. Terzi *et al* (2019) compared various models to determine which were most effective at representing spatial and temporal changes, managing uncertainties, conducting cross-sector evaluations, incorporating adaptation strategies, and handling complex data. The results showed that system dynamic and hybrid models had the greatest potential for assessing multiple risks and adapting to climate change (Terzi *et al* 2019). In addition, Tilloy *et al* (2019) identify different types of hazard interrelations (i.e. triggering, change condition, compound, independence and mutually exclusive) and study 19 modeling methods (stochastic, empirical, and mechanistic) that can be leveraged to assess these hazards in the European context. The authors also provide insights into how to account for cascading hazards (e.g. how a storm can lead to landslides) and compounding hazards (e.g. extreme heat with a concurrent drought) to help better understand the overall impact of climate risks. Gallina *et al* (2020) present a multi-risk approach that combines different climate hazards, exposure, and vulnerability factors, using GIS and statistical techniques to identify high-priority multi-hazard and multi-vulnerability areas in different spatial and temporal scales. More recently, Hochrainer-Stigler *et al* (2023) propose a six-step framework for analyzing and managing risk across different levels in five pilot regions in Europe (Scandinavia, Danube Region, Veneto Region, North Sea, and Canary Islands). This integrated approach seeks to enhance the practical application of multi-risk assessment, encompassing single to multi and systemic risks.

There are further key methodological improvements needed to overcome analytical challenges. For instance, how to comprehensively describe the potential cascade impacts under different future scenarios (Gallina *et al* 2016), considering the different spatial and temporal scales to identify the wide range of disparate risks (Brown and Berry 2022), and including a detailed analysis of risk interactions (i.e. aggregation, compounding or cascading) and dynamic interdependencies among and within the risk components (Gallina *et al* 2016, Terzi *et al* 2019, Simpson *et al* 2021, Ward *et al* 2022). Additionally, Zscheischler *et al* (2018) emphasize the importance of interdisciplinary collaboration in understanding the complex interactions between various risk drivers, such as urbanization, infrastructure, and anthropogenic emissions, and how they compound to shape risks. Jurgilevich *et al* (2017) highlight the importance of incorporating risk dynamics into CRA by considering changes in exposure and vulnerability over time, as well as integrating biophysical and socio-economic aspects to effectively address present and future challenges. These improvements should be complemented with enhanced ways to communicate and visually present the many risk features (*see* section 3.4.5), such as cause-effect relationships (e.g. how deforestation leads to increased flood risk), feedback loops, the combined effects of risk drivers (e.g. land regulations affecting on both the number of elements exposed and hydrological conditions associated to floods), and how risks evolve over time and across different locations, enabling more informed decision-making (Lieske 2012, Terzi *et al* 2019, Menk *et al* 2022). Overall, more than an impediment, complexity of climate risks offers new areas for innovation and development, which can enable more comprehensive and dynamic CRAs.

3.4.2. Addressing and embracing uncertainty

When projecting and predicting risks, each component of the CRA involves various sources of uncertainty (table 1), which should be treated carefully (Cremen *et al* 2022). Modeling future changes and variability of impacts on each risk component is a methodological challenge that has not been fully addressed (Menk *et al* 2022). Defining the plausibility of future outcomes is not an easy task due to the intrinsic uncertainty of the response of climate to human-caused changes, uncertainties in the representation of processes by climate models, and uncertainties related to the scenarios themselves that are built around narratives of projections of factors such as changes in population and global governance that also have associated uncertainties (Hawkins and Sutton 2009, Harrington *et al* 2021). Projecting future changes in vulnerability is highly uncertain, considering that it also depends on socio-economic aspects such as education, wealth, health, and how they interact (Jurgilevich *et al* 2017). Additionally, CRAs are often constrained by limited information about risk dynamics, future exposure and vulnerability, and 'hidden' risk factors across socio-ecological systems (Jurgilevich *et al* 2017, Melo-Aguilar *et al* 2022, Rising *et al* 2022, Zebisch *et al* 2022).

In the face of this challenge, van der Sluijs (2012) discusses two possible directions for dealing with (deep) uncertainty: one where uncertainty is a missing piece of current knowledge status and the other, accepting uncertainty and including it into CRAs when possible.

Several studies have explored ways to reduce uncertainty in CRAs. Kaspersen and Halsnæs (2017) found that detailed and spatially explicit data can lower overall uncertainty and help identify vulnerable assets, demonstrated through a case study in Denmark. Additionally, Harrington *et al* (2021) suggest a methodology for assessing uncertainties in

Table 1. Sources of uncertainty.

Source of uncertainty	Source
Structural uncertainty: incomplete understanding of processes and components in climate, impact, and economic models.	(Kaspersen and Halsnæs 2017)
The noise of natural fluctuations: distinguishing climate change impacts in specific locations from natural fluctuations.	(Kaspersen and Halsnæs 2017)
Downscaling methods: estimating the probability of low-frequency, high-intensity events in specific locations by downscaling data from global climate models.	(Kaspersen and Halsnæs 2017)
Cross-sectoral sensitivities: changes in sectoral sensitivities in a changing climate.	(Challinor *et al* 2018)
Physical teleconnections: changing physical teleconnections that can affect sectors and regions differently.	(Challinor *et al* 2018)
Unexpected changes in systems: unprecedented socio-economic and environmental changes and their interactions with climate change effects.	(Conway *et al* 2019)
Incomplete climate impact pathways: insufficient characterization of climate change effects in the human and ecological systems, including direct and indirect impact pathways, webs of interconnections, and propagation mechanisms at various temporal and spatial scales.	(Conway *et al* 2019, Melo-Aguilar *et al* 2022)
Masking of climate change effects: overlapping climate change effects (exempting extreme events) with other dynamics, like urban development or demographic changes.	(Conway *et al* 2019)
Risk aggregation: assumptions made upon integrating information from different scales and sources to assess overall risks and priorities.	(Harrington *et al* 2021)
Relative importance of each input factor: quantifying the relative importance of every risk factor in different exposed systems and in an evolving landscape of multiple risks.	(Harrington *et al* 2021, Melo-Aguilar *et al* 2022)
Evolving adaptive capacity: modeling how quickly and effectively people and systems will adapt to the changing climate.	(Harrington *et al* 2021)
Spatial patterns of hazards: representing the spatial distribution of climate hazards and their impacts against local risk thresholds for different types of hazards.	(Harrington *et al* 2021, Rising *et al* 2022)
Temporal variations: variability of climate impacts over time, including feedback loops and interacting risks.	(Rising *et al* 2022)
Unpredictable events: unidentified or yet unknown risks, including 'black swan' events.	(Rising *et al* 2022)
Individualization of impacts: estimating the extent of impacts and their spatiotemporal probability and frequency precisely, within varied risk perceptions and risk-aversion attitudes across the society.	(Kaspersen and Halsnæs 2017, Rising *et al* 2022)
Uncertain datasets: intrinsic uncertainty in input data and inconsistency between datasets used for climate modeling.	(Melo-Aguilar *et al* 2022)

the 'Reasons for Concern' framework by quantifying multiple dimensions of uncertainty, including model-related uncertainty, uncertainty related to future socioeconomic development, and uncertainty related to local risk thresholds and its variance depending on the governance and severity of the climate hazard in a given location. Similarly, Melo-Aguilar *et al* (2022) propose a standardized probabilistic framework that treats each component (indicators and weights) of a composite risk index as a probability density function. By quantifying and propagating uncertainties associated with each element of the risk assessment, the authors provide a confidence level of the risk value and simulated future scenarios in an illustrative application in the Balearic Islands, Spain.

However, with the paradigm of 'uncertainty reduction' potentially reaching its limits, 'making uncertainty manageable' is a promising path to be pursued by, for example, following an event-based storyline approach (e.g. Sillmann *et al* 2021), investigating adaptation tipping points (e.g. Kwadijk *et al* 2010) or exploring 'solution spaces' for adaptation options (e.g. Haasnoot *et al* 2020).

3.4.3. CRA approaches and choices

The urgency of addressing climate change has brought forth diverse methods to assess climate risk, ranging from *top–down* global modeling to *bottom–up*, more localized assessments. However, this variety of scaled approaches has created a challenge for decision-makers and relevant stakeholders, especially at sub-national levels, where not only strengths but also limitations and inherent trade-offs of CRA approaches also play a significant role in the selection process.

On the one hand, top–down approaches can be applied at a large scale (e.g. national), having results that are replicable and scalable (Conway *et al* 2019, Zebisch *et al* 2021), and represent conditions at different timeframes (Menk *et al* 2022) with supportive data and objective rigor (Melo-Aguilar *et al* 2022). On the other hand, bottom–up approaches can reveal new information on the risk and its implications in a given context (Zebisch *et al* 2021, Menk *et al* 2022). These approaches can unpack the impacts of risks on individuals' lives and the individuals' responses and reactions to specific risks (Terzi *et al* 2019), capturing the numerous factors and risk processes that interact in intricate ways (Berkhout *et al* 2013, Aznar-Siguan and Bresch 2019, Terzi *et al* 2019, Brown and Berry 2022, Kropf *et al* 2022).

While both, top–down and bottom–up approaches, come with their individual advantages CRA results from both approaches tend to lead to an incomplete understanding of the complex interplay between climate and socio-economic systems and, thus, may lead to a failure to address the root causes of climate risk adequately. With regards to top–down approaches, these face major difficulties related to the assumptions for assessing future climate risks, as well as their ambiguity in defining 'referenced conditions' and the 'shifting baselines' syndrome (Brown and Berry 2022). Top–down approaches often have 'blind spots' in the prediction of future risks due to insufficient historical data (Challinor *et al* 2018). Moreover, their high reliance on primary climate data rather than bioclimatic data, makes them unsuitable for evaluating climate risks in ecosystems and biodiversity (Brown and Berry 2022). In contrast, bottom–up approaches face challenges related to high subjectivity (Melo-Aguilar *et al* 2022) and low consistency of results (Zebisch *et al* 2021). These approaches heavily rely on participant data, expertise and local knowledge, which can vary widely between different groups of participants (Cavan and Kingston 2012, Melo-Aguilar *et al* 2022, Menk *et al* 2022) and lack precision and spatial distinction (Zebisch *et al* 2021). Bottom–up approaches tend to simplify the complexity of risk processes in order to ensure wider and more active participation by representing conditions at a specific time without explaining changes over time, the evolution of risks, or risk interactions within system components (Menk *et al* 2022). For instance, *Participatory Climate Scenario Planning* focuses narrowly on how future climate conditions will be impacted by socio-economic dynamics, neglecting the influence of socio-economic dynamics on climate risk factors (Conway *et al* 2019).

Recent CRA literature increasingly includes the combination of top–down and bottom–up approaches, often referred to as *integrated or hybrid approaches* (UNDRR 2022). Doing this enhances the usefulness (Peng *et al* 2021) and robustness (Onyango *et al* 2016) of CRAs, not only balancing the deficits of each approach but reinforcing their strengths. For instance, integrated assessments, such as the ones in Denmark and Italy by Kaspersen and Halsnæs (2017) and Torresan *et al* (2016) respectively, consider various factors like human responses, bioclimatic processes, and socio-economic dynamics, and have the potential to incorporate the concerns of relevant stakeholders. Hybridization (i.e. the combination of top–down and bottom–up approaches) of CRA approaches provides a more complete picture of risks when compared to individual methods used in isolation, not only by capturing both large-scale (e.g. hydrometeorological phenomena and environmental changes from climate models and projections) and local conditions (e.g. the adaptive capacity of communities, and stakeholders' perceptions of risk) but also mitigating deficits of each method. For example, they can cover 'blind spots' in models (Challinor *et al* 2018) by capturing notions of how risks affect people's lives, behavior, and responses (Terzi *et al* 2019); insights into the non-monetary and indirect effects of climate risks on specific assets, systems, or groups at the local level (Menk *et al* 2022) as well as conditions for system failure scenarios (Shortridge and Zaitchik 2018). Likewise, they can supplement participatory processes with information on climate risks at different timeframes as well as their spatial concentration, dynamics and distribution (Zebisch *et al* 2021) to generate narrative-based descriptions that are locally relevant for decision-makers (Conway *et al* 2019). Thus, the hybridization of CRA approaches seems to be the most comprehensive strategy for understanding current and future climate risks in the literature.

Nevertheless, with the combination of approaches, new challenges arise. Data gathered from each approach tends to be different, and harmonizing it can be problematic (Conway *et al* 2019). Combining data can raise verification and reproducibility issues, considering that some aspects, such as exposure and vulnerability, are sometimes assessed using indirect or subjective methods (Melo-Aguilar *et al* 2022). While there has been some progress in developing climate services and improving data quality, there is still some work to do in developing and upscaling frameworks for quality assurance and harmonizing information across platforms in Europe (Street *et al* 2022). Other emerging issues are related to the need for data-rich environments, high computational resources and expertise, more complicated validation and verification processes, and additional sources of uncertainty (Conway *et al* 2019, Terzi *et al* 2019, Zennaro *et al* 2021, Kondrup *et al* 2022).

3.4.4. Improving data as the key to overcome challenges
Beyond access and availability of reliable data, one of the major challenges in conducting CRAs is ensuring the quality, granularity, temporal consistency, and interoperability of data, tailored specifically to climate risk factors (i.e. hazard, exposure and vulnerability). Literature indicates that developing more consistent and comprehensive datasets on exposure and vulnerability, especially socio-economic data, as well as enhancing the data on extreme weather events, can significantly enhance the projection of future risk dynamics (Jurgilevich *et al* 2017, Gallina *et al* 2020, Zennaro *et al* 2021). Aligning to this, Menk *et al* (2022) highlight the importance of overcoming data scarcity and inconsistency (e.g. due to heterogeneous spatial scales or resolution) to improve the accuracy of CRAs. Also, Zebisch *et al* (2021) indicate that refining or downscaling climate model data to local conditions can be a step towards more reliable and applicable risk assessments. Moreover, Challinor *et al* (2018) suggest that comprehensive datasets can reduce uncertainty in model-based frameworks and enhance the description of risk transmission pathways across sectors and borders. Altogether, this can aid in calibrating and validating models with climate and socio-economic data more consistently (Lissner *et al* 2012, Zebisch *et al* 2021).

Additional improvements may arise if data representing the system related to qualitative aspects such as socio-economic information, stakeholder preferences and local perception of risk is adequately collected and integrated into models (Terzi *et al* 2019, Melo-Aguilar *et al* 2022). This must be done carefully, for example, when choosing the right indicators of vulnerability that can represent the actual conditions while being univocally comprehensible for policymakers and stakeholders (Parker *et al* 2019). Addressing these data challenges not only improves the quality of CRAs but also ensures that derived adaptation strategies are grounded in a more accurate and holistic understanding of climate risks.

3.4.5. Influencing decision-making
CRA provides essential information for decision-making, empowering decision-makers to undertake local adaptation action. However, translating CRA results and scientific information into accessible and actionable formats can be challenging. Through a case study in Ireland, McDermott and Surminski (2018) demonstrate that local decision-makers actions are ultimately guided by political realities (e.g. various competing goals must be balanced, decision scenarios with high uncertainty, the timespan of decisions, the need of public support), and normative choices (e.g. defining 'acceptable risk levels' and determining 'adequate' protection levels), which involves broader consensus and stakeholder participation to secure decisions' acceptability.

The literature shows ways to overcome this challenge and meet the expectations of decision-makers. To do that, it is essential to build on a robust evidence base that can account for the unequal distribution of benefits and costs ('winners' and 'losers') of the changing climate (Peng *et al* 2021), and is characterized by high confidence levels and widespread consensus (Torresan *et al* 2016, Brown and Berry 2022). This can be particularly beneficial when power imbalance and conflicting interests exist, fostering inclusive assessments and more just and equitable risk management decisions (Challinor *et al* 2018, Menk *et al* 2022).

Moreover, the literature suggests ways to enhance the interpretability of the CRA results, especially at higher levels of aggregation. The increasing volume of data, when properly interpreted (McDermott and Surminski 2018), can be used to develop relevant information (Gallina *et al* 2016, Zebisch *et al* 2021) and lead to better decisions. To do so, CRA results need to be translated and contextualized to make them more accessible, relevant and actionable, while aligning with the specific needs of different stakeholders, such as government agencies, communities, and individuals (Conway *et al* 2019, Melo-Aguilar *et al* 2022). Although the process of translating and contextualizing information may imply simplification, loss of information, and even misinterpretation (e.g. over- or underestimating results, or data misrepresentation), it is also bringing innovative communication strategies aiming to ensure the effective communication of climate risk-related information. For example, through climate impact chains (e.g. Zebisch *et al* 2021, 2022, Estoque *et al* 2022, Menk *et al* 2022, Lückerath *et al* 2023), multi-layer risk maps (e.g. Torresan *et al* 2016, Ronco *et al* 2017, Gallina *et al* 2020), network maps and flowcharts (e.g. Yokohata *et al* 2019), online interactive visuals (e.g. Herring *et al* 2017), burning embers diagrams (e.g. Zommers *et al* 2020), narratives (e.g. Dessai *et al* 2018, Jack *et al* 2020), storylines (e.g. Shepherd *et al* 2018, Shepherd 2019, Jack *et al* 2020, Sillmann *et al* 2021, Young *et al* 2021, Kunimitsu *et al* 2023, Tanaka *et al* 2023, van den Hurk *et al* 2023b), and virtual 3D simulations (e.g. Haynes *et al* 2018, Wang *et al* 2019, Van Gevelt *et al* 2023). Continuously improving communication strategies is pivotal in matching climate risks and adaptation responses (Brown and Berry 2022). Showcasing effective communication strategies to decision-makers is indeed a critical challenge for the CRA community.

4. Discussion

This section discusses future directions and opportunities within the domain of CRA, drawing from relevant literature insights. Current operationalization of risk components, challenges (especially complexity and uncertainty), as well as developments in concepts and frameworks, call for new perspectives in the CRA field. The discussion and conclusion unfold in four main points, namely new tools for CRA, inclusive CRA, chances for pushing boundaries in the field, and reimagining CRAs.

4.1. Technological advances for more robust CRAs

The CRA field is rapidly advancing, driven by new technologies and a deeper understanding of climate risks. In Europe, the future of CRA is being shaped by technological initiatives like *Destination Earth* (DestinE). It aims to create high-precision digital replicas of the Earth—'digital twins'—to monitor and predict environmental change, supported by a cloud-based core service platform offering data-driven decision-making tools, a data lake consolidating various data sources, and two pilot digital twins for climate adaptation and extreme weather (Bauer *et al* 2021, Hoffmann *et al* 2023). Besides that, accessible and user-friendly decision-making tools, like DESYCO (*see* Torresan *et al* 2016), have been developed, focusing on integrating local information (e.g. vulnerability, exposure, impacts) and global climate data (e.g. hazards, climate and socio-economic scenarios) to create tailored, practical CRAs. Also, open-source platforms like CLIMADA (Aznar-Siguan and Bresch 2019) enable resource-limited regions to conduct effective CRAs and indicating a trend towards more accessible, transparent, and collaborative risk assessment methods. By enhancing access to data, complex computations can be made more manageable. This can be facilitated by promoting the use of data management best practices (such as the FAIR principles), virtual data labs (e.g. the European Open Science Cloud platform), and fostering collaboration and knowledge-sharing between users (i.e. scientists, local governments, community groups, and other stakeholders). Such actions can ultimately support the trust-building of local CRAs.

Artificial intelligence and machine learning are at the forefront data-driven CRA methods using techniques such as decision-trees, random forests, and artificial neural networks (Zennaro *et al* 2021). These, along with cloud computing and satellite imagery, are enhancing the data collection, availability, quality, and processing, as well as the precision and applicability of CRAs (see Mosavi *et al* 2018, Kotchi *et al* 2019, Tsatsaris *et al* 2021, Zennaro *et al* 2021, Avalon-Cullen *et al* 2023). For example, researchers may use machine learning and remote sensing to enhance the predictive capabilities of CRA models by analyzing complex and high-resolution climate data in real-time. Similarly, these technologies offer means for facilitating decision-making and implementation. For instance, artificial intelligence can assist decision-making by processing large datasets to identify risk patterns, trends, and dynamics to prioritize adaptation measures, while remote sensing can enable practitioners (e.g. Civil Protection, NGOs) near real-time monitoring of climate impacts (e.g. flood, drought, urban heatwaves) in critical areas (e.g. water, food, energy, health, transport) to pre-emptively act and address climate risks. Additionally, emerging fields like citizen science, big data analytics, and network analysis hold significant potential for innovating CRA practices (more in Challinor *et al* 2018, Pollard *et al* 2018, Zennaro *et al* 2021, Avalon-Cullen *et al* 2023). They suggest a future where CRA is more interactive, data-driven, and socially informed, emphasizing the importance of adopting these technologies for advanced, effective risk management and adaptation planning. We encourage exploring and leveraging these new technologies to their full potential in the field of CRA.

4.2. Local stakeholder engagement in CRA

Local stakeholder involvement is increasingly recognized as a crucial element in the effectiveness of CRAs (e.g. Gallina *et al* 2016, Torresan *et al* 2016, Conway *et al* 2019, Peng *et al* 2021, Brown and Berry 2022, Porter and Clark 2023). Incorporating local knowledge and perspectives can have two-fold benefits: provide a deeper understanding of the local contexts including hidden aspects of risks that models cannot capture and build a shared understanding of the problem at hand—particularly important for better decision-making processes. Recent research in Europe (see Terzi *et al* 2019, Menk *et al* 2022, André *et al* 2023, Lückerath *et al* 2023) underscores the importance of participatory governance as a critical path for improving CRAs (Arribas *et al* 2022), advocating for the active involvement of all relevant parties to utilize localized information and foster decision ownership.

Future CRAs are expected to increasingly consider the behavior and perceptions of individuals, businesses, and governments. Integrating these human elements, societal dynamics and other factors (e.g. collective memory, past experiences, previous societal interests and decisions, social acceptability) promises to make CRAs more context-specific and relevant. In this regard, CRAs need more participatory and inclusive spaces, like stakeholder workshops, which have been identified as valuable for understanding the roots, drivers and impacts of local climate risks (e.g. Torresan *et al* 2016, Melo-Aguilar *et al* 2022, Menk *et al* 2022, Zebisch *et al* 2022). Consulting stakeholders during the formulation and representation of problems will be essential (Peng *et al* 2021), as well as emphasizing a more transparent means to assess climate risks (Bressan *et al* 2024).

To achieve this, a blending of scientific methods from both natural and social sciences is anticipated (Aerts *et al* 2018). An integrated approach, combining top–down and bottom–up insights, is seen as essential for a comprehensive and nuanced understanding of climate risks (Conway *et al* 2019). Coupling these approaches in iterative data exchange can improve the understanding of cause-effect dynamics, feedback, and connections across systems. This suggests a shift towards more holistic, interdisciplinary CRAs that better reflect and address local needs and complexities.

4.3. Areas for future research

Recent research and conceptual developments in the CRA literature pointed out new areas to be explored that we proposed as potential key research frontiers and emerging knowledge gaps:

- **Cause-effect relationships with human well-being**: link climate impacts directly to human well-being and understanding how (chronic) environmental shocks (e.g. prolonged droughts), reinforce vulnerabilities (see Aerts *et al* 2018).
- **Societal dimensions of climate risks**: delve into aspects such as trust, risk-related behavior, normative choices, political realities, social ties, perception, disparity and tolerance (or aversion).
- **Vulnerability and exposure dynamics**: encompass the study of changes in exposure and vulnerability under diverse future socioeconomic scenarios and development pathways and understanding changes in the risk distribution over time and space due to the dynamic interplay and variation of exposure, vulnerability, hazards.
- **Responses modulating climate risks**: consist of integrating into the CRA aspects such as the effectiveness and limits of adaptation measures, residual risks, and the influence of response performance on the risk profiles over time (including the risk of maladaptation).
- **Risks under transient scenarios, and risk distribution**: involves assessing probabilities and impacts of future events in transitional climate scenarios (time-dependent), as well as incorporating evolving non-climatic factors (e.g. population growth, land-use change, ecosystem shift, economic development) in projecting future risks. It also refers to understanding changes in the risk distribution over time and space due to the dynamic interplay and variation of exposure, vulnerability, and hazards.
- **High-resolution models**: enhancing downscaling techniques and producing high-resolution climate models at the regional, sub-national, and local level, as well as advancing technical and human resources and scientific methods for integrating those into CRA.
- **Other emerging topics**: comprise low-likelihood high-impact events, systemic risk transmission mechanisms, tipping points, and early signs of system disruptions.

Addressing these areas while achieving a unified understanding of vulnerability will be essential for not only estimating climate risks more precisely but also for managing them more effectively.

4.4. CRAs under a systemic approach

As the field advances, newfound knowledge and understanding of climate risks have created opportunities to refine and enhance CRA. The conceptual shift over the past decade—from climate vulnerability to climate risk and stress tests—has been of crucial importance for advancing climate adaptation and resilience planning. Given the complex nature of climate risks, the CRA community is undergoing a notable shift towards a more systemic perspective (UNDRR 2022), examining interrelationships between multiple climate risks, as well as integrating multiple hazards and socio-economic dynamics.

A systemic approach in CRA accounts for various forms of vulnerability (*e.g. physical, economic, social, and ecological*) and adaptation limits when assessing the risks. This is achieved through evaluating indicators of sensitivity, adaptive capacity, system stability, resilience, and hazard threshold values. Likewise, a systemic analysis of climate risks necessitates a deeper understanding of how risks can propagate across various sectors and regions (risk transmission), the factors that increase the severity of risks (risk amplifiers), correlations between local risks and climate phenomena in distant areas (teleconnections), how multiple impacts converge into a larger effect (impact aggregation), and how initial climate-related disruptions trigger a cyclical chain of effects that accelerate or intensify risk conditions (feedback loops).

In this context, findings suggest that a leading CRA practice worldwide, including in Europe, involves the integration of top–down and bottom–up approaches in iterative cycles of data exchange (see Terzi *et al* 2019, Menk *et al* 2022). Combining quantitative with qualitative approaches, and leveraging citizen science, the internet, and social media can enhance CRAs' comprehensiveness. Such a hybrid approach provides a better understanding of cause-effect dynamics, cross-system connections, and hidden impacts or '*blind spots*' in models.

Evaluating risk pathways from a systemic perspective is also crucial for future CRAs and risk scenarios. This involves exploring risk pathways in ecological and human systems under varying levels and rates of climate change and anthropogenic pressures, assessing the impacts of socio-economic pathways on risk dynamics and variability, estimating the timing of risk emergence, and exploring future opportunities. The latter shifts the focus of CRA, from a problem-oriented to a solution-oriented perspective by including the evaluation of potential benefits arising from changing climatic conditions (as done in the third UKCCRA; Watkiss and Betts 2021) and proactive and effective climate risk management (e.g. in terms of creation of new markets, products, services or safeguarding development goals).

This review indicates that uncertainty remains a major challenge for decision-making, and a more systemic CRA approach not only increases complexity (e.g. due to inter-system dependencies and cascading effects), but also the associated uncertainty. Thus, managing uncertainty while continuing to look for ways to reduce it seems to be the way to move forward in future CRAs. Combining probabilistic methods with event-based storylines and integrating confidence and sensitivity analysis in CRA results seem to be promising remedies to manage uncertainty. This encompasses developing, utilizing, and integrating a variety of climate and socio-economic scenarios that support the analysis of cross-system dynamics and facilitate formulating adaptation options that, instead of being optimized for a certain future, are optimized for a multiplicity of plausible futures.

In essence, integrating systemic thinking opens avenues to further refine the conceptualization, methodological development, and implementation of future CRAs. These may include utilizing system dynamics or network analysis to map risk propagation within and across systems, identifying vulnerabilities and resilience nodes in interconnected systems, or embedding feedback loops and tipping points in risk models. Similarly, advancing CRAs towards a more systemic approach requires progress in other areas, such as leveraging advanced technologies like AI, machine learning, remote sensing, and big data analytics for real-time risk assessment and modeling system's complexity; strengthening data interoperability and availability (particularly at lower decision-making scales) for comprehensive and consistent risk analysis across systems; enhancing stakeholder engagement to identify less-visible risks and system interdependencies; and exploring societal and institutional dynamics to better understand how governance structures and collective behavior shape risk outcomes.

Embracing these advancements will lead to better understanding of climate risks and their impacts, fostering more informed and effective decision-making. Collaboration across disciplines is essential to not only leverage technology, data, and collective knowledge, but also build a more comprehensive, flexible, and effective approach to CRA. Yet, bridging the gap between advancements in conceptualization and method refinement within academic circles and their practical application in real-world CRA is imperative. This review highlights advanced theoretical developments in CRA, which have not yet been translated into practice. Addressing this issue ensures that academic progress yields tangible, actionable, and useful knowledge for practitioners, thereby enhancing the overall utility of CRAs.

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

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Appendix. Content and thematic analysis

Table A.1. Guiding questions, coding and thematic categories.

Guiding questions	Codes	Description	Thematic categories
Which tools, methods and approaches have been applied?	'Tool' and underneath: - 'Approach' - 'Scale' - 'Time' - 'Metrics' - 'Scenario' - 'projection'	This code covers tools or methods, as well as approaches (quantitative, qualitative, hybrid) that have been applied to CRA. Scales, timeframes, metrics, and the choice of future scenarios/projections were also included.	Technical implementation choices
How were risk, and its components conceptualized and considered?	'Risk' and underneath: - 'Hazard' - 'Exposure' - 'Vulnerability' - 'Responses' - 'Impacts'	It includes conceptual and analytical considerations regarding risks and each of its components: hazard, exposure, and vulnerability. Responses, as a fourth component of risk, were also considered. Additionally, the conceptualization of impacts was also included.	Risk conceptualization
Are there technical/ methodological shortfalls?	- 'Drawback' - 'Limitation'	Drawbacks are shortcomings, disadvantages, or negative aspects of a particular method, approach, or practice in CRA. Limitations refer to the inherent restrictions or boundaries that exist within the CRA process, which influence the analysis and its outcomes. Both represent weaknesses.	Drawbacks and limitations
Which challenges and barriers were identified regarding CRA?	'Challenges'	General difficulty, obstacle, or problem that the study faced and needs to be overcome. It ranges from conceptual and analytical issues, such as uncertainty and complexity, to practical and perceptible aspects, such as decision-making relevancy, stakeholder consensus, data quality and availability.	Challenges
What are the most pressing issues that need to be addressed in the field of CRA?	'Gaps'	Areas where critical information, data, or knowledge is missing or incomplete, and hinders the understanding of climate-related risks and their impacts.	Remaining gaps
Are there promising trends and/or new perspectives which are relevant for CRA?	'Trends'	This code relates in a more general or conceptual sense to emerging concepts, recurrent topics, or areas of innovation in the CRA field.	Trends and emerging concepts
What would be future directions or opportunities for CRA to enhance effectiveness, relevance, and comprehensiveness?	'Outlook'	It refers to potential directions on a particular issue in the field, based on the discussions and recommendations of the studies. It covers mainly scientific issues but extends to practical, technological, and political aspects.	Future directions

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References

Abbass K, Qasim M Z, Song H, Murshed M, Mahmood H and Younis I 2022 A review of the global climate change impacts, adaptation, and sustainable mitigation measures *Environ. Sci. Pollut. Res.* **29** 42539–59

Adger W N, Brown I and Surminski S 2018 Advances in risk assessment for climate change adaptation policy *Phil. Trans. R. Soc.* **376** 20180106

Aerts J C J H, Botzen W J, Clarke K C, Cutter S L, Hall J W, Merz B, Michel-Kerjan E, Mysiak J, Surminski S and Kunreuther H 2018 Integrating human behaviour dynamics into flood disaster risk assessment *Nat. Clim. Change* **8** 193–9

Agulles M, Melo-Aguilar C and Jordà G 2022 Risk of loss of tourism attractiveness in the Western Mediterranean under climate change *Front. Clim.* **4** 1019892

André K *et al* 2023 Improving stakeholder engagement in climate change risk assessments: insights from six co-production initiatives in Europe *Front. Clim.* **5** 1120421

Ara Begum A *et al* 2022 Point of departure and key concepts *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed H-O Pörtner, D C Roberts, M Tignor, E S Poloczanska, K Mintenbeck, A Alegría and M Craig (Cambridge University Press) pp 121–96

Arribas A *et al* 2022 Climate risk assessment needs urgent improvement *Nat. Commun.* **13** 4326

Avalon-Cullen C, Caudill C, Newlands N K and Enenkel M 2023 Big data, small island: earth observations for improving flood and landslide risk assessment in Jamaica *Geosciences* **13** 64

Aznar-Siguan G and Bresch D N 2019 CLIMADA v1: a global weather and climate risk assessment platform *Geosci. Model Dev.* **12** 3085–97

Baldissera Pacchetti M, Coulter C, Dessai S, Shepherd T G, Sillmann J and Van Den Hurk B 2023 Varieties of approaches to constructing physical climate storylines: a review *Wiley Interdiscip. Rev.* **15** e869

Battiston S, Dafermos Y and Monasterolo I 2021 Climate risks and financial stability *J. Financ. Stab.* **54** 100867

Bauer P, Stevens B and Hazeleger W 2021 A digital twin of Earth for the green transition *Nat. Clim. Change* **11** 80–83

Berg B L, 2006. Qualitative research: methods in the social sciences (https://doi.org/10.1037/e668352010-001)

Berkhout F, van den Hurk B, Bessembinder J, de Boer J, Bregman B and van Drunen M 2013 Framing climate uncertainty: socio-economic and climate scenarios in vulnerability and adaptation assessments *Reg. Environ. Change* **14** 879–93

Bernard H R 2013 *Social Research Methods: Qualitative and Quantitative Approaches* (Sage)

Berrouet L M, Machado J and Villegas-Palacio C 2018 Vulnerability of socio—ecological systems: a conceptual framework *Ecol. Indica* **84** 632–47

Birkmann J and Mechler R 2015 Advancing climate adaptation and risk management. New insights, concepts and approaches: what have we learned from the SREX and the AR5 processes? *Clim. Change* **133** 1–6

Bouwer L M 2013 Projections of future extreme weather losses under changes in climate and exposure *Risk Anal.* **33** 915–30

Bressan G, Duranovic A, Monasterolo I and Battiston S 2024 Asset-level climate physical risk assessment and cascading financial losses *Nat. Comm.* **15** 5371

Brown I and Berry P 2022 National climate change risk assessments to inform adaptation policy priorities and environmental sustainability outcomes: a knowledge systems perspective *Clim. Change* **175** 24

Brusselaers J F, Hochrainer-Stigler S, Tesselaar M, Ciullo A and Zhu Q 2023 Synthesis of climate impacts and risks and ways to build resilience *RECEIPT Project, Deliverable 4.4* (submitted)

Cancelliere A 2017 Non stationary analysis of extreme events *Water Resour. Manage.* **31** 3097–110

Cardona O D, Van Aalst M K, Birkmann J, Fordham M, Mc Gregor G, Rosa P, Pulwarty R S, Schipper E L F, Sinh B T and Décamps H 2012 Determinants of risk: exposure and vulnerability *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) pp 65–108

Carter T R, Benzie M, Campiglio E, Carlsen H, Fronzek S, Hildén M, Reyer C P O and West C 2021 A conceptual framework for cross-border impacts of climate change *Glob. Environ. Change* **69** 102307

Cavan G and Kingston R 2012 Development of a climate change risk and vulnerability assessment tool for urban areas *Int. J. Disaster Resil. Built Environ.* **3** 253–69

Challinor A J, Adger W N, Benton T G, Conway D, Joshi M and Frame D 2018 Transmission of climate risks across sectors and borders *Phil. Trans. R. Soc.* **376** 20170301

Chen D *et al* 2021 Framing, context and methods *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) pp 147–286

Cheng L and AghaKouchak A 2014 Nonstationary precipitation intensity-duration-frequency curves for infrastructure design in a changing climate *Sci. Rep.* **4** 7093

Cheng L, AghaKouchak A, Gilleland E and Katz R W 2014 Non-stationary extreme value analysis in a changing climate *Clim. Change* **127** 353–69

Ciullo A, Martius O, Strobl E and Bresch D N 2021 A framework for building climate storylines based on downward counterfactuals: the case of the European Union Solidarity fund *Clim. Risk Manage.* **33** 100349

Conway D *et al* 2019 The need for bottom-up assessments of climate risks and adaptation in climate-sensitive regions *Nat. Clim. Change* **9** 503–11

Cremen G, Galasso C and McCloskey J 2022 Modeling and quantifying tomorrow's risks from natural hazards *Sci. Total Environ.* **817** 152552

Cutter S L, Boruff B J and Shirley W L 2003 Social vulnerability to environmental hazards *Soc. Sci.* Q **84** 242–61

Dawson R J *et al* 2018 A systems framework for national assessment of climate risks to infrastructure *Phil. Trans. R. Soc.* **376** 20170298
De Ruiter M C, De Bruijn J A, Englhardt J, Daniell J E, De Moel H and Ward P J 2021 The asynergies of structural disaster risk reduction measures: comparing floods and earthquakes *Earths Future* **9** e2020EF001531
Dessai S, Bhave A, Birch C, Conway D, Garcia-Carreras L, Gosling J P, Mittal N and Stainforth D 2018 Building narratives to characterise uncertainty in regional climate change through expert elicitation *Environ. Res. Lett.* **13** 074005
Estoque R C, Ooba M, Seposo X T, Togawa T, Hijioka Y, Takahashi K and Nakamura S 2020 Heat health risk assessment in Philippine cities using remotely sensed data and social-ecological indicators *Nat. Commun.* **11** 1581
Estoque R C, Ooba M, Togawa T, Yoshioka A, Gomi K, Nakamura S, Tsuji T, Hijioka Y, Watanabe M and Kitahashi M 2022 Climate impact chains for envisaging climate risks, vulnerabilities, and adaptation issues *Reg. Environ. Change* **22** 133
European Environment Agency 2024 *European Climate Risk Assessment* (Publications Office)
Field C B *et al* 2014 Technical summary climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*
Gallina V, Torresan S, Critto A, Sperotto A, Glade T and Marcomini A 2016 A review of multi-risk methodologies for natural hazards: consequences and challenges for a climate change impact assessment *J. Environ. Manage.* **168** 123–32
Gallina V, Torresan S, Zabeo A, Critto A, Glade T and Marcomini A 2020 A multi-risk methodology for the assessment of climate change impacts in coastal zones *Sustainability* **12** 3697
Golnaraghi M 2018 *Climate Change and the Insurance Industry: Taking Action as Risk Managers and Investors* (The Geneva Association)
Grossi P, Kunreuther H and Patel C C (eds) 2005 *Catastrophe Modeling: A New Approach to Managing Risk, Huebner International Series on Risk, Insurance, and Economic Security* (Springer Science+Business Media)
Haasnoot M, Biesbroek R, Lawrence J, Muccione V, Lempert R and Glavovic B 2020 Defining the solution space to accelerate climate change adaptation *Reg. Environ. Change* **20** 37
Harrington L J, Schleussner C-F and Otto F E L 2021 Quantifying uncertainty in aggregated climate change risk assessments *Nat. Commun.* **12** 7140
Harris K, Lager F, Jansen M K and Benzie M 2022 Rising to a new challenge: a protocol for case-study research on transboundary climate risk *Weather Clim. Soc.* **14** 755–68
Hawkins E and Sutton R 2009 The potential to narrow uncertainty in regional climate predictions *Bull. Am. Meteorol. Soc.* **90** 1095–108
Haynes P, Hehl-Lange S and Lange E 2018 Mobile augmented reality for flood visualisation *Environ. Model. Softw.* **109** 380–9
Herring J, VanDyke M S, Cummins R G and Melton F 2017 Communicating local climate risks online through an interactive data visualization *Environ. Commun.* **11** 90–105
Hochrainer-Stigler S *et al* 2023 Towards a framework for systemic multi-hazard and multi-risk assessment and management *iScience* **26** 106736
Hoffmann J, Bauer P, Sandu I, Wedi N, Geenen T and Thiemert D 2023 Destination Earth—A digital twin in support of climate services *Clim. Serv.* **30** 100394
Hurrell J, Meehl G A, Bader D, Delworth T L, Kirtman B and Wielicki B 2009 A unified modeling approach to climate system prediction *Bull. Am. Meteorol. Soc.* **90** 1819–32
IPCC 2007 Climate Change 2007: synthesis Report *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC)
IPCC 2014 Climate change 2014: synthesis report *Intergovernmental Panel on Climate Change*
IPCC 2021 Climate change 2021: the physical science basis *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* 1st edn (Cambridge University Press)
IPCC 2023a *Climate Change 2022—Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* 1st edn (Cambridge University Press) (https://doi.org/10.1017/9781009325844)
IPCC 2012 Managing the risks of extreme events and disasters to advance climate change adaptation (SREX) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* ed C B Field, V R Barros, T F Stocker, D Qin, D J Dokken, K L Ebi, M D Mastrandrea, K J Mach, G K Plattner, S K Allen, M Tignor and P M Midgley (Cambridge University Press) p 3–21
IPCC 2023b Climate change 2023: synthesis report *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* 1st edn, ed H Lee and J Romero (Core Writing Team) (Intergovernmental Panel on Climate Change (IPCC)) (https://doi.org/10.59327/IPCC/AR6-9789291691647)
Jack C D, Jones R, Burgin L and Daron J 2020 Climate risk narratives: an iterative reflective process for co-producing and integrating climate knowledge *Clim. Risk Manage.* **29** 100239
Jurgilevich A, Räsänen A, Groundstroem F and Juhola S 2017 A systematic review of dynamics in climate risk and vulnerability assessments *Environ. Res. Lett.* **12** 013002
Kaspersen P S and Halsnæs K 2017 Integrated climate change risk assessment: a practical application for urban flooding during extreme precipitation *Clim. Serv.* **6** 55–64
Klein R J, Midgley G F, Preston B L, Alam M, Berkhout F G, Dow K and Shaw M R 2014 Adaptation opportunities, constraints and limits *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed C B Field *et al* (Cambridge University Press) ch 16, pp 899–944
Klinke A and Renn O 2002 A new approach to risk evaluation and management: risk-based, precaution-based, and discourse-based strategies *Risk Anal.* **22** 1071–94
Kondrup C, Mercogliano P, Bosello F, Mysiak J, Scoccimarro E, Rizzo A, Ebrey R, de Ruiter M, Jeuken A and Watkiss P (eds) 2022 *Climate Adaptation Modelling, Springer Climate* (Springer International Publishing) (https://doi.org/10.1007/978-3-030-86211-4)
Kopp R E, Easterling D R, Hall T, Hayhoe K, Horton R, Kunkel K E and LeGrande A N 2017 Potential surprises: compound extremes and tipping elements *Climate Science Special Report: Fourth National Climate Assessment, Volume I* (U.S. Global Change Research Program) ch 15 (https://doi.org/10.7930/J0GB227J)
Kotchi S, Bouchard C, Ludwig A, Rees E and Brazeau S 2019 Using Earth observation images to inform risk assessment and mapping of climate change-related infectious diseases *Can. Commun. Dis. Rep.* **45** 133–42
Kropf C M, Ciullo A, Otth L, Meiler S, Rana A, Schmid E, McCaughey J W and Bresch D N 2022 Uncertainty and sensitivity analysis for probabilistic weather and climate-risk modelling: an implementation in CLIMADA v.3.1.0 *Geosci. Model Dev.* **15** 7177–201

Kunimitsu T, Baldissera Pacchetti M, Ciullo A, Sillmann J, Shepherd T G, Taner M Ü and Van Den Hurk B 2023 Representing storylines with causal networks to support decision making: framework and example *Clim. Risk Manage.* **40** 100496

Kwadijk J C J *et al* 2010 Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands *WIREs Clim. Change* **1** 729–40

Laino E and Iglesias G 2023 Extreme climate change hazards and impacts on European coastal cities: a review *Renew. Sustain. Energy Rev.* **184** 113587

Lam J S L and Lassa J A 2017 Risk assessment framework for exposure of cargo and ports to natural hazards and climate extremes *Maritime Policy Manage.* **44** 1–15

Lieske D J 2012 Towards a framework for designing spatial and non-spatial visualizations for communicating climate change risks *Geomatica* **66** 27–36

Lissner T K, Holsten A, Walther C and Kropp J P 2012 Towards sectoral and standardised vulnerability assessments: the example of heatwave impacts on human health *Clim. Change* **112** 687–708

Lückerath D, Rome E and Milde K 2023 Using impact chains for assessing local climate risk—A case study on impacts of extended periods of fluvial low waters and drought on a metropolitan region *Front. Clim.* **5** 1037117

Lung T, Lavalle C, Hiederer R, Dosio A and Bouwer L M 2013 A multi-hazard regional level impact assessment for Europe combining indicators of climatic and non-climatic change *Glob. Environ. Change* **23** 522–36

Lyubchich V, Newlands N K, Ghahari A, Mahdi T and Gel Y R 2019 Insurance risk assessment in the face of climate change: integrating data science and statistics *WIREs Comput. Stat.* **11** e1462

Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J and Shukla P R 2018 *Global Warming of 1.5 C: IPCC Special Report on Impacts of Global Warming of 1.5 C Above Pre-Industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (Cambridge University Press)

McDermott T K J and Surminski S 2018 How normative interpretations of climate risk assessment affect local decision-making: an exploratory study at the city scale in Cork, Ireland *Phil. Trans. R. Soc.* **376** 20170300

Mechler R, Bouwer L M, Linnerooth-Bayer J, Hochrainer-Stigler S, Aerts J C J H, Surminski S and Williges K 2014 Managing unnatural disaster risk from climate extremes *Nat. Clim. Change* **4** 235–7

Melo-Aguilar C, Agulles M and Jordà G 2022 Introducing uncertainties in composite indicators. The case of the impact chain risk assessment framework *Front. Clim.* **4** 1019888

Menk L, Terzi S, Zebisch M, Rome E, Lückerath D, Milde K and Kienberger S 2022 Climate change impact Chains: a review of applications, challenges, and opportunities for climate risk and vulnerability assessments *Weather Clim. Soc.* **14** 619–36

Middelanis R, Willner S N, Otto C, Kuhla K, Quante L and Levermann A 2021 Wave-like global economic ripple response to Hurricane Sandy *Environ. Res. Lett.* **16** 124049

Mosavi A, Ozturk P and Chau K 2018 Flood prediction using machine learning models: literature review *Water* **10** 1536

Nobanee H, Dilshad M N, Abu Lamdi O, Ballool B, Al Dhaheri S, AlMheiri N, Alyammahi A and Alhemeiri S S 2022 Insurance for climate change and environmental risk: a bibliometric review *Int. J. Clim. Change Strateg. Manage.* **14** 440–61

Nowell L S, Norris J M, White D E and Moules N J 2017 Thematic analysis: striving to meet the trustworthiness criteria *Int. J. Qual. Methods* **16** 160940691773384

O'Neill B C *et al* 2017 The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century *Glob. Environ. Change* **42** 169–80

O'Neill B *et al* 2022 Key risks across sectors and regions *Climate Change 2022 Impacts Adaptation and Vulnerability Contrib. Work. Group II Sixth Assessment Report Intergovernmental Panel on Climate Change* (https://doi.org/10.1017/9781009325844.025.2412)

OECD 2018 *National Risk Assessments: A Cross Country Perspective* (Organisation for Economic Co-operation and Development)

Onyango E A, Sahin O, Awiti A, Chu C and Mackey B 2016 An integrated risk and vulnerability assessment framework for climate change and malaria transmission in East Africa *Malar J.* **15** 551

Oppenheimer M, Campos M, Warren R, Birkman J, Luber G, O'Neill B and Takahashi K 2014 Emergent risks and key vulnerabilities *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed C B Field (Cambridge University Press) pp 1039–99

Parker L, Bourgoin C, Martinez-Valle A and Läderach P 2019 Vulnerability of the agricultural sector to climate change: the development of a pan-tropical climate risk vulnerability assessment to inform sub-national decision making *PLoS One* **14** e0213641

Peng W, Iyer G, Bosetti V, Chaturvedi V, Edmonds J, Fawcett A A, Hallegatte S, Victor D G, Van Vuuren D and Weyant J 2021 Climate policy models need to get real about people—here's how *Nature* **594** 174–6

Pirani A, Fuglestvedt J S, Byers E, O'Neill B, Riahi K, Lee J-Y, Marotzke J, Rose S K, Schaeffer R and Tebaldi C 2024 Scenarios in IPCC assessments: lessons from AR6 and opportunities for AR7 *npj Clim. Action* **3** 1

Pollard J A, Spencer T and Jude S 2018 Big Data approaches for coastal flood risk assessment and emergency response *WIREs Clim. Change* **9** e543

Porter J J and Clark C 2023 Usable, but unused: a critical story of co-producing the UK's climate change risk assessments *Environ. Sci. Policy* **139** 83–91

Ranasinghe R *et al* 2021 Climate change information for regional impact and for risk assessment *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) pp 1767–926

Reisinger A *et al* 2020 *The Concept of Risk in the IPCC Sixth Assessment Report: A Summary of Cross-Working Group Discussions: Guidance for IPCC Authors* (Intergovernmental Panel on Climate Change)

Rising J, Tedesco M, Piontek F and Stainforth D A 2022 The missing risks of climate change *Nature* **610** 643–51

Ronco P, Zennaro F, Torresan S, Critto A, Santini M, Trabucco A, Zollo A L, Galluccio G and Marcomini A 2017 A risk assessment framework for irrigated agriculture under climate change *Adv. Water Resour.* **110** 562–78

Ruane A C *et al* 2022 The climatic impact-driver framework for assessment of risk-relevant climate information *Earths Future* **10** e2022EF002803

Shepherd T G *et al* 2018 Storylines: an alternative approach to representing uncertainty in physical aspects of climate change *Clim. Change* **151** 555–71

Shepherd T G 2019 Storyline approach to the construction of regional climate change information *Proc. R. Soc.* **475** 20190013

Shortridge J E and Zaitchik B F 2018 Characterizing climate change risks by linking robust decision frameworks and uncertain probabilistic projections *Clim. Change* **151** 525–39

Sillmann J, Shepherd T G, van den Hurk B, Hazeleger W, Martius O, Slingo J and Zscheischler J 2021 Event-based storylines to address climate risk *Earths Future* **9** e2020EF001783

Simpson N P *et al* 2021 A framework for complex climate change risk assessment *One Earth* **4** 489–501

Street R, Alterio I, Hewitt C, Golding N, New S and Mysiak J 2022 Enabling climate action: messages from ECCA2021 calling

for re-imagining the provision and use of knowledge and information *Clim. Risk Manage.* **36** 100428
Sutanto S J, Vitolo C, Di Napoli C, D'Andrea M and Van Lanen H A J 2020 Heatwaves, droughts, and fires: exploring compound and cascading dry hazards at the pan-European scale *Environ. Int.* **134** 105276
Tanaka T, Kawase H, Imada Y, Kawai Y and Watanabe S 2023 Risk-based versus storyline approaches for global warming impact assessment on basin-averaged extreme rainfall: a case study for Typhoon Hagibis in eastern Japan *Environ. Res. Lett.* **18** 054010
Terzi S, Torresan S, Schneiderbauer S, Critto A, Zebisch M and Marcomini A 2019 Multi-risk assessment in mountain regions: a review of modelling approaches for climate change adaptation *J. Environ. Manage.* **232** 759–71
Thiery W *et al* 2021 Intergenerational inequities in exposure to climate extremes *Science* **374** 158–60
Thompson J 2022 A guide to abductive thematic analysis *Qual. Rep.* **27** 1410–21
Tilloy A, Malamud B D, Winter H and Joly-Laugel A 2019 A review of quantification methodologies for multi-hazard interrelationships *Earth-Sci. Rev.* **196** 102881
Torresan S, Critto A, Rizzi J, Zabeo A, Furlan E and Marcomini A 2016 DESYCO: a decision support system for the regional risk assessment of climate change impacts in coastal zones *Ocean Coast Manage.* **120** 49–63
Tsatsaris A, Kalogeropoulos K, Stathopoulos N, Louka P, Tsanakas K, Tsesmelis D E, Krassanakis V, Petropoulos G P, Pappas V and Chalkias C 2021 Geoinformation technologies in support of environmental hazards monitoring under climate change: an extensive review *ISPRS Int. J. Geo-Inf.* **10** 94
UNDRR, ISC 2020 *Hazard Definition and Classification Review: A Technical Report*
UNDRR 2022 *Technical Guidance on Comprehensive Risk Assessment and Planning in the Context of Climate Change*
United Nations General Assembly 2016 *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction. Note by the Secretary-General* Document No. A/71/644 (United Nations General Assembly) (available at: https://docs.un.org/en/A/71/644)
van den Hurk B *et al* 2023a Climate impact storylines for assessing socio-economic responses to remote events *Clim. Risk Manage.* **40** 100500
van den Hurk B, White C J, Ramos A M, Ward P J, Martius O, Olbert I, Roscoe K, Goulart H M D and Zscheischler J 2023b Consideration of compound drivers and impacts in the disaster risk reduction cycle *iScience* **26** 106030
van der Sluijs J P 2012 Uncertainty and dissent in climate risk assessment: a post-normal perspective *Nat. Cult.* **7** 174–95
Van Gevelt T, McAdoo B G, Yang J, Li L, Williamson F, Scollay A, Lam A, Chan K N and Switzer A D 2023 Using virtual simulations of future extreme weather events to communicate climate change risk *PLOS Clim.* **2** e0000112
Vanem E 2015 Non-stationary extreme value models to account for trends and shifts in the extreme wave climate due to climate change *Appl. Ocean Res.* **52** 201–11
Walenta J 2020 Climate risk assessments and science-based targets: a review of emerging private sector climate action tools *WIREs Clim. Change* **11** e628
Wang C, Hou J, Miller D, Brown I and Jiang Y 2019 Flood risk management in sponge cities: the role of integrated simulation and 3D visualization *Int. J. Disaster Risk Reduct.* **39** 101139
Ward P J *et al* 2022 Invited perspectives: a research agenda towards disaster risk management pathways in multi-(hazard-)risk assessment *Nat. Hazards Earth Syst. Sci.* **22** 1487–97
Warren R F, Wilby R L, Brown K, Watkiss P, Betts R A, Murphy J M and Lowe J A 2018 Advancing national climate change risk assessment to deliver national adaptation plans *Phil. Trans. R. Soc.* **376** 20170295
Watkiss P and Betts R 2021 Method *The Third UK Climate Change Risk Assessment Technical Report*
Yokohata T *et al* 2019 Visualizing the interconnections among climate risks *Earths Future* **7** 85–100
Young H R, Shepherd T G, Acidri J, Cornforth R J, Petty C, Seaman J and Todman L C 2021 Storylines for decision-making: climate and food security in Namibia *Clim. Dev.* **13** 515–28
Zebisch M, Schneiderbauer S, Fritzsche K, Bubeck P, Kienberger S, Kahlenborn W, Schwan S and Below T 2021 The vulnerability sourcebook and climate impact chains—a standardised framework for a climate vulnerability and risk assessment *Int. J. Clim. Change Strateg. Manage.* **13** 35–59
Zebisch M, Terzi S, Pittore M, Renner K and Schneiderbauer S 2022 Climate impact chains—A conceptual modelling approach for climate risk assessment in the context of adaptation planning *Climate Adaptation Modelling* ed C Kondrup, P Mercogliano, F Bosello, J Mysiak, E Scoccimarro, A Rizzo, R Ebrey, M de Ruiter, A Jeuken and P Watkiss (Springer International Publishing) pp 217–24
Zennaro F, Furlan E, Simeoni C, Torresan S, Aslan S, Critto A and Marcomini A 2021 Exploring machine learning potential for climate change risk assessment *Earth-Sci. Rev.* **220** 103752
Zommers Z *et al* 2020 Burning embers: towards more transparent and robust climate-change risk assessments *Nat. Rev. Earth Environ.* **1** 516–29
Zscheischler J *et al* 2018 Future climate risk from compound events *Nat. Clim. Change* **8** 469–77