CLIMAAX
climate ready regions

# Deliverable D1.4 – Climate risk assessment framework

## WP1 – Framework for local and regional climate risk assessment

Grant Agreement 101093864

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HORIZON-MISS-2021-CLIMA-02-01 - Development of climate change risk assessments in European regions and communities based on a transparent and harmonised Climate Risk Assessment approach



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# Document Information

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| Brief Description | The Climate Risk Assessment Framework developed in WP1 is a central component of the CLIMAAX project. The Framework contextualizes the output of the risk workflows and thus supports and guides applicants through their Climate Risk Assessment journey. The deliverable also outlines a possible connection to Climate Risk Management to streamline efforts contributing to the EU Mission Adaptation and resilience building. |
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# Abbreviations and acronyms

| Abbreviation / acronym | Description |
|---|---|
| AR e.g. AR6 | Assessment Report from the IPCC, e.g. Assessment Report 6 |
| CRA | Climate Risk Assessment |
| CoP | Community of Practice |
| CRM | Climate Risk Management |
| EEA | European Environmental Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| NUTS | Nomenclature of Territorial Units for Statistics |
| P2R | Pathways2Resilience; an EU Horizon Project on building climate resilience for regions |
| RCP | Representative Concentration Pathways |
| SSP | Share Socioeconomic Pathways |
| UCPM | Union Civil Protection Mechanism |
| UK | United Kingdom |



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# Executive Summary

With climate change increasingly affecting people, assets and the environment, it is important for Climate Risk Assessments (CRA) to progress in understanding the scope and scale of climate risks to plan and implement adaptation and Climate Risk Management (CRM) responses.

In the context of the EU Horizon 2020 project CLIMAAX, we have developed an inclusive and harmonized CRA framework adapted for the European regional and local level to ensure comparability and quality adherence. The Framework aligns with state-of-the-art methodologies and is further complemented by risk workflows tailored for risk quantification across European regions, thus forming the CLIMAAX Handbook. Our approach integrates insights from Union Civil Protection Mechanism (UCPM) documents, European National Adaptation Plans and Strategies, peer-reviewed literature, as well as existing CRA frameworks and international standards to respond to needs, recent advancements and best practices in the CRA field. The framework was collaboratively developed with five European pilot regions and reflects on a survey from the CLIMAAX Community of Practice (CoP; see CLIMAAX Deliverable 1.3[1]) to ensure feasibility and applicability while pursuing adaptive flexibility.

The practical need of the CRA Framework led to a five-step assessment cycle (*Scoping*, *Risk Exploration, Risk Analysis*, *Key Risk Assessment*, *Monitoring & Evaluation*), underpinned by a conceptual context addressing *principles* (most importantly social justice, equity and just resilience), *technical choices* (e.g., future scenarios), and *participatory processes* (learning, communication, consultation), which lie at the very centre of the framework. In the Risk Analysis step the Framework is strongly supported by multiple risk workflows which estimate climate risk. Finally, the ultimate goal of the Framework is to contextualise the Risk Analysis outcome and provide relevant information that can be harnessed for CRM which may be relevant to the CRA cycle itself. Therefore, the next step is to further use climate risk estimations to develop management and adaptation strategies. Regions and communities that want to improve their climate resilience are encouraged to connect with the CLIMAAX sister project Pathways2Resilience (P2R), which focuses on resilience building and strategy design based on CRA and thus moves forward with the CLIMAAX vision.

[1] https://www.climaax.eu/public-deliverables/



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# 1 Introduction

Understanding and managing climate risks is crucial for safeguarding current and future development and well-being. Climate Risk Assessments (CRAs) play a pivotal role in this process, serving as a key tool for identifying people, areas, sectors, and communities that are vulnerable to ongoing and future climate change impacts. CRAs help guide decision-makers in addressing the most pressing risks — those with the most potential for significant, severe, and adverse outcomes. By doing so, CRA supports local and regional development planning with strategies and policies that account for future climate scenarios and highlight needs, gaps, and limitations in current Climate Risk Management (CRM) practices.

A CRA aims to identify risks as well as underlying risks drivers emerging from climate change. As climate-related risks result from the interplay of hazard, vulnerability, exposure (and response) (Ara Begum *et al.*, 2022), it is crucial to understand risk beyond the physical properties of weather phenomena in order to prioritize needs and perspectives of communities and groups that are disproportionately affected by climate-related risk.

Despite the progress at national levels, there is a pressing need for more localized CRAs across Europe. The local and regional level poses unique challenges but also opportunities. The risks faced by regions and communities can differ significantly from national CRAs due to a variety of context-specific factors, such as geography, infrastructure, demographics, socioeconomic dynamics, environmental features or specific, more localized knowledge available. Regional and local CRAs can offer a nuanced understanding of these climate risks by tailoring the assessment to the unique social, economic, environmental, and political landscapes of each area. Detailed insights and better information on localized climate risks and their components (hazard, exposure, and vulnerability) enhance decision-making and empower regional and local governments to act decisively.

### Objectives of a CRA

Understand (key) risks as well as underlying risks drivers emerging from climate change.

Identify specific areas, populations, and systems most at risk from current and future climate variability and change.

Prioritize the needs and perspectives of the groups disproportionately affected by current and future climate-related risks (under the principles of Social Justice and Equity).

Prepare the ground for effective CRM by identifying entry points for adaptation and resilience planning.

CLIMAAX is part of the EU Mission Adaptation, which aims at supporting European regions, cities and local authorities to build resilience against climate change. The project takes up the Mission's first specific objective "Preparing and planning for climate resilience" by providing a flexible and state-of-the-art CRA Framework adapted for regions and local communities. Assessing climate-related risk is crucial for local and regional resilience building as it allows for



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an estimation of where CRM is needed. Moreover, regional and local CRAs facilitate the participation of local stakeholders and leverage local knowledge (e.g. environmental conditions, historical climate patterns, and previous experiences) to produce more accurate, comprehensive and relevant outcomes. Here, the CLIMAAX project goes hand in hand with its sister project, Pathways2Resilience (P2R) which includes or builds on Climate Risk Assessments for regional resilience journeys and thus targets the second specific objective “Accelerating transformations to climate resilience” from the EU Mission Adaptation (European Commission, 2021).

The CLIMAAX Framework builds on state-of-the-art knowledge, bottom-up consensus of best practice and recommended approaches to establish an inclusive, harmonized, and shared framework for CRA. This was influenced by Deliverable 1.2 *Desk review of existing CRA frameworks* as well as Task 1.1 with inputs from the community of practice collected through a dedicated survey. Existing risk conceptualisations and CRA frameworks usually agree on core steps (scoping, risk analysis, risk identification/exploration) and often show cyclical as well as iterative approaches. Beyond the analytical steps, it is of crucial importance to consider social perspectives of climate risk, such as social equity and just resilience. Also, vulnerable, marginalised groups of society are often disproportionately affected by climate risks (EEA, 2022; Schinko *et al.*, 2023). These factors should be included and harnessed, e.g., through participatory processes. Therefore, considering these aspects together with the immediate possibility of quantifying climate risk through the risk workflows provided in the CLIMAAX Handbook makes it necessary to embed the risk outcome in a broader context to guarantee a holistic, high-quality CRA that can lead to efficient CRM.

The structure of our proposed CRA Framework aims at targeting these aspects, adapted for a regional to local level, while focusing on proven steps, thus ideally bringing together qualitative and quantitative input. The first layer of the CLIMAAX Framework is the conceptual background (principles, technical choices, and participatory processes), which takes up conceptual, social, but also technical aspects of an encompassing CRA. The second layer adds five operational framework steps to the structure which consist of *Scoping*, *Risk Exploration*, *Risk Analysis*, *Key Risk Assessment,* and *Monitoring & Evaluation*. The CLIMAAX Framework is built around the risk workflows to guide, support and contextualise risk calculated in the Risk Analysis step. Evaluating these risks also bridges the gap between assessment of climate risks and effective CRM and thus makes the CLIMAAX CRA Framework a key element for informing decision-makers in their journey of building resilience.

This deliverable provides a short overview of existing CRAs and conceptualisations that have influenced the CLIMAAX CRA Framework (Chapter 2). It then dives into relevant definitions and the conceptual background (3.1; 3.2), explaining pertinent principles, technical choices and describing the central role of participatory processes that are needed for an inclusive CRA (Chapter 3). Section 3.3 then focuses on the five operational framework steps and outlines the logic behind the risk workflows in the *Risk Analysis* step (3.3.3). Chapter 4 sketches how results



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from the CRA can interplay with CRM efforts and how they feed back into the CRA Framework. The deliverable concludes with a summary and an annex that provides more detailed information on technical choices (future scenarios, downscaling, global warming levels, low-likelihood high-impact outcomes) as well as guiding questions for each section.

# 2 Examples of existing CRA Frameworks

To guarantee a standardized, yet flexible, state-of-the-art CRA, the CLIMAAX Deliverable 1.2 was substantially dedicated to identifying existing CRA frameworks. It has done so by delving into current climate risk conceptualization, considering a substantial amount of peer-reviewed and grey literature.

Several existing CRAs have contributed to the development of the CLIMAAX CRA Framework. While the ISO standards for Climate Risk Assessment and Management (ISO, 2018, 2020, 2021; see CLIMAAX Deliverable 1.2[2]) provided a firm foundation, the IPCC risk conceptualization of the sixth Assessment Report (AR6; Ara Begum *et al.*, 2023) with climate risk as an interplay of hazard, exposure, vulnerability and response, constitutes the central conceptual pillar of the CLIMAAX Framework (Figure 1e). Further, the six-step methodology for CRA (Figure 1a) (Mechler *et al.*, 2021), the CRA framework presented in the GIZ Climate Risk Sourcebook (Figure 1b) (Zebisch *et al.*, 2023), the Myriad framework for systemic multi-hazard and multi-risk assessment (Figure 1c) (Hochrainer-Stigler *et al.*, 2023) and the Technical Guidance on comprehensive risk assessment (Figure 1d) (UNDRR, 2022) provided substantial input that enriched the understanding and implementation of robust risk management strategies within the CLIMAAX Framework (Figure 1). The CLIMAAX Framework also benefitted from good practices that were included throughout the developing process, such as the climate change risk assessment from the United Kingdom (UK Government, 2022), where risk evaluation in context of its urgency played a key role.

[2] https://www.climaax.eu/public-deliverables/



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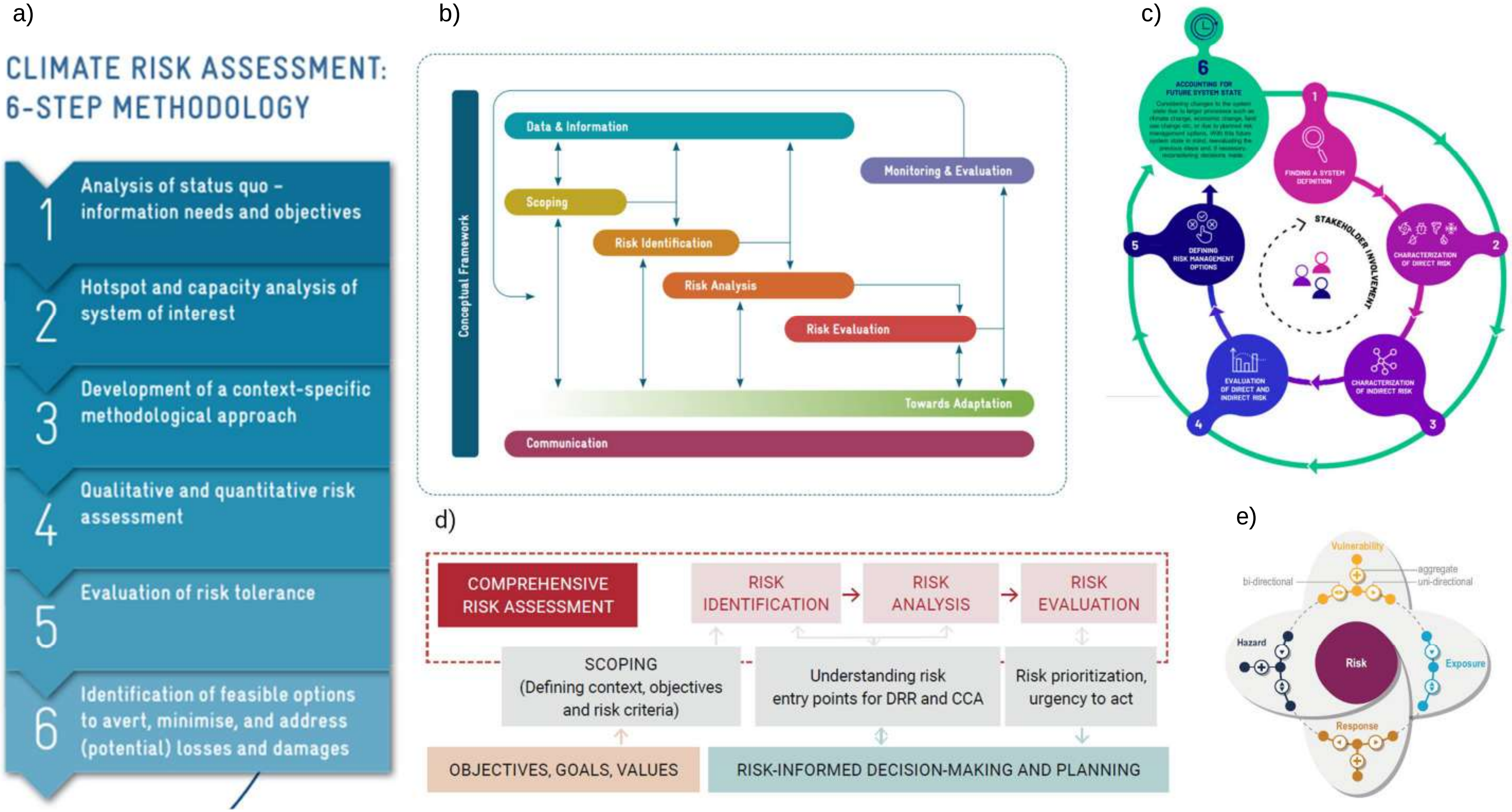


Figure 1. Climate Risk Assessment Frameworks and conceptualizations that informed the CLIMAAX Framework. a) 6-step methodology for climate risk assessment (Mechler et al., 2021); b) Climate Risk Assessment Framework from the GIZ Climate Risk Sourcebook (Zebisch et al., 2023); c) Myriad Framework (Hochrainer-Stigler et al., 2023); d) Technical Guidance on comprehensive Risk Assessment (UNDRR, 2022); e) conceptualization of climate-related risk according to IPCC AR6 (Ara Begum et al., 2023).

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# 3 CLIMAAX Climate Risk Assessment Framework

Considering state-of-the-art knowledge, relevant concepts and existing CRA frameworks, the CLIMAAX CRA Framework has been developed as an inclusive, up-to-date, and standardised yet flexible approach designed to enhance the regional and local assessment of climate risks. The Framework consists of a five-step process (see Figure 2) — *Scoping*, *Risk Exploration*, *Risk Analysis*, *Key Risk Assessment* and *Monitoring and Evaluation.* The CLIMAAX Framework provides systematic guidance on the sound preparation and implementation of CRA as well as its links to CRM, being accompanied by a comprehensive set of guiding questions and risk workflows as part of the CLIMAAX Handbook. While the Framework covers various aspects, including technical choices, stakeholder engagement, risk prioritization, sense-making, and active learning for future CRA iterations, the risk workflows, on the other hand, are designed to quantitatively assess climate risks. These risks may arise from multiple hazards such as floods, droughts, extreme heat, wildfires, and windstorms and may be assessed through easy-to-follow to more advanced risk workflows (see definitions in section 3.1 and section 3.3.3 for application). State-of-the-art methodologies, global and European level datasets, and a user-friendly interface support the workflows. This makes the Framework and risk workflows, uniting in the online CLIMAAX Handbook, a versatile, comprehensive, and dynamic resource with practical value for a wide range of potential users at the local level.

Subsequent sections delve deeper into the CLIMAAX Framework, detailing its conceptual foundations (Section 3.2) and operational steps (Section 3.3). These sections describe each step of the Framework and lead through climate risk quantification by connecting to the risk workflows provided in the Risk Analysis step. With the Framework, the CLIMAAX consortium aims to encourage European regions and communities to undertake comprehensive local CRAs and to empower relevant local decision-makers and stakeholders to assume ownership and act upon their climate risks. Support for implementing the CRA output and moving towards CRM is outlined in Chapter 4 and will be further provided through linking to the Pathways2Resilience project[3] funded by the European Mission on Adaptation.

[3] https://www.pathways2resilience.eu/



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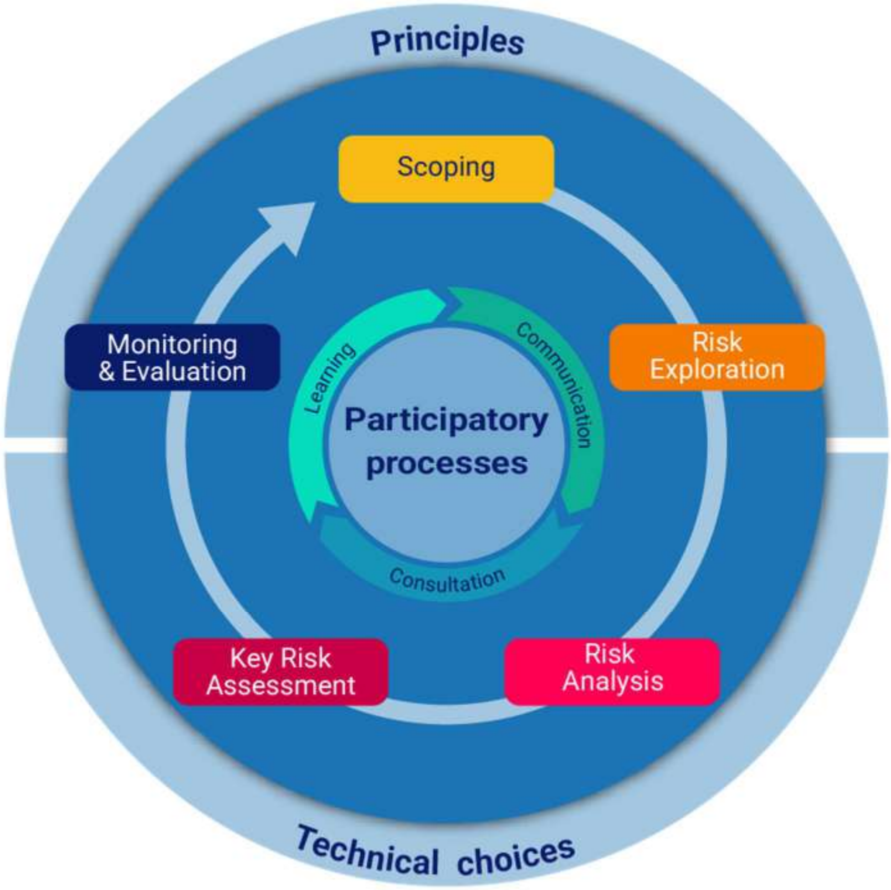


*Figure 2. The CLIMAAX Framework for Climate Risk Assessment. The three pillars' Principles, Technical Choices and Participatory Processes form the conceptual background and foster the five operational Framework steps Scoping, Risk Exploration, Risk Analysis (risk workflows), Key Risk Assessment and Monitoring & Evaluation. Credit: CLIMAAX Consortium.*



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## 3.1 Before you start

### Definition of terms for a common understanding of risk

Risk is defined as "[t]he potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems." (Reisinger *et al.*, 2020, p. 4). It can be calculated as an interplay of climate hazards (e.g. frequency and intensity of droughts), exposure (e.g. a land area where agriculture is conducted) and vulnerability (e.g. presence or absence of irrigation) and also includes human responses (Ara Begum *et al.*, 2022).

A climate-related Hazard is "the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resource" (IPCC, 2022, p. 5) such as floods, droughts, heatwaves, and other extreme weather events that may have a sudden or slow onset. Climate change can alter the frequency, magnitude, and duration of extreme weather events which are especially relevant for a climate risk context.

Vulnerability is defined as " the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt."(IPCC, 2022, p. 5). It further includes "all relevant environmental, physical, technical, social, cultural, economic, institutional, or policy-related factors that contribute to susceptibility and/or lack of capacity to prepare, prevent, respond, cope or adapt" (UNDRR, 2022, p. 19). The Climate Risk Sourcebook (Zebisch *et al.*, 2023, p. 19) defines the reduction of vulnerability as "one of the biggest levers" for climate risk management.

Exposure refers to "(t)he 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, p. 1048).

Response
In addition to hazard, exposure and vulnerability, climate risk also depends on how a society adapts to climate events. Adaptation responses (also called climate risk management interventions or options) may entail planned adaptation (physical constructions, nature-based solutions, planned relocation) or autonomous adaptation (behavioural changes or forced migration).

### Stakeholders, Experts, Priority Groups, Users

Stakeholders from policy (e.g. ministries, agencies, government and state offices, agencies) relevant public and private sectors.

Experts are scientists, practitioners, or policy advisors with robust knowledge (e.g. universities, institutes, climate, and meteorological services).

Priority groups: Representatives from vulnerable or marginalized groups, exposed areas, or other relevant communities in society.

Users are directly related to the (technical) use of the CLIMAAX Climate Risk Assessment Framework and risk workflows.



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## Supporting Definitions

Adaptation is "(…) the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities" (IPCC, 2023).

Climate Risk Management (CRM) includes plans, actions, strategies or policies that "reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risk" (IPCC, 2023, p. 2921). CRM has the goal of reaching resilience and adaptation.

Risk Outcome is the quantitative result(s) of the Risk Workflow(s) as part of Risk Analysis and feeds into the Key Risk Assessment for their contextualisation and evaluation.

Workflow refers to the application of Risk Analysis step through the CLIMAAX Handbook which quantifies climate risk according to the six climate-related hazards: floods, drought, wildfire, heatwaves, wind and snow. Workflows are coded in Python and can be modified by users and adapted to use local data.

Further supporting definitions will be continuously added to the CLIMAAX Handbook[4] page according to the need of (pilot) regions and applicant communities.

[4] https://handbook.climaax.eu/intro.html



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## 3.2 Conceptual Background

A CRA needs to stand on solid ground, targeting and enabling success factors, while simultaneously providing operational steps for practical implementation. The conceptual background of the CLIMAAX Framework is organized around a three-pronged design:

1. Principles – a collection of principles, norms, and recommended practices that forms a grassroot, community-based standard on how climate risk assessment can facilitate transformative adaptation.[5]
2. Technical choices – clear technical specification of considerations needed for conducting a CRA such as selection of scenarios, use and selection of local data, timeframe, spatial scale.
3. Participatory processes – approaches for implementing an inclusive CRA which support local and regional communities in identifying shared goals and priorities for coordinated CRM efforts.

### 3.2.1 Principles

Adhering to key principles throughout a CRA process helps ensure a common background and provide context for the operational framework steps. Special emphasis of principles is given at the beginning and ending of a CRA cycle. This section describes key principles being central to a comprehensive CRA approach (UNDRR, 2021) that is fair, robust, and prudent. The implementation of these principles requires a robust and open multi-stakeholder process, support of local officials, planners and stakeholders in climate action planning (e.g. UN Habitat, 2015) and thus is strongly connected to participatory processes.

Social justice, equity and inclusivity – Both, impacts and responses to climate change, affect people and communities in different ways. Many groups in society are particularly vulnerable to climate risks or unequally profit from risk mitigation actions. Age, health conditions, gender, the socioeconomic status (income, living conditions, education), ethnicity as well as social networks may particularly affect the individual climate vulnerability and climate risk situation (EEA, 2022), e.g., when a hazard strikes. For example, migrant communities, communities in low-income neighbourhoods, poor and elderly people, disabled, and women are disproportionally affected by climate impacts and disasters may further worsen preexisting inequalities (Breil *et al.*, 2021). A comprehensive treatment of social justice is needed in a CRA to address distributional,

[5] Transformative Adaptation stands in contrast to incremental adaptation and is defined as "adapting to climate change resulting in significant changes in structure or function that go beyond adjusting existing practices including approaches that enable new ways of decision making on adaptation" (IPCC, 2022, p. 164). In its specific objective 2 the EU Mission Adaptation (European Commission, 2021) aims at accelerating transformative adaptation, resilience and solutions.



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procedural and restorative aspects (Schinko *et al.* 2023). The concept of just resilience aims at targeting the particular needs of vulnerable and marginalised groups and "leaving no one behind". This includes a broader understanding of underlying social drivers of climate risk as well as its distributional aspects of costs and benefits. The IPCC describes three aspects of climate justice: procedural justice, distributive justice, and recognition (Ara Begum *et al.*, 2022). The interpretation of justice and fairness depends on a common agreement on what a society perceives as just" (Breil et al., 2021, p. 16) which puts emphasis on the need for inclusiveness and participation throughout the CRA process.

**Social Justice**

The Climate-ADAPT platform established by the European Environment Agency (EEA) has gathered, among other, information, guidance, tools and case studies about just resilience as part of key EU actions in EU's adaptation policy (link). Most recently, an EEA report on urban adaptation in Europe dedicated one chapter to just resilience, including guidance on how to put it into practice. You can find the report here.

Quality, rigour, and transparency – Throughout a CRA, quality, rigour and transparency need to be ensured as it is important to guarantee applicability, comparability, validation, and the possibility of standardisation. The CLIMAAX Framework and workflows, uniting in the CLIMAAX Handbook, provide state-of-the-art guidelines and practices, which are supported by scientific findings, international standards, and pilot region applications. Assuming ownership of the CRA process, its individual steps and the risk outcome supports a rigorous and transparent CRA. Further, using local and regional data and (climate) services or connecting with local and regional data hubs and data spaces may increase transparency.

Precautionary approach – A CRA is always confronted with uncertainties, complexities and changing conditions. Flexibility in the CLIMAAX Framework and various mechanisms in the risk workflows aim at minimising such impacts. However, CRAs are a multifactorial process where variables, such as societal values, may change over time; where evidence or confidence is restricted, the process benefits from a precautionary approach instead of inaction. This involves considerations in the *Scoping* step (e.g., which stakeholder or priority groups to consult and include) or regards the risk evaluation process in the *Key Risk Assessment* step.

### 3.2.2 Technical Choices

The second pillar of the CLIMAAX Framework consists of sound technical choices. These are a crucial part of a CRA and encompass considerations of relevant scenarios, time periods, climate datasets (observations, reanalyses, models)Error! Reference source not found. and the extent



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of local data integration. Since the Climate Risk Analysis requires technical choices in the risk workflows, this section focuses on providing more context on these elements.

Technical choices should reflect the information needs of context-specific applications. Exploring these would benefit from collaboration with local climate change experts. It is recommended to build on the latest IPCC assessment (IPCC, 2022), which comprehensively delves into regional climate at the European and sub-regional scales, as well as the first European Risk Assessment (European Environment Agency, 2024). Factsheets are available that summarise the IPCC assessment of European regional climate information[6] and climate impacts and risk[7].

### Climate change scenarios

Future climate and socioeconomic conditions, their complexities and their implications in the context of CRA need to be further understood and explored for the development of CRM strategies that are effective and build long term resilience. Future climate change is typically explored through climate models driven by different emissions scenarios of greenhouse gas emissions, pollutants, and emissions related to land use that are based on projections of future socioeconomic trends, including population, economic and technological development, energy use, and other factors. While they are not predictions of the future, but instead referred to as projections, scenarios can be used in a CRA as a valuable tool to understand how hazards and socioeconomic conditions may change in the future.

Two main approaches are currently widely used with climate models to explore future climate. These are the Representative Concentration Pathways (RCPs; van Vuuren *et al.*, 2011), linking present and future greenhouse gas concentrations, and Shared Socioeconomic Pathways[8] (SSP's; Kriegler *et al.*, 2014), developed around narratives of plausible trends of socioeconomic futures in the 21st century (country-level socioeconomic data that is used in SSPs can be explored in the SSP Extensions Explorer[9]). Choosing between SSPs and RCPs can lead to different CRA outcomes and associated policy considerations. Scenarios can be used to analyse climate risks within various socioeconomic futures, considering factors like population growth and technological advancement without specifying climate outcomes. Climate risks vary within each scenario group, and hence, their policy implications. For instance, SSP1 – "Taking the Green Road" emphasizes sustainability with high investment in green technologies and low population growth and thus predicts a lower level of risk in comparison to SSP3— "A Rocky

[6] https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC_AR6_WGI_Regional_Fact_Sheet_Europe.pdf
[7] https://www.ipcc.ch/report/ar6/wg2/downloads/outreach/IPCC_AR6_WGII_FactSheet_Europe.pdf
[8] The narratives of the SSP framework are broadly characterised as representing 'sustainability' (SSP1), a 'middle-of-the-road' path (SSP2), 'regional rivalry' (SSP3), 'inequality' (SSP4), and 'fossil fuel-intensive' (SSP5) development (O'Neill et al., 2017).
[9] https://ssp-extensions.apps.ece.iiasa.ac.at/



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Road", characterized by regional rivalry, low technological investment, high population growth with higher vulnerability and regional disparities in future climate conditions.

Coupled SSP-RCP scenarios that are used to drive climate models span a broad plausible range of future drivers of climate change, for example *very low* or *low greenhouse gas emissions* (SSP1-RCP1.9 and SSP1-RCP2.6, respectively) under the assumption of accelerated and effective climate policy implementation, to *intermediate emissions* (e.g., SSP2-RCP4.5), or to *very high emissions scenarios* in the absence of additional climate policies (SSP3-RCP7.0 or SSP5-RCP8.5)[10]. Considering a range of scenarios allows for the exploration of 'scenario uncertainty' in the projected climate outcomes.

The EUCRA report (European Environment Agency, 2024) selected two 'cornerstone' scenarios that can be compared given their divergent trends in climatic and socio-economic outcomes. It describes a Paris-compliant emission trajectory combined with modest challenges to adaptation (further referred to as the 'Warming to the Challenge scenario'), and a Paris non-compliant trajectory combined with high challenges to adaptation (further referred to as the 'Struggling in the Heat' scenario).

### Take home message

High or very high-end emissions scenarios can be explored to assess future risk. Given current policies, very high-end emissions scenarios have become less likely but cannot be ruled out. Warming levels >4°C may result from very high emissions scenarios but can also occur from lower emission scenarios if climate sensitivity or carbon cycle feedback are higher than the best estimate.

Comparison of projected changes (anomalies) to pre-industrial, historical conditions, or a low-end emissions scenario can be helpful as a baseline to assess current and future conditions.

High-end emissions scenarios are useful to explore high risk outcomes. Comparison with more moderate risk outcomes, and the related implications for adaptation strategies, expected from low-end emissions scenarios may also be beneficial.

[10] The scenarios are labeled SSPx-y, where 'SSPx' refers to the Shared Socio-economic Pathway or 'SSP' describing the socio-economic trends underlying the scenario, and 'y' refers to the approximate level of radiative forcing (in watts per square metre, or W $m^{-2}$) resulting from the scenario in the year 2100.



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### Climate models

Different climate models – global and regional – are used in climate modelling studies, including international modelling intercomparison projects, the most prevalent of which are the Coupled Climate Model Intercomparison Project – CMIP and the Coordinated Regional Downscaling Experiment – CORDEX, both coordinated by the World Climate Research Programme. Climate models are mathematical representations of the physical and biogeochemical processes and interactions that make up the Earth's climate. Results from modelling studies allow for the exploration of 'model uncertainty', in other words, how well models represent climate change by comparing multiple simulations of the same model (model ensemble) or multiple models (multi-model ensemble / intercomparison). Internal variability is another type of uncertainty of the climate system that affects regional climate, particularly on timescales of years to decades and need to be considered to understanding changes in climate conditions. To explore this source of uncertainty, each model is run multiple times to generate an ensemble forced by the same scenario.

#### Take home message

Model projections are used to explore what-if scenarios of future climate based on different socioeconomic futures. Each model projection is a possible outcome, but not a prediction.

- Covering multiple scenarios to explore possible future regional climate and to assess the robustness of adaptation options in future scenarios can be a beneficial approach.
- The average of the climate model outputs can be considered a best estimate, while the spread indicates the uncertainty.

### Global warming levels

How hazards change with increasing global warming levels can be an effective means of communication of climate change and risk since many stakeholders are familiar with a reference to global warming, particularly given the framing in the Paris Agreement. Many climatic changes at global and regional scales are directly related to increasing temperatures, becoming larger with every increment of global warming. A widely used example is the IPCC risk assessment (Smith *et al.*, 2009) that is synthesised by level of surface warming, as illustrated in the burning ember diagram (Zommers *et al.*, 2020).

Regional characteristics and patterns that are consistent with a level of global warming include climate extremes, such as extreme temperatures and heavy precipitation, and, in some regions, agricultural and ecological droughts. Increases in the proportion of intense tropical cyclones; and reductions in Arctic Sea ice, snow cover and permafrost with increasing temperatures have been identified for many regions (IPCC, 2021).

The consistency of patterns of change with increasing global warming tends to be higher for temperature-related variables than for variables in the hydrological cycle or variables



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characterizing atmospheric dynamics and for intermediate to high-end emissions scenarios than for low-end emissions scenarios.

These patterns can be explored using data from climate model projections, irrespective of scenario of whether the level of global warming is reached earlier or later in model runs. Assessing whether indices or variables are suited to be integrated in terms of global warming levels first requires analysis of scenario-based projections. This approach may not always be suitable, for example for changes in precipitation patterns, local effects related to aerosols or land use patterns can be important. This also applies for sea level rise that is affected by the rate of warming and time-integrated warming rather than warming at a given time, and so is related to other processes whereas their evolution is scenario-dependent (Hermans *et al.*, 2021).

**Take home message**

For near-term decisions, it is important to assess the uncertainties of the model projections, while the choice of which scenario is used is less important. From the mid-century onwards (for mid- to long-term decisions), assessing the implications of which scenario is used becomes more important.

### Choice of time horizon

Scenario-based information can be analysed relative to different time horizons, or time slices, in addition to considering a continuous (transient) time series over the course of this century or even following centuries. A time horizon over the next years and decade may be more relevant for assessing immediate risks, while a longer time horizon that extends to later in the century is necessary for assessing longer-term trends. In the latest IPCC report, 2021-2040 is referred to as near term, 2041-2060 as mid-term, and 2081-2100 as long term, relative to 1850–1900, which is used as a proxy for the pre-industrial period (IPCC, 2021).

**Take home message**

Current conditions, including yearly variations, as well as variations in the coming decades do not significantly change until the 2050s. Scenario choice impacts outcomes from the mid-century onwards only.

### Integration of local data

The selection of datasets for a CRA should follow the risk definition of the IPCC where risk results from the interaction of climate-related *hazards*, elements *exposed* to these hazards, and the *vulnerability* of the exposed elements (IPCC, 2012, 2014). Local data (hazard, vulnerability, exposure) can help provide a more detailed and accurate picture of the potential risks and impacts of climate change. This applies to locally collected climate variables as well as data



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that can help identify vulnerable populations that may be disproportionately impacted by climate change. Integrating local data can also help ensure that climate risk assessments are tailored to the specific needs and concerns of local communities.

Datasets on these three risk drivers should be combined to assess risk comprehensively. The specific datasets required for the CRA rely on the risk assessment method used (see section 3.3.3 and Deliverable 2.4 for more detail). For instance, if damages to buildings or infrastructure are assessed, damage functions are needed in addition to data of the exposed elements (i.e. buildings, infrastructure) to characterize their vulnerability to the particular hazard studied (e.g. flooding); if the aim of the CRA is to assess impacts on the population, data of the population and individual characteristics that determine the population's vulnerability, such as age, education levels and income, should ideally be combined (Cutter, Boruff and Shirley, 2003; Reimann *et al.*, 2024).

When selecting such datasets for a CRA, the following potential limitations should be considered:

- Availability of data: While it seems that an abundance of datasets is available, data that can be directly used as an input to a CRA can be limited. Therefore, a first screening of suitable datasets available for the CRA at hand is necessary. To ease this process, CLIMAAX inventoried different hazard, exposure, and vulnerability datasets that are readily available for European countries under current as well as future conditions, i.e., scenarios (see Deliverable 2.2 for hazard datasets and Deliverable 2.3 for exposure and vulnerability datasets).
- Data uncertainties: Any dataset selected for CRA is characterized by a range of uncertainties that stem from factors such as the data collection method, the data calculation type or the modelling approach used for producing the data. Data collection is subject to uncertainties due to measurement errors or incompleteness of collected data, for instance related to their spatial coverage. As opposed to hazard data that are often validated against in-situ measurements, exposure and vulnerability data are often modelled from secondary data sources, which adds another layer of uncertainty (e.g. Leyk *et al.*, 2019).
- Spatial scale of analysis: Data selection should be aligned with the spatial scale of the analysis. For a Europe-wide CRA, datasets that are available for all European countries are needed. These data often lack local spatial detail, which makes them less suitable for a regional- to local-scale CRA. Therefore, it is advisable to collect high-resolution data, for example from national or regional statistics offices or environmental protection agencies, whenever possible. Similarly, more datasets may be available at regional to local scales as compared to Europe-wide data. Challenges related to local data may be, for example, missing data and short data time series, as well as different spatial scales



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compared to gridded data sets, and these need to be accounted for in assessing uncertainties from their use for CRA.

### Treatment of uncertainty

> **Uncertainty Guidance**
>
> For more background information see, for example, the Climate-Adapt guidance on managing uncertainty, including what is meant by uncertainty, communicating uncertainty, and how to factor in uncertainty.

Uncertainty is an inherent part of risk. Especially for policy- and decision-makers it is important to effectively communicate uncertainties and limitations of a CRA, for example with clear and transparent reporting, uncertainty narratives, or the identification of key sources of uncertainty. Technical choices related to the use of climate models, including future regional climate projections, allow us to explore the relative contributions of key sources of uncertainty that are important to consider when assessing future regional climate risk: scenario uncertainty, model uncertainty, and uncertainty due to natural variability (Hawkins and Sutton, 2009). For current conditions and the next couple of decades, uncertainties in regional temperature changes remain mainly dominated by model uncertainty, for example from how climate processes are parameterised in models, and in uncertainties due to the representation of natural variations of climate on daily to decadal timescales. Beyond that, by the mid-century onwards, scenario uncertainty becomes critical.

Due to these limitations, any CRA approximates the actual risk, and the results should always be interpreted with caution, carefully considering the limitations stemming from e.g., the data or scenarios used. Please consult Deliverables 2.2 and 2.3 for a more in-depth discussion of data availability and uncertainties.

## 3.2.3 Participatory Processes

Participatory processes are fundamental for the assessment of vulnerability, which is often qualitative and value-laden, to appropriately take on issues of social justice, equity and adaptive capacity (CARE, 2019; Mechler *et al.*, 2021; Zebisch *et al.*, 2021; UNDRR, 2022). Engaging via participatory processes is at the heart of the CLIMAAX Framework. It allows for inclusion of multiple bottom-up aspects that are relevant to undertake a comprehensive CRA. An inclusive approach is essential to translate and implement the CRA in the context of real-world experiences (such as local knowledge) needed for shared, community adaptation strategies.

Regions should engage with stakeholders from policy or relevant public and private sectors, experts (scientists, practitioners, or policy advisors with robust knowledge) or priority groups



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(representatives from vulnerable or marginalized groups and exposed areas[11]) by organising in-person group workshops, group meetings, discussion rounds or other types of meetings and interactions that a region considers beneficial. Further, the inclusion of local knowledge may be facilitated through "participatory GIS mapping" or "triangulation", which aims at combining methods and different sources of knowledge (Hermans *et al.*, 2022). To avoid or overcome stakeholder fatigue, it is important to facilitate a targeted outreach, emphasize mutual benefits, and navigate diverse opinions to achieve meaningful consensus. Increasingly complex climate risk and interplay with socio-economic vulnerabilities and exposure demands a more integrated approach to climate risk management. This includes a comprehensive treatment of justice and inclusive governance structures and decision-making (Schinko *et al*., 2023).

Exchange is encouraged throughout the CRA process with relevant stakeholders, experts, and priority groups by engaging in bidirectional learning, communication, and consultation. While it is widely accepted that the inclusion of multiple perspectives, such as the local context and knowledge, are beneficial for an extensive CRA, this is a challenge in practice. Slinger *et al.* (2023) recommends placing emphasis on developing a co-design process that fosters collaboration.

[11] For more detailed information see deliverable "Refined and updated framework to co-evaluate citizen and stakeholder engagement methodologies" provided by the AGORA Horizon project.



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## 3.3 Operational Framework steps

The CRA framework identifies five operational steps: *Scoping*, *Risk Exploration*, *Risk Analysis*, *Key Risk Assessment* and *Monitoring & Evaluation*. The *Scoping* phase defines objectives, sets the context, and identifies stakeholders and risk ownership. *Risk Exploration* is strongly informed by the *Scoping* step as it sets the conditions of analysis: selection of future scenarios, or relevant risk workflows by exploring of hazard, exposure, and vulnerability maps. After the risk workflow application in the *Risk Analysis* step, the individual risk outcome (possibly composed of several hazards, risk workflows or the application of various scenarios) is evaluated and contextualised in the *Key Risk Assessment* step (severity and urgency of risk resulting in key and less urgent risks), thus identifying potential entry points for CRM and risk reduction. *Monitoring & Evaluation* puts emphasis on summarising the CRA process and surveilling climate risks while gathering knowledge and data that is relevant for a learning process. An overview of the five operational steps and sub-steps is shown in

Figure 3.

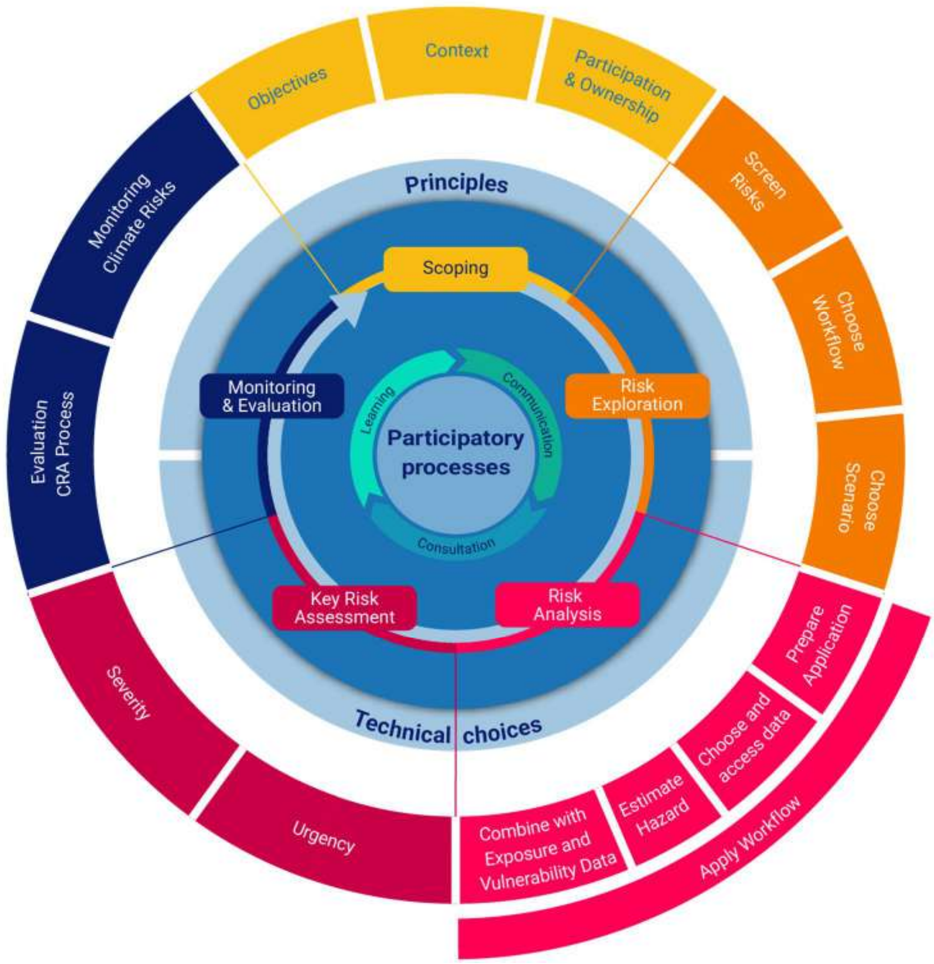




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*Figure 3. Detailed CLIMAAX Climate Risk Assessment Framework with the five main operational steps and corresponding sub-steps. Credit: CLIMAAX consortium.*



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To better illustrate the Framework (sub-)steps on the ground, guiding questions were prepared (see Annex Guiding Questions) for the pilot regions which will also make part of the CLIMAAX Handbook and can therefore be used for applicants. Depending on a region's/community's situation, needs or focus, the respective guiding questions can help to translate the aim of the Framework to the applied context on the ground.

### 3.3.1 Scoping

A comprehensive CRA profits from an extensive scoping as it sets the ground for further steps and therefore lays the foundation for the extent and quality of the CRA. This initial process defines objectives (desired results of the analysis), context (subject of analysis, conditions), identifies stakeholders and assigns risk ownership. This step should result in an agreement on the approach to be used for the analysis. All sub-steps are informed by a predefined set of principles emerging from the conceptual background described in section 3.2.1.

The definition of objectives is an important task to better understand *purpose*, expected *outcome* and temporal and geographical *boundaries* of the CRA. Such considerations may entail a first brainstorming exercise, outlining expectations and needs and may already include relevant hazards, impacted sectors or vulnerable or disproportionally affected groups. It is beneficial to outline the temporal and spatial boundaries as well as limitations of the risk assessment and/or adaptation measures, thus providing relevant insights for next steps of the CRA.

When conducting the scoping step, a region should elaborate on the context of their CRA (context analysis) by linking it *both to the background that it comes from as well as the space that it will inform*. This implies a broad contextualization ranging from risk relevant governance and policy aspects for the region (procedural, legislative, institutional conditions), the formulation of a clear system definition for the risk assessment including temporal and spatial dimensions as well as the consideration of available time and resources.
The ideal implementation of an inclusive CRA is hybrid (UNDRR, 2022; Bachmann *et al.*, 2023) and thus combines top-down application and knowledge together with bottom-up perspectives and experiences. Therefore, it is important for a region to decide the extent of participatory processes that are desired, also in the light of available resources. Once this is clarified, it is necessary for a region to identify a first set of stakeholders by identifying representatives of, for example, impacted sectors, vulnerable groups or disproportionally affected areas, ministries, academia, civil protection agencies or other local and regional entities involved in CRM planning. A proper CRA profits from insights from a variety of fields sharing their expertise or addressing their needs and concerns. Besides the *Who*, it is also relevant to decide *When* and *How* stakeholders, experts and priority groups should be included. Planning this thoroughly is important as stakeholder participation may lead to an increase of (time) efforts. Furthermore, in this step it is crucial to allocate ownership of risk to ensure communication and efficient CRM



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(Zebisch *et al.*, 2023) by making stakeholders or the entity, who is executing the CRA, responsible for the relative risk.

Throughout this task relevant principles from the conceptual background should be reflected and find application through, for example, stakeholder selection, setting of goals and boundaries, and clearly defining the process to ensure quality and rigour.

Tip: Stakeholder selection is not necessarily concluded in the Scoping phase. Depending on a region's Risk Outcome, the inclusion of stakeholders may be reassessed or changed as part of the *Key Risk Assessment* step which evaluates outcomes of the *Risk Analysis*, and thus indicates a back-and-forth of the process.

Tip: It can be beneficial for regions to include national (climate) risk or adaptation documents such as risk and vulnerability assessments prepared in an EU context.

### 3.3.2 Risk Exploration

Carrying out the Risk Exploration step kicks off a comprehensive process that starts with screening risks (their underlying hazards, exposures, and vulnerabilities) that are most apparent or of significant concern to key stakeholders and the wider public. A preliminary, rapid analysis of sectors (including activities, supply chains, processes, and infrastructure) and geographic areas at risk (such as ecosystems, landscapes, and communities) can be conducted based on insights from experts and stakeholders during the scoping phase (Zebisch *et al.*, 2023). It is useful for stakeholders to consider past and ongoing impacts on different sectors, areas and priority groups, and connect them to specific risks (current and future) to make risk "more tangible" at this early stage of the CRA process (Zebisch *et al.*, 2022).

A deeper dive into the system aspects may concretize affected entities (key systems, elements, sectors, communities, social groups, sub-regions), functions or processes that hold significant value in the local context (e.g. stakeholder interests, community priorities or public agenda) and a priori reveal (transboundary) connections or dependencies (Zebisch *et al.*, 2022, 2023). These considerations are key for exploring risk in more depth and to choose *Risk Workflows*.

From this step, involved actors and relevant stakeholders narrow down and prioritize potential risks by broadly exploring hazards, exposures and vulnerabilities while gathering relevant data and information for the choice of workflow(s). It is crucial to also select future scenarios that are relevant for the region before moving to the *Risk Analysis* step and starting to use the risk workflows. The following subsections will delve deeper into the screening of risks as well as the selection of workflows and climate scenarios.



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Tip: At this stage it's crucial to rely as much as possible on factual evidence regarding climate hazards, impacts and risks if available. The focus should especially lie on those hazards that are most likely to result in severe consequences for the region.

### Screen Risks

The primary objective of screening risks is to quickly scrutinize a region's climate risk context. To do so, we recommend harnessing participatory approaches (such as consultations with experts, stakeholders, and priority groups; possibly also group consultations with all relevant actors) alongside data-driven methods to gather insights from experts and stakeholders, beyond the initial risk considerations from the scoping step. It is important to complement data and observations on the rate of change, frequency, intensity, and duration of these events with stakeholders' perceptions and local knowledge. Where possible, the exploration can dive deeper and cover relevant risk-related aspects, such as monetary and non-monetary impacts, cascading effects, affected sectors, spatial extent, pervasiveness, and implications across sectors, regions, boundaries or generations (Jones *et al.*, 2004). This process also involves reflecting on existing CRM strategies to not only set a baseline, but also understand their effectiveness in past events and envisage their potential performance against ongoing impacts or near-future risks (Porst, Voss and Kahlenborn, 2022; Zebisch *et al.*, 2023). All this together can help to get a bigger and better picture of the local climate-related risks.

Experts and stakeholders then prioritize risks based on the outcomes of this first participatory process, considering objectives and scope defined in the scoping step and depending on the level of knowledge of the risks in the region. Lastly, a summary of key discussion points and risk screening results can be shared with stakeholders and the public to ensure transparency, seek feedback, and validate findings.

The overall output of the risk screening substep is to shortlist risks based on the knowledge and perception of stakeholders and experts while including past and ongoing impacts, expected future changes, and local concerns. Additionally, it helps to highlight areas where additional information, data, or knowledge is needed, thus paving the way for appropriate *Risk Workflow* selection.



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### Data Spaces and Hubs

Data spaces and hubs are designed to facilitate data sharing, collaboration, and analysis across different stakeholders and organizations.

The DRMKC Risk Data hub is an extensive tool that explores disaster risk and vulnerability, provides resources in a learning and training space as well as automated access to data. The IPCC Interactive Atlas is a valuable resource to access and explore observations, reanalyses and observational products. This is a novel tool for flexible spatial and temporal analyses of much of the observed and projected climate change information underpinning the assessment of the physical basis of climate change, including a regional synthesis for the climatic impact-drivers assessed in the report. This product has been extended and incorporated into the Copernicus Climate Change Service (C3S) to become the Copernicus Interactive Climate Atlas (C3S Atlas). It facilitates global and regional in-depth assessment of past trends and future changes in key variables and (extreme) indices for different periods across emission scenarios or for different policy-relevant global warming levels (e.g. 1.5°, 2°, 3° and 4°). Different graphical climate products such as maps and timeseries (or stripes) can be interactively customized to display temporally- or spatially aggregated values (or changes relative to different baselines) over flexible seasons, periods and regions.

Further data spaces and hubs of interest may be: Climate Data Explorer, index-based interactive EEA report, Climate Solutions Explorer, European Drought Impacts Database EDID or PESETA IV.

Tip: Utilizing maps and visual aids to depict exposure, vulnerability, climate-related hazards, and risks facilitates discussion on the nature and extent of impacts, identifying local risk hotspots, and understanding direct and indirect effects.

Tip: When concluding the risk exploration step, it is important to formulate risk statements that include the system boundaries, the time horizon (e.g., ongoing, near-term, mid-term, long-term), affected entities (e.g. sectors, communities, social groups, sub-regions), relevant hazards, impacts or risks (e.g. increase of heavy rain events, drought and heat impacts), scenario assumptions (e.g. climate change, population growth). This clarity supports subsequent substeps: *Choose Workflow* and *Choose Scenario*.

## Choose Workflow

Within the Risk Analysis step, various risk workflows are proposed to conduct a detailed quantitative analysis of climate risks (Figure 4). Following the prioritization of hazards or risks identified in the *Screen Risks* sub-step, the main goal here is to select the most suitable workflows.

Each workflow follows 'stepwise' data processing and is included and further described in the CLIMAAX Handbook. These workflows support:



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- The estimation of risks from the combination of hazard, exposure and vulnerability data.
- The analysis of damages using damage curves alongside Hazard and Exposure data.
- The evaluation of assets or populations exposed to specific climate-related hazards.

The workflows allow for both a current risk analysis based on historical data *and* future climate change projections to quantify future risk emerging from climatic shifts. The selection of the appropriate workflow(s) is crucial for accurately assessing and understanding the range of possible impacts, facilitating informed decision-making and CRM planning.


*Figure 4. Currently available Workflows in the CLIMAAX Handbook. Source: Screenshot from the CLIMAAX Handbook.*

Tip: One Risk Workflow may have several options (e.g., the floods workflows may analyse flash, river, or coastal floods). Make sure you understand the purpose, focus and advantages of each possibility.

### Choose Scenario

Based on the interests and concerns of the regions and their key stakeholders defined in *Scoping* and further refined in *Screen Risks*, the objective of this sub-step is to identify a suiting scenario. Selecting scenarios may range from simple SSP-RCP considerations (see 3.2.2 Technical Choices) to a more detailed, needs-driven, and decision-focused process considering climate models, downscaling, global warming levels or low-likelihood high-impact events (*see* Annex). Depending on the workflows, RCP and coupled SSP-RCP scenarios are offered to support users in this task, thus ensuring a useful risk analysis.

Choosing the right set of scenarios is crucial for the decision-context and policy output. It will help understand and characterize potential future risks while informing the development and evaluation of different CRM strategies.

#### Simple Scenario Guidance

1. Get familiar with the available scenarios. Know their underlying assumptions such as future emissions, socio-economic developments or feedback loops and tipping points.

2. Consider your decision maker's needs, interests or risk aversion.

3. Be clear on your envisaged time horizon. Most climate scenarios don't show a difference until 2050 (but vary regarding uncertainty of the model projections).

4. Consider using a variety of scenarios to compare their results.



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### 3.3.3 Risk Analysis

Once the Risk Exploration is completed, the Risk Analysis allows for the quantification of the risk in a given region. This is carried out through the risk workflows provided in the CLIMAAX Handbook. In the previous step, the user defined the type of risk workflow and hazard they are interested in; here, the user will follow five main steps to calculate their individual Climate Risk. Technical knowledge (e.g., of Python or similar modelling tools) is needed for the application of the risk analysis workflows.

The first action to be undertaken is Setting the Environment for the CRA. Within the Handbook, the user can find all the necessary information for accessing the workflow that was selected in the Risk Exploration step. Applying the risk workflows require a Python installation, cloning of relevant GitHub repositories and the installation of necessary packages.[12] For this, the user can follow the instructions provided in the Readme of the repository.

Second, the user will Access Data on hazard, exposure, and vulnerability. Based on the region of interest, the user can decide whether to use precalculated European/large-scale datasets available in the CLIMAAX Handbook about hazard (e.g. wildfire, flood water depth, and heatwave), exposure (e.g. population, critical infrastructure), and vulnerability (e.g. GDP) or to implement their own local data. The latter requires advanced users, while basic users can benefit from data provided through workflows. Once this is completed, it is possible to visualize the maps of hazard, exposure, and vulnerability to have a preliminary idea of the hotspots areas potentially affected by high risk.

Third, the user can Estimate the Hazard either by selecting precalculated hazard maps based on large-scale European free datasets or by calculating an individual hazard map based on local data following the guidelines provided in the CLIMAAX Handbook. As climate risk not only depends on climate-related hazards but also on the exposure and vulnerability of a region/society to the respective hazard (Ara Begum *et al.*, 2022), the fourth step combines hazard data with Exposure and Vulnerability to assess risk according to the equation:

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability}$$

Finally, Climate Risk can be estimated, and different visualization options are proposed (Figure 5). For example, risk can be visualized as risk map using different colours for different categories of risk (e.g. red as high risk and green as low risk). Moreover, the user can visualize a map of the exposed population for a snapshot in time, or they can visualize a diagram of

[12] Successful CLIMAAX applicants can run the workflows on the ECMWF servers through JupyterHub hosted at ECMWF cloud infrastructure. In that environment, all workflows are readily available together with the necessary libraries.



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changes of exposed population for a certain area and specific risk categories (e.g. time series of population exposed to high drought risk). More details about the Risk Analysis step, risk workflows, and risk visualization are reported in the CLIMAAX Deliverable 2.4. available here[13].

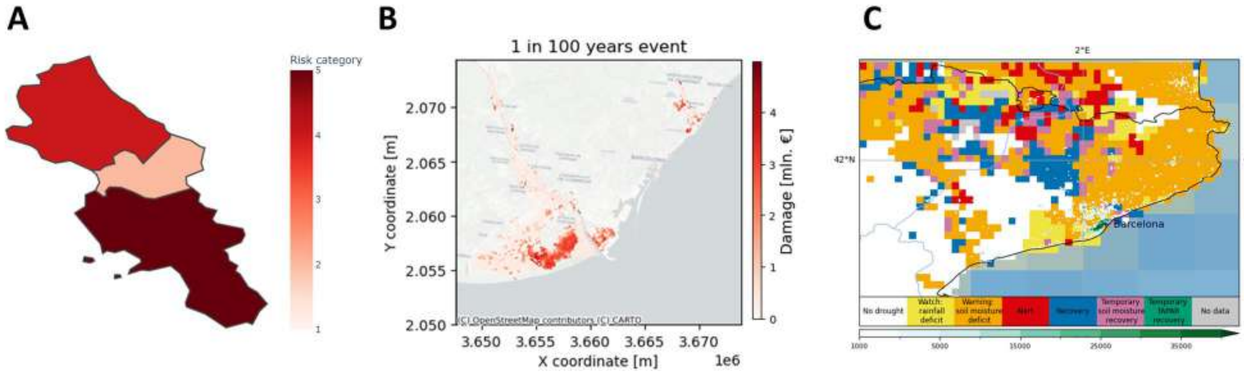


*Figure 5. Examples of the different outputs from the three risk assessment approaches with A drought risk indexing, B coastal flood damage, and C drought exposed population. Credit: CLIMAAX consortium.*

## Event-based climate storylines

Event-based physical climate storylines (or in brief: climate event storylines) are a complementary approach to produce climate information relevant for decision making.

Climate event storylines have been proposed as a way to assess climate risk in relation to other economic and societal risks and associated uncertainties that are relevant to decision-making (AR6 WGI Section 1.4.4.2, Chen *et al.*, 2021). Storylines are defined as a physically self-consistent unfolding of past events, or of plausible future events or pathways (Shepherd *et al.*, 2018). No *a priori* probability of the storyline is assessed; emphasis is placed instead on understanding the driving factors involved, and the plausibility of those factors. The storyline selection and design process are done in close interaction with stakeholders. The impact of climate change will be felt by stakeholders in these sectors in different ways. By following a bottom-up approach, the storyline will focus on specific information needs at stakeholder level. The aim is for stakeholders to get insights on possible climate impacts, as well as perspectives for adaptation options.

The storyline approach can directly link with disaster risk management practices and protocols at local level that are using stress-testing methods. Van den Hurk *et al.* (2023) and Baldissera Pacchetti *et al.* (2023) provide guidelines and examples for a step-by-step storyline development.

Climate event storylines have been recently recognized in the IPCC Sixth Assessment Report (IPCC, 2022) to have multiple benefits:

[13] https://www.climaax.eu/public-deliverables/



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- are a particular approach to put historic events in the context of a changing climate.
- provide climate information that is integrated with socioeconomic information.
- explore low-likelihood but potentially high-impact events that may be neglected in traditional probabilistic approaches.
- improve understanding of cross-sector interactions for the purpose of informing CRM.

Event-based storylines put emphasis on the qualitative understanding of the driving factors involved and the plausibility of those factors rather than quantitative precision. *'Storylines as a physically self-consistent unfolding of past events'* bring together the experiences of how an extreme event was experienced in a descriptive narrative that can be used to be better prepared for the future. The use of past events as baseline for storyline development assures a credible justification for the selection of events and provides highly relevant context of the already experienced risks.

One benefit of storylines is that they allow for the explicit inclusion of CRM options. Storylines enable the identification of challenges that may prevent appropriate risk management: a false perception of preparedness, a lack of whole system thinking that underestimates the dimension of possible risks, responsibility that continues to be outsourced to others and nobody acting. By articulating the links between risk and their management in a coherent way that can be understood by stakeholders the storylines can motivate policy change and action.

Multiple iterations are needed for the development of a climate storyline and its supportive elements. The box below illustrates the summary of a recent storyline application by Koks *et al.* (2023). Also, the H2020 project RECEIPT, finalized in 2024, provides an interactive visualization platform[14] for multiple storylines as well as an online quiz[15]. These tools allow the public to explore and understand the storyline approach. The storyline development process feeds the imagination of possible linkages and gradually converges towards the identification of the most thought-provoking or challenging future scenarios. A combination of expert inputs and stakeholder engagement is needed to identify meaningful storylines that provide real and actionable insight.

Tip: Future storylines (as a combination of past events and climate change information) are helpful to explore what-if-things-had-been-different situations by exploring intensity or frequency of climatic drivers and the societal response, for example. Climatic drivers include long term changes but also the timing, spatial patterns, and co-occurrence of events in different

[14] https://www.climateimpactstories.eu/
[15] https://www.quiz.climatestorylines.eu/



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regions; future economic and social dimensions can refer to expected changes in demography, economic structure and many more aspects of societal response.

**Storyline Example**

Koks *et al.* (2023) developed an event-based storyline framework to assess the influence of future climatic and socioeconomic conditions on coastal flood impacts to critical infrastructure. The storylines combine quantitative methods of sea level rise, coastal inundation, and critical infrastructure physical damage assessments into an integrated modelling approach. The study re-imagined three historic events: storm Xaver, storm Xynthia, and a storm surge event along the coast of Emilia Romagna (Italy). The results indicated that northern Germany would benefit mostly from coordinated adaptation action to reduce the flood impact, whereas the southwestern coast of France would find the highest damage reduction through asset-level 'autonomous' adaptation action. The storyline approach helped to improve the scientific understanding of how coastal flood risk are assessed and best managed and forced a distillation of the science into an accessible narrative to support policymakers and asset owners to make progress towards more climate-resilient coastal communities.

### 3.3.4 Key Risk Assessment

The outputs of the climate risk analysis generate information on extent, duration, frequency and intensity of risks and thus already provides comprehensive insight on relevant risks to be considered. As a further analytical step, *key risks* may be identified.[16] The IPCC defines key risks as risks that "have potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate-related hazards with vulnerabilities of societies and exposed systems" (IPCC, 2023). This analytical step can provide additional insights into the *severity* of risks and *urgency* for further attention to be paid to understanding and eventually managing risks. The two entry points to such analysis are Risk Severity and Risk Urgency.

Risk Severity can be defined as the extent of potential, serious adverse impacts from climate events in terms of leading to compromising agent's or system's objectives (potential heavy loss of income and livelihoods, malfunctioning of infrastructure, serious disruption of ecosystems etc). The subjective judgement (risk perception) of risk (IPCC, 2023) may result in an indication of risk severity.

On the other hand, Risk Urgency is associated with the temporal dimension of risk and relates to the urgency of acting on severe risks as well as acting on opportunities arising from risk assessment. As the technical report of the third UK Climate Change Risk Assessment (CCRA3) (Betts, Haward and Pearson, 2021) suggests, urgency relates to addressing negative (*downside*)

[16] This step has also been termed risk evaluation.



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risks, as well as to harnessing opportunities (*upside risk*) associated with risk assessment and management (see Figure 7). For example, if a development plan is being conducted in a region, inputs on current and future risks may be required to appropriately plan for e.g. new housing. Here, it is crucial to avoid negative, downside risks (such as structural loss in events) and consider upside risks in the form of suitable adaptation measures (e.g., nature-based solutions) or insurance coverage (which is a profit opportunity for the insurance sector and a source of additional tax income for the community or region).

Severity and urgency partially inform each other (where urgency is dependent on severity), and are suggested to be considered jointly during this step of the key risk assessment, which can be done by stakeholders and/or experts (Figure 6).

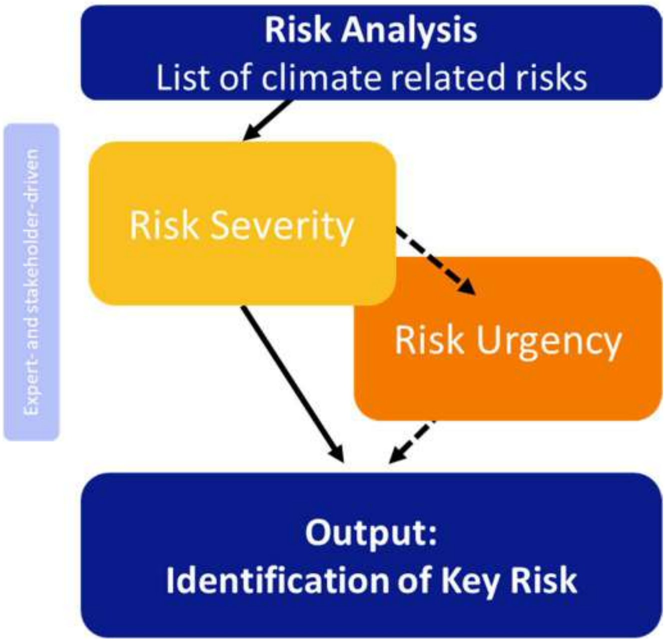


*Figure 6. Key Risk Assessment considering severity and urgency. Credit: CLIMAAX consortium.*

Practically speaking, risks may be considered severe if their impacts (O'Neill *et al.*, 2022; Magnan, O'Neill and Garschagen, 2023; Zebisch *et al.*, 2023; European Environment Agency, 2024):

- Are high in magnitude, likelihood, or duration (e.g. severe impacts, large areas, cascading effects, irreversibility).
- Affect functioning of relevant systems and processes.
- May occur during critical timing of processes (e.g. increased precipitation projected for harvest seasons).
- Coincide with low ability for adaptation or CRM and may incur adaptation limits.

Further, the urgency of risks is related to the timing of (severe) risks and depends on (Betts, Haward and Pearson, 2021)*:*

- Their severity.
- Hazards having been observed or projected to worsen significantly.
- CRM measures implemented that are insufficient and/or in the planning stages.
- Emergent development and business opportunities arising from addressing risk.



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Table 1 provides further insight into processes and indicators to be used for understanding risk severity and urgency. We propose two modes of engagement: a stakeholder-driven assessment and an expert-driven, but stakeholder informed assessment.

*Table 1. Processes and indicators for understanding risk severity and urgency.*

| Mode/Aspect | Risk Severity | Risk Urgency |
|---|---|---|
| *Stakeholder driven assessment*<br><br>*Outcome: Stakeholder priority ranking of key risks to further closely monitor and manage based on qualitative data insight* | Consider anecdotal evidence of socio-economic consequences of observed events for ranking of key risks.<br>Employ available information on implemented and planned CRM. | Broadly consider qualitative observed and projected changes in temporal aspects of risk.<br>Derive basic overview of currently planned CRM and emergent development and business opportunities, related to addressing risks. |
| *Expert-driven and stakeholder informed*<br><br>*Outcome: Quantitative/ qualitative priority ranking of key risks to further closely monitor and manage including concrete actions and timing* | Assess consequences of impacts and risks through statistics of observed events or models of future risk. Rank risks according to survey-based stakeholder risk preference (acceptable, tolerable, intolerable risks).<br>Assess adaptive capacity and implemented and planned CRM using relevant indicators. Consider non-climatic risk drivers. | Consider quantitative observed and projected changes in temporal aspects of risk using climate scenarios.<br>Derive basic detailed currently planned CRM and emergent social and business opportunities, which may be affected by risks. Apply Urgency Scoring Framework (Warren *et al.*, 2018). |

Linking risk outcomes from the *Risk Analysis* step with assessments of risk severity and urgency as evaluated by experts and stakeholders brings in a strong bottom-up aspect. It also allows incorporation of insights on adaptation responses or climate risk management interventions. Even if only one risk workflow has been chosen, regions can still profit by adding more detail to the climate risk analysed by assessing relevance and urgency. A qualitative or even quantitative approach (e.g. with financial or social indicators) provides the possibility to rank calculated risks. Further, it may be beneficial to include considerations that go beyond direct and tangible impacts of potential climate risks and consider indirect and intangible impacts such as environmental, cultural, or psychological damage.

As part of *Risk Severity*, stakeholders and experts would consider implemented adaptation responses and climate risk management together with the level of adaptive capacity. Indicators



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may be taken from different sources, such as the *Regional Resilience Maturity Framework* (see P2R project[17]) and may include regional governance and institutional capacity; plans and policy instruments; human resources and technical skills; participatory governance and stakeholder engagement; public support, awareness and climate change communication; financial capabilities; innovation.

The different aspects of risk discussed in the Key Risk Assessment can be ranked in high/medium/low risk profiles which may then be hierarchically ordered and assigned as "key" or "less urgent" risk (see Table 2 for example). Key Risks are recommended to be included directly in CRM strategies and plans (see Chapter 4 Integration in Climate Risk Management) while less urgent risks can be further monitored.

*Table 2. Example of climate-related risk evaluation and ranking through participation and consultation of experts and non-experts. "No." refers to the number of stakeholders or experts consulted (which can vary for each risk). In this case the evaluation would result in a prioritization of heatwave and flood risk, thus assigning them as "key risks" which need to be addressed through CRM. Table adapted from Mechler* et al. *(2019).*

| Perceived severity and urgency of associated risk | High | | Moderate | | Low | | Total | |
|---|---|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % | No. | % |
| Heatwave | 55 | 78,57 | 13 | 18,57 | 2 | 2,86 | 70 | 100 |
| Flooding | 50 | 71,43 | 15 | 21,43 | 5 | 7,14 | 70 | 100 |
| Drought | 13 | 18,57 | 27 | 38,57 | 30 | 42,86 | 70 | 100 |

Tip: The Key Risk Assessment step is a crucial point for reflecting on principles from the conceptual background (especially social justice/just resilience and the precautionary approach) as well as context, objectives and risk ownership that were set during the scoping step.

[17] https://www.pathways2resilience.eu/regional-resilience-journey-map/



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### 3.3.5 Monitoring and Evaluation

Monitoring and evaluation (M&E) is both a departure and ending point, as the goal of the CRA is to iteratively go through its process while aiming at continuous improvement. This step therefore also brings in another momentum of opportunities. The M&E step is essential for ensuring climate-related risks (key and less urgent risks) are effectively monitored and managed and that climate risk management efforts can have appropriate impact. It may include participatory processes and has a special focus on the *learning* component.
M&E also has a strong temporal aspect as the dynamic nature of climate change requires constant evaluation to "determine whether it remains suitable to support achieving the objectives" (ISO, 2018, p. 8) that have been set. The process can therefore be characterized as a continuous or iterative process which "(...) should not occur once, at a fixed point" as it cannot be considered "complete" (Zebisch *et al.*, 2023, p. 112).

The M&E step therefore unites two separate but also connected sub-steps. While Monitoring has its focus on the *process*, Evaluation puts emphasis on the *outcome.* Monitoring therefore refers to the surveillance of climate hazards and their respective risks, whereas Evaluation aims at (re-)evaluating the Climate Risk Assessment itself. In Monitoring, regions should consider *Less Urgent Risks* as well as *Key Risks* and observe them over time. Putting them into context in relation to specific objectives, principles or needs that were set earlier (e.g., during *Scoping* or *Risk Exploration*) concludes the cycle. On the other hand, Evaluation comprises of an iterative reflection on the Climate Risk Assessment cycle and its robustness, including a comparison of factual and projected climate risk situations. The frequency of Evaluation is defined by the region and may vary according to Risk Outcomes, objectives, or policy interest. Learning is of key significance in this step as evaluation may continuously generate new knowledge and data and can thus influence processes about, e.g., governance, policy and decision-making or relevant ministries and institutions. Depending on the issues and needs of a region, it can be beneficial to collect quantitative/qualitative data that is needed for improving future iteration of the CRA. It is crucial to understand what works well and what does not and act upon it– both in the CRA process, and in dealing with risks.

Both M&E steps can facilitate participatory processes and include relevant stakeholders for most extensive engagement and comprehensive understanding of the CRA, thus "(...) ensuring that the overall narrative of adaptation progress is robust, consistent and contextualized" (Climate-ADAPT, 2024).

Selecting indicators for this process is crucial to summarize the output of the CRA and make it more valuable. Indicators should therefore be linked to specific objectives (CoastAdapt, 2017), sectors as well as stakeholder's needs and can be assessed quantitatively or qualitatively, where, however, "[i]n some cases, a qualitative, interpretative summary of the individual results



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can be preferred" (ISO, 2021, p. 13). While it is difficult to provide a full set of indicators due to the heterogeneity of regions and risk situations, regions can define their individual indicators that are more relevant for their context and purposes. For this it is helpful to follow the SMART scheme *specific*, which encourages indicators to be *specific*, *measurable*, *achievable*, *relevant* and *time-bound*. Climate-related risks require indicators that embrace periodical reassessment and should refer to a baseline to track changes over time effectively. Tracking changes of indicators, possibly identifying risk thresholds or trigger levels, may be helpful to indicate a potential overshoot of risk tolerance and need to be attributed to (further) CRM measures. Depending on the focus of the M&E, indicators may change. Table 33 provides a non-exhaustive list of potential M&E indicators: here, the process of Climate Risk Monitoring refers to workflow specific and unspecific indicators, whereas Climate Risk Assessment Evaluation provides an initial set of performance indicators, i.e., *efficacy*, *usefulness* and *impact*. Further indicators may be taken from the Sendai Framework[18].

*Table 33. Non-exhaustive selection of indicators for the M&E process with a) workflow specific and workflow unspecific indicators for Climate Risk Monitoring and b) performance indicators for the Climate Risk Assessment itself.*

a)

| Indicators for Climate Risk Monitoring | |
|---|---|
| Workflow nonspecific indicators | |
| Frequency, intensity, spatial distribution, and duration of climate events; public awareness and engagement; institutional capacity | |
| Workflow specific indicators | |
| Workflow | Indicators/impacts |
| Flood Risk | Number of overflows; losses and damages (injuries, hospitalisations, fatalities, livestock, crops, business, tourism, buildings, etc.); disruption of public infrastructure |
| Drought Risk | Losses and damages to agriculture (crops, livestock); availability of tap water; extent of agricultural areas and people affected |
| Heatwave Risk | Health impacts (hospitalisations and fatalities); economic productivity |
| Wildfire Risk | Number of fires; extent of affected areas and people; loss and damages (injuries, hospitalisations, fatalities, agricultural and forest areas, farm and wild animals, buildings, tourism, etc.); disruption of public infrastructure |
| Snow Risk | Disruption of public infrastructure; loss and damages (injuries, hospitalisations, fatalities, livestock, business, buildings, etc.) |
| Windstorm Risk | Disruption of public infrastructure; losses and damages (injuries, hospitalisations, fatalities, livestock, business, buildings, forests, etc.) |

[18] https://www.undrr.org/implementing-sendai-framework/monitoring-sendai-framework



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b)

| Indicators for the Evaluation of Climate Risk Assessment Process | |
|---|---|
| Performance Indicators | Examples |
| Efficacy | Efficient use of resources, e.g. time, staff, cost |
| Usefulness | Raised awareness, improved understanding of risk (Public awareness and engagement, institutional capacity, funding and investment) |
| Impact | Applicability for Risk Assessment and CRM (number of times used, acceptance by experts and stakeholder, translation of results into CRM) |

Communication is part of the participatory processes and should thus be enforced throughout the whole CRA, to decrease the risk of generating plans and policies which are not relevant (Beek *et al.*, 2022). However, at this stage it is especially important to communicate results to the public and/or key audiences with a focus on policy- and decision-makers. Regular reporting (e.g., interim reports about decision on workflows or relevant priority groups) or a continuous dialogue with policy- and decision-makers may enhance relevance and accountability of the CRA and the process (ibid.). Eventually, a CRA should support learning over time, inform policy making, policy revision and indicate entry points for CRM.

Tip: The output of the M&E step can inform a report or plan to document and communicate results. This should also include marginalized and disproportionately affected groups (social justice/just resilience) as well as gender, educational or socio-economic aspects.

Tip: At this stage it can be relevant to reassess targets, objectives and responsibilities in national/sectoral adaptation plans or strategies and include them in the M&E process.



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# 4 Integration in Climate Risk Management

At the local level, climate risk management (CRM) addresses the unique challenges that the changing climate is bringing to the region. It focuses on developing and implementing strategies that anticipate, prevent, and prepare for climate risks, as well as enhancing the ability of natural and human systems to adapt, withstand, respond and recover from climate-related shocks and stresses (GIZ, 2021; UNDRR, 2022; USAID, 2022).

The assessment of key climate risks, consisting of severity and urgency, is foundational to inform CRM decisions (see 3.3.4 Key Risk Assessment). The *Key Risk Assessment* helps to prioritize climate risks based on their potential impact, the immediacy with which they need to be addressed, the local adaptive capacity and readiness to respond to these risks, and the risk perception of the public and key stakeholders. While CRM decisions must be informed by the CRA (UNDRR, 2022; USAID, 2022; Zebisch *et al.*, 2023), risk perception also plays a crucial role in influencing public support for CRM and adaptation strategies (IPCC, 2022). Therefore, the quantitative risk estimation of the CRA (ideally combined with qualitative, participatory approaches) must be used to inform and raise awareness among relevant stakeholders, key local actors, or priority groups. This not only facilitates initiating adequate CRM actions but also ensures public buy-in and alignment with local priorities and needs.

The climate risk profile of a region, including its projected changes over time, is the primary indicator of "*what"*, "*where"* and "*how"* CRM and adaptation responses should be initiated (UNDRR, 2022; USAID, 2022; Zebisch *et al.*, 2023). However, there are additional entry points for CRM. Previous risk management interventions and ongoing adaptation processes in place can reveal valuable opportunities for introducing additional or complementary measures (Zebisch *et al.*, 2023). Moreover, CRM and adaptation responses undertaken in other areas can offer insights into what could be applicable and how to design and implement it for the region's particular situation. These are good practices that encourage proactively learning from past experiences and current CRM actions to inform the planning of future adaptation processes (Mysiak *et al.*, 2018; EEA, 2022).

CRM is a comprehensive process involving various iterative and dynamic steps (GIZ, 2021; UNDRR, 2022). In the context of the EU Mission on Adaptation to Climate Change, CRM and adaptation planning are further addressed by e.g., the Pathways to Resilience (P2R) programme[19] — an initiative complementary to CLIMAAX – or the Regilience project[20]. Figure 7 presents a simplified view of an approach to CRM with linkage to the CRA Framework, consisting of four major steps:

[19] https://www.pathways2resilience.eu/
[20] https://regilience.eu/



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- Identifying potential adaptation options that can either reduce the vulnerability of climate impacts or enhance its resilience. This step involves detailing all possible actions, approaches, and strategies that could be taken to manage identified climate risks. These could include structural, technological, nature-based, community-based, institutional, behavioural, financial, and informational interventions. In this step, stakeholder engagement is fundamental to ensure that the options are viable and aligned with the needs and capacities of the affected communities.

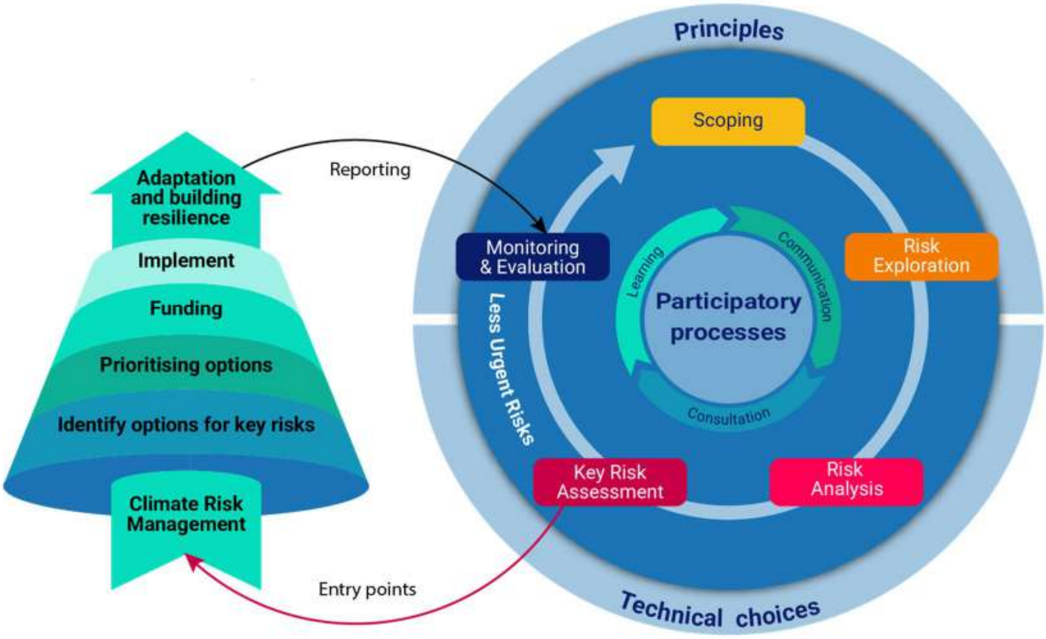


*Figure 7. The CLIMAAX Framework for CRA with linkage to CRM with the goal of adaptation and building resilience. Credit: CLIMAAX consortium.*

- Prioritizing adaptation options based on criteria such as cost-effectiveness, feasibility, impact, and stakeholder preferences. This step involves a detailed analysis to assess the benefits and drawbacks of each adaptation option, considering both short-term and long-term implications. Prioritization helps in allocating limited resources to the most effective and efficient CRM strategies and adaptation responses. It may also consider other aspects, such as implementation readiness and immediate performance, based on the level of urgency identified in the Key Risk Assessment.
- Securing funding consists of identifying potential sources of finance for the prioritized CRM and adaptation measures, which could include government budgets, international climate funds, private-sector investments, or public-private



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partnerships. The process also entails ensuring that the financial mechanisms are in place to support the implementation of chosen options and the intervention's long-term financial sustainability. This is of particular relevance given that effective and secured funding strategies allow for turning planned adaptation projects into actionable responses.

- Implementing the chosen CRM and adaptation responses. This involves not only executing and managing the interventions but also continuously coordinating various stakeholders, such as government agencies, local communities, and private entities, to ensure successful implementation. Stakeholders that have been involved since the beginning of the process are more likely to have the buy-in necessary for implementation. It also requires integrating and aligning the CRM and adaptation responses into local development planning and regional policies. Importantly, the implementation of the responses should be regularly monitored and evaluated to assess the effectiveness and progress of building resilience to the targeted climate risk. This allows for adjustments and improvements over time, ensuring that the CRM endeavours deliver the expected outcomes adequately and timely and preventing interventions from inducing maladaptation.

In CRM, defining risk ownership is essential. Risk ownership refers to the assignment of accountability for identifying, assessing, and managing specific climate risks to designated individuals or organizations (Zebisch *et al.*, 2023). It is the cornerstone for defining responsibilities and delineating roles at each stage of the CRM process. This is crucial for ensuring that risks are not only recognized but also actively managed through tailored CRM strategies (Young and Jones, 2017; Young *et al.*, 2017; Zebisch *et al.*, 2023). For instance, local governments might take ownership of urban flood risks, engaging in infrastructure planning and community education, while agricultural businesses might own risks related to drought, focusing on water conservation practices and crop diversification. This clear demarcation of responsibilities ensures that all stakeholders are engaged and accountable, facilitating a coordinated and effective response to climate risks while enhancing transparency. Moreover, it enables stakeholders to understand their specific duties and how they contribute to the broader CRM objectives, as well as fostering resource mobilization, effective resilience-building against key climate risks and proactive adaptation to future climate conditions (Wissman-Weber and Levy, 2018).

Utilizing the SMART approach (see 3.3.5) to track the implementation and performance of CRM and adaptation responses supports the monitoring and evaluating climate risks. On the one hand, establishing specific, measurable, and relevant metrics of the effectiveness of CRM and adaptation actions allows for targeted data collection directly connecting to critical areas of the specific identified risk. On the other hand, achievable and time-bound CRM interventions allow for tracking progress in reducing vulnerability and enhancing local adaptative capacity.



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Adopting this reporting approach is helpful for CRA, considering that an objective evaluation of the CRM effectiveness can indicate unattended areas or drivers of risk. Such would need to be further addressed through other actions, as well as revealing segments of residual risks. Therefore, the systematic tracking and reporting process is essential not only for transparent communication or for updating risk management plans but also for informing new cycles of CRA and the need to analyse additional facets of climate risks.



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# 5 Conclusion

With climate risks becoming more frequent and severe, communities are urged to prepare for climate resilience through CRM action. A comprehensive and inclusive CRA plays a key role in indicating direction and extent of climate risk in areas, sectors and communities and thus allows to determine where efforts are needed, or opportunities emerge. Due to highly heterogenous socioeconomic and geographic situations and needs (e.g., orientation of the economy, infrastructure, demographics, etc.) especially local and regional communities profit from flexible and adaptable approaches that enable them to design and develop their plans, strategies and policies accordingly.

The CLIMAAX Framework for regional to local CRA provides the possibility to identify climate-related risk through the five operational framework steps: *Scoping*, *Risk Exploration*, *Risk Analysis*, *Key Risk Assessment* and *Monitoring & Evaluation*. The steps are supported by a conceptual background delving into principles (most importantly just resilience), technical choices and participatory processes to be considered. While technical choices (such as scenario selection, time horizons or use of local data) offer important reflections needed for decisions related to Risk Analysis (and therefore CLIMAAX Handbook application) the three participatory processes *learning*, *communication* and *consultation* are located at the very centre of the CRA Framework and thus indicate their key role throughout the CRA process.

What makes the CLIMAAX Framework distinct and powerful is its alignment with state-of-the-art knowledge and on the ground needs which profoundly contributed to the Framework structure and content. Further, the active integration and collaboration between the CLIMAAX Framework and risk workflows, resulting in the CLIMAAX Handbook, allow to embed and contextualise the relative risk outcome as estimated in the Risk Analysis step. This is urgently needed to guide users through a comprehensive and inclusive process by illustrating important considerations, topics and sub-steps (e.g., by providing guiding questions; see Annex II). Further, it is important to showcase the importance of leveraging participatory processes throughout relevant steps. The Framework also provides a means for regions and communities to strengthen their CRA activities across the European region, thus effectively contributing to the implementation of the Mission Adaptation goal of supporting EU regions, cities, and local authorities in their efforts to build resilience against the impacts of climate change.

This deliverable also outlines the importance of connecting CRA with CRM efforts. Through several linkages to CRM options, such as the CLIMAAX sister project P2R, as well as a chapter on the integration of the CLIMAAX Framework into the CRM process, the Framework connects to the EU Mission adaptation vision with the ultimate goal to enhance decision-making and empower regional and local governments to act decisively.



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# Annex to 3.4.2 Technical Choices

Plausible, relevant, and consistent future regional climate information requires technical choices to develop global to regional climate information that is relevant and useful for stakeholders at national and sub-national scales to support the assessment of climate risk. The context and values of users, including practitioners and communities, frame the development of user-relevant regional information through a 'distillation process' that builds on the latest available scientific and technical evidence. To synthesise and communicate information effectively, the co-production of relevant products, such as data and graphics, plausible storylines, with users is important to reflect their needs and address their questions. Climate information can be constructed from multiple lines of evidence including observational and model-based data, literature, process understanding and expert knowledge.

## Choice of climate modelling results

Different climate models, be it global or regional, are used in international modelling intercomparison projects (e.g. the Coupled Climate Model Intercomparison Project – CMIP, and Coordinated Regional Downscaling Experiment – CORDEX, respectively) that are coordinated by the World Climate Research Programme. This range of model results allows for the exploration of ‘model uncertainty’ of the climatic response. In addition, internal variability of the climate system affects climate, particularly on timescales of years to decades and at regional scales and adds another source of uncertainty to future climate outcomes. To explore this source of uncertainty, each model is run multiple times to generate an ensemble forced by the same scenario. Collectively, the ensemble members represent a range of possible climate futures based on the climate model, GHG scenario, and initial model state. Each simulation is a unique "ensemble member" representing the model-uncertainty range. Considered together, the ensemble members are used to provide a more comprehensive understanding of possible climate outcomes as well as to better quantify uncertainties in the projections. While each ensemble member provides a possible climate outcome, the ensemble average of a set of simulations (e.g., historical simulations) is generally considered to be more accurate than any single ensemble member, it is important not to lose important information on uncertainty provided by the ensemble set. Various techniques are applied to estimate ensemble average and uncertainty range.

The spread of the ensemble indicates the level of uncertainty in the simulations and helps identify regions or variables where tend to models agree or diverge. In regional analyses, it is often assumed that models that are the most skilled in simulating historical climate are likely to be more skilled in simulating future climate. The less skilled models that are outliners in the simulations at the regional level may be removed from the analysis or given a lower weight. However, model weighting (model sub-selection) based on model performance (‘optimal



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weighting') may exclude plausible simulations due to uncertainties in the observed record used to evaluate historical model performance and the effects of internal variability, such that 'equal weighting' of all ensemble members generally performs better than a single ensemble member (Weigel *et al.*, 2010). The latest IPCC report interprets the CMIP6 5–95% ensemble range as the *likely* uncertainty range. A sub-selection was performed for three key global climate variables (global surface temperature, global mean sea level rise and ocean heat content) based on the use of multiple lines of evidence and expert judgement (see Box 4.1 in Lee and Marotzke, IPCC 2021).

### Enhancing regional resolution through downscaling and bias correction

Global climate model (GCM) (e.g., CMIP6) simulations are mainly performed at spatial resolutions on the order of two hundred kilometres (i.e., 200-km by 200-km). Many climate-related phenomena, however, occur at scales not resolved at these coarse scales, particularly in regions with complex topography and coastlines. This can result in an insufficient representation of precipitation (e.g., snowfall vs rainfall and extremes), temperatures (e.g., orographic effects and heatwaves), winds (e.g., sea breezes and gusts), hydrology (e.g., snowmelt and flood), etc. An accurate simulation of these climatic characteristics, however, are typically necessary for climate risk assessment and impact studies at local and regional scales. Downscaled climate data is widely used for assessing the potential impacts of climate change on various sectors, such as agriculture, water resources and ecosystems, and can be more tangible and relevant to local stakeholders, policymakers, and resource managers. Doblas-Reyes and Sörensson et al. (IPCC, 2021), included a comprehensive assessment of different approaches to enhance regional climate information, including fitness-for-purpose, and the use of multiple sources of evidence such as observations and re-analyses.

Generally, there are two main types of downscaling techniques: (i) dynamical downscaling and (ii) statistical downscaling. In addition, bias adjustment (or correction) techniques can be used to further refine GCM outputs, sometimes in conjunction with dynamical and statistical downscaling.

Dynamical downscaling involves the use of regional climate models to simulate the climate within a specific region at a higher resolution, typically 10s of kilometres or less. Output from GCMs is used as boundary conditions for a regional climate model that has higher resolution, physics and dynamics, and topographic and land cover data, thus refining the climate simulations. In other words, they aim to enhance regional detail in response to large-scale forcing through a more realistic representation of physics and dynamics by including finer-scale topography, vegetation, and land/water coverage. This approach generally improves the simulation of regional climate and provides more detailed characteristics of temperature, wind, moisture, and precipitation in comparison to GCM simulations. Finally, dynamical downscaling



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is computationally intensive, often requiring high-performance computing systems to perform the simulations.

Statistical downscaling uses empirical relationships between large-scale atmospheric variables simulated by GCMs and observed local scale climate data to estimate the hydroclimatic variables at a finer spatial scale. The relationships are typically developed using historical records and simulations and then applied to future projections from global models. Statistical downscaling is computationally less demanding compared to dynamical downscaling but relies on the assumption that the historical statistical relationships are valid in the future. There are numerous downscaling approaches, including regression methods, weather typing, analog-based methods of past weather patterns, Markov chain stochastic weather generators, and machine learning techniques.

Bias adjustment is the 'correction' of global model systematic biases. Biases are inherent in climate models due to various factors, including limitations in representing physical and dynamical processes, representation of sub-grid processes and inaccuracies surface data. Bias adjustment techniques can reduce these biases by applying statistical adjustments directly to the climate model output to align the model output with the observational data for specific variables of interest (typically temperature and precipitation). These adjustments are often based on statistical properties computed from the observed data, such as mean, variance and distributional characteristics.

### Global warming levels

Evaluating climatic changes, as well as impacts and risk, for the level of global warming relative to pre-industrial levels is useful since many changes in the climate system, both at global and regional scales, are directly related to increasing temperatures, becoming larger with every increment of global warming. This includes increases in the frequency and intensity of hot extremes, marine heatwaves, heavy precipitation, and, in some regions, agricultural and ecological droughts; an increase in the proportion of intense tropical cyclones; and reductions in Arctic Sea ice, snow cover and permafrost (IPCC, 2021). The IPCC risk assessment of 'reasons for concern' (Smith *et al.*, 2009) is aggregated by level of surface warming, as illustrated in the burning ember diagrams (Zommers *et al.*, 2020). There is also a near-linear relationship between increasing cumulative $CO_2$ in the atmosphere and mean global surface temperatures (Allen et al., 2009), which means that global surface temperatures will continue to increase with increasing $CO_2$ emissions. Global warming levels can be an effective means of communication of climate change and risk, instead of a transient, or temporal, evolution of scenario-based information, since many stakeholders are familiar with a reference to global warming, particularly given the framing in the Paris Agreement.



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Global warming levels are generally calculated for 20-year means relative to the 1850-1900 proxy for pre-industrial times from scenario-based model simulations. The levels of global warming can also be deduced from the literature that considers scenarios. The relationship between regional climate information at global warming levels and from scenarios is explained in Cross-Chapter Box 11.1 in(Seneviratne *et al.*, 2021). For many variables, the pattern of response at global and regional scales is consistent for a given level of global warming, regardless of the timing when that level is reached in each model simulation. Regional characteristics and patterns that are consistent with a level of global warming and are not sensitive to the emissions scenario, including climate extremes such as extreme temperatures and heavy precipitation, have been identified for many regions and are referred to as the regional climate sensitivity to global warming by Seneviratne and Hauser (2020). These patterns are also consistent independent of whether the level of global warming is reached earlier or later in model runs. This consistency tends to be higher for temperature-related variables than for variables in the hydrological cycle or variables characterizing atmospheric dynamics and for intermediate to high-emissions scenarios than for low-emissions scenarios. Assessing whether indices or variables are suited to be integrated in terms of global warming levels requires information from scenario-based projections. This approach may not always be suitable, for example where there are strong radiative forcing effects related to aerosols, where land use changes are important. This also applies for sea level rise that is affected by the rate of warming and time-integrated warming rather than warming at a given time, and so is related to processes where their evolution is scenario-dependent (Hermans *et al.*, 2021).

### Low-likelihood, high impact outcomes and storylines

Plausible low-likelihood, high impact outcomes should be assessed as part of a comprehensive risk assessment. They are important to take into account outcomes that could lead to significant impacts (Shepherd, 2019; Sillmann *et al.*, 2021; van den Hurk, 2022; van den Hurk *et al.*, 2023). Model-based results of outcomes outside the *very likely* probability range (90–100%) could be excluded from probability-based analyses, for example potential changes in extremes and particularly at regional and local levels. Alternative approaches such as storylines that put more emphasis on the plausibility of these outcomes, for example based on process-based understanding and expert knowledge. A physical climate storyline is a self-consistent and plausible physical trajectory of the climate system, or a weather or climate event, on time scales from hours to multiple decades (Shepherd et al., 2018). A variety of different physical storyline approaches have been used in the literature including exploring outcomes conditional to distinct large-scale climatic features, or events that are similar in counterfactual climates, or based on expert judgement. A summary is provided in Box 10.2 in Doblas-Reyes and Sörenssen et al. in IPCC 2021.



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# Annex Guiding Questions

| | | | |
|---|---|---|---|
| Scoping | Objectives | 1 | What is your objective of the CRA? |
| | | 2 | What is the purpose of your CRA? What is the expected outcome? (These two questions should entail a brainstorming exercise on, among other things, an evaluation of the potential climate change impacts on different aspects of society; an estimation of the current and future climate risks; a first prioritization the most significant and urgent risks; inform the development and implementation of adaptation strategies, etc.) |
| | | 3 | How should your objective feed into policy and decision-making? |
| | | 4 | Which limitations and boundaries may the CRA have or do you see the region confronted with in this context? E.g. worst case scenario in the context of adaptation measures? |
| | | 5 | How do your envisaged objectives and envisaged outcomes come together? Does this somehow influence the communication of your results? |
| | Context | 6 | How have climate hazards, risks and impacts been assessed/handled in your region until now? |
| | | 7 | What is the governance context (policies, regulations, legal obligations, strategies, available time and resources etc.) of the assessment? |
| | | 8 | Which regional targets may be impacted by climate hazards/risk? |
| | | 9 | How is your CRA relevant system defined (e.g., systems of interest, affected entities, functions and processes at risk, connections, dependencies, spatial and temporal scales)? |
| | | 10 | Which sectors are relevant in your regions and which ones may be impacted by climate risk? |
| | | 11 | What is your envisaged time horizon for the CRA in terms of risk outcome(s)? E.g. 20 years, 2050, 2100? |
| | | 12 | Where do you place value for your region? What outcome should be avoided with respect to the assigned values? |
| | | 13 | How bad could things plausibly get? |
| | | 14 | Are there known/suspected thresholds or tipping points (environmental/economic/social)? |
| | | 15 | How do you expect your hazards to change in the future? |
| | | 16 | What is your expected tolerance of risk (e.g. heat, drought, flooding) and how may it be helpful or restricting in your CRA process? |



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| | Participation & Ownership | 17 | Who could be important stakeholders/groups to be included for participatory processes? It is helpful to clearly define the set of stakeholders that should be consulted throughout the CRA. However, this set of stakeholders can change throughout the process – especially with the outcome of the climate risk workflows. |
| | | 18 | Who are relevant representatives of known vulnerable groups or exposed areas? |
| | | 19 | How does your legal framework allow the inclusion of key groups? |
| | | 20 | How is the risk assessment ownership regulated? |
| | | 21 | How and who do you want to communicate your results to? |
| Risk Exploration | | 22 | How is the scoping phase applied? Which parts of the scoping phase are relevant for the workflow and scenario selection? |
| | | 23 | How does the existing stakeholder knowledge come into play? |
| | Screen Risks | 24 | Which climate-related hazards and potential risks are relevant for your context?<br>o What is the current situation? Where is the hazard occurring? Who is being affected?<br>o Which hazards are observed/expected for the community/region?<br>o How will this situation evolve in the future (e.g., 10, 20, 50 years)? How may this risk evolution influence your envisaged time horizon defined in the scoping phase?<br>o Do you want to focus on current or future hazards?<br>o Which hazards do you want to cover in this risk assessment? |
| | | 25 | Which data or knowledge do you have on these hazards/impacts/risks? Which data, information or knowledge is further needed? |
| | Choose Workflow | 26 | Having in mind the Scoping phase and including insights from the previous sub-step of exploring risk, which workflows are relevant for your CRA? Why? |
| | Choose Scenario | 27 | Including Scoping considerations and taking advantage of the Technical Choices described in the conceptual Framework part, which scenarios are relevant for your workflows? Why? |
| Risk Analysis | | | Conduct quantitative Risk Analysis (risk workflows) |
| Key Risk Assessment | | 28 | How are risks perceived by stakeholders/experts/relevant groups? What are shortcomings according to these groups? |
| | | 29 | Which stakeholders/experts/relevant groups that have not been identified in the scoping process, may be of relevance now in the light of the Risk Analysis results? |



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| | 30 | Are there adaptation/responses already in place? (e.g. question for stakeholders) |
| | 31 | What response/adaptation actions are already in place? |
| | 32 | When and where do you cross your coping capacity? |
| | 33 | How are the risks affecting stakeholders, systems, sectors or vulnerable groups? |
| | 34 | What are opportunities emerging from the calculated risk(s)? |
| | 35 | Which are the less urgent risks that need to feed into the monitoring process? |
| Risk Severity | 36 | What are relevant stakeholders, experts or representatives that need to be considered? |
| | 37 | How important is financial capacity, income, poverty etc. for the risk severity? Which other indicators may be important for risk severity? |
| | 38 | (optional) What is your region's resilience maturity? How do you evaluate your specific risk outcome in the light of the given resilience maturity? |
| | 39 | What adaptation options are already in place? |
| | 40 | Which risk outcome is acceptable/tolerable/intolerable? |
| Risk Urgency | 41 | How does Risk Severity affect the Risk Urgency? |
| | 42 | Which risks need to be addressed urgently? Which aspects influence the urgency? |
| | 43 | How can you rank your risk outcome (from Risk Analysis/workflows) in an urgency scoring? |
| Monitoring & Evaluation | 44 | Which indicators for your M&E fit your case best? |
| | 45 | What is your envisaged reassessment period for the monitoring climate risks? |
| | 46 | Do you want to focus on the M&E of the risks or also include respective adaptation measures? |
| | 47 | Are both, key and less urgent risks, included? |
| | 48 | How are key risks dealt with? Do necessary steps contribute to alleviation of the identified risk? |
| | 49 | What are key indicators, metrics, methods and means to track the risks, as well as the progress on adaptation and resilience-building? |
| | 50 | What works well? What does not? |



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| | 51 | How do you evaluate the performance in the CRA itself? What could have been improved? Which stakeholders were relevant and should be included more? |
| | 52 | What role do stakeholders play in your M&E (e.g. also in the light of a policy outcome?) |
| | 53 | Is learning ensured? How? |
| | 54 | What is the feedback from stakeholders? |
| | 55 | Is new data available regarding the risks and/or the system? What else is needed (e.g., data, resources, competencies, research) to understand the risks better? |
| | 56 | How do you want to communicate your final outcome? |
| Efficacy | 57 | How efficiently did you use your resources (e.g. time, staff, cost)? |
| | 58 | How might your efficiency/non-efficiency have impacted the CRA process? |
| Impact | 59 | How would you value the impact of the CRA regarding an improved understanding of risk (e.g. public awareness and engagement, institutional capacity, funding and investment)? |
| Usefulness | 60 | How do you evaluate the applicability of the Risk Assessment for CRM practices (e.g. number of times used, acceptance by experts and stakeholder, translation of results into CRM)? |



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