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Advances in complex climate change risk assessment for adaptation

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Recent advances in climate change risk assessment and management and their application across cities, coastal zones, and finance highlight promising opportunities for near-term action to better govern complex climate change risk and advance adaptation implementation. Positioning applications of participatory modeling, climate risk assessment, adaptation pathways planning, and systemic fiscal disaster risk modeling across variations in time, space, and sector, examples point towards more actionable insights and governance conditions to accelerate equitable adaptation and address inaction caused by uncertainty and complexity.

In an increasingly interconnected and globalized world, the impacts of climate change are affecting societies, economies, and the environment. Growing evidence highlights climate change impacts that cascade and compound across time, sectoral and geographical boundaries, and jurisdictions[1]. They expose the vulnerabilities of interdependent social-ecological systems and highlight the need for a systemic understanding of the dynamic nature of complex climate risks to inform adaptation and risk management. These complex dynamics make a full accounting of climate change risks in assessment and adaptation highly challenging[2].

Further, multiple types of societal responses that aim to reduce climate change risks in one system or for one group can exacerbate impacts in another system and other groups[3]. The distributional effects of both climate change impacts[4] and the consequences of responses to them[5]—including inaction, maladaptive or malmitigative responses—highlight the need to reduce prevailing differences in climate change responses, including in the tools and their application to advance more equitable outcomes.

Understanding of complex climate change risks has improved substantially over the last 10 years[6]. Many of these developments have focused on methodological advances, including complex statistical and machine learning methods[7] or on digital risk assessment tools that enable system risk interdependencies to be identified[8]. Policy and practice require clearer insights into the scope of complex climate risk and its integration into adaptation and risk management strategies, planning, and implementation[9].

Effective climate adaptation requires actionable knowledge, but research on climate risks is often inaccessible or impractical for local actors and policymakers due to disconnects between researchers, decision-makers, and governance challenges[10]. Recent methodological advancements aim to bridge this gap by improving risk assessments for real-world implementation. Key approaches include adaptation pathways planning, participatory modeling, and systemic fiscal disaster risk modeling (Fig. 1). These methods, applied to cities, coastal zones, and financial services, seek to generate actionable insights and governance frameworks to accelerate adaptation and address inaction caused by uncertainty and complexity.

Cities

Urban areas are hubs of both complex risks and areas of opportunity for acting at scale on climate change. By 2050, there will be more than 2 billion additional people living in cities, about 90% of which will be in African and Asian cities. This presents uncharted global opportunities for risk-informed urban development. The forthcoming IPCC Special Report on Cities has raised expectations for substantially enhancing awareness, policy, and actions across mitigation and adaptation within cities. Yet there are key climate change risk assessment and management needs for cities that, if filled, could enable adaptations that can be implemented, monitored, and adjusted as the climate changes.

Compound and cascading risks across cities require assessment methodologies that account for interdependencies, uncertainty, and change and are conducted on a whole systems basis. Decision-making under uncertainty methods and tools[11] are increasingly being used in such contexts globally[12] (Box 1). In the New Zealand case, despite progress made to date in using such methods and tools[13], further and ongoing assessment of cascading risks is needed to understand the dependencies and feedback loops across all domains, locations, and timescales for effective climate change adaptation[14]. Pathways planning, including DAPP and other DMDU methodologies, offers a useful approach to do this for cities and infrastructure planning. Through the identification and assessment of alternative sequences of measures in response to different future scenarios, pathways allow for robust decision-making over different timeframes, depending on the decision lifetime, for progressive, flexible implementation across multiple different sectors or systems at risk. It also allows for iterative pathway updates informed by monitoring, evaluation, and learning that reflect changes in climate change risk as finer resolution projections evolve. A multi-sectoral perspective using a pathways framework can analyze system interconnectivity and better manage cascading risks by asking under what conditions an adaptation option may fail to deliver on objectives—this may be imminent or at some time in the future.

Coastal zones

Multiple meters of sea-level rise are projected over the coming decades and centuries, even at the current level of global warming (+1.2 °C above

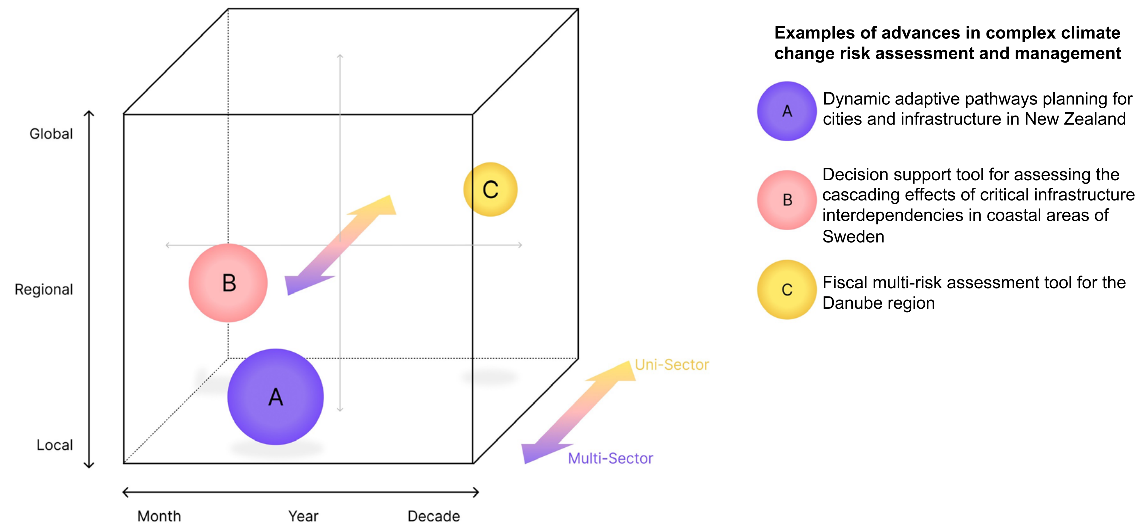

Fig. 1 | Examples of methodological advances in complex climate change risk assessment and where they place focus across different geographic, temporal, and sectoral dimensions. The cross-scale nature of examples highlights the diversity and multi-level requirements of climate risk information for decision making.

Box 1 | Climate change risk assessment for cities and infrastructure in New Zealand

The first New Zealand National Climate Change Risk Assessment 2020 (NCCRA) identified ten priority risks across natural, human, economy, and built environment domains, and included the effect of cascading impacts and descriptions of dependencies between these risks. This informed a review of current and planned adaptation action based on decision urgency, where early action would avoid being locked into an undesirable or current pathway; where action required a long lead time; and where actions had long-term implications. It also recognized the risk of maladaptation where conventional adaptation planning and risk assessment practices, processes, and tools do not account for uncertainty and change over long timeframes.

The NCCRA informs adaptation options for multiple sectors across infrastructure, transport networks, energy and telecommunications with attention to the greatest impact on marginalized people. This reflects recognition of the increasing costs that extreme events are placing on the State, communities and individuals, particularly for provision of safe water supplies, wastewater and stormwater on top of aging infrastructure.

The NCCRA also identified governance as the key enabler for adaptation action with specific reference to the need for new institutional arrangements across legislative and decision-making frameworks, coordination within and across levels of government, and funding mechanisms. The National Adaptation Plan that followed, enabled by the Climate Change Response Act[47], provides the governance architecture for adaptation implementation, with the funding mechanism yet to be added via a proposed Adaptation Act.

Several recent examples in New Zealand are using Dynamic Adaptive Pathways Planning (DAPP)[13] to assess the strategic options for water supply, wastewater, and stormwater management affected by multiple hazards, including sea-level rise and rising groundwater[48]. Having a robust set of alternative pathways gives decision makers options for the future, depending on how that future unfolds, before adaptation thresholds are reached, and with appropriate lead-time for implementation. To decide which alternative pathway needs to be taken, and when, is informed by monitoring, evaluation, and learning. While there is no set time frame in which monitoring activities should occur, between 6 months to annual cycles ensures updated climate risk information is fed into the planning process[44]. Doing this within the DAPP framework enables decision makers to explore the sensitivity of different adaptation options to a range of plausible climate futures and to potential surprises occurring at different times in the future. This enables a better understanding of the risks of locking in inflexible adaptation options in the short-term that increase risk over time and spatially, so that decisions can be made now that retain flexibility to change in the future.

pre-industrial)[15]. By 2100, the global increase in coastal and fluvial flooding is projected to affect up to 880 million people and USD 14,178 billion in assets[16]. Additionally, approximately a billion people are projected to be at risk from coastal-specific climate hazards in the mid-term, regardless of the climate change scenario[16]. Coastal zones need decision-support tools that are user-friendly and tailored to their local climate adaptation needs, where the immediate effects are manifest. Such tools can help identify which infrastructures should be prioritized for adaptation investment and strategies to maximize resilience in coastal areas.

Societies increasingly rely on interconnected infrastructure to sustain economies and well-being, yet cascading effects from multiple coastal hazards present severe challenges. While several methods assess societal interdependencies, practical implementation for climate change risks remains limited. The lack of data on infrastructure, assets, and human impacts, as well as optimal response options, is a considerable challenge to risk assessments, but these can be mitigated through effective stakeholder involvement and transparent systems of data sharing and new methods (Box 2). The variety of systems interactions and possible cascading effects

Box 2 | Assessing cascading effects from critical infrastructure interdependencies in coastal areas in Sweden

A decision-support tool has been developed to assist in prioritizing climate adaptation investments for effective short-term cascading risk planning at regional scales, involving multiple stakeholders within the infrastructure sectors[49]. This hydrometeorological resilience assessment tool addresses systemic vulnerabilities arising from infrastructure interdependencies, which can lead to potential cascading risks when these infrastructures are exposed to flood hazards.

Applying the tool in Halmstad, Sweden, generated detailed maps of infrastructure networks and hydrometeorological risk areas, enabling planners to simulate node failures across sectors and visualize cascading risk metrics. This adaptation support helped prioritize critical and social infrastructure to mitigate systemic impacts efficiently. Users transitioned from general hazard awareness to a more concrete, actionable understanding of risk. This tool is tailored for regional managers to understand systemic climate risks before focusing on more localized solutions to address infrastructure vulnerabilities. It is particularly suitable for supporting short-term planning decisions, as it is designed as a pragmatic tool focused on identifying immediate actions and measures to improve systemic resilience.

The application of the tool assisted local planners in developing the municipality's climate adaptation strategy, by including public utilities under risks that were previously overlooked[49]. For instance, a wastewater treatment plant at risk of coastal flooding and a power plant vulnerable to river flooding were identified as critical infrastructures requiring prioritized flood protection measures in the municipality's adaptation strategy, due to their high disruptive potential. Implementation gaps for adaptation involve increasing collaboration and data sharing between sectors to improve interdependency mapping, recommendation of measures that are tailored for specific infrastructure types, and consideration of more detailed flood hazard characteristics, such as flood depths and flow velocities, for risk evaluation.

that need to be accounted for when managing climate risks in complex systems, including accounting for the impacts of climate change on ecological infrastructure, demand tools such as network-based models that planners can use to understand the range of potential harmful consequences of climate change risks. Conceptual models of risks, such as causal loop diagrams, climate impact chains, and fuzzy cognitive mapping, offer similar benefits by characterizing interactions of different elements at risk to enhance understanding of the systems under investigation[17]. These methods, which often model feedback loops, nonlinear interactions, and cascading effects of risks and responses, offer strong integration with stakeholder perspectives, which helps to identify key system elements that stakeholders perceive as important to protect.

Public finance and insurance

Climate change is driving disaster losses and is thus considered a major concern for insurers, reinsurers, and public finance[16]. Disaster and climate risk have been shown to adversely impact sovereign debt as well as creditworthiness[18] and subsequently the cost of public borrowing, leading to further negative cascading impacts across the public position and the overall economy[19]. The growing pressures from physical climate change impacts and necessary policy responses on transition risks for the finance sector, with flow-on effects to the wider economies of nations, are driving a focus on the role of the private sector in adaptation, funding, and implementation[20]. This realization will become increasingly transparent as the private sector reports on the impacts of climate change on its businesses. For instance, insurance industry compensation for climate-related insured losses now regularly exceeds $100 billion a year[21], increasingly rendering some places uninsurable[22].

National governments are key risk bearers, with increasingly interconnected climate and other types of risks, challenging fiscal and economic stability. They are generally not only responsible for financing public sector losses but also for assisting with private sector and household damages for the vulnerable or to support economic recovery and rehabilitation post-disaster. Usually, governments fund post-disaster contingencies ex-post through ad-hoc measures such as budget diversion or proactively ex-ante through catastrophe funds, sovereign insurance (including regional insurance pools e.g., Caribbean Catastrophe Risk Insurance Facility Segregated Portfolio Company and the African Risk Capacity), contingent credit lines offered by development banks, or regional ex-post reserve funds for impact cost sharing (European Union Solidarity Fund)[23]. Fiscal resources available are also dependent on overall macroeconomic conditions and, therefore, closely linked to other risk realizations.

Finance and insurance sector is heavily exposed, and thus also driven towards innovation in addressing complex climate risks through sector-specific approaches, including microfinance, sustainability-linked loans, catastrophe bonds, and weather index insurance[24], with varying degrees of accessibility, impact, and appropriateness across different hazard and socio-economic contexts[25]. Yet, given solvency pressures from increases in risks associated with regard to climate change, the sector has been considering extending the business model of insurance so risks get uninsurable (e.g., due to large uncertainties), too costly (e.g., due to massively increased losses), or unmanageable (e.g., due to hazard and risk interdependencies)[26]. Extensions to the business model considered include more effective risk signaling, enhanced risk reduction efforts, as well as decreases in exposure to risk[22]. In addition, governments, insurers/reinsurers, as well as banks can support the management of complex climate risks through new public-private partnerships and by including sustainability dimensions explicitly in finance portfolios[27]. However, in terms of providing (or rejecting) insurance cover to households, industry, and governments, the traditional (re)insurance pricing and underwriting model of single-hazard coverage remains intact, while compounding, repeating, and cascading impacts in some regions can be covered by business interruption policies[28].

Integrating risk dynamics into budget planning can better link risk assessment with risk management and adaptation strategies that would eventually require regional and global pooling arrangements to deal with these future risks effectively. For example, fiscal stress estimations (Box 3), can be further aligned with a risk-layer approach to determine strategies for both risk reduction and risk financing based on the frequency and scale of the natural hazard event. Enhancing public-private partnerships is essential to prevent insurance schemes from becoming unaffordable or unavailable. The resulting financial effect on governments through their contingent, explicit, and moral liabilities only strengthens the call to increase such efforts

Box 3 | Fiscal resilience in the Danube region in the context of multi-risks

In Europe, the Danube Region comprises 14 countries with varying levels of fiscal resilience and exposure to different natural hazards. A "fiscal resource gap" has been estimated in this region to understand fiscal resilience to multi-hazard events[34]. It estimates the return period of loss events for which a country would not be able to finance its losses. Such a stress testing methodology builds and extends the risk assessment of disasters by indicating thresholds when governments are challenged in meeting the demands for funding and must think about other options. Due to the focus on governments and budget planning processes, the approach can be positioned at the country as well as the regional level (considering cross-scale socio-economic interdependencies), focusing on annual and decadal timescales, centered on the financial sector as a key entry point for dealing with complexities involved with the management of such multi-hazards and risks.

The approach provides a differentiated picture with certain countries exhibiting high fiscal resilience, with fiscal resource gaps emerging only at longer return periods (e.g., Germany), while others, such as Serbia, Hungary, and Slovakia, experience these gaps more frequently. The analysis also reveals that fiscal gaps arise sooner when multiple hazards-risks are considered, as opposed to individual risks. Additionally, fiscal gaps are more pronounced when considering disaster risk types beyond natural hazard types, such as pandemics, and when including their potential impact on finance-related adaptation. As the approach is standardized, the results can be applied to the global scale as well. Importantly, complex climate risks in the context of fiscal resilience are closely related to other types of risks and finance instruments (such as the European Solidarity Fund that helps governments funding gaps in the emergency phase) need to account for these dependencies, as else, they would fail exactly at the time of need[34].

in the future. Both public and private finance play a specific role in adaptation. This ranges from regulatory measures and providing incentives for risk reduction to the inclusion of risks within budgetary as well as business practices. Due to the large uncertainties, continuous updating and careful navigation through the uncertainty space is needed, with new approaches such as Storylines and DAPP-multi risk, to be applied to reduce complexity to manageable steps. DAPP-Multi Risk (DAPP-MR) is an extension of the DAPP framework, designed to support decision-making under conditions of deep uncertainty in complex, multi-risk systems[29]. While the original DAPP approach helps identify flexible and robust adaptation strategies over time by mapping out sequences of actions (or "pathways") and their associated tipping points, DAPP-MR expands this by explicitly accounting for multiple interacting hazards (e.g., floods and droughts), cross-sectoral dependencies (e.g., between agriculture, housing, and shipping), temporal dynamics (how risks and decisions evolve over time), and nonlinear feedbacks between sectors and risks[29].

Governing and enabling adaptation

Emerging lessons across cities, coasts, and in the financial sector highlight at least five key enablers that need to be considered to govern for more equitable outcomes, given challenges of complex climate change risk management and adaptation across sectors, scale, and time:

1. Integrate equity considerations in planning and implementation.
2. Action in the short term needs to avoid long-term lock-in and maladaptation.
3. Invest in accessible and actionable knowledge.
4. Integrate diverse and multi-disciplinary knowledge.
5. Assess local dimensions of adaptation feasibility.

Firstly, it is imperative that adaptation integrates equity considerations in planning and implementation. This is critical as land-use planning in cities across the world has reproduced uneven exposure and socio-economic vulnerability when it does not consider who benefits or loses from adaptation[30]. The distribution of resources, benefits, and burdens associated with adaptation strategies often reflects existing power imbalances, which can result in marginalization of vulnerable communities. To overcome this, adaptation strategies must prioritize fairness and ensure that the voices and needs of all stakeholders, particularly those most affected by climate change risks, are integrated into decision-making processes[4]. Drawing on lessons from the methodological advances presented in Fig. 1, assessing cascading effects from critical infrastructures can contribute to more equitable outcomes in climate change adaptation in coastal zones by focusing on residential areas that are most vulnerable. City planning, for example, often neglects poorer areas or informal settlements where higher numbers of migrant populations tend to live, resulting in a higher likelihood of these areas being cut off from critical infrastructure such as healthcare facilities during floods[31–33]. Thus, such a tool helps identify inequities in exposure and access to essential services and supports targeted adaptation investments in underserved or high-risk communities. DAPP also addresses these concerns through including marginalized and vulnerable communities in the risks and adaptation options identification processes (e.g., scoping when a certain community faces what they consider unacceptable risk), through consideration of local knowledge and values in assessment, and through co-production of solutions, which enhances legitimacy and fairness[13]. At national and regional levels, fiscal stress testing explicitly acknowledge the disparities between governments' abilities to absorb and respond to shocks[34]. This information can also provide evidence for more equitable allocation of adaptation finance, especially to countries with high exposure and low fiscal capacity. Similarly, with no disaster insurance market fully reliant on a purely risk-based premium model, there is scope for providing explicit insurance premium subsidies or implicitly through spatial risk pooling between high and low hazard zones[18,35].

Secondly, action in the short term needs to avoid long-term lock-in and maladaptation. Traditionally, risk management strategies are often subject to path dependencies and lock-ins, such as for insurance, which makes it difficult to apply them in the context of complex climate risks, which are dynamic, require a longer-term outlook, and need pathway planning to deal with uncertainty[36]. It is critical to understand that climate risk can emerge from currently available pathways that reach their limits at higher warming levels, from inappropriate adaptation responses to climate change, as well as from inaction. Adaptation options that limit flexibility can create a false sense of security and increase residual risks due to engendering more development when the adaptation measure fails (e.g., levee effect). Dynamic adaptive decision making is essential to manage uncertainties and changing risks, using tools that enable adaptation options to be stress-tested using different scenarios of future conditions. This gives decision makers better information of the risks they face and for deciding what level of risk can be appropriate for each locality. For example, the DAPP method includes sets of different adaptation options and pathways that can be implemented when information on risks are known[29]. The options and pathways can be integrated with community values, vulnerabilities, and government standards, starting with low-regret actions and scaling up as capacity grows[29]. This avoids the least desirable options and pathways, such as those that are very high cost or come with more severe trade-offs, until necessary. Fiscal multi-risk stress testing and assessing cascading effects of critical infrastructure are also helpful in this regard, as they help avoid maladaptation associated with siloed planning and encourage cross-sectoral coordination, helping governments avoid overcommitting to sunk investments in costly adaptation measures[34].

Thirdly, communication of and the accessibility of actionable knowledge requires substantial investments in public understanding of climate risk and feasible adaptation options as well as sector-specific understanding of how climate impacts manifest in compounding and cascading ways through ongoing capacity building amongst public, advisors, practitioners, and decision-makers[37]. Investment in more equitable distributions of climate change literacy is critical because deficits in climate change literacy can amplify existing and historical injustices and prevailing inequities in adaptation capacity associated with how best to make informed responses to climate change[38–40]. Action-based early warning systems (e.g., via signals and triggers monitored in an adaptation plan[41]) can provide essential information for how knowledge on risks is understood and responded to. This can include provision of nationally consistent risk information through agreed methodologies for risk assessment that address non-stationarity; targeted research on projected scope and scale of cascading and compounding risks; and education, training, and professional development for adaptation under changing risk conditions. For example, DAAP achieves this through the use of serious games, scenario-based learning, through making climate change risks more tangible and time-bound, and through integrating local observations and community feedback[42]. Assessment of critical infrastructures enhances public understanding of climate change risk through helping the public and decision-makers visualize how one failure can trigger others, making climate risks more tangible. This also includes the provision of public information on insurance premiums a fiscal risks for current and future multi-hazard events, e.g., using traffic light approaches to visually represent the urgency and need for assessing and managing hazards and their interactions[34].

Fourth, integration of diverse and multi-disciplinary knowledge into assessment processes is important to undertake culturally appropriate assessments. This includes opening avenues for different ontological understandings (e.g., integration of Indigenous and local knowledges) in risk understanding, and transitioning from centralized to locally-led adaptation processes[43]. For example, DAPP enhances the integration of diverse and multi-disciplinary knowledge in climate change adaptation by creating a structured, inclusive, and iterative decision-making process[12,44]. It brings together scientists, policymakers, engineers, community leaders, and NGOs; it facilitates knowledge co-production, where different types of expertise are valued equally and DAAP builds shared understanding and trust across disciplines and sectors[12,13]. The finance and fiscal sectors are intrinsically connected with many other sectors, either as enablers for investment as well as steering risk reduction and financing efforts to manage risks across sectors. This necessitates an integrated and multi-disciplinary perspective that has to include not only quantitative but also qualitative dimensions within the decision-making process, for example, using knowledge co-development processes[45].

A fifth key factor concerns adequate assessment of local dimensions of adaptation feasibility. Adaptation options that are effective in one context may or may not be suited to other contexts[46]. Assessing local dimensions of adaptation feasibility ensures necessary steps are taken for assessment and tools to be applied in diverse contexts, particularly including capacity, technology, and finance in lower-resourced groups and regions. For example, the DAAP approach goes beyond assessing the effectiveness of adaptation options. It also considers how local financial (e.g., cost-effectiveness and funding availability), social and cultural acceptability (e.g., community support and consideration of equity impacts), institutional/governance (e.g., policy alignment and administrative capacity), and technological conditions (e.g., availability of technology and expertise)—especially in diverse and resource-constrained contexts—will affect adaptation options and the pathways they afford[13]. Feasibility is notoriously linked to public and private finance, which highlights adaptation funding frameworks needed to increase investment in adaptation actions; new public and private-sector financial instruments to support adaptation; and institutional frameworks integrated across all levels of government (horizontally and vertically) for better coordination. A risk-layering approach often used for fiscal multi-risk stress testing and assessments allows local governments to match adaptation options (e.g., infrastructure, insurance, contingency funds) to the type and scale of risk they face, which allows prioritization of cost-effective and feasible solutions based on fiscal capacity and risk exposure over different timeframes.

Data availability

No new data sets were created.

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Competing interests
The authors declare no competing interests.

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