HP 4 THEMATIC SERIES

HOW MINISTRIES OF FINANCE CAN ASSESS AND MANAGE PHYSICAL CLIMATE RISKS AND ADAPTATION

Available analytical tools and emerging good practice

JUNE 2025

A report of the Coalition of Finance Ministers for Climate Action Helsinki Principle 4 initiative: Economic Analysis for Green and Resilient Transitions

About this report

This publication is a product of the Helsinki Principle 4 (HP4) workstream under the Coalition of Finance Ministers for Climate Action. The overall aim of HP4 is to mainstream climate action into economic and fiscal policy. The report forms part of an effort focused to improve macroeconomic analysis and modeling tools for Ministries of Finance (MoFs) to drive climate action, including the capacity to assess the economic impacts of physical climate risk, climate mitigation, and adaptation measures.

The impacts of climate change are visible around the world, as communities and economies face new heat records, unprecedented extreme rainfall events, severe droughts, and catastrophic storms. Without action, physical climate risks will pose ever-growing macro-critical risks. MoFs face an escalating need for public expenditures to deal with extreme climate shocks or chronic events, such as droughts and sea level rise, with physical impacts already putting at risk economic development strategies as well as investments into the green transition. Any further warming will accelerate the various transmission channels that exist between the physical climate and our economic systems.

This report reflects on the most pertinent physical risk and adaptation questions for MoFs and explores tools and methods to help those working on the core functions of public finance to understand the scale of the physical risk challenge today and in the future, including what this means for their different areas of responsibility. It illustrates the current landscape of existing tools and methods available to MoFs, and provides examples of analysis in practice, before outlining lessons learned, challenges with existing tools, and how to overcome them. The report concludes with recommendations for practitioners, those developing economic tools, and end users, with a list of available tools provided in the Appendix.

A number of contributions to the Compendium of Practice that also forms part of this work program have been incorporated into the report (see Table A). As well as the Compendium, the report is complemented by a range of other reports, including a survey of the world's MoFs, an overview of the analytical tools available to MoFs, and further thematic reports in areas related to the pressing climate policy needs of MoFs. A summary of the overall program objectives is also captured in a separate report.

This report was developed by the Grantham Research Institute on Climate Change and the Environment at the London School of Economics and Political Science (LSE) in collaboration with the Coalition of Finance Ministers for Climate Action. The principal authors are Professor Swenja Surminski (Grantham Research Institute/Marsh McLennan) and Daniela Baeza Breinbauer (Grantham Research Institute). Project team support was provided by Hipolito Talbot-Wright, Nick Godfrey and Anika Heckwolf (all Grantham Research Institute), Dr Andy King (Flint Global), and Dr John Asafu-Adjaye (African Centre for Economic Transformation), with guidance from Mads Libergren (Ministry of Finance of Denmark). It benefited from review contributions from Dr Jane Mariara (Partnership for Economic Policy), Dr Benjamin Lerch (Swiss Federal Department of Finance), Ariana Jessa (UK Climate Change Committee), Daisy Jameson (Grantham Research Institute), Aurelien Billot, Simon Black, and Emanuele Massetti (all Fiscal Affairs Department of the International Monetary Fund), and the members of the Steering Group and Technical Advisory Group. We also extend our gratitude to the many individuals and institutions who contributed to the Compendium of Practice that supported this workstream. The report was edited by Georgina Kyriacou and Paul Fishman, and designed by Zoe Kay.

About this report

Table A. Compendium of Practice contributions

Institution	Authors	Title
European Union—European Commission	Diana Radu	A structured approach to disaster risk financing in the EU Member States
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)	Naima Abdulle, Sebastian Homm, Christian Fischle, Victoria Montenegro	Modeling climate-resilient economic development: GIZ's approach to supporting sustainable economic growth
IMF Fiscal Affairs Department	Emanuele Massetti	The critical role of Ministries of Finance in investment in adaptation and the analytical principles and tools available
London School of Hygiene & Tropical Medicine	Andrew Haines	The health co-benefits of climate change mitigation: why climate leadership by Ministries of Finance can help them to deliver on their core objectives of economic development and responsible management of public finances
Grantham Research Institute on Climate Change and the Environment	David Stainforth	Climate tipping points
ETH Zürich	Lint Barrage	Latest developments in upgrading DICE-2023: findings and implications for Ministries of Finance
ETH Zürich	Lint Barrage	New approaches to quantifying the fiscal impacts of physical climate change
University of East Anglia	Rachel Warren	Methodological recommendations for Ministries of Finance on climate change risk assessment and the enhancement of damage functions
Marsh McLennan	Swenja Surminski	How the analytical tools and methods used in the (re) insurance industry can support Ministries of Finance in their understanding of physical climate risks and their efforts to support climate adaptation
Munich Climate Insurance Initiative (MCII)	Florian Waldschmidt, Soenke Kreft	Showcasing CLIMADA
IMF Fiscal Affairs Department	Carolina Renteria, Tjeerd Tim	Fiscal risks of climate change: Quantitative Climate Change Risk Assessment Fiscal Tool (Q-CRAFT)
Network for Greening the Financial System (NGFS)	Thomas Allen, Benjamin Alford, Léopold Gosset	The NGFS's approach to the macroeconomic assessment of physical risks
Network for Greening the Financial System (NGFS)	Thomas Allen, Benjamin Alford, Paul Champey	The NGFS's approach to modeling the short-term macroeconomic implications of climate change and the transition
Network for Greening the Financial System (NGFS)	Thomas Allen, Benjamin Alford, Paul Champey	Short-term climate scenarios
Insurance Development Forum	Nick Moody	Support for sovereign climate and disaster risk functions: the Global Risk Modelling Alliance
Finland—Prime Minister's Office	Saara Tamminen, Kristiina Niikkonen	Improving the inclusion of nature and ecosystem service impacts in assessments of the economic impacts of climate risk by Ministries of Finance and economic decision-makers: the experience of Finland

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Table A. (continued)

Institution	Authors	Title
Canada—Department of Finance		The challenges of uncertainty in climate-economy modeling
Paul Watkiss Associates	Paul Watkiss	Global adaptation finance costs, the adaptation finance gap, and adaptation investment planning
Morocco—Ministry of Finance		Models for evaluating policies to mitigate greenhouse gas emissions and adapt to climate change in Morocco
World Resources Institute (WRI)	Vanessa Pérez-Cirera, Luis Miguel Galindo, Rajat Shrestha	Informing economic modeling approaches for effective climate transitions
World Bank		Strategic climate risk modeling for economic resilience: a guide for Ministries of Finance
C3A	Etienne Espagne, William Hynes, Kevin Carey	C3A's assessment of the emerging analytical needs of Ministries of Finance: opportunities and challenges

Disclaimer

This report was prepared at the request of, and with guidance from, the Ministry of Finance of Denmark as Lead of the Coalition's Helsinki Principle 4 initiative 'Economic Analysis for Green and Resilient Transitions' and its Steering Group, with input from its Technical Advisory Group. The views, findings, interpretations, and conclusions expressed are a synthesis of the diverse views of the authors, contributors, and reviewers. While many Coalition members and partners may support the general thrust of the arguments, findings, and recommendations made in this report, the report does not necessarily reflect the views of the Coalition, its members, or the affiliations of the authors, nor does it represent an endorsement of any of the views expressed herein by any individual Member.

Suggested citation: Coalition of Finance Ministers for Climate Action (2025) *How Ministries of Finance Can Assess and Manage Physical Climate Risks and Adaptation: Available Analytical Tools and Emerging Good Practice.* Report for the HP4 initiative 'Economic Analysis for Green and Resilient Transitions'.

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The physical impacts of climate change have become a macro-relevant and, for some countries, a macro-critical issue, significantly affecting the responsibilities of Ministries of Finance (MoFs) worldwide. These impacts can directly damage physical assets and infrastructure, with significant harm to public sector, household, and firm balance sheets, while having wider systemic effects that disrupt livelihoods and economic activities, with consequences for fiscal policy, growth, employment, trade, inflation, and access to health and education. These impacts can also further threaten the stability of the public finances, as well as the broader stability of financial systems, as cascading effects propagate through the system when loan or insurance mechanisms lack sufficient coverage.

It is increasingly important for MoFs to take strong action to address and respond to these risks. However, to build resilience and promote adaptation effectively, MoFs need to be able to answer the pressing policy questions facing them.

This report categorizes the potential role of Ministries of Finance in building resilience and adaptation, as well as the relevant policy questions that need to be answered, in three key areas:

- **First, MoFs face questions regarding the direct and indirect economic and fiscal consequences of physical risks**. To manage climate risks effectively, MoFs can benefit from a comprehensive understanding of current and future climate hazards, risk drivers, and impacts on the economy, public finances, and financial sector. This can allow MoFs to be better prepared to protect their economies from the negative consequences of climate change, for which they have a wide array of economic and fiscal policy tools and financial instruments available.
- **Second, moving beyond assessing physical risks, MoFs can play an important role in government efforts on adaptation**, defined as adjusting to the actual or expected effects of climate change to enhance resilience and reduce harm from long-term climatic change and more frequent extreme weather events. Assessing the costs and benefits of investment in adaptation to enhance resilience is critical across all climate scenarios and can be integrated with mitigation efforts to ensure a successful green transition. While effective adaptation requires a multisectoral approach because climate risks are deeply interconnected with sectors such as agriculture, health, and finance, MoFs play a central role in driving adaptation both within their core functions and across government. MoFs can develop targeted fiscal policies and invest in resilience to safeguard fiscal stability. Given the fiscal constraints and the multiple priorities facing MoFs, they can benefit from a robust understanding of the effects of adaptation on fiscal policy and the financial sector, and its broader macroeconomic implications.
- **Third, adaptation requires substantial investment from both public and private sectors, with MoFs playing a key role in assessing funding needs and determining how to mobilize public and private resources**. By leveraging economic policy options and financial instruments, MoFs can also incentivize private investment to finance adaptation. Understanding the magnitude and financial implications of financing adaptation is key to assessing and mobilizing investment.

To assess the impacts of physical climate risks and adaptation measures, build resilience, and develop robust adaptation strategies, MoFs can leverage a diverse array of economic analysis and modeling tools that offer valuable insights to inform decision-making tools, models and case studies.

A wide array of tools are available, as covered in this report, including:

- **Multiple tools that draw on models focused on climate hazards and link them with models that assess the economy to understand the overall economic implications of climate physical risks.** Such models include integrated assessment models (IAMs), catastrophe models, and loss and damage assessments.

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- **Tools to identify and quantify potential adaptation solutions,** covering both bottom-up approaches, where adaptation options, costs, and benefits are explicitly modeled at the local level, and top-down approaches, where adaptation is assessed empirically by observing differences in climate vulnerability across regions. This includes utilizing cost–benefit analysis and real options analysis to evaluate the economic trade-offs of different adaptation strategies or manage the uncertainties behind future climate change physical risks.
- **Multiple tools and frameworks that can help assess financing requirements and aid MoFs in understanding how to finance adaptation**. This includes assessing gaps in adaptation plans and accounting for climate change adaptation expenditure in the budget through methodologies such as climate budget tagging (CBT), climate public expenditure and institutional review (CPEIR), and public expenditure and financial accountability—climate (PEFA-C). When developing disaster risk finance approaches, methodologies such as risk layering can help MoFs determine whether it is more appropriate for them to reduce risk, insure against risk, or compensate stakeholders in the event of a disaster.

While climate risk modeling and analysis are still evolving, open-source tools, and global institutions and initiatives, are increasingly providing access to valuable resources, alongside a growing set of examples from countries and institutions.

The report draws on case study examples of analysis in practice provided by more than 20 contributions to the overall program's Compendium of Practice. The report highlights how these examples can guide and inform effective decision-making and adaptation strategies. The report also:

- Illustrates example case studies, tools, and approaches for identifying and quantifying current and future physical climate impacts on the macroeconomy and public finances
- Provides detailed instructions for various tools and models for the estimation of physical climate risk and macroeconomic outcomes relevant for MoFs: (1) IAMs; (2) social accounting matrices; (3) scenario-based approaches; (4) catastrophe models; (5) loss and damage assessments; (6) extreme event attribution; (7) asset-level analysis; and (8) impact chain frameworks
- Outlines example case studies, tools, and approaches for identifying and quantifying potential adaptation solutions to manage physical risks
- Details example case studies, tools, and approaches designed to help MoFs decide how to finance adaptation.

While analytical and modeling challenges remain, it is critical for MoFs to take early action to invest in analytical capability, collaborate with researchers, and expand their understanding of options for investing in adaptation.

Lastly, while using macroeconomic tools and models can provide valuable insights for policymakers, the scale, urgency, and complexity of physical climate risks require engagement and cooperation across government. This report therefore emphasizes the need for closer engagement between modelers and policymakers within MoFs and across government to better integrate climate risks into fiscal policies and meet the demands of practical decision-making. Moreover, it emphasizes the importance of cross-government coordination and capacity-building efforts to improve climate risk management, with opportunities for collaboration and knowledge exchange helping to bridge gaps between expertise and resources. Neither advice on which tools, data, and models are most useful for MoFs nor guidance on what approaches they should avoid are currently widely available. The Coalition's Community of Practice is designed to help address this gap and we hope that this report can serve as a starting point for these discussions.

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Conclusions

- **Prompt policy decisions regarding the management of physical climate risks through adaptation are crucial**. However, without clearly defined adaptation objectives, the answer to 'how much adaptation?' often remains subjective and normative. Ministries of Finance have an important role to play by:
  - Identifying and assessing current and future physical climate risks and their impacts on the macroeconomy and public finances
  - Identifying and evaluating potential adaptation solutions and their costs and benefits
  - Determining financing mechanisms for adaptation.
- **MoFs need to act now to improve their understanding of physical climate risks and their economic and fiscal consequences**. A good first step to incorporate analytical tools for physical risk would be to invest in improved tools and data collection that accurately reflect the economic impacts of climate change, including updated damage functions and models that account for non-linear relationships and tipping points.
- **Users in MoFs should acknowledge the limitations of their analytical tools and assess their effectiveness, but uncertainty should not prevent action**. It is crucial to balance detailed analytics with practical, policy-focused analysis, as the costs of inaction are high. This involves implementing low- and no-regret actions that provide economic and social benefits despite climate uncertainty.
- **The integration of adaptation into macroeconomic assessments remains a developing area, with a variety of both bottom-up and top-down modeling strategies providing initial frameworks for commencement**. Nine tools and models for assessing physical climate risk and its macroeconomic implications are:
  - Integrated assessment models (IAMs)
  - Input–output models
  - Computable general equilibrium (CGE) models
  - Scenario-based approaches
  - Catastrophe models
  - Loss and damage assessments
  - Extreme event attribution
  - Asset-level analysis
  - Impact chain frameworks.
- **Damage functions are a core element of the climate risk analysis that MoFs undertake, for example when using IAMs such as the dynamic integrated climate–economy (DICE) model**. It is essential for MoFs to acknowledge that current damage functions tend to undervalue the economic repercussions of physical climate risks due to the constraints of existing methodologies.
- **MoFs need tools and strategies to address common policy questions, particularly:**
  - Integrating adaptation into macroeconomic evaluations
  - Managing uncertainty in climate projections and economic responses
  - Overcoming the focus on addressing or reducing risks rather than retrospective response to impacts
  - Incorporating non-linear effects and tipping points

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    - Capturing the complexity of compound and cascading impacts across systems
    - Broadening analysis to include compounding shocks, adaptation limits, and ecological system interactions.
- **Analyzing the economics of adaptation requires a collaborative approach**, combining engineering studies to assess adaptation types and their effectiveness with economic evaluations of costs and benefits. Open-source resources such as the CLIMADA tool support climate adaptation strategies by simulating the economic impacts of extreme weather events.
- **Investing in adaptation offers co-benefits, often referred to as 'triple dividends,' and highlights the important connections between adaptation, mitigation, and development investments**. However, these aspects are frequently ignored in analyses conducted by MoFs or lack clear definitions. Only climate-resilient development investments that incorporate current and future physical risk trends contribute to adaptation efforts.
- **Data and tools alone cannot improve decision-making in MoFs**. Clear communication between analysts and policymakers is essential. Additionally, managing physical risks overlaps with other policy areas, often resulting in unclear risk ownership. MoFs can promote coordination among departments for climate adaptation and encourage collaboration and knowledge-sharing with those assessing physical risks and adaptation.

1. Introduction

To date, 2024 is regarded as the warmest year on record, with temperatures exceeding 1.5°C above the preindustrial average. The impacts have been visible around the world, as communities and economies face new heat records, unprecedented extreme rainfall events, severe droughts, and catastrophic storms. Without action, physical climate risks will pose ever-growing macro-critical risks for economies and public finances. Economic development strategies and investments in the green transition will continue to be under threat from the physical impacts, while Ministries of Finance (MoFs) face an escalating need for public expenditure to deal with extreme climate shocks or chronic events, such as droughts and sea level rise. Any further warming will accelerate the various transmission channels that exist between the physical climate and our economic systems, with the risk of irreversible changes occurring or tipping points being breached increasing with every additional 0.1°C above a 1.5°C temperature rise (Moller et al., 2024).

For MoFs this raises a range of policy challenges:

- What impact does a changing climate have on the economy now and over different time periods, and what is the cost of action versus inaction?
- What could be the scale of costs to public budgets from more frequent severe extreme events?
- What should be set aside in terms of public sector financing for contingencies?
- How much should be invested in resilient transitions, and how should this be paid for?
- What new sources of revenue are needed?
- How can investment be balanced with other development needs with limited fiscal space?

The purpose of this report is to provide MoFs with a structured framework to integrate enhanced understanding and assessment of, and response options for, the challenges posed by physical climate risks into macroeconomic policy. The report systematically presents tools for quantifying physical climate risks, assessing adaptation solutions, and financing adaptation efforts, ensuring that MoFs have access to relevant methodologies for informed decision-making.

In this pursuit, the report starts with a reflection on the most pertinent challenges physical climate risks pose for MoFs in Section 2. Section 3 then discusses how MoFs can respond to these challenges in three clear steps: establishing the magnitude of risks, evaluating solutions, and identifying how to finance them. Section 4 then provides insights from a comprehensive survey of 59 MoFs (see CFMCA, 2025a).

Sections 5–7 illustrate the current landscape of existing tools and methods available to MoFs, drawing on case study examples of analysis in practice provided by 22 contributions to the team's Compendium of Practice (CFMCA, 2025b). Specifically, Section 5 illustrates example case studies, tools, and approaches for identifying and quantifying current and future physical climate impacts on the macroeconomy and public finances. Detailed instructions are provided for several tools and models for the estimation of physical climate risk and macroeconomic outcomes relevant for MoFs: (1) integrated assessment models (IAMs); (2) social accounting matrices; (3) scenario-based approaches; (4) catastrophe models; (5) loss and damage assessments; (6) extreme event attribution; (7) asset-level analysis; and (8) impact chain frameworks. Section 6 outlines example case studies, tools, and approaches to identify and quantify potential adaptation solutions to manage physical risks, and Section 7 details examples designed to help MoFs decide how to finance adaptation.

Lessons learned, challenges with existing tools, and how to overcome them are discussed in Section 8, and the report concludes with recommendations for practitioners, those developing economic tools, and end users in Section 9.

The Appendix expands on numerous elements of the main report to provide further technical details. It provides a comprehensive list of available models and tools, followed by detailed instructions for IAMs, and the dynamic integrated climate–economy (DICE) model in particular, catastrophe models, and sources of modeling uncertainty. An expanded table further outlines tools and models for the estimation of physical climate risk and macroeconomic outcomes relevant for MoFs, while another expanded table further illustrates examples of programs, initiatives, alliances, and tools available to MoFs for analyzing the economic impacts of physical risks.

2. What challenges do physical climate risks pose for Ministries of Finance?

Physical risk and adaptation bring a mix of well-known and completely new challenges to the core functions of Ministries of Finance

The impacts of a warming climate are increasingly visible around the world. The climate has already warmed by an average of 1.3°C relative to the preindustrial average, impacting communities and economies through new heat records, unprecedented extreme rainfall events, severe droughts, and catastrophic storms. Both slow-onset chronic developments, such as sea level rise and droughts, and acute physical climate risks, such as extreme events, put pressure on public budgets (Angeli et al., 2022).[1] Any further warming will accelerate the various transmission channels that exist between the physical climate and economic systems, with some irreversible changes and tipping points potentially being breached once warming exceeds 1.5°C over the long term (as described in the Introduction, the 1.5°C threshold was breached in 2024). While humans have historically adapted to various environments, developing structures to withstand disasters and building resilience, climate change threatens to intensify these challenges by introducing unforeseen impacts to new regions and amplifying the frequency and severity of events in already vulnerable areas.

Climate change has systemic implications; however, costs will have different impacts depending on whether they come from acute or chronic risks. Although acute risks, such as extreme weather events like hurricanes or floods, can damage or destroy assets, these can typically be rebuilt once an event has passed. In contrast, structural costs represent more permanent losses. These are often associated with chronic risks, such as the slow-onset effects of climate change, and include the inability to invest in or maintain assets in specific areas. For instance, rising sea levels may render coastal areas uninhabitable, leading to permanently abandoned buildings. Similarly, reduced precipitation can severely affect the suitability of land for agriculture.

Moreover, the increasing frequency and intensity of extreme weather events caused by climate change can also bring structural costs. Certain areas may become too risky for human activity or economic investment. For instance, the Intergovernmental Panel on Climate Change (IPCC) warns that continued global temperature rise could make specific locations in the tropics uninhabitable due to heat waves. In places like California in the United States, extreme weather events drive up insurance costs, leaving homeowners more vulnerable and at higher risk of displacement (Collier et al., 2021; Brunetti et al., 2021).

[1] Physical risks are usually split into two categories. **Acute physical risks** are sudden and severe weather events that can cause immediate damage and trigger indirect or cascading impacts. Examples include hurricanes, tornadoes, heavy rainfall, flooding, heat waves, tropical cyclones, and storm surges. Wildfire is also often exacerbated by prolonged periods of high temperatures and drought conditions (TCFD, 2017). **Chronic physical risks** involve longer-term changes and persistent environmental shifts that affect systems and infrastructure as they evolve. Examples include rises in average temperatures, sea level rise, changes in precipitation patterns, and ocean acidification (TCFD, 2017).

The intricate and multifaceted impacts of physical climate change are starting to have macroeconomic implications. At the macroeconomic level, current understanding of the impacts revolves around the following aspects (see BIS, 2021; Lepore and Fernando, 2023):

- **Economic growth effects:** physical climate risks, particularly extreme weather events, have predominantly negative macroeconomic impacts. These are generally smaller for wealthier countries, especially when events are sufficiently insured. However, over-reliance on insurance may trigger financial stability concerns.
- **Financial system risks:** if banks/investors do not price physical risks in lending/investment practices adequately, damage of physical assets, including real estate, productive capital, and infrastructure, can result in property and casualty insurance losses, damage to household and firm balance sheets, increases in defaults, and potential financial sector distress.
- **Impacts on public finances:** physical climate risks impact public finances significantly by increasing expenditures and reducing revenues. Governments face rising costs from disaster response, infrastructure repair, and social safety nets, as well as long-term healthcare expenses linked to climate-related health issues. Economic disruptions from climate events can reduce tax revenues, deplete property tax bases, and affect trade-related income. Additionally, frequent disasters and heightened vulnerabilities can lead to increased sovereign debt and higher borrowing costs. Public infrastructure losses and the role of governments as insurers of last resort further strain budgets, making climate risks a major challenge for fiscal stability.
- **Productivity and output effects:** productivity and output decrease through weaker investment, lower productivity, higher mortality rates, and capital losses, with agriculture being particularly vulnerable because of its direct dependence on climate conditions. Heat waves impair outdoor worker productivity and water stress reduces agricultural and energy production.
- **Inflationary effects:** physical risks may influence inflation, particularly through food and energy prices, though such effects have tended to dissipate over time. However, because the frequency and severity of events are expected to increase, this dissipation is not guaranteed; just because supply chains can react now, this does not mean it will always be possible.

Table 2.1. Climate-related fiscal risk factors and illustrative climate change channels

Risk factor	Climate change channels
Macroeconomic risks	
Economic growth (GDP or industry-level growth)	Drought, excessive rainfall, storms, etc. cause shocks to economic growth by disrupting agriculture, fishing, mining, tourism, transport, hydropower, and insurance, and affect revenue and spending. There is also a reduction in income tax revenue if climate hazards affect workers' health and productivity, employment, and output. Payouts for unemployment insurance and other social protection schemes may also differ from planned levels. Extreme weather events in other countries can potentially boost the demand for exports or affect commodity prices.
Trade	Changes and disruptions to trade affect customs duty collection.
Commodity prices	Increased severity and likelihood of extreme weather events in large producers increases the volatility of world commodity prices. For extractive exporters, government revenue differs from expected levels. Change in agricultural prices may affect domestic farm and food subsidy spending.
Interest rates	Shortages in food or energy supply, inter alia, may cause inflation spikes.
Exchange rates	A disaster may cause devaluation of the currency and increase external debt service costs. Government procurement spending on imports may also differ from expectations.

Table 2.1. (continued)

Risk factor	Climate change channels
Contingent liabilities	
Physical damage to public assets	Destruction of government buildings or damage to public infrastructure through climate-related disasters. Unexpected spending may occur for relief and to repair and reconstruct government buildings and public assets.
State-owned enterprises (SOEs)	Damage or lost revenue from operation disruptions from extreme events and increased costs for carbon-intensive operations. There is also an expectation that governments will cover SOE losses as sovereign loan guarantees are called.
Public–private partnerships (PPPs)	Infrastructure damage and/or losses from extreme weather events. There is also an expectation that the government will cover losses if a PPP project fails. Costs may also be due to contractual obligations.
Humanitarian and health crises	Changing climate and increased severity and likelihood of extreme weather events may affect the spread of vector-borne diseases, deaths, etc. An increase in health spending, emergency relief, aid, and social safety nets is expected.
Judicial awards	Courts may determine that governments are liable for climate adaptation measures.

Source: Volz et.al., 2020; see Appendix for a breakdown of supply and demand side impacts based on Volz et.al., 2020

Unmanaged physical risks pose a significant threat to development and economic prosperity (Talbot-Wright and Vogt-Schilb, 2023; Hallegatte et al., 2017). Without action, physical climate risks will pose ever-growing macro-critical risks for economies and public finances. Economic development strategies and investments in the green transition will be under threat from the physical impacts, while MoFs face an escalating need for public expenditures to deal with extreme climate shocks or chronic events, such as droughts and sea level rise. For example, extreme weather events can devastate homes or critical infrastructures, such as bridges, leaving communities and businesses unable to function. Beyond the immediate loss of assets, the destruction of infrastructure disrupts livelihoods by halting operations and cutting off revenue streams. For households, particularly those with limited access to finance, the loss of property can have cascading effects, forcing families to divert resources from essential needs such as health and education to finance reconstruction. These disruptions can create profound, systemic consequences for both individual well-being and broader economic stability. Dealing with these consequences and adapting and building resilience to this changing environment will demand significant multisectoral action. Lack of preparation for physical risk on the part of the real economy and the financial sector increases these financial and economic risks. Evidence shows that adaptation to prepare for the impacts from climate change is not happening to the extent or at the speed needed to support a climate-resilient economy (BoE, n.d.). This can also hamper efforts to decarbonize, for example when investments in the low-carbon transition are at risk from physical impacts, or when a changing climate makes those investments unviable.

It is evident, therefore, that physical climate change and adapting to it poses significant challenges for MoFs. Slow-onset developments and acute risks put pressure on public budgets as governments typically provide financial support and emergency aid to assist impacted populations and rebuild lost assets, which can increase public debt and potentially impair sovereign credit ratings, thereby restricting access to finance (Gomez-Gonzalez et al., 2024). If left unmanaged, these damages put hard-earned development gains at risk, hamper economic growth, and have profound social impacts, underscoring the need for robust fiscal planning and climate risk management. Physical risk can also propagate through the financial system as assets left as collateral are destroyed, liquidity for payment is shortened, or insurance companies are left to deal with risk levels beyond their expectations.

The need for MoFs to integrate physical risks and adaptation into their decision-making applies across their core functions (CFMCA, 2020, 2023; UNESCAP, 2024):

- **Economic strategy and planning:** MoFs need to incorporate climate risks into macroeconomic forecasting and planning for better assessment, develop strategies for climate-resilient economic development, assess sectoral vulnerabilities, and plan for economic diversification.
- **Fiscal policy and budgeting:** MoFs need to reduce fiscal vulnerabilities to a changing climate. This requires managing the fiscal implications, such as increased disaster relief and recovery spending, rising costs for infrastructure maintenance and climate-proofing, or potential revenue losses from climate-vulnerable sectors. Strategies include risk finance through insurance, management of contingent liabilities, and setting aside pre-authorization spending for quick access to relief funds. Financial instruments can complement the use of budgets and sovereign funds. MoFs also need to find ways to finance adaptation, for example through bonds or by accessing global adaptation funds.
- **Financial policy and regulation:** MoFs play a key role in ensuring financial stability by assessing climate risks, developing policies to improve disclosure and management in the financial sector, and mobilizing private finance for climate resilience. One of the policy options for MoFs and financial regulators is to set regulations for firms to assess and disclose their exposure to physical risks. Governments can also assess physical risks directly, making this information available to relevant stakeholders. MoFs, in coordination with other government institutions, can play a significant role in promoting financial inclusion (i.e., access to banking, insurance, and loans), reducing the exposure of household assets to physical risks and increasing the tools available to them to cope. MoFs can also add mandatory assessments, require public disclosure, and move investment through public demand. In a similar fashion, MoFs can use instruments such as subsidies and tax relief, and/or coordinate with sectorial ministries to change regulations for other kinds of incentives (such as requiring certain materials) to promote investment in adaptation.
- **Public investment management:** MoFs may need to consider climate-proofing of public investments and infrastructure to make them resilient to the physical impacts of climate change and extreme weather events, prioritizing climate-resilient investments, and developing new financing mechanisms for adaptation projects. Although the private sector can play a significant role, governments could set aside additional resources to fund relevant adaptation projects, ranging from gray infrastructure such as dikes, and nature-based solutions, to ensuring redundancy in critical infrastructure. Governments can also ensure that all investment and procurement procedures account for physical risks by requiring risk assessments to be conducted in the preparation/proposal phases.
- **Intergovernmental fiscal relations:** MoFs need to coordinate climate action across different levels of government and develop fiscal transfer mechanisms to support local climate resilience. Certain scenarios define climate risks and adaptation as being under MoF mandate as well under other Ministries. Furthermore, recognizing that most countries have not fully integrated climate considerations into financial sector policies, MoFs should consider how best to collaborate.

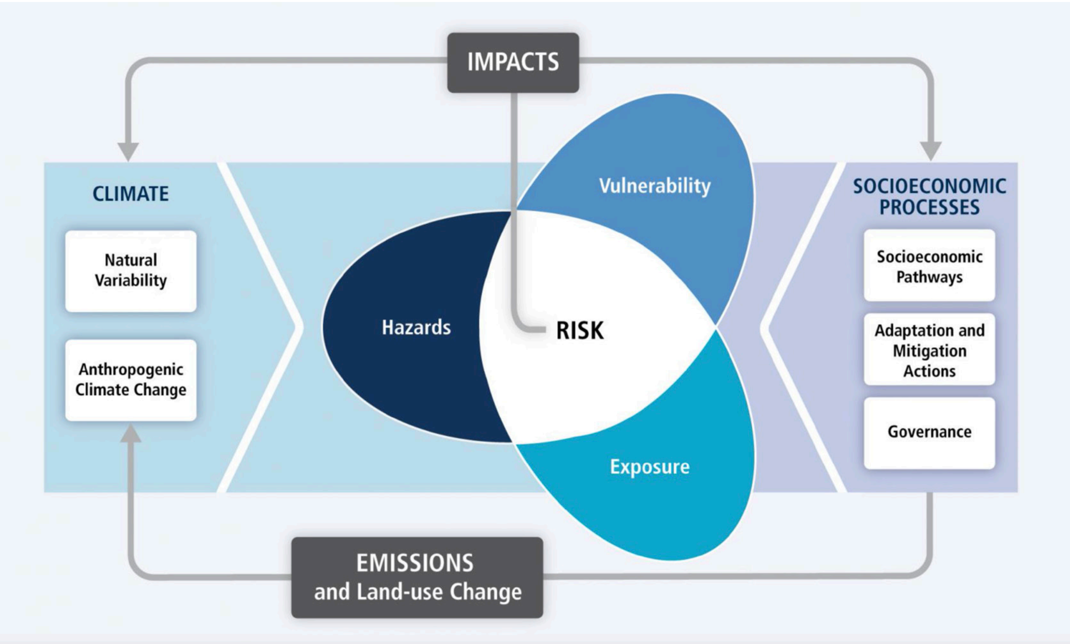
The scale of these impacts depends on many factors and varies across countries and regions. The management of physical risks is very context specific and highly interdependent with other policy areas, such as economic development, natural capital, and risk finance/insurance. Different countries/regions are exposed to different hazards and experience the financial impacts in different ways. In simple terms, the cost of physical climate impacts depends on how well countries, sectors, and communities can prepare for, respond to, absorb, and recover from shocks and chronic shifts. Factors such as the structure of the economy, country size and geographic location, as well as overall vulnerability, the state of the public finances, adaptive capacity, and existing adaptation levels all matter. While the scale and complexity of this challenge vary across countries and regions, adaptation and resilience-building—despite being sector-specific—will require significant investments and the reallocation of resources, both public and private, to protect, transform, and, in some cases, relocate assets and communities in many nations.

3. How can Ministries of Finance respond to these challenges?

A 'handshake' between climate science and economics is required

To address the pertinent policy questions, Ministries of Finance need to establish the urgency and magnitude of physical climate risks, evaluate solutions, and decide how to pay for them. At the heart of this is the interplay of hazard, exposure, and vulnerability, all of which influence the size of the impact (Figure 3.1), and the effectiveness of mitigation efforts in keeping future warming levels low and of adaptation efforts in increasing the resilience of communities and economies.

Figure 3.1. Climate risk drivers



Source: IPCC, 2014a

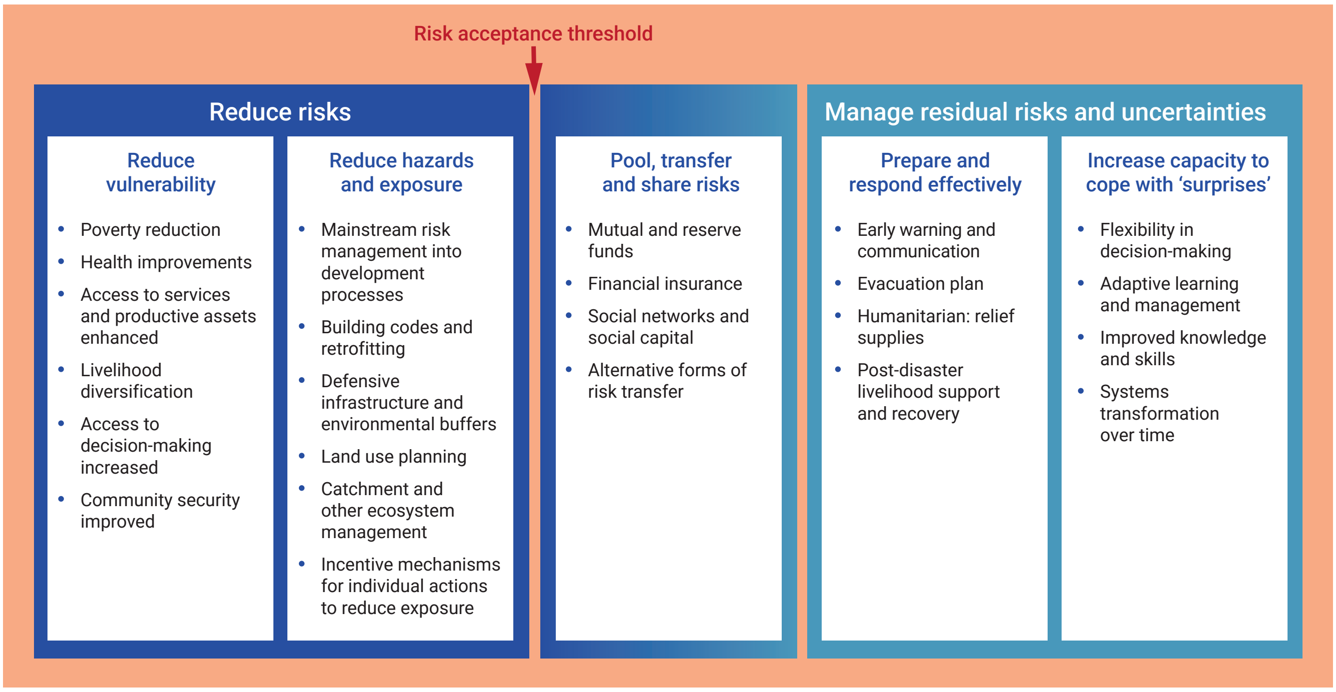
The economic analysis of these aspects combines risk identification, risk quantification, and evaluation of policies and other interventions. This requires what is often called a 'handshake' between climate science and economics: establishing a relationship between risk drivers—climate hazards, exposure, vulnerability—and their interaction with macroeconomic data to understand the magnitude of the problem, the need for adaptation, and the role that different adaptation interventions can play in addressing these risks, and the expected costs and benefits (ECA, 2022; IFAD, 2022; GIZ, 2023a).

Quantification is key to assessing physical risks and their impacts on the economy, budgets, and the financial sector, as well as the potential effectiveness and opportunities of adopting various policy options. However, not all of these can and will be quantifiable due to their complex nature and many interdependencies. Robust decision-making will enable MoFs to navigate physical risks effectively and drive impactful adaptation and resilience strategies.

This requires different levels and types of data to establish scale, urgency, and relevance, and to advise on response measures, their effectiveness, and costs in the face of uncertainty and data gaps. Empirical data on the economic impacts of extreme climate events and long-term changes remains limited and is often based on historical observations that may not be representative of future conditions (Dicks et al., 2023). Furthermore, macroeconomic models rely on sector indicators that are often difficult to identify, such as the elasticity of demand. Catastrophe models are also subject to challenges as data on the local vulnerabilities of infrastructure is scarce, and the approach inherently assumes that vulnerability is not dynamic and not influenced by the adaptive behavior of at-risk populations (Botzen et al., 2019). And where data exists, it can easily overwhelm the non-expert decision-maker. A key challenge for MoFs and other end users is navigating the abundant open-access tools, data platforms, and guidance, which approach physical climate risks from varying perspectives and aim to answer different questions. The wide range of free data and analytics is a positive development, but end users can easily become overwhelmed or frustrated. This frustration often arises because the data or analytical results may not align with their decision-making timelines, or because they struggle to understand the compatibility of the data and approaches provided.

Adaptation requires enhancing a country's resilience to climate change impacts while managing the associated economic and fiscal challenges. The management of physical climate risks requires an integrated climate risk management approach that considers different measures and types of adaptation interventions. Such an approach touches all the core responsibilities of MoFs, as is clear from Figure 3.2, demonstrating the importance of them being able to mainstream climate into their work.

Figure 3.2. Climate risk management



Source: IPCC, 2012

In the face of physical climate risks, MoFs have a range of critical levers that they can pull, spanning economic, fiscal, and financial policy. For example:

- **Incorporating climate adaptation considerations into long-term economic strategies**, investment decisions with long lifetimes, and national development plans to avoid costly risk creation or maladaptation.
- **Allocating funds specifically for adaptation measures in national budgets**. This includes investing in climate-resilient infrastructure, supporting vulnerable sectors such as agriculture, and funding research and development for adaptation technologies.

- **Providing financial support and guidance to local governments** for implementing adaptation measures, recognizing that many adaptation actions occur at the local level.
- **Planning for contingent liabilities**, for example in the context of infrastructure damages and repairs, or health and social costs.
- **Implementing fiscal policies that incentivize adaptation measures**. This could include tax incentives for climate-resilient investments or adjusting subsidies to promote adaptive practices in various sectors.
- **Developing strategies to attract private sector investment in adaptation projects**. This could involve creating favorable policy environments, risk-sharing mechanisms, or public–private partnerships.
- **Actively engaging with international climate finance mechanisms** to access additional resources for adaptation projects (e.g., working with multilateral development banks and climate funds).

The underpinning analysis needs to mature from risk assessment to impact quantification and enabling of adaptation

Understanding and addressing all these pertinent policy questions requires a wide set of modeling and non-modeling analytical tools addressing both the physical and economic aspects of climate change risks. Risk assessments are the fundamental basis for any decisions on physical risks, but in practice they often fall short of economic evaluations or lack a recognition of adaptation measures.

MoFs are facing a mix of familiar but shifting challenges, as well as completely new types of policy questions. A number of these questions are rooted in disaster risk management or development finance, and MoFs can build on existing expertise, for example in risk finance and contingency planning. Other challenges are fairly new for MoFs, for example specific questions that arise from the interplay between a low-carbon transition and physical risks, with the need to make sure that all the efforts made to achieve decarbonization are not disrupted or destroyed by a changing climate, and the interplay between physical risks and equity, such as in the context of a just transition and the growing social burdens arising from resilience challenges among vulnerable communities. Another example is the growing recognition that nature loss plays a key role in our ability to deal with climate change and that natural capital is a key source of resilience; to date, there have been few macroeconomic assessments of the scale of nature loss and its impacts on nature-based services. For many MoFs, adaptation is still a fairly new concept, although deeply related to the long-established disaster risk management field. This report adopts the United Nations Framework Convention on Climate Change (UNFCCC) definition of adaptation: "adjustments in ecological, social or economic systems in response to actual or expected climatic stimuli and their effects. It refers to changes in processes, practices and structures to moderate potential damages" (UNFCCC, n.d.).

For MoFs there are three key steps needed to address physical climate risks:

1. **Identify and quantify current and future physical climate risks and impacts on the macroeconomy and public finances**. This involves understanding resilience gaps, accounting for risks to public budgets and sovereign ratings, integrating these risks into fiscal planning, and understanding the impacts on key macroeconomic variables such as GDP, income, and unemployment. For example, estimating the budgetary impact of increased climate events or evaluating the macroeconomic effects of maladaptation are key concerns. This requires a robust understanding of the scale and materiality, and of which channels the impacts will be felt through, when and where. Examples of typical questions arising are:
    - *What are the current and future economic impacts of physical climate risks?*
    - *How large will the likely impacts on the public budget from increased climate events be if government does not act to enhance resilience?*

- *How will physical risks impact sovereign risk ratings?*
- *How large are current and future resilience and protection gaps?*
- *How should the macro-impacts of maladaptation and unmitigated risk creation be assessed?*

2. **Identify and quantify potential solutions**. Different interventions can reduce vulnerability by either reducing risk or transferring risks, or a combination of these. Understanding the costs and benefits is relevant for MoFs when considering adaptation intervention among their multiple priorities based on an understanding of where the largest resilience gaps are and how best to address them. Examples of typical questions arising are:
   - *How should the optimal level of adaption be identified in the absence of clear standards?*
   - *What financial tools exist to address the risks, and will they remain available/affordable?*
   - *What adaptation investments are needed, where are they needed, and by when?*
   - *How can MoFs best prioritize adaptation interventions today and in the future, taking into account economic and non-economic considerations, including equity and social justice?*
   - *What is the return on investment in adaptation?*
   - *What are the costs and (co-)benefits of adaptation interventions in the short, medium and long term?*

3. **Decide how to pay for/finance adaptation**. Financing adaptation and resilience entails overcoming investment barriers, mobilizing private and public capital, and leveraging innovative financial instruments such as resilience bonds. How much of the adaptation should be funded by the government? And which funding instruments should be used (e.g., new taxes, public debt, etc.)? MoFs can also explore tax reforms and international funding to support resilience efforts; for instance, working to understand the implications of developing integrated solutions that combine risk transfer mechanisms with adaptation financing to address the rising costs of capital. Many countries will need to find ways to finance adaptation in the face of budget constraints, increasing costs of capital, and growing liabilities. Examples of typical questions arising are:
   - *How much of the adaptation should be funded by the government? And which funding instruments should be used (e.g., new taxes, public debt, etc.)?*
   - *How can adaptation be incentivized?*
   - *How should barriers to adaptation investment be overcome and how should the mobilization of more private sector capital be supported?*
   - *How can managed retreat and relocation be funded?*
   - *What sources of adaptation finance exist and how can these be accessed effectively?*
   - *How can international adaptation finance be accessed effectively?*
   - *How should adaptation be financed when physical risk exposure increases the cost of capital?*
   - *What new debt financing instruments are needed for resilience (e.g., resilience bonds; blue bonds[2])?*
   - *How should integrated solutions be developed that combine the transfer of residual risks with adaptation finance?*

[2] Resilience bonds are a financial instrument designed to help governments, municipalities, and organizations fund climate adaptation and disaster risk reduction projects. They are an evolution of catastrophe bonds but with an added incentive for proactive resilience investments. Blue bonds are a type of debt instrument specifically designed to raise capital for projects that aim to protect, conserve, and sustainably manage ocean and water ecosystems.

4. A clear and growing need for mainstreaming physical risk and adaptation

A recent survey of Ministries of Finance deepens our understanding of global approaches to climate change risk assessment and planning

There is compelling evidence of rising macroeconomic impacts from physical risks, but this is far from mainstreamed into MoFs' day-to-day decision-making. According to the recent survey[3] conducted by the Coalition of Finance Ministers for Climate Action for Helsinki Principle (HP) 4, MoFs are particularly concerned about climate-related expenditures, but face difficulties in incorporating climate-related issues into their analyses.

Rising macroeconomic impacts from physical risks are evident, yet they are not integrated into the daily decision-making of MoFs. When surveyed and in subsequent discussions, 71% of the MoFs rated their level of concern about the impacts of physical climate risks on government spending at 4 or 5 (on a 5-point scale with 5 being 'extremely concerned') and 58% expressed these levels of concern about GDP, with lesser worries about physical, natural and human capital (38%), employment (36%), interest rates and credit ratings (27%), and state-owned enterprises (22%). In terms of government revenue, 51% of MoFs rated their level of concern about the impacts of physical climate risks at 4 or 5. The Survey Report indicates that emerging market and developing economies (EMDEs) show greater concern than advanced economies (AEs) about these macroeconomic implications.

Almost half (48%) of MoFs are actively involved in the development or shaping of national adaptation and resilience plans, while 28% are considering this. Slightly fewer (46%) MoFs currently undertake disaster risk financing and insurance activities, with 28% considering it, while 37% of MoFs are implementing green budgeting, and 43% are exploring its implementation. The financial implications of adaptation remain unquantified in a substantial number of countries. Almost half (44%) of MoFs have yet to conduct analysis to estimate public expenditure and financing needs for adaptation and resilience to climate change, and only around quarter (26%) report that they have done so (see Figure 4.1).

MoFs report limited progress in the use of climate-related analytical tools. MoFs in both advanced and emerging economies have made limited progress in integrating physical climate change and transition considerations into their analytical tools and models. Most countries have yet to integrate, or consider the integration of, physical climate impacts in key analytical functions (i.e., policy appraisal, financial sector policy, tax and fiscal policy, budget protections, and macroeconomic forecasting). Most progress has been made on budget projections, where approximately 35% of countries report full or partial integration (see Figure 4.2).

The use of tools and methods varies by country and risk type, leading to diverse quantifications and warnings about model limitations and data issues. The majority of MoFs do not use dedicated climate–economy models, with 56% of respondents reporting not using them for mitigation or adaptation. Only 20% have dedicated internal climate–economy models that differ from general economic models, while 12% use external models (see Figure 4.3).

[3] This report draws on a global survey of the world's MoFs, the results of which are described in detail in 'A Global Survey of Ministries of Finance: The pressing policy questions Ministries of Finance face in driving green and resilient transitions and their use of analytical tools to address them' (CFMCA, 2025a). The world's first comprehensive survey of MoFs, it focused on understanding existing analytical capabilities for driving climate action. Fifty-nine MoFs from the Coalition of Finance Ministers for Climate Action membership and beyond responded to the survey, close to one-third of the world's MoFs. Combined with semi-structured interviews with 15 MoFs, the Survey Report draws out where MoFs currently stand in relation to integrating climate into modeling and analytical work, capability gaps, and the most pressing policy and analytical questions they face in this regard.

Figure 4.1. Has the Ministry of Finance conducted any analysis to estimate public expenditure and financing needs for adaptation/resilience? (%)

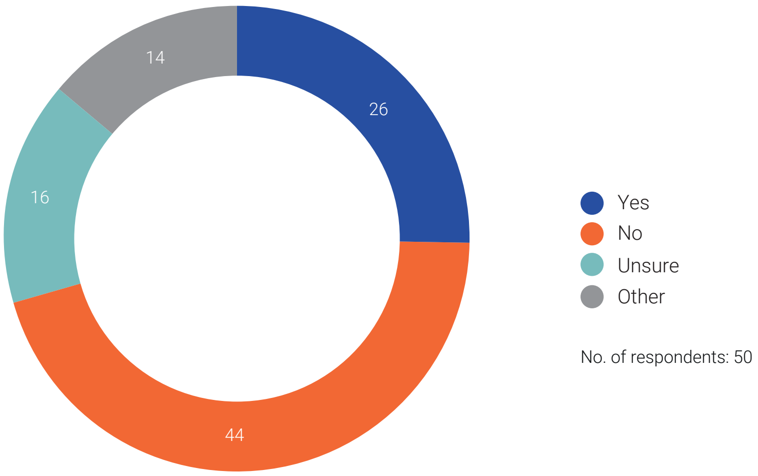
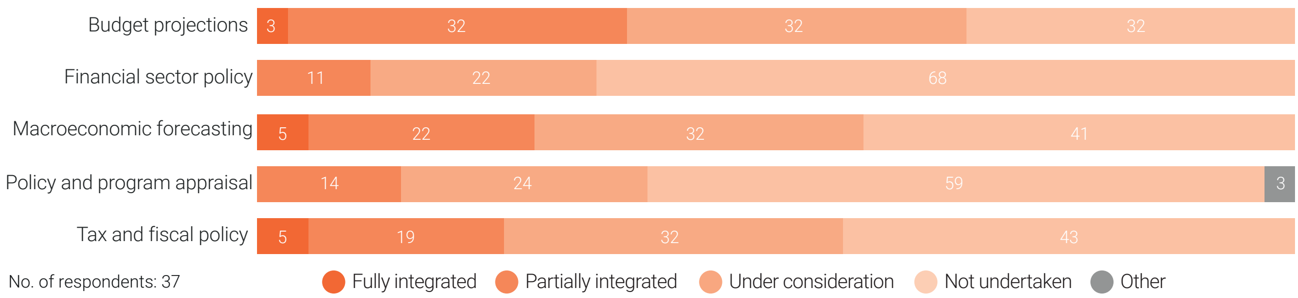
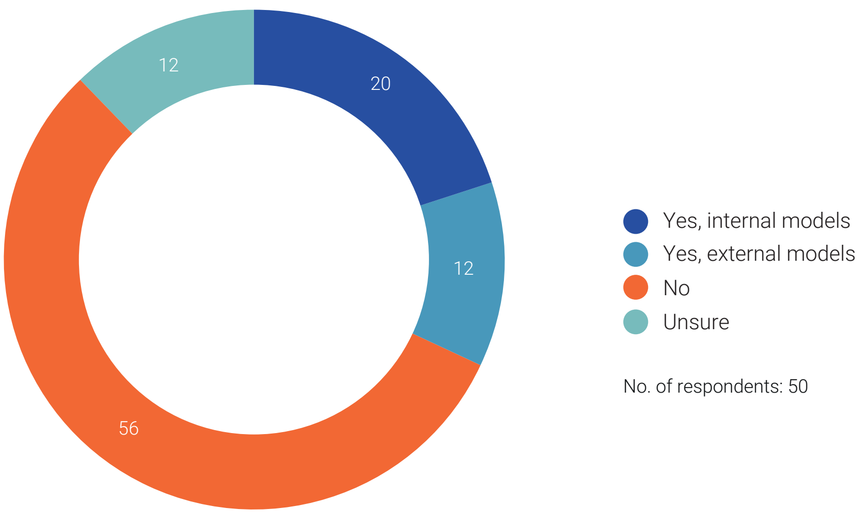


Figure 4.2. To what extent has the Ministry of Finance integrated physical climate considerations/ adaptation into core analytical functions? (%)



Source: CFMCA (2025a)

Figure 4.3. Does the Ministry of Finance use dedicated climate–economy models of mitigation and adaptation policies that differ from the general economic models being used?



Source: CFMCA (2025a)

The survey revealed that fewer than half of the MoFs have used climate-related scenarios to inform economic policy analyses. Furthermore, most MoFs do not integrate specific climate-related dynamics such as tipping points or compound risks into their analytical exercises. Only 15% of MoFs have considered tipping points in their climate-related analyses, while 66% have not, and 20% are unsure. Only 17% have considered compounding risks, with 54% not having done so, and 29% unsure. Regarding trade effects, 27% of MoFs have included them in their climate analyses, while 44% have not, and 29% are unsure. Additionally, only 22% have accounted for wider risks in their climate-related exercises, with 41% not having done so, and 37% unsure.

In the absence of global standards, various guides and pilots have emerged to fill analytical gaps and improve user-focused results. Recent advances include enhanced modeling capabilities through better climate data, sophisticated catastrophe modeling, integration of network models for indirect impacts, and the application of big data and artificial intelligence (AI)/machine learning (ML) techniques. While there are valuable lessons to be learned, there are no universal solutions. Countries have different needs, data conditions, and priorities that must be considered in any analysis. Comprehensive contributions can be found in the Compendium of Practice, with Sections 5 and 6 in this report summarizing recent approaches by MoFs and programs initiated by international organizations, academics, and the private sector to support them. Further details can be found in the contributions to the Compendium of Practice referenced below.

When mainstreaming physical climate considerations into their core functions, MoFs most commonly face barriers related to analytics, staffing, and skill constraints. MoFs have identified several barriers to integrating climate-related issues into economic analysis, including staffing and skill limitations, data challenges, difficulties in model development, and financial constraints.

MoFs have expressed various support needs to improve their climate-related analytical capabilities: 51% require access to off-the-shelf models of climate change, 74% need assistance to develop in-house climate analytical capabilities, and 60% need help maintaining these capabilities. Additionally, 62% of MoFs need support for domestic data collection, and 68% want access to online climate data dashboards.

Furthermore, 60% of MoFs seek the latest empirical research in climate economics, 81% request access to the latest developments in modeling, and 74% need help accessing relevant case studies.

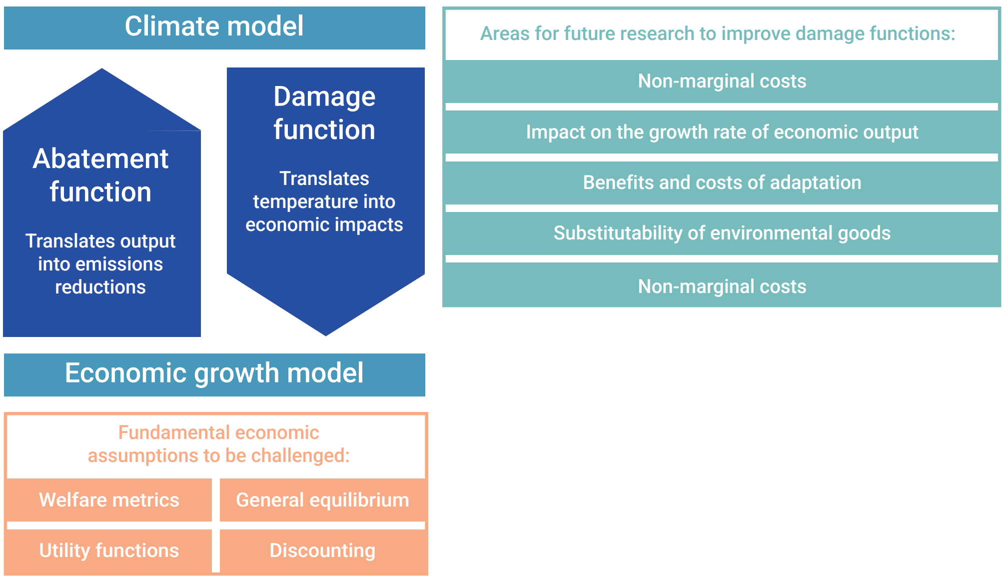
5. Tools and approaches for identifying and quantifying physical climate impacts on the macroeconomy and public finances

Understanding physical climate risks and their impacts is essential for decision-making

A core element of managing and adapting to physical climate risks is a sound understanding of current and future risks and their economic impacts. Methodologies for the analysis vary depending on scope, scale, and purpose, but in general terms all include two main components (Figure 5.1):

- Models focused on climate hazards, including climate change and natural variability, which can be single hazard, for example flooding or drought, or multi-hazard
- Models that enable assessments of economic consequences, usually via damage functions and analyses of exposure, vulnerability, and other socioeconomic processes influencing risk levels.

Figure 5.1. Components of integrated assessment models for macroeconomic considerations



Source: Rising et al. 2022

In basic terms, these models form our understanding of climate impacts through two key inputs: assumption-driven climate and socioeconomic data, which can then be analyzed globally or regionally to arrive at impact indicators, such as 'number of people affected by extreme events', 'direct economic damages' and 'people at risk of hunger' over time. A common illustration of the approach at the macro-level is provided by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (see ISIMIP, 2016 for a diagrammatic illustration of its process and mission).

Assessing the costs associated with physical climate change remains a complex endeavor that necessitates transparent and robust strategies to integrate insights from physical sciences with economic impact assessments and analyses (Lepore and Fernando, 2023). Extreme events already lead to the materialization of both explicit (e.g., relief or disaster-specific transfers to local governments, government guarantees for firms) and implicit contingent liabilities (e.g., public support to distressed financial institutions). Floods, droughts, and other extreme weather events harm sovereign assets, increase public debt, and can impact sovereign credit ratings negatively, impeding access to finance (NGFS, 2024a).

Simultaneously, the physical risks posed by climate change can have far-reaching indirect consequences on public finances, particularly through health and social impacts: recovery from increased incidence of heat-related illnesses, vector-borne disease, respiratory problems, and/or community displacement may require public funds—reducing tax revenues. These risks, whether acute or chronic, can have profound implications for economic growth, productivity, inflation, and financial stability. Given that climate hazards diminish the capacity and resources available to respond to subsequent events, they can exacerbate one another, resulting in more severe impacts when they occur simultaneously or consecutively. Moreover, the relationship between GDP growth and temperature is likely non-linear, with marginal temperature increases becoming more costly at higher initial temperatures (Kalkuhl and Wenz, 2020).

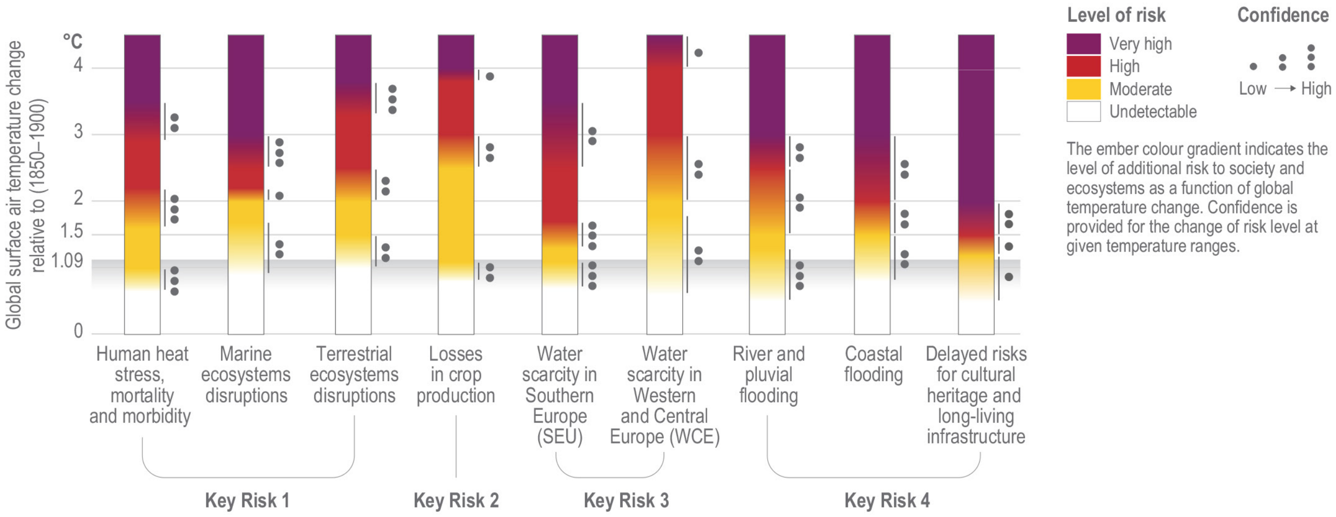
Existing methodologies differ conceptually and methodologically, particularly in terms of the type of climate information used and the way socioeconomic considerations are included, which explains the often highly varied results. Table 5.1 highlights some of the commonly applied mechanisms, including the established

Table 5.1. Tools and models for estimating physical climate risk on macroeconomic outcomes relevant for Ministries of Finance[4]

Tools/models	Overview	Challenges when using in Ministry of Finance context
Integrated assessment models (IAMs)	These draw on damage functions to assess long-term economic impacts of climate change using various scenarios.	Oversimplification of extreme weather effects and limited short-term indicator observation.
Input–output (I–O) models	These estimate indirect costs and market vulnerabilities, capturing sector interdependencies.	Oversimplify systems and fail to capture post-disaster mechanisms.
Computable general equilibrium (CGE) models	CGE models simulate how an economy responds to changes in policy, technology, or external conditions by accounting for the interactions between various sectors, households, and markets. They are an extension to basic I–O models by drawing from a detailed representation of economic agents and their behaviors to account for possible substitution effects and analyze the equilibrium where supply and demand balance across the entire economy.	Greatest shortcomings are their reliance on simplifying assumptions, such as perfect competition, static or overly rigid behavioral parameters, and the quality of input data, which can limit their ability to accurately capture real-world complexities and dynamic adjustments.
Scenario-based approaches	These compare baseline scenarios with climate risk scenarios to assess financial impacts.	Speculative assumptions and complexity can lead to biased outcomes.
Catastrophe models	These estimate potential losses from extreme events and create hazard maps for exposure assessment.	Depend on assumptions about land value and limited natural hazard data.
Loss and damage assessments	These evaluate economic and non-economic losses from climate change impacts for policy decisions.	Data limitations and challenges in valuing non-market losses.
Extreme event attribution (EEA)	This is designed to quantify how climate change influences specific economic costs from extreme events.	Complexity and data quality issues hinder accurate attribution of economic losses.
Asset level analyses	These assess climate change impacts on fiscal sustainability through stress tests.	Narrow focus on specific assets may overlook broader economic impacts.
Impact chain frameworks	These provide four-step assessment of climate event consequences, from hazards to financial impacts.	Data reliability issues may hinder comprehensive assessments.

[4] For more details see the Appendix and the corresponding HP4 Compendium of Practice contributions (CFMCA, 2025b).

Figure 5.2. 'Burning embers' diagram of key risks for Europe under low to medium adaptation



Source: Figure 13.28 in Bednar-Friedl et al., 2023

approach of assessing impacts through integrated assessment models or catastrophe models, as well as a range of additional methods for sectoral or asset-level analysis. This is a non-exhaustive selection of commonly used tools, with some notes on their application and reflections on known shortfalls for macroeconomic assessment of physical climate risks.

MoFs often use IAMs such as the DICE model,[5] drawing on two types of damage functions: process based (the majority) and empirical. The latter provide larger and perhaps more realistic estimates of levels of climate change risk, but are necessarily based on spatial and temporal extrapolation, exclude the implications of climate–economy interactions that have yet to occur or have not been captured in the data used, and probably still underestimate risks. As noted above, tools that use economic damage functions include IAMs and computable general equilibrium models (CGEs). MoFs can use these models to (a) project future climate-related risk to the global economy; (b) balance the costs and benefits of global climate change mitigation policies to determine an 'optimal' level of global warming; (c) inform national scale mitigation policy; and (d) examine the cost-effectiveness of proposed policies. It is recommended instead to perform a global risk assessment by referring to the global climate change projections summarized in the IPCC's Sixth Assessment Report. The 'burning embers' diagrams, which show how risk accrues with global warming (Bednar-Friedl et al., 2023), are informative in this respect (Figure 5.2). Of potential interest to MoFs, the report also contains regional chapters and a regional atlas.

Damage function choices greatly influence macroeconomic analysis outcomes, but there are significant concerns about the inadequacy of common approaches leading to underestimation of impacts. Within any of these approaches the choice of damage function, which relates changes in temperature to economic impacts in various dimensions, is particularly important and plays a key role in determining model outcomes. They are crucial components in both IAMs and catastrophe models. However, estimates of climate change impacts in damage functions have often failed to adequately capture distributional impacts, non-market impacts, adaptation measures, and tipping points, leading to potential underestimation of risks (Dicks et al., 2023). It is thus important to ensure that all kinds of impacts are included in damage functions. See Section 8 for further details on the limitations of estimates of climate change impacts in damage functions.

[5] See the Appendix for a brief overview of the DICE model, which employs damage functions, taken from 'Latest developments in upgrading DICE-2023: findings and implications for Ministries of Finance,' a contribution from ETH Zürich to the HP4 Compendium of Practice, and for more details on the limitations of damage functions.

Table 5.2. Examples of programs, initiatives, alliances, and tools available to Ministries of Finance for analyzing the economic impacts of physical risks[6]

Name	Description	Country applications	Model type
Coastal Impact and Adaptation Model (CIAM) used by the IMF	Estimates costs of sea-level rise and adaptation strategies using a global model divided into coastal segments	Used in Antigua and Barbuda, Curacao, the Dominican Republic, Jamaica, Morocco, Palau, Papua New Guinea, Vanuatu	Cost–benefit analysis framework combined with geospatial modeling
IMF's Quantitative Climate Change Risk Assessment Fiscal Tool (Q-CRAFT)	Excel-based tool for assessing long-term fiscal risks from climate change across 170 economies	Used in Armenia, Azerbaijan, Georgia, Jamaica, Kenya, Morocco, Rwanda, Seychelles, the Netherlands, Uganda	Scenario-based modeling integrating projections of physical climate risks with economic and fiscal frameworks
Global Risk Modelling Alliance (GRMA)	Helps MoFs manage climate risks by combining global and local data for adaptation planning	Used to support the development of the Climate Prosperity Plan (CPP) in Madagascar, for flood risk analysis in Pakistan, and for urban flooding modeling in Ghana	Does not prescribe a specific modeling technique; various types depending on context and needs
IMF's Climate Macroeconomic Assessment Program (CMAP)	Assists countries in integrating climate considerations into macro-fiscal frameworks using the debt–investment–growth and natural disasters (DIGNAD) model	First pilot in Samoa, assessing disaster risk management and adaptation investments	Dynamic stochastic general equilibrium (DSGE) models and integrated assessment models (IAMs)
ADB's Climate Resilient Fiscal Planning Framework	Framework for climate-resilient fiscal planning focusing on risk assessment, management, and resource optimization	Used in Armenia to enhance climate fiscal planning	Does not prescribe a specific modeling technique—may use various economic models such as I–O and CGE
Global Shield Against Climate Risks	Aims to enhance prearranged finance against climate risks, linking adaptation and social protection	Bangladesh, Costa Rica, The Gambia, Ghana, Jamaica, Madagascar, Malawi, Pacific SIDS, Pakistan, the Philippines, Senegal	Does not prescribe a specific modeling technique; various types depending on context and needs
Oasis Loss Modelling Framework (OasisLMF)	Open-source platform developed by the private sector for risk modeling and management	Recommended by GRMA for sovereign risk functions	Probabilistic catastrophe modeling with stochastic event generation, hazard modeling, vulnerability assessment, and financial modeling
UNEP Resilient Planet Data Hub	Portal for pre-computed risk data for organizations beginning to understand climate risks	Not specified	Central to its methods is the Global Resilience Index Risk Viewer, which utilizes insurance modeling techniques, probabilistic risk assessment, scenario analysis, and geospatial modeling
CO-designing the Assessment of Climate CHange Costs (COACCH) project	Provides updated damage functions for climate risk, including fisheries	Not specified	IAMs and sectoral economic models, combining detailed sector-specific analyses with macroeconomic models, such as CGE and econometric models
Climate Impact Explorer's ISIMIP	Offers a consistent climate change impact modeling framework with over 100 models contributing	Not specified	IAMs and sectoral impact models, integrating models from various disciplines, such as agriculture, water, ecosystems, health, and energy
Network on Greening the Financial System (NGFS)	Explores macroeconomic impacts of climate change and develops climate scenarios for monetary policy	Not specified	A combination of macroeconomic, financial, and climate models, including IAMs, climate scenarios, and stress-testing frameworks
CLIMADA	An open-source analytical tool for assessing physical risks and developing climate adaptation strategies, supporting decision-making	Ethiopia, Honduras, Vietnam, Ghana, Madagascar, Niger	A probabilistic risk modeling approach to simulate economic impacts of extreme weather events

[6] For full details see the Appendix and the HP4 Compendium of Practice case studies.

Table 5.2 gives an overview of tools that are currently used by countries to improve their understanding of the macroeconomic impacts. More details can be found in the Appendix and the corresponding Compendium of Practice contributions. Importantly, all have specific characteristics and functions that may make them not universally applicable. For example, CMAP is specifically aimed at helping small and low-income countries build resilience and develop policy responses to cope with the economic impacts of climate change (EU et al., 2021). There are also tools explicitly designed for those unable to afford expensive licenses by offering a range of open-source resources, such as CLIMADA[7] and the OASIS Loss Modelling Framework.

In their efforts to quantify the impacts of physical risks, MoFs are in some cases developing their own suite of models and tools or utilizing those developed by others.

For example, Morocco's MoF employs various tools to quantify climate impacts. Largely focused on agriculture, the ministry employs a macro-econometric model with a regionalized agricultural model (MIMPAS), as well as a general monetary and multisectoral macrodynamic model for ecological shifts (GEMMES) coupled with a hydrological and agricultural model on physical impacts (LPMJL). Recent advances involve coupling the new GEMMES model with the LEAP sectoral technoeconomic model and employing extensions of their own CGE model.[8] However, the ministry has highlighted its need to further leverage new approaches in understanding issues pertaining to the financing of resilience building under budgetary constraints.[9]

The United Kingdom has adopted a hybrid approach to estimate the economic costs of climate change, combining bottom-up sector models—for example, models that assess the physical impacts and economic damages from floods—and top-down approaches, including economic IAMs, macroeconomic models (e.g., CGE models), econometric models, and macro-fiscal models.[10]

In Finland, economic risks related to ecosystems are analyzed using forest and agricultural models integrated with macroeconomic models. Current and future economic risk levels for selected sectors have been assessed using the sector models and their results fed into the macroeconomic model to obtain partial national and regional economic estimates. Based on the results, the cascading risks in Finland are expected to be larger than damage from extreme weather events (Antti et al., 2011). In forest ecosystems alone, the impacts of changing climate and disturbances may be substantial, and new modeling approaches have been developed to cover both carbon sequestration and biodiversity-related impacts for forests (Repo et al., 2024; Forsius et al. 2021). The Finnish Prime Minister's Office has started conducting annual societal sustainability assessments to scope research results and knowledge gaps on the ecosystem related risks to the Finnish economy and society in the short to medium term, in addition to the various other sustainability challenges. In addition, with leadership from the Prime Minister's Office, Finland's new €50m EU-funded LIFE Priodiversity project focuses on biodiversity policy coherence among various ministries, including the MoF.[11]

[7] See 'Showcasing CLIMADA,' contribution from the Munich Climate Insurance Initiative (MCII) to the HP4 Compendium of Practice.

[8] See 'Models for evaluating policies to mitigate greenhouse gas emissions and adapt to climate change in Morocco,' contribution from the Ministry of Finance of Morocco to the HP4 Compendium of Practice.

[9] ibid.

[10] See 'Methodological recommendations for Ministries of Finance on climate change risk assessment and the enhancement of damage functions,' contribution from the University of East Anglia to the HP4 Compendium of Practice.

[11] 'Improving the inclusion of nature and ecosystem service impacts in assessments of the economic impacts of climate risk by Ministries of Finance and economic decision-makers: the experience of Finland,' contribution from the Prime Minister's Office of Finland to the HP4 Compendium of Practice.

6. Tools and approaches for identifying and quantifying potential adaptation solutions to manage physical risks

Methods are being adapted and enhanced to keep pace with a rapidly escalating threat

Adaptation has not yet been integrated into macroeconomic assessments of physical climate risks, with many of the models and tools described in Section 5 excluding adaptation or assuming 'perfect/full adaptation' levels, neglecting the interaction between varying adaptation levels and economic impacts. To account for the impacts of adaptation measures (or the lack thereof) and better understand their potential impacts on the economy and the financial system, central banks and supervisors can explore metrics and tools that incorporate and measure the impact of adaptation (NGFS, 2024d).

This is an evolving area, requiring the combination of long-established approaches (e.g., IAMs, cost–benefit analysis [CBA], cat models) with more recent and innovative analytics. Much of the analysis to date has come out of the field of disaster risk management, now feeding into an emerging field of 'economics of adaptation.' Importantly, recent disasters have exposed the inadequacies of current risk management practices in both high- and low-income countries, highlighting how current approaches to resilience are unable to cope with today's levels of risk, let alone keep pace with a rapidly escalating threat (Marsh McLennan, 2023).

Examples of macroeconomic impact assessments of physical risks with and without adaptation that have been conducted as part of national climate change risk and adaptation assessments include the World Bank's **Economics of Adaptation to Climate Change (EACC)** methodology, developed between 2008 and 2010 to help countries assess economy wide climate impacts and identify adaptation responses using a CGE model. Recently these assessments have been supported by using the open-source **CLIMADA** tool as part of the Economics of Climate Adaptation (ECA) framework (ECA, n.d.). CLIMADA is an analytical tool for assessing physical risks and developing climate adaptation strategies, supporting decision-making by using a probabilistic risk modeling approach to simulate economic impacts of extreme weather events. It aids policymakers in identifying cost-effective adaptation measures and facilitates financial planning for MoFs. UN University and MCII have supported MoFs in Ethiopia, Honduras, and Vietnam with CLIMADA for climate adaptation studies.[12] In 2022, the Global Risk Modelling Alliance (GRMA) demonstrated flood management benefits in Ghana using CLIMADA and is analyzing tropical cyclone risk in Madagascar.[13] In Niger, CLIMADA assessed drought impacts, revealing that ecosystem-based adaptation investments could save US$9.7 billion in humanitarian costs.

Another example is the **EU's PESETA** (Projection of Economic impacts of Climate change in Sectors of the European Union) project, which uses IAMs and sector-specific economic models to evaluate the impacts of climate change

[12] See 'Showcasing CLIMADA' , op. cit..
[13] See 'Support for sovereign climate and disaster risk functions: the Global Risk Modelling Alliance', contribution from the Insurance Development Forum to the HP4 Compendium of Practice.

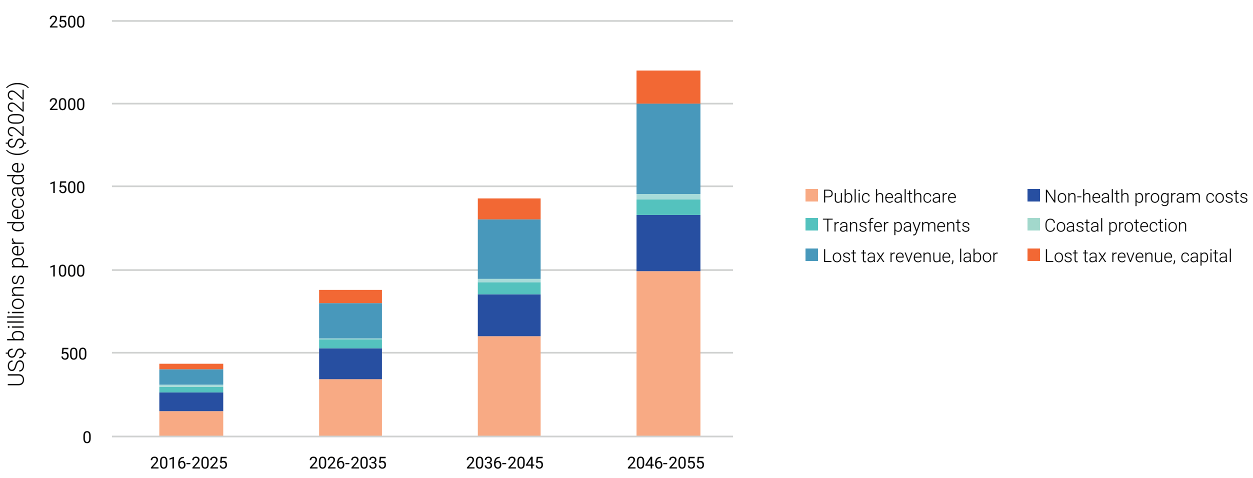
on different sectors of the European economy. The project combines climate projections with economic and environmental models to assess potential damages across sectors such as agriculture, health, energy, and infrastructure. It also uses damage functions and CBA to quantify the economic consequences of climate change under various emission scenarios and adaptation strategies. The project used physical and monetary metrics to inform the EU Strategy on Adaptation to Climate Change in 2021 (Watkiss and Hunt, 2012). In addition, drawing on high-resolution climate data with sectoral impact and economic models, the **American Climate Prospectus (ACP)** project incorporated market-driven adaptation via the ability of its CGE model to capture the effects of any direct impacts on linked markets through price changes. However, while the project's empirical analyses were specifically employed to reflect existing endogenous adaptation to weather events, it failed to capture any policy-driven adaptation (Ciscar et al., 2019).

Bottom-up and top-down modeling approaches for macroeconomic evaluation of adaptation interventions provide useful insights for MoFs. The macroeconomic evaluation of adaptation interventions is still at an early stage, with bottom-up and top-down modeling approaches offering useful starting points when appraising adaptation options. For example, a 2022 study uses a 'top-down meets bottom-up' approach to inform climate adaptation for water system planning. Drawing on a **chain of models**, the top-down approach assesses climate risks on adaptive management of water resources over several climate projections. The bottom-up approach uses a participatory process to identify future demand scenarios and local priorities for adaptation. A hydroeconomic model and cooperative game theory are then employed to identify cost-effective combinations of adaptation measures, cost allocations, and equity implications (Pulido-Velazquez, 2022).

Adaptation in climate–economic impact assessments can use either bottom-up modeling approaches, top-down modeling approaches, or both:

- Bottom-up modeling explicitly represents adaptation options, their costs, and their benefits. For example, the U.S. EPA Coastal Property Model (Lorie et al., 2020) optimizes adaptation strategies for each location-year, deciding whether to abandon, elevate, or armor/nourish buildings threatened by sea level rise. Similarly, by incorporating CGE models, global trade models (e.g., Costinot et al., 2016) can optimize crop choice, labor/capital allocation, and trade to adapt to agricultural productivity losses, thus informing the choice of intervention. This approach can also capture feedback effects such as moral hazard and fiscal impacts, for example the moral hazard effect of Jakarta's sea wall (Hsiao, 2023) and the fiscal costs/benefits of U.S. coastal investments (Barrage, 2024a).

Figure 6.1. Fiscal costs of climate change



Source: Barrage (2024a)

- Top-down modeling quantifies adaptation empirically by observing heterogeneity in climate vulnerability. For example, mortality impacts from extreme heat decrease significantly with higher incomes and warmer average temperatures (Figure 6.1), while the share of capital destroyed by cyclones declines with better financial markets, higher incomes, and cyclone experience. Empirical methods can also quantify the impact of public programs on climate vulnerability, such as improved public healthcare reducing mortality from extreme temperatures (Cohen and Dechezleprêtre, 2022; Mullins and Corey, 2020), public crop insurance increasing crop sensitivity to heat (Annan and Schlenker, 2015), and building codes decreasing wildfire damages (Baylis and Boomhower, 2021).

Economic analysis of adaptation interventions requires **cross-disciplinary approaches**, for example combining engineering studies to identify types of adaptation and their effectiveness under different conditions with the need for maintenance regimes using an **economic estimation of costs and (co-)benefits of adaptation interventions**. For this, the economics of adaptation involves employing **cost–benefit analyses** and **real option analysis** to evaluate the economic trade-offs of different adaptation strategies by assessing investment needs to estimate financial requirements for effective adaptation and drawing on network models to prioritize and identify the co-benefits of adaptation measures. A key challenge in climate change adaptation economics is that costs and benefits often occur at different times and places. For instance, the costs of adaptation measures are typically incurred now, while benefits, such as reduced disaster damage, may only be realized later, depending on uncertain future climate change (GIZ, 2023b).

Welfare economics and CBA provide a basis for calculating investment needs based on economic efficiency. What to do, when, how, and at what cost ultimately relies on ethical choices that should reflect the preferences of each society. CBA, complemented by distributional impact analysis, helps maximize social welfare by avoiding resource waste. The social value of avoided climate impacts should exceed the social cost of adaptation (net present value > 0). The optimal protection level maximizes net benefits across adaptation strategies. Consistent application of CBA across development programs ensures no missed opportunities and maximizes development potential.[14]

CBA is a reasonable starting point for the economics of climate change adaptation but faces criticism. Adaptation costs are often over-estimated and benefits under-estimated. CBA struggles with risk and uncertainty, particularly for low-probability catastrophic events. Probabilistic extensions of CBA can inform adaptive risk management, incorporating frequency analysis and anticipatory adaptation (Weitzman, 2009).

Similarly, dynamic influence diagrams model adaptation benefits and interactions, informing trade-offs between policy objectives (Pollino and Hart, 2008). They assess intervention effectiveness across sectors while accounting for unintended impacts (maladaptation) (Molina et al., 2013). For example, a new dam's flood risk reduction could be evaluated alongside locust control's crop protection, capturing secondary effects such as displacement (Pittock and Hartmann, 2011).

The assessment of the benefits of adaptation interventions and options is an emerging area. One example of the different approaches applied by countries is a recent evaluation of a large-scale adaptation project, the Grand Ethiopian Renaissance Dam (GERD), which employs a river basin analytical modeling framework adaptable to future uncertainties. This approach allows experts to estimate the dam's performance under various climate scenarios (Basheer et al., 2023). In the UK, a hybrid approach for England's Climate Change Risk Assessment 3 (CCRA3) combined bottom-up and top-down analyses to assess climate change economic costs, finding that early adaptation investments can yield high value for money (Watkiss et al., 2021). Benefit–cost ratios range from 2:1 to 10:1, indicating significant net economic benefits.[15] The Thames Estuary 2100 project in the UK employs a real

[14] See 'The critical role of Ministries of Finance in investment in adaptation and the analytical principles and tools available,' contribution from the IMF Fiscal Affairs Department to the HP4 Compendium of Practice.

[15] See 'Methodological recommendations for Ministries of Finance on climate change risk assessment and the enhancement of damage functions,' contribution from the University of East Anglia to the HP4 Compendium of Practice.

options approach for flood risk management, allowing flexible adaptation pathways based on climate projections (UK Environment Agency, 2023). Furthermore, IFAD evaluates resilience through recovery indicators based on farmers' self-assessments post-shock, using the Resilience Design and Monitoring Tool to design and monitor resilience-building interventions (IFAD, 2022). IFAD's Resilience Design and Monitoring Tool uses a systems-based modeling approach to assess and enhance the resilience of agricultural systems and rural communities to climate change and other shocks. The tool integrates data from various sectors, such as agriculture, water, and livelihoods, and applies scenario analysis to support decision-making for designing resilient projects and interventions.

In the UK, ClimateXChange has conducted case studies on climate change adaptation economics, analyzing a 2015/16 flood event in Aberdeenshire using CBA to compare flood damage prevention benefits with adaptation costs (CCC, 2024).

Other notable programs and tools for MoFs assessing adaptation options include the ECONADAPT project, which develops economic methods for assessing adaptive capacity, categorizing adaptation options based on their characteristics and potential benefits. Drawing on climate data, economic models, and policy analysis, the project uses a combination of IAMs, CBA, and decision-support tools to assess the costs and benefits of climate change adaptation strategies under different scenarios. GIZ's CRED (Climate Risk and Early Warning Systems) program, which models climate change economic impacts, also enables evidence-based adaptation measures. The program uses a combination of risk modeling, early warning systems, and vulnerability assessments to enhance resilience to climate change and natural hazards. The program typically incorporates hazard models, vulnerability analysis, and exposure assessments to quantify the impacts of climate risks, with a focus on improving forecasting and preparedness. Kazakhstan and Georgia have utilized this methodology to assess long-term macroeconomic impacts and adaptation effects, respectively. Kazakhstan's findings indicate that climate change threatens food security and economic growth without adaptation, while Georgia's investments in adaptation yield significant co-benefits, enhancing GDP and creating jobs (GIZ, 2021a).

An important component of these assessments is the evaluation of the **benefits of adaptation**, including its role in determining macro-level losses and economic impacts. It is widely recognized that investing in climate adaptation offers substantial potential economic benefits, such as avoiding costs from climate damages, creating jobs, enhancing productivity, and creating social and environmental **co-benefits**, including reduced healthcare costs by preventing disease outbreaks and other health impacts caused by climate change (World Bank, 2023). For example, investments in agriculture, such as improved irrigation systems, can enhance agricultural productivity and food security, leading to economic stability in rural areas. Moreover, by mitigating extreme heat and improving air quality, adaptation measures can improve worker health and productivity, raising economic output (World Bank, 2023). The magnitude of the benefits depends on context, including the specific policy, baseline exposure to pollution, sources of pollution, and prevailing patterns of physical activity and food consumption.[16] However, these investments come with challenges, including high initial costs, opportunity costs, and potential economic displacement. The overall impact depends on the effectiveness and efficiency of the adaptation measures implemented. Poorly designed adaptation measures can also lead to maladaptation, where interventions increase vulnerability to climate risks or create new problems. This can result in wasted investments and economic losses (World Bank, 2023).

Assessment of the co-benefits of adaptation interventions is emerging but is not common practice. The triple resilience dividend (TRD) framework is an important tool when making an investment case for adaptation interventions or seeking adaptation finance. The concept of the TRD refers to the multiple benefits that investments in resilience and adaptive measures can provide. **These benefits are categorized into three main 'dividends'**:

[16] See 'The health co-benefits of climate change mitigation: why climate leadership by Ministries of Finance can help them to deliver on their core objectives of economic development and responsible management of the public finances,' contribution from the London School of Hygiene & Tropical Medicine to the HP4 Compendium of Practice.

1. **Avoiding loss and damage**. This is the most direct benefit and involves minimizing the loss and damage caused by climate-related events such as floods, droughts, storms, and other natural disasters. By enhancing resilience, communities can protect infrastructure, reduce economic disruptions, and save lives.
2. **Unlocking economic potential**. Investments in resilience often stimulate economic activity and growth. For instance, building more resilient infrastructure can create jobs and encourage investment. Additionally, resilient systems are more reliable and efficient, reducing maintenance costs and improving productivity.
3. **Additional co-benefits**. Resilience initiatives often have co-benefits that improve social well-being and environmental health. These can include improved public health, enhanced ecosystems, better social cohesion, and overall improved quality of life. For example, green infrastructure projects can provide recreational spaces, enhance biodiversity, and improve urban air quality.

This framework can assist adaptation investment appraisals. The World Bank, World Resources Institute (WRI), Global Center on Adaptation and other organizations are using it to inform adaptation expenditure (Heubaum et al., 2022).[17]

[17] See also 'Informing economic modeling approaches for effective climate transitions,' contribution from the World Resources Institute to the HP4 Compendium of Practice.

7. Tools designed to help Ministries of Finance decide how to finance adaptation

Assessing financial requirements and deciding how to meet them remains an emerging field for Ministries of Finance

The initial costs of adaptation measures can be substantial, placing a financial burden on governments, businesses, and communities. This is particularly challenging for developing nations that possess limited financial resources. Furthermore, funds designated for adaptation may redirect resources from other developmental priorities, potentially resulting in underinvestment in other essential areas (World Bank, 2021). The assessment of financing requirements for adaptation is a developing field, with existing reports frequently presenting a broad spectrum of estimates. For instance, UNEP's Adaptation Gap Report compiled data from various sources to assess the status of national adaptation planning globally and performed comprehensive analyses of adaptation finance flows. It estimated current financial investments and juxtaposed these against the projected needs for effective adaptation. The report examined the execution of adaptation actions across diverse sectors such as agriculture, water, and ecosystems, subsequently evaluating the effectiveness of these actions and investigating the co-benefits of integrating adaptation and mitigation efforts (UNEP, 2022).

The findings regarding the gap illustrate the state of international public finance, which, despite an upward trend, remains significantly below the expected costs of adaptation. This gap also highlights the challenges in transforming adaptation priorities stated within national adaptation plans (NAPs) or nationally determined contributions (NDCs) into investment-ready programs. Additionally, there are challenges associated with mobilizing the necessary finance to implement NAP and NDC priorities from various sources (including international public, domestic public, and private sectors [both international and domestic]). Concurrently, the majority of international public finance sources (multilateral funds, development banks, and development partners) have primarily concentrated on developing adaptation projects, limiting the potential for more strategic investments. Consequently, a critical priority is to advance the adaptation investment process upstream, adopting a more strategic (or programmatic) approach to adaptation investments which is currently being promoted through adaptation investment planning.[18]

In the absence of well-defined adaptation objectives, the inquiry into 'how much adaptation?' tends to remain subjective and normative. MoFs can evaluate acceptable thresholds, the level of risk a country is willing to accept, and what degree of protection is considered economically optimal.

A significant obstacle to allocating budgets for adaptation is the lack of clarity regarding current expenditures and their locations. The analysis of adaptation finance and its tracking within budgets is an emerging field. Recent advances in climate modeling and analysis have shown promise in developing practical tools to enhance efficiency in sourcing and allocate resources optimally across various intervention options, including adaptation (BIS, 2021; NGFS, 2024a). Progress in public expenditure reviews, asset-level analysis, and debt sustainability analysis, such as climate budget tagging and tracking (CBT) and disaster budget tagging and tracking (DBT), can facilitate the integration of climate risks into financial planning (Choi et al., 2023; Alton and Mahul, 2017). Budget tagging and

[18] See 'Global adaptation finance costs, the adaptation finance gap, and adaptation investment planning,' contribution from Paul Watkiss Associates to the HP4 Compendium of Practice.

tracking of public expenditures on climate adaptation and disaster resilience have been employed to explore financing gaps and resource availability for climate investments. While there has been an increase in suggestions for integrated and coherent investments in climate adaptation and resilience across government ministries, common objectives are recognized to varying degrees within national policy frameworks. CBT is becoming increasingly prevalent across countries, while DBT remains underutilized, and systems that allow simultaneous tracking across both are even rarer (Choi et al., 2023). A significant challenge that may hinder MoFs' ability to monitor existing adaptation expenditures stems from the cross-cutting and departmental nature of adaptation investments.

The lack of shared definitions explains a large fraction of the wide range observed in estimates of adaptation investment needs. Important differences stem from different assumptions about economic development and future vulnerability, climate change itself, and adaptation technology. However, the inclusion or exclusion of broad development investments that would be needed even without climate change can dramatically change estimates of investment needs in adaptation (Hallegatte et al., 2017). Different criteria to define optimal adaptation are also important sources of differences in estimates of investment needs[19] (for further reading see Bellon and Massetti, 2022; Aligishiev et al. 2022). It is useful to start by defining investment needs in climate change adaptation as the difference between optimal investment levels with and without climate change (strict additionality definition). This definition intentionally excludes investments in development that would be optimal even without climate change. While a more educated population can better adapt to future climate challenges, climate change itself does not inherently increase the optimal number of school years or the optimal teacher–student ratio. But if tropical cyclones intensify in Tonga due to climate change, for example, and building stronger schools costs more, the education budget may be affected. The bulk of education spending should not be counted as an adaptation to climate change, but any increase in spending needs attributable to climate change should be counted as an adaptation investment. If a looser definition is used, and all investment that helps reduce vulnerability to climate change is counted as adaptation to climate change, virtually all investment in development becomes an investment in adaptation. This distinction is particularly relevant for tracking adaptation spending in national budgets and international climate finance.[20]

Considering the crucial role that private capital can play in enhancing financial resilience, it can be important to foster regulatory environments that encourage the mobilization of both international and domestic private capital. The concept of resilience monetization and credit can motivate the private sector by identifying investment opportunities and providing incentives throughout the value chain of stakeholders involved in resilience financing. This approach encompasses blended finance, which includes the capacity to offtake risks, and opens up the possibility of establishing resilience credit as a distinct asset class. Resilience monetization illustrates the co-benefits of mitigation and adaptation, linking the outcomes of the former with the carbon market, thus offering an opportunity for value creation (beyond mere market returns) for financiers (IFAD, 2022; ECA, 2022). Lastly, the emerging agenda surrounding loss and damage has prompted new evaluations of financial needs. For instance, the Country Climate and Development Reports (CCDRs) diagnostic tool aids in integrating climate adaptation and development objectives at the national level. CCDRs have underscored the necessity to enhance the mobilization of capital from both the private sector and the international community, while also emphasizing the importance of formulating integrated climate and disaster risk finance strategies. (Alton and Mahul, 2017).

Disaster risk finance approaches offer insights for adaptation optimization. One approach frequently used in the disaster risk and insurance context is risk layering, which enables an optimization of adaptation and risk finance interventions (Mechler et al., 2014).

Another approach is the **assessment of the protection gap**, which describes the difference between total economic damage and insured damages, for example from Swiss Re, and as outlined in the contributions from Marsh

[19] See 'The critical role of Ministries of Finance in investment in adaptation and the analytical principles and tools available,' contribution from the IMF Fiscal Affairs Department to the HP4 Compendium of Practice.
[20] ibid.

McLennan[21] and the World Bank[22] in the Compendium of Practice. While not specifically economic analyses in themselves, these assessments require data about losses and liabilities and use this to investigate how a mix of interventions can keep the financial impacts on a country as low as possible through the combination of risk finance and risk reduction efforts. This involves assessing financial protection gaps by quantifying liabilities across governments, businesses, and households. It then combines insights on risks, insurance, and adaptation/resilience to develop a '**holistic view of risk**,' as shown in Figure 7.1. The NGFS encourages the use of such assessments, noting that central banks and supervisors could further examine the importance of insurance for the wider financial system and efforts to reduce protection gaps (NGFS, 2024d).

These types of assessment show how countries can combine different tools for managing climate risks as the frequency and severity of climate-related shocks increase. This can help manage the government's financial needs for emergency response following climate and other shocks. Disaster resilience finance instruments, such as sovereign risk insurance, catastrophe bonds or wrappers, are then assessed for comparative benefits by employing CBA to consider how they can provide financial cushioning during climate shocks. While catastrophe bonds, which act as contingent credit lines providing immediate financial support after a natural disaster, have been issued to nine countries, a catastrophe wrapper has only been used by the government of Belize thus far. This innovative financing instrument was developed to make debt servicing more sustainable by providing coverage for a blue loan debt payment after an eligible hurricane event in the country (Alton and Mahul , 2017). Protection gap analysis can be used to establish how much a country would need to spend on infrastructure repairs, invest in irrigation measures, and fund the maintenance of protection infrastructure, for example in the context of flooding. MoFs can leverage the expertise of existing insurance programs such as pools and utilize the underlying data collected through these schemes to inform climate adaptation assessments (Crick et al., 2018).

In the **Netherlands**, the government has completed several spending reviews related to climate adaptation, climate mitigation, and environmental policy. These reviews are used to identify policy options that incentivize investment in adaptation and resilience (EU et al., 2021). Other examples of **expenditure analysis through climate policy review** include **Burkina Faso** and **Niger'**s combined disaster and climate change public expenditure and institutional review tool, **Ethiopia'**s combined disaster risk reduction and climate change

Figure 7.1. Holistic risk management

Source: Marsh McLennan[23]

[21] See 'How the analytical tools and methods used in the (re)insurance industry can support Ministries of Finance in their understanding of physical climate risks and their efforts to support climate adaptation' contribution from Marsh McLennan to the HP4 Compendium of Practice.

[22] See 'Strategic climate risk modeling for economic resilience: a guide for Ministries of Finance,' contribution from the World Bank to the HP4 Compendium of Practice.

[23] See the contribution cited in footnote 21. See also Marsh McLennan, 2024.

adaptation budget tagging and tracking system, **Kenya'**s separated climate-relevant expenditure reporting for non-state and state actors, and the **Pacific Climate Change Finance Assessment Framework (PCCFAF)** (Choi et al., 2023). PCCFAF has been recognized as good practice in the UNFCCC Standing Committee on Finance's 2018 biennial report. The framework builds on **Vanuatu'**s climate public expenditure and institutional review, as well as the public expenditure and financial accounting methodology. Notably, the PCCFAF extends tagging and tracking of climate finance flows to include gender-responsive planning and budgeting. However, climate budget tagging and tracking lacks standardized methods and taxonomy across countries, and evidence on the actual impact of CBT and DBT remains limited (Choi et al., 2023). Table 7.1 provides example tools used for expenditure reviews across Africa.

In the UK, the Long-term Investment Scenarios (LTIS) report addresses the challenges of managing flood and coastal erosion risk amid several factors, including asset deterioration, climate change, and a growing population. Under a high climate change scenario, effective current planning outcomes can reduce risk by 4% if investments are made in conventional flood and coastal erosion risk management (FCERM) activities. However, this reduction is counterbalanced by increased damages resulting from the ongoing shortcomings of existing planning policies and their implementation. In a plausible extreme climate change scenario, there are more areas where new investments may not be cost-effective. If investment decisions are based solely on cost and damages avoided, many assets would be left to deteriorate, consequently increasing overall risk. The LTIS 2019 edition introduces new scenarios that quantify the substantial benefits associated with investing in very high levels of protection. However, it acknowledges that social and technical limitations may render such investments difficult or even unfeasible in many areas. The findings from these new scenarios indicate that the overall economic optimum

Table 7.1. Examples of disaster and climate policy and expenditure review tools used in Africa

Tool	Country applications
Climate Public Expenditure and Institutional Review (CPEIR)	Benin (2017); Eswatini (2021); partial review in Ethiopia (2014); Ghana (2015, 2021); Kenya (2016); Morocco (2012); Mozambique pending govt validation (2016); Rwanda (2013); unsuccessful attempt in Seychelles (2018); Tanzania (2013); Uganda (2013)
Joint Disaster and Climate Public Expenditure and Institutional Review (DCPEIR)	Reviews have begun in both Burkina Faso and Niger but have yet to be finalized
Risk Sensitive Budget Review (R-SBER)	Angola, Botswana, Cameroon, Cote d'Ivoire, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea-Bissau, Kenya, Namibia, Rwanda, Sao Tome and Principe, Tanzania, and Zambia conducted reviews in 2020
Investment Planning and Financing Strategies for Disaster Risk Reduction (IPFSDRR)	Comoros (2015); Madagascar (2015); Mauritius (2015); Niger (2016); Seychelles (2015); Zanzibar, Tanzania (2015); Togo (2016)
Disaster Risk Financing Diagnostic (DRFD)	Eswatini (2022); Lesotho (2019); Sierra Leone (2022); South Africa (2022)
Public Expenditure and Financial Accountability Climate (PEFA-C)	Ethiopia (2021)
Climate Policy Initiative Climate Finance Landscape Assessments (CFLA)	Kenya (2021); Nigeria (2022); South Africa (2021)
Public Environment Expenditure Review (PEER)	Mauritius (2016); Mozambique (2012)
Tracking of Public Sector Environment Expenditure (TPSEE)	Mauritius (2018)
Biodiversity Public Expenditure Review (BPER)	Seychelles (2019)

Source: Steele et al., 2022; UNDRR, 2020; UNDRR, 2016 level of investment is higher than previously estimated, now exceeding £1 billion in long-term annual averages. The revised estimate reflects a more comprehensive understanding of the range of medium to high climate change scenarios and incorporates a better assessment of the broader impacts of flooding (UK Environment Agency, 2019).

All EU Member States practice some form of disaster risk financing (DRF) as all of them have been confronted with such events at various times. The most common way to deal with the financial consequences of disasters in EU Member States is ad hoc financing. In fact, there is limited evidence of natural disaster funds or other prearranged funding in the national budgets of EU Member States (Radu, 2021, 2022). The reformed EU economic governance framework introduces reporting requirements for EU Member States regarding macro-fiscal risks from climate change, contingent liabilities from climate and natural disasters, and associated fiscal costs. Acknowledging the current data availability and methodological challenges, these reporting requirements apply 'to the extent possible.' Radu proposes steps to enhance climate-resilient budgets for the EU.[24]

Further examples of programs, initiatives, alliances, and tools available to MoFs to assess adaptation investments and finance can be found around the world:

- **The ADB Climate Adaptation Investment Planning initiatives, UNDP adaptation accelerator, and the NDC Partnership** assist countries in transforming their NDCs and NAPs into adaptation investment plans that create pipelines of bankable projects. This strategic approach integrates adaptation into existing government

Box 7.1. The example of Rwanda

Rwanda has one of the most advanced climate policy frameworks, making it a valuable case study for climate mainstreaming and finance. Policy interest in climate change was sparked by a 2009 study on the economics of climate change, leading to the development of the Green Growth and Climate Resilient Strategy (GGCRS) in 2011. This strategy laid the foundation for Rwanda's climate mainstreaming agenda, integrating climate considerations into its medium-term development plan and sector strategies. The country introduced:

- Mainstreaming guidance
- Climate-related indicators in its budget circular
- Climate budget tagging analysis.

The National Strategy for Transformation (NST-1) (2018–2025) further advanced this with key performance indicators (KPIs) linked to these goals. This progress continues with the GGCRS II (2024) and the upcoming NST2 (2025–2030).

The GGCRS also led to the establishment of the Rwanda Green Fund in 2012, initially a demand-driven challenge fund that invited competitive proposals focused on thematic areas or funding priorities.

- To date, 14 calls for proposals have been held, resulting in over 50 funded projects.
- Over time, the fund has evolved to take on a hybrid role, offering strategic programming alongside its original demand-led model, for instance, by integrating sector mainstreaming efforts.
- The fund has also been instrumental in securing additional climate finance from multilateral funds, development partners, and foundations, mobilizing US$350 million to date.
- Most recently, the fund launched a blended finance facility known as the Rwanda Green Investment Facility (Ireme Invest), in partnership with the Rwanda Development Bank. This facility supports private sector mitigation and adaptation projects through a project preparation fund, led by the Green Fund, and a concessional credit facility led by the Development Bank. It has already mobilized US$20 million for project preparation and US$100 million in concessional finance from GCF, AfDB, and EIB for on-lending.

In addition, the Rwandan Ministry of Finance and Economic Planning (MINECOFIN) has developed a Climate and Nature Finance Strategy (CNFS) with a dedicated climate finance unit. This strategy supports a whole-of-economy approach, aiming to unlock large-scale investments to drive Rwanda's climate and environmental goals.

[24] See 'A structured approach to disaster risk financing in the EU Member States,' contribution from the European Union—European Commission to the HP4 Compendium of Practice.

planning and financing frameworks, including medium-term national development plans and public financial management systems, to enable more programmatic adaptation investments (ADB, 2023a; UNDP, 2024).

- **The Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI)** offers disaster risk insurance to Pacific Island countries, covering tropical cyclones and earthquakes. It gathers data on hazard events and losses, aiding countries in prioritizing climate adaptation and disaster risk reduction investments. For instance, Fiji has utilized PCRAFI data to enhance its national disaster management plan and secure funding for resilient infrastructure projects.
- **The World Bank's DRFIP Financial Response Design Tool** is available online for MoFs to guide financial and policy decisions regarding risk finance. It emphasizes assessing the short-term financing gap and costs of financial instruments. Governments should identify liquidity needs post-climate shock, using catastrophe risk models to estimate emergency losses. A mix of financial instruments, such as contingency reserves, contingent credit lines, climate-resilient debt clauses, and sovereign risk transfer instruments, should be strategically combined based on risk profiles and funding needs.

Leveraging insurance into adaptation planning can also facilitate access to adaptation financing. In addition to the PCRAFI (see Table A3), other examples exist of how MoFs can leverage the expertise and data of existing insurance programs such as risk pools and national insurance schemes to inform climate adaptation assessments (Surminski, 2018). For example, in the U.S., data from the National Flood Insurance Program has been used to update flood risk maps and identify areas that are at high risk of flooding. This information supports local governments in developing floodplain management regulations and investing in flood mitigation projects (Lehman, 2023). In the UK, **Flood Re**[25] data has been instrumental in informing the country's national flood risk assessment and in supporting local authorities in prioritizing flood defense investments (Flood Re, 2024). Across the Caribbean, data from the **Caribbean Catastrophe Risk Insurance Facility (CCRIF)** is used by member countries to assess their vulnerability to climate-related hazards and develop national adaptation plans. For example, the Bahamas used CCRIF data to enhance its hurricane preparedness and response plans, including the construction of more resilient infrastructure (CCRIF SPC, 2024). Countries such as Malawi and Kenya have also used **African Risk Capacity** data to improve their drought risk assessments and develop more effective drought mitigation and adaptation strategies (African Risk Capacity, 2024).

Financial response design tools, including value-for-money analytics, can help to identify a cost-effective mix of instruments. When using the DRFIP Financial Response Design Tool, MoFs are encouraged to seek guidance from experts to ensure that appropriate input assumption settings are used to make a fully informed use of the tool's outputs and, if necessary, develop a more tailored analysis to address the specific financial or policy questions they are seeking to answer. Vital to risk financing approaches is the concept of risk layering, aiming to secure the adequate amount of liquidity based on the severity and the frequency of disasters at the lowest possible cost.

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[25] Flood Re is a reinsurance scheme in the UK that allows insurers to offer affordable flood insurance to high-risk properties. It collects extensive data on flood claims and payouts, which is used to assess flood risk and guide adaptation measures.

8. How Ministries of Finance can navigate common challenges when analyzing physical risks and adaptation

It is important to start work now with imperfect data and tools, refining and enhancing over time

Physical climate risks and adaptation are far from mainstreamed for financial decision-making. This is problematic as MoFs need robust analysis to underpin their decision-making. There are strong analytical tools, for example from disaster risk management and risk finance, that can help with the quantification. Dealing with current risks and learning from the past can be useful starting points for increasing future resilience. But the nature of climate change means that the world is already in 'uncharted territory,' with complex **interdependencies and tipping points** leading to even more widespread and profound direct and indirect impacts on natural and human systems than currently estimated. The growing number of pilots and initiatives emerging allows a glance into what works, where the key challenges remain, and how not only the analytics but also the communication and ownership of risk all play a role in helping to mainstream physical risk and adaptation into MoFs' decision-making.

The good news, as shown in the previous chapters, is that there is an arsenal of analytical measures that can be deployed, with a growing number of 'economics of adaptation' studies and assessments, based on improved data and analysis of hazards, exposure, and vulnerability. There are significant advantages in starting now and refining over time, rather than deferring action while waiting for more precise data. Delaying action risks not only escalating the costs associated with physical climate risks but also losing the potential co-benefits from timely adaptation measures. This is particularly relevant in the adaptation space, where waiting for economic models to catch up could mean missing significant opportunities for proactive intervention. While MoFs will need to remain adaptable and deploy analytical measures in various ways, depending on needs and capacities, good practice approaches tend to be (1) evidence-driven; (2) cost-effective; (3) forward-looking and dynamic; (4) coordinated and collaborative; and (5) barrier-addressing (ADB, 2023b). Importantly, no approach is or will ever be perfect due to the complexities of climate and socioeconomic systems. A pragmatic balance is needed between detailed analysis and practical decision-making support, especially in data-poor contexts. Guidance and recommendations from various organizations can assist in assessing the economic impacts of climate risks. Early feedback, collaboration, and simplified processes can improve the integration of model development and adaptation planning, fostering evidence-based policymaking and inter-ministerial cooperation. A 'white box' approach with detailed handbooks aids transparency and capacity development.[26]

Rather than being paralyzed by complexity, MoFs should consider the following recommendations:

1. **Enhance data and tools**: invest in improved analytical tools and data collection that accurately reflect the economic impacts of climate change, including the use of updated damage functions and models that account for non-linear relationships and tipping points.
2. **Integrate adaptation into decision-making**: actively incorporate adaptation considerations into macroeconomic planning and fiscal policies. This includes recognizing the long-term benefits of adaptation investments and their role in mitigating future risks.

[26] See 'Modeling climate-resilient economic development—GIZ's approach to supporting sustainable economic growth,' contribution from GIZ to the HP4 Compendium of Practice.

3. **Foster cross-government collaboration**: establish collaborative frameworks across different government sectors to ensure a comprehensive approach to managing physical climate risks. This can enhance the understanding of interdependencies and improve overall resilience.
4. **Build capacity and communication**: invest in training and capacity-building initiatives within the MoF to better understand climate risks and adaptation strategies. Additionally, MoFs should ensure clear communication between analysts and decision-makers to align analytical outputs with policy needs.

For MoFs it is important to integrate insights from different tools and models and to make sense of analytical findings and communicate this to decision-makers. For MoFs, developing a clear narrative from climate risk assessments is challenging. Various government entities or third parties conduct these assessments, but the results provide information that MoFs often struggle to integrate into their decision-making due to lack of translation into clear numbers or indicators that fit into MoF tools and assessments. When conducting assessments the results are often not in a format suitable for immediate decision support. For example, the detailed and specific number required may not be forthcoming—ranges as well as illustrations of impact challenges may be more informative for decision-makers than an absolute number. As with all projects and future assessments, MoFs need to be very clear in communicating risks and uncertainties.

A broadly helpful tangible step in addressing climate uncertainty in economic modeling would be to create and maintain a database of potential climate scenarios that includes estimates of their likelihood under different assumptions about global climate mitigation actions. This would allow researchers to assign probabilities to sensitivity analysis and make better recommendations for policies that have different outcomes across scenarios.[27] Effectively communicating findings amid uncertainty and data gaps is crucial. For MoFs, navigating this uncertainty can be difficult. Modelers and analysts can assist MoFs in interpreting data and integrating insights into their macroeconomic models for forecasting and fiscal risk management. The broader community can also support this process by promoting collaboration and providing guidance on managing uncertainty. By implementing these strategies, MoFs can better navigate the complexities of physical climate risks and enhance their capacity to make informed financial decisions that support resilience and adaptation.

Robust analytical tools from disaster risk management can aid in quantifying these risks, with the case studies and stakeholder engagement presented here highlighting several aspects that MoFs should be aware of when assessing and addressing physical climate risks.

Current tools are prone to underestimate the scale of economic impacts

Existing analytical tools often underestimate the economic impacts of climate change, failing to capture complex interactions and tipping points. This leads to a lack of accurate modeling of the relationship between climate variables and economic outcomes. For example, economic models such as DICE often fail to accurately assess climate change impacts due to limitations in damage functions, which struggle with extrapolation and regional applicability. These models represent the relationship between global warming and sea level rise inadequately, and the choice of damage function and discount rate significantly affects climate policy benefits. The relationship between GDP growth and temperature is non-linear, with higher costs associated with marginal temperature increases. Damage functions often overlook distributional impacts and adaptation measures, leading to an underestimation of risks.

Many climate impacts remain understudied, and current evaluations often miss significant risks to lives and livelihoods. The relationship between climate variables (e.g., temperature, precipitation) and economic outcomes

[27] See 'The challenges of uncertainty in climate-economy modeling,' contribution from the Canadian Department of Finance to the HP4 Compendium of Practice.

involves complex, non-linear interactions that are difficult to model accurately. Many processes that are vital to climate change, including complex and cascading risks as well as tipping points, are frequently absent from economic assessments (DeFries et al., 2019). Indeed, a report by the Royal Society (Royal Society, 2023) underlines that "Even the most sophisticated approaches do not yet capture broader system-wide risks [...] or the non-linearities in climate scenario modelling." Specifically, independent determinants of physical risk can accumulate, and individual physical hazards of climate change can also interact into compounding risks. Moreover, physical risks can have cascading effects where a change in the condition of one variable creates or exacerbates shifts across other variables (Carter et al., 2021; NGFS, 2024c). Physical risks can have cascading effects, compounding the overall impact on public finances, which can result in increased public debt and hinder economic growth. Modeling the complex interactions between climate variables and economic outcomes is challenging, with many significant processes omitted from assessments. Independent physical risks can accumulate and lead to compounding effects, complicating the understanding of economic impacts. Furthermore, economic impacts can manifest as sudden shocks or gradual trends, with acute impacts often having spillover effects on other regions.

Physical climate risks do not respect borders, necessitating an understanding of international risk transmission. These risks can destabilize economies, making it essential for finance leaders to adapt to these challenges. Understanding these interdependencies is crucial for developing robust financial strategies. Nature-related scenario frameworks are limited in providing meaningful insights due to the complexity of ecosystems and the absence of a universal metric for nature, such as CO_2-equivalents.[28]

Damage functions have frequently failed to adequately account for non-market effects, adaptation measures, and tipping points, which can lead to an underestimation of risks (Dicks et al., 2023). A broad spectrum of climate impacts remains understudied or difficult to quantify and is absent from current evaluations of climate risks to lives and livelihoods. (Rising et al. 2022). Even the COACCH project's updated damage functions (see Section 5, Table 5.2) underestimate the full scale of global economic damages because the literature (which is the necessary basis for all damage functions) cannot fully capture the large economic costs associated with the whole range of climate change risks. Further, for example, many current models of climate change risks to agriculture and ecosystems exclude the effects of extreme weather events. In contrast, the risk assessment in the IPCC Sixth Assessment report (Bednar-Friedl et al., 2023) uses a simple diagram to convey levels of concern about risks, which is based on the full scientific understanding of the risks.

A practical illustration of these deficiencies is underscored by the IMF's acknowledgment that its key macroeconomic forecasting frameworks continue to overlook five critical realities concerning climate adaptation, natural capital, and debt sustainability. First, baseline macroeconomic forecasts that disregard climate change impacts are utilized, yet they are unrealistic. Second, nature risks impact baseline macroeconomic forecasts and expected volatility. Third, it is essential to consider the maintenance and enhancement of both 'hard' infrastructure and natural capital to foster resilience against climate change and nature loss. Fourth, forecasts must account for the productivity of a country's natural capital and its contribution to long-term economic growth, and fifth, climate risks are significant globally as vulnerability is present across market-access countries as well as low-income countries (Barbier and Burgess, 2023).

Tipping points further increase the complexity of assessing risks and impacts

Estimating economic damages decades into the future is fraught with uncertainties. While it is essential to analyze the potential macroeconomic and fiscal sustainability implications of climate change, scientists are only beginning to understand tipping points and the severity and timing of impacts given their compounding and cascading nature

[28] See 'C3A's assessment of the emerging analytical needs of Ministries of Finance: opportunities and challenges,' contribution from C3A to the HP4 Compendium of Practice.

(Zebisch, 2023). This poses a challenge for MoFs tasked with assessing the magnitude of risks and deciding on the cost-effectiveness of actions. For example, over the last few years, the threat of local and global tipping points, which are thresholds that once passed lead to irreversible shifts in natural systems, have been widely acknowledged, but their potential impacts, particularly related to global tipping points, are not fully considered from the perspective of MoFs. Locally, these changes can arise, for example, when a small rise in temperature leads to the collapse of a certain crop, with potential national and regional implications. Impacts include the significant costs associated with large-scale relocation and what this implies for public finance (Butler et al., 2022), scenarios where regions such as Florida become indefensible due to porous ground, and the broader social and economic implications of mass migration caused by a breach of tipping points.

No fully integrated modeling tools exist, but scenario analysis can help to inform how these developments may impact public finances and economic growth. At the very least, decision-makers should acknowledge the possibility of these tipping points being breached and should consider what the implications could be. MoFs will continue to encounter barriers in incorporating anticipatory financial analyses and budgeting approaches to address these long-term risks. However, it is essential that these potential challenges be factored into future financial planning to mitigate the profound fiscal, social, and infrastructure-related consequences of sea level rise and other climate tipping points. Box 8.1 provides a brief overview of climate tipping points and recommended steps to overcome analytical challenges, drawn from a contribution from Professor David Stainforth.[29]

Box 8.1. Climate tipping points

Definition. The term 'climate tipping point' refers to phenomena including Amazon dieback, shutdown (or slowdown) of the Atlantic meridional overturning circulation (AMOC), thaw of boreal permafrost, and acceleration in the disintegration of ice sheets. The concept of a climate tipping point encapsulates two essential aspects of our understanding of climate change: first, that it might well not be a steady process but rather could involve relatively sudden and substantial changes; and second, that such changes might be irreversible on timescales relevant to human societies; i.e., hundreds to thousands of years.

State of research. Predicting the likelihood and/or timing of crossing a tipping point under any particular scenario for global climate policies is hampered by the fundamental characteristics of human-induced climate change—specifically, the nonlinear connections between different aspects of the climate system and the fact that the system is being driven into a state that it is has never been in before; i.e., the problem is extrapolatory. As a consequence, we may have robust information that certain tipping points are plausible (possibly even expected) under particular scenarios for emissions, but we are unlikely to have the probabilities of occurrence that are sought by those modeling the economy. It is useful to consider research on climate tipping points in three domains: (1) information about the likelihood of crossing a tipping point, (2) information about the consequences of crossing a tipping point, and (3) early warning systems (EWSs) that tell us how close we are to a tipping point. Our understanding of all three is dominated by research using global climate and earth system models (GCMs and ESMs).

Relevance to Ministries of Finance. It is important to embed robust assessments of our latest understanding of climate tipping points into economic strategy and policy because, despite the uncertainty surrounding them, they could potentially have a first order effect on the impacts of climate change on national output and welfare. They impact both the character and spatial pattern of the changes that we should expect, and the timing and rate at which these changes may occur.

Ways forward. What is missing in the academic study of tipping points is twofold. First, a big picture analysis of the risks and physical consequences of crossing climate tipping points, which allows for diverse perspectives on the uncertainties and conditionalities. Crucially, this must involve stepping back to question how to interpret model-based information for both predictions and for uncertainty quantification. Second, a similar big picture, questioning analysis of economic assessments of tipping points and the consequences for the global and national economies. These two tasks are inextricably intertwined.

[29] See 'Climate tipping points,' contribution from the Grantham Research Institute on Climate Change and the Environment to the HP4 Compendium of Practice.

Data and analytical challenges remain, and there is often a disconnect between macroeconomic analysis, sectoral data, and common climate impact assessments

There are significant data challenges regarding the economic consequences of climate events, with limited empirical data often based on historical observations that may not be representative of future conditions (Dicks et al., 2023). Furthermore, macroeconomic models rely on sector indicators that are often difficult to identify, such as the elasticity of demand. Catastrophe models are also subject to challenges as data on local vulnerabilities of infrastructure is scarce, and the approach inherently assumes that vulnerability is not dynamic and not influenced by the adaptive behavior of at-risk populations (Botzen et al., 2019). And where data exists, it can easily overwhelm the non-expert decision-maker.

A key challenge for MoFs and other end users is navigating the abundant open-access tools, data platforms, and guidance, which approach physical climate risks from varying perspectives and aim to answer different questions. The wide range of free data and analytics is a positive development, but end users can easily become overwhelmed or frustrated. This frustration often arises because the data or analytical results may not align with their decision-making timelines, or because they struggle to understand the compatibility of the data and approaches provided.

There is a clear disconnect between current macroeconomic analyses and climate impact assessments, raising concerns that recognizing this complexity could lead to inaction. For instance, in large and economically strong countries there are many compelling arguments for investment, yet immediate macroeconomic concerns are small and thus rarely the primary driver. Furthermore, current disaster risk management processes are fragmented and climate-resilient budgeting practices are lacking.

Moreover, managing uncertainty is further complicated by the lack of harmonized approaches to national-level risk assessments.[31] While some assessments make attempts at incorporating reproducible indices such as the 'life-years index,' the large majority of assessments lack harmonization in metrics for assessing loss, damage, and future scenarios of adaptation (UNDRR, 2015; Noy, 2024). However, there is already sufficient information available for MoFs to begin analyzing the fiscal implications of climate-related physical damage and the benefits of investing in adaptation (CFMCA, 2025c).

There is enough evidence now to bring adaptation into MoF decision-making

An overarching challenge is the treatment of uncertainty, but recognizing complexities and dealing with uncertainties should not become an excuse for inaction. Anyone working on physical climate risks and adaptation also needs to find robust and pragmatic ways of dealing with uncertainty. Uncertainties in future climate change and vulnerability remain large, but policymakers must manage similar risks in other sectors.[32]

All climate and socioeconomic models are subject to sources of uncertainty. Moreover, these uncertainties can reinforce each other where uncertainty in emissions scenarios and socioeconomics baselines can compound into added uncertainty in climate changes, local hazards, economic damages, and costs of adaptation (Rising et al., 2022). This needs to be acknowledged and managed but should not lead to paralysis.

Four specific sources of uncertainty are discussed in the Appendix (Box A2): internal variability, initial condition uncertainty, model imperfection, and scenario uncertainty (Stainforth et al., 2007; Hawkins and Sutton, 2009).

[30] See 'A structured approach to disaster risk financing in the EU Member States,' contribution from the European Union—European Commission to the HP4 Compendium of Practice.

[31] See 'Methodological recommendations for Ministries of Finance on climate change risk assessment and the enhancement of damage functions,' contribution from the University of East Anglia to the HP4 Compendium of Practice.

[32] See 'Fiscal risks of climate change: Quantitative Climate Change Risk Assessment Fiscal Tool (Q-CRAFT),' contribution from the IMF Fiscal Affairs Department to the HP4 Compendium of Practice.

However, strategies already exist to mitigate uncertainty concerns for MoFs to move forward with their application. For example, because regional climate models, which are most relevant for policymaking, are exposed to higher levels of uncertainty than global climate models, it has been suggested that statistical downscaling may add value by providing results closer to actual observations.

Moreover, the use of economic damage functions can be complemented by other methods to assess risk, as there are key aspects of substantial additional climate risk that cannot easily be quantified in economic terms or are not represented in the damage functions, that voters and decision-makers will be concerned about. Such other methods include the study of physical metrics of climate change risks, such as those made available in the IPCC Sixth Assessment Report.

If required to use damage functions, it is important to select the most up-to-date, complete approaches and models that are probabilistic. Importantly, the upper tails of the resultant estimates of climate related risk should be used in informing policy decisions.[33]

Utilizing economic risk assessments for adaptation planning remains underdeveloped

Conducting a climate risk assessment is one thing, utilizing it for adaptation and resilience planning is another. Adaptation is still mostly absent from fiscal and industrial/economic planning, and the economics of adaptation remain a niche exercise. Despite the emergence of new analytical tools, most of the current macroeconomic modeling tools still underrepresent, if they do not fully omit, adaptation, or, if it is included, it is based on very simplistic assumptions about adaptation. This hampers the integration of adaptation into macroeconomic decision-making (Royal Society, 2023). Resilience and adaptation measures can moderate the impact of climate change but are not always fully reflected in the modeling of risk, which could disincentivize these measures. Until today, few economic considerations have been incorporated into a country's NDC or NAP process, and economic stakeholders tend to remain absent from these processes.

Many current models do not adequately account for the benefits of adaptation, or the costs associated with climate risks. The application of economic risk assessments in adaptation planning is underdeveloped. While climate risk assessments are necessary, effectively utilizing them for adaptation remains a challenge, with many existing models inadequately representing adaptation measures. However, while the economic case for adaptation is widely known among experts, there are a range of challenges that hamper the mainstreaming of adaptation into MoF decision-making, including the lack of consensus as to what constitutes a 'well-adapted' country or what level of climate change should be adapted to.

After defining adaptation, it is necessary to adopt a principle to choose how much to spend on adaptation. Without an optimality criterion, it is not possible to say how much investment is needed. This is a complex problem because there is not a right/wrong answer. Governments have wide latitude in choosing their own principle—for example, preserving present levels of risks, economic efficiency, or protecting certain populations—but it is important to make a transparent choice and then to consistently apply the same criterion to determine all other development goals.[34]

CBA approaches are increasingly facing scrutiny for their limitations in effectively addressing climate change adaptation. A major issue is the challenge of capturing risk and uncertainty, particularly regarding low-probability, high-impact events. The benefits of adaptation actions are often difficult to quantify, as they may vary in scale and certainty. Nevertheless, probabilistic extensions to CBA can enhance adaptive risk management, especially for floods, by considering the probabilistic nature of new information. Other enhancements include frequency analysis of extremes, real option analysis, and anticipatory adaptation, which are crucial for making efficient decisions in projects with significant upfront costs and long lifespans (CCC, 2024).

[33] See 'Methodological recommendations for Ministries of Finance on climate change risk assessment and the enhancement of damage functions,' contribution from the University of East Anglia to the HP4 Compendium of Practice.

[34] See 'The critical role of Ministries of Finance for investment in adaptation and the analytical principles and tools available,' contribution from the IMF Fiscal Affairs Department to the HP4 Compendium of Practice.

9. Suggested next steps for Ministries of Finance, research, and analysis

Practitioners, those developing economic tools, and end users can take steps to integrate physical risks and adaptation into day-to-day MoF decision-making

There are several immediate actions that can enhance the integration of physical risk and climate adaptation into MoF decision-making.

First, balance should be sought between providing the most accurate, detailed analyses and ensuring that analyses are pragmatic and timely for policymaking. This involves offering transparent insights and simple narratives while being mindful of the limitations of models and the uncertainties inherent in climate data. MoFs can identify actions that manage current climate impacts, pursue initiatives with positive returns regardless of future climate scenarios, and utilize existing resources to develop flexible responses to an uncertain climate future.

Additionally, MoFs should justify early adaptation actions in economic terms by employing the adaptation pathway approach. This includes recognizing the net economic benefits of low- and no-regret actions today, identifying cost-effective early actions to prevent future economic costs, and developing adaptive management plans for decisions with long lead times or uncertain impacts.

Establishing clear risk ownership and responsibilities within MoFs is crucial. This can be achieved by embracing leadership roles, engaging stakeholders, continuously updating risk assessments, and considering the appointment of a chief risk officer (CRO) to communicate risks effectively to policymakers.

To address analytical gaps, MoFs should utilize a diverse portfolio of model types to assess complex climate risks comprehensively, rather than relying on a single approach. They should also recognize interdependencies with other policy areas, such as the role of nature and equity in climate adaptation, and the connections between transition and physical risks.

Encouraging cross-governmental development of adaptation standards and goals is essential. MoFs should work toward establishing clear targets for adaptation, exploring scenarios that align with international agreements, and ensuring that economic forecasts incorporate these scenarios. It is important to remember that adaptation is a multisectoral challenge with multisectoral policies (Talbot-Wright and Vogt-Schilb, 2023). MoFs play a key role given the capacity of their policies to enable other sectors in implementing adaptation policy. MoFs can help by (1) understanding the economic impacts of physical risks and incorporating them into adaptation targets; (2) making adaptation plans and targeting realistic access to finance; and (3) helping funnel the private sector investment toward sectoral needs.

Finally, setting success criteria for tools and models is vital. MoFs should collaborate with tool designers to agree on guiding principles that ensure robust and pragmatic approaches to climate adaptation economics. Opportunities for collaboration and knowledge exchange should be embraced, fostering transparency in the use of tools and models, and improving communication across disciplines to effectively manage physical climate risks. To help guide this it may be useful to establish guiding principles, such as those recently developed by the Economic Advisory Group of the UK's Climate Change Committee (Robinson, 2024).

Box 9.1. Principles from the first Interim Report by the Advisory Group on the Economics of Climate Risk and Adaptation to the UK Climate Change Committee

(1) Develop a method—using core economic methods of assessing costs and benefits—for establishing quantified goals for achieving the vision of a well-adapted UK and the investment requirements to reach that vision.

(2) Ensure inequality and vulnerability are central to any assessments of the costs and benefits of expenditure on climate change adaptation. This will be critical for developing legitimacy for adaptation investments.

(3) Move away from a pure focus on CBA toward a mix of approaches that focus on the economics of risk and uncertainty. These include real-options analysis and multi-criteria analysis.

(4) Evidence of macroeconomic impacts of climate change on the UK economy have value but should not act as a barrier to more immediate decision-making.

(5) Incorporate a place-based approach that can accommodate adaptation actions that use different entry points for reducing risk.

(6) Develop an adaptation framework that can be adopted and flexed at different governance scales.

(7) Take explicit account of how residual risk can be handled. Understand what level of risk the country is willing to tolerate and how to respond to the limits of adaptation.

(8) Consider explicitly adaptation to international/transboundary risks.

(9) Focus on low-probability and high-impact events and more frequent lower impact events that degrade adaptive capacity over time.

(10) Take explicit account of where economics struggles to provide guidance on adaptation policy.

While the selection of analytical approaches may seem difficult, and in many cases MoFs will be restricted to use what they have due to lack of resources for developing further capabilities, there is a set of steps that officials, analysts, and those working on improving physical risk analysis can embrace. **Regardless of country-specific conditions, the following actions would ensure that the understanding of risks and impacts leads to effective responses**:

- **Start immediate action**: MoFs can begin integrating adaptation measures into decision-making processes now, rather than waiting for more precise data. This proactive approach can help avoid escalating costs and missed opportunities for intervention.
- **Balance immediate and long-term strategies**: while addressing current crises, MoFs can also consider long-term resilience-building strategies that support both adaptation and mitigation investments.
- **Utilize a range of analytical measures rather than rely on one**: deploy a range of analytical tools and methods. Utilize a combination of quantitative and qualitative data to inform decision-making about climate adaptation risks, ensuring a comprehensive understanding of impacts across different contexts.
- **Engage with climate scenarios**: establish and maintain a database of potential climate scenarios, including their likelihood under various global climate mitigation actions. This will aid in sensitivity analysis and inform policy recommendations.
- **Address underlying vulnerabilities**: MoFs can focus on both the impacts of extreme events and the root causes of vulnerability and exposure to climate risks, recognizing that these factors significantly contribute to financial losses.
- **Enhance communication**: foster constant communication between modelers and end users to ensure that analyses are relevant and practical for decision-making. This should include ongoing engagement throughout the analytical process.

- **Invest in capacity-building**: equip ministries with the necessary skills to understand and address climate risks comprehensively. This includes training staff, enhancing data collection capabilities, and developing robust tools for climate risk assessment.
- **Engage with stakeholders**: proactively engage with researchers and modelers to expand the evidence base and improve methods for incorporating climate impacts into macroeconomic risk assessments.
- **Promote cross-government collaboration**: encourage a collaborative approach across various sectors and departments to effectively manage physical climate risks and enhance resilience.

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Appendix

Table A1. Available models and tools

Source	Title	Link
GIZ	Handbook on Macroeconomic Modelling for Climate Resilience	https://www.giz.de/en/downloads/giz2023-en-handbook-macromodelling-resilience.pdf
World Bank	Climate Knowledge Portal	https://climateknowledgeportal.worldbank.org/
GFDRR	Adaptation Performance Tracking (ADAPT)	https://advisory.eib.org/about/adapt.htm
	FloodRe	https://www.floodre.co.uk/
	ClimAdapt tool	https://www.coford.ie/news/climadaptaweb-baseddecisionsupportsystemdss.html
	Community-based Risk Screening Tool—Adaptation and Livelihoods (CRiSTAL)	https://www.iisd.org/cristaltool/
FAO	CROPWAT tool	https://www.fao.org/land-water/databases-and-software/cropwat/en/
	Dynamic Interactive Vulnerability Assessment (DIVA model)	https://climate-adapt.eea.europa.eu/en/metadata/tools/dynamic-interactive-vulnerability-assessment-model-diva
	Water Evaluation and Planning System (WEAP System)	https://www.weap21.org/
UK government	UK Treasury's Green Book Supplementary Guidance on Climate Change	https://www.gov.uk/government/collections/the-green-book-and-accompanying-guidance-and-documents
Zurich Insurance Group	Zurich Flood Resilience Alliance tool	https://floodresilience.net/zurich-flood-resilience-alliance/
Swiss Re	CatNet	https://www.swissre.com/reinsurance/property-and-casualty/solutions/property-solutions/catnet.html
AXA	Climate Risk Management Solutions	https://axaxl.com/climate-risk
Goldman Sachs	Climate Risk Modelling Framework	https://www.goldmansachs.com/investor-relations/corporate-governance/sustainability-reporting/2023-awm-tcfd-report.pdf
WRI	RAMP	https://www.wri.org/initiatives/resilience-and-adaptation-mainstreaming-program-ramp
EU	Projection of Economic impacts of climate change in Sectors of the EU based on boTtom-up Analysis (PESETA project)	https://climate-adapt.eea.europa.eu/en/metadata/projects/peseta-projection-of-economic-impacts-of-climate-change-in-sectors-of-the-european-union-based-on-bottom-up-analysis
	Project COIN (Cost of Inaction: Assessing the costs of climate change for Austria)	https://ccca.ac.at/en/climate-knowledge/coin
	In-depth economic analysis of individual policy instruments and measures for adapting to climate change and the project Economics of Climate Change Adaptation	
OECD	Project on Losses and Damages from Climate Change	https://www2.oecd.org/environment/cc/losses-and-damages/
IMF	Climate Change Policy Assessment for Small States	https://www.imf.org/en/Topics/climate-change/resilience-building

Table A1. (continued)

Source	Title	Link
World Bank	Economics of Adaptation to Climate Change (EACC)	https://www.worldbank.org/en/news/feature/2011/06/06/economics-adaptation-climate-change
ADB	Economics of Climate Change in the Pacific	https://www.adb.org/sites/default/files/publication/31136/economics-climate-change-pacific.pdf
IADB	Understanding the Economics of Climate Adaptation in Trinidad and Tobago	https://publications.iadb.org/en/understanding-economics-climate-adaptation-trinidad-and-tobago
ETH Zurich	CLIMADA	https://climada.ethz.ch/
NGFS	Climate Scenarios	https://www.ngfs.net/ngfs-scenarios-portal/
	Climate Macroeconomic Modelling Handbook	https://www.ngfs.net/en/publications-and-statistics/publications/climate-macroeconomic-modelling-handbook

Box A1. Dynamic integrated model of climate and the economy (dynamic integrated climate–economy [DICE] model)

The DICE model is one of the most foundational and widely used integrated models for the climate, energy policy, and the macroeconomy. William Nordhaus developed the DICE model based on his earlier pioneering integration of greenhouse gas emissions, the global carbon cycle, the climate system, and climate change impacts into an otherwise conventional (Ramsey) growth model and was awarded the Nobel Memorial Prize in Economic Sciences for this work. Since its inception in the early 1990s (Nordhaus, 1992), the DICE model and its components have been used in countless studies and policy applications (Barrage, 2019). In particular, the DICE model offers the following:

- A transparent and internally consistent framework (based on a standard Ramsey growth model) for analyzing interplays between the macroeconomy, greenhouse gas emissions, climate policies, and climate change. For example, the model can be used to quantify the social cost of carbon (SCC), which measures the present value of all future damages that one additional ton of carbon dioxide emitted today is expected to cause. That is, the SCC measures the external costs that polluters impose on the rest of society through consumption of, e.g., fossil energy resources. The SCC has fundamental policy relevance, for example, as the value that policymakers may want to attach to changes in carbon emissions in CBA of new policies (e.g., refrigerator efficiency standards), or to inform appropriate values for subsidy levels to clean energy, or, perhaps most fundamentally, to inform carbon pricing policies that seek to ensure that fossil energy resources are only consumed to the extent that their benefits outweigh their costs. The DICE model can also characterize cost–benefit-optimal climate policy paths under different parameter choices, quantify cost-effective policy paths given policy targets (e.g., a global 2°C maximum temperature change limit), and characterize the costs and benefits of arbitrary policy paths under different parameter scenarios.
- Portable modules and quantifications for key elements of the climate change problem, including climate change damage functions, dynamic estimates of aggregate emissions reduction costs, a simplified carbon cycle–climate system representation, dynamic social cost of carbon estimates, and a flexible discounting module, inter alia.
- Publicly available and well-documented code, user manual, and data sources, which can readily be modified by users for their particular purposes.

In **IAMs**, damage functions estimate the economic costs that would occur for absolute changes in global mean temperature or other climate variables. They provide estimates of the aggregate economic costs of climate change impacts at a global or regional scale over long time horizons (often 200 years or more) and typically relate changes in temperature to economic losses, often expressed as a percentage of GDP. IAMs use stylized damage functions that are necessarily simplified due to the global scale and long time horizons they cover. These functions are often calibrated using a combination of expert judgment, meta-analysis of existing impact studies, and statistical methods. Current damage functions in IAMs have been criticized for representing the full range of climate change impacts inadequately, particularly for higher levels of warming. Misrepresentations can (and have) led to an underestimation of the overall costs of climate change, which can be used to justify lower ambition in climate mitigation and adaptation. Recent research has focused on developing more comprehensive damage functions that incorporate a wider range of climate impacts based on physical impact models (Van der Wijst, 2023).

In **catastrophe modeling**, damage functions are used to estimate losses from specific natural hazards. They relate the intensity of a hazard (e.g., wind speed, flood depth) to the expected damage or loss for different types of assets or structures. Catastrophe model damage functions are typically more detailed and hazard-specific than those in IAMs. They often provide estimates of damage at the individual building or asset level, rather than aggregate economic impacts, derived from historical loss data, engineering studies, and expert judgment. Catastrophe models often use probabilistic damage functions to account for uncertainties in the relationship between hazard intensity and damage. Several studies analyze historical data to estimate how storms and temperature changes have impacted economic growth and GDP.

Box A2. Sources of modeling uncertainty

Internal variability refers to changes due to factors that are external to the climate system, such as solar radiation and volcanic emissions, and could influence the results of climate models. Climate models investigating near-future impacts on smaller regions are at most risk of this kind of uncertainty. This poses a critical challenge in assessing climate impacts given that binding policy is often established nationally, or at times regionally. Predictions of regional change are more relevant than global predictions—especially when a global mean does not translate to evenly distributed impacts.

Initial condition uncertainty (ICU) refers to the ways in which a model's prediction is affected by imprecise knowledge of the current state of the system given a lack of underlying information or evidence on the physical impacts of climate change (Dicks et al., 2023). Initializing a model with values for the current state is crucial given that even a small difference in how the system is characterized at the starting point will produce different results. ICU can be decomposed into separate categories, microscopic ICU and macroscopic ICU, to define whether a certain variable might influence final estimates (Stainforth et al., 2007). Microscopic ICU results from imprecise information about 'small' rapidly mixing scales, which for simplicity can be thought of as weather patterns. Macroscopic ICU derives from imprecise knowledge of the state of variables with relatively 'large' slowly mixing scales, or longer timescales.

Scenario uncertainty refers to the effects of uncertainty in future emissions of greenhouse gases (Hawkins and Sutton, 2009). However, the level of greenhouse gas emissions a model assumes is driven by further socioeconomic assumptions on the future state of economic growth, population, production processes, technological innovation, and, of course, climate policies—both their implementation and enforcement mechanisms (Dicks et al., 2023).

Model imperfection refers to uncertainty driven by imprecise knowledge of, and inability to perfectly simulate, the Earth's climate (Stainforth et al., 2007). Model imperfection is decomposed into two areas of influence: (a) model uncertainty and (b) model inadequacy. Model uncertainty is driven by the challenges in appropriately representing climatic processes within a given model via parametrization schemes and applying the optimal resolution for a given investigation. Many elements within a model are not based on physical understanding, but rather hypothesized statistical relationships, which attempt to provide values for inputs such as clouds, precipitation, radiation, gravity waves, convection, and land surface.

Table A2. Expanded table on tools and models for estimation of physical climate risk on macroeconomic outcomes relevant for Ministries of Finance

Tools/models	Overview	Challenges when using in Ministry of Finance context
Conventional approaches for macro-analysis		
IMF Integrated assessment models (IAMs)	IAMs such as DICE and FUND integrate data on climate science, economics, and policy to assess long-term impacts on productivity, potential output, and economic growth. IAMs help in understanding the broader economic consequences of climate change and the effectiveness of various mitigation strategies. They draw on damage functions to attempt to model the entire impact chain from climate change to economic impacts. These models allow for scenario analysis of different mitigation pathways to infer the economic impact of physical risks. Models typically use different climate scenarios, which are dependent on the level of global emissions (e.g., 1.5°C versus 4°C warming) to project potential impacts under various futures, exploring long-term impacts, often to 2050 or 2100. These assessments tend to be at the global, regional or national scale.	IAMs can be subject to oversimplification of the effects of extreme weather events, leading to underestimation of risks (GIZ, 2021b; Newman and Noy, 2023). Additionally, IAMs are often structured with long time horizons, limiting observation of short-term indicators crucial to the performance of financial assets. Instead, recent examples demonstrate the value of using short-term macroeconomic shock scenarios (Carlin et al., 2022) to assess the impact on GDP, inflation, exchange rates, trade, fiscal indicators, and financial markets.
Social accounting matrices	Models based on social accounting matrices (SAMs) have two central elements of value for the quantification of physical climate risks: (1) For the estimation of indirect costs (2) To inform determinants of risk, particularly market-based 'vulnerability' and 'response' drivers Both input–output (I–O) and computable general equilibrium (CGE) models aim to represent trade flows of production inputs and their outputs across sectors in an economy realistically. SAM-based models are particularly useful for their ability to capture the impact of a disaster on a specific sector and model the indirect impacts to inputs supplied to other sectors (Okuyama and Santos, 2014). CGE models tend to be preferred across the literature for their non-linearity and inclusion of demand and supply in equilibrium across numerous markets. Because they are able to capture substitution possibilities when estimating relative price and quantity changes, they are well suited to estimate the long-term consequences of hazards (Rose and Liao, 2005). Further, because they can also be employed to investigate resilience to natural disasters by substituting interrupted inputs (Rose and Wei, 2013), their application could inform market-related drivers of the 'vulnerability' and 'response' determinants of risk. Moreover, the ability to capture economic interdependencies between sectors and across countries facilitates estimation of the compounding severity of losses if numerous sectors fail simultaneously.	While I–O models are valuable for their low information demands, their constant linear structure and substantial assumptions are found to oversimplify macroeconomic systems (Miller and Blair, 2009). I–O models are unable to capture mechanisms that may smooth impacts after natural disasters—such as input substitutions—or mechanisms that impact final outcomes, such as supply-side shocks with production constraints, changes in technology, or price changes.
Scenario-based approaches and sensitivity analysis	Scenario-based approaches and sensitivity analysis are used to assess the financial implications of climate-related risks. These methods involve comparing baseline scenarios with those reflecting varying degrees of climate risk. This helps in understanding potential impacts on financial institutions and the broader financial system. Such analyses are used for developing macroprudential policies and managing systemic risks.	These approaches rely on speculative assumptions and generalizations, including linearity, which may lack the specificity needed for detailed policy decisions. The complexity of creating comprehensive scenarios can lead to incomplete or biased outcomes, while temporal and spatial limitations restrict their scope.

Table A2. (continued)

Tools/models	Overview	Challenges when using in Ministry of Finance context
Catastrophe models	Catastrophe models estimate potential losses from extreme events and provide opportunities for improved estimation of the 'exposure' determinant of risk events (NGFS, 2024a). Because these models simulate the physical outcomes of natural hazards using geographic information systems (GISs), they are useful for the creation of hazard maps, which provide more detailed estimates of drivers of exposure, such as inundation depths and flow velocity (Jonkman et al., 2008). Depending on available data, hazard maps can be built at the city, regional or global levels to estimate damage to infrastructure and land (de Moel et al., 2015).	Catastrophe models rely on assumptions on the value of land or buildings and limited records of natural hazard characteristics (Schröter et al., 2018).
Loss and damage (L&D) assessments	L&D assessments evaluate the impacts and costs associated with adverse effects of climate change, despite mitigation and adaptation efforts. Assessments quantify the economic and non-economic loss and damage to inform policy decisions, secure funding for recovery, and implement effective adaptation strategies.	L&D is subject to data limitations, challenges in valuing non-market losses, and difficulty in capturing temporal and spatial variations.
Additional approaches that can help inform Ministries of Finance about physical climate risks		
Extreme event attribution (EEA)	EEA aims to quantify the portion of economic costs from specific extreme events that can be statistically attributable to human-caused climate change (Noy, 2021; Newman and Noy, 2023).	EEA relies heavily on complex models and high-quality data. EEA also struggles to capture indirect and long-term economic impacts, focusing primarily on immediate physical damages. The inherent complexity and variability of extreme events, along with biases in model assumptions, can complicate accurate attribution and quantification of economic losses.
Asset-level analyses	Asset-level analyses involve assessing the potential impacts of climate change on fiscal sustainability. Acute physical risks can be investigated via stylized stress tests to observe the impacts of extreme weather events on deviations of debt-to-GDP projections from a given baseline. Asset-level analyses are used by national governments, international organizations, and private institutions to strategize on the integration and mobilization of disaster risk finance and climate adaptation. Asset- or sector-specific assessments take location-specific aspects into account.	For MoFs, these analyses may focus too narrowly on specific assets, overlooking broader systemic and indirect economic impacts. Additionally, aggregating asset-level findings to derive macroeconomic insights can be problematic, leading to potential misrepresentations.
Impact chain frameworks	These frameworks offer a four-step assessment of the consequences of a climate event, assessing: (1) Climate hazards (2) Physical impacts (3) Financial impacts for the asset (4) Impacts for financial institutions	Each step requires data that might not always have reliable sources, if it is available at all. In this case, alternative approaches, such as exposure mapping and scoring approaches, can be employed to identify highly exposed/vulnerable assets for further investigation via asset-level analyses (Gallo and Lepousez, 2020).

Table A3. Expanded examples of programs, initiatives, alliances, and tools available to Ministries of Finance for analyzing the economic impacts of physical risks

Name	Description/application	
Coastal Impact and Adaptation Model (CIAM) used by the IMF	IMF staff use the state-of-the-art CIAM to estimate the cost of sea level rise under alternative adaptation strategies. CIAM is a global model used to estimate the economic cost and benefits of adaptation to sea level rise (Diaz, 2016). The global coastline is divided into more than 12,000 segments of different lengths grouped by country. Each segment is further divided into areas of different elevation. For each segment, the model has data on capital, population, and wetland coverage at different elevations. By using projections of local sea-level rise from Kopp et al. (2014), it is possible to estimate the areas that will be inundated and the amount of capital and population at risk. While the model is capable of considering the impact of storms on periodic inundations in addition to sea level rise, it does not consider increased risks from river floods. The model calculates the cost of sea level rise—protection costs plus residual losses—under alternative adaptation options: (1) no adaptation; (2) protection; and (3) planned retreat. By comparing sea level rise costs across all scenarios it is possible to find the least-cost adaptation strategy for each coastal segment and to calculate the lowest possible cost of sea level rise for the country.	Countries in which CIAM has been used include Antigua and Barbuda, Curacao, the Dominican Republic, Jamaica, Morocco, Palau, Papua New Guinea, Togo, and Vanuatu. Model results are clearly preliminary and incomplete but are very useful to suggest a practical way to think about a very complex problem, based on an objective assessment of benefits and costs of adaptation. Governments are presented with alternative adaptation strategies, each one having its own costs, benefits, and policy hurdles. The no-adaptation case is used to provide a benchmark high-cost scenario that can materialize without any pre-emptive action. Costs are estimated for different categories of impacts, from loss of life due to storm flooding to loss of assets and ecosystem services. The case of full coastline protection is used to illustrate that it is often possible to avoid permanent inundation of coastal areas and minimize storm flood impacts, but this usually comes with large investment needs in protection. The case of planned retreat shows a strategy that does not have direct public finance costs and it is usually the least costly for society as a whole, but it comes with its own planning and distributional challenges.
The IMF's Quantitative Climate Change Risk Assessment Fiscal Tool (Q-CRAFT) available through the IMF Fiscal Risk Toolkit	Q-CRAFT is an Excel-based tool created by the IMF's Fiscal Affairs Department to help governments worldwide to assess long-term macroeconomic fiscal risks from climate change. It projects key economic and fiscal variables—such as GDP, fiscal deficit, and debt-to-GDP ratio—for over 170 economies through the end of the century. Utilizing state-of-the-art empirical data on the macroeconomic impacts of climate change, Q-CRAFT analyses how these economic and fiscal variables may evolve under different physical climate risk scenarios. This transparent and flexible tool can be adapted to national circumstances, incorporating country-specific climate risks such as sea level rise and natural disasters, and is applicable to countries at any development stage.	Q-CRAFT has been used by different countries across the globe, including Armenia, Azerbaijan, Georgia, Jamaica, Kenya, Morocco, Rwanda, Seychelles, the Netherlands, and Uganda.
Global Risk Modelling Alliance (GRMA)	The GRMA is designed to help MoFs combine the best of global and local, public and private sources, equipping them to build assumptions about the risks they own. The aim is that MoFs should then be able to manage this process themselves, not as technical experts, but as capable risk managers who can define the right questions for adaptation planning, commission the analysis, and know where to go for support. A principle of the GRMA is that the analysis should be as close as possible to the risk owner—supporting ministries to learn the language of risk for themselves and understand how models work. The GRMA starts work in countries by bringing together ministries, departments, agencies, and research institutions, each with its own view on impacts of concern, and knowledge of exposures, hazards or vulnerabilities. Usually under the leadership and political mandate of a MoF, a synthesis emerges of prioritized risk questions, and the modeling required to address them. The GRMA operates at the request of sovereigns and each program is co-defined with a locally led technical working group. Country programs include quantifying risk for critical national infrastructure to help prioritize resilience measures and identify the point at which it is more efficient to transfer the risk to financial markets. Every country is at a different stage in its journey of risk understanding and has different resources at its disposal and different levels of political support for developing a risk function.	In Madagascar, modeling of the macroeconomic impacts of climate shocks has been undertaken to support the development of Madagascar's Climate Prosperity Plan (CPP). Additionally, the GRMA has supported the development of a multi-hazard risk profile at commune-level resolution, accounting for cyclone and flood, but also less well understood hazards such as drought, landslides, erosion, fires, red sandstorm, and locust invasion. The GRMA has also established a single data sharing facility in the country to better manage and exploit data on hazards, exposure, capacity, vulnerability, damage, and loss. In Pakistan, the GRMA has undertaken a high-resolution flood risk analysis for Sindh and Balochistan to improve the financial effectiveness of the BISP shock-responsive social protection program. In Ghana, the GRMA has supported the modeling of the impact of urban flash flooding in up to five cities, with a view to the protection of micro-businesses, the majority of those being run by women. The greatest political support the GRMA has encountered was in a West African country, but it was also the least well equipped. In this case the most obvious need was for some basic exposure mapping, with insight into the impacts of rapid demographic change in the next 10–20 years.

Table A3. (continued)

Name	Description	Country applications
The IMF's Climate Macroeconomic Assessment Program (CMAP)	The IMF's CMAP is a key initiative that assists member countries in integrating climate considerations into their macro-fiscal frameworks. The macro-fiscal analysis conducted under CMAP assesses whether a country has adequate climate financing, based on rough cost estimates of mitigation and adaptation plans using existing project estimates and the sustainable development goals (SDGs) costing method. It also evaluates whether these financing plans are consistent with debt sustainability. The program employs the debt–investment–growth and natural disasters (DIGNAD) model, which is a dynamic two-sector small open economy model designed to simulate the impact of natural disasters and associated policy trade-offs. DIGNAD assumes the existence of two types of public capital: standard physical capital, which is vulnerable to natural disasters, and adaptation capital, which is more resilient. The government can access a variety of financing sources, including external concessional loans and international grants. The model captures key mechanisms and policy issues relevant for debt sustainability analysis, particularly the linkages between public adaptation investment, economic growth, and debt.	Samoa is the first pilot country where a CMAP has been conducted. The country's disaster risk management framework includes several elements of a risk-layering strategy, although gaps remain. Simulations using the IMF's DIGNAD model suggest that investing an additional 2% of GDP in adaptation capital over the next five years could save Samoa approximately 4.5% of 2021 GDP in output losses if a typical natural disaster occurs in 2027 (IMF, 2022). However, while the DIGNAD model is well suited for analyzing the impact of acute natural disaster shocks, it is less equipped to analyze slow-moving climate changes such as sea level rise and average temperature increases (EU et al., 2021).
ADB's Climate Resilient Fiscal Planning Framework	This tool outlines a framework for climate-resilient fiscal planning—based on three functions—to help decision-makers scale up and align finance with investment in adaptation and resilience: (1) Assess climate-related fiscal risks to identify, model, and disclose the impact of climate-induced physical risks on fiscal sustainability (2) Manage climate-related fiscal risks to guide risk assignment and risk reduction, transfer, and retention strategies (3) Optimize resources to mobilize and manage public and private sources of finance for investment in adaptation	The framework was applied to the Armenian context to assess progress toward climate fiscal risk assessment, management, and resource optimization. It was found that the country has made good progress to date in strengthening climate-resilient fiscal planning. However, recommendations linked to the framework's three functions were made to build on progress: (1) Develop a sector-by-sector understanding of climate risk by improving data collection systems and upgrading the hydrometeorological observation network to inform risk management (2) Establish the proposed Fiscal Risk Council to guide prioritization of adaptation investments and build a climate risk assignment framework to quantify risks and help the government take a balanced approach to risk layering in its budget and to integrate this with its medium-term expenditure framework (3) Undertake a long-term fiscal sustainability analysis to harness private sector adaptability, ingenuity, and financing for priority adaptation investment
Global Shield Against Climate Risks	The Global Shield aims to substantially increase and enhance prearranged and trigger-based finance against climate and disaster risks while aiming to link with efforts on climate change adaptation (risk reduction measures such as early warning systems) and social protection systems. To achieve its objective, the Global Shield will provide grant-based technical and financial support for developing a variety of instruments at the household, community, and national levels. Guided by its systemic, coherent, and sustained approach, the Global Shield financing builds on already existing structures and programs and will be complemented by the new Global Shield Financing Vehicles, encompassing the Global Shield Solutions Platform (GSSP), the Global Shield Financing Facility (GSFF), the Climate Vulnerable Forum (CVF), and the V20 Joint Multi-Donor Fund. The support provided by the Global Shield is centered around a country-led, demand-driven, in-country process with an interactive multi-stakeholder consultation. The Global Shield works with the Global Risk Modelling Alliance to assess climate risks, identify urgent financial protection needs, and request tailored support packages to close protection gaps.	The designated focal point of the lead Ministry heads the process as the In-Country Coordinator and is responsible for convening the key stakeholders and ensuring that in-country process outputs are finalized and endorsed. In its initial phase, the Global Shield started activities in one pathfinder region and eight pathfinder countries, namely the Pacific Small Island Developing States, Bangladesh, Costa Rica, Ghana, Jamaica, Malawi, Pakistan, the Philippines, and Senegal. The new cohort of Global Shield countries was announced by the Global Shield Board in April 2024 and includes the following countries: The Gambia, Madagascar, Peru, Rwanda, and Somalia.

Table A3. (continued)

Name	Description/application
OASIS Loss Modelling Framework (OasisLMF)	OasisLMF is unique in being developed and maintained almost entirely by the private sector. Originally conceived to improve industry efficiency in mature markets using an open-source platform and set of open data standards, it has become an ecosystem for model developers and users. Its base code is truly open source, it has a sustainable business model and it is therefore recommended by the GRMA for sovereigns growing their risk functions.
UNEP Resilient Planet Data Hub	The hub is not a risk modeling platform, but a portal for pre-computed risk data across the categories of people, planet, and prosperity. Designed for organizations taking their first steps in climate and disaster risk understanding, non-experts can make choices about the hazards and impacts of greatest concern and can select future epochs and warming pathways to compare results.
The COACCH project (Van der Wijst et al., 2023	The COACCH project is an example of recent high-quality and more up-to-date damage functions for climate risk, encompassing a number of dimensions not normally covered in earlier studies, such as risks to fisheries.
Climate Impact Explorer's Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)	With the aim of offering a consistent climate change impact modeling framework, more than 100 models had contributed to the initiative by 2021. The participating impact models are listed on the ISIMIP website where a factsheet is provided for each model. To participate, impact modeling teams agree to run a minimal set of model experiments. These include scenario experiments that simulate the evolution of sectoral impact variables until at least 2100 under specific trajectories in terms of climate and socioeconomic forcings, for which they are provided with the corresponding input data. The resulting output data became open access after an embargo period and can be downloaded.
Network on Greening the Financial System (NGFS)	The NGFS has been exploring the macroeconomic impact of climate change for both its work on the development of climate scenarios and on the implications for monetary policy. Climate scenarios have mostly focused on long-term dynamics, aiming to unravel the possible structural changes required in the energy system to meet long-term climate objectives and the evolution of physical risk under different temperature pathways. To complete its analytical toolkit, the NGFS is developing the first vintage of its short-term climate scenarios, which will be released early 2025.

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