STAFF

CLIMATE

NOTES

Economic Principles for Integrating Adaptation to Climate Change into Fiscal Policy

Matthieu Bellon and Emanuele Massetti

IMF STAFF CLIMATE NOTE 2022/001

Economic Principles for Integrating Adaptation to Climate Change into Fiscal Policy

IMF Staff Climate Note 2022/001

Matthieu Bellon and Emanuele Massetti*

RECOMMENDED CITATION: Bellon, Matthieu, and Emanuele Massetti, 2022. "Economic Principles for Integrating Adaptation to Climate Change into Fiscal Policy." IMF Staff Climate Note 2022/001, International Monetary Fund, Washington, DC.

ISBN:	978-1-51359-237-4 (Paper) 978-1-51359-266-4 (ePub) 978-1-51359-273-2 (PDF)
JEL Classification Numbers:	H23; H30; H40; O23; Q54; Q58
Keywords:	Climate change, adaptation, development, fiscal policy.
Authors' email addresses:	mbellon@imf.org emassetti@imf.org

* The authors are grateful to James Daniel and James Roaf for continuous support and extensive comments. They thank Seung Mo Choi (AFR) for important contributions, Andrew Ceber (FAD) for providing very valuable inputs and feedback, IMF and WB colleagues for helpful comments and suggestions, Joey Kilpatrick for first-rate research assistance, and Von Allena for preparing the document.

Economic Principles for Integrating Adaptation to Climate Change into Fiscal Policy

Matthieu Bellon and Emanuele Massetti
March 2022

Summary

Adaptation to climate change is a necessity for advanced and developing economies alike. Policymakers face the challenge of facilitating this transition. This Note argues that adaptation to climate change should be part of a holistic development strategy involving both private and public sector responses. Governments can prioritize public investment in adaptation programs with positive externalities, address market imperfections and policies that make private adaptation inefficient, and mobilize revenues for, and distribute the benefits of, adaptation. Although the choice of what should be done and at what cost ultimately depends on each society's preferences, economic theory provides a useful framework to maximize the impact of public spending. Cost-benefit analysis, complemented by the analysis of distributional effects, can be used to prioritize adaptation programs as well as all other development programs to promote an efficient and just transition to a changed climate. While compensations may be needed to offset damages that are either impossible or too expensive to abate, subsidies for adaptation require careful calibration to prevent excessive risk taking.

This Staff Climate Note is part of a series of three Notes (IMF Staff Climate Note 2022/001, 2022/002, and 2022/003) that discuss fiscal policies for climate change adaptation. *This first Note examines the economic principles that can guide the integration of climate change adaptation into fiscal policy. A second Note (Aligishiev, Bellon, and Massetti 2022, henceforth Note 2) discusses the macro-fiscal implications of climate change adaptation. It reviews evidence on the effectiveness of adaptation at reducing climate change damages, on residual risks, and on adaptation investment needs, and suggests ways to integrate climate risks and adaptation costs into national macro-fiscal frameworks. It stresses that lower-income vulnerable countries, which have typically not contributed much to climate change, face exacerbated challenges that warrant increased international support. A third Note (Bellon and Massetti 2022, henceforth Note 3) considers how to translate adaptation principles and estimates of climate impacts into effective policies. It argues that, for all countries, adaptation solutions can be guided by an extension of the IMF (2019a) three-pillar disaster resilience strategy to address changes in both extreme and average weather. It suggests that governments can support an efficient implementation of adaptation solutions by factoring climate risks and adaptation plans into budgets, macro-frameworks, and, in the management of public investment, assets and liabilities.*

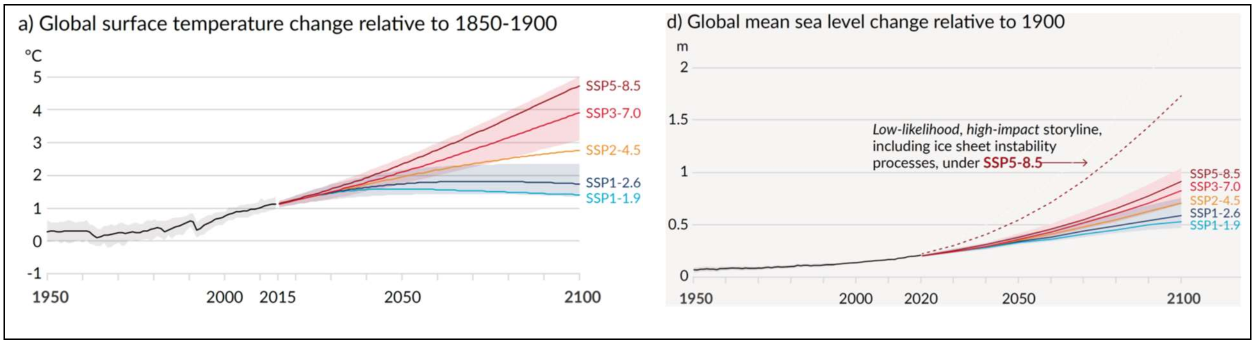
Framing Adaptation to Climate Change

Adaptation is Needed in All Countries and Can be Macro-Critical

Climate is changing and will continue to change even with intensive mitigation efforts. Global temperature was about one degree Celsius higher in the first two decades of the 21st century than in the pre-industrial era. Temperature is expected to increase by an additional 0.5 to 0.8 degree Celsius by the end of the century, and possibly by more, even in scenarios with very strong mitigation (Shared Socio-Economic Pathways [SSP]1–1.9 and SSP2–2.6 in Figure 1; for a description of scenarios, see Annex 1). Scenarios with less warming are very unlikely given existing technological, economic, and social constraints. There are instead significant additional risks if pledges to reduce net greenhouse gas (GHG) emissions to zero by around midcentury are not followed by commensurate actions.

Mitigation has limited effect on sea-level rise until midcentury. Strong mitigation can substantially reduce the probability of worst-case scenarios, but the sea level will continue to rise throughout this century and beyond, even if the global temperature stops rising. In 2100, sea level is expected to rise by an additional 30 cm above the 20 cm already recorded, even if the global temperature increase stays below 1.5 degrees Celsius (SSP1–1.9 scenario in Figure 1). Lower sea-level rise is unlikely, while weaker mitigation will lead to higher sea-level rise.

Figure 1. Temperature and Sea-Level Change in Intergovernmental Panel on Climate Change Scenarios



Source: Figure SPM.8, Panels (a) and (d) from IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press. For more information, see Annexes 1 and 2.

All countries will be affected, and lower-income and small vulnerable nations face the largest challenges even if they are responsible for a tiny fraction of cumulative emissions. Many low-income countries already have high temperatures, and additional warming will be harmful. They also have a relatively large fraction of economic activity in agriculture, usually the most climate-sensitive sector of the economy. Being poor amplifies the welfare effects of climate (Schelling 1992; Mendelsohn 2012). Countries that are already hot and dry will face additional stress (Duenwald and others, forthcoming). Small countries exposed to destructive climate extremes—such as tropical cyclones—are very vulnerable because they cannot transfer risks easily (Cantelmo, Melina, and Papageorgiou 2019; IMF 2016). Low-lying island states face an existential threat from sea-level rise (Melina and Santoro 2021). All of these countries are, currently and historically, responsible for a tiny fraction of cumulative emissions. Adaptation is a necessary response to a problem they did not cause.

Climate change adaptation is the process needed to minimize losses and maximize benefits from climate change (Intergovernmental Panel on Climate Change [IPCC] 2021a). Adaptation is needed to address risks from changes both in average conditions and in the frequency and intensity of extreme weather, for example by improving resilience to droughts in agriculture (see Box 2), changing where and how crops are grown, managing water resources better, addressing sea-level rise, and making infrastructure more resilient to extreme weather.

Climate adaptation is not entirely new because individuals, firms, and societies have adapted to a wide range of climates. Adaptation gaps remain, especially in low-income countries, but climate affects consumption and production decisions across the world (Massetti and Mendelsohn 2018). Climate influences what people eat and how they dress, how they build their houses, and how they spend their free time. Climate drives specialization in agriculture (Seo and Mendelsohn 2008a, 2008b; Kurukulasuriya, Kala, and Mendelsohn 2011; Di Falco and Veronesi 2013), energy (Mansur, Mendelsohn, and Morrison 2008; Aroonruengsawat and Auffhammer 2011; Yao 2021), tourism (Bigano, Hamilton, and Tol 2006; Maddison 2001), and many other climate-sensitive economic sectors (Kahn 2016), in both advanced and developing economies. The process of adaptation to different local climates has slowly occurred over the centuries as local climates were broadly stable.

With climate change, individuals, firms, and societies have to reconsider and update how adapted they are to present and future conditions. Challenges arise from having a substantial share of world capital and population anchored in locations potentially exposed to climate change effects. The complexity, the cost, and the limits of adaptation increase with the speed of climate change.

At its core, climate change adaptation requires a constant and dynamic readjustment of consumption, production, and public policies. This process can be framed as a dynamic optimization problem under uncertainty (Lemoine 2018). In most places, climate adaptation will likely consist of adopting technologies, behaviors, and public policies used today in other places with a similar climate. Technological innovation might be needed in places with already extreme climates and where new challenges will emerge. To a large extent, adaptation is like other societal challenges that require technological diffusion, innovation, and behavioral change (Mendelsohn 2000, 2012; Massetti and Mendelsohn 2018; Kahn 2016; Tol, Fankhauser, and Smith 1998). The case of low-lying island countries, where much of the land surface is projected to be underwater, is an exception that deserves specific analyses (World Bank 2017).

Governments in every country can help by prioritizing adaptation policies with positive externalities, by removing the market imperfections and policies that hinder efficient private adaptation, and by ensuring a just transition. Individuals and firms have strong incentives to adapt because many adaptation benefits tend to be local and private. Therefore, progress on adaptation is not affected by coordination problems as much as progress on mitigation is. However, there is a clear role for governments when adaptation has large externalities. Market inefficiencies and policy failures may also limit private adaptation or create distortions. Poor countries may not be able to afford adaptations needed for a just transition to a new climate, implying international support would be necessary to support entire countries' adaptation, especially small and vulnerable developing economies.

Ensuring efficient and just adaptation can be macro-critical in many countries because adaptation can greatly reduce the impacts, costs, and inequalities caused by climate change. Returns to adaptation have been estimated to be large, both in sectoral and global models (Note 2). Estimates of climate change costs without adaptation can be much larger than estimates that include adaptation, even after factoring in adaptation costs (Massetti and Mendelsohn 2018; Hallegatte, Rentschler, and Rozenberg 2019, 2020; Hallegatte and others 2013). Building ex ante resilience greatly reduces ex post remedial costs, for both countries and international donors (IMF 2019a, 2019b; Cantelmo, Melina, and Papageorgiou 2019; Marto, Papageorgiou, and Klyuev 2018; Cantelmo and others 2019).

Adaptation can also be macrocritical because investment needs may be large, especially in small vulnerable economies (Note 2; IMF 2021a, 2021d; Farid and others 2016; Agarwal and others 2021). For example, infrastructure to protect coasts against future sea-level rise is estimated to cost from 1 to 10 percent of GDP annually during the construction phase in some small developing states.

Additional international support is needed as many lower-income countries face high adaptation needs while being challenged by limited fiscal space, limited capacity, or both. International organizations such as the IMF could support these countries via capacity development and by helping them to mobilize financial assistance (Note 3; IMF 2019a, 2020a; Duenwald and others, forthcoming).

Despite all the potential benefits, adaptation cannot replace mitigation. Adaptation and mitigation are both needed to help reduce damages from climate change. Delayed mitigation efforts can be in part compensated by more adaptation, but without strong mitigation it is not possible to stabilize global temperature, and adaptation would become either impossible or too expensive.

Optimal Adaptation

There is a large amount of adaptation to different climates across the world, but is adaptation optimal? Regions that are frequently exposed to tropical cyclones have adapted to at least some extent, for example by developing early warning systems and advanced building codes (Bakkensen and Mendelsohn 2016; Agarwal and others 2021; Hsiang and Narita 2012). However, powerful storms inevitably cause damage and casualties (IMF 2021b; Acevedo 2014, 2016; Bakkensen and Barrage 2020; Mendelsohn and others 2012). Does that mean that they have not adapted? Should these regions have invested more in protection?

To answer these questions, it is necessary to adopt a normative principle. Without an optimality criterion, it is neither possible to take stock of the current situation nor to make policy recommendations. The chosen criterion should be transparent and consistently applied throughout government programs.

This Note argues that principles of welfare economics can be useful to guide policymakers on adaptation, as for other development programs. What to do, when, how, and at what cost ultimately relies on ethical choices that should reflect the preferences of each society. However, cost-benefit analysis (CBA), complemented by analysis and correction of distributional impacts, can help decision makers maximize overall social welfare by avoiding wasting scarce resources. To achieve this goal, it is essential that CBA is applied to adaptation as well as to all other development programs in a consistent manner.

The difference between optimal and observed adaptation is defined as the *adaptation gap*. Investment needs are estimated in relation to this gap and vary depending on the normative criterion used (Note 2).

Uncertainty in Climate and Socioeconomic Scenarios

Even as strong climate trends are emerging globally, climate projections remain uncertain, especially at the local level. It is certain that temperatures will increase everywhere in the world, and the impact on other climate conditions are emerging with greater clarity at the macro-regional level. Intense precipitations will become more frequent in some areas, while droughts will intensify in others. Glaciers and sea ice will retreat. Tropical cyclones will likely bring more precipitation, and their patterns and intensity will change. There is, however, uncertainty about the magnitude of these changes and how and when they will manifest at the local level, where many of the adaptation decisions have to be made.[1] Box 1 provides an introduction to climate science, while a more extensive but still accessible overview is available in the Summary for Policy Makers and Technical Summary of the IPCC Working Group I reports (IPCC 2021b; Arias and others 2021).

How climate will exactly change at any given level of GHG concentrations is uncertain, but so are future emissions, impacts, economic growth, policy, technology, and other social developments. Adaptation needs are affected by all these uncertainties because they are a function of total GHG emissions, the climate response to these emissions (for example, changes in rainfall patterns), physical impacts (for example, floods), vulnerability (for example, population location and level of development), technology (for example, flood forecasts), and policy (for example, past investment in flood barriers, early warning systems, building codes, and land planning). To explore this wide range of potential outcomes, researchers have developed a scenario matrix architecture that is widely used, including by the IPCC contributors. These climate scenarios (Annex 1) and socioeconomic scenarios (Annex 2) are used extensively to estimate climate change damages and adaptation needs and are therefore important to policymakers and economists working on climate change.

Box 1. An Introduction to Climate Science

The climate system is chaotic and hard to predict in the short term but can be predictable in the long term. Chaos is what makes it hard to predict weather accurately beyond a few days. However, weather is constrained by stable exogenous forces called *boundary conditions* including geography and the global heat balance regulated by, among others, greenhouse gases. As a result, stable weather patterns emerge over time, assuming that boundary conditions are not affected by, for example, increased anthropogenic greenhouse gas emissions.

The long-term distribution of weather is called "climate." Temperature, precipitation, droughts, and tropical cyclones all have their own long-term probability distributions in a certain place at a certain time. Climate change is about the transformation of all these probability distributions.

Scientists use a 20- to 30-year time window to define the climate of a region. Deviations from the norm must be persistent to imply that climate has changed. It is certain that temperature is increasing virtually everywhere. Very high temperatures, defined based on the historical climate, are becoming more frequent. Very cold days are becoming less frequent. Warming is faster at high latitudes and on land.

[1] We follow Reisinger and others (2020) and use risks and climate risks to indicate expected negative effects on human or ecological systems resulting from the dynamic interactions between climate-related hazards and the systems' exposure and vulnerability. The term uncertainty is used for both quantifiable uncertainty and unquantifiable uncertainty (also referred to as deep uncertainty).

There is strong confidence in detecting all these trends and in attributing them to increasing greenhouse gas concentrations.

However, for rainfall and extreme events, natural variability of weather can be mistaken for climate change. Strong natural variability in rainfall patterns makes it hard to detect trends and to make projections in many areas of the world (Vicente-Serrano and others 2021). Unusually long meteorological droughts, strong tropical cyclones, and extreme rainfall are rare but part of the historic climate of many regions in the world. To identify robust trends in climate extremes, it is necessary to use many years of data. For extreme heat, extreme precipitation, and droughts the Intergovernmental Panel on Climate Change (IPCC) uses 50 years of data (Arias and others 2021). This poses challenges because observations in the past were not as good as today. For example, bias in counting strong hurricanes before the satellite era (1970s) may reveal a secular positive trend that disappears after accounting for missed storms (Vecchi and others 2021).

Attributing any extreme event to climate change is difficult. Attribution science is a growing research area, but it is still developing. Scientists simulate climate with and without growing greenhouse gas emissions to estimate the probability that a certain event is recorded. If there is a significant difference, it is reasonable to suspect that climate change is responsible for the increase in probability of observing a certain event, but not that specific event.

There are three sources of uncertainty in climate scenarios. The first is called *internal variability* and is due to the chaotic dynamics of climate. It dominates the first 20 years of each scenario and can be quantified in probabilistic terms if enough data is available. The second is called *model uncertainty* and emerges because the exact functioning of the climate system is unknown. It is impossible to know with what probability each model is the correct representation of the true climate system. This is a cause of *deep uncertainty*, and it is usually the main source of uncertainty 20 to 50 years into the future. Finally, *scenario uncertainty* emerges because future concentrations of greenhouse gases in the atmosphere depend on future technologies, socioeconomic developments, and policy (Annexes 1 and 2). As all these factors cannot be predicted in probabilistic terms, this is a second cause of *deep uncertainty* and becomes more important 50 years into the future.

Climatologists use multiple lines of evidence—observations, models, theory—to detect trends, to attribute them to climate change, and to make projections. Economic policymakers should rely on such assessments by climate scientists. Useful references can be found in the IPCC reports and the interactive IPCC Atlas (Gutiérrez and others 2021).

Adaptation and Sustainable Economic Development

Synergies between Development and Climate Resilience

Climate vulnerability and development are strongly related. Development reduces climate vulnerability and reductions in climate vulnerability facilitate economic development (Schelling 1992; Marto, Papageorgiou, and Klyuev 2018; IMF 2017; Hallegatte and others 2016; IPCC 2022).

As a result, advanced economies are less climate-sensitive than developing ones (Figure 2, panel 1). Structural differences (for example, agriculture, a vulnerable sector, contributes less to GDP in advanced economies), resilient and protective infrastructure, lower poverty rates, greater financial inclusion, and more efficient insurance markets help advanced economies adapt to a wider range of climates and to deal with extreme weather. In advanced economies, weather extremes often cause losses larger in absolute terms than in low-income ones, but the impact of these extreme events and the loss of life are generally much smaller in relative terms. Empirical evidence suggests that income per capita generally reduces the impact of weather shocks (Kahn 2005; Dell, Jones, and Olken 2012; Mendelsohn and others 2012; Bakkensen and Mendelsohn 2016; Acevedo and Noah, forthcoming; Pondi, Mo Choi, and Mitra, forthcoming). For the same level of income, quality of institutions and low-income inequality reduce mortality from climate disasters (Kahn 2005; Toya and Skidmore 2007; Acevedo and Noah, forthcoming).

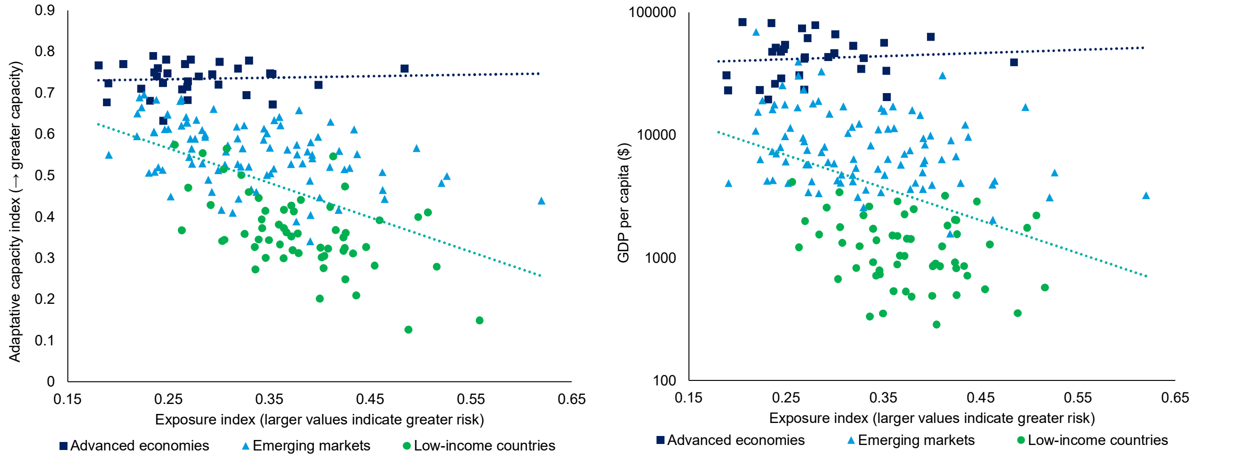
Climate adaptation enhances development and reinforces a virtuous cycle. Infrastructure damage by climate shocks are a drag on people and firms by hindering access to essential goods and services (for example, education, health, food supplies), by reducing the utilization rate of key production inputs (for example, electricity), and by forcing suboptimal input choice (for example, small power generators) (Hallegatte, Rentschler, and Rozenberg 2019). The greatest benefit of climate adaptation is a more productive and stable economy in the long term, and a more equitable and sustainable development. In some cases, investments in adaptation may also have environmental and employment cobenefits.

The importance of development for climate resilience is reflected by strong correlations between indicators of adaptative capacity and development. Human development indicators are often used in the mix of indicators measuring adaptation capacity (Burton 1996; Adger and others 2007). The left figure of Figure 2, panel 2, highlights the strong positive correlation between adaptation capacity and GDP per capita. The effect of income per capita is highly nonlinear, with declining marginal benefits. However, other factors, such as the quality of institutions, play an important role at all levels of income and explain differences between adaptive capacity and GDP per capita (left figure of Figure 2, panel 2). Progress in developing adaptive capacity can therefore be achieved by promoting economic development and by building high-quality institutions.

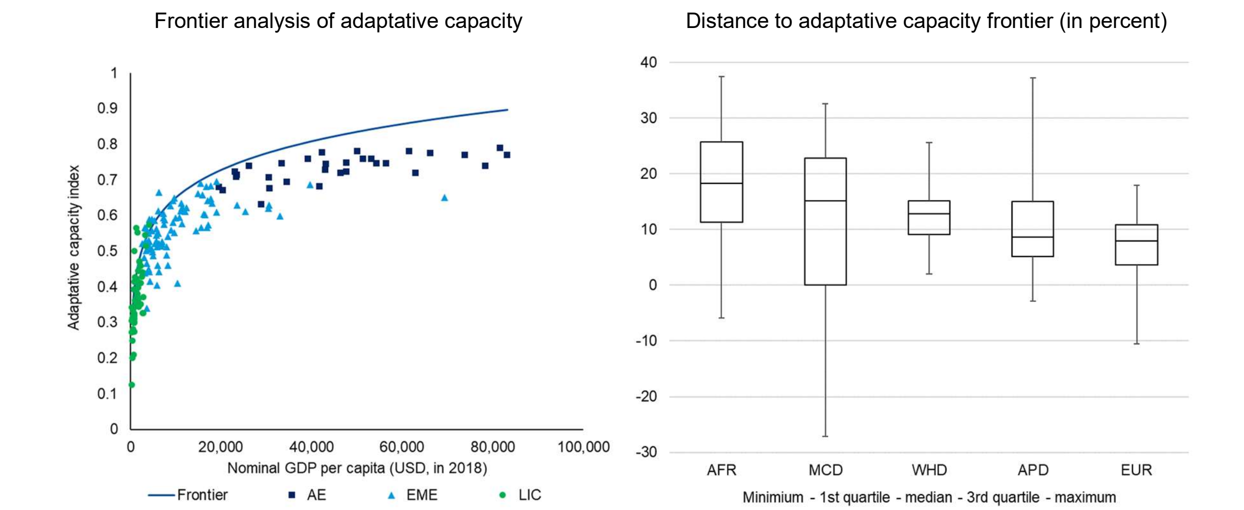
There is scope to reduce climate risks further in all countries at all levels of income, starting now (IPCC 2022). A frontier analysis, estimated as a function of GDP per capita, can help to identify leaders and laggards compared with peers at similar income levels. Distance to the frontier tends to be larger in Africa and the Middle East, but there are also vast disparities within regions (left figure of Figure 2, panel 2). There is potential to reduce risks and improve the overall efficiency of all economies, starting from present exposure to climate hazards. Once started, this process can be built upon to address new risks from climate change.

Figure 2. Development, Adaptive Capacity, and Exposure Indices

1. Adaptative Capacity and GDP per Capita versus Exposure Indices



2. Adaptative Capacity Indices



Source: Staff calculations based on 2015–18 data from the European Commission, the United Nations University Institute for Environment and Human Security, the University of Notre Dame, and the April 2020 *World Economic Outlook*.

Note: AE = advanced economies; AFR = sub-Saharan Africa; APD = Asia and Pacific; EME = emerging markets; EUR = Europe; LIC = low-income countries; MCD = Middle East and North Africa; WHD = Western Hemisphere. *Frontier analysis methodology*: We fit a stochastic production model of log adaptive capacity with a single input, the logarithm of log GDP per capita in US dollars. The linear relationship between the two variables is estimated assuming disturbances that are a mixture of two components. One has a strictly nonnegative half-normal distribution that captures inefficiency, and the other has a symmetric normal distribution that captures measurement errors and other shocks unrelated to adaptation. The latter implies that a country can lie above the frontier. The linear coefficient is estimated to be 1.7 with a p-value < 0.001, and the null hypothesis of no technical inefficiency is rejected at the 0.001 level. *Adaptive capacity and exposure*: We construct country-by-country composite indices on adaptive capacity and exposure to climate change risks, using the European Commission's Index for Risk Management, the World Risk Index by the United Nations University Institute for Environment and Human Security, and the University of Notre Dame's Global Adaptation Index, for which we were able to obtain disaggregated information. The composite index of adaptive capacity captures socioeconomic, infrastructure, and institution characteristics that contributes to better climate risk management capacity, and the index on exposure to climate change risks measures exogenous risks based on the physical characteristics of natural disasters. We build the composite indices for every source using the aggregation rules inherent to each source. We standardize the composite indices before averaging across the three sources.

Success Stories: Declining Impacts from Climate Disasters

Deaths from natural disasters have steadily declined for the last hundred years, despite fast global population growth. The deadliest natural disasters—drought, extreme temperature, floods, and storms—caused 25 deaths per 100,000 people in the 1920s compared with 0.33 deaths per 100,000 people in the 2010s, a 98 percent reduction.[2] Natural disasters are now at the bottom of the list of causes of death, responsible for 0.20 percent of all deaths in the 2010s (Global Burden of Disease 2018). As a comparison, cardiovascular diseases, the leading causes of mortality, are responsible for 31 percent of all deaths. Among all climate disasters, deaths due to extreme temperature (both cold and hot) are the leading cause of mortality (0.16 per 100,000 people).

When accounting for rising wealth and population growth, economic losses due to climate disasters exhibit a modest or no upward trend at the global level. The nominal value of economic losses in the world has increased over time, but a large fraction of this change is due to a growing and wealthier population. Losses expressed as a share of GDP, thereby accounting for population and wealth changes, sometimes show no trend (Bouwer 2011; Weinkle and others 2018; Pielke 2021) or a more modest positive trend compared with nominal damages (Barthel and Neumayer 2012; Estrada, Botzen, and Tol 2015).

The contained increase in climate disaster losses is the result of development cobenefits and deliberate investment in risk reduction. Technological and economic progress enable individual and collective investment in protection. As societies get richer, they invest more in safety standards, including reducing climate risks.

Dire Warnings: Unequal Impacts and Poverty Traps

Adaptation will be particularly challenging for the poor. Rich households have greater ability to adapt than poor households in countries of all income levels. Farmers living in isolated rural areas have more limited adaptation capacity than urban dwellers (IMF 2020a). Even if exposed to the very same climate shocks, poor households will suffer more because they tend to live in more vulnerable dwellings built in more vulnerable areas (for example, steep terrain or in low-lying, flood-prone areas) and because they tend to lack access to the resources that can help them recover (for example, savings, access to finance, support networks).

Climate change has the potential to worsen inequality between and within countries. While global estimates of climate change damages vary widely in the literature, there is universal convergence on the result that the welfare impact of climate change will generally be worse for the poor as the result of both higher exposure to climate hazards and lower adaptive capacity (Note 2).

The virtuous cycle between development and resilience has stalled or is at risk in some countries. Sub-Saharan Africa, the Caribbean, and some countries in the Middle East and Asia and the Pacific are at particular risk from extreme weather with limited adaptation capacity (Box 2) (IMF 2018, 2020a, 2020b, 2021b, Arias and others 2021; Grenada 2021; Acevedo 2016; Duenwald and others, forthcoming). With climate change, some countries may even risk entering a vicious cycle of low economic growth and increasing climate vulnerability that may resemble a poverty trap. To avoid such a vicious cycle, capacity development, large investments, or both may be needed, and external help may be necessary (IMF

---

[2] The data on victims of natural catastrophes is from EM-DAT, CRED/UCLouvain, Brussels, Belgium – www.emdat.be. Global population data is from the US Census. Compiled by Our World in Data (https://ourworldindata.org/).

2020a, Arias and others 2021; Agarwal and others 2021; Duenwald and others, forthcoming). Many of these efforts overlap with other development needs. For example, enhancing agricultural technologies, improving communications, widening access to electric power, and strengthening coping mechanisms would boost agriculture productivity, welfare, and increase resilience against droughts in sub-Saharan Africa (Box 2) (IMF 2018, 2020a, 2020b, 2021c).

Integrating Adaptation into the Development Agenda

A Multidimensional, Just, and Efficient Development Agenda

The strong link between development and climate vulnerability suggests that adaptation to climate change should be an integral part of development planning in all countries. In the Paris Agreement (Article 7), adaptation is established as "the global goal of enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development." Investments in climate change adaptation are similar to other investments in development because their common objective is to maximize future welfare given the available resources.

As governments face many competing needs and often limited fiscal space, they must carefully allocate resources across all possible uses, including adaptation to climate change, while considering the distributional effects of their programs (IMF 2020a). This requires information on how effective spending is across alternative programs and how spending affects different groups in society. With this information, governments can prioritize interventions across sectors, income, and population groups, and across present and future generations, to achieve the right balance between efficiency and fairness. The outcome of this process will be a just and efficient sustainable development trajectory. Given society's preferences on goals and distributional outcomes, economic theory can help to guide spending allocation in a way that maximizes social welfare.

Cost benefit analysis is a tool to assess the net contribution of a program to society's welfare based on society's preferences.[3] CBA aims at measuring all the impacts of a program, including externalities and non-market impacts, and monetizes them using different methods. Non-market impacts cover, among others, the impacts on the environment, on mortality, and on morbidity. CBA provides a more comprehensive assessment of a program contribution to social welfare than analyses based only on GDP impacts. For example, GDP impact analyses do not consider the full cost of losing human lives, which is measured in CBA using the willingness of society to pay to avoid preventable deaths.[4] CBA captures the impact on reduced morbidity using the direct cost of providing health services, as well as the disutility of being sick.

The same CBA rules and methods used for other development programs can be applied to adaptation programs. International organizations and governments have published numerous guidelines for CBA (Hutton and Rehfuess 2006; European Commission 2015; Organisation for Economic Co-operation and Development 2018; Asian Development Bank 2013). After determining who has standing in the program, estimating, and monetizing market and non-market impacts, net benefits (benefits minus

---

[3] *Social welfare* is used here with the narrow meaning it has in CBA. It is equal to the sum of consumer surplus, producer surplus, and government surplus. Government surplus measures the net change of public finances, including changes in debt.

[4] More precisely, CBA uses the Value of Statistical Life. See Cameron (2010) and Boardman and others (2017) for a discussion of theory and practical implementation issues.

costs) are discounted and summed to calculate the net present value (NPV) of the program. The standard prescription is that only programs with NPV greater than zero (NPV > 0) should be financed (Boardman and others 2017).

All projects with a positive NPV are not necessarily self-funding, and additional measures may be needed to ensure their financial sustainability. For example, additional spending to make some public infrastructure more resilient and prevent future damages can have a positive NPV even if strengthening costs exceed avoided reconstruction costs. This would be the case because CBA includes benefits to producers and consumers (for example, reduced service disruptions) as well as benefits from avoided casualties. Therefore, additional financing measures may be required to ensure sustainability. When financing is needed, its cost should be included in CBA calculations (for example, the welfare cost of raising taxes or the impact of additional borrowing on costs and macro-fiscal stability).

The lack of fiscal space and capacity may prevent some countries from financing all viable projects, especially lower-income countries. These constraints also likely limit investment in education, health, and other development goals. Adaptation and other development priorities should be jointly considered, including synergies and trade-offs among different goals. Assuming financing is fully fungible, competing programs should be ranked using CBA and programs with the highest ranking should be financed.[5] If financing is not fully fungible, the same logic and the same methods can be applied within earmarked financing projects.

By consistently investing in projects with the highest returns, governments can maximize the impact of their spending. This means, for example, saving the largest number of lives, providing access to education to the largest number of children, ensuring that the largest possible number of people are above the poverty line, and boosting long-term growth.

Cost-Benefit Analysis Challenges

Lack of data, uncertainty in estimating the benefit of adaptation, and lack of capacity may limit the practical implementation of CBA. Adaptation to climate change can be a relatively new area of intervention for some governments and important data may be missing. Estimating the benefit of adaptation (that is, the avoided cost of climate change) may be particularly challenging in case of systemic changes, because they involve poorly understood tipping points (Note 2), and because standard valuation methods may be inaccurate (for example, Boadway 1974). The cost and complexity of managing unprecedented large adaptation projects, such as protecting large portions of the coastline from sea-level rise, can also be challenging. Capacity building to improve public financial management (PFM), and specifically CBA and project implementation, could play an important role in addressing the adaptation challenge (see Note 2).

Estimating net benefits for adaptation programs that have a very long lifetime can be complex. Coastal protection climate-resilient infrastructure and water distribution systems are examples of investment in adaptation with large upfront costs and benefits that accrue slowly over time. Predicting the impact of these projects and monetizing benefits far in the future is difficult and subject to deep uncertainty. However, these challenges are shared by other long-lived investments, such as early age

---

[5] The general rule in CBA is to invest in all projects with NPV > 0, but countries are subject to budget constraints and some projects with positive returns may be outside the fiscal space. Ranking projects using their benefit-to-cost ratio allows selecting the most efficient and affordable set of projects.

education, railroads, and hydroelectric power plants. CBA is routinely applied to many investments with long lifetimes, and the same guidance developed for other sectors can be used for adaptation projects (see, for example, Boardman and others 2017). For all these projects, the choice of the discount rate is very important and subject to uncertainty. Guidelines have been developed for the choice of the discount rate (Asian Development Bank 2013; Boardman and others 2017). For programs that stretch more than 50 years into the future, a declining discount rate could be used (Gollier, Koundouri, and Pantelidis 2008; Arrow and others 2013, 2014; Gollier and Weitzman 2010). However, there are merits in using CBA even for long-lived projects. A major difficulty for all these projects is to overcome the reluctancy of policymakers to invest in projects that have a much longer time horizon than the usual electoral cycle. CBA can help by allowing decision makers to acknowledge benefits over the entire lifetime of the project.

Despite limitations, CBA can play an important role in helping decision makers to consistently collect, aggregate, and compare information on adaptation projects. CBA was applied to environmental programs with large non-market benefits, such as the Clean Air Act in the United States (US Environmental Protection Agency 1999), and one of the very first applications was by Tinbergen in 1954, to select optimal flood risk management in the Netherlands, a program subject to systemic risks (Bos and Zwaneveld 2017).

Distribution and Equity

The NPV of a program measures the aggregate net benefit in society, but distributional impacts can be critical and should be estimated by the analysts and assessed by the government. In standard CBA applications, gains and losses are summed across society, and across present and future generations, treating everyone equally. The underlying rationale for recommending investment when NPV > 0 is that the program may not make everyone better off but winners can potentially compensate losers (Kaldor-Hicks compensation principle). Governments can redistribute the aggregate gains of a project to implement their preferred distributional outcome using direct compensations or, more broadly, fiscal policy. This includes choosing how to collect revenues to offset the cost of adaptation (Note 2). The distribution of benefits and costs should reflect society's preferences and is a normative judgment left to governments.

When the NPV is negative, the standard recommendation in CBA is not to invest in adaptation, but governments can still compensate those negatively affected. When NPV < 0, the cost of protection is larger than its benefit. Not investing helps those that would have had to pay for the cost of protection but hurts those that would have benefited from protection. Society would in this case save resources by compensating those that suffer from climate change damages rather than paying for protection.

Governments could decide to use adaptation policies for redistribution motives within and between countries. This may lead to scaling up adaptation programs for the most vulnerable beyond what CBA would call for. Conversely, equity considerations may lead to scaling back adaptation programs when the net benefits fall on the wealthiest part of the population.

Governments would benefit from weighing the costs and benefits of redistributive adaptation programs against those of other available redistribution instruments. If a combination of efficient adaption policies with dedicated redistributive programs can have larger aggregate net benefits for the entire population and for the most vulnerable, it should be preferred.

Box 2. Adaptation Strategies for Countries Vulnerable to Droughts[1]

Despite remarkable progress in avoiding the worst outcomes, recent droughts in Central Asia, Africa, and South America still threatened the lives of millions. Droughts have long-lasting adverse economic effects and contribute to food insecurity, mass migration, conflict and fragility, and other socioeconomic concerns. As climate change intensifies, so will the intensity and frequency of droughts.

In sub-Saharan Africa, each drought reduces medium-term annual growth by 1 percentage point. This is about eight times that in the rest of the world's emerging market and developing economies. Low-income households are most severely affected as their coping mechanisms are limited and they often depend on rain-fed agriculture. While there are many channels through which this impacts growth, a striking one is a marked increase in school dropouts and deterioration of infant health.

Recent IMF research shows that the following key adaptation policy areas, when adequately integrated into near- and medium-term budgets, could impactfully reduce vulnerability to droughts and support sustainable and inclusive growth.

First, raise agricultural productivity and reduce its sensitivity to inclement weather. This calls for a multipronged approach spanning improvements in mobile networks, irrigation, erosion protection, and seed quality. For example, in Ghana, cocoa's drought resistance was bolstered with improved seed varieties, planting non-coca trees for shade, and improving irrigation systems. In Ethiopia, some farmers' yields rose by up to 40 percent with the development of wheat varieties resistant to rust (a fungal disease). Better mobile phone networks mean better access to early warning systems and weather information—even in the form of simple voice messages—that enable more productive and climate smart agriculture. Overall, raising farmers' awareness would also accelerate implementation of these measures.

Second, invest in diversified energy sources. Electricity is critical for agriculture as it powers irrigation systems and deep tube-well pumps. But one-fifth of sub-Saharan Africa's electricity is generated from hydropower—which is susceptible to droughts. Diversifying green electricity sources over the long term will not only increase electrification, but also reduce carbon emissions and create jobs. In Kenya, access to electricity rose from 40 to 70 percent of the population in large part through small, off-grid, solar-powered energy plants The pay-as-you-go mobile money model may also have some advantages in terms of accessibility and scalability (IMF 2020a).

Third, strengthen coping mechanisms. Following a drought, higher incomes from diversified sources and access to finance and social assistance, among others, act as buffers that help people and businesses cope. Policies can support diversifying income sources and improving access to finance. In particular, social protection programs, such as health and unemployment insurance, can be adapted to cover impacts resulting from droughts and other climate shocks.

[1] Prepared by Seung Mo Choi (African Department).

Compensation might be more efficient than investments to achieve society's equity preferences. Some populations might face devastating disasters in areas where protective infrastructure would have a negative NPV, even after factoring in non-market impacts. If such populations tend to already be poor and vulnerable, society's equity preferences may warrant the building of such infrastructure. The authorities should consider whether the cost implied by the negative NPV is consistent with what society is willing to pay to address other inequitable situations (for example, would the cost be consistent with spending to reduce health risks?). It might be the case that the negative NPV is beyond what society would be willing to pay for equity considerations. In such cases, it is still important to achieve society's equity preference and support the affected population in alternative ways. This can take the form of relocation subsidies or other forms of supports with less stringent conditionality. In the latter case, moral hazard issues should be considered, as post-disaster relief might still be expected in addition to ex ante compensation for those who decided to stay in the risky area.

To ensure consistency across multiple programs, including all development investments, governments can standardize how they assess trade-offs across different groups in society and across different goals. There are several ways to carry out this analysis (Boardman and others 2017):

Multigoal analysis. The government establishes some important goals besides economic efficiency, like reducing the number of people living in poverty and preservation of cultural heritage. If the impacts of the program on these goals could be monetized—for example, by estimating the willingness to pay (WTP) of society to attain them—they should be added in the NPV calculation. If they cannot be monetized, governments would benefit from assessing trade-offs transparently and consistently. This exercise should be conducted considering a wide array of alternative development programs that can attain the same goals, so that governments can select the most efficient combination of programs. For example, means-tested cash transfers can be compared to adaptation programs in attaining the goal of reducing poverty.

Distributionally weighted CBA. If the main concern of the government is about the distribution of costs and benefits of the project, net benefits can be calculated for different groups in society and then they can be multiplied by a weight that reflects the relative importance of that group (Adler 2016; Fleurbaey and Abi-Rafeh 2016; Robinson, Hammitt, and Zeckhauser 2016). For example, if net benefits to those living below the poverty line are three times more important than those living above the poverty lines, they should be weighted accordingly. Although reaching consensus on a set of distributional weights is difficult in practice, using the same set of weights for all government programs can help to deal with equity issues consistently.

Social welfare function. A more systematic approach to assess alternative goals and distributional issues would rely on a social welfare function that reflects preferences across different goals and on inequality aversion. The combination of programs that maximizes the social welfare function with a given budget constraint should be selected. Although appealing and conceptually useful, this approach cannot be easily implemented because it is hard or maybe impossible to estimate such a function (Arrow 1951).

If there is a strong preference for a specific set of results, cost-effectiveness analysis can replace CBA. Cost-effectiveness analysis does not estimate the benefits of a project because it is assumed that the necessity of the intervention has already been established using other criteria. The objective of cost-effectiveness analysis is to find the least expensive solution to attain the desired set of goals.

Governments should be careful about setting goals without comparing costs and benefits, because even the least-cost alternative may lead to a net loss for society if benefits are low.

In What Cases Is Government Intervention Warranted?

Investments in adaptation are similar to other investments that firms, individuals, and governments make to maximize profits or utility. It is then possible to apply standard economic analysis to study adaptation to climate change.[6]

In perfectly competitive markets (complete structure of property rights, atomistic participants, complete information, and no transaction costs), individuals and firms are expected to adapt efficiently. Perfectly competitive markets are a purely hypothetical construct, but they provide a useful benchmark to develop a theory of government intervention, for adaptation policies as well as other government policies. With competitive markets, profit-maximizing firms change the mix of inputs, technology, and/or output in response to climate change, given the price of inputs and outputs. For example, farmers change the amount of water they use, irrigation technologies, and the crops they grow. Consumers change their consumption bundle (for example, warming leads to higher demand for air conditioning). All these adjustments are adaptation to climate change that do not need government intervention, a concept sometimes called *autonomous adaptation*.

In imperfectly competitive markets, adaptation is inefficient, and governments should intervene mirroring standard prescriptions for public policy from economic theory.

- Some market imperfections pertain to the nature of the adaptation goods themselves. For example, markets invest suboptimally in adaptations with large positive externalities and public goods, such as information about climate change, emergency preparedness plans, seawalls, basic research in new materials, and technologies to cope with higher temperature. Markets invest excessively in adaptations that have negative externalities, such as air conditioners.
- In many instances, resilience depends on networks, such as a system of dikes, a water network, or a transportation network (Feng and Li 2021). As adaptation in each component of a network has impacts on the rest of the network that may not be captured, private adaptation will tend to be underprovided. Government coordination may be needed to internalize all the benefits for society (Hallegatte and others 2016; Kunreuther and Heal 2003; Heal and Kunreuther 2010).
- The extent of needed cooperation for adaptation projects depends on the extent of the externality that is addressed by the project. Building a more resilient storm water drainage system may only require cooperation at the city level. If risks from sea-level rise are localized, each locality may invest in its own system of protection. The central government can provide adaptations with local effects, but that would be equivalent to a transfer of wealth between regions when projects are financed from national resources. As risks grow in scope and complexity, cooperation might be needed at the national or even the international level, for example to manage floods in

---

6 Earlier work on the economics of adaptation includes Fankhauser, Smith, and Tol (1999); Mendelsohn (2000); Nordhaus and Boyer (2000); Kahn (2016); Auffhammer (2018); Massetti and Mendelsohn (2018); Tol (2018); and papers in the special issue edited by Fisher-Vanden, Popp, and Sue Wing (2014) are surveys of the literature. For studies by international organizations, see Agrawala and Fankhauser (2008); Organisation for Economic Co-operation and Development (2009, 2015); Hallegatte and others (2018); and Hallegatte, Rentschler, and Rozenberg (2019, 2020). The necessary condition for financing a project in CBA relies on the Kaldor-Hicks compensation principle, which in turn is closely related to Pareto improvements with transfers. The discussion in this section deals with discrete programs. More generally, efficiency requires that the marginal benefit of adaptation is equal to its marginal cost.

transnational rivers. In general, the optimal distribution of responsibilities across levels of government also depends on the existing allocation of responsibilities.

- Other market imperfections affect the broad functioning of the economy and make adaptation to climate change inefficient. For example, a poor business environment and inefficient credit markets hamper opportunities for farmers to invest in new capital to grow crops that are more suitable to the new climate.
- Moral hazard may cause insufficient investment in adaptation if consumers, firms, and local government expect central governments to provide relief. To avoid moral hazard, governments can implement regulations that minimize risk taking. Examples include zoning that prohibits construction in flood zones, building codes, mandatory evacuations, and mandatory insurance. A similar issue applies to governments expecting post-disaster relief from the donor community. In some cases, it can be more cost-effective for donors to support ex ante investment to reduce risks (IMF 2019a, 2020b).
- Governments may also consider correcting market distortions resulting from their own policies (policy failure). For example, subsidies to inputs can lead to inefficient use. Of particular concern is subsidized water use, which may worsen water scarcity problems due to climate change (Kochhar and others 2015; Olmstead 2014). Barriers to international trade also prevent efficient climate-change-induced reallocation of capital, land use, and other resources to maximize their productivity. Governments may consider removing these distortions as part of a comprehensive plan to improve the efficiency of the economy, while taking into consideration the distributional implications of these measures.

Market failures, credit constraints in particular, can be severe for low-income consumers and small firms. Market reforms that target these crucial inefficiencies have large positive benefits because they enhance economic development, including adaptation to climate change.

Subsidies are necessary to provide the socially optimal amount of the adaptations with positive externalities. For example, subsidies are needed for investments in research and development in new drought-resistant seeds, in new ways to manage sea-level rise, and in more efficient cooling technologies. Subsidies are also needed for public goods, which include protection of key assets that ensure safe and reliable functioning of networks.

In the absence of externalities, subsidies can be inefficient because they distort choices away from the optimal consumption basket and investment portfolio. In addition, increased taxation to finance subsidies may lead to additional deadweight losses and the revenue might be better used for other purposes. If the goal of subsidies to adaptation is to alleviate poverty, unconditional income transfers may be preferred because they are nondistortionary. However, if governments are bound to compensate agents for losses from climate events also in the form of public health or rescuing operations, or if agents believe that governments will compensate them, subsidies to private adaptation may lower future government liabilities and reduce moral hazard. These positive effects on government finances will be captured by changes in government surplus in CBA. However, these are second-best outcomes. Overall efficiency improves if risks are fully priced. Government compensation leads to inefficient (excessive) risk taking at social level.

International Aid

At the global level, there is growing demand to increase international aid toward low-income vulnerable countries with large climate change adaptation needs based on equity arguments.

While efficient adaptation to the *present* climate remains an issue in many countries (Note 3), climate change creates new risks for low-income and vulnerable countries. These risks are expected to increase inequality within countries and relative to higher-income countries even if lower-income countries have typically not contributed much to climate change themselves.

Conditionality of international aid on investments in adaptation is a double-edged sword. Development partners can choose to condition their support on using such support only toward adaptation goals. While such conditionality may facilitate the mobilization of resources toward vulnerable countries, it may also lead to invest in adaptation projects that contribute less to society's goals than other development projects. Adaptation to climate change is only one of the many competing development goals. International donors should thus weigh the costs and benefits of investments in adaptation against those of alternative uses of international aid, if adaptation finance is not additional to existing development assistance or does not have other strong development benefits.

Cost-Benefit Analysis Amid Large Risks and Deep Uncertainty

CBA can account for risks with known probabilities by weighting the NPV in future scenarios using their respective probabilities to calculate the expected NPV of a project. However, the effect of uncertainty on welfare is lost in the aggregation method. If preferences are risk-neutral, the probability-weighted NPV provides the correct estimation of society's WTP for the adaptation program. However, with risk-averse preferences, risk can matter.

For idiosyncratic risks that can be pooled and covered with actuarially fair insurance, uncertain future outcomes can be reduced to certain outcomes. The expected NPV of a program would thus be the correct measure of society's WTP for the program. For example, a program that aims at reducing hail damages to all farmers in a country may rely on historical probabilities of hail damage for the country because each year the amount of total hail damage will be close to the expected value. Some farmers will suffer from hail, some not, but pooling risks across many farmers will make actual losses for society very close to the expected losses.

When a program value depends on systematic risks (for example, the catastrophic failure of coastal protections in a small island state, or hypothetically, a large asteroid collision) pooling risks is difficult or impossible. The benefit of a program could be measured by estimating the WTP for the program *before* knowing the actual future outcomes, which is known as the *option price* (Boardman and others 2017). This method accounts for the large welfare cost from rare but potentially catastrophic outcomes. Unfortunately, the estimation of the option price is not simple (Boardman and others 2017).

As many factors that affect benefits and costs of long-term adaptations are affected by deep uncertainty (Box 1, and Annexes 1 and 2), CBA may have to be complemented by alternative decision methods. A measure of social net benefits can be developed under alternative scenarios. With this information, policymakers can make informed decisions that reflect society's attitudes toward risks with known and unknown probabilities. For example, policymakers may select solutions that deliver acceptable outcomes in most scenarios instead of solutions with larger expected benefits but with high probability of large negative outcomes. Alternatively, they could select the program that leads to the best outcome in the worst-case scenario. There is not an optimal way to deal with this complex process and various methods have been proposed (Hallegatte 2009; Hallegatte and others 2012, 2021; Etner, Jeleva, and Tallon 2012; Hallegatte, Rentschler, and Rozenberg 2020; Behar and Hlatshwayo 2021). Note 3 discusses how uncertainty could be factored in PFM. Governments would benefit from establishing transparent rules that are consistently applied across all programs, for climate change adaptation as well as for other development goals.

How Should Adaptation Unfold over Time in Practice?

Decision-making under uncertainty can be very complex and a complete treatment is out of the scope of this Note. It is useful to conclude with some practical suggestions on how to frame the process of adaptation to climate change.

Adaptation should not be considered a one-time adjustment because climate will continue changing over the entire century and beyond. Adaptation is a dynamic process that should be integrated into development planning. Any new investment should reflect the effect of future climate during the lifetime of the investment.

Amid all this uncertainty, when could governments start planning adaptation to climate change? Adaptation as a process should start now because climate has changed and will continue to change. However, the exact timing of investments in adaptation depends on many factors including the characteristics of the investment at stake, local vulnerabilities, present climate, expectations about future climate, risk tolerance, and impediments, such as access to finance (Lemoine 2018). In some cases, waiting until capital becomes obsolete and replacing it with better-adapted capital may greatly contain adaptation costs and result in tolerable damage. If capital has a long remaining lifetime, retrofitting can be a viable strategy, even though it is usually more costly.

It is useful to consider separately adaptation that requires capital that depreciates faster than climate change and adaptation which requires capital which depreciates more slowly.[7] In the first case, adaptation will likely occur as a sequence of gradual adjustments over time for which long-term planning is not necessary (Mendelsohn 2000; Lemoine 2018; Massetti and Mendelsohn 2018). Farmers who switch crops as a response to higher temperatures will slowly select the capital needed to grow new crops. Alternatively, there can be a large difference between climate at the beginning and at the end of the lifetime of some critical infrastructure (including transportation networks and water and other public utility systems). At any point in time, this kind of long-lasting capital will likely be suboptimal because investment choices are discrete while climate change is continuous (Kelly, Kolstad, and Glenn 2005). Therefore, it might be cost-effective to adjust project designs to allow for cheaper modifications in the future, namely *real options* (for example, building larger-than-needed foundations for seawalls to allow for a future increase in their heights). In other cases, advanced planning can help to save costs (for example, use zoning regulation to “move” urban areas away from exposed coastlines by banning new constructions within a certain distance to the coastline and by gradually increasing this distance over time). Allowing faster depreciation of capital that is not climate resilient could free up resources that can be used for more resilient capital.

A practical way forward may be to start addressing adaptation gaps to the present climate, especially when they are large and involve short-lived capital. For example, emergency preparedness plans do not need investment in infrastructure, have large benefits with the present climate, and will have large benefits under future climate. Other examples include rebuilding or retrofitting

---

[7] As a reference, the lifespans in years of infrastructure investment are estimated to be as follows: thermal power plants (20 to 60), buildings (30 to 150), transport (30 to 200), water (30 to 200), and land-use plans (> 100). Based on Hallegatte (2009) and Ranger, Reeder, and Lowe (2013).

infrastructure that is wholly inadequate to deal with present climate risks. Governments will start accumulating knowledge and experience in dealing with present challenges without the complication of having to forecast long-term scenarios.

For climate change projections at the local level, governments can consult climatologists who can interpret and adapt available knowledge to the local situation. Each location has its own challenges and uncertainties. However, it is possible to highlight some recurring features.

- When the investment horizon is up to 20 years, the *natural variability* of climate will likely be much stronger at the local level than most of the underlying climatic trends, with the general exception of temperature and sea-level rise trends. *Model uncertainty* is dominated by natural variability over this time horizon (Box 1). *Scenario uncertainty* is also limited until approximately midcentury (Box 1). For example, best estimates and very likely ranges of temperature and sea-level rise across emissions scenarios are very similar until 2040 (Figure 1, and Annexes 1 and 2). Over this time horizon, uncertainty can be quantified in probabilistic terms using the observed distribution of climate, corrected using robust trends in temperature and in other variables. Due to deep uncertainty, it is impossible to rule out abrupt departures, especially of extremes, from the recent past. However, climate scenarios typically display strong inertia in this time frame.
- For investment horizons of 20 to 30 years, *model uncertainty* is the most important source of uncertainty (Box 1). The full set of scenarios produced by climate models should be used to study the distribution of future temperature and of other climate variables, including extreme events. This distribution cannot be interpreted as an objective probability distribution because the exact probabilities of each scenario are unknown (*deep uncertainty*). The average outcome should be interpreted as the "best estimate," not as an expected value. The 90 percent range—as well as other ranges—is not a 90 percent confidence interval, but it represents a broad area of consensus among climatologists. Scenarios can be used to develop subjective probabilities that can be used in CBA, or they can be used as the foundation of robust decision-making methods under uncertainty.
- For investment horizons longer than 30 years, *scenario uncertainty* becomes dominant (Box 1). Analysts should consider model runs for different scenarios separately and apply robust decision-making methods under uncertainty to consider the possibility of very different climate change projections. Emission scenarios should be matched with appropriate socioeconomic scenarios (Annex 2).

Uncertainty declines sharply as we move from local to regional and from regional to global scales. We do not know exactly yet when, where, and by how much, but we know that temperature will increase, that sea level will rise, that glaciers will melt, and that extreme climate events will become more frequent and more intense in at least some regions. This means that solutions should be developed now even if we will only know later when and where these solutions will be needed. Innovations that make adaptation capital flexible will be particularly valuable (for example, seawalls that can be upgraded if sea level rises faster than previously expected) (Dechezlepretre and others 2020).

Annex 1. Climate Change Scenarios

Climate scientists develop scenarios of future warming using representative emission scenarios from integrated assessment models. In the most recent Intergovernmental Panel on Climate Change assessment report (IPCC 2021b), each emission scenario is based on a storyline chosen among five standardized future socioeconomic, technological, and policy developments, called Shared Socio-Economic Pathway (SSP). The emission scenario is indicated with its level of radiative forcing (RF) in 2100. RF is the excess energy trapped by Greenhouse Gases (GHGs) in the atmosphere above the pre-industrial level and is measured in watts per square meter (W/m^2). For example, the lowest warming scenario is SSP1–1.9, which indicates that SSP1 was used and the level of RF in 2100 is equal to 1.9 W/m^2.

The effects of alternative emissions trajectories on temperature will become relevant around midcentury and on sea-level rise after midcentury. Across future IPCC scenarios, the best estimate of mean temperature change in 2046 to 2065 with respect to the 1850- to 1900-level ranges between 1.6°C and 2.4°C, and between 1.4°C and 4.4°C in 2081 to 2100. Mean sea-level rise above the 1995 to 2014 level ranges from 0.18 m to 0.23 m in 2050, and from 0.38 m to 0.77 m in 2100. Sea-level rise has strong inertia, so all scenarios lead to similar best estimates at least up to 2050. Annex Table 1.1 does not include scenarios of very fast sea-level rise that are very uncertain. A low-likelihood marine ice sheet instability scenario, with the extreme Representative Concentration Pathway (RCP) 8.5 emission scenario, that could add an additional meter of sea level rise by 2100 cannot be ruled out due to deep uncertainties (Arias and others 2022, Box TS.4).

Annex Table 1.1. Intergovernmental Panel on Climate Change Global Mean Temperature and Sea-Level Rise Scenarios

		2021–2046		2046–2065		2081–2100	
	Scenario	**Best Estimate**	**Very Likely range**	**Best Estimate**	**Very Likely Range**	**Best Estimate**	**Very Likely Range**
Global Mean Surface Temperature Change (C)	SSP1–1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
	SSP1–2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
	SSP2–4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
	SSP3–7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
	SSP5–8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7
		2030		**2050**		**2100**	
	Scenario	**Best Estimate**	**Likely Range**	**Best Estimate**	**Likely Range**	**Best Estimate**	**Likely Range**
Global Mean Sea-Level Rise (m)	SSP1–1.9	0.09	0.08 to 0.12	0.18	0.15 to 0.23	0.38	0.28 to 0.55
	SSP1–2.6	0.09	0.08 to 0.12	0.19	0.16 to 0.25	0.44	0.33 to 0.61
	SSP2–4.5	0.09	0.08 to 0.12	0.21	0.18 to 0.26	0.56	0.44 to 0.76
	SSP3–7.0	0.10	0.08 to 0.12	0.22	0.19 to 0.28	0.68	0.55 to 0.90
	SSP5–8.5	0.10	0.09 to 0.12	0.23	0.20 to 0.30	0.77	0.63 to 1.02

Source: Temperature: Arias and others (2021c, Cross-Section Box TS.1). Sea level: Fox-Kemper and others (2021, Table 9.9).
Note: Global mean surface temperature has increased by 1.1°C between 1850–1900 and 2010–2019. Global mean sea level has increased by 20 cm between 1901 and 2018. The scenarios project sea-level rise in meters relative to a baseline of 1995–2014 sea level.

Annex 2. Socioeconomic Scenarios

Economists and analysts working on long-term adaptation to climate change must properly match emission scenarios and socioeconomic scenarios. The cost of climate change and adaptation needs depend on both future climate and future levels of development because vulnerability greatly depends on development.

Each socioeconomic scenario (SSP) provides an internally consistent set of assumptions on economic development, society, and technology (Riahi and others 2017; O'Neill and others 2014). Annex Table 2.1 summarizes assumptions on population and GDP for the four SSPs used by climate scientists.

Annex Table 2.1. Global Economic and Population Scenarios Used by the Intergovernmental Panel on Climate Change

		2020			2030	
	GDP (T PPP)	Population (M)	GDP/Capita ('000 PPP)	GDP (T PPP)	Population (M)	GDP/Capita ('000 PPP)
SSP1	102	7,576	13,439	291	8,062	36,133
SSP2	101	7,611	13,302	231	8,262	27,996
SSP3	97	7,698	12,659	174	8,514	20,396
SSP5	102	7,552	13,493	365	8,054	45,282
		2050			**2100**	
	GDP (T PPP)	**Population (M)**	**GDP/Capita ('000 PPP)**	**GDP (T PPP)**	**Population (M)**	**GDP/Capita ('000 PPP)**
SSP1	291	8,062	36,133	565	6,958	81,258
SSP2	231	8,262	27,996	539	9,032	59,711
SSP3	174	8,514	20,396	270	12,620	21,415
SSP5	365	8,054	45,282	1,031	7,375	139,797

Source: This table is based on data from the Shared Socio-Economic Pathways (SSP) database hosted by the IIASA Energy Program at https://tntcat.iiasa.ac.at/SspDb. The underlying scientific data was published in Riahi and others (2017).
Note: SSP1 is the sustainable development pathways and yields both low emissions and rapid economic growth (Vuuren and others 2017). SSP2 describes continuation of current trends (Fricko and others 2017). SSP3 describes a world with strong regional rivalry, with high emissions and low economic growth (Fujimori and others 2017). SSP5 describes a world with very fast economic growth supported by fossil fuels (Kriegler and others 2017).

With the last assessment report, the IPCC has matched RCPs and SSPs to ensure consistency. The highest emission scenario was previously labeled as RCP8.5 and now as SSP5–8.5. The lowest emission scenarios, RCP2.6 and RCP1.9, are matched with the "sustainable development" pathway SSP1 (SSP1–1.9 and SSP1–2.6).

Some combinations of RCPs and SSPs are incompatible. The socioeconomic scenarios do not include climate change feedbacks on the economy nor the impact of economic growth on emissions. Therefore, GHG emission scenarios and socioeconomic scenarios cannot be chosen independently as some scenarios are incompatible: low (high) development scenarios are inconsistent with high (low) emission scenarios. Hence, the highest emission scenarios, RCP8.5 is compatible only with SSP5, a scenario of fast growth and low-income inequality worldwide.

The highest emission scenario is often referred to as a "no policy" scenario but can be supported only by extreme use of coal and very fast economic growth (Hausfather and Peters 2020; Pielke and Ritchie 2021). Although it is impossible to attach exact probabilities to these scenarios, most models indicate that with no mitigation, RF would be between 6.0 and 7.0 w/m^2 in 2100. With national climate pledges and mitigation measures, global temperature is expected to rise by 2.7°C by the end of the century, in line with the SSP2–4.5 scenario (UN Environment Programme 2021).

References

Acevedo, Sebastian. 2014. “Debt, Growth and Natural Disasters: A Caribbean Trilogy.” IMF Working Paper 14/125, International Monetary Fund, Washington, DC.

Acevedo, Sebastian. 2016. “Gone with the Wind: Estimating Hurricane and Climate Change Costs in the Caribbean.” IMF Working Paper 16/199, International Monetary Fund, Washington, DC.

Acevedo, Sebastian, and Alphonse Noah. Forthcoming. “What Causes Natural Disasters? The Role of Development, Weather, and Climate Change.” IMF Working Paper, International Monetary Fund, Washington, DC.

Adger, W. Neil, Shardul Agrawal, M. Monirul Qader Mirza, Cecilia Conde, Karen O’Brien, Juan Pulhin, Roger Pulwarty, Barry Smit, and Kiyoshi Takahashi. 2007. “Assessment of Adaptation Practices, Options, Constraints and Capacity.” In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 719–43. Cambridge University Press.

Adler, Matthew D. 2016. “Benefit–Cost Analysis and Distributional Weights: An Overview.” *Review of Environmental Economics and Policy* 10 (2): 264–85.

Agarwal, Ruchir, Vybhavi Balasundharam, Patrick Blagrave, Eugenio M. Cerutti, Ragnar Gudmundsson, and Racha Mousa. 2021. “Climate Change in South Asia: Further Need for Mitigation and Adaptation.” IMF Working Paper 21/217, International Monetary Fund, Washington, DC.

Agrawala, Shardul, and Samuel Fankhauser. 2008. *Economic Aspects of Adaptation to Climate Change Costs, Benefits and Policy Instruments: Costs, Benefits and Policy Instruments*. Paris: OECD Publishing.

Aligishiev, Zamid, Matthieu Bellon, and Emanuele Massetti. 2022. “Macro-Fiscal Implications of Adaptation to Climate Change.” IMF Staff Climate Note 2022/002, International Monetary Fund, Washington, DC.

Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld, 2021: Technical Summary. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Aroonruengsawat, Anin, and Maximilian Auffhammer. 2011. “Impacts of Climate Change on Residential Electricity Consumption: Evidence from Billing Data.” In *The Economics of Climate Change: Adaptations Past and Present*, 311–42. Chicago: University of Chicago Press.

Arrow, K. J. 1951. *Social Choice and Individual Values*. New York: John Wiley & Sons, Inc.

Arrow, Kenneth, Maureen Cropper, Christian Gollier, Ben Groom, Geoffrey Heal, Richard Newell, William Nordhaus, et al. 2013. “Determining Benefits and Costs for Future Generations.” *Science* 341 (6144): 349–350.

Arrow, Kenneth J., Maureen L. Cropper, Christian Gollier, Ben Groom, Geoffrey M. Heal, Richard G. Newell, William D. Nordhaus, R. Pindyck, W. Pizer, P. Portney, T. Sterner, R. S. J. Tol, and M. Weitzman. 2014. “Should Governments Use a Declining Discount Rate in Project Analysis?” *Review of Environmental Economics and Policy* 8 (2): 145–63.

Asian Development Bank (ADB). 2013. *Cost-Benefit Analysis for Development: A Practical Guide*. Mandaluyong City, Philippines: Asian Development Bank.

Auffhammer, Maximilian. 2018. "Quantifying Economic Damages from Climate Change." *Journal of Economic Perspectives* 32 (4): 33–52.

Bakkensen, Laura A., and Robert O. Mendelsohn. 2016. “Risk and Adaptation: Evidence from Global Hurricane Damages and Fatalities.” *Journal of the Association of Environmental and Resource Economists* 3 (3): 555–87.

Bakkensen, Laura, and Lint Barrage. 2020. “Climate Shocks, Cyclones, and Economic Growth: Bridging the Micro-Macro Gap.” University of Arizona and University of California at Santa Barbara. http://www.laurabakkensen.com/wp-content/uploads/2019/11/Bakkensen_Barrage_2019.pdf

Barthel, Fabian, and Eric Neumayer. 2012. “A Trend Analysis of Normalized Insured Damage from Natural Disasters.” *Climatic Change* 113 (2): 215–37.

Behar, Alberto, and Sandile Hlatshwayo. 2021. "Strategic Foresight at the International Monetary Fund." IMF How To Note, International Monetary Fund, Washington, DC.

Bellon, Matthieu, and Emanuele Massetti. 2022. “Planning and Mainstreaming Adaptation to Climate Change in Fiscal Policy.” IMF Staff Climate Note 2022/003, International Monetary Fund, Washington, DC.

Bigano, Andrea, Jacqueline M. Hamilton, and Richard S. J. Tol. 2006. “The Impact of Climate on Holiday Destination Choice.” *Climatic Change* 76 (3–4): 389–406.

Boadway, Robin W. 1974. "The Welfare Foundations of Cost-Benefit Analysis." *The Economic Journal*, 84 (336): 926–39.

Boardman, Anthony E., David H. Greenberg, Aidan R. Vining, and David L. Weimer. 2017. *Cost-Benefit Analysis: Concepts and Practice*. Cambridge University Press.

Bos, Frits, and Peter Zwaneveld. 2017. “Cost-Benefit Analysis for Flood Risk Management and Water Governance in the Netherlands: An Overview of One Century.” CPB Background Document, CPB Netherlands Bureau for Economic Policy Analysis, The Hague, Netherlands.

Bouwer, Laurens M. 2011. “Have Disaster Losses Increased Due to Anthropogenic Climate Change?” *Bulletin of the American Meteorological Society* 92 (1): 39–46.

Burton, Ian. 1996. “The Growth of Adaptation Capacity: Practice and Policy.” In *Adapting to Climate Change*, 55–67. New York: Springer.

Cameron, Trudy Ann. 2010. “Euthanizing the Value of a Statistical Life.” *Review of Environmental Economics and Policy* 4 (2): 161–78.

Cantelmo, Alessandro, Giovanni Melina, and Chris Papageorgiou. 2019. “Macroeconomic Outcomes in Disaster-Prone Countries.” IMF Working Paper 19/217, International Monetary Fund, Washington, DC.

Cantelmo, Alessandro, Leo Bonato, Giovanni Melina, Gonzalo Salinas, Sònia Muñoz, and Chris Papageorgiou. 2019. “Policy Trade-Offs in Building Resilience to Natural Disasters: The Case of St. Lucia.” IMF Working Paper 19/54, International Monetary Fund, Washington, DC.

Dechezlepretre, Antoine, Samuel Fankhauser, Matthieu Glachant, Jan Stoever, and Simon Touboul. 2020. *Invention and Global Diffusion of Technologies for Climate Change Adaptation: A Patent Analysis.* Washington, DC: The World Bank Group.

Dell, Melissa, Benjamin F Jones, and Benjamin A Olken. 2012. “Temperature Shocks and Economic Growth: Evidence from the Last Half Century.” *American Economic Journal: Macroeconomics* 4 (3): 66–95.

Di Falco, Salvatore, and Marcella Veronesi. 2013. “How Can African Agriculture Adapt to Climate Change? A Counterfactual Analysis from Ethiopia.” *Land Economics* 89 (4): 743–66.

Duenwald, Christoph, Yasser Abdih, Kerstin Gerling, Vahram Stepanyan, Lamiae Agoumi, Abdullah AlHassan, Gareth Anderson Anja Baum, Mehdi Benatiya Andaloussi, Chen Chen, Sahra Sakha, Sergejs Saksonovs, Faten Saliba, and Jesus Sanchez. Forthcoming. “Feeling the Heat—Adapting to Climate Change in the Middle East and Central Asia.” IMF Departmental Paper, International Monetary Fund, Washington, DC.

Estrada, Francisco, W. J. Wouter Botzen, and Richard S. J. Tol. 2015. “Economic Losses from US Hurricanes Consistent with an Influence from Climate Change.” *Nature Geoscience* 8 (11): 880–84.

Etner, Johanna, Meglena Jeleva, and Jean-Marc Tallon. 2012. "Decision Theory under Ambiguity." *Journal of Economic Surveys* 26 (2): 234–70.

European Commission. 2015. *Guide to Cost-Benefit Analsysis of Investment Projects. Economic Appraisal Tool for Cohesion Policy 2014-2020.* Luxembourg: Publications Office of the European Union.

Fankhauser, Samuel, Joel B. Smith, and Richard S. J. Tol. 1999. “Weathering Climate Change: Some Simple Rules to Guide Adaptation Decisions.” *Ecological Economics* 30 (1): 67–78.

Farid, Mai, Michael Keen, Michael Papaioannou, Ian Parry, Catherine Pattillo, Anna Ter-Martirosyan, and others. 2016. “After Paris: Fiscal, Macroeconomic, and Financial Implications of Climate Change.” IMF Staff Discussion Note 16/01, International Monetary Fund, Washington, DC.

Feng, Alan, and Haishi Li. 2021. “We Are All in the Same Boat: Cross-Border Spillovers of Climate Risk through International Trade and Supply Chain.” IMF Working Paper 21/13, International Monetary Fund, Washington, DC.

Fisher-Vanden, Karen, David Popp, and Ian Sue Wing. 2014. "Introduction to the Special Issue on Climate Adaptation: Improving the Connection between Empirical Research and Integrated Assessment Models." *Energy Economics* 46: 495–99.

Fleurbaey, Marc, and Rossi Abi-Rafeh. 2016. “The Use of Distributional Weights in Benefit–Cost Analysis: Insights from Welfare Economics.” *Review of Environmental Economics and Policy* 10 (2): 286–307.

Fox-Kemper, B., H. T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S. S. Drijfhout, T. L. Edwards, N. R. Golledge, et al. 2021. “Ocean, Cryosphere and Sea Level Change Supplementary Material.” In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, and others. Cambridge University Press.

Fricko, Oliver, Petr Havlik, Joeri Rogelj, Zbigniew Klimont, Mykola Gusti, Nils Johnson, Peter Kolp, M. Strubegger, H. Valin, M. Amann, T. Ermolieva, N. Forsell, M. Herrero, C. Heyes, G. Kindermann, V. Krey, D. L. Mccollum, M. Obersteiner, S. Pachauri, S. Rao, E. Schmid, W. Schoepp, and K. Riahi. 2017. “The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century.” *Global Environmental Change* 42 (January): 251–67.

Fujimori, Shinichiro, Tomoko Hasegawa, Toshihiko Masui, Kiyoshi Takahashi, Diego Silva Herran, Hancheng Dai, Yasuaki Hijioka, and Mikiko Kainuma. 2017. “SSP3: AIM Implementation of Shared Socioeconomic Pathways.” *Global Environmental Change* 42 (January): 268–83.

Global Burden of Disease. 2018. *Global Burden of Disease Study 2017 (GBD 2017) Results*. Seattle: Institute for Health Metrics and Evaluation.

Gollier, Christian, and Martin L Weitzman. 2010. “How Should the Distant Future Be Discounted When Discount Rates Are Uncertain?” *Economics Letters* 107 (3): 350–53.

Gollier, Christian, Phoebe Koundouri, and Theologos Pantelidis. 2008. “Declining Discount Rates: Economic Justifications and Implications for Long-Run Policy.” *Economic Policy* 23 (56): 758–95.

Government of Grenada. 2021. "Grenada: Disaster Resilience Strategy." Ministry of Finance and Ministry of Climate Resilience paper. St. George's.

Gutiérrez, J.M., R.G. Jones, G.T. Narisma, L.M. Alves, M. Amjad, I.V. Gorodetskaya, M. Grose, N.A.B. Klutse, S. Krakovska, J. Li, D. Martínez-Castro, L.O. Mearns, S.H. Mernild, T. Ngo-Duc, B. van den Hurk, and J.-H. Yoon, 2021: Atlas. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press

Hallegatte, Stéphane. 2009. “Strategies to Adapt to an Uncertain Climate Change.” *Global Environmental Change* 19 (2): 240–247.

Hallegatte, Stéphane, Jun Rentschler, and Julie Rozenberg. 2019. *Lifelines: The Resilient Infrastructure Opportunity*. Washington, DC: World Bank.

Hallegatte, Stéphane, Jun Rentschler, and Julie Rozenberg. 2020. *Adaptation Principles: A Guide for Designing Strategies for Climate Change Adaptation and Resilience*. Washington, DC: World Bank.

Hallegatte, Stéphane, Ankur Shah, Casey Brown, Robert Lempert, and Stuart Gill. 2012. "Investment Decision Making under Deep Uncertainty—Application to Climate Change." World Bank Policy Research Working Paper 6193, World Bank, Washington, DC.

Hallegatte, Stéphane, Rubaina Anjum, Paolo Avner, Ammara Shariq, Michelle Winglee, and Camilla Knudsen. 2021. "Integrating Climate Change and Natural Disasters in the Economic Analysis of Projects: A Disaster and Climate Risk Stress Test Methodology." World Bank, Washington, DC.

Hallegatte, Stéphane, Colin Green, Robert J. Nicholls, and Jan Corfee-Morlot. 2013. "Future Flood Losses in Major Coastal Cities." *Nature Climate Change* 3 (9): 802–06.

Hallegatte, Stéphane, Adrien Vogt-Schilb, Mook Bangalore, and Julie Rozenberg. 2016. *Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters*. Washington, DC: World Bank Publications.

Hallegatte, Stéphane, Carter Brandon, Richard Damania, Yunziyi Lang, John Roome, Julie Rozenberg, and Arame Tall. 2018. "The Economics of (and Obstables to) Aligning Development and Climate Change Adaptation: A World Bank Group Contribution to the Global Commission on Adaptation." Discussion Paper, Global Commission on Adaptation, Rotterdam, Netherlands.

Hausfather, Zeke, and Glen P. Peters. 2020. "Emissions–the 'Business as Usual' Story Is Misleading." nature. https://www.nature.com/articles/d41586-020-00177-3

Heal, Geoffrey, and Howard Kunreuther. 2010. "Social Reinforcement: Cascades, Entrapment, and Tipping." *American Economic Journal: Microeconomics 2 (1): 86-99.*

Hsiang, Solomon M, and Daiju Narita. 2012. "Adaptation to Cyclone Risk: Evidence from the Global Cross-Section." *Climate Change Economics* 3 (02): 1250011.

Hutton, Guy, and Eva Rehfuess. 2006. *Guidelines for Conducting Cost-Benefit Analysis of Household Energy and Health Interventions*. Geneva: World Health Organization.

International Monetary Fund (IMF). 2016. "Small States' Resilience to Natural Disasters and Climate Change—Role for the IMF." IMF Staff Report, Washington, DC.

International Monetary Fund (IMF). 2017. "Seychelles: Climate Change Policy Assessment." IMF Country Report, Washington, DC.

International Monetary Fund (IMF). 2018. "Republic of Mozambique: Selected Issues." IMF Country Report, Washington, DC.

International Monetary Fund (IMF). 2019a. "Building Resilience in Developing Countries Vulnerable to Large Natural Disasters." IMF Policy Paper. Washington, DC: International Monetary Fund.

International Monetary Fund (IMF). 2019b. "Eastern Caribbean Currency Union: Selected Issues Paper." Washington, DC.

International Monetary Fund (IMF). 2020a. "Adapting to Climate Change in Sub-Saharan Africa." In *Regional Economic Outlook: Sub-Saharan Africa—COVID-19: An Unprecendented Threat to Development*. Washington, DC, April.

International Monetary Fund (IMF). 2020b. "Botswana: 2019 Article IV Consultation." IMF Country Report, Washington, DC.

International Monetary Fund (IMF). 2021a. "Climate Change Challenges in Latin America and the Caribbean." In *Regional Economic Outlook: Western Hemisphere—A Long and Winding Road to Recovery*. Washington, DC, October.

International Monetary Fund (IMF). 2021b. "Dominica: Disaster Resilience Strategy." IMF Country Report, Washington, DC.

International Monetary Fund (IMF). 2021c. "Republic of Congo: Selected Issues." IMF Country Report, Washington, DC.

International Monetary Fund (IMF). 2021d. "Vanuatu: Article IV Consultation." IMF Country Report, Washington, DC.

Intergovernmental Panel on Climate Change (IPCC). 2021a. Annex VII: Glossary [Matthews, J.B.R., V. Möller, R. van Diemen, J.S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, S. Semenov, A. Reisinger (eds.)]. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Intergovernmental Panel on Climate Change (IPCC). 2021b. Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Intergovernmental Panel on Climate Change (IPCC). 2022. Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.

Kahn, Matthew E. 2005. "The Death Toll from Natural Disasters: The Role of Income, Geography, and Institutions." *Review of Economics and Statistics* 87 (2): 271–84.

Kahn, Matthew E. 2016. "The Climate Change Adaptation Literature." *Review of Environmental Economics and Policy* 10 (1).

Kelly, David L., Charles D. Kolstad, and Glenn T. Mitchell. 2005. "Adjustment Costs from Environmental Change." *Journal of Environmental Economics and Management* 50 (3): 468–95.

Kochhar, Kalpana, Catherine Pattillo, Yan Sun, Nujin Suphaphiphat, Andrew Swiston, Robert Tchaidze, Benedict Clements, Stefania Fabrizio, Valentina Flamini, Laure Redifer, Harald Finger, and an IMF Staff Team. 2015. "Is the Glass Half Empty or Half Full?: Issues in Managing Water Challenges and Policy Instruments." IMF Staff Discussion Note 15/11, International Monetary Fund, Washington, DC.

Kriegler, Elmar, Nico Bauer, Alexander Popp, Florian Humpenöder, Marian Leimbach, Jessica Strefler, Lavinia Baumstark, Benjamin Leon Bodirsky, Jérôme Hilaire, David Klein, Ioanna Mouratiadou, Isabelle Weindl, Christoph Bertram, Jan-Philipp Dietrich, Gunnar Luderer, Michaja Pehl, Robert Pietzcker, Franziska Piontek, Hermann Lotze-Campen, Anne Biewald, Markus Bonsch, Anastasis Giannousakis, Ulrich Kreidenweis, Christoph Müller, Susanne Rolinski, Anselm Schultes, Jana Schwanitz, Miodrag Stevanovic, Katherine Calvin, Johannes Emmerling, Shinichiro Fujimori, and Ottmar Edenhofer. 2017. "Fossil-Fueled Development (SSP5): An Energy and Resource Intensive Scenario for the 21st Century." *Global Environmental Change* 42: 297–315.

Kunreuther, Howard, and Geoffrey Heal. 2003. "Interdependent Security." *Journal of Risk and Uncertainty* 26 (2): 231–249.

Kurukulasuriya, Pradeep, Namrata Kala, and Robert Mendelsohn. 2011. "Adaptation and Climate Change Impacts: A Structural Ricardian Model of Irrigation and Farm Income in Africa." *Climate Change Economics* 2 (2): 149–74.

Lemoine, Derek. 2018. "Estimating the Consequences of Climate Change from Variation in Weather." NBER Working Paper W25008, National Bureau of Economic Research, Cambridge, MA.

Maddison, David. 2001. "In Search of Warmer Climates? The Impact of Climate Change on Flows of British Tourists." *Climatic Change* 49 (1–2): 193–208.

Mansur, Erin T., Robert Mendelsohn, and Wendy Morrison. 2008. "Climate Change Adaptation: A Study of Fuel Choice and Consumption in the US Energy Sector." *Journal of Environmental Economics and Management* 55 (2): 175–93.

Marto, Ricardo, Chris Papageorgiou, and Vladimir Klyuev. 2018. "Building Resilience to Natural Disasters: An Application to Small Developing States." *Journal of Development Economics* 135: 574–86.

Massetti, Emanuele, and Robert Mendelsohn. 2018. "Measuring Climate Adaptation: Methods and Evidence." *Review of Environmental Economics and Policy* 12 (2): 324–41.

Melina, Giovanni, and Marika Santoro. 2021. "Enhancing Resilience to Climate Change in the Maldives." IMF Working Paper 21/96, International Monetary Fund, Washington, DC.

Mendelsohn, Robert. 2000. "Efficient Adaptation to Climate Change." *Climatic Change* 45 (3–4): 583–600.

Mendelsohn, Robert. 2012. "Development and Climate Adaptation." In *Climate Change and Common Sense: Essays in Honour of Tom Schelling*, edited by Robert W. Hahn and Alistair Ulph, 245. Oxford: Oxford University Press.

Mendelsohn, Robert, Kerry Emanuel, Shun Chonabayashi, and Laura Bakkensen. 2012. "The Impact of Climate Change on Global Tropical Cyclone Damage." *Nature Climate Change* 2 (3): 205–09.

Nordhaus, William D, and Joseph Boyer. 2000. *Warming the World: Economic Models of Global Warming*. Cambridge, MA: MIT Press.

Organisation for Economic Co-operation and Development (OECD). 2009. *Integrating Climate Change Adaptation into Development Co-Operation: Policy Guidance*. Paris: OECD Press.

Organisation for Economic Co-operation and Development (OECD). 2015. *Climate Change Risks and Adaptation: Linking Policy and Economics*. Paris: OECD Press.

Organisation for Economic Co-operation and Development (OECD). 2018. *Cost-Benefit Analysis and the Environment*. Paris: OECD Press.

Olmstead, Sheila M. 2014. "Climate Change Adaptation and Water Resource Management: A Review of the Literature." *Energy Economics* 46: 500–09.

O'Neill, Brian C., Elmar Kriegler, Keywan Riahi, Kristie L. Ebi, Stephane Hallegatte, Timothy R Carter, Ritu Mathur, and Detlef P. van Vuuren. 2014. "A New Scenario Framework for Climate Change Research: The Concept of Shared Socioeconomic Pathways." *Climatic Change* 122 (3): 387–400.

Pielke, Roger. 2021. "Economic 'Normalisation' of Disaster Losses 1998–2020: A Literature Review and Assessment." *Environmental Hazards* 20 (2): 93–111.

Pielke Jr, Roger, and Justin Ritchie. 2021. "Distorting the View of Our Climate Future: The Misuse and Abuse of Climate Pathways and Scenarios." *Energy Research & Social Science* 72: 101890.

Pondi, Eric, Seung Mo Choi, and Pritha Mitra. Forthcoming. "Sub-Saharan Africa Growth and Resilience Building Towards Climate-Related Disasters." IMF Working Paper, International Monetary Fund, Washington, DC.

Ranger, Nicola, Tim Reeder, and Jason Lowe. 2013. "Addressing 'Deep' Uncertainty over Long-Term Climate in Major Infrastructure Projects: Four Innovations of the Thames Estuary 2100 Project." *EURO Journal on Decision Processes* 1 (3–4): 233–262.

Reisinger, Andy, Mark Howden, Carolina Vera, Mathias Garschagen, Margot Hurlbert, Sylvia Kreibiehl, Katharine J. Mach, Katja Mintenbeck, Brian O'Neill, Minal Pathak, Roque Pedace, Hans-Otto Pörtner, Elvira Poloczanska, Maisa Rojas Corradi, Jana Sillmann, Maarten van Aalst, David Viner, Richard Jones, Alexander C. Ruane, Roshanka Ranasinghe. 2020. *The Concept of Risk in the IPCC Sixth Assessment Report: A Summary of Cross-Working Group Discussions*. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Riahi, Keywan, Detlef P. van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O'Neill, Shinichiro Fujimori, Nico Bauer, Katherine Calvin, Rob Dellink, Oliver Fricko, Wolfgang Lutz, Alexander Popp, Jesus Crespo Cuaresma, Samir K. C., Marian Leimbach, Leiwen Jiang, Tom Kram, Shilpa Rao, Johannes Emmerling, Kristie Ebi, Tomoko Hasegawa, Petr Havlik, Florian Humpenöder, Lara Aleluia Da Silva, Steve Smith, Elke Stehfest, Valentina Bosetti, Jiyong Eom, David Gernaat, Toshihiko Masui, Joeri Rogelj, Jessica Strefler, Laurent Drouet, Volker Krey, Gunnar Luderer, Mathijs Harmsen, Kiyoshi Takahashi, Lavinia Baumstark, Jonathan C. Doelman, Mikiko Kainuma, Zbigniew Klimont, Giacomo Marangoni, Hermann Lotze-Campen, Michael Obersteiner, Andrzej Tabeau, and Massimo Tavoni. 2017. "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview." *Global Environmental Change* 42 (January): 153–68.

Robinson, Lisa A., James K. Hammitt, and Richard J. Zeckhauser. 2016. “Attention to Distribution in US Regulatory Analyses.” *Review of Environmental Economics and Policy* 10 (2): 308–28.

Schelling, Thomas C. 1992. “Some Economics of Global Warming.” *The American Economic Review* 82 (1): 1–14.

Seo, S. Niggol, and Robert Mendelsohn. 2008a. “An Analysis of Crop Choice: Adapting to Climate Change in South American Farms.” *Ecological Economics* 67 (1): 109–16.

Seo, S. Niggol, and Robert Mendelsohn. 2008b. “Climate Change Impacts and Adaptations on Animal Husbandry in Africa.” *African Journal of Agricultural and Resource Economics* 2: 65–82.

Tol, Richard S. J. 2018. “The Economic Impacts of Climate Change.” *Review of Environmental Economics and Policy* 12 (1): 4–25.

Tol, Richard S. J., Samuel Fankhauser, and Joel B. Smith. 1998. “The Scope for Adaptation to Climate Change: What Can We Learn from the Impact Literature?” *Global Environmental Change* 8 (2): 109–23.

Toya, Hideki, and Mark Skidmore. 2007. “Economic Development and the Impacts of Natural Disasters.” *Economics Letters* 94 (1): 20–25.

United Nations Environment Programme (UNEP). 2021. *Emissions Gap Report 2021: The Heat Is On - A World of Promises Not Yet Delivered*. Nairobi: UN Environment Programme.

US Environmental Protection Agency. 1999. "The Benefits and Costs of the Clean Air Act, 1990 to 2010." US Environmental Protection Agency, Washington, DC.

Vecchi, Gabriel A., Christopher Landsea, Wei Zhang, Gabriele Villarini, and Thomas Knutson. 2021. “Changes in Atlantic Major Hurricane Frequency since the Late-19th Century.” *Nature Communications* 12 (1): 4054.

Vicente-Serrano, S. M., R. García-Herrera, D. Peña-Angulo, M. Tomas-Burguera, F. Domínguez-Castro, I. Noguera, N. Calvo, C. Murphy, R. Nieto, L. Gimeno, J. M. Gutierrez, C. Azorin-Molina, and A. El Kenawy. 2021. “Do CMIP Models Capture Long-Term Observed Annual Precipitation Trends?” *Climate Dynamics* (November).

Vuuren, Detlef P. van, Elke Stehfest, David E. H. J. Gernaat, Jonathan C. Doelman, Maarten van den Berg, Mathijs Harmsen, Harmen Sytze de Boer, Lex F. Bouwman, Vassilis Daioglou, Oreane Y. Edelenbosch, Bastien Girod, Tom Kram, Luis Lassaletta, Paul L. Lucas, Hans van Meijl, Christoph Müller, Bas J. van Ruijveng, Sietske van der Sluis, and Andrzej Tabeau. 2017. “Energy, Land-Use and Greenhouse Gas Emissions Trajectories under a Green Growth Paradigm.” *Global Environmental Change* 42 (January): 237–50.

Weinkle, Jessica, Chris Landsea, Douglas Collins, Rade Musulin, Ryan P. Crompton, Philip J. Klotzbach, and Roger Pielke. 2018. “Normalized Hurricane Damage in the Continental United States 1900–2017.” *Nature Sustainability* 1 (12): 808–13.

World Bank. 2017. "Climate Change and Disaster Management." World Bank Group, Washington, DC.

Yao, Jiaxiong. 2021. “Electricity Consumption and Temperature: Evidence from Satellite Data.” IMF Working Paper 21/22, International Monetary Fund, Washington, DC.

PUBLICATIONS

ISBN 978-1-5135-9237-4

Economic Principles for Integrating Adaptation to Climate Change into Fiscal Policy

IMF STAFF CLIMATE NOTE 2022/001