STAFF

# CLIMATE

NOTES

# Macro-Fiscal Implications of Adaptation to Climate Change

Zamid Aligishiev, Matthieu Bellon, and Emanuele Massetti

IMF STAFF CLIMATE NOTE 2022/002

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# Macro-Fiscal Implications of Adaptation to Climate Change

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## Summary

Adaptation reduces climate change damages but is costly and cannot eliminate all risks. Governments have to decide on an acceptable balance of residual risks and to determine adaptation investment needs by weighing costs, benefits, and distributional effects. A literature review suggests that well-designed and well-implemented adaptation can have large returns. Global public adaptation needs in 2030 are estimated in the literature at around ¼ percent of world GDP per year, but with very large disparities across countries and high uncertainty. Our analysis points to annual adaptation costs exceeding 1 percent of GDP for some developing countries, and above 10 percent of GDP for some island states. Many of these countries—despite typically not having contributed to global warming—face high adaptation needs while being challenged by limited fiscal space, limited capacity, or both, calling for additional support from the international community. To help guide national fiscal policies, countries could integrate climate risks and the cost of adaptation into their macro-fiscal frameworks. Shock scenarios are useful to reflect short-term impacts of climate disasters, while the long-term analysis of risks and uncertainties surrounding climate change requires scenarios that cover impacts from changes in both average and extreme events, as well as adaptation policies.


***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.*** *The first Note (Bellon and Massetti 2022a, henceforth Note 1) examines the economic principles that can guide the integration of climate change adaptation into fiscal policy. It argues that climate change adaptation should be part of a holistic, sustainable, and equitable development strategy. To maximize the impact of scarce resources, governments need to prioritize among all development programs, including but not limited to adaptation. To this end, they can use cost-benefit analysis while ensuring that the decision-making process reflects society's preferences about equity and uncertainty. This second Note discusses the macro-fiscal implications of climate change adaptation. A third Note (Bellon and Massetti 2022b, henceforth Note 3) considers how to translate adaptation principles and estimates of climate impacts into effective policies. It argues that adaptation solutions can be guided by an extension of the IMF's (2019b) three-pillar disaster resilience strategy to address changes in both extreme and average weather, for all countries. It suggests that public financial management (PFM) institutions can support an efficient implementation of adaptation solutions by factoring climate risks and adaptation plans into budgets and macro-frameworks, and in the management of public investment, assets, and liabilities.*

## Adaptation Benefits, Costs, and Needs

**Climate change adaptation is the process needed to minimize losses (and maximize benefits) from climate change.** Adaptation is needed to address risks from changes both in average conditions and in frequency and intensity of extreme weather, for example by improving dryland agriculture, using water resources better, managing sea-level rise, and making infrastructure more resilient. As climate is changing and will continue to change even with intensive mitigation efforts, adaptation to climate change is a necessity for advanced and developing economies alike (Note 1).

**Despite all the potential benefits, adaptation cannot replace mitigation (Intergovernmental Panel on Climate Change [IPCC] 2022).** Adaptation to climate change aims at controlling local climate damages, whereas climate change mitigation aims at controlling global climate change. Mitigation is a global coordination problem because it will fail if too many or large enough countries opt out of global efforts. For the most part, however, adaptation can succeed (or fail) at the local level independently from adaptation efforts in the rest of the world. For example, protection from sea-level rise in one island country does not depend on adaptation in other countries. Adaptation and mitigation are both needed to help reduce damages from climate change. Without strong mitigation, it is not possible to stabilize global temperature, and adaptation would become either impossible or too expensive.

**Governments would benefit from starting to evaluate the macro-fiscal implications of adaptation to climate change.** Adaptation can help to substantially reduce climate change costs. In the long term, well-managed adaptation frees resources and increases fiscal space if the reference scenario assumes unmitigated climate change impacts. But adaptation competes for budget resources with other public programs in the short term and may seem to reduce fiscal space if the reference scenario does not include climate change damages.

**The full cost of climate change is the sum of the cost of adaptation and the cost of residual risks.** Climate risks that are either impossible or too expensive to eliminate will put additional strains on the economy and public finances. Governments can start planning for climate change by estimating and incorporating projected climate damages as well as adaptation benefits and costs in their macro-fiscal frameworks. While all countries would benefit from this exercise, it will be most important for vulnerable developing economies, and especially in small developing island states threatened by both climate disasters and sea-level rise.

**Assessing macro-fiscal impacts of adaptation to climate change requires estimating climate change impacts and the effectiveness and cost of adaptation.** This information is needed for governments to decide on an acceptable level of residual climate change risks and to determine adaptation investment needs. These decisions involve weighing facts and preferences, including society's specific ethical norms and risk aversion. While economic principles cannot be the sole criteria in this process, they can play an important role. In particular, cost-benefit analysis (CBA), complemented with an assessment of distributional impacts, can help decision makers maximize overall social welfare by avoiding wasting scarce resources (Note 1).

### Adaptation Benefits: The Avoided Cost of Climate Change

**The benefit of adaptation can be estimated by comparing the cost of climate change with and without adaptation.** This principle applies at both the project (for example, building a bridge with or without higher resilience standards) and macroeconomic levels. However, determining benefits can be challenging because of difficulties in estimating alternative projections with climate change impacts where

the only difference is how agents adapt (see Massetti and Mendelsohn 2018 for a literature review of methods). Using different combinations of climate change and socioeconomic projections allows for the estimation of adaptation benefits under a range of possible conditions.

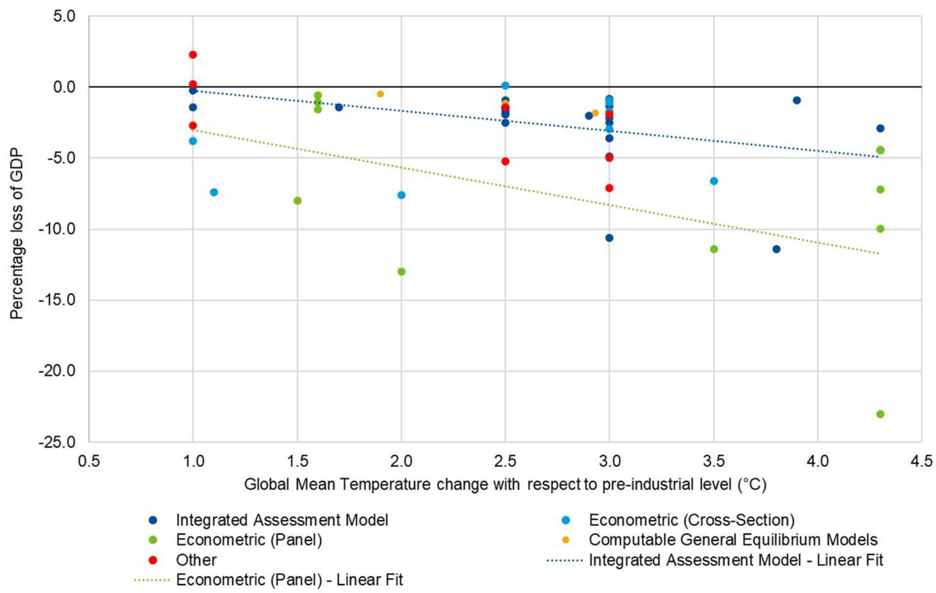
**Estimating adaptation benefits is difficult and characterized by large uncertainties, but there is growing consensus that benefits are large.** Sectoral studies report climate adaptation returns (benefit-cost ratios) as high as 100 to 900 percent (Hallegatte, Rentschler, and Rozenberg 2019; Global Center on Adaptation [GCA] 2018). For example, long-term savings from investment in resilience and coping mechanisms can reach 300 percent for droughts and 1,200 percent for storms in sub-Saharan Africa (IMF 2020a). Large benefits of investing in adaptation are also found in other regions (Asian Development Bank 2013; Ahmed and Suphachalasai 2014; Westphal, Hughes, and Brömmelhörster 2015; Agarwal and others 2021; IMF 2021a; Duenwald and others, forthcoming). These extremely high returns can be surprising. They cover programs such as disaster preparedness and public health measures with low costs and high benefits. They can also be found when adaptation is about marginal shifts in production, such as when farmers switch crops (Massetti and Mendelsohn 2018), or when improvements in building design helps prevent the collapse of large infrastructure.

**As total investment in adaptation increases, adaptation costs are expected to increase faster than benefits, eventually leading to smaller net benefits.** It is useful to distinguish between marginal and average returns to adaptation. As for many other investments, there is evidence that investment in adaptation may have declining marginal returns. The literature uses macroeconomic simulations over the entire century to estimate global average returns for the “optimal” level of adaptation. These models assume diminishing returns of adaptation investment, from high initial levels down to zero for the last investment projects at the optimum. Results point to high average returns, from 80 to 100 percent (De Bruin, Dellink, and Tol 2009; Bosello, Carraro, and De Cian 2010; Agrawala and others 2011). This is higher than typical average returns of investing in standard infrastructure in countries with large investment gaps, which is estimated to be between 15 and 20 percent (see Berg and others 2012 for a literature review).

**As direct evidence on the benefits of adaptation is limited, useful insights can be inferred from estimates of climate change costs that use different assumptions on adaptation.** Figure 1 provides a review of climate costs estimated under various methods. Linear trend lines highlight average costs respectively from integrated assessment models (IAMs) and panel econometric studies at different levels of global warming. IAMs produce consistently lower economic costs at each level of warming because they include a substantial amount of adaptation, whereas panel econometric studies include limited or no adaptation at all. As a result, costs of climate change are roughly twice as large with panel econometric models than with IAMs. As costs estimated with IAMs include a larger range of hazards than panel econometric studies, the comparison may underestimate the benefit of adaptation (see Annex 1 for a review of methods and limitations, and Annex Table 1.1 for a list of studies).

**While Figure 1 is based on a comprehensive literature review of global climate change cost estimates, all studies share limitations that likely underestimate total climate change costs.** None of the studies considers the cost from crossing climate tipping points (for example, quick melting of the Greenland Ice Sheet) or from societal collapse (for example, mass migration and war), and coverage of nonmarket impacts is limited (for example, biodiversity loss). It is unclear how effective adaptation can be to limit the cost of these large impacts. Furthermore, these estimates are global costs expressed as a percentage of global GDP. Costs in developing countries and in small vulnerable economies are much larger as a percentage of their national GDP. See Annex 1 for a discussion of the literature.

**Figure 1. Climate Change Costs and Estimation Methods**




Source: Staff elaboration compiled from surveys in Tol (2009, 2014), Kahn and others (2021), and Howard and Sterner (2017).

Note: Global mean temperature change with respect to 1850–1900 and percentage global loss of GDP with respect to a scenario with no climate change in the year in which the temperature level is reached. Different colors denote different methods. The trend lines are a linear fit of damages estimated with integrated assessment models and panel econometric studies. Estimates of damages for warming greater than 5°C are not included because impacts are highly speculative at those levels of warming and unlikely to be observed in this century. Studies that provide estimates of damages only for some regions and that use the social cost of carbon as a metric of climate change costs are not included because they are not easily comparable. See Annex 1 for details and a list of studies included in the figure.

**Reaping the full benefits of public adaptation projects will take time and capacity building.** Both micro- and macro-level estimates of adaptation benefits tend to underestimate the cost of adaptation because they assume optimal design and execution. Large investments may face obstacles because benefits accrue in the long term while costs are upfront (Guo and Quayyum 2020). Large adaptation returns are estimated on specific projects (for example, early warning systems, incremental building upgrades), can take years to materialize (when disaster losses are avoided), and assume perfect implementation. In practice, the execution of sizable public investment in adaptation will at least face the same challenges as other public investments with typically large efficiency losses (IMF 2015, 2020b), and with possibly larger losses, because authorities are building capacity in this new area.

## Defining Adaptation Investment Needs

**Investment needs in climate change adaptation can be defined as the difference between optimal investment levels with and without climate change** (strict additionality definition). Quantification of adaptation needs requires defining optimality and developing economic models that can derive optimal investment levels under scenarios with and without climate change (see Annexes 1 and 2 in Note 1 for a synthesis and discussion of climate and socioeconomic scenarios used in the literature).

**This definition can be applied to identify planned or executed climate change adaptation spending.** For specific projects in practice, a simplified application is to count the projects that are only implemented because of climate change and, for those who would be implemented anyway, to count the

additional cost incurred to adapt them to climate change impacts. This definition can be relevant to track climate change adaptation spending in national budgets and in international aid.

**The adoption of strict additionality to define climate change adaptation needs excludes the cost of closing the gap to achieve an optimal level of adaptation to current climate conditions.** This distinction can have important implications in countries that are far from optimally adapted to the current climate. For these countries, investment needs to make their economy more resilient and better adapted to the current climate can be substantial relative to (or even exceed) the additional cost of strengthening adaptation investments to address the additional effects from climate change. For example, some flood-prone areas could benefit from investing in protective infrastructure under current climate conditions, and optimal adaption to climate change may imply additional costs for stronger infrastructure. The additional costs implied by climate change can be small compared to the cost of the project designed for current conditions.

**A broader definition of adaptation needs that includes adaptation to the current climate should still exclude investment needs that are primarily driven by other development needs.** Adaptation costs can be hard to separate from other development needs when development and adaptation are self-reinforcing. For example, education has sometimes been cited as an adaptation cost because climate change makes education investment even more needed, especially for the most vulnerable. A more educated population can learn faster about new technologies and can transition more easily to climate-resilient practices and sectors. However, climate change will likely have negligible effects, if any, on education goals. Therefore, the bulk of education needs should not generally be counted as adaptation needs. In specific cases, a fraction of the spending that is primarily directed to other goals can be counted toward adaptation needs, but only when specific costs can be related to climate impacts. This would be the case when investing in education infrastructure incurs additional costs because buildings need to be made more resilient to new climate extremes. For example, cyclones can inflict heavy damages to schools and prevent their use for a long time (IMF 2020e). If tropical cyclones intensify in Tonga due to climate change, for example, the increase in the cost of protection is attributable to climate change and satisfies the requisite of additionality.

**Alternative definitions that would classify investments that are primarily driven by development needs as adaptation needs would lead to very large and potentially misleading estimates of adaptation gaps.** Such definitions may lead countries and international donors to double count some development needs.

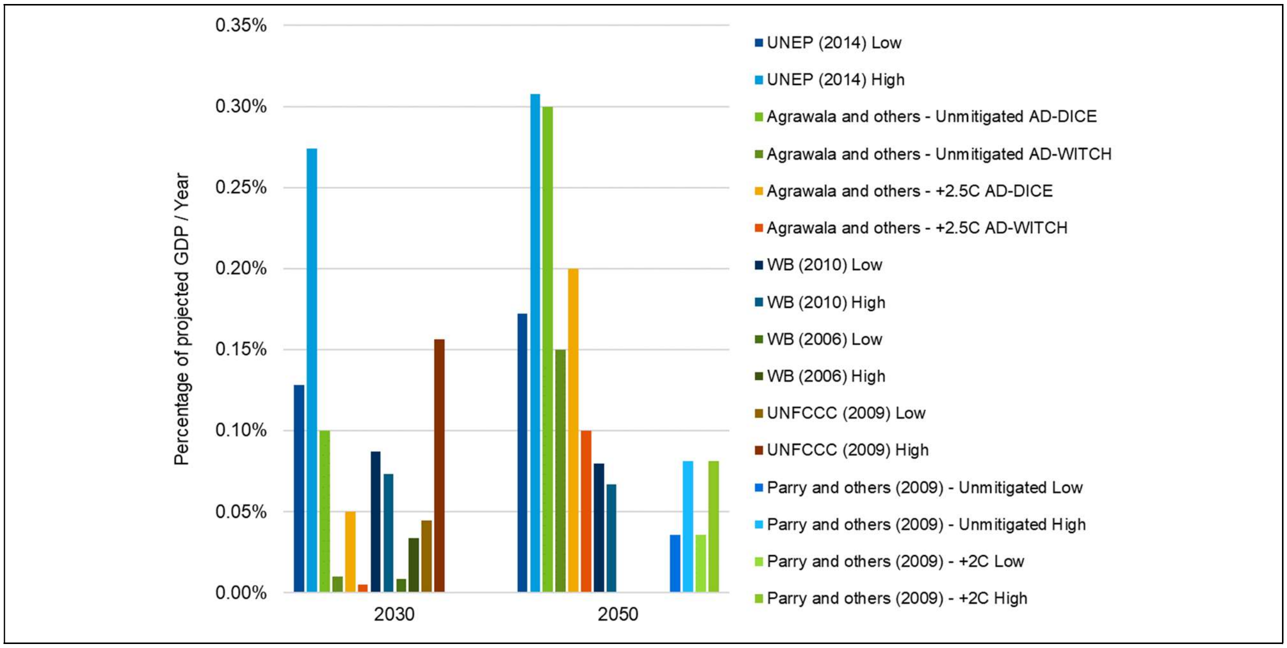
### Estimates of Adaptation Needs

**Global public adaptation needs are estimated at around ¼ percent of world GDP per year on average but may not be representative of the challenge faced by many countries.** Estimates in the literature indicate that global investment needs in climate change adaptation for developing countries range from insignificant amounts to $300 billion annually in 2030 and between $50 billion and $500 billion annually in 2050. As a share of average annual global GDP, investment needs in 2030 range from almost nothing to about 0.3 percent of projected 2030 global GDP per year (Figure 2). In 2050, investment needs increase in all studies, even after accounting for global economic growth. These estimates are highly uncertain because they rely on just a few studies and they are not recent. The wide ranges can be explained by differences in the definition of needs and in assumptions about future development and climate change (Box 1).

**Countries' bottom-up self-assessment of their needs tends to be larger, even as high as 100 or 250 times higher than global averages for some lower-income vulnerable countries.** The 46 countries that included adaptation cost estimates in their Nationally Determined Contribution estimated a total, collective cost for these measures of $783 billion by 2030 (or about 1.5 percent of their GDP annually from 2015 on average) (Buchner and others 2019).

**Small island countries face among the greatest challenges.** Climate change effects are projected to entail very large costs for all small island countries, and sea-level rise threatens the very existence of some small low-lying islands (World Bank 2017). For example, estimates of cumulative resilience needs for Dominica, Fiji, Grenada, and Tonga range from 100 to 500 percent of GDP, although some of these needs might be defined very broadly (Grenada 2021; IMF 2020e, 2021b; Government of the Republic of Fiji 2017).

## Figure 2. Estimates of Global Investment Needs in Adaptation




Source: Staff meta-analysis based on the studies cited below..

Note: In 2014, the United Nations Environment Programme (UNEP 2014) started an "Adaptation Gap Report" series in which they publish annually a review of the literature that estimates investment needs in adaptation. The literature reviewed has not changed over the years and consists of three studies: United Nations Framework Convention on Climate Change (UNFCCC; 2009a), World Bank (WB; 2010a, 2010b, 2010c), and a study led by the Organisation for Economic Co-operation and Development in 2009–2011 (Agrawala and others 2011). Figure 2 reports the UNEP review and estimates in the studies reviewed by the UNEP separately.

### Box 1. Differences and Limitations of Estimates of Global Adaptation Needs

**Estimates of adaptation investment needs can vary widely because of different definitions of adaptation needs and different assumptions about future development levels.** Some differences can be attributed to the inclusion or exclusion of broad development investments that would be needed even without climate change (Hallegatte and others 2018). Some studies assume more baseline development, implying lower baseline climate vulnerability and therefore lower adaptation needs, while others do the opposite and obtain larger needs. For example, studies might differ in how much progress in public health is assumed, with a direct impact on adaptation estimates. Public health capacity is beneficial to address climate change as it can reduce infectious diseases faster than climate change makes them worse. However, public health would be expected to improve as economies grow, even without climate change, and different studies include a lower or greater share of future public health investment in adaptation needs (Tol, Ebi, and Yohe 2007).

**To a lesser extent, differences in estimates of adaptation needs also stem from different assumptions about adaptation goals, climate change, and adaptation technology.** Some studies assume economic efficiency to define adaptation goals. Other studies aim at achieving other goals, such as preserving the current level of risk or reducing climate damages to zero. Studies can also make different assumptions about the returns to adaption policies and about the extent of future warming and climate change impacts.

**Beyond estimates of global adaptation needs, granular analyses of climate vulnerabilities at the national and local level are also essential.** Climate can vary tremendously at the national and local level. In addition, economic activity tends to be very unevenly distributed over space and can rely on well-functioning critical infrastructure (for example, the main road connecting an otherwise isolated production center). As a result, key vulnerabilities emerge where climate risks intersect with densely populated areas or focal infrastructure (Hallegatte and others 2019).

**The multifaceted impacts of climate change are challenging and explain the scarcity of comprehensive assessments of national adaptation needs and cross-country comparisons.** While studies that focus on one sector or one source of climate risk abound, rigorous independent studies that consider adaptation gaps across sectors and risks at the national or regional level are less frequent, even in advanced economies (the review in Organisation for Economic Co-operation and Development 2021 points to some exceptions). Country documents such as National Adaptation Plans (Note 3), Disaster Resilience Strategies (for example, for Dominica and Grenada; IMF 2021b; Grenada 2021), or the joint IMF-World Bank Climate Change Policy Assessments also provide useful references (for example, IMF 2020e), as should the forthcoming World Bank Country Climate and Development Reports and IMF Climate Macroeconomic Assessment Program Reports.

**In this Note, we illustrate the magnitude of adaptation needs and cross-country heterogeneity by focusing on two types of adaptation investment: strengthening physical assets and investing in coastal protection.** Knowing the size of adaptation investment needs is often critical for the policymakers in charge of designing affordable adaptation strategy.

**Strengthening climate resilience of physical assets is one of the essential aspects of addressing adaptation gaps.** Among various adaptation policies, investing in infrastructure resilience is estimated to be the costliest and essential to safeguarding inclusive growth (GCA 2018; Hallegatte and others 2019).

Other costly adaptation policies include better water management systems, dryland agriculture, and disaster relief.

**Starting by adapting infrastructure to existing climate risks can be a practical way forward.** Even the costs of adapting to the present climate can be challenging to estimate because they require knowledge about the current resilience of infrastructure, the optimal level of resilience, and the costs of upgrading infrastructure. With these challenges in mind, we provide a systematic analysis of the magnitude of cross-country adaptation needs by focusing on existing gaps and on specific climate risks—floods and storms—which are estimated to be the major sources of infrastructure disruption (Lange and others 2020). Our estimation approach relies on the identification of exposed infrastructure by crossing two detailed global maps, on the location of natural hazards and on the location of infrastructure, by assuming different levels of initial resilience for different country income groups (Annex 2). We estimate the cost of strengthening public infrastructure, both existing assets and infrastructure projects, to improve their resilience to floods and storms. We do so by estimating the share of assets that needs strengthening and by applying strengthening unit costs.

**Strengthening exposed existing and projected public assets could cost, respectively, 0.2 and 0.4 percent of GDP annually for 2021 to 2025, with large disparities across countries (Annex 2).** The estimates correspond to strengthening that was estimated to have benefit-to-cost ratios above one in a very large range of scenarios (estimates of the optimal level of strengthening would be much harder to derive at the global level). Figure 3, panel 1, shows that emerging markets face the largest costs, followed by low-income countries. Large costs result from the combination of a base effect (emerging markets have more assets and more investment projects than low-income countries) and greater exposure (infrastructure in emerging markets and low-income countries are more likely to be exposed). A similar exercise shows that the costs of improving asset resilience in the private sector could be twice as high, but somewhat more evenly distributed across income groups (Annex 2).

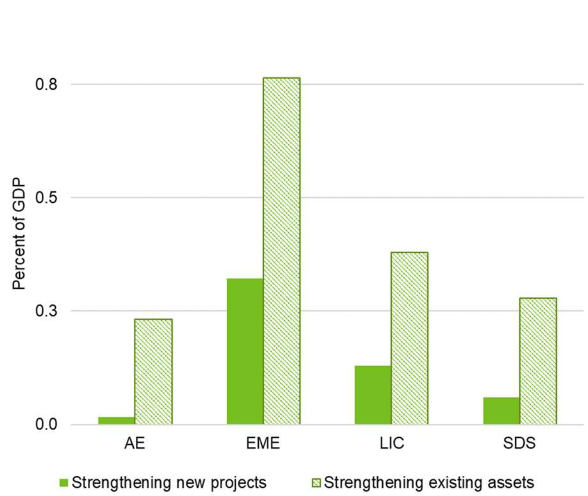
**Other recent IMF research estimates costs of similar magnitude.** Studies find that over the next decade adaptation needs in sub-Saharan Africa range between US$30–50 billion (2–3 percent of regional GDP) (IMF 2020a) and in some Middle East and Central Asia countries between 0.1 percent and 3.3 percent of GDP (IMF 2020c; Duenwald and others, forthcoming). In small islands exposed to both tropical cyclones and sea-level rise, adaptation costs can be very large (Grenada 2021; IMF 2019a, 2021a, 2021b, 2021f).

**Where future risks are better identified, like those stemming from sea-level rise, countries can and should develop adaptation plans now.** When possible, a gradual approach to land planning that bans new construction close to exposed coasts can incentivize the relocation of assets at low cost. In some, but not all, places, it can be efficient to build infrastructure for coastal protection. In some places, restoring or planting mangrove forests can be an efficient nature-based protection with environmental cobenefits (GCA 2018). Coastal protection costs have been extensively studied and countries can start deciding now where and when to build protective infrastructure and how to finance such construction.

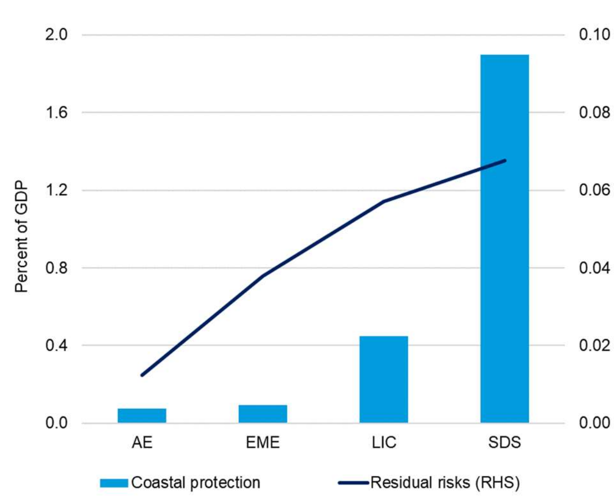
**Coastal protection needs are estimated at 0.1 percent of GDP annually for 15 years, with much larger costs for small developing states in the Pacific and the Caribbean.**[1] Figure 3, panel 2, provides a second illustration of cross-country adaptation needs focusing on the cost of coastal protection. It reports estimates based on Nicholls and others (2019). Protection needs are defined as the cost of reaching a protection level that minimizes the sum of construction costs, maintenance costs, and residual flood damage to assets to 2100 (Annex 2). Figure 3, panel 2, reports the average construction and maintenance costs in the first 15 years where most of the new dikes would be expected to be built. Costs vary significantly and tend to be larger for low-income and small developing states. Even among small developing states, there are large disparities as some small island developing states face double digit costs. Coastal protection is estimated to help contain (and sometimes lower) residual risks to low levels (at or below 0.2 percent of GDP).

### Figure 3. Public Sector Adaptation Costs to Selected Current and Future Climate Risks

1. Annual Costs of Strengthening Infrastructure Resilience to Current Storm and Flood Risks




2. Annual Costs of Coastal Protection Against Future Sea-Level Rise




Source: Hallegatte and others (2019); Hallegatte, Rentschler, and Rozenberg (2019); Rozenberg and Fay (2019); Nicholls and others (2019); IMF, Capital Stock 2019 Dataset; IMF, World Economic Outlook database; and staff calculations.

Notes: AE = advanced economies; EME = emerging market economies; LIC = low-income countries; SDS = small developing states.

## Addressing Challenging Adaptation Needs

**To keep adaptation investment affordable, it is crucial to monitor asset conditions and ensure efficient selection, execution, and maintenance of investment projects.** For example, physical assets that face small climate risks or that are less essential to the rest of the economy may not need

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[1] The estimation of coastal protection costs was done independently from the other study on strengthening costs, implying that there could be some overlap. The simple average of coastal protection needs across all countries is estimated at 1 percent of annual GDP.

strengthening. Assets in areas that face overwhelming climate risks can be relocated, possibly rebuilt, when cost effective. Strengthening governance to avoid substitution with cheaper design or lower-quality material at the construction stage and to avoid skimping on maintenance is essential to save on future repair or replacement costs.

**Financing large adaptation costs will challenge many countries' fiscal space.** This is especially the case for lower-income countries, which have typically not contributed much to global warming yet suffer from the largest damages, are burdened with large and competing development needs, and typically have limited fiscal space (IMF 2018, 2020a, 2020b, 2021a, 2021d, 2021f). Financing adaptation costs will require domestic revenue mobilization, a reprioritization of investment plans or other spending, the support of the donor community, or a combination of all these sources (Cevik and Nanda 2020; IMF 2013; Cohen and Jalles 2020). Table 1 lists countries with high adaptation costs that may face financing challenges.

### Table 1. Adaptation Costs and Pre–COVID-19 Fiscal Space

| | At least some fiscal space or moderate/low risk of debt distress | At-risk fiscal space or high risk of debt distress |
|---|---|---|
| Above-median strengthening costs | Azerbaijan, Bangladesh, Botswana, China, Colombia, Dominican Republic, Indonesia, Japan, Korea, Mauritius, Mexico, Netherlands, Peru, Philippines, Thailand, Vietnam | Angola, Costa Rica, Fiji, India, Iran, Lao People's Democratic Republic, Malaysia, Pakistan, Uganda |
| Below-median strengthening costs | Algeria, Australia, Canada, Chile, Czech Republic, Denmark, Estonia, France, Ireland, Israel, Kazakhstan, Latvia, Lithuania, Morocco, New Zealand, Poland, Qatar, Russia, Saudi Arabia, Singapore, Slovak Republic, Sweden, Switzerland, Turkey, United Kingdom,Germany, United States | Argentina, Brazil, Egypt, Hungary, Italy, Jordan, Lebanon, Nigeria, Oman, Slovenia, South Africa, Spain, Swaziland, Uruguay |

Sources: Hallegatte and others (2019); Hallegatte, Rentschler, and Rozenberg (2019); IMF staff reports; and staff calculations.

Note: Fiscal space assessments are estimated for advanced and emerging market economies and are based on the debt sustainability assessment from the last published IMF Article IV report; risks of debt distress are estimated for low-income countries and are taken from the last published debt sustainability assessment. These assessments were done pre–COVID-19 and do not reflect developments since the outset of the pandemic. Median total strengthening costs are estimated at 0.2 percent of GDP. Missing countries are absent because of the lack of data.

**International financing flows toward adaptation are hard to track and fall short of commitments and needs.** The financing of adaptation-related activities is often embedded in projects that are not purely related to adaptation, which makes adaptation finance challenging to track. Furthermore, data on private sector and within-country public sector investment is often missing (Richmond and others 2020). In 2009, developed countries committed to jointly mobilize $100 billion per year by 2020 in climate finance for action in developing countries, including but not only for adaptation (UN Framework Convention on Climate Change 2009b). Adaptation needs are estimated to be around $0.25 trillion per year by the midcentury (Figure 2). Yet studies identify only $22 billion in adaptation financing flows in 2015 to 2016 and $30 billion in 2017 to 2018 on average (Buchner and others 2019). Further, annual aid for adaptation from official creditors to low-income developing countries was just $10 billion in 2018 (IMF 2020c).

**The disbursement of international aid for adaptation is hampered by demanding conditionalities and low capacity in targeted countries (Box 2).** Donors often require that some PFM standards are in place before disbursing financial support. However, the countries that need support and that would benefit the most from it also tend to have PFM standards below requirements and little scope to improve them on a timely basis. While strengthening PFM is essential to ensure effective progress on adaptation (Note 3), unachievable requirements might hold up all progress if donor financing is necessary.

**There is a strong case for additional international support toward vulnerable countries based on needs and equity considerations.** The cost analysis makes clear that adaptation needs tend to be higher in countries with less fiscal space, lower institutional capacity, and a larger share of the global poor. For many of these countries, securing multilateral and bilateral aid is essential as their needs exceed revenue mobilization potential and Sustainable Development Goals require greater, not less, spending in other areas. It will also be important to improve their project design and implementation capacity. Also, given that these countries did not cause global warming, there seems to be a strong case for additional (that is, that does not crowd out existing) support from the donor community (Box 2). International organizations such as the IMF could play a useful role in supporting these countries via capacity development and catalyzing financial assistance.

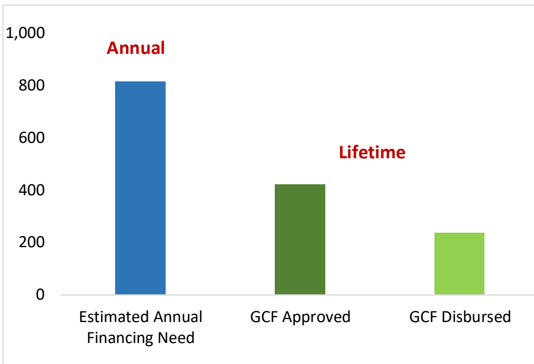
**International support for climate adaptation investment can be a cost-effective alternative to disaster relief for international donors.** Increased spending in adaptation investment can lead to a net reduction of total spending for donors that already provide support for disaster alleviation by reducing climate change risks before they materialize. The scope for savings should be assessed on a case-by-case basis and not taken for granted, but there can be scope for large efficiency gains in protection. These gains are particularly pronounced in the case of small island states. Melina and Santoro (2021) show that the cumulated discounted fiscal savings in post-disaster relief from an investment program to increase resilience of public infrastructure in the Maldives are more than double the extra spending to finance it. The recent Climate Macroeconomic Assessment Program pilot estimated savings of a similar magnitude in the case of Samoa, highlighting that savings are increasing in the expected intensity of natural disasters (IMF, forthcoming).

### Box 2. Unlocking Access to Climate Finance for Pacific Island Countries[1]

**Pacific island countries (PICs), which are globally among the most exposed to climate hazards, have an urgent need to invest in climate adaptation.** IMF (2021c) estimates that PICs need almost $1 billion every year over the next 10 years, or about 6½ to 9 percent of GDP on average, to upgrade and retrofit public sector infrastructure and coastal protection systems. However, access to climate finance has been disappointing so far, and PICs face many challenges (Fouad and others 2021).

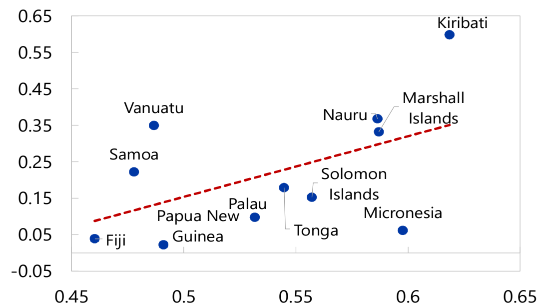
**These critical investment needs notwithstanding, PICs generally have limited fiscal space, low administrative capacity, and underdeveloped private sectors.** As such, they are typically constrained to rely on bilateral partners, or grant-based instruments from multilaterals and major climate funds (such as the Green Climate Fund [GCF]). Thus far, PICs have faced significant challenges in getting accredited for direct access from facilities such as the GCF due to low capacity in public financial management (PFM). Unfortunately, the speed at which sufficient PFM capacity for direct access could be developed in PICs is inconsistent with the speed at which these countries need to adapt to climate change.

**Figure 2.1. Green Climate Fund Financing versus Estimated Annual Adaptation Needs for Pacific Island Funding**
*(Millions of US dollars)*




Source: Green Climate Fund (GCF); and IMF staff calculations.

**Figure 2.2. Exposure to Climate Change and Approved Climate Adaptation Funding**
*(Share of GDP)*




Source: Staff elaboration based on Chen and others (2015) and Organisation for Economic Co-operation and Development (2021).

Note: Tuvalu is not shown on chart, as it is an outlier in terms of amount of approved climate adaptation funding as percent of GDP, at over 200 percent.

**Indirect access to GCF through international accredited entities (such as the World Bank, Asian Development Bank, or the UN Development Programme) has been more successful for PICs, with faster approvals and larger projects.** However, even with attempts to streamline requirements, the total amount approved by the GCF for all PIC projects since 2015 has only been about half of the estimated *annual* adaptation needs for the region. And out of this amount, only about half has actually been disbursed (Figure 2.1). The good news is that the countries more exposed to climate change have, on average, had more funds approved for climate adaptation (Figure 2.2) (Chen and others 2015; Organisation for Economic Co-operation and Development 2021). Nevertheless, faster approvals and disbursements are urgently needed for all PICs.

**To meet the challenge of addressing climate adaptation needs, PICs, climate funds, and the IMF could work better together.** PICs could strategically decide which of their priority projects are best financed through bilateral channels, which are better suited for climate funds, and obtained through international or direct access. Where resource constraints allow, PICs could establish dedicated climate units, preferably within ministries of finance, to coordinate the financing of priority climate projects. PICs should continue to build PFM capacity, with a focus on strong audit, robust control frameworks, and strengthened public investment practices, that are at the center of GCF accreditation requirements. Climate funds could consider further streamlining accreditation and approval requirements for small and fragile countries and consider increasing reliance on ex post monitoring. The IMF could further integrate analysis of climate issues into macroeconomic surveillance and continue to provide capacity development support to countries to build stronger PFM and public investment management practices.

[1]This box was prepared by Natalija Novta (Asia and the Pacific Department) and Gemma Preston (Fiscal Affairs Department).

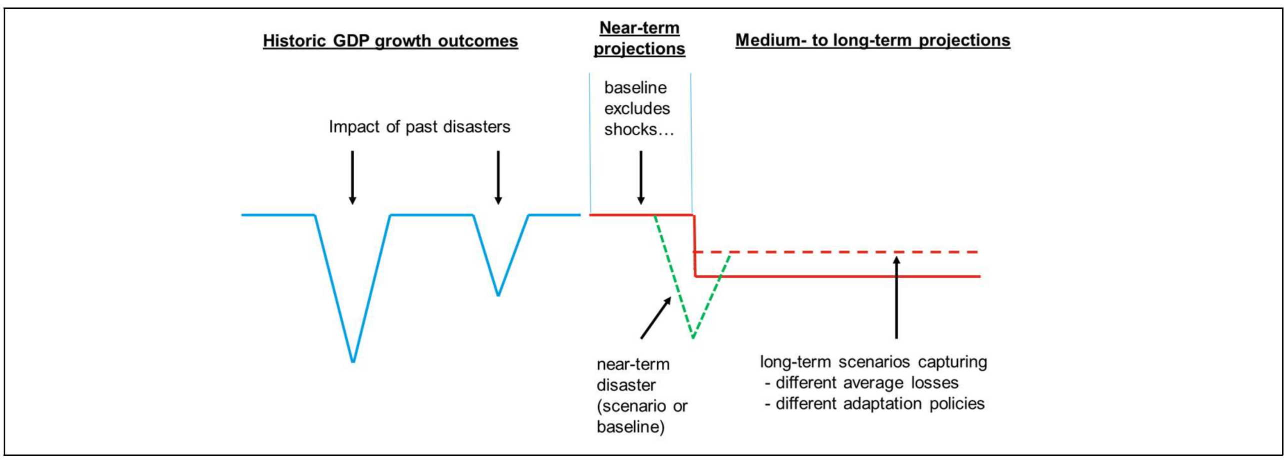
## Integrating Adaptation into Macro-Fiscal Frameworks

### Macro-Framework Implications of Climate Risks and Adaptation Policies

**Macro-fiscal policies should be supported by frameworks that reflect climate risks and envisaged adaptation policies.** IMF guidance for both low-income and market-access countries recommends analyzing the impact of climate when assessing fiscal sustainability (IMF 2016, 2018, 2021e). For vulnerable countries, the success of macro-fiscal policies can be compromised by present and future climate risks. Additional specific measures may be needed to cope with those risks (for example, the accumulation of fiscal buffers).

**It is useful to study separately the macro-fiscal implications of a weather-disaster shock and of cumulative climate change effects (Figure 4 and Box 3).** The short-term macro forecast baseline may not include the impact of weather disasters as these risks could instead be covered by alternative shock scenario analyses. Temporary-shock scenarios developed using short- to medium-term projections (3 to 10 years) help assess structural and financial protection strategies and prepare for post-disaster needs. At longer time horizons, macro-framework projections could be updated to reflect the cumulative effects of climate risks, covering both slow-moving gradual changes in average climate conditions and cumulative changes in extreme weather. This is a complex exercise that requires capacity building and a continuous dialogue between policymakers, economists, and scientists. It would be equally recommended to assess the cumulative impact of these changes on key macro-fiscal variables (such as potential growth, spending, and debt). Scenarios can also be useful to reflect risks about cumulative effects.

### Figure 4. Illustrative Growth Projections/Scenarios with Disaster Impacts




Sources: IMF 2016; and staff modifications.

**The implications of weather disasters can be macro-critical and are best examined with short- to medium-term shock scenarios (IMF 2016)**. Relevant scenarios would examine the economy's response to a temporary weather disaster of relevant scale (either based on the average size over 10 to 20 years or based on tail events with recurring frequencies of 50 or 100 years). These scenarios would determine the adequate size of buffers and risk-reduction strategies as these cannot be derived from historical averages that dilute severe disaster impacts. Scenarios would help to assess medium-term fiscal and debt sustainability and supplement the analysis of risks to growth potential.

- ***Natural disasters reduce GDP through multiple channels.*** By destroying assets and harming human lives, disasters cut production inputs (Acevedo 2016; Acevedo and others 2018). Additionally, disasters have adverse effects on productivity. Strong complementarities between assets imply that the destruction of some infrastructure can lower the productivity of other assets. For example, the destruction of power infrastructure will make it difficult to operate plants, damages to transportation networks prevent labor and intermediary inputs getting to where they are needed, and hampered communication infrastructure aggravates the misallocation of inputs. Decreasing returns to scale also imply congestion effects (when surviving infrastructure is overwhelmed) that reduce productivity further.
- ***Humanitarian relief and reconstruction to address disrupted productivity have large multipliers.*** In addition to moral reasons, humanitarian relief is essential to avoid permanent adverse effects on labor. Fast reconstruction is justified by high returns exceeding predisaster levels: restored assets have positive externalities as they allow other assets to return to normal operations and help to ease congestion effects.
- ***Natural disasters tend to worsen the fiscal balance ex post in several ways* (IMF 2019b).** The drop in GDP reduces government revenues while grants from the international community may provide some relief. Lifeline support to affected populations (provision of public services, social assistance, in-kind transfers) and public and private sector reconstruction support (grants to other government units, transfers) lead to increases in current expenditure. The reconstruction of damaged public assets raises capital expenditure, whereas disruption may slow the execution of other public investment projects. This creates "explicit" liabilities (impact on government-owned assets) and "implicit" liabilities (expected government support even in the absence of formal contract). Below the line, financing needs are likely to trigger additional borrowing. The destruction of assets and borrowing damage the government balance sheet.
- ***Assessing disaster risks to the baseline should inform the adequate size of fiscal buffers and spending on risk-reduction infrastructure.*** Addressing the consequences of large climate shocks requires ex ante policy adjustments. For example, ex post financial and liquidity constraints could be addressed ex ante with additional fiscal buffers (self-insurance) or by contracting contingent financing instruments (see also Note 3; IMF 2021a). Examining liabilities, both explicit and implicit, can inform financing plans and also prepare for post-disaster response. In some cases, additional investment in risk-reduction infrastructure to limit ex post liabilities is also desirable, both for countries and international donors (IMF 2019a).

**For most countries until 2030, weather disasters are not expected to be significantly different from those already experienced (Note 1), but a careful re-evaluation of existing risks can be beneficial.** If the effect of present climate risks is already fully accounted for in growth projections, it is unlikely that a reduction in GDP growth baseline is needed. However, in some cases, a re-evaluation of recent local data on the materialization of climate risks and on socioeconomic changes (for example, change in land use with implication for climate impacts and new developments in areas more at risk) may predict greater impact from disasters than previously envisaged in the baseline. Such cases would warrant lowering GDP potential for some years. Alternatively, the updated risk assessment and new opportunities could lead a country to invest in reducing these climate risks and protect, or possibly improve, future growth potential (Box 3).

**At longer horizons, climate change is projected to create new challenges, some of which will not be caused by weather disasters.** Permanently higher average temperatures and different rainfall patterns will lead to slow-moving but pervasive changes in productivity (for example, new tourism and

agricultural conditions). Sea-level rise will transform vast coastal areas, creating challenges for coastal cities and infrastructure, and threatening the existence of small low-lying islands. Previously unexperienced droughts and floods can put hydropower plants under stress, while power demand may simultaneously soar due to increased use of air conditioning. All significant climate change effects, including those that won't take the form of disaster episodes, should be reflected in macro-frameworks.

**Climate change could create large risks that would affect long-term debt sustainability.** In long-term scenarios that assume little or no climate change mitigation, the literature predicts that vulnerable countries will have significantly lower GDP per capita levels by 2050 relative to a baseline without climate change (Mendelsohn, Dinar, and Williams 2006; Cevik and Nanda 2020; Cevik and Jalles 2020, 2021; IMF 2021b, 2021e; Grenada 2021) within the time horizon considered in debt sustainability assessments. Country or regional studies can be leveraged to identify areas of vulnerabilities (sometimes with impact estimates) and can be supplemented by studies that analyze specific risks in depth (for example, for temperature increase, see Kahn and others 2021; for sea-level rise, see Desmet and others 2018; and for the Caribbean and Pacific Islands, see Simpson and Harrison 2010 and Asian Development Bank 2013).

**Long-term sustainability would be best assessed with long-term scenarios accounting for the cumulative effects of climate change and underpinned by coherent adaptation policy narratives.** Macroeconomists can use sensitivity analysis and explore the implications of alternative macro-fiscal and climate projections in stress scenarios using relevant studies from the literature. It would be useful for these scenarios to explicitly account for adaptation policies. This can be illustrated by the case of sea-level rise where damages can be estimated to be large, but adaptation such as relocation or coastal protection investment can reduce damages effectively. For example, without coastal protection against sea-level rise, Suriname is estimated to incur annual losses gradually increasing to around 1¾ percent of GDP by 2080 (Simpson and Harrison 2010). Data from a follow-up study suggest that investing in coastal protection of 2 percent of GDP for 10 years would contain these losses to no more than 0.1 percent until 2100. Coastal protection is not the only adaptation strategy. Desmet and others (2018) show that relocation, in the form of migration and the rise of new productive clusters away from exposed coasts, is an effective adaptation strategy and can reduce GDP losses by a factor of 10. For Suriname, their model predicts annual costs below 0.3 percent of GDP and migration outflows that would reduce population by 2.4 percent by 2200. Taken together, these studies highlight the important role of adaptation policies in long-term scenarios, the need to explain adaptation assumptions in projections, and suggest that a well-planned gradual approach starting now can be cost effective.

**Climate change and adaptation policies will impact inequality.** Within countries, climate effects tend to have a disproportionate effect on the poor (Hallegatte and others 2016a). There is also some evidence that adaptation investment can reduce inequality (as done with Debt, Investment, Growth, and Natural Disaster [DIGNAD] in IMF 2020a) but more work is needed to better understand the distributional impact of adaptation.

### General Equilibrium Models of Adaptation to Analyze Growth-Debt Trade-Offs

**General equilibrium (GE) models are useful to determine whether development plans, including adaptation, and financing strategies are coherent.** Investments in adaptation deliver benefits, but they can be costly. In particular, costly investment in resilience puts strain on public budgets but shores up growth when natural disasters occur. Therefore, general equilibrium models can be useful to assess whether specific adaptation strategies are sustainable under a plausible calibration of key economic relationships and climate shock realizations.

**GE models can also be used to compare the costs and benefits of reform packages.** Reforms aimed at protecting the economy from climate risks can be combined and supported by supplementary measures. The success of protection strategies can hinge on these supplementary reforms whose effects are best illustrated with GE model simulations, like those generated by the IMF DIGNAD model (Annex 1). For example, improvements in public finance management can be instrumental for the development and implementation of adaptation investment plans to deliver on expected returns. Lowering borrowing costs by mobilizing concessional financing from development partners or domestic revenues can help to safeguard debt sustainability despite costly adaptation measures. Alternatively, simulations can be used to determine the magnitude of the reforms needed to ensure adaptation plans are sustainable.

**The implications of climate uncertainty for physical protection and insurance policy options need to be analyzed by running large numbers of shock scenarios.** This approach can be implemented by repeating simulations of deterministic models based on different random climate shocks and by stochastic models. Such an approach also encompasses dynamic stochastic general equilibrium (DSGE) models, like the IMF's Flexible System of Global Models (see also IMF 2019b; Cantelmo and others 2019; Fernandez-Corugedo, Gonzalez, and Guerson, forthcoming) that can explicitly incorporate the distributions of climate shocks. This approach improves on dynamic general equilibrium models that are limited to the study of a few specific disaster shock scenarios.

**DSGE models can be used to analyze the long-term implications of climate shocks and shifts in their distribution on investment.** Recent developments in structural modeling (see Levintal 2018; Fernández-Villaverde and Levintal 2018) provide a way to evaluate how the distribution of climate shocks affects macroeconomic outcomes. For example, Cantelmo, Melina, and Papageorgiou (2019) assume that agents' expectations about weather-related disaster shocks affect the stochastic steady state of their model and find that the higher expected frequency of natural disasters hinders private investment spending even in the absence of an actual disaster realization, as the return on investment is expected to be lower, and thereby contribute to aggravate the effect of climate change on GDP.

**DSGE models are useful to assess welfare trade-offs of climate change policies (Box 4).** Although climate change is associated with substantial welfare losses (Donadelli and others 2017), policies designed to counter its effects do not necessarily lead to higher welfare outcomes. Financing adaptation investment through taxes, for instance, also includes some adverse effects. In this case, adaptation investment improves social welfare by cushioning the economy from the impact of climate change but also produces a welfare loss as higher taxes tend to decrease private consumption and incentives to work. Considering such trade-offs is imperative to the formulation of cost-effective adaptation policies, and this can be facilitated by nonlinear DSGE models. The micro-foundations on which these models are built allow economists to disentangle the channels through which climate change and climate change policies affect labor market outcomes and households' consumption choices and can help with the design of supplementary policy to alleviate negative effects.

**DSGE models can also quantify the effects of stochastic shocks and the expected cost-benefits of adaptation policies that reduce risks, including insurance policy options (IMF 2016)**. For example, DSGE models can be used to calculate the probability that post-disaster financing needs would exceed a particular level in a given year (or group of years) under different insurance options (standard commercial insurance contracts, self-insurance by accumulating savings, state-contingent debt instruments such as catastrophe bonds). Stochastic DSGE models have been coupled with deterministic models to study near term dynamics to study, for example, impacts on income distribution (for example, Guerson, Guo, and Mendes-Tavares 2022).

**The wealth of information provided by DSGE models comes at a cost.** In addition to their stochastic capabilities, DSGE models can typically feature many sectors, including detailed energy sectors, and can be tailored to study distribution issues across heterogeneous agents. However, using, developing, or calibrating these models to new settings requires capacity and time.

**DSGE results can also be very sensitive to model calibration and, as for other models, to the assumed probability distribution of climate variables, which is uncertain and changing.** As discussed in Note 1, analysts can use observed climate risks for scenarios with a time horizon of less than 20 years, possibly updated with observed robust climate trends. For scenarios with a time horizon of between 20 and 30 years, analysts can use all the climate scenarios available in the literature to define probability distributions of extreme weather and other climate outcomes while keeping in mind that these are not objective risks (Note 1). For simulations at very long horizons (more than 30 years into the future), analysts could rely on different combinations of greenhouse gas emission scenarios and socioeconomic scenarios (Note 1).

### Box 3. Malawi: Mainstreaming Climate Change into Macroeconomic Projections[1]

Malawi is one of the most vulnerable countries to climate change in sub-Saharan Africa. Over the past decade, it has experienced severe droughts, floods, and insect infestations. The recent trends in the frequency and intensity of these natural disasters warranted some adjustments to the baseline macroeconomic projections. Post-disaster studies also found that ramping up resilience to climate shocks could contribute to a virtuous cycle of self-reinforcing adaptation and development. Consequently, since 2019, the macro-fiscal implications of climate change have been integrated into the IMF's analysis for Malawi. The following describes one of several approaches which have been applied.

**First**, baseline macroeconomic projections incorporated climate shocks, applying event studies:

- *Near-term real GDP growth* was calculated based on the expected value of growth adjusted for offsetting factors such as the fiscal multiplier effect from public investment and social protection spending. The expected value of growth was based on growth (1) absent any climate shocks (for example, 5 percent) and (2) if a climate shock hits (for example, 3 percent = 5 percent – 2 percent)—calculated as growth absent a shock less the historical drop in growth when a climate shock hits based on event studies (for example, 2 percent).
- *Medium-term real GDP growth* projections factored in the positive impact from resilience-building policies (for example, infrastructure) net of projected disaster impacts—in this case, these were derived from historical data.
- *Inflation* was projected following the same logic as for real GDP growth with adjustments for anticipated monetary policy adjustments and, over the medium term, increased resilience of agricultural production to climate shocks.
- *Public investment social protection* targeting resilience were assumed to increase in line with the latest Post-Disaster Needs Assessments (PDNA). Figure 3.1 provides an example, where, following severe flooding in 2019, the PDNA estimated climate-resilient rebuilding (mainly infrastructure) would cost 4.5 percent of GDP—spread out over five years (Figure 3.1, panel 1). Based on discussions with development partners, assumptions were also made on what they would finance and whether grants or loans would be applied (Figure 3.1, panel 2). Keeping in mind limited fiscal space, the domestically financed portion relied on (1) revenue mobilization, including consideration of a carbon tax; (2) reducing nonpriority spending; and (3)

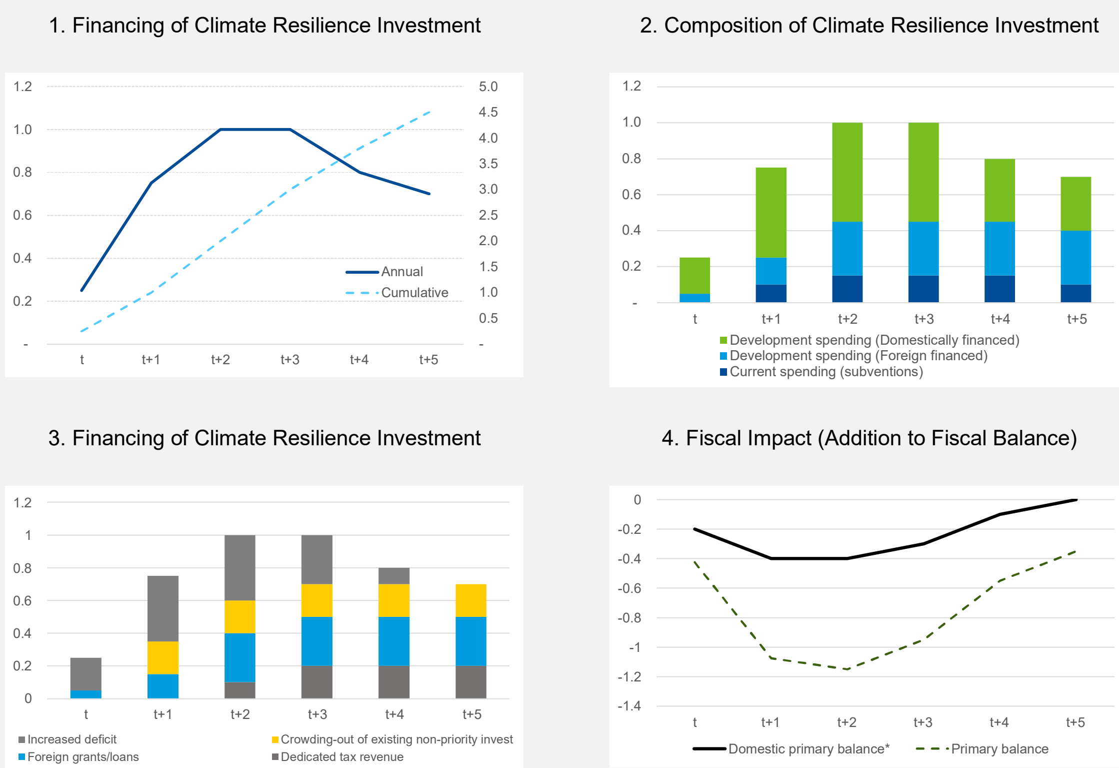
larger fiscal deficits (Figure 3.1, panels 3 and 4)—all of which had implications for debt projections.

- *Balance of payments* effects were a function of assumptions on development partner financing and net exports. Export and import projections applied a similar logic to those for real GDP and inflation, except import projections also relied on the marginal propensity to import related to public investment.
- *Financial sector* impact was assumed to be limited due to the low levels of access to finance in Malawi. Large firms who would borrow from the banking system tend to have already invested in their own resilient infrastructure.

**Second**, Malawi's debt sustainability analysis included alternative tail risks scenarios, where the magnitude of the climate shocks assumed in the baseline were amplified. This helped to assess fiscal space and the adequacy of existing and planned buffers. Moreover, it highlighted the potential for large additional balance of payments and fiscal financing needs.

**Third**, statistical data that would be key to enhancing the analysis was discussed with the authorities. These include macroeconomic and climate data that would enable more sophisticated analysis, including applying dynamic general equilibrium models, vector autoregression models, and model simulations of future climate shocks.

### Figure 3.1. Malawi: Investment Scenario with Fiscal Impacts




Source: IMF staff calculations based on a simulation exercise for Malawi, as of March 2020.

Note: Current primary balance is defined as the sum of planned climate-dedicated taxation, crowding out of investment, and current spending on climate subventions less domestically financed development spending.

[1]This box was prepared by Pritha Mitra, Jung Eun Yoon, and Mai Farid.

**Box 4. Social Welfare in Disaster-Prone Countries**

**Natural disasters take a heavy toll on social welfare in disaster-prone countries.** Disaster-prone countries, which are often low-income developing states, are a subset of all climate-vulnerable countries with a substantially higher probability of experiencing weather-related natural disasters in any given year. Being small in surface, population, or the size of their economy, such countries experience much larger capital damages and economic losses as a fraction of GDP in the aftermath of natural disasters (Centre for Research on the Epidemiology of Disasters n.d.). On average, disaster-prone countries have lower levels of income, private expenditure, and social welfare. Cantelmo, Melina, and Papageorgiou (2019) find that more frequent and powerful weather disasters in these countries cause an average welfare loss equivalent to a permanent reduction in consumption of 1.6 percent.

**In the absence of adaptation, climate change will exacerbate the divergence in welfare and income between disaster-prone and non-disaster-prone countries.** Climate change has the potential to make weather-related natural disasters more frequent and more powerful, putting greater pressure on the social welfare and growth prospects of disaster-prone countries (Intergovernmental Panel on Climate Change 2021, 2022; Gutiérrez and others 2021; Note 1). Macroeconomic models that can simulate uncertainty about weather and economic growth can be used to estimate the effects of changes in the probability distribution of natural disasters, their assumed intensity, or both. For example, Cantelmo, Melina, and Papageorgiou (2019) use a nonlinear dynamic stochastic general equilibrium model with a stochastic steady state to estimate the welfare and macroeconomic effects of an increase in the frequency of natural disasters by 35 percent and an increase of damages per disaster by 82 percent. Under this scenario, they find that the welfare losses from natural disasters increase by a factor of seven.

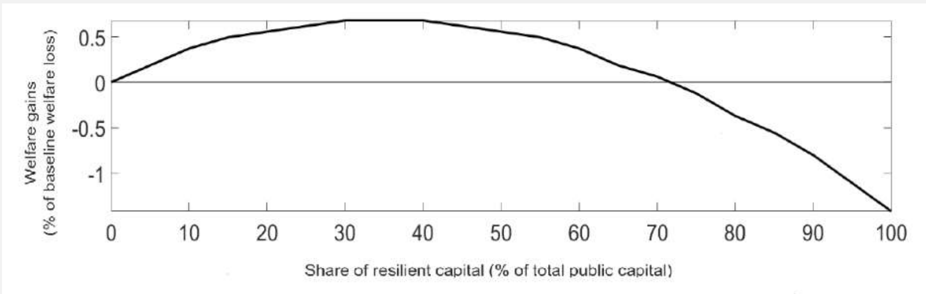
**Adaptation investment can reduce welfare losses from more frequent and more severe natural disasters, but programs paid for by domestic resources imply a welfare trade-off.** Ex ante adaptation can cushion the economy from the impact of natural disasters (Marto, Papageorgiou, and Klyuev 2018; Acevedo and others 2018; Cantelmo, Melina, and Papageorgiou 2019) and, therefore, increase social welfare, but financing adaptation via taxes can also reduce welfare. The net effect depends on a multitude of factors, including the return on adaptation capital and the efficiency of public finance management. As shown in Figure 4.1, for the disaster-prone countries studied Cantelmo, Melina, and Papageorgiou (2019), an increase in adaptation investment has positive effects up to a point (35 percent share of resilient capital in the total capital stock) where the marginal utility of an additional unit of resilient capital (benefits) becomes equal to the marginal disutility implied by the need to finance it (costs). The marginal disutility of investing beyond this point is larger than the marginal utility. Additional investment beyond this point implies net costs, and they would not be warranted based on pure cost-benefit considerations (see Note 1 for a discussion of cost-benefit analysis applied to climate change adaptation). Similar trade-offs should be expected with other sources of financing that do not expand the resource envelope of the economy.

**International donors can relax domestic trade-offs by expanding the resource envelope of the economy, but cost-effectiveness considerations remain important.** Higher grant disbursements improve social welfare, and a sufficiently strong contribution from international donors can, in principle, close the welfare gap. Cantelmo, Melina, and Papageorgiou (2019) illustrate this point by showing that financing the entire extra cost of accumulating 35 percent share of resilient capital (the optimal level in

Figure 4.1) with grants reduces the welfare gap between the average disaster-prone and non-disaster-prone countries by half.

**Donors would maximize the welfare impact of their contribution and recipient countries the impact of scarce international aid by financing the most cost-effective programs and by strengthening recipient countries' capacity.** Ex post relief accelerates the recovery, preserves debt sustainability, reduces the need to mobilize resources from the population, and contributes to a less volatile consumption path. However, the same improvement in social welfare can be achieved through financing ex ante resilience with, often, only a fraction of the funding. International aid is limited, and governments would maximize its impact by channeling it toward projects with the highest benefit-cost ratio (Note 1). The development community would also benefit from improving vulnerable countries' capacity to access climate funds and to implement adaptation programs (Box 2), including by providing more technical assistance.

**Figure 4.1. Welfare Gain from Investing in Resilient Capital in Disaster-Prone Countries**




Source: Cantelmo, Melina, and Papageorgiou (2019)

# Annex 1. Estimating Climate Change Costs and Adaptation Benefits

## Methods

**To estimate the impact of climate change on the economy, it is necessary to compare a scenario in which the economy evolves as if climate was stable and a scenario in which the economy evolves in response to a changing climate.** As it is impossible to observe how the economy evolves under two different climates, researchers build scenarios using different methods. Impacts can vary depending on how much adaptation is assumed to occur as a response to climate change. Some models allow for no or very minimal adaptation, whereas other models deploy a wide range of responses. Comparison of results across studies is complicated because models used in the literature differ in how much adaptation to include in their estimates of climate change damages. To estimate the economic benefit of adaptation, models must incorporate adaptation mechanisms that can be turned on and off to generate scenarios with and without adaptation. The benefit of such adaptation can then be measured by comparing economic losses under climate change with and without adaptation. Not all models have this degree of flexibility to study climate change impacts and adaptation. Some methods can be used to estimate climate change damages without or with minimal adaptation. Other methods can be used to estimate the impact of climate change with adaptation, but they are "black boxes" where the adaptation mechanisms cannot be easily controlled. This annex provides a synthetic overview of the main methods to study climate change impacts and adaptation. For much more detailed recent reviews of the literature see 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).

**It is possible to separate the methods used in the literature to estimate climate change impacts and adaptation in two broad groups.** The first group relies on the parameterization of models that can simulate the economy or other sectoral outcomes (for example, crop yields, energy and water demand) as a function of exogenous variables and model parameters. These can be called "simulation models" because they can simulate how the exogenous variables (GDP, yields, etc.) evolve under different choices of exogenous variables, including climate. Simulation models can be very complex and computationally intensive. The second group relies on econometric methods to estimate reduced form functions of how climate affects the economy or other variables of interest. Econometric models have a much lower level of detail of simulation models but also avoid many ad hoc assumptions that are needed in large simulation models.

### Simulation Models

**Simulation models have been extensively used to estimate both the benefit and costs of adaptation.** These types of studies cover sectoral models without optimizing agents, like engineering models (used to study water management systems or sea-level rise protection) (Hurd and others 2004; Lund, Cai, and Characklis 2006; Nicholls and Tol 2006; Yohe and others 1996; Hallegatte and others 2013; Diaz 2015), forestry models (to study optimal tree selection, rotation, and management) (Sohngen and Mendelsohn 1998; Sohngen, Mendelsohn, and Sedjo 2001), or agriculture models (used to identify optimal management and crop selection) (Tubiello and Fischer 2007; Blanc and Reilly 2017; Reilly and others 2003). They also include partial equilibrium and GE models with optimizing agents where adaptation is chosen efficiently and allowing for the study of autonomous adaptation, including through

trade and factor reallocation (Bosello, Carraro, and De Cian 2013; Bosello, Roson, and Tol 2006; Costinot, Donaldson, and Smith 2016). The advantage of simulation studies is that they can measure the effect of different adaptation solutions by turning them on and off in various simulations. They can also simulate the impact of climates that have not been experienced yet. For this reason, they have been used extensively to study virtually all climate-sensitive sectors, with protection from sea-level rise as a primary application. These studies provide explicit estimates of adaptation investment needs and residual damage. The disadvantage of these models is that they rely on many assumptions on behavior, technology, and costs that make them very sensitive to alternative parameterizations.

**Two special classes of simulation methods are Integrated Assessment Models and Computable General Equilibrium Models.**

- **Integrated Assessment Models (IAMs)** integrate the energy system, the economy, the climate system, and in some cases land, in a single framework. The models used for studies surveyed in Figure 1 are DICE and its regional variant RICE (Nordhaus 1992, 1993; Nordhaus and Boyer 2000), FUND (Tol 1997, 2018), and PAGE (Plambeck and Hope 2006). Other IAMs used for cost-benefit assessment of climate mitigation are MERGE (Manne, Mendelsohn, and Richels 1995) and WITCH (Bosetti et al. 2006, 2007, 2013). This is a small set of models. Many energy-economy models that are also commonly called IAMs do not describe the feedback of the climate system on the economy and are used to study climate mitigation policy without estimating mitigation benefits (Weyant 2017).

  IAMs are primarily concerned with long-term dynamics of capital accumulation, investment in the energy sector, and climate change. Few sectors of the economy are modeled in detail. Countries are aggregated in macro-regions or in a single global region. These modes calibrate a macroeconomic damage function that relates global GDP and temperature starting from sectoral and regional studies, including evidence from econometric studies. Impacts are estimated assuming different levels of adaptation, which can be efficient in some models or inefficient in others. The cost of private adaptations is not always included in IAMs, which overestimates the benefit of adaptation. Technological progress in adaptation (for example, better heat- and drought-resistant crops or more efficient protections against sea-level rise) is also not always included in IAMS, which underestimates the potential benefit of adaptation. The net effect is uncertain because these biases have opposite effects.

  Although there are differences across IAMs, a wide range of impacts is considered: temperature change, sea-level rise, tropical cyclones, and catastrophic events. In some cases, nonmarket losses (for example, losses from ecosystems and amenity values) are monetized and included among damages.

  Several authors have criticized the use of IAMs, especially their use in cost-benefit analysis of climate mitigation policy. One recurring theme is the inability to model catastrophic climate outcomes (for example, Pindyck 2013). While in many cases IAMs include extreme impacts and catastrophic events in their damage functions, the models do not include dynamics that can lead to societal collapses.

- **Computable general equilibrium models (CGEs)** include many sectors and many regions, with trade among regions and sectors. This greater sectoral and geographic detail can usually be accommodated by shortening the simulation horizon relative to IAMs. The long-term dynamic

relationship between the economy and climate cannot be reproduced with the same detail of IAMs. These models rely on exogenous climate shocks and are parameterized using econometric evidence.

CGEs can provide many useful insights on aggregate climate change impacts and on market adaptations, with the possibility to estimate how each channel (for example, international trade) contributes to reducing (or amplifying) climate change impacts. Dynamic Stochastic General Equilibrium (DSGE) models reviewed in the main text of this Note also belong to this class but have not yet been applied to estimate global climate change costs.

### Econometric Methods

**Econometric models based on cross-sectional analysis** are used to estimate climate change impacts at both sectoral and macroeconomic levels and to identify climate adaptations (Mendelsohn, Nordhaus, and Shaw 1994; Schlenker, Haneman, and Fisher 2005; Nordhaus 2006; Kalkuhl and Wenz 2020). A reduced form equation in which economic variables (for example, GDP per capita, agricultural rents), or sectoral output (for example, crop yields, water use), are a function of climate and control variables is estimated using cross-sectional variation. The estimated climate coefficients are used to predict the effect of climate change on the dependent variable. This method allows including present-day adaptation. Impacts are estimated using the climate coefficients estimated with the cross-sectional analysis with climate variables as expected in the future. These models assume that the same kinds of adaptations that are observed across climates today will spread following climate change. Cross-sectional studies are also used to identify climate adaptations by comparing what people do in different climates. There is evidence that climate affects consumption and both private and public investment in climate sensitive sectors like agriculture, energy, recreation, tourism, and investment in resilience to extreme events (Massetti and Mendelsohn 2018). However, this literature does not generally provide estimates of the economic benefit of adaptation. The advantage of cross-sectional econometric models is that they rely on observed behavior and project future adaptations from what individuals and governments do to respond to a wide range of climates. The main challenge for these studies is to control for confounding variables, such as geographic and socioeconomic characteristics that are correlated with both climate and the adaptation studied (Deschênes and Greenstone 2012; Blanc and Schlenker 2017).

**Econometric models based on panel analysis** identify the effect of weather shocks on changes of GDP per capita, using either fixed effects or first differences. Impacts of warming are projected using short-term elasticities, without accounting for adaptation that relies on stocks. To identify the effect of weather, these methods focus their attention on the impact of unexpected shocks over short periods of time and are therefore unable to capture adaptation benefits that take time to unfold (Mendelsohn and Massetti 2017; Lemoine 2018; Massetti and Mendelsohn 2018; Tol 2018; Letta and Tol 2019; Kolstad and Moore 2020). Theslow adjustment of capital makes impacts from unexpected deviations of weather from normal conditions different from slow-moving climate change. Inferring climate change impacts from unexpected shocks implies that the short-term imperfections are permanent. For example, as heat extremes become more frequent, we may see more increased mortality from heat stress in households in areas where mild temperatures have not stimulated the adoption of air conditioning, but as it becomes clear that the temperature distribution has shifted, it is reasonable to expect that air conditioning will be adopted and mortality will converge to that in areas that today already have air conditioning. Projecting mortality at the end of the century using elasticities estimated using weather shocks implies that air conditioning—or any other adaptation—will never be adopted over the next 80 years.

For this reason, this literature is generally not used to estimate the economic benefit of adaptation, with some exceptions. Some studies compare the effect of weather shocks in different climates or over time to learn if weather shocks have different impacts in different climates, a result that can be interpreted as evidence of adaptation (Schlenker and Roberts 2009; Deschênes and Greenstone 2011; Burke and Emerick 2016). Kahn and others (2021) measure weather shocks relative to a trailing moving average of weather. With this method, the authors estimate that adaptation has the potential to halve the long-term cost of warming.

## Estimates of Climate Change Damages

**Figure 1 in the main text displays estimates of global climate change damages from a comprehensive review of the literature.** The full list of studies is available in Annex Table 1.1. Studies that estimate regional costs as well as studies that estimate climate change damages using the metric of the social cost of carbon are not included because they are not easily comparable with the others.

**Estimating the cost of climate change is a complex exercise with many sources of uncertainty.** The estimates reported in Figure 1 reveal that damages from global warming in the range of +1.5°C to +2.5°C (approximately SSP1–2.6) could lead to a median loss of 1.5 percent [–13.0, +0.1] of annual global GDP in 2100, with respect to its reference level without climate change (ranges are in brackets). With +2.9°C to +4.3°C of global warming (approximately SSP3–7.0), the median predicted loss increases to 3.3 percent [–23, –0.8] of GDP in 2100 (see Figure 1). These ranges reflect the status of the literature but do not span all possible future outcomes because of the inherent limitations of studies.

**How is it possible to reconcile estimated average costs that can seem rather small with the large concern expressed by scientists and the international community?** The answer is that these studies may substantially underestimate the global cost of climate change in several ways and that global averages do not reveal the unequal distribution of climate change impacts, which imply devastating impact for some small vulnerable countries:

- The costs presented in Figure 1 are global averages that hide large negative effects in developing countries that are already hot, in small vulnerable nations, as shown in the academic literature (Mendelsohn, Dinar, and Williams 2006; Dell, Jones, and Olken 2012) and in several recent IMF studies (IMF 2018, 2020b, 2021d, 2021f). Some small island developing states are at risk of disappearing due to sea-level rise (World Bank 2017). However, by being small and often poor, very large loss-to-GDP ratios in these countries do not contribute significantly to global damages (IMF 2021f). Global average costs are also attenuated by potential gains in some colder countries in some studies (Burke, Hsiang, and Miguel 2015; Kalkuhl and Wenz 2020). Within countries, disadvantaged sectors of the population will suffer larger welfare losses. These uneven effects of climate change are of great concern for economic and ethical reasons and because they could push some countries to unsustainable fiscal territory and may lead to global macro instability.
- Some studies that use IAMs include damages from only some climate catastrophes and losses enter as expected values (Nordhaus and Boyer 2000; Stern 2007). Econometric studies only consider temperature and sometimes precipitation (Burke, Hsiang, and Miguel 2015; Dell, Jones, and Olken 2012). This means that worst-case scenarios are missing from Figure 1. Some studies that we do not include in our review because they cannot be easily compared simulate the cost of crossing “tipping points” and find that damages can be substantially large, but there is large

uncertainty in the literature (Cai, Lenton, and Lontzek 2016; Nordhaus 2019; Dietz and others 2021). The existence of low-probability but high-negative impact events that cannot be easily quantified (Weitzman 2011) is the one of the main factors behind the declared intention to keep global warming below +2.0°C and possibly +1.5°C.

- Nonmarket impacts (for example, biodiversity loss and loss of desirable climatic conditions) are also imperfectly included by some of the IAMs, as these estimates are uncertain and hard to quantify. The future value of nonmarket irreplaceable goods may be underestimated (Sterner and Persson 2020; Hoel and Sterner 2007).
- None of the studies surveyed in Figure 1 consider the possibility of crossing societal tipping points triggered by climate change (for example, social conflicts, wars, disruptive migration flows) because empirical data to quantify these risks is lacking.
- Finally, GDP only measures economic output and is at best a partial measure of welfare. It does not reflect the welfare losses resulting from channeling more resources for investment away from consumption (as would be needed if post-disaster reconstruction needs become more frequent). GDP losses also underestimate welfare losses when consumption losses are concentrated on certain groups, on poorer people as is expected with climate change (Hallegatte and others 2016a).

## Annex Table 1.1. Survey of the Literature on the Economic Costs of Climate Change

| Author | Temperature Change (degree Celsius) | Global GDP Loss (percentage) | Notes |
|---|---|---|---|
| | ***Integrated Assessment Models*** | | |
| **Tol (2013)** | 1.0 | –1.4 | |
| **Nordhaus (2017)** | 1.0 | –0.2 | Calculated using DICE2016R-090916ap-v2, which was used by Nordhaus (2017) |
| **Gunasekera and others (2008)** | 1.7 | –1.4 | The study uses +1.3°C with respect to temperature in 2000; adjusted by adding 0.4°C |
| **Hope (2006)** | 2.5 | –0.9 | |
| **Manne and Richels (2005)** | 2.5 | –1.9 | |
| **Manne, Mendelsohn and Richels (1995)** | 2.5 | –1.4 | |
| **Nordhaus (2017)** | 2.5 | –1.5 | Calculated using DICE2016R-090916ap-v2, which was used by Nordhaus (2017) |
| **Nordhaus and Boyer (2000)** | 2.5 | –1.5 | |
| **Nordhaus and Yang (1996)** | 2.5 | –1.7 | |
| **Plambeck and Hope (1996)** | 2.5 | –2.5 | |
| **Tol (1995)** | 2.5 | –1.9 | |
| | | | *Continued* |

| Author | Temperature Change (degree Celsius) | Global GDP Loss (percentage) | Notes |
|---|---|---|---|
| | *Integrated Assessment Models (continued)* | | |
| **Nordhaus (2013)** | **2.9** | **–2.0** | |
| **Hope (2011)** | 3.0 | –0.8 | |
| **Nordhaus (2014)** | 3.0 | –10.6 | |
| | 3.0 | –4.9 | |
| **Nordhaus (2017)** | 3.0 | –2.2 | Calculated using DICE2016R-090916ap-v2, which was used by Nordhaus (2017) |
| **Nordhaus (1994a)** | 3.0 | –3.6 | |
| **Nordhaus (1994b)** | 3.0 | –1.3 | |
| **Nordhaus (2008)** | 3.0 | –2.5 | |
| **Gunasekera and others (2008)** | 3.8 | –11.4 | The study uses +1.3°C with respect to temperature in 2000; adjusted by adding 0.4°C |
| **Stern (2007)** | 3.9 | –0.9 | Includes market impacts and catastrophes |
| **Nordhaus (2017)** | 4.3 | –4.4 | Calculated using DICE2016R-090916ap-v2, which was used by Nordhaus (2017) |
| **Stern (2007)** | 4.3 | –2.9 | Includes market impacts and catastrophes |
| | *Cross Section Econometrics* | | |
| **Horowitz (2009)** | 1.0 | –3.8 | |
| **Choinière and Horowitz (2000)** | 1.1 | –7.4 | |
| **Horowitz (2009)** | 2.0 | –7.6 | Linearly extrapolated from impact of 1°C as the study finds impacts are almost linear |
| **Mendelsohn and others (2000)** | 2.5 | +0.1 | |
| **Nordhaus (2006)** | 3.0 | –0.9 | Only warming; output weights |
| | 3.0 | –1.1 | Warming and drying; output weights |
| | 3.0 | –1.7 | Only warming; population weights |
| | 3.0 | –3.0 | Warming and drying; population weights |
| **Kalkuhl and Wenz (2020)** | 3.5 | –6.6 | |
| | *Panel Econometrics* | | |
| **Pretis and others (2018)** | 1.5 | –8.0 | |
| **Kahn and others (2021)** | 1.6 | –0.6 | Fast adaptation |
| | 1.6 | –1.6 | Medium adaptation |
| | 1.6 | –1.1 | Slow adaptation |

*Continued*

| Author | Temperature Change (degree Celsius) | Global GDP Loss (percentage) | Notes |
|---|---|---|---|
| | | *Panel Econometrics (continued)* | |
| **Pretis and others (2018)** | 2.0 | –13.0 | |
| **Kalkuhl and Wenz (2020)** | 3.5 | –11.4 | |
| **Burke, Hsiang, and Miguel (2015)** | 4.3 | –23.0 | |
| **Kahn and others (2021)** | 4.3 | –4.4 | Fast adaptation |
| | 4.3 | –10.0 | Medium adaptation |
| | 4.3 | –7.2 | Slow adaptation |
| | | *Computable General Equilibrium Models* | |
| **Bosello and others (2012)** | 1.9 | –0.5 | |
| **Dellink and others (2014)** | 2.5 | –1.1 | |
| **Roson and Van der Mensbrugghe (2012)** | 2.9 | –1.8 | |
| | | *Other Methods* | |
| **Tol (2002)** | 1.0 | –2.7 | Aggregation from sectoral studies; globally averaged prices for nonmarket goods |
| | 1.0 | +0.2 | Aggregation from sectoral studies; equity weights |
| | 1.0 | +2.3 | Aggregation from sectoral studies; simple aggregation |
| **Fankhauser (1995)** | 2.5 | –1.4 | Aggregation from sectoral studies. |
| **Schauer (1995)** | | –5.2 | Expert elicitation |
| **Nordhaus (1994a)** | 3.0 | –1.9 | Expert elicitation |
| **Howard and Sylvan (2015)** | 3.0 | –5.0 | Expert elicitation; median response of economists |
| | 3.0 | –7.1 | Expert elicitation; mean response of economists |

Source: Staff elaboration compiled from surveys in Tol (2009, 2014), Kahn et al. (2021), and Howard and Sterner (2017).
Note: Several studies in previous surveys have not been included if (1) they were not published in peer-reviewed journals and with 10 or fewer citations in Google Scholar at the time of writing; (2) they measure the impact on life satisfaction, utility, or happiness; (3) they lack estimates of global impacts; and (4) global mean surface temperature change with respect to the pre-industrial level is greater than 5°C

# Annex 2. The Costs of Making Infrastructure More Resilient

**The current climate is already a source of risks for physical infrastructure that should be addressed.** While many important and necessary adaptation policies are needed (strengthening early warning systems, agriculture systems, and water resources management), investing in infrastructure resilience is the costliest (GCA 2018). Vulnerabilities to floods and storms have been estimated to be the costliest source of climate risks in the present (Centre for Research on the Epidemiology of Disasters n.d.) and into the future (Lange and others 2020). However, starting by addressing the existing vulnerabilities is the most practical step forward. Hence, we focus on the cost of strengthening existing exposed economic assets and investment projects to improve their resilience to floods and storms.

**We estimate upgrading costs with a systematic cross-country, bottom-up approach.** This approach is based on country exposure to natural hazards and the additional costs that would be incurred to make exposed assets more resilient. We proxy the location of all infrastructure with the location of roads and railways. To identify which assets need strengthening, we use two detailed global maps: one shows the location of natural hazards and the other the location of roads and railways (Koks and others 2019). The share of exposed assets by country is approximated by the share of the kilometers of roads and railways that are exposed to natural hazards. A kilometer of road or railway is assessed to be exposed if its construction standards are such that it gets damaged at least once every hundred years. Construction standards are assumed to differ between high-income countries, upper-middle-income countries, and all others, and to increase with income following (Rozenberg and Fay 2019).

**The incremental costs of making exposed assets more resilient are estimated using the average values corresponding to the set of technical options from (Miyamoto International 2019)**. Even as they are economically sensible, the technical solutions do not guarantee that assets cannot be damaged by natural hazards and do not include all possible options to reduce risks, including more cost-effective alternatives or more expensive options that could further reduce risks. Based on the exposure and incremental cost measures, we estimate the following:

- ***Strengthening costs for investment projects*** are computed using average investment projections over 2021 to 2025. Investment projections are multiplied by the estimated share of exposed assets, and by a unit cost of 15 percent.[2] Hence, the average exposure of future projects is assumed to be the same as the exposure of existing assets. Public and private investment projections are from the *World Economic Outlook* (IMF 2020f). When projections are unavailable, we assume that future investment to GDP ratios remain constant at the last observed level in the IMF Investment and Capital Stock Dataset 2019. Achieving the Sustainable Goals would require additional investments (IMF 2019a). Those would need to be made more resilient and add to the costs. The costs are expressed in annual values.
- ***Strengthening costs of existing assets*** are computed as the capital stock that won't be depreciated by 2030 (in 10 years), multiplied by the estimated share of exposed assets and by a unit cost of 50 percent. The total costs are annualized by assuming constant investment in percent of GDP over the next 10 years. We use the 2017 levels of public capital stock and the

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[2] These unit cost estimates are based on engineers and experts' assessment of average strengthening costs (Hallegatte, Rentschler, and Rozenberg 2019; Miyamoto International 2019).

depreciation rates from the IMF Investment and Capital Stock Dataset 2019. In some cases, it may be more cost-effective to abandon some exposed assets or tear down and rebuild them better. The fraction of the capital stock that won't be depreciated within 10 years is equal to $(1 - \delta)^{10}$, where δ denotes the depreciation rate.

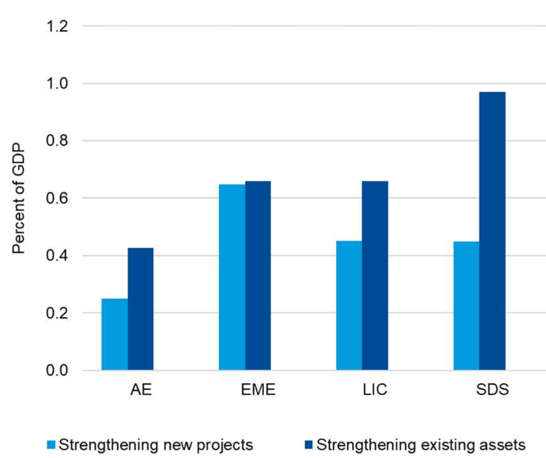
**The simple cross-country average of adaptation costs is estimated at 0.1 and 0.3 percent of GDP for strengthening investment projects and existing assets, respectively.** These estimates are similar to the weighted averages presented in the main text because the few small countries with very high costs are averaged with many countries with very small cost estimates. Also, these estimates can seem low compared with the large stock of existing assets and investment projects but reflect the fact that only 10 percent of assets are estimated to be exposed to floods and storm on average.

**The cost estimates of strengthening public assets vary considerably across nations.** Costs tend to be lower for advanced economies because of higher construction standards and therefore smaller shares of exposed assets, and because of lower public investment as a share of GDP. However, advanced economies have a larger stock of existing assets, making the costs of strengthening these relatively closer to costs in other countries. Assets and investment projects in low-income countries and small developing states tend to be most exposed, thereby leading to high-cost estimates. The costs are highest for emerging economies because they typically combine larger exposure as in low-income countries and small developing states with large stocks of existing assets and investment projects.

**Strengthening exposed future and existing private assets could cost, respectively, 0.4 and 0.6 percent of GDP annually between 2021 and 2025 (Annex Figure 2.1).** These costs are estimated to be almost twice as large as in the public sector (main text Figure 3). In contrast with public sector cost estimates, private sector costs are more evenly distributed across income groups and across new and existing infrastructure. This reflects the fact that higher private investment and larger shares of private-owned infrastructure in more advanced countries compensate for lower exposure. As for Figure 3, these estimates do not correspond to optimal investment but represent strengthening costs that are expected to be lower than avoided damages in a large range of scenarios.

### Annex Figure 2.1. Adaptation Costs to Selected Current Climate Risks in the Private Sector (2021–25)

Annual Costs of Strengthening Private Assets Resilience to Current Storms and Flood Risks




Sources: Hallegatte, Rentschler, and Rozenberg (2019); Hallegatte and others (2019); IMF, Capital Stock 2019 Dataset; IMF, World Economic Outlook database; and staff calculations.

# Annex 3. The IMF's Debt, Investment, Growth, and Natural Disaster (DIGNAD) Model: An Application to Developing Economies in Asia and the Pacific[1]

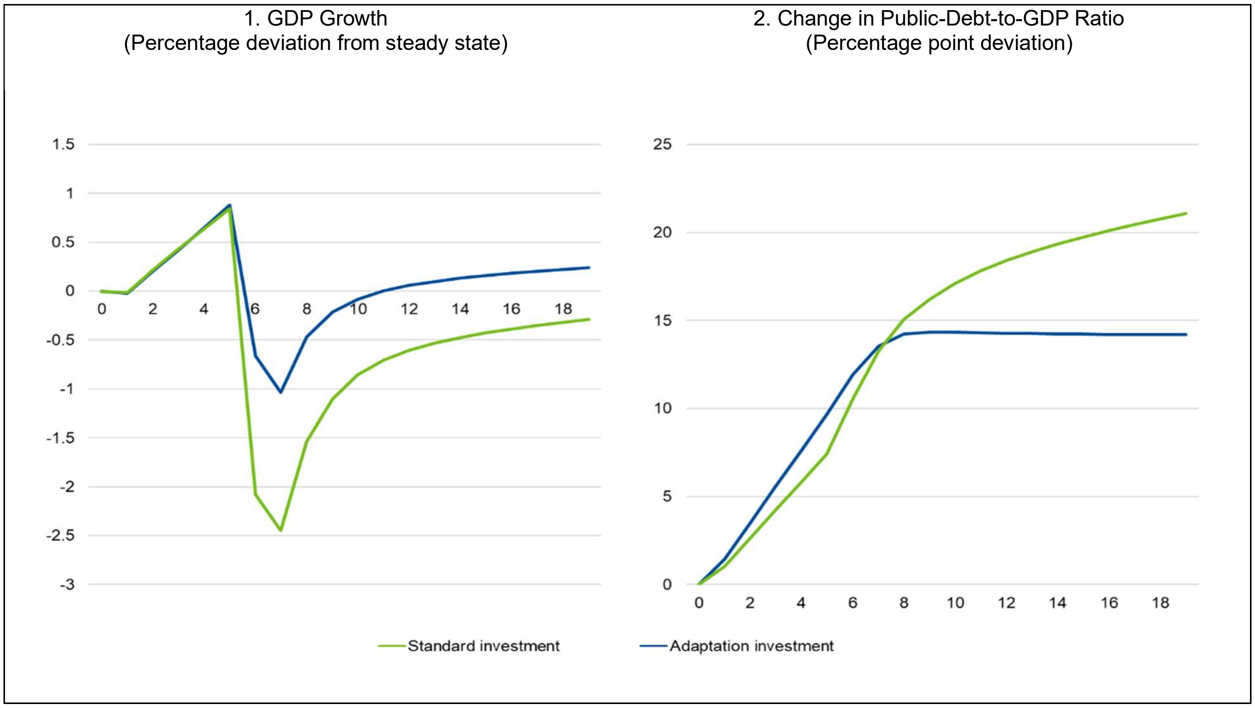
**The IMF's workhorse DIGNAD model extends the Debt, Investment, and Growth (DIG) model of Buffie and others (2012) to analyze natural disasters and adaptation infrastructure.** The DIGNAD model, developed in Marto, Papageorgiou, and Klyuev (2018), is a dynamic low-income or emerging-country open-economy model that incorporates natural disasters and resilient infrastructure to examine the nexus between public investment and growth, different financing strategies (external concessional, external commercial, and domestic), and fiscal reaction rules. It captures high rates of return on public capital, either standard or resilient, as well as significant inefficiencies in public investment and absorptive capacity constraints, which are pervasive in developing economies. The model captures the main mechanisms and policy issues of interest for debt sustainability analysis, particularly those associated with the linkages between public adaptation investment, economic growth, and debt.

**In the model, a natural disaster has multiple adverse effects on the economy which can be mitigated by investing in resilient infrastructure.** Natural disasters impact the economy through the following channels: (1) permanent damages to public infrastructure, (2) permanent damages to private capital, (3) temporary losses of productivity, (4) increased inefficiencies in public investment during the reconstruction process, and (5) an increase in risk premium for borrowing costs. Investment in adaptation infrastructure is costlier than investment in standard infrastructure but reduces the damages inflicted by a natural disaster (for example, seawalls) and depreciates at a lower rate. Investing in adaptation infrastructure is useful as a complement to conventional infrastructure as it raises the marginal product of other capital by helping withstand the impact of natural disasters, and crowds in private investment.

**The growth-debt trade-off of boosting adaptation investment can be examined with calibrated model simulations.** For example, IMF (2021c) calibrates a DIGNAD model as an economy whose macroeconomic indicators are averages for developing economies in Asia and the Pacific. The model is used to simulate two investment scale-up plans (standard investment versus investment in adaptation), and examine the evolution of growth and public debt after a large natural disaster hits the economy. Investment is financed by commercial debt and takes place over five years before the disaster strikes (in year 6), as reaping benefits from disaster resilience would require substantial accumulation of adaptation investment.

[1] The development of the DIGNAD model is part of a research project on macroeconomic policy in low-income countries (IATI Identifier: GB-1-202960) supported by the U.K.'s Foreign, Commonwealth and Development Office (FCDO) and the partners in the IMF's COVID-19 Crisis Capacity Development Initiative (CCCDI)—Belgium, Canada, China, Germany, Japan, Korea, Spain, Singapore, and Switzerland.

**Annex Figure 3.1. The Positive Effects of Investing in Resilient Infrastructure on Growth and Debt Stability**




Source: IMF (2021d).

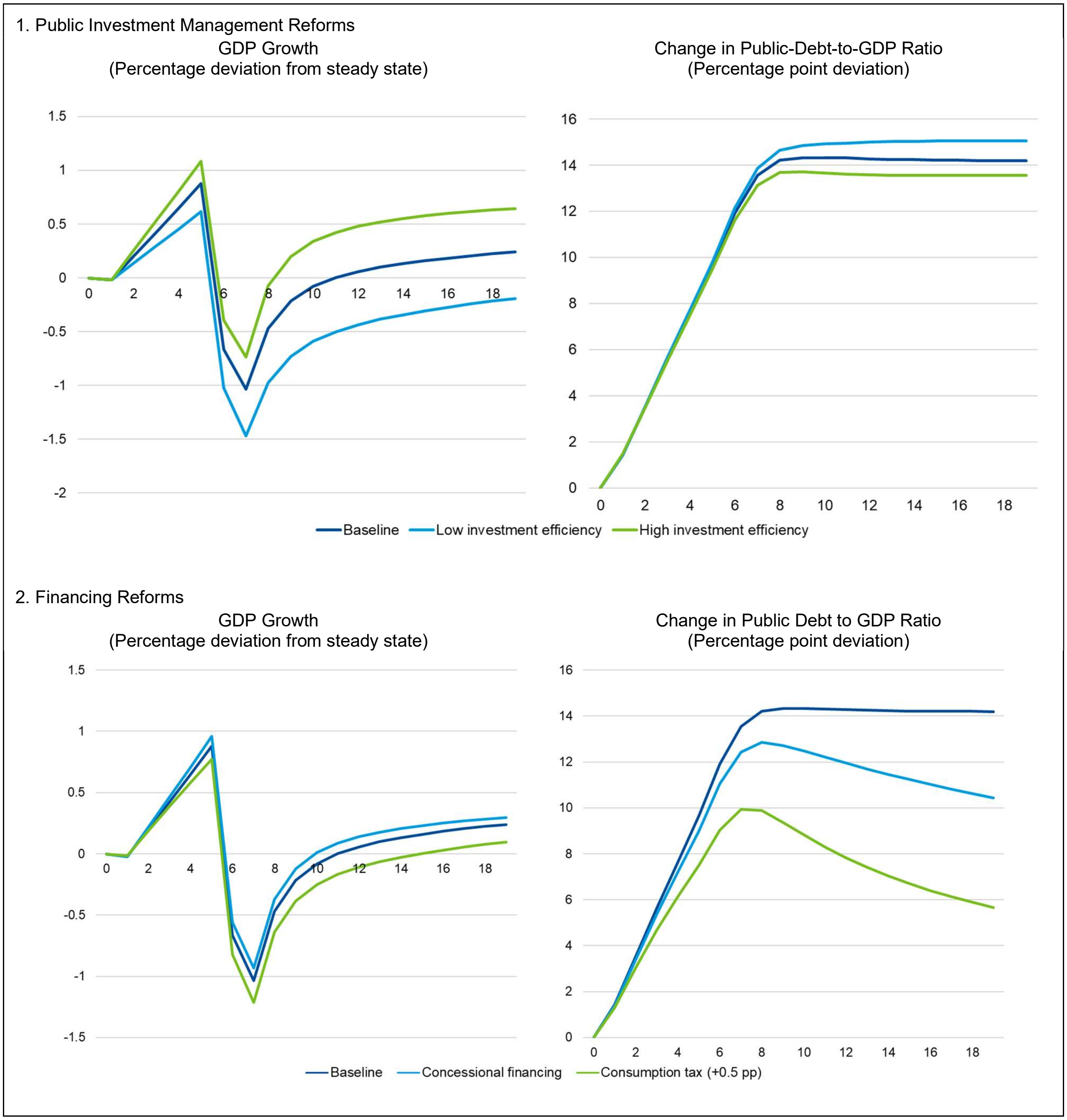
**Adaptation investment, albeit costly, can make the economy resilient against natural disasters, limiting a post-disaster rise in public debt.** The growth and public debt paths for the two investment scenarios are shown in Annex Figure 3.1. Standard investment is less costly than investment in adaptation but does not shield the economy from natural disasters. Post-disaster spending needs push debt on an unsustainable trend and imply significant output losses over the medium term. Post-disaster output losses are softened in the adaptation investment scenario, by more than half compared to the scenario of standard investment. More expensive adaptation investment implies higher public debt in initial years. Unlike debt in the standard investment scenario, however, the debt level stabilizes over the long term due to smaller and less persistent output losses and smaller reconstruction needs.

**Better public investment management can lessen the growth-debt trade-off for adaptation investment.** Weak management can lead to poor maintenance and wasteful investment in low-exposure areas or in assets that should be relocated because of overwhelming risks. The benefits of improved public investment management (PIM) efficiency are illustrated in Annex Figure 3.2, panel 1. If PIM efficiency improves from the lowest levels observed in the region ("low investment efficiency" scenario in Annex Figure 3.2, panel 1) to those of best performers ("high investment efficiency" scenario), output resilience against natural disasters further improves and public debt paths are brought down. The results echo those for the Solomon Islands (IMF 2018), which show that PIM reforms amplify the benefits of adaptation investment.

**Financing adaptation investment with concessional external financing or revenue mobilization can also alleviate the growth-debt trade-off.** Alternative financing options for adaptation investment are examined in Annex Figure 3.2, panel 2. Financing adaptation investment with foreign concessional loans can put public debt on a decreasing path after the disaster by freeing up resources to repay debt faster. Foreign concessional financing also reduces domestic financing needs by the government and avoids

crowding out private investment. Alternatively, countries can mobilize domestic revenues to finance adaptation investment. A consumption tax increase can put public debt on a faster declining path than under the concessional financing scenario, even though the tax burden negatively affects output by depressing private demand. While not included in the simulations in Annex Figure 3.2, panel 2, rationalizing government spending can also put public debt on a declining path.

## Annex Figure 3.2. The Role of Public Investment Management and Financing Reforms in Strengthening Adaptation Investment Strategies




Source: IMF (2021d).

# References

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, Mico Mrkaic, Natalija Novta, Evgenia Pugacheva, and Petia Topalova. 2018. “The Effects of Weather Shocks on Economic Activity: What Are the Channels of Impact?” IMF Working Paper 18/144, International Monetary Fund, Washington, DC.

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, Francesco Bosello, Carlo Carraro, Kelly De Bruin, Enrica De Cian, Rob Dellink, and Elisa Lanzi. 2011. “Plan or React? Analysis of Adaptation Costs and Benefits Using Integrated Assessment Models.” *Climate Change Economics* 2 (03): 175–208.

Ahmed, Mahfuz, and Suphachol Suphachalasai. 2014. *Assessing the Costs of Climate Change and Adaptation in South Asia*. Mandaluyong City, Philippines: Asian Development Bank.

Asian Development Bank. 2013. “The Economics of Climate Change in the Pacific.” Mandaluyong City, Philippines.

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

Bellon, Matthieu, and Emanuele Massetti. 2022a. “Economic Principles for Integrating Climate Change Adaptation into Fiscal Policy.” IMF Staff Climate Note 2022/001, International Monetary Fund, Washington, DC.

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

Berg, Andrew, Rafael A. Portillo, Edward F. Buffie, Catherine A. Pattillo, and Luis-Felipe Zanna. 2012. “Public Investment, Growth, and Debt Sustainability; Putting Together the Pieces.” IMF Working Paper 12/144, International Monetary Fund, Washington, DC.

Blanc, Elodie, and John Reilly. 2017. “Approaches to Assessing Climate Change Impacts on Agriculture: An Overview of the Debate.” *Review of Environmental Economics and Policy* 11 (2): 247–57.

Blanc, Elodie, and Wolfram Schlenker. 2017. “The Use of Panel Models in Assessments of Climate Impacts on Agriculture.” *Review of Environmental Economics and Policy* 11 (2): 258–79.

Bosello, Francesco, Carlo Carraro, and Enrica De Cian. 2010. “Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage.” *Climate Change Economics* 1 (02): 71–92.

Bosello, Francesco, Carlo Carraro, and Enrica De Cian. 2013. “Adaptation Can Help Mitigation: An Integrated Approach to Post-2012 Climate Policy.” *Environment and Development Economics* 18 (3): 270–90.

Bosello, Francesco, Robert J. Nicholls, Julie Richards, Roberto Roson, and Richard S. J. Tol. 2012. "Economic Impacts of Climate Change in Europe: Sea-Level Rise." *Climatic Change* 112 (1): 63–81.

Bosello, Francesco, Roberto Roson, and Richard S. J. Tol. 2006. "Economy-Wide Estimates of the Implications of Climate Change: Human Health." *Ecological Economics* 58 (3): 579–91.

Bosetti, Valentina, Carlo Carraro, Marzio Galeotti, Emanuele Massetti, and Massimo Tavoni. 2006. "WITCH: A World Induced Technical Change Hybrid Model." *The Energy Journal* 27 (1): 13–38.

Bosetti, Valentina, Emanuele Massetti, and Massimo Tavoni. 2007. "The WITCH Model. Structure, Baseline, Solutions." *FEEM Nota Di Lavoro* 10.07.

Bosetti, Valentina, Carlo Carraro, Enrica De Cian, Emanuele Massetti, and Massimo Tavoni. 2013. "Incentives and Stability of International Climate Coalitions: An Integrated Assessment." *Energy Policy* 55: 44–56.

Buchner, Barbara, Alex Clark, Angela Falconer, Rob Macquarie, Chavi Meattle, Rowena Tolentino, and Cooper Wetherbee. 2019. *Global Landscape of Climate Finance 2019*. Climate Policy Initiative.

Burke, Marshall, and Kyle Emerick. 2016. "Adaptation to Climate Change: Evidence from US Agriculture." *American Economic Journal: Economic Policy* 8 (3): 106–40.

Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. 2015. "Global Non-Linear Effect of Temperature on Economic Production." *Nature* 527 (7577): 235–39.

Cai, Yongyang, Timothy M. Lenton, and Thomas S. Lontzek. 2016. "Risk of Multiple Interacting Tipping Points Should Encourage Rapid CO 2 Emission Reduction." *Nature Climate Change* 6 (5): 520–25.

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.

Centre for Research on the Epidemiology of Disasters. n.d. "EM-DAT: The CRED/OFDA International Disaster Database." www.emdat.be

Cevik, Serhan, and João Tovar Jalles. 2020. "Feeling the Heat: Climate Shocks and Credit Ratings." *IM*F Working Papers 20/286, International Monetary Fund, Washington, DC.

Cevik, Serhan, and João Tovar Jalles. 2021. "An Apocalypse Foretold: Climate Shocks and Sovereign Defaults." *Open Economies Review* 1–20.

Cevik, Serhan, and Vibha Nanda. 2020. "Riding the Storm: Fiscal Sustainability in the Caribbean." *International Review of Applied Economics* 34 (3): 384–99.

Chen, Chen, Ian Noble, Jessica Hellmann, Joyce Coffee, Martin Murillo, and Nitesh Chawla. 2015. "University of Notre Dame Global Adaptation Index Country Index Technical Report." University of Notre Dame, South Bend, IN.

Choinière, Conrad, and John K. Horowitz. 2000. "A Production Function Approach to the GDP-Temperature Relationship." https://papers.ssrn.com/sol3/papers.cfm?abstract_id=267352

Cohen, Charles, S. Ali Abbas, Myrvin Anthony, Tom Best, Peter Breuer, Hui Miao, Alla Myrvoda, Eriko Togo, and Tobias Adrian. 2020. "The Role of State-Contingent Debt Instruments in Sovereign Debt Restructurings." IMF Staff Discussion Note 006, International Monetary Fund, Washington, DC.

Costinot, Arnaud, Dave Donaldson, and Cory Smith. 2016. "Evolving Comparative Advantage and the Impact of Climate Change in Agricultural Markets: Evidence from a 9 Million-Field Partition of the Earth." *Journal of Political Economy* 124 (1): 205–48.

De Bruin, Kelly C., Rob B. Dellink, and Richard S. J. Tol. 2009. "AD-DICE: An Implementation of Adaptation in the DICE Model." *Climatic Change* 95 (1–2): 63–81.

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.

Dellink, Rob, Elisa Lanzi, Jean Chateau, Francesco Bosello, Ramiro Parrado, and Kelly de Bruin. 2014. "Consequences of Climate Change Damages for Economic Growth: A Dynamic Quantitative Assessment." OECD Publishing, Paris.

Deschênes, Olivier, and Michael Greenstone. 2011. "Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the US." *American Economic Journal: Applied Economics* 3 (4): 152–85.

Deschênes, Olivier, and Michael Greenstone. 2012. "The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather: Reply." *The American Economic Review* 102 (7): 3761–73.

Desmet, Klaus, Robert E. Kopp, Scott A. Kulp, Dávid Krisztián Nagy, Michael Oppenheimer, Esteban Rossi-Hansberg, and Benjamin H. Strauss. 2018. "Evaluating the Economic Cost of Coastal Flooding." NBER Working Paper 24918, National Bureau of Economic Research, Cambridge, MA.

Diaz, Delavane B. 2016. "Estimating Global Damages from Sea Level Rise with the Coastal Impact and Adaptation Model (CIAM)." *Climatic Change* 137 (1): 143–156.

Dietz, Simon, James Rising, Thomas Stoerk, and Gernot Wagner. 2021. "Economic Impacts of Tipping Points in the Climate System." *Proceedings of the National Academy of Sciences* 118 (34).

Donadelli, Michael, Marcus Jüppner, Max Riedel, and Christian Schlag. 2017. "Temperature Shocks and Welfare Costs." *Journal of Economic Dynamics and Control* 82: 331–355.

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.

Fankhauser, Samuel. 1995. *Valuing Climate Change: The Economics of the Greenhouse*. London: Earthscan.

Fernandez-Corugedo, Emilio, A. Gonzalez, and Alejandro Guerson. Forthcoming. “Natural Disasters and Ex-Ante Resilience in the Caribbean and Central America: A DSGE Investigation.” IMF Departmental Paper, International Monetary Fund, Washington, DC .

Fernández-Villaverde, Jesús, and Oren Levintal. 2018. “Solution Methods for Models with Rare Disasters.” *Quantitative Economics* 9 (2): 903–944.

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.

Fouad, Manal, Natalija Novta, Gemma Preston, Todd Schneider, and Sureni Weerathunga. 2021. “Unlocking Access to Climate Finance for Pacific Island Countries.” IMF Departmental Paper 21/020, International Monetary Fund, Washington, DC.

Global Center on Adaptation. 2018. “Adapt Now: A Global Call for Leadership on Climate Resilience.” Global Center on Adaptation and World Resources Institute, Rotterdam, Netherlands.

Government of the Republic of Fiji. 2017. "Climate Vulnerability Assessment: Making Fiji Climate Resilient." https://www.fisheries.gov.fj/images/Publications/climate-vulnerability.pdf.

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

Guerson, Alejandro, Camila Perez Marulanda, Carolina Brozdowski, Salma Khalid, Marina Mendes Tavares, and Wei Guo. 2022. "Dominica: Selected Issues." IMF Selected Issue paper, International Monetary Fund, Washington, DC.

Gunasekera, Don, Melanie Ford, Edwina Heyhoe, Andrew Gurney, Helal Ahammad, Steven Phipps, Ian Harmann, John Finnigan, and Markus Brede. 2008. “Global Integrated Assessment Model.” *Australian Commodities* 15 (1): 195–216.

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

Guo, Wei, and Saad Quayyum. 2020. "Building Resilience to Natural Disaster in Vulnerable States: Savings from Ex Ante Interventions." Chapter 9 in *Well Spent: How Strong Infrastructure Governance Can End Waste in Public Investment,* edited by Gerd Schwartz, Manal Fouad, Torben S. Hansen, and Genevieve Verdier. Washington, DC: International Monetary Fund

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

Hallegatte, Stephane, 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, Stephane, Mook Bangalore, Laura Bonzanigo, Marianne Fay, Tamaro Kane, Ulf Narloch, Julie Rozenberg, David Treguer, and Adrien Vogt-Schilb. 2016a. *Shock Waves: Managing the Impacts of Climate Change on Poverty. Climate Change and Development*. Washington, DC: World Bank.

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

Hallegatte, Stephane, 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.

Hallegatte, Stephane, Julie Rozenberg, Jun Erik Maruyama Rentschler, Claire Marion Nicolas, and Charles James Edward Fox. 2019. "Strengthening New Infrastructure Assets: A Cost-Benefit Analysis." World Bank Policy Research Working Paper 8896, World Bank, Washington, DC.

Hoel, Michael, and Thomas Sterner. 2007. "Discounting and Relative Prices." *Climatic Change* 84 (3): 265–2=80.

Hope, Chris. 2006. "The Marginal Impact of CO2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern." *Integrated Assessment* 6 (1).

Hope, Chris. 2011. "The Social Cost of CO2 from the PAGE09 Model." Kiel Institute for the World Economy, Kiel, Germany.

Horowitz, John K. 2009. "The Income–Temperature Relationship in a Cross-Section of Countries and Its Implications for Predicting the Effects of Global Warming." *Environmental and Resource Economics* 44 (4): 475–4=93.

Howard, Peter H., and Thomas Sterner. 2017. "Few and Not so Far between: A Meta-Analysis of Climate Damage Estimates." *Environmental and Resource Economics* 68 (1): 197–225.

Howard, Peter H., and Derek Sylvan. 2015. "The Economic Climate: Establishing Expert Consensus on the Economics of Climate Change." *Institute for Policy Integrity* 438–41.

Hurd, Brian, Mac Callaway, Joel Smith, and Paul Kirshen. 2004. "Climatic Change and US Water Resources: From Modeled Watershed Impacts to National Estimates."*Journal of the American Water Resources Association* 129–48.

International Monetary Fund (IMF). 2013. "Macroeconomic Issues in Small States and Implications for Fund Engagement." IMF Policy Paper 008, Washington, DC.

International Monetary Fund (IMF). 2015. "Making Public Investment More Efficient." Policy Paper. Washington, DC: International Monetary Fund.

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). 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 (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). 2020c. *Fiscal Monitor: Policies for the Recovery*. Washington, DC, October.

International Monetary Fund (IMF). 2020e. "Kingdom of Tonga: Climate Change Policy Assessment." Washington, DC.

International Monetary Fund (IMF). 2020f. *World Economic Outlook*. Washington, DC, April.

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. “Fiscal Policies to Address Climate Change in Asia and the Pacific.” IMF Departmental Paper 21/07, Washington, DC.

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

International Monetary Fund (IMF). 2021e. “Review of The Debt Sustainability Framework for Market Access Countries.” IMF Policy Papers, Washington, DC.

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

International Monetary Fund (IMF). Forthcoming. "Samoa CMAP." Washington, DC.

Intergovernmental Panel on Climate Change (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.

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. 2016. “The Climate Change Adaptation Literature.” *Review of Environmental Economics and Policy* 10 (1): 166–78.

Kahn, Matthew E., Kamiar Mohaddes, Ryan N. C. Ng, M. Hashem Pesaran, Mehdi Raissi, and Jui-Chung Yang. 2021. “Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis.” *Energy Economics* 104, 105624.

Kalkuhl, Matthias, and Leonie Wenz. 2020. “The Impact of Climate Conditions on Economic Production. Evidence from a Global Panel of Regions.” *Journal of Environmental Economics and Management* 103: 102360.

Koks, Elco E., Julie Rozenberg, Conrad Zorn, Mersedeh Tariverdi, Michalis Vousdoukas, S. A. Fraser, J. W. Hall, and Stephane Hallegatte. 2019. “A Global Multi-Hazard Risk Analysis of Road and Railway Infrastructure Assets.” *Nature Communications* 10 (1): 1–11.

Kolstad, Charles D., and Frances C. Moore. 2020. “Estimating the Economic Impacts of Climate Change Using Weather Observations.” *Review of Environmental Economics and Policy* 14 (1): 1–24.

Lange, Stefan, Jan Volkholz, Tobias Geiger, Fang Zhao, Iliusi Vega, Ted Veldkamp, Christopher P. O. Reyer, Lila Warszawski, Veronika Huber, Jonas Jägermeyr, Jacob Schewe, David N. Bresch, Matthias Büchner, Jinfeng Chang, Philippe Ciais, Marie Dury, Kerry Emanuel, Christian Folberth, Dieter Gerten, Simon N. Gosling, Manolis Grillakis, Naota Hanasaki, Alexandra-Jane Henrot, Thomas Hickler, Yasushi Honda, Akihiko Ito, Nikolay Khabarov, Aristeidis Koutroulis, Wenfeng Liu, Christoph Müller, Kazuya Nishina, Sebastian Ostberg, Hannes Müller Schmied, Sonia I. Seneviratne, Tobias Stacke, Jörg Steinkamp, Wim Thiery, Yoshihide Wada, Sven Willner, Hong Yang, Minoru Yoshikawa, Chao Yue, and Katja Frieler. 2020. “Projecting Exposure to Extreme Climate Impact Events Across Six Event Categories and Three Spatial Scales.” *Earth’s Future* 8 (12): e2020EF001616.

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

Letta, Marco, and Richard SJ Tol. 2019. “Weather, Climate and Total Factor Productivity.” *Environmental and Resource Economics* 73 (1): 283–305.

Levintal, Oren. 2018. “Taylor Projection: A New Solution Method for Dynamic General Equilibrium Models.” *International Economic Review* 59 (3): 1345–1373.

Lund, Jay R., Ximing Cai, and Gregory W. Characklis. 2006. “Economic Engineering of Environmental and Water Resource Systems.” *Journal of Water Resources Planning and Management* 132 (6): 399–402.

Manne, Alan, Robert Mendelsohn, and Richard Richels. 1995. “MERGE: A Model for Evaluating Regional and Global Effects of GHG Reduction Policies.” *Energy Policy* 23 (1): 17–34.

Manne, Alan S., and Richard G. Richels. 2005. “MERGE: An Integrated Assessment Model for Global Climate Change.” In *Energy and the Environment*, edited by Adrian Bejan, Peter Vadász, and Detlev G. Kröger, 175–89. New York: Springer.

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 O., and Emanuele Massetti. 2017. "The Use of Cross-Sectional Analysis to Measure Climate Impacts on Agriculture: Theory and Evidence." *Review of Environmental Economics and Policy* 11 (2): 280–98.

Mendelsohn, Robert, William D. Nordhaus, and Daigee Shaw. 1994. "The Impact of Global Warming on Agriculture: A Ricardian Analysis." *The American Economic Review* 84 (4): 753–71.

Mendelsohn, Robert, Ariel Dinar, and Larry Williams. 2006. "The Distributional Impact of Climate Change on Rich and Poor Countries." *Environment and Development Economics* 11 (02): 159–78.

Mendelsohn, Robert, Wendy Morrison, Michael E. Schlesinger, and Natalia G. Andronova. 2000. "Country-Specific Market Impacts of Climate Change." *Climatic Change* 45 (3): 553–69.

Miyamoto International. 2019. *Overview of Engineering Options for Increasing Infrastructure Resilience*. Washington, DC: World Bank.

Nicholls, Robert J., and Richard S. J. Tol. 2006. "Impacts and Responses to Sea-Level Rise: A Global Analysis of the SRES Scenarios over the Twenty-First Century." *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 364 (1841): 1073–95.

Nicholls, Robert John, Jochen Hinkel, Daniel Lincke, and Thomas van der Pol. 2019. "Global Investment Costs for Coastal Defense through the 21st Century." World Bank Policy Research Working Paper 8745, World Bank, Washington, DC.

Nordhaus, William D. 1992. "An Optimal Transition Path for Controlling Greenhouse Gases." *Science* 258 (5086): 1315–19.

Nordhaus, William D. 1993. "Optimal Greenhouse-Gas Reductions and Tax Policy in the" DICE" Model." *The American Economic Review* 83 (2): 313–17.

Nordhaus, William. 1994a. "Expert Opinion on Climatic Change." *American Scientist* 82 (1): 45–51.

Nordhaus, William. 1994b. *Managing the Global Commons: The Economics of Climate Change*. Volume 31. Cambridge, MA: MIT Press.

Nordhaus, William. 2006. "Geography and Macroeconomics: New Data and New Findings." *Proceedings of the National Academy of Sciences* 103 (10): 3510–17.

Nordhaus, William. 2008. *A Question of Balance*. New York: Yale University Press.

Nordhaus, William. 2013. *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. New York: Yale University Press.

Nordhaus, William. 2014. "Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches." *Journal of the Association of Environmental and Resource Economists* 1 (1/2): 273–312.

Nordhaus, William. 2017. "Revisiting the Social Cost of Carbon." *Proceedings of the National Academy of Sciences* 114 (7): 1518–23.

Nordhaus, William. 2019. “Economics of the Disintegration of the Greenland Ice Sheet.” *Proceedings of the National Academy of Sciences* 116 (25): 12261–69.

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

Nordhaus, William D., and Zili Yang. 1996. “A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies.” *The American Economic Review*: 741–65.

Organisation for Economic Co-operation and Development (OECD). 2021. “Statement from OECD Secretary-General Mathias Cormann on Climate Finance in 2019.” https://www.oecd.org/environment/statement-from-oecd-secretary-general-mathias-cormann-on-climate-finance-in-2019.htm

Pindyck, Robert S. 2013. "Climate Change Policy: What Do the Models Tell Us?" *Journal of Economic Literature* 51 (3): 860–72.

Plambeck, Erica L., and Chris Hope. 1996. “PAGE95: An Updated Valuation of the Impacts of Global Warming.” *Energy Policy* 24 (9): 783–93.

Pretis, Felix, Moritz Schwarz, Kevin Tang, Karsten Haustein, and Myles R Allen. 2018. “Uncertain Impacts on Economic Growth When Stabilizing Global Temperatures at 1.5 C or 2 C Warming.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376 (2119): 20160460.

Reilly, John, Francesco Tubiello, Bruce McCarl, D. Abler, R. Darwin, K. Fuglie, S. Hollinger, C. Izaurralde, S. Jagtap, and J. Jones. 2003. “US Agriculture and Climate Change: New Results.” *Climatic Change* 57 (1–2): 43–67.

Richmond, Morgan, Chavi Meattle, Valerio Micale, Padraig Oliver, and Rajashree Padmanabhi. 2020. “A Snapshot of Global Adaptation Investment and Tracking Methods.” Climate Policy Initiative, London.

Roson, Roberto, and Dominique Van der Mensbrugghe. 2012. “Climate Change and Economic Growth: Impacts and Interactions.” *International Journal of Sustainable Economy* 4 (3): 270–85.

Rozenberg, Julie, and Marianne Fay. 2019. *Beyond the Gap: How Countries Can Afford the Infrastructure They Need While Protecting the Planet.* Washington, DC: World Bank Publications.

Schauer, Michael J. 1995. “Estimation of the Greenhouse Gas Externality with Uncertainty.” *Environmental and Resource Economics* 5 (1): 71–82.

Schlenker, Wolfram, and Michael J. Roberts. 2009. “Nonlinear Temperature Effects Indicate Severe Damages to US Crop Yields under Climate Change.” *Proceedings of the National Academy of Sciences* 106 (37): 15594–98.

Schlenker, Wolfram, W. Michael Hanemann, and Anthony C. Fisher. 2005. “Will US Agriculture Really Benefit from Global Warming? Accounting for Irrigation in the Hedonic Approach.” *The American Economic Review* 95 (1): 395–406.

Simpson, Murray C., and M. Harrison. 2010. *Quantification and Magnitudeof Losses and Damages Resulting from the Impacts of Climate Change: Modelling the Transformational Impacts and Costs of Sea Level Rise in the Caribbean*. Geneva: United Nations Office for Disaster Risk Reduction.

Sohngen, Brent, and Robert Mendelsohn. 1998. “Valuing the Impact of Large-Scale Ecological Change in a Market: The Effect of Climate Change on US Timber.” *American Economic Review*: 686–710.

Sohngen, Brent, Robert Mendelsohn, and Roger Sedjo. 2001. “A Global Model of Climate Change Impacts on Timber Markets.” *Journal of Agricultural and Resource Economics*: 326–43.

Stern, Nicholas. 2007. *The Economics of Climate Change: The Stern Review*. Cambridge, MA: Cambridge University Press.

Sterner, Thomas, and U. Martin Persson. 2020. “An Even Sterner Review: Introducing Relative Prices into the Discounting Debate.” *Review of Environmental Economics and Policy* 2 (1).

Tol, Richard S. J. 1995. “The Damage Costs of Climate Change toward More Comprehensive Calculations.” *Environmental and Resource Economics* 5 (4): 353–74.

Tol, Richard S. J. 1997. “On the Optimal Control of Carbon Dioxide Emissions: An Application of FUND.” *Environmental Modeling & Assessment* 2 (3): 151–63.

Tol, Richard S. J. 2002. “Estimates of the Damage Costs of Climate Change. Part 1: Benchmark Estimates.” *Environmental and Resource Economics* 21 (1): 47–73.

Tol, Richard S.J. 2009. “The Economic Effects of Climate Change.” *The Journal of Economic Perspectives* 23 (2): 29–51.

Tol, Richard S. J. 2013. “The Economic Impact of Climate Change in the 20th and 21st Centuries.” *Climatic Change* 117 (4): 795–808.

Tol, Richard S.J. 2014. “Correction and Update: The Economic Effects of Climate Change.” *Journal of Economic Perspectives* 28 (2): 221–26.

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., Kristie L. Ebi, and Gary W. Yohe. 2007. “Infectious Disease, Development, and Climate Change: A Scenario Analysis.” *Environment and Development Economics* 12 (5): 687–706.

Tubiello, Francesco N, and Günther Fischer. 2007. “Reducing Climate Change Impacts on Agriculture: Global and Regional Effects of Mitigation, 2000–2080.” *Technological Forecasting and Social Change* 74 (7): 1030–56.

United Nations Environment Programme (UNEP). 2014. “Adaptation Gap Report 2014.” UN Environment Programme, Nairobi, Kenya.

United Nations Framework Convention on Climate Change (UNFCCC). 2009a. “Investment and Financial Flows to Address Climate Change - An Update.” Bonn, Germany.

United Nations Framework Convention on Climate Change (UNFCCC). 2009b. “Copenhagen Accord.” Bonn, Germany.

Weitzman, Martin L. 2011. "Fat-tailed Uncertainty in the Economics of Catastrophic Climate Change." *Review of Environmental Economics and Policy* 5 (2): 275–92.

Westphal, Michael I., Gordon A. Hughes, and Jörn Brömmelhörster. 2015. "Economics of Climate Change in East Asia." Asian Development Bank, Mandaluyong City, Philippines.

Weyant, John. 2017. “Some Contributions of Integrated Assessment Models of Global Climate Change.” *Review of Environmental Economics and Policy* 11 (1): 115–37.

World Bank. 2010a. “Economics of Adaptation to Climate Change - Synthesis Report.” Washington, DC.

World Bank. 2010b. “The Cost to Developing Countries of Adapting to Climate Change - New Methods and Estimates.” Washington, DC.

World Bank. 2010c. “World Development Report 2010: Development and Climate Change.” Washington DC.

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

Yohe, Gary, James Neumann, Patrick Marshall, and Holly Ameden. 1996. “The Economic Cost of Greenhouse-Induced Sea-Level Rise for Developed Property in the United States.” *Climatic Change* 32 (4): 387–410.

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