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A multi-country study of forward-looking economic losses from floods and tropical cyclones[1]

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A Multi-Country Study of Forward-Looking Economic Losses from Floods and Tropical Cyclones[1]

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ABSTRACT: The study provides forward-looking estimates for economic damages from floods and tropical cyclones (TC) for a wide range of countries using global datasets. Damages are estimated for three Intergovernmental Panel on Climate Change (IPCC) scenarios and aggregated at the country level, building them from geographically disaggregated estimates of hazard severity and economic exposures across 183 countries. The results show that, for most countries, floods and TC's damage rates increase (i) during the estimation span of 2020 to 2100, and (ii) with more severe global warming scenarios. In line with other global studies, expected floods and TCs damages are unevenly distributed across the world. The estimates can be used for a wide range of applications, as damage rates represent the key variable connecting climate scenarios to economics and financial sector risk analysis.

[1] This paper relies heavily on the IMF Working Paper: A Multi-Country Study of Forward-Looking Economic Losses from Floods and Tropical Cyclones (Fornino and others 2024). All authors are from the IMF. The views expressed are those of the authors and do not necessarily represent the views of the IMF, its Executive Board, or IMF management. The boundaries, colors, denominations, and any other information shown on the maps do not imply, on the part of the International Monetary Fund, any judgement on the legal status of any territory or any endorsement or acceptance of such boundaries.

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1. Introduction

The frequency and intensity of natural hazards have increased across several regions in the world since 1950s (Arias and others, 2021). These hazards can cause large economic losses. On a global level, economic loss associated with natural hazards has averaged around $170 billion per year over the past decade, with peaks of $300 billion in some years (UNDRR, 2022). Further, economic losses from these events have risen significantly since the 2000s, in line with their amplified intensity and frequency (UNDRR, 2022). As many countries prepare measures to reduce risks from these natural hazards, it becomes of first order importance to assess future economic losses from the latter under various climate scenarios.[3]

This paper aims to bridge the gap between economic and climate literature by adopting a simple framework for analyzing losses from floods and tropical cyclones (TCs) on a forward-looking basis. We propose a methodology to estimate economic losses from natural hazards that can be applied to a wide range of countries globally.[4] We apply the methodology to estimate forward-looking losses from (riverine and coastal) floods and TCs for a large number of IMF member countries (183 for floods and 89 for TCs) under three Intergovernmental Panel on Climate Change (IPCC) scenarios.[5]

Damages arise as the interaction of three components: the projections of individual hazards (hazard severity), the exposure of economic assets to these hazards, and their resulting vulnerability in the event the hazard materializes. We rely on global datasets for each of these components, with the goal to maximize the coverage of IMF member countries. In terms of hazards, we focus on floods and TCs and used data procured from the private vendor Jupiter Intelligence.[6] For exposures, we use publicly available datasets on spatially disaggregated GDP with global coverage as a proxy for the distribution of physical assets, which is consistent with future socio-economic projections, available decennially up to 2100. To measure vulnerability, we adopt damage functions from existing academic studies and publicly available datasets which translate the magnitude of hazards into quantifiable damages.

Our results point to three key takeaways from the analysis. First, most countries we consider will experience an increase in floods and tropical cyclones damages by mid-century. These countries represent a significant share of the global economy. Second, for most countries considered, damages are higher for more severe climate scenarios, pointing to a positive correlation between global flood and tropical cyclones risks and global warming. Third, floods and tropical cyclones risks are unevenly distributed across the world.

[3] For example, we refer to Duenwald and others (2022) for a discussion of the importance of climate adaptation strategies for the Middle East and Central Asia region.

[4] The terms *losses* and *damages* are used interchangeably in this paper.

[5] Floods considered in this study include river and coastal floods, but not rainfall-induced flooding, given data availability (see Section 3.1).

[6] The literature and data on vulnerability and damages from other hazards, such as droughts and wildfires, is still limited, especially at global scale. Therefore, this study focuses exclusively on floods and tropical cyclones.

2. Literature Review

The direct losses from floods and TCs are the focus of this study.[7] There is a growing literature on indirect losses from hazards which are not reviewed here. We instead focus on direct losses, which are likely to serve as a lower bound of total losses, in relation to individual hazards, as they ignore indirect losses. Further, we focus on two hazards only (floods and TCs). This choice is based on the availability of hazards and vulnerability data.

2.1 Floods

The direct damages from floods mainly depend on the depth of the water. Damage functions for floods link the depth of water to damages—either in percentage of total value or as the absolute damage amount—and can be applied to both types of floods. Even though many different inundation characteristics, like depth, duration, velocity may influence the amount and degree of damage, in the current state-of the-art of flood damage evaluation mainly inundation depth is incorporated in damage functions as it seems to have the most significant influence.

Several studies in the literature use a multi-model framework, integrating simulations of river flow and flooding processes with datasets on exposures and flood protections to determine damages from floods. Alfieri and others (2017) find: (i) a positive correlation between atmospheric warming and future flood risk at global scale, and (ii) risks are unevenly distributed across the world. Similarly, Dottori and others (2018) analyze socioeconomic costs of river floods, using a multi-model framework. The study finds particularly higher impacts under 3 degrees Celsius warming scenario, with uneven regional distribution. Smith and others (2019) use high-resolution (approx. 30 x 30 m) population density to map flood exposure to population data for 18 countries. The results of the study when compared to other studies suggest that exposure estimates are sensitive to the resolution of the underlying hazard data.

Huizinga and others (2017) estimate empirical damage curves for each continent and asset type, which are now widely used in the literature.[8] To estimate these damage curves, the authors collected a large and globally consistent dataset on flood damages and then produced damage curves providing fractional damage as a function of water depth based on the data. Damage curves are estimated by damage class (residential, commerce, industry, transport, roads, railroads, agriculture) and continent.

[7] Direct damages are caused by the hazard event itself. Indirect damages do not occur through the event itself but subsequently via connections between system elements as defined by Bachner and others (2023).
[8] These damage functions are available on the JRC website. These functions have also been used by the NGFS. See, Bertram and others (2021).

Table 1: Global Studies on Economic Losses from Floods

	Year	Coverage	Publicly available damage function	Forward Looking
Huizinga and others	2017	Global – by continent Maximum damage available for 200+ countries	Yes	No
Smith and others	2019	18 developing countries	Yes	No
Alfieri and others	2017	Global	Based on Huizinga and others (2017)	Yes
Dottori and others	2018	Global	Based on Huizinga and others (2017)	Yes

Note: Studies focusing on a single country are excluded.

2.2 Tropical Cyclones

TCs typically inflict damage due to strong sustained surface winds, storm surge-driven inundation, and torrential rain. The maximum sustained windspeed is the most important factor to quantify the impact of TCs, also used as an input to damage functions for the assessment of direct economic damage (Emanuel (2011), Czajkowski and Done (2014)).

A large part of the literature on TCs damages focused on the United States. For the United States, damage functions are available for different building types (FEMA, 2011), as well as for aggregate economic losses for several regions of the U.S. Atlantic and Gulf Coasts (Hallegatte, 2007).

The literature on TCs with global coverage is expanding. Yamin and others (2014) conduct a risk assessment for around 200 countries on TCs. Damage functions are obtained from the HAZUS MH 2.1 Hurricane Model, however, calibrated only for the USA and consider building type and characteristics.[9] Mendelsohn and others (2012) studies global TC damages using an integrated assessment model based on USA's elasticity of damages with respect to storm intensity to calibrate the global damage function. Bakkensen and Mendelsohn (2019) address this modelling drawback, by broadening the damage estimates for a larger set of countries using both a cross-sectional model and an error components model with country and time fixed effects to calculate damage functions. This study shows that the United States is an outlier in TC vulnerability (i.e., much higher elasticities), conditional on its income levels and exposure, hence the risk of overestimating losses when using USA-based damage functions for other countries. Gettelman and others (2017) adopted the TC damage model from the open-source natural catastrophe modelling tool CLIMate ADAptation (CLIMADA)[10] using spatially disaggregated GDP to estimate the impact of future changes in TCs on damages. Authors find increasing global storm damage by around 50 percent in 2070 in comparison to 2015, despite decreasing storm numbers in the future and strong landfalling storms increase in East Asia.

[9] HAZUS is a multi-hazard loss estimation methodology developed by the Federal Emergency Management Agency (FEMA, 2011).
[10] The CLIMADA cyclone damage model produces damage estimates by year and spatial location based on a set of probabilistic cyclone tracks.

Eberenz and others (2021) developed regionally calibrated damage functions by comparing simulated damages to historical reported damages. Reported damage estimates used in the study are available from the International Disasters Database (EM-DAT). For the regional calibration of the TCs impact model, distinct calibration regions were defined based on geography, data availability, and patterns in damage ratios.[11] The impact functions provided by the study feature considerable differences in the slope and level of uncertainty across model regions. Authors note the largest uncertainties for the North-West Pacific regions.

Table 2: Global Studies on Economic Losses from Tropical Cyclones

	Year	Coverage	Publicly available damage function	Forward Looking
Yamin and others	2014	Global	No – based on damage functions calibrated for the USA	No
Mendelsohn and others	2012	Elasticities based on the USA data.	Yes	Yes
Bakkensen and Mendelsohn	2019	Global – 87 countries that report damage from TCs	No	No
Eberenz and others	2021	Global	Yes – with regionally calibrated damage functions	No
Gettelman and others	2017	Global – 73 countries	No – Results calibrated to the USA data	Yes

Note: Studies focusing on a single country are excluded.

3. Data

Damages from physical risks arise as the interaction of three components: hazard, vulnerability, and exposure. In this section we discuss the data used to quantify each of these components.

3.1 Hazard data

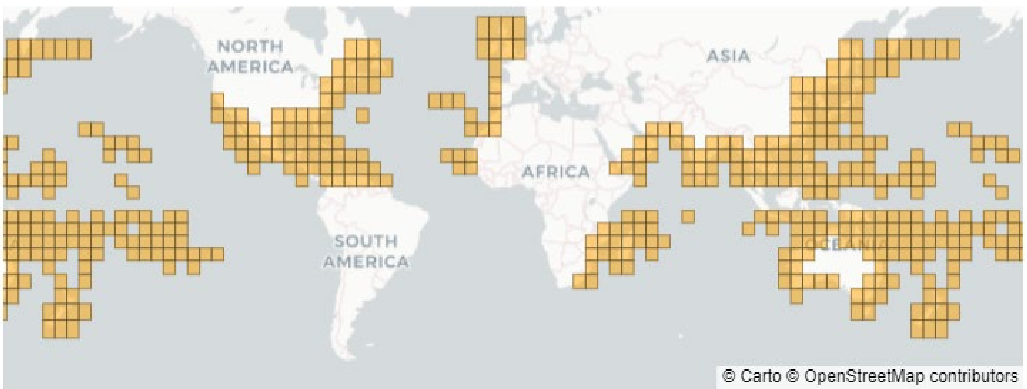
In this study, we used hazard data for floods and TCs severity supplied by the private vendor Jupiter Intelligence.[12] For floods, data covers river and coastal flood depth projections under different scenarios, using data from GCMs as an input.[13] The Jupiter Intelligence's inland river flooding model uses projected regional changes in extreme streamflow to estimate how flood depth and extent may change in a future climate. For coastal floods, multiple climate projection datasets are used to estimate the effects of sea-level rise and storm surge and tides on coastal inundation, as well as storm surge and lake levels on lake shoreline inundation. Values of sea-level rise, long-term lake levels and surge and tides from the same climate scenario are combined to produce a unified estimate of the expected water levels for each scenario. Then river and coastal floods results are consolidated into a single estimate. For TCs, hazards data reflect wind speeds, defined as the maximum 1-minute sustained wind speed at 10 meters above ground level. This measure is produced using data from GCMs and a synthetic TCs model. The maximum 1-minute sustained windspeed

[11] These functions are also used by the NGFS.
[12] Additional details, including selection of locations, are provided in Fornino and others (2024).
[13] Rainfall-induced flooding is currently not available.

variable from the vendor dataset is used in the damages' calculation only for areas where TCs have been observed historically (Figure 1). This approach guarantees consistency between the methodology on the hazards and vulnerability.

We use data for the mean levels for flood depth and wind speed, for 10, 20, 50,100, 200, and 500-year return periods. The data also covers fraction of land flooded in 3 arcseconds grids for 10, 20, 50,100, 200, and 500-year return periods. These measures are provided for a baseline (climate for 10-year period centered on 1995) and projections from 2020-2100 with 5-year increments under three scenarios: SSP1-2.6, SSP2-4.5, and SSP5-8.5, which represent a low, intermediate and very high GHG emission scenario respectively.[14] The three scenarios are drawn from the IPCC Sixth Assessment Report (IPCC, 2021). As an example, Figure 2 shows flood depth for 1-in-500-year return period in 2050 under the scenario SSP2 4.5.

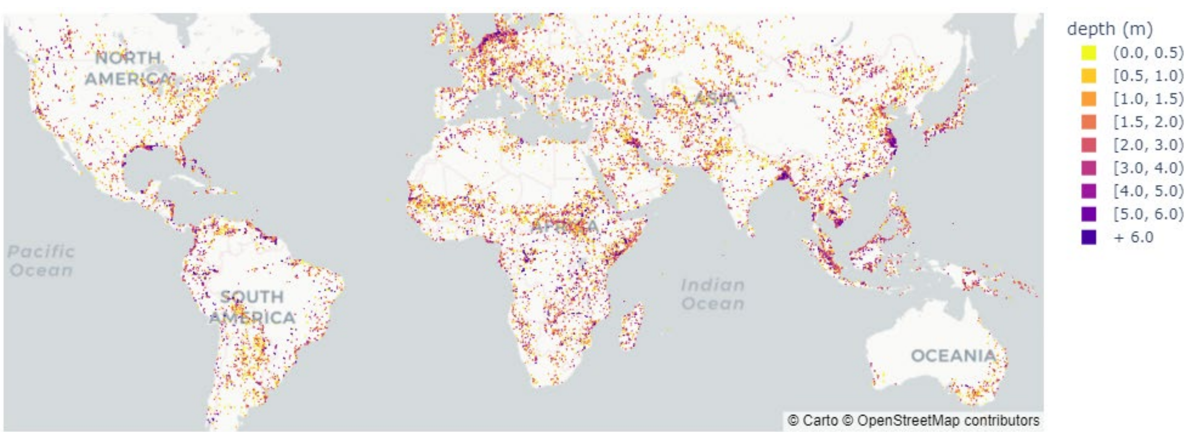
Figure 1: Tropical Cyclones grids



Source: Jupiter Intelligence. Notes: Grids that consider TC simulations in wind parameter estimates from Jupiter Intelligence

Figure 2: Jupiter Intelligence flood depth

flood depth in meters



Source: Jupiter Intelligence. Notes: Values for mean depth meters for 1-in-500 year in 2050 under SSP2-4.5

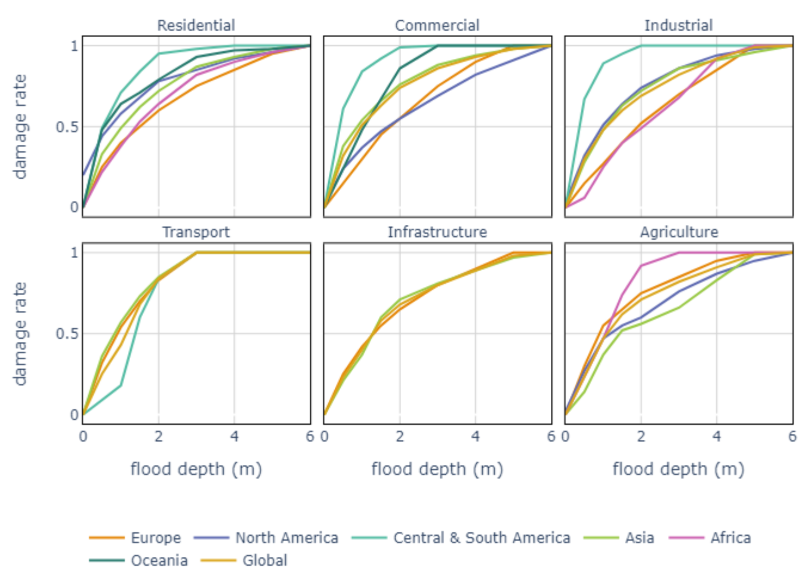
[14] We note that the SSP5 - 8.5 represents an extreme scenario, and its plausibility is currently debated in the literature. However, as noted in (IPCC, 2023), this scenario cannot be ruled out. Furthermore, for some of the potential applications of our results, such as financial sector stress testing analysis, it is important to adopt extreme scenarios to analyze the potential implications of tail risk events.

3.2 Vulnerability – Damage functions

Damage functions relate economic damages to climate inputs. Hazards can be linked to economic and financial exposures using damage functions that define the impacts of specific hazards on real assets and activities (BIS, 2021). These functions can be estimated using different methodologies, including by using empirical approaches looking at correlative relationship between past data on damages and hazards variables and using simulated data of physical hazards and models to explicitly describe the system behavior in response to climate change (Feyen and others 2020). Damage functions vary by hazard, type, and geographical location (e.g., regions, continents, or countries) of exposures. This granularity is intended to capture differences in the way in which a climate hazard of the same intensity differently impacts physical assets at different locations–for example because of different climate resilience of existing infrastructure. We selected the functions estimated by Huizinga and others (2017) and Eberenz and others (2021), as they are widely used, publicly available and provide globally consistent coverage.

The damage functions provided by Huizinga and others (2017) can be used to calculate damages from floods. These functions are piecewise linear, depicting fractional damage as a function of water depth for a variety of categories: buildings and contents (residential, commercial, and industrial), transport facilities, infrastructure (roads and railroads) and agriculture (Figure 3). The functions have been calibrated using quantitative data from multiple studies. Damage functions vary also by geography, they are calibrated for six continents: Europe, Africa, Asia, Oceania, North America, South and Central America.[15]

Figure 3: Floods damage functions by asset type



Source: Huizinga and others (2017)

[15] As noted by the authors the amount of historical data in which acute events are properly recorded is larger for the countries and continents with a more established systematic damage assessment 'tradition', like the USA, Australia, Japan and South Africa. However, and specifically in the African continent (except South Africa), the information available is not equally distributed over the continent and mostly available for sub-Saharan Africa.

The damage functions provided by Eberenz and others (2017) are calibrated for the assessment of economic damages caused by TCs. These functions are regionally calibrated (Figure 4) by using simulated damages from CLIMADA and reported damages. The functional form is sigmoidal, expressing the percentage of damage as a function of wind speed:

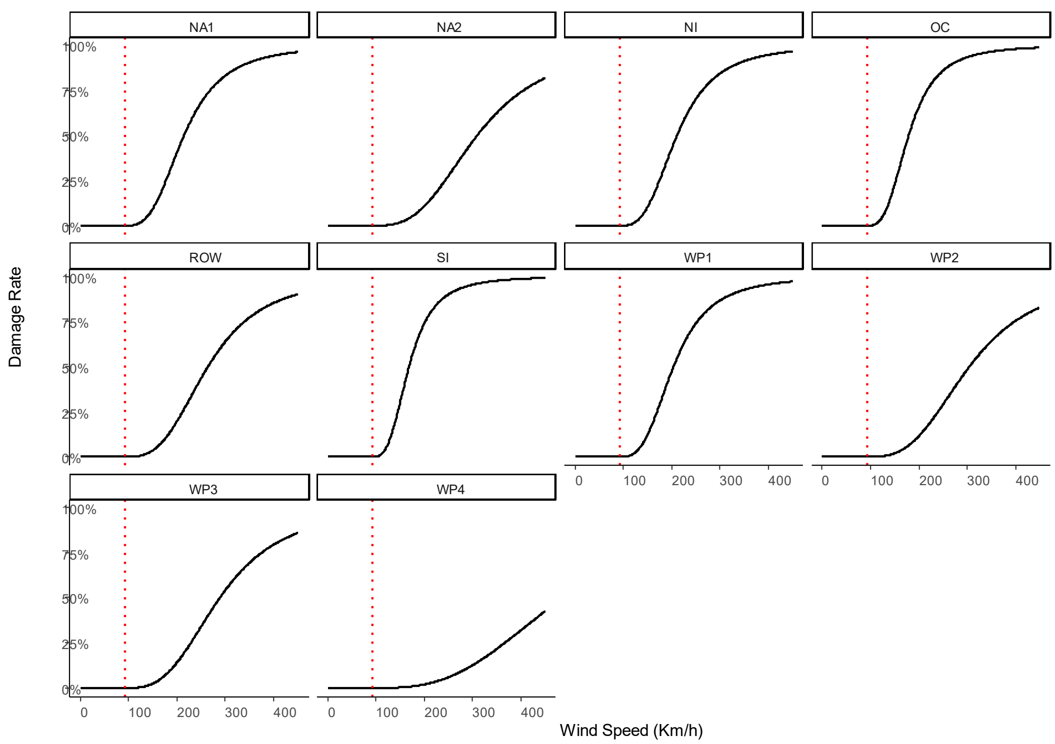
$$f = \frac{v_n^3}{1 + v_n^3},$$

where

$$v_n = \frac{MAX[(V - V_{thresh}),0]}{V_{half} - V_{thresh}}.$$

In this formula, V is the 1 min sustained wind speed at 10 m above ground per storm event. V_{thresh} is a minimum threshold for the occurrence of impacts, as no directly wind-induced damage is expected for low wind speeds. V_{half} is the slope parameter, signifies the wind speed at which the function's slope is the steepest and the impact reaches 50 percent of the exposed asset value. This functional form, introduced by Emanuel (2011), builds on empirical studies relating wind to damage suggesting a high power-law dependence of damage on wind speed (Pielke 2007). Emanuel (2011) argues that on physical grounds damage should vary as the cube of the wind speed over a threshold value. Further, the fraction of the property damaged should approach unity at very high wind speeds.

Figure 4. Calibrated TC Damage Functions by Regions



Source: Eberenz and others (2021)
Notes: The red dotted line represents a windspeed of 25.7 m/s, or 92.5 km/h, which is the threshold below which the damage rate is assumed to be zero. Regional groupings are defined in detail in appendix Table A.1 of Eberenz at al (2021), p.409. For reference, NA=North Atlantic, NI=North Indian, OC=Oceania, ROW=Rest of the World, SI=South Indian, WP=North West Pacific. Numbers denote sub-regional groupings of countries that share similar characteristics. NA2=CAN, USA, WP2=PHL, WP3=CHN, WP4=HKG, KOR.

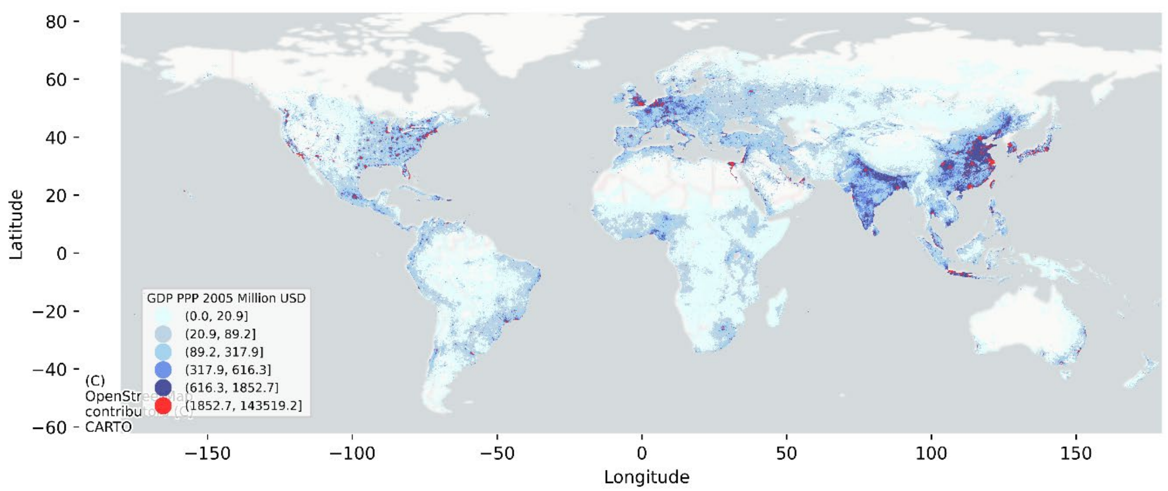
3.3 Exposures

We proxy economic exposures using downscaled GDP data. Several studies have developed methodologies to downscale national or subnational GDP data into finer spatial units, combining it with other auxiliary datasets (such as population data). In these datasets, each GDP value has an associated latitude and longitude, which corresponds to the centroid of the corresponding geographical grid cell. In particular, Murakami and others (2021) develop a downscaling methodology to estimate gridded GDP under different SSPs, which we use in our analysis. Details of the downscaling approach are provided in Fornino and other (2024).

The global dataset of downscaled GDP data at 30 arcminutes is publicly available. The dataset spans between 1980 and 2100 by 10-year intervals. The data between 1980–2010 are estimated by downscaling actual GDPs by country, while those between 2020–2100 are estimated by downscaling projected GDPs under three SSPs (SSP1-2.6; SSP2-4.5; and SSP5-8.5). Figure 5 illustrates Gridded GDP under SSP2-4.5 scenario for 2050.

Figure 5: Gridded GDP SSP2-4.5 for 2050

GDP PPP 2005, Million USD



Source: Murakami and others (2021)

Notes: GDP groupings have been defined using the following percentiles [0, 50, 75, 90, 95, 99, 100]

4. Methodology

This section provides the methodology adopted to estimate damages. We define damage rates as the loss of value of assets, expressed in percent of the value of those assets before being hit by the hazard. Damage rates from floods and TCs are calculated separately. Caution should be applied if interested in combining damages from both floods and TCs, as these events are likely to be correlated, for example, with TCs possibly leading to flooding. In this section, we describe how damage rates for a specific location (given by latitude and longitude) are computed and we detail how location-level damage rates are used to calculate aggregate damage rates at the country level. The methodology can be applied for different projection horizons and scenarios, as depicted in Section 5.

4.1 Location-level damage rate

The calculation of the damage rate at the individual location requires applying the damage function to the hazard data for that point. The variables $depth_{c,i,RP,t,s}$, $frac_{c,i,RP,t,s}$, and $wind_{c,i,RP,t,s}$ denote the flood depth, fraction of land flooded, maximum sustained windspeed respectively in country c, location i, return period RP, projection year t and scenario s. The RP denotes the return period at which specified hazard intensity is expected; for example, the 1-10 years flood depth denotes the severity of a hazard that is expected to occur no more than once in 10 years.[16] Next, we denote the damage function for floods as df_{floods} and the damage function for TCs as df_{storms}. These functions take as inputs either the flood depth or the maximum sustained windspeed and return the fraction of assets that are lost as a result.

For floods, the specific damage function depends on the percentage of built-up area in the location. For each covered cell in the gridded dataset, we divide the exposure measure into built-up and non-built-up areas using the land cover data Copernicus Global Land Operations "Vegetation and Energy" (CGLOPS-1) for 2019 from Buchhorn and others (2020). At the time of the analysis, this was among the few publicly available datasets that cover built-up areas, but this data is rapidly evolving and further granularity can be integrated in the future. For built-up areas, we combine the residential, commercial, and industrial damage functions (Figure 3), by equally weighting each function, while for non-built-up areas we consider agriculture and infrastructure damage functions. For TCs the damage function differs by country groups (Figure 4).

The damage rate for floods is defined as:

$$d_{c,i,RP_j,t,s} = frac_{c,i,RP_j,t,s} * df_{floods}(depth_{c,i,RP_j,t,s}).$$

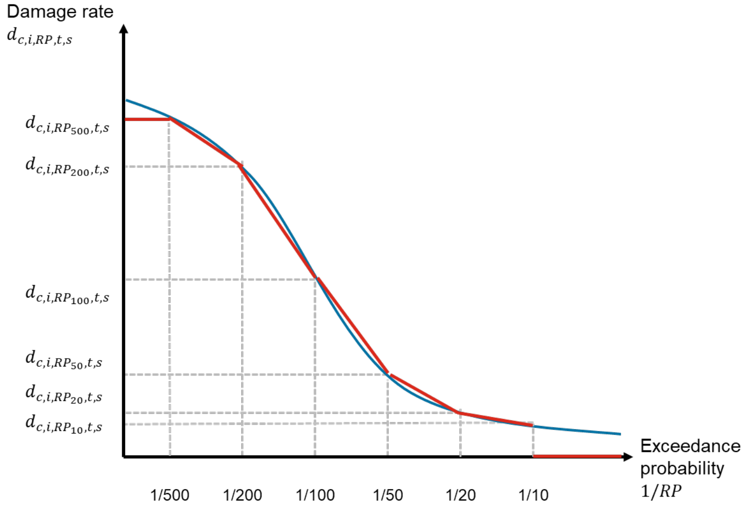
The damage rate for TCs is defined as:

$$d_{c,i,RP_j,t,s} = df_{storms}(wind_{c,i,RP_j,t,s}).$$

Expected annual damage rate can be calculated using the damage rates for different return periods for a given location. Hazard data are available for 10, 20, 50,100, 200 and 500-year return periods, which are denoted as $RP_{10}, RP_{20}, RP_{50}, RP_{100}, RP_{200}, RP_{500}$. The trapezoidal rule is used to approximate the area under the damage-return curve (Figure 6).

[16] The return period is the inverse of the probability of that flood depth or wind level being exceeded in a year. It is common practice to provide hazard severity data for specific return periods and to use the data to estimate the average expected damage per year.

Figure 6: Damage-probability curve



Source: IMF staff calculations

For floods and TCs, the discretized random variable $d_{c,i,t,s}$, with severity measure $sev_{c,i,t,s} \geq 0$, is defined as follows:

$$d_{c,i,t,s} = \begin{cases} 0, if\ sev_{c,i,t,s} < sev_{c,i,RP_{10},t,s} \\ \dfrac{d_{c,i,RP_j,t,s} + d_{c,i,RP_{j+1},t,s}}{2}, \quad if\ sev_{c,i,RP_j,t,s} \leq sev_{c,i,t,s} < sev_{c,i,RP_{j+1},t,s} \\ d_{c,i,RP_{500},t,s}, \ if\ sev_{c,i,t,s} \geq sev_{c,i,RP_{500},t,s} \end{cases}$$

where $j \in \overline{RP} = \{10, 20, 50, 100, 200, 500\}$. In turn, the location-level expected annual damage rate can be calculated as:

$$E[d_{c,i,t,s}] = \sum_{j \in \overline{RP}} \left(\frac{1}{RP_j} - \frac{1}{RP_{j+1}}\right)\left(\frac{d_{c,i,RP_j,t,s} + d_{c,i,RP_{j+1},t,s}}{2}\right) + \frac{d_{c,i,RP_{500},t,s}}{RP_{500}}.$$

4.2 Country-level expected damage rate

Damage rates for specific locations in a country are aggregated to obtain country-level damage rates, which incorporate both hazard and exposure factors. We consider all locations $i = \{1, \dots, n\}$ in a country c for which we have hazard data, so that n represents the number of cells considered in country c. We denote the gridded GDP at a location as $GDP_{c,i,t,s}$, and the total GDP of the country as $GDP_{c,t,s}$. We define the country-level expected damage rate for a specific year and scenario, denoted with $E[D_{c,t,s}]$, as the weighted average of the location-level expected damage rates, where the weight of a location is given by its GDP:

$$E[D_{c,t,s}] = \sum_{i=1}^{n} E[d_{c,i,t,s}] \frac{GDP_{c,i,t,s}}{GDP_{c,t,s}}$$

Key results of the paper in the next section focus on the country-level expected damage rate by time and scenarios, hereafter referred to as damage rate for simplicity. Results are also presented in terms of the change in levels and relative change of the damage rate in a given year and scenario relative to the historical baseline, which represents the hazard for the 10-year period centered around 1995 and GDP in 2000. These are defined, respectively, as

$$E[D_{c,t,s}] - E[D_c](\text{baseline})$$

and

$$(E[D_{c,t,s}]/E[D_c](\text{baseline})) - 1.$$

These variables provide information on whether and how flood and TCs risks are expected to change in the future, as well as how these changes vary depending on the scenario considered.

5. Results

This section discusses floods and TCs damages, respectively, and compares results with other studies. We selected 2050 and 2100 as projection horizons to showcase our results. The year 2050 is important for convergence to net zero in time to successfully mitigate global warming, while 2100 is the furthest year available in the sample at our disposal.

5.1 Floods damages

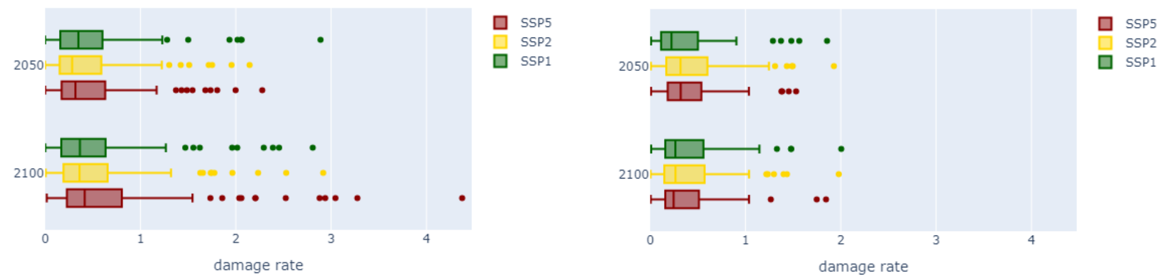
Flood risks are projected to increase for most countries by mid-century. Depending on the scenario considered, 58-67 percent of the countries (representing 74-80 percent of global GDP in 2020) display an increase in the country-level expected damage rate in 2050 relative to the baseline (Table 3). The median damage rate for these countries is 0.28-0.35 percent in 2050 and 0.36-0.41 percent in 2100 depending on the scenario. For the remaining countries, 25-33 percent (representing 18-25 percent of global GDP in 2020) display a decrease in flood risks, and the rest display no change. The median damage rate for these countries is 0.22-0.32 percent in 2050 and 0.25-0.27 percent in 2100 depending on the scenario. The number of countries with rising flood risks increases over time and with global warming, being highest under the SSP5-8.5 scenario.

Table 3: Key statistics for flood damages

Time	Scenarios	# of countries (median country-level damage rate in percent) with increasing flood risks	# of countries (median country-level damage rate in percent) with decreasing flood risks
2050	SSP1-2.6	107 (0.35)	60 (0.22)
	SSP2-4.5	115 (0.28)	52 (0.32)
	SSP5-8.5	123 (0.32)	45 (0.32)
2100	SSP1-2.6	121 (0.36)	47 (0.26)
	SSP2-4.5	117 (0.36)	51 (0.27)
	SSP5-8.5	124 (0.41)	44 (0.25)

The variability of damage rates increases for more severe scenarios at the end of the century for countries with increasing risks. Figure 7 shows the distribution of damage rates, conditional on the damage rate increasing (LHS) or decreasing (RHS) relative to the baseline year. The number of extreme observations increases as well. Most of these are countries characterized by having a small land area, and hence more concentrated flood risks and economic activity, such as small island countries. The distribution of damage rates for countries with decreasing damage rates is more stable across time and scenarios, with the extreme observations scattered in various regions.

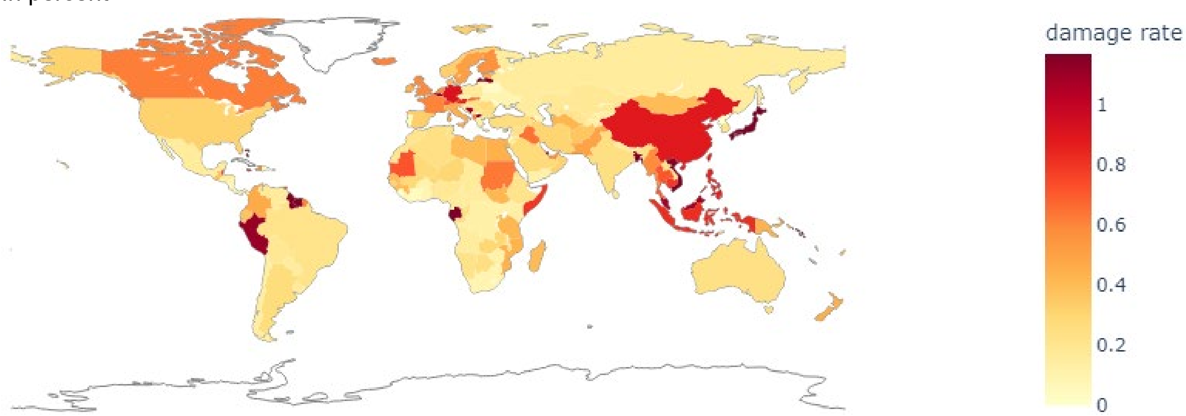
Figure 7: Floods' damage rates for countries with increasing (left-hand panel) and decreasing (right-hand panel) damages relative to the baseline.
In percent



Source: IMF staff calculations

In line with other global studies (Alfieri and others 2017; Dottori and others 2018) we find that floods risks are unevenly distributed across the world. We focus our attention to the SSP2-4.5 scenario, which represents an intermediate emissions scenario. Similar general findings hold for the other scenarios SSP1-2.6 and SSP5-8.5, representing a low and very high greenhouse gas emission scenarios.[17] We find that the countries among the top 10 with the largest damage rates in the three scenarios are in different geographical regions, mostly in tropical and sub-tropical regions, and most have a small land area.

Figure 8: Floods' damage rate for 2050 under SSP2-4.5
In percent



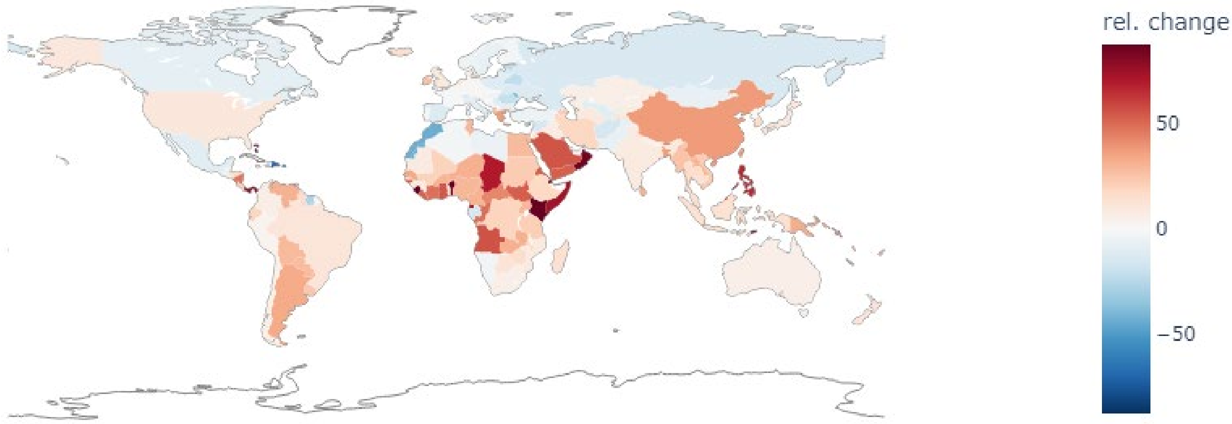
Source: IMF staff calculations

[17] The results are available in Fornino and others (2024).

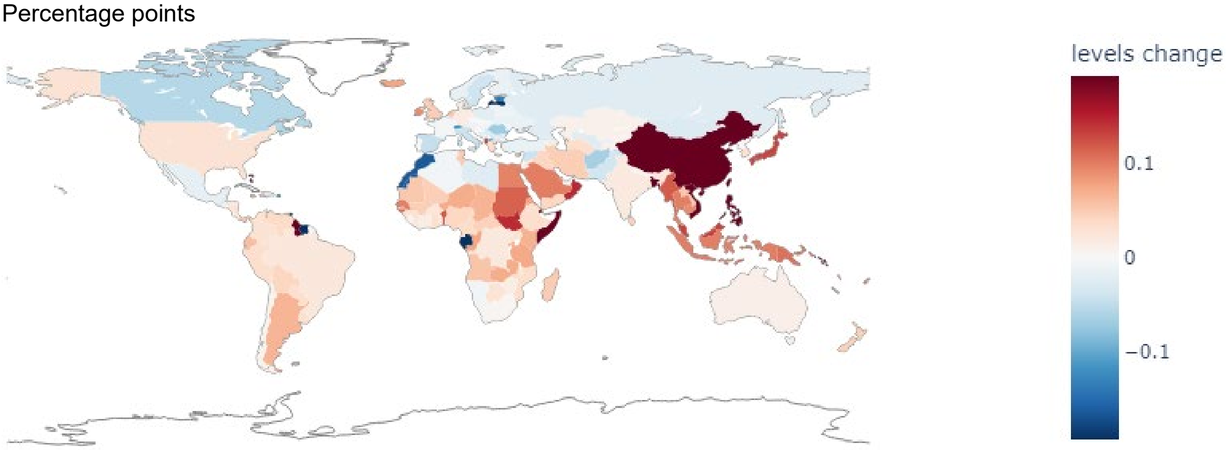
Several countries experience significant relative increases in floods' damages already by 2050, relative to the baseline, as well as by the end of the century. The relative changes have a median of 8.46 and 17.37 percent by 2050 and 2100, respectively. The largest relative changes in damage rates are in South America, Africa, and Southeast Asia. The changes in levels reflect a similar geographical distribution but are generally small, with a median of 0.02 percentage points in 2050 and 0.03 in 2100. It is important to consider all these three metrics together when assessing flood risks for a specific country to have a complete picture.

Figure 9: Floods' damage rate relative and levels change between the baseline and 2050 under SSP2-4.5

Relative change
In percent



Levels change
Percentage points



Source: IMF staff calculations

Country-level damage rate changes over time and scenarios are mainly driven by corresponding changes of the hazard severity (flood depth). For most countries damage rates increase over time and as we consider more severe scenarios. An important driver of this findings is the change in (average) flood depth over time, which displays generally increasing trends across time and scenarios. However, certain regions of the world including in high-latitude regions such as Canada and some parts of Europe, are expected to experience drier climates which can lead to a decrease in riverine floods risks.[18] More details on the drivers of floods hazard damages are provided in Fornino and others (2024).

5.2 Tropical cyclones damages

Most countries historically exposed to TCs will see an increase in damages associated to TCs in future decades (Table 4). We calculate projected damages from TCs for 89 countries that are in regions where such events are in the historical record. Depending on the scenario, 66-67 percent of the exposed countries (with the exposed areas representing 40-42 percent of global GDP in 2020) display an increase in country-level expected damage rate in 2050 relative to the baseline, with a median damage rate for these countries of 0.11-0.12 percent in 2050 and 0.12-0.16 percent in 2100 depending on the scenario (Table 4).[19] In the sample, 16-17 percent (with exposed areas representing 4-5 percent of global GDP in 2020) display a decrease in TC risks. The number of countries with increasing damage rates is highest for SSP5-8.5.

Table 4: Key statistics for TCs damages

Time	Scenarios	# of countries (median country-level damage rate in percent) with increasing TC risks	# of countries (median country-level damage rate in percent) with decreasing TC risks
2050	SSP1-2.6	59 (0.11)	15 (0.0019)
	SSP2-4.5	60 (0.11)	14 (0.0006)
	SSP5-8.5	59 (0.12)	15 (0.0025)
2100	SSP1-2.6	57 (0.12)	17 (0.0015)
	SSP2-4.5	60 (0.13)	14 (0.0012)
	SSP5-8.5	63 (0.16)	11 (0.0007)

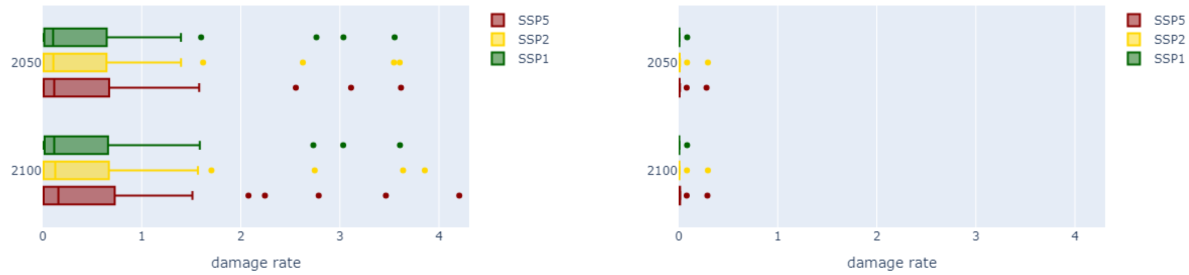
The distributions show that the variability of damage rates increases for more severe scenarios at the end of the century for countries that will see an intensification of risk. In Figure 10, we plot the distribution of damage rates conditional on the damage rate increasing (left-hand panel) or decreasing (right-hand panel) relative to the baseline year. The number of extreme observations is overall stable for countries with increasing and decreasing damage rates. All the extreme values in the Figure 10 (left-hand panel) are island countries; small island countries are among the top five countries by damage rate for 2050 and 2100 in the different scenarios.

[18] While flood risks are expected to decrease for these countries, other hazards such as droughts and wildfires might be increasing. Hence, our results should not be interpreted as physical risks being decreasing overall for these countries.

[19] When only certain parts of a country are exposed to TCs, we account only for the GDP within these grids.

Figure 10: Tropical cyclones' damage rates for countries with increasing (left-hand panel) and decreasing (right-hand panel) damages relative to the baseline

In percent

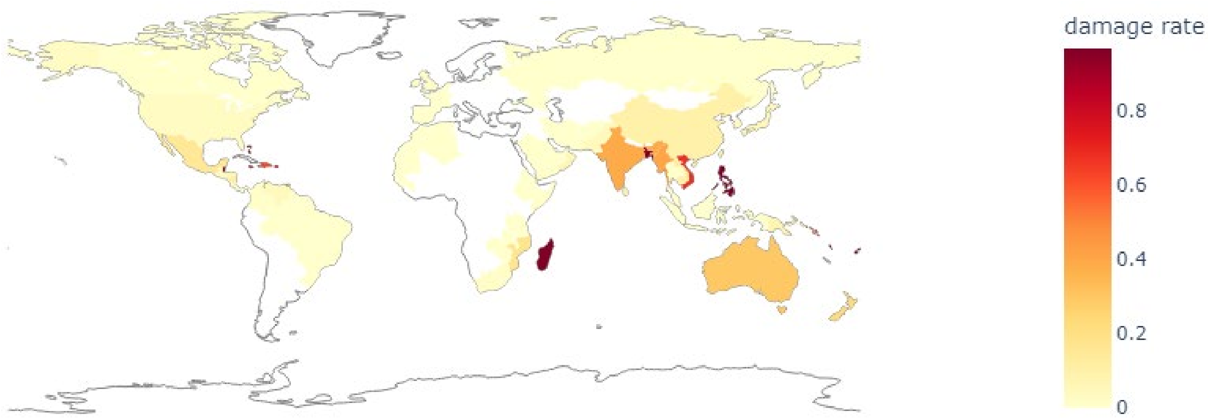


Source: IMF staff calculations

Geographical distribution of TC's damages indicate concentration in certain regions under SSP2-4.5 scenario. Similar general findings hold for the other scenarios SSP1-2.6 and SSP5-8.5.[20] Countries with the highest damage rates are in the Caribbean, South and Southeast Asia, Eastern Africa, and Oceania.

Figure 11: Tropical cyclones' damage rate for 2050 under SSP2-4.5

In percent



Source: IMF staff calculations

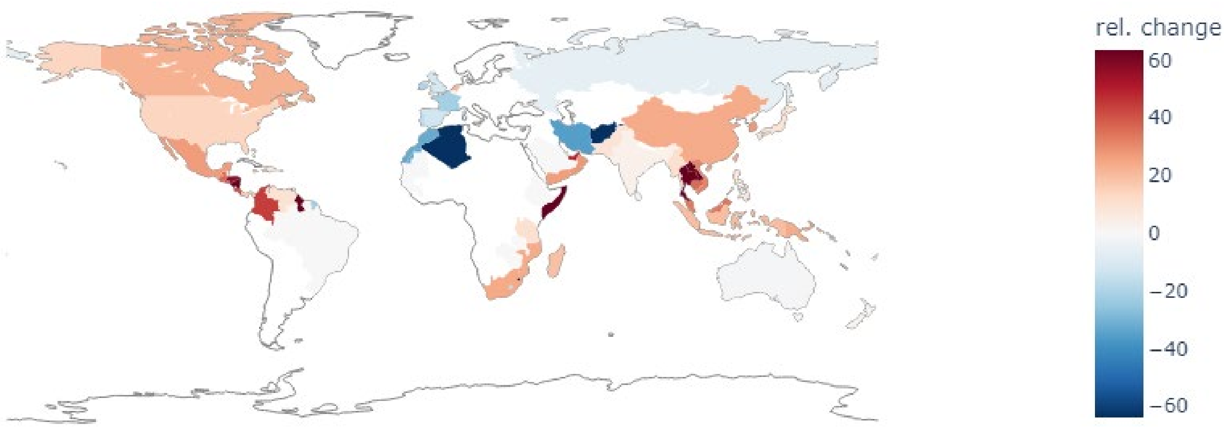
Most countries historically exposed to TCs experience increases in TCs related damage rates. Countries show a relative change median of 6.95 percent by 2050, which reaches 14.20 by the end of the century. North and Central and South America, and countries along the coast from Eastern Africa to Oceania, show the largest changes. High changes in the levels of damage rates are observed in countries in the Caribbean, Southeast Africa, and Southeast Asia. Drivers of TCs hazard damages are provided in Fornino and others (2024).

[20] The results are available in Fornino and others (2024).

Figure 12: Tropical cyclones' damage rate relative and levels change between the baseline and 2050 under SSP2-4.5

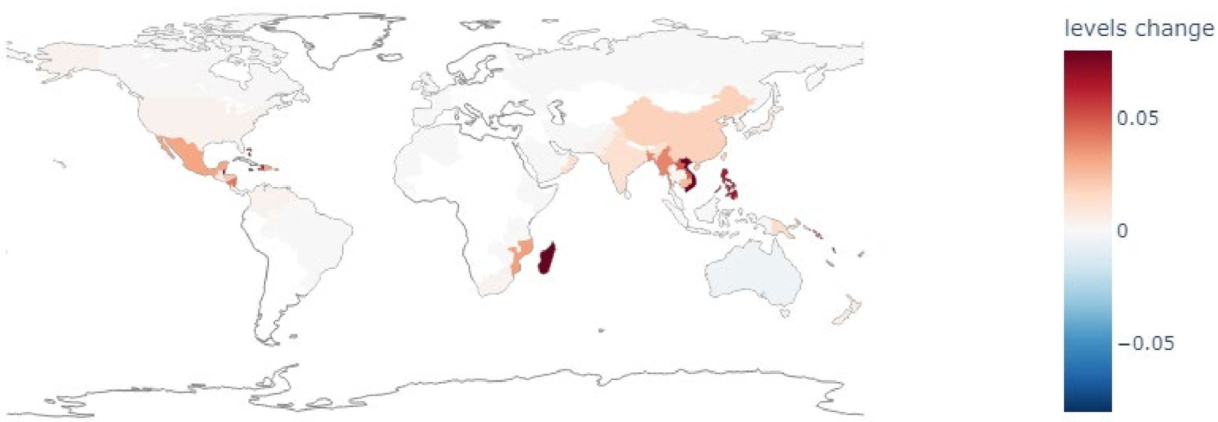
Relative change

In percent



Levels change

Percentage points



Source: IMF staff calculations

5.3 Limitations

While our results provide a useful starting point for the analysis of physical risk, there are several important limitations and challenges. For example, hazards projections are subject to uncertainty from the climate modelling and statistical techniques used to produce them. Adaptation measures, which are an important factor, are challenging to measure and as such not explicitly accounted for in this study.[21] Furthermore, this study analyzed floods and TCs damages in isolation. As explained above, combining damage rates from floods and TCs may prove challenging given the likely correlation between these events. Finally, given the wide range of countries covered, we relied on global datasets. When focusing on a single country calibrated data for the specific country might be more useful. A detailed description of limitations and comparison of results with other studies are available in Fornino and others (2024).

6. Conclusions

The IMF recently integrated climate change considerations in its work program, as climate change is found to be macro-critical.[22] For example, IMF's surveillance work now routinely includes the impact of climate change on fiscal and monetary policy, while a new climate-related financial instrument, the Resilience and Sustainability Facility, has been recently introduced.[23] The focus on climate change also spotlighted some important data gaps. The IMF's Data Gaps Initiative 3 (DGI-3) aims to bridge policy-related data gaps by developing suitable methodologies to develop adequate data.[24] In particular, recommendation #5 of the DGI-3 focuses on forward looking physical and transition risk indicators to assist policymakers in determining the timing and scope of climate policies.

The damage estimates provided by this study are a step towards closing forward-looking, physical risk-related data gaps. The estimates can be used for cross-country assessments of the importance of certain physical risks (floods and TCs) and connect future climate projections to economic and financial sector risk analysis. Nowadays, most of the available estimates are backward looking and often subject to limitations such as missing data. Our results provide forward-looking estimates for floods and TCs risks at country-level based on granular data, expanding the available literature. Finally, as discussed above, these results can be used as inputs to the calibration step of quantitative macroeconomic models that may be used for policy assessments.

[21] Only for floods in the USA, England, the Netherlands, and Germany Jupiter assumes that locations protected by levees will be protected up to and including a 100-year flood.

[22] See Kristalina Georgieva's speech available here.

[23] The Resilience and Sustainability Facility (RSF) provides affordable long-term financing to countries undertaking reforms to reduce risks to prospective balance of payments stability, including those related to climate change and pandemic preparedness.

[24] Further details on DGI-3 can be found here.

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CBRT-IFC WORKSHOP ON ADDRESSING CLIMATE CHANGE DATA NEEDS: THE GLOBAL DEBATE AND CENTRAL BANKS' CONTRIBUTION

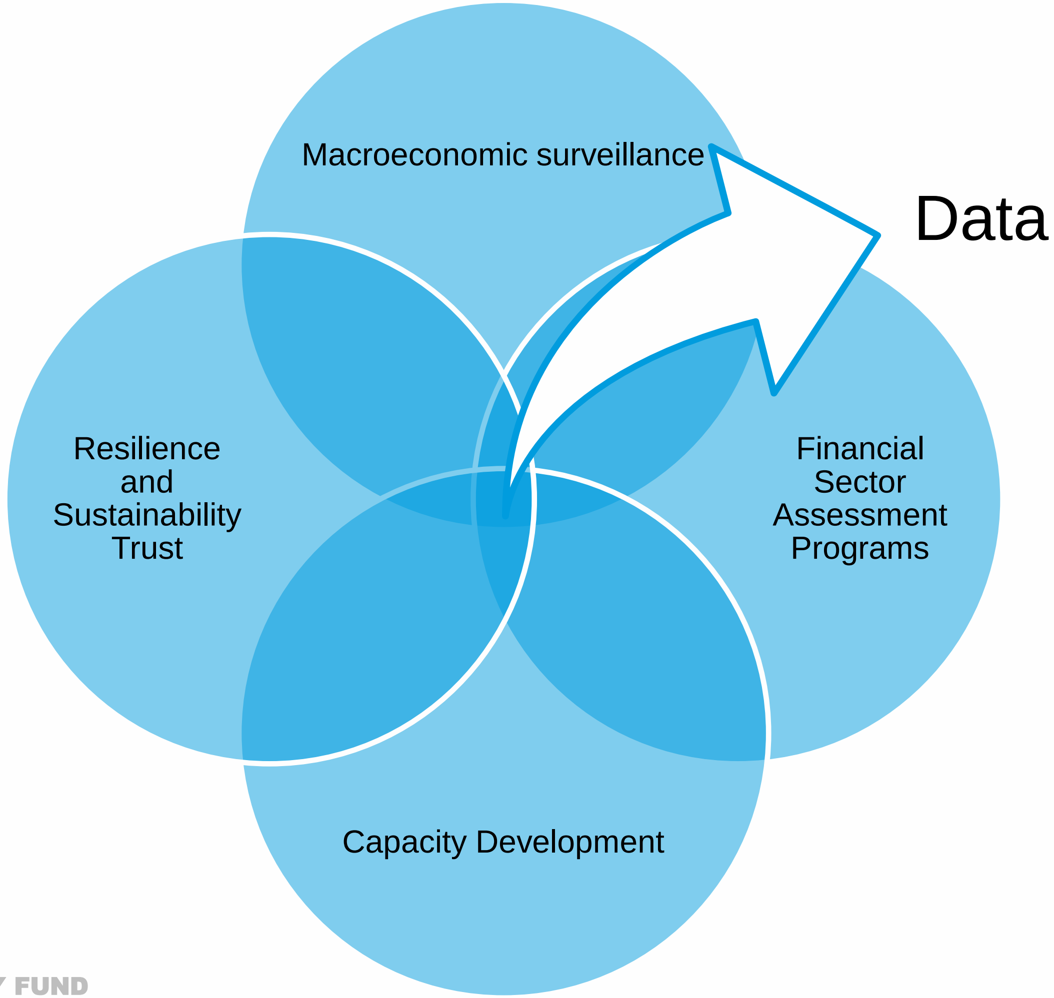
A MULTI-COUNTRY STUDY OF ECONOMIC LOSSES FROM FLOODS AND TROPICAL CYCLONES

MICHELE FORNINO, MAHMUT KUTLUKAYA, CATERINA LEPORE AND JAVIER URUÑUELA LÓPEZ

MAY 6, 2024

IMF's work require high quality, consistent and comparable data

- The IMF is systematically covering climate-related issues through lending, analytical, surveillance, and capacity development work.



Climate related data are critical for the Fund

Informed decisions at local, national, and global levels.

Design **effective policies**.

Economic damages from physical risks: Key variable linking climate scenarios and the risk assessments

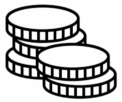
The Resilience and Sustainability Trust

G20 DATA GAPS INITIATIVE 3
DELIVERING INSIGHTS FOR ACTION

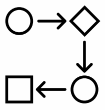
- Diagnostic tool e.g., for FSAP - Stage 1 climate risk framework
- Calibrate macro scenarios for stress testing analysis in FSAPs
- Relevant for RST countries to assess forward looking physical risks
  - Financial risks
  - Fiscal risks
- Input to macro-models:
  - Shock to capital
  - Assess mitigation and adaptation strategies (e.g., DIGNAD)
- Recommendation 5: Forward looking physical and transition risk indicators.
  - to monitor the impact of climate change on the economy and the financial system.

What do we do?

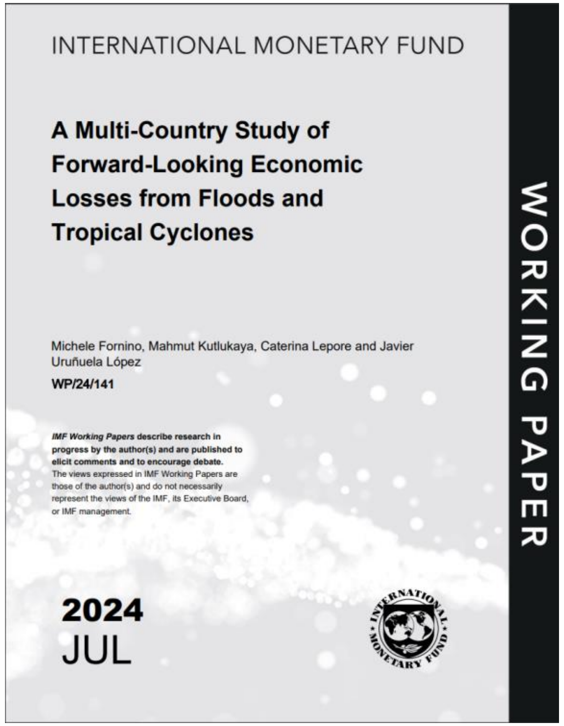
- We estimate forward-looking economic losses from floods and tropical cyclones under three IPCC scenarios.
  - ➢ Floods impacts in 183 countries
  - ➢ TCs impact in 89 countries
    - Why specifically floods and TCs?
      - Data availability – Vulnerability and hazards



- Losses are aggregated at country level building from highly-geographically-disaggregated estimates.



- A simple methodology that is applied to a wide range of countries and customizable for further analysis (e.g., granular exposures data).


INTERNATIONAL MONETARY FUND

A Multi-Country Study of Forward-Looking Economic Losses from Floods and Tropical Cyclones

Michele Fornino, Mahmut Kutlukaya, Caterina Lepore and Javier Uruñuela López

WP/24/141

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2024
JUL

WORKING PAPER

- Working paper available online: A Multi-Country Study of Forward-Looking Economic Losses from Floods and Tropical Cyclones

Hazards Data

JUPITER™

Jupiter provides forward-looking, scenario-based physical climate risk projections at a high geographical resolution for risk management, risk disclosure, and resiliency planning.

	Jupiter
Hazards:	**8 hazards** flood, tidal flood, wind speed, heat, hail, drought, fire, precipitation, cold
Scenarios:	**Three scenarios** SPP1 RCP 2.6, SSP2 RCP 4.5, SSP5 RCP 8.5 and Baseline (1986-2005)
Time series:	Datapoints every 5-years
Horizon:	**2020 - 2100**
Hazards indicators:	**24 metrics**
Uncertainty bound:	Mean, lower and upper bound values
Different return periods:	Only for floods, wind speed and precipitation for 1-in-10-, 20-, 50-, 100- and 500-years
Scores:	Hazard, Change and Overall scores

- The data is provided for specific locations, identified by latitude and longitude.
- 100k locations spread over all IMF member countries.
- Locations were selected to maximize GDP coverage.
  - 97% of global GDP coverage
- The data does not correspond to single events but summarizes the probability distribution or statistics of a parameter related to the hazard in each location.
- Data for different return periods is estimated using the distribution of the maximum values in a year for a specific location.

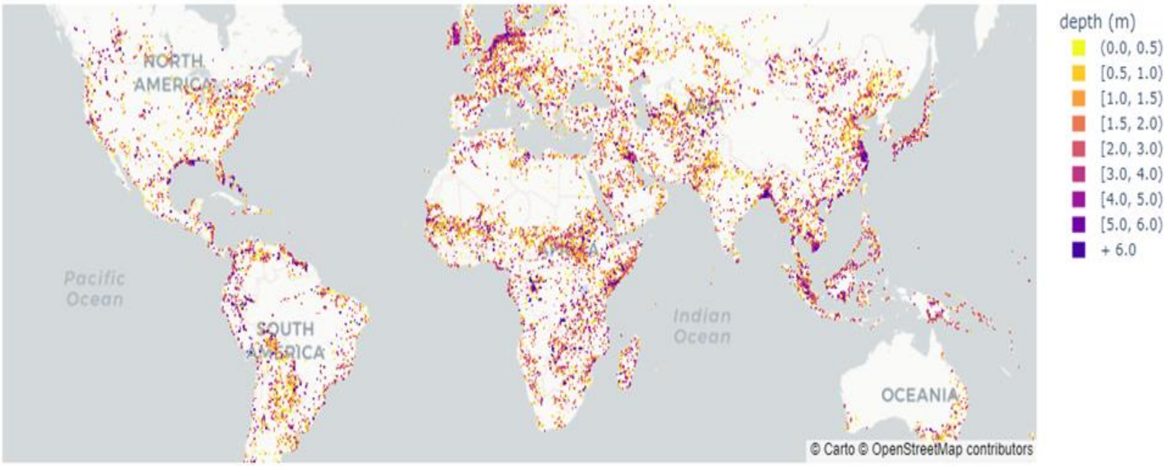
The annex includes the process followed to estimate the climate parameter for the Floods and TCs by Return Period and the process of the 100k locations selection.

Hazards Data: Floods and TCs

JUPITER™

- **Floods (river and coastal) depth and fraction flooded by return periods**.

- **Maximum 1-minute sustained wind speed at 10 meters above ground level by return period**.

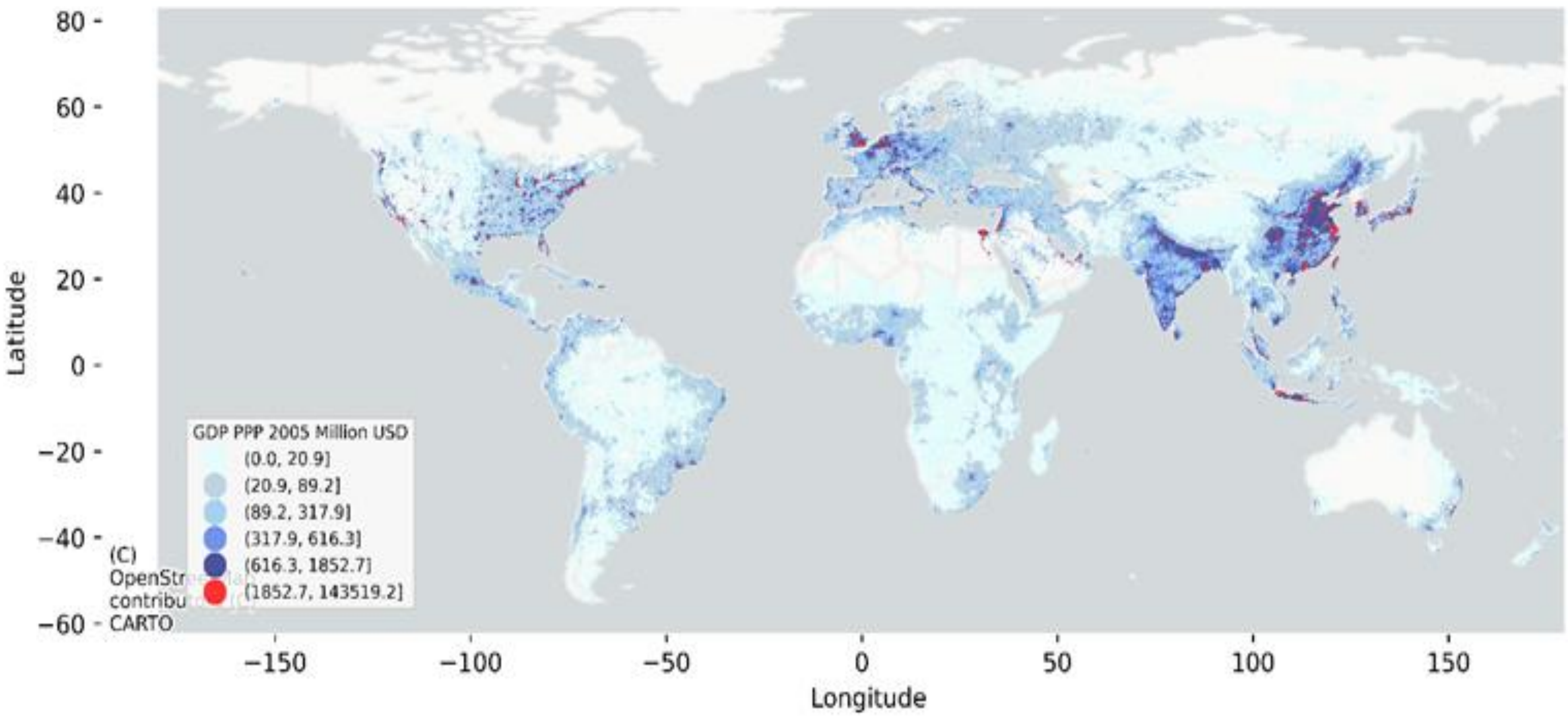


Note: Jupiter flood depth: mean depth meters for 1-in-500 year in 2040 under SSP2 RCP 4.5 (only positive values are reported).

Note: Grids that consider tropical cyclones simulations in wind parameter estimates from Jupiter.

Exposures

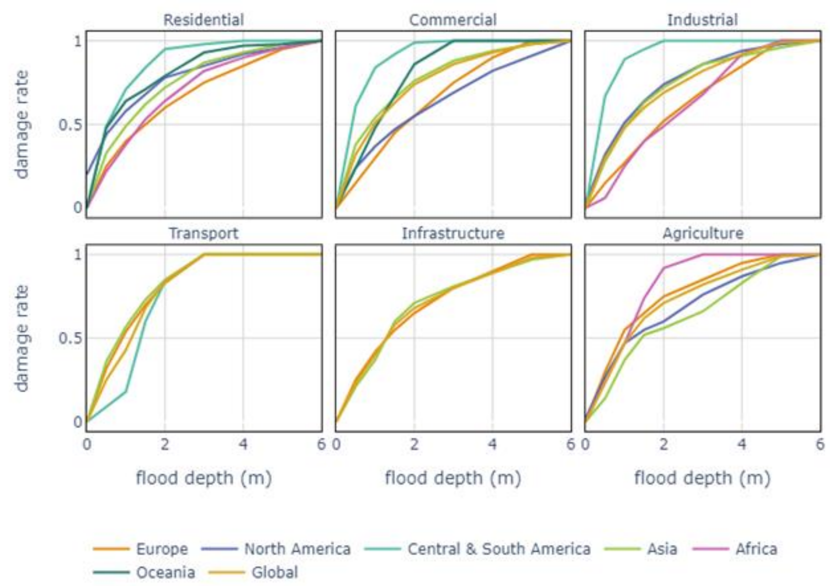
- Murakami et al., (2021) - downscaled GDP projections under all five SSPs at 5 arcminutes for 2010-2100 (10-years intervals).



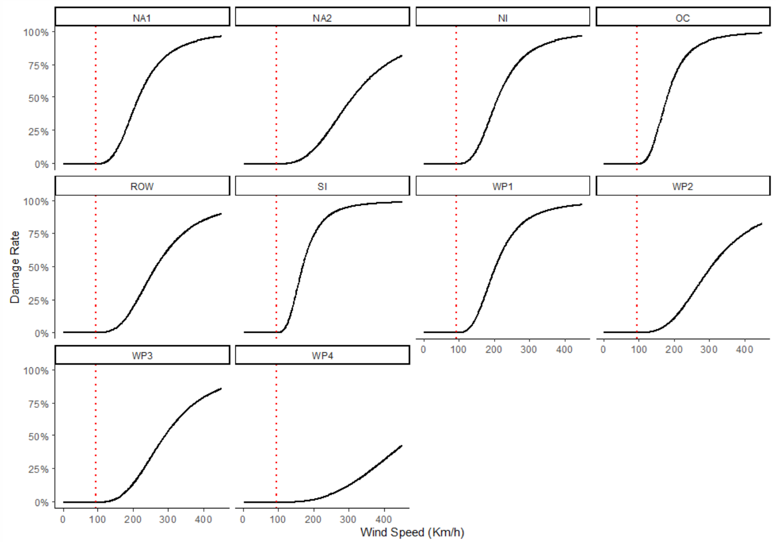
Source: Murakami D, Yoshida T and Yamagata Y (2021) “Gridded GDP Projections Compatible With the Five SSPs (Shared Socioeconomic Pathways)”.
Notes: Gridded GDP under SSP2 in 2040. GDP has been grouped by the following percentiles [0, 50, 75, 90, 95, 99, 100].

Vulnerability: Floods and TCs damage functions

- Huizinga, de Moel, and Szewczyk (2017)
- For each GDP cell: Divide the exposure into built-up and non-built-up based on Copernicus Global Land Operations “Vegetation and Energy” (CGLOPS-1).
  - For built-up areas: Combine the residential, commercial, and industrial damage functions, by equally weighting.
  - For non-built-up areas: Consider agriculture and infrastructure damage functions.

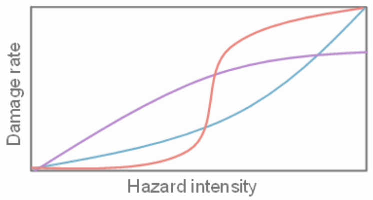


- Eberenz et al. (2021)
- Regionally calibrated damage functions (sigmoidal).
- No directly wind-induced damage is expected for low wind speeds.



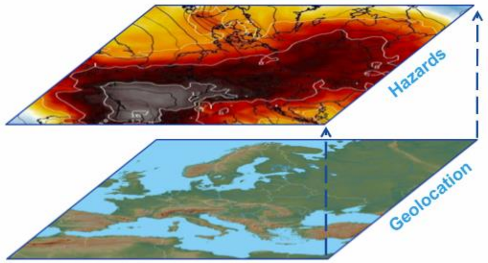
Source: Eberenz et al (2021) and IMF Staff Calculations.
Note: The red dotted line represents the lower threshold of windspeed (25.7 m/s or 92.52 Km/h) below which the damage rate is assumed to be zero.

Methodology



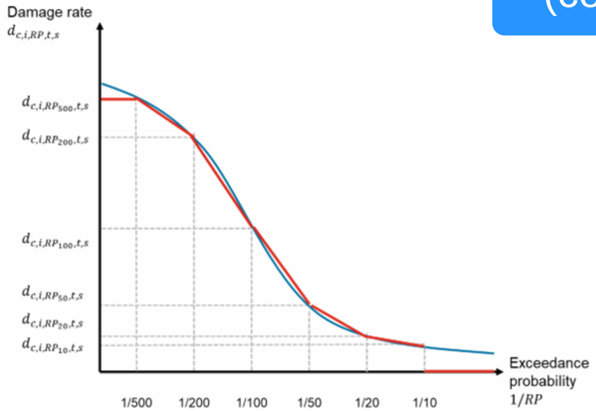
- Damage functions by regions
- Geolocational hazards data (by location and return period)

Damage rate
(location level)

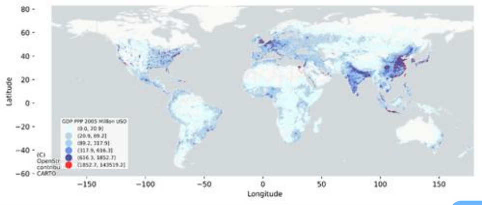


Expected damage rate
(location level)

- Calculate expected annual damage rate based on the damage rates by return period



Gridded GDP



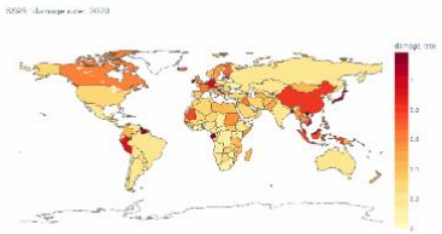
- Aggregate locations damage rates at the country level by linking to GDP exposure

Aggregation
(country level)

Analysis

- Country level damage rate
- Levels change
- Relative change

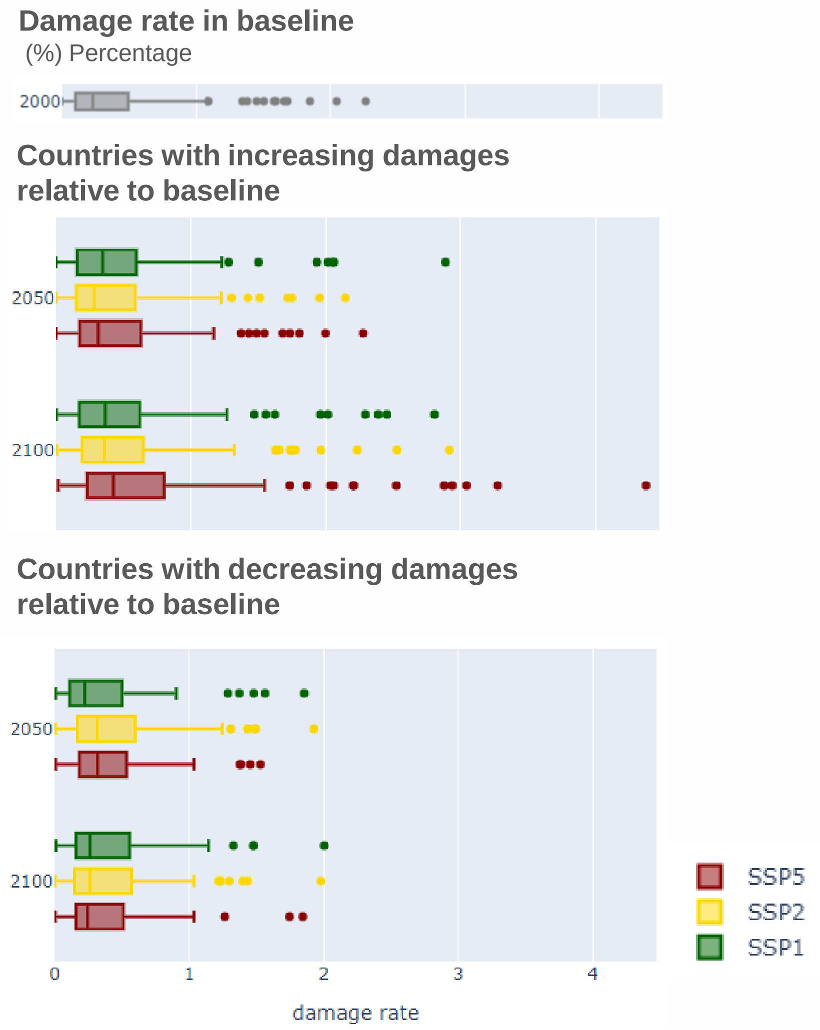
Country damage rates



Damage rates: the loss of value of assets, expressed in percent of the value of those assets before being hit by the hazard.

Flood risks are projected to increase for most countries by mid-century

- **58-67 percent of the countries display an increase in the country-level expected damage rate** in 2050 relative to the baseline (74-80 percent of global GDP in 2020)
- **25-33 percent display a decrease in flood risks** (18-25 percent of global GDP in 2020), and the rest display no change.
- **The variability of damage rates increases for more severe scenarios.**
- **Extreme observations are countries characterized by having a small land area.**

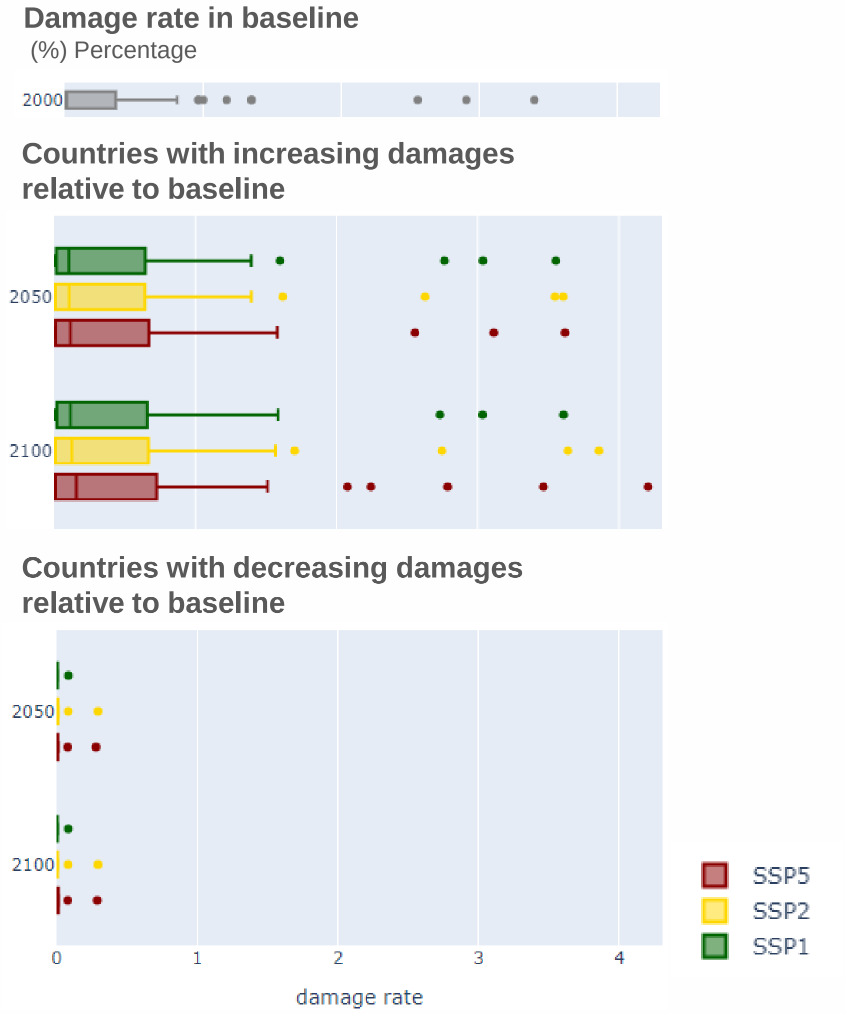


Number of countries
183
107
115
123
121
117
124
60
52
45
47
51
44

Source: IMF staff calculations

Most countries will see an increase in damages associated to TCs in future decades

- **66-67 percent of the exposed countries display an increase in country-level expected damage rate** in 2050 relative to the baseline (40-42 percent of global GDP in 2020).
- **16-17 percent display a decrease in TC risks** (4-5 percent of global GDP in 2020).
- The number of countries with **increasing damage rates is highest for SSP5-8.5**.
- **Extreme values are island countries**, with small island countries being among the top five countries through years and scenarios.



Number of countries

Number of countries
89
59
60
59
57
60
63
15
14
15
17
14
11

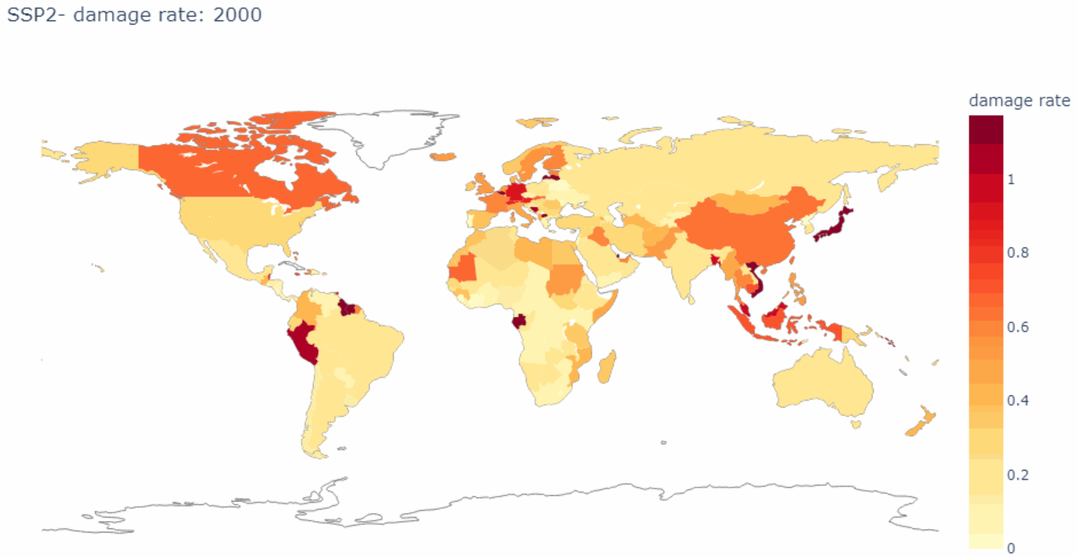
Source: IMF staff calculations

Damage rates

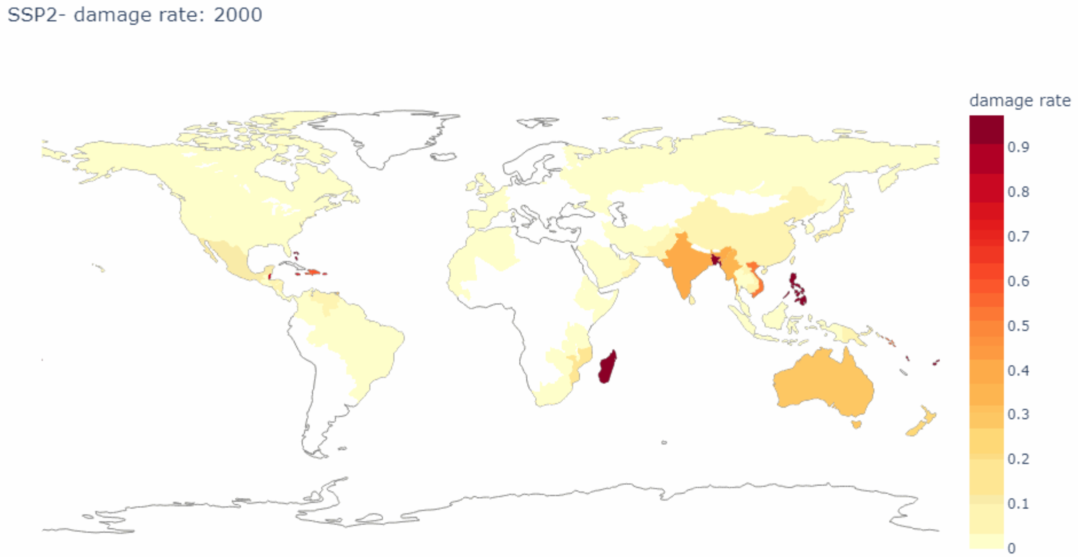
- **Flood risks are unevenly distributed across the world for the SSP2-4.5** scenario; similar general findings hold for the other scenarios, SSP1-2.6 and SSP5-8.5.
- Countries among the **top 10 with the largest damage rates** in the three scenarios are **not in specific geographical region, but most have a small land area**.

- Distribution of TC's damages indicates **concentration in certain regions under SSP2-4.5**; similar general findings hold for the other scenarios, SSP1-2.6 and SSP5-8.5.
- Countries with the **highest damage rates are in the Caribbean, South and Southeast Asia, Eastern Africa, and Oceania**.

Damage rate SSP2, 2000-2100
In percent



Damage rate SSP2, 2000-2100
In percent



Source: IMF staff calculations

A note of caution: caveats and limitations

- Hazards data.
  - Uncertainties in climate modelling.
  - Global dataset with only 100k locations, hence data might not always be representative (in particular for floods).
- Exposures data.
  - Gridded GDP is a proxy of assets/capital.
  - The output to capital ratio (Y/K) is assumed constant within a country, given a lack of granular data for every country.
- Adaptation and mitigation measures.
  - Challenging to measure
  - Not explicitly accounted for in this study (with the exceptions of some countries).
- Damage functions.
  - Calibration
  - Availability
- Hazards are considered in isolation.
  - Caution should be applied if interested in combining damages from different hazards.
- Focus on direct damages.
  - indirect damages not accounted for.