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The Economic Impact of Tropical Cyclones: Case Studies in General Equilibrium

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Abstract

We present a new framework for estimating the long-run economic impacts of natural disasters. Our approach combines a disaster impact model with a general equilibrium model of the economy. We apply the methodology to study the effects of tropical cyclones in the United States, the Caribbean islands, Japan, China, and the Philippines. Our results show that the post-disaster recovery after a single shock can take several decades, with notable cumulative negative effects for frequently affected regions. For instance, cyclone activity reduces long-run aggregate consumption between 0.3 - 22 %, depending on the region. To evaluate the robustness of our results, we extend the model with two additional scenarios. First, we consider endogenous economic productivity gains from specialization. Second, we add a scenario where climate change alters the intensity and frequency of future disasters. The extensions slightly modify the numerical results but do not change the qualitative conclusions.

Keywords: Tropical Cyclones, Climate Change, Growth, General Equilibrium
JEL Codes: C63, O11, Q54

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1 Introduction

Tropical cyclones are among the costliest natural catastrophe events, causing approximately $50 billion of damage per year on average since the year 2000 (EM-DAT, 2020). In addition to their direct effects through loss of lives and destruction of economic assets, tropical cyclones can permanently shape regional growth dynamics by causing prolonged reconstruction periods (Hsiang & Jina, 2014) and forced relocation (Deryugina et al., 2018). Future cyclone impacts might increase for two main reasons. First, the development of coastal regions increases the exposures (Gettelman et al., 2018). Second, climate change could increase cyclones' intensity and frequency (IPCC, 2021). Yet, to our knowledge, there are few and sometimes inconclusive quantitative estimates of the general equilibrium dynamics and the long-term effects of cyclones' strikes on economic growth and its determinants.

We present a new framework for evaluating cyclones' effects on economic growth and welfare. We integrate tools from both the economics and climate science literature. First, we employ a probabilistic disaster impact model to quantify the direct annual losses to regional capital stocks using historical and synthetic cyclone tracks (Aznar Siguan & Bresch, 2019). Then, we feed the estimations of capital destruction into a dynamic, multi-sectoral general equilibrium growth model (Bretschger et al., 2017). With the economic model, we track the components of GDP (investments, consumption, import, and exports), explain the short-term, and appraise the long-term impacts of tropical cyclones on economic growth. Combining both models allows us to derive globally consistent cyclone damage estimates, providing new results on cyclones' long-run general equilibrium effects on economic growth.

We gather data from different sources. The disaster impact model uses satellite data from the International Best Track Archive for Climate Stewardship (IBTrACS) database to model the cyclones' tracks (Knapp et al., 2010). We also use satellite imagery for estimating the spatial distribution of exposed assets based on nighttime light intensities (Román et al., 2018). The spatial resolution of the data enables damage estimates on a detailed 10×10 km global grid. We calibrate the economic model with the Global Trade Analysis Project

dataset. It provides a sectoral decomposition of economic activities and bilateral trade flows for 129 world regions. We focus our analysis on the USA, the Caribbean islands, Japan, China, and the Philippines. These regions are regularly exposed to tropical cyclones and show considerable heterogeneity in size, economic structure, and overall cyclone exposure.

In our setting, the immediate economic response after a cyclone strike is a jump in aggregate investments and a consequent drop in consumption to replace the damaged capital stock. Hallegatte & Przyluski (2010) refer to this tradeoff as *"forced investment"* since the reconstruction efforts can spur economic activity while there is still an overall reduction in welfare. Although the reconstruction in our model is relatively quick, it can take several decades to catch up with the benchmark growth path where no shocks occur. For some economic variables, such as the aggregate output and consumption levels, the post-disaster trajectory remains below the reference path for the entire simulation period.

Our results also highlight the dissimilarity between cyclone impacts on GDP and welfare. Whereas the long-run average drop in consumption ranges from 0.3% in the U.S. to more than 20% in the Philippines, the respective GDP reductions are only 0.1% and 6%. Since consumption is our model's sole determinant of welfare, the GDP changes alone fail to capture the cyclones' full welfare effect. GDP, in this case, masks the opposite impacts cyclones have on individual GDP components, producing artificially small aggregate changes (Mohan et al., 2018).

A long-run quantification of the effect of tropical cyclone shocks on the economy ought to take into consideration *i)* the underlying mechanisms of economic growth and *ii)* climate change. The general equilibrium model allows us to consider growth dynamics based on either physical capital accumulation or knowledge creation with endogenous productivity gains from specialization. Compared to physical capital accumulation, the knowledge-based growth engine dampens the negative cyclone impacts due to higher productivity and additional incentives for investing in new capital varieties. Under this growth specification, in extreme cases, cyclones' long-run effect on GDP can even become positive due to very high investment

levels. The long-run GDP loss that results from the cumulative effect of thirty years of cyclone activity is, on average, roughly 1.5-3 times smaller when knowledge is the driver of growth.

Finally, to study the role of climate change on future cyclone intensity and frequency, we recalibrate the regional cyclone damage distributions under two Representative Concentration Pathway (RCP) scenarios. Under the intermediate RCP4.5 scenario, cyclone intensity increases in the North Atlantic basin (the U.S. Atlantic coast and Caribbean islands) with no changes in event frequency, driving up the total economic losses. On the other hand, cyclone frequency in the Northwestern Pacific basin (Japan, China, and the Philippines) falls with only a slight increase in intensity, leading to lower mean damages at the end of the century. Under the high-emissions RCP8.5 scenario, cyclone damages increase in all considered regions. In the US, for instance, the aggregate capital stock in 2100 under RCP8.5 is approximately 1% lower compared to the same year under constant climate conditions. The Philippines is the most affected region. Climate change could increase consumption losses from cyclones by an additional 11% under such severe warming scenario.

Related literature

The empirical evidence on the link between disasters and economic growth is inconclusive. For instance, Skidmore & Toya (2002) find a positive relationship between climatic disaster frequency and economic growth due to a shift from physical to human capital investments. On the other hand, Hsiang & Jina (2014), analyzing tropical cyclones, finds a negative long-run impact on output and long-run growth with no clear evidence of a rebound effect during the two decades following the catastrophe. Strobl (2012) focus their analysis on the Central American and Caribbean regions and estimate the average hurricane to reduce the output growth rate by roughly 0.84%.

Several works attempt to reconcile the diverging empirical evidence. One explanation is the difference between the *risk* of disasters occurring and the consequences after experiencing

a disaster *strike* (Akao & Sakamoto, 2018; Bakkensen & Barrage, 2018). Whereas disaster strikes can cause output losses due to capital destruction and business interruptions, disaster risk might induce higher precautionary savings, thereby inflating the economy's growth rate. However, Douenne (2020) casts doubt on the possible role of precautionary savings in explaining the positive relationship between economic growth and disasters. A positive relationship would require unreasonably high values of intertemporal substitution elasticity and relative risk aversion when calibrating an endogenous growth model with U.S. data.

Another explanation for the inconclusive empirical findings lies in the relative damages disasters might cause depending on the capital variety. As cyclones are particularly destructive to physical capital, frequent disasters might steer investments towards accumulating human capital instead, thereby enhancing productivity (Skidmore & Toya, 2002; Ikefuji & Horii, 2012; Akao & Sakamoto, 2018). Whether natural disasters mainly affect productive capital stocks or durable consumption goods might also play a role (Strulik & Trimborn, 2019). Losing productive capital harms economic performance, whereas only replacing damaged durable goods can boost output, potentially pushing GDP above the pre-disaster level.

A third possible explanation for positive tropical cyclone impacts is the process of creative destruction. As (Akao & Sakamoto, 2018, p.90) write, *"By destroying old factories and roads, disasters allow new and more efficient infrastructure to be built, providing an opportunity for the economy to transform itself into a more productive one in the long run."* Older capital vintages might also be more susceptible to disaster damages than newer variants, amplifying the effect (Okuyama et al., 2004). However, much depends on the affected region and the economic sector. For instance, Crespo Cuaresma et al. (2008) find that the creative destruction effect only occurs in sufficiently developed economies. According to Loayza et al. (2012), on the other hand, storms can cause significant damage to agriculture, while capital stock upgrades only boost industrial growth. Other mechanisms might also dampen the productivity gains from creative destruction. For instance, small firms might not afford the business interruptions and worker re-training that are often necessary when replacing

lost capital goods with new variants (Hallegatte & Dumas, 2009; Hallegatte & Przyluski, 2010).

Several studies also highlight the role of institutions as a determinant of disaster impacts. Kahn (2005), for instance, finds that countries with higher-quality institutions suffer fewer disaster-related deaths. Education, trade openness, and financial system maturity also matter for disaster resilience (Toya & Skidmore, 2007; Felbermayr & Gröschl, 2013, 2014). The high institutional quality helps endure the initial catastrophe shock and enables faster deployment of resources for reconstruction, thus reducing negative disaster spillovers to the broader economy (Noy, 2009).

Specialized cyclone impact models provide another way to estimate the disasters' long-run economic consequences (Mendelsohn et al., 2012; Gettelman et al., 2018). In particular, future losses might increase as the value of exposed assets goes up with coastal development and as climate change alters the intensity and frequency of disasters. Although rich in spatial detail, these analyses frequently rely on predefined GDP projections to quantify long-term effects. However, as disasters become increasingly harmful, they are more likely to affect consumption, investment patterns, and the underlying growth trajectories. Models featuring fixed economic growth paths cannot – by design – capture these feedback mechanisms.

This chapter contributes to the literature by considering the impacts of cyclone strikes on long-run economic development. Empirical works such as Hsiang & Jina (2014) provide insight into the causal effect of cyclone shocks on GDP. However, they have to deal with several confounding factors and only analyze the effects in partial equilibrium. On the other hand, disaster impact models such as Gettelman et al. (2018) represent cyclone damages in great detail but typically do not capture the economic adjustments over time. Our general equilibrium approach uses the spatial detail of a full disaster impact framework while capturing the endogenous dynamics during the recovery period. All model components rely on global datasets, allowing us to consistently evaluate country-level impacts, incorporating direct damages and the secondary effects through trade linkages. Finally, through changes in

a single elasticity parameter, the economic model can also capture different assumptions regarding the underlying determinants of growth, from a standard capital accumulation setting to an endogenous representation where gains from specialization drive growth.

2 Methodology

This section describes the disaster impact framework, the economic growth model, and the integration of the two systems. We focus our study on five regions: the US, the Caribbean islands, Japan, China, and the Philippines. These regions are frequently exposed to damages from tropical cyclones and vary drastically in the structure and size of their economies. All model components rely on globally consistent datasets, which makes extending the regional coverage of the analysis straightforward.

2.1 Disaster impact model

Quantifying the direct disaster impacts requires data describing the exposures (the spatial distribution of vulnerable physical assets) and the hazards (tracks and wind speeds of historical cyclones). We access both datasets and run the analysis using the open-source CLIMADA (CLIMate ADAptation) platform (Aznar Siguan & Bresch, 2019; Bresch & Aznar-Siguan, 2021).

Exposure

To estimate the annual disaster impacts, we first need to construct the spatial distribution of physical assets in all regions of our study. We use the *LitPop* model (Eberenz et al., 2019), which combines nighttime light satellite imagery with gridded population accounts to obtain a globally consistent estimate of the asset distribution.

Satellite imagery is convenient for its public availability, global spatial coverage, and frequent update schedule. Our nighttime light intensity data comes from NASA's Black

Marble suite, available at a global resolution of approximately 500 meters (Román et al., 2018). Our base year for the nighttime light data is 2016. However, there are some known caveats in using satellite light intensities as a proxy for economic activity. These include, among others, high measurement errors in luminosity data, saturating pixel values, and bright pixels leaking light into their adjacent pixels, thus inflating their value (Eberenz et al., 2019; Chen & Nordhaus, 2011).

To overcome some of the above issues, the LitPop model supplements the nighttime light data with global population estimates from the Gridded Population of the World database (CIESIN, 2016). The database provides globally disaggregated population counts with a resolution of 1×1 km. We give equal weight to the light intensity (Lit) and population data (Pop) and compute the share of the physical assets (A_i) in each pixel i out of N total pixels for a given country as:

$$A_i = \frac{Lit_i^n Pop_i^m}{\Sigma_i^N (Lit_i^n Pop_i^m)},$$

where m and n denote the tuneable share parameters. We use an aggregated resolution of 10×10 km for the final asset exposures. Since we model cyclone damages as destroyed capital stock, we use the value of the produced capital stock from the World Bank wealth accounts as the region-specific indicator for aggregate physical asset value (World Bank, 2018). Hence, the value of physical capital per land area is the product of the country's total capital stock value and pixel-specific capital share. Figure 1 illustrates the resulting distribution of exposed capital stocks for the U.S. state of Florida.

Hazard

Next, we estimate the cyclone damages based on historical cyclone tracks. We obtain the path and the maximum sustained wind speed of each recorded cyclone from 1950 to 2019 from the International Best Track Archive for Climate Stewardship (IBTrACS) database (Knapp et al., 2010). That represents a set of 6,907 tropical cyclone tracks, illustrated in Figure 2.

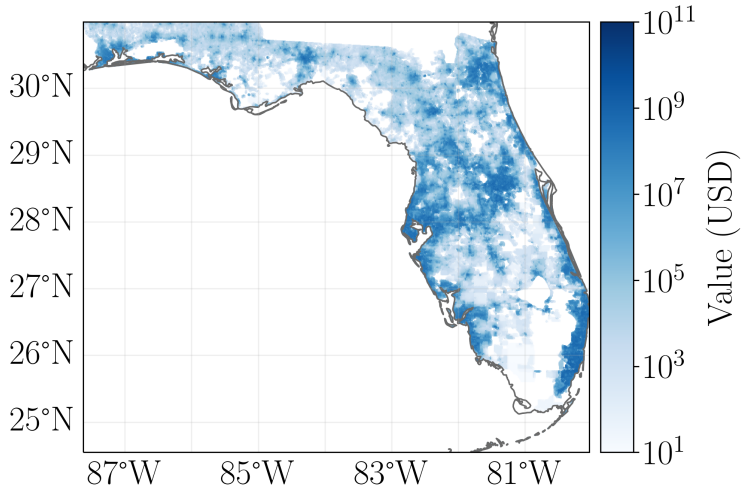

Figure 1: Estimated distribution of capital stocks in the U.S. state of Florida. Each pixel is weighted according to its nighttime light intensity and population density. For each region in our sample, we distribute the aggregate capital stock value according to the pixel-specific shares.

Among them, 1,079 happened in the North Atlantic basin (containing the Caribbean islands and the U.S. Atlantic coast), and 2,040 in the Northwest Pacific Ocean basin (containing Japan, China, and the Philippines). For each historical cyclone in the IBTrACS database, we construct 50 synthetic cyclone tracks that are random walk processes under parameters controlling their distance from the original observations. The synthetic tracks inherit several features from their historical counterparts, such as changes in wind speeds on landfall — which are relevant for the damage computation. These additional synthetic data improve the probabilistic description of the annual cyclone activity compared to using only historical storm tracks. The augmented dataset contains 55,029 and 104,040 events for the North Atlantic and the Northwestern Pacific basin, respectively.

We use maximum wind speed to measure storm intensity as it is a common choice in the literature (Hallegatte, 2007; Pielke Jr., 2007; Narita et al., 2009; Nordhaus, 2010). The storm intensity allows us to construct a proxy for capital destruction caused by each cyclone. We use the damage function from Emanuel (2011) to translate cyclone wind speeds into capital destruction. The fraction of capital damaged by storm j at location i, and time t, $\delta_{i,j,t}$ varies

with wind speeds exceeding a threshold value:

$$\delta_{i,j,t} = \frac{v_{i,j,t}^3}{1 + v_{i,j,t}^3}, \tag{1}$$

where,

$$v_{i,j,t} \equiv \frac{\max\{V - V_{thresh}, 0\}}{V_{half} - V_{thresh}}. \tag{2}$$

Similar to Emanuel (2011), we set the wind speed below which there are no damages at $V_{thresh} = 25.7m/s$. The parameter $V_{half} = 74.7m/s$ determines the wind speed that destroys 50% of the capital stock Sealy & Strobl (2017). We aggregate the output $\delta_{i,j,t}$ by the year of each event j to compute statistics such as the mean and the standard deviation of damage for all regions.

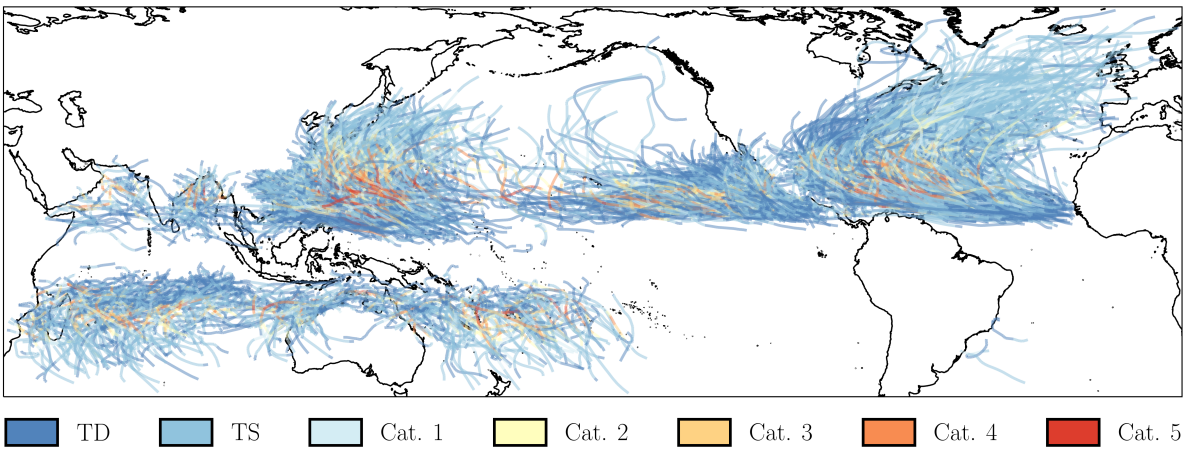

Figure 2: Global tropical cyclone activity for 1950-2019 based on the IBTrACS database (Knapp et al., 2010). The intensity levels from lower to higher wind speeds are tropical depression (TD), tropical storm (TS), and hurricanes of category 1 to 5 (Cat. 1-5) on the Saffir-Simpson hurricane wind scale.

Ultimately, we want to represent cyclone damages as annual economic shocks. Although the synthetic cyclone tracks extend our pool of disaster events, our dataset still only contains estimates for seventy annual cyclone damages (from 1950 to 2019). The small number of data points in our sample may limit us from having a good overview of tropical cyclones' impact on the economy. To overcome this limitation, we enlarge our sample on annual

damage estimates by creating a set of synthetic years. More specifically, we create 5,000 additional synthetic years of tropical cyclone activity by assuming the disaster frequency to follow a Poisson distribution Emanuel (2013); Bakkensen & Barrage (2018) and then resampling a corresponding number of random events from the collection of synthetic and historical cyclone tracks. Appendix E provides additional details on the data generation process.

Table 1 summarizes the main damage statistics from the set of 5,070 years of damages for each region of our study. We detect no sign of systematic bias between the historical and the augmented sample. The three statistics we use to compare the two samples are roughly similar although the augmented sample has a much broader set of yearly damage estimates. Table 1 also highlights the considerable regional variation in relative cyclone-induced capital damages, ranging from an additional depreciation rate of 0.15% in the U.S. to 2.67% in the Philippines.

	USA	CAR	JPN	CHN	PHL
	Historical sample				
% of events that cause damages	29.84	13.07	19.41	33.28	22.21
Mean damage, $\bar{\delta}_{TC}$ (%)	0.15	0.59	1.10	0.40	2.67
Std. of damages, σ_{TC}	0.21	1.51	1.82	0.51	6.43
	Augmented sample				
% of events that cause damages	26.82	13.50	18.68	28.74	21.64
Mean damage, $\bar{\delta}_{TC}$ (%)	0.09	0.65	0.84	0.40	2.73
Std. of damages, σ_{TC}	0.14	1.67	1.51	0.50	5.67

Table 1: Yearly cyclone damage statistics region. The historical sample only contains the cyclone observations between 1950-2019. The augmented sample corresponds to the 5,070 years that we simulate from the historical tracks augmented by their 50 respective synthetic tracks.

2.2 Economic model

This section describes the main features of the economic growth model, as well as the datasets used for model calibration.

Numerical framework

We employ a dynamic, multi-regional and multi-sectoral numerical general equilibrium model based on Bretschger et al. (2011) and Bretschger et al. (2017). The production structure of the economy consists of *i*) final good producers, *ii*) producers of intermediate goods, and *iii*) producers of intermediate composites. The separation between intermediate goods and intermediate composites is one of the framework's key features. It enables switching on endogenous productivity gains from increasing capital varieties with a simple change of model parameters. The time horizon of the theoretical model formulation is infinite with discrete increments but approximated using a finite number of periods in the numerical implementation. A detailed technical description of the model is available in Appendix A.

Each regional economy consists of a forward-looking representative household, maximizing the discounted sum of utility from consumption. Households also own all firms and factors of production. Labor and capital are mobile across sectors, and all countries are open to trade. We model international trade using the Armington (1969) assumption, which treats goods produced in different regions as imperfect substitutes. As opposed to an assumption of small open economies, our trade specification allows changes in regional production and demand patterns to affect world prices. Consequently, disaster impacts in one country can spill over to other regions via global supply chain links. The model consists of nested constant elasticity of substitution (CES) blocks that combine domestic and imported goods from various sectors into consumption aggregates and production input bundles.

Economic accounts and calibration

We calibrate the economic model using the Global Trade Analysis Project (GTAP) database (Narayanan et al., 2012). GTAP provides unified base-year economic accounts for 129 regions, 57 commodities, and five primary production factors. The dataset describes the flow of goods across sectors and regions and how the regional agents allocate them between final demand, intermediate production inputs, or trade. We use the GTAP data as a static snap-

shot of the economy and extrapolate —using a set of exogenous parameter assumptions— an initial balanced growth path on which all sectors grow at the same rate. The dataset also includes sectoral greenhouse gas emissions, which allows the construction of additional climate policy scenarios. Appendix B contains details on the sectoral and regional aggregation of the raw GTAP data.

In addition to the dollar-valued economic accounts from GTAP, the model requires various sector- and region-specific elasticity values. The elasticity estimates for consumer demand and the substitution elasticities between different production inputs are among the most important determinants of our numerical results. We use estimates mainly from the MIT Economic Projection & Policy Analysis model (Paltsev et al., 2005) and Narayanan et al. (2012). The numerical values are available in Appendix C.

2.3 Model integration

In summary, we can describe our modeling framework as follows. We generate data on cyclone activity in all five regions of our study based on historical and synthetic cyclone tracks. By combining the cyclone tracks data with a damage function from wind and the spatial distribution of economic assets, we compute the capital destruction caused by each cyclone in the sample. We aggregate this capital destruction estimate by year and obtain a distribution over the annual capital depreciation due to cyclone exposure for each economy. We consider the region-specific cyclone shocks as a yearly and unexpected increase in the natural depreciation level of capital. We calibrate our economic growth model to a balanced growth path in the absence of cyclones. Finally, introducing the shocks, we can run counterfactual simulations and compare how the economic trajectories differ between the reference growth path and the one affected by cyclones.

Numerical general equilibrium models provide a flexible instrument for analyzing the multi-sectoral adjustment of prices after an economic shock. Their deterministic structure, however, imposes some limitations on modeling the impacts of rare natural disasters such as

tropical cyclones. Introducing disaster impacts in an arbitrary time step t, without further adjustments, would imply that for the periods preceding t, all agents in the model have perfect information over the timing and magnitude of the upcoming event. Agents would then react to disasters with optimal precautionary savings, producing an overly optimistic description of disaster impacts.

We choose a solution algorithm that maintains the forward-looking nature over the model's economic variables but treats the disaster realizations as unanticipated shocks. To model an unanticipated disaster occurring at time τ, we first solve for a reference equilibrium path without shocks from the initial period t_0 to the terminal time T, such that $t_0 < \tau < T$. We then fix all the variables from the reference equilibrium until τ, and re-run the model with the shock. In other words, we only allow the agents to adjust their behavior in the period $t \geq \tau$. In the newly constructed sub-model, from τ to T, the shock occurs in the first period of the simulation. Agents have no chance of anticipating the shock. We combine the solution from the reference equilibrium and the one from the sub-model by using the reference equilibrium values for $t < \tau$ and the sub-model values for $t \geq \tau$. In the absence of shocks, this alternative method produces the same numerical results as only simulating the reference equilibrium path.

3 Results

We analyze the simulation results in four parts. First, we study the impulse response of the economy after a single year of cyclone activity. It illustrates the primary economic mechanisms and provides intuition for the recovery period dynamics under a single fixed-magnitude shock. Second, for the paper's main results, we run the model with recurring probabilistic shocks to study the cumulative long-run disaster effects. We then provide two sensitivity scenarios to scrutinize the main long-run modeling assumptions. We first recalibrate the general equilibrium model to introduce endogenous productivity gains from

specialized capital varieties. Finally, we alter the cyclone damage distribution to analyze how climate change might affect the intensity and frequency of future disasters. We present all numerical results as counterfactual simulations to a no-shock baseline economy.

3.1 Impulse response to a single cyclone shock

Consider first the effect of an individual cyclone shock. Figure 3 decomposes the general equilibrium response into expenditure-side GDP contributions. We simulate a shock at time $t = 5$ that increases capital depreciation compared to a year without disaster events. The magnitude of the shock for all countries is one standard deviation above the regional mean, as described in Table 1. [1] The overall picture is relatively similar for all regions. GDP falls on impact, followed by a catch-up period of faster growth and reinvestment. The higher depreciation increases the marginal productivity of capital, bringing greater returns on investment. Consequently, savings increase as a response to the reconstruction efforts. However, the increase in savings comes at the expense of lower consumption, reducing welfare. The magnitude of the investment jump ranges from 0.06% in the U.S. to more than 4% in the Philippines.

International trade linkages are another determinant of the recovery period's shape and duration. Following the disaster, the trade balance deteriorates in all regions. Countries use more imports to facilitate reconstruction efforts while exports suffer from the lost local production capacity and increased domestic investment demand. Thus, the trade channel highlights the additional flexibility that international openness can provide in the disaster aftermath. For most regions, the trade volumes converge relatively quickly to their original levels, closing the gap between the benchmark trajectory within a few years of the shock.

For the post-disaster periods, capital depreciation returns to its natural level, and the regional economies gradually return to their original steady-state path. Reconstruction is often relatively fast. For instance, reaching the pre-disaster capital stock level takes three

[1] The shock distributions have a strong positive skew, producing relatively low mean damages.

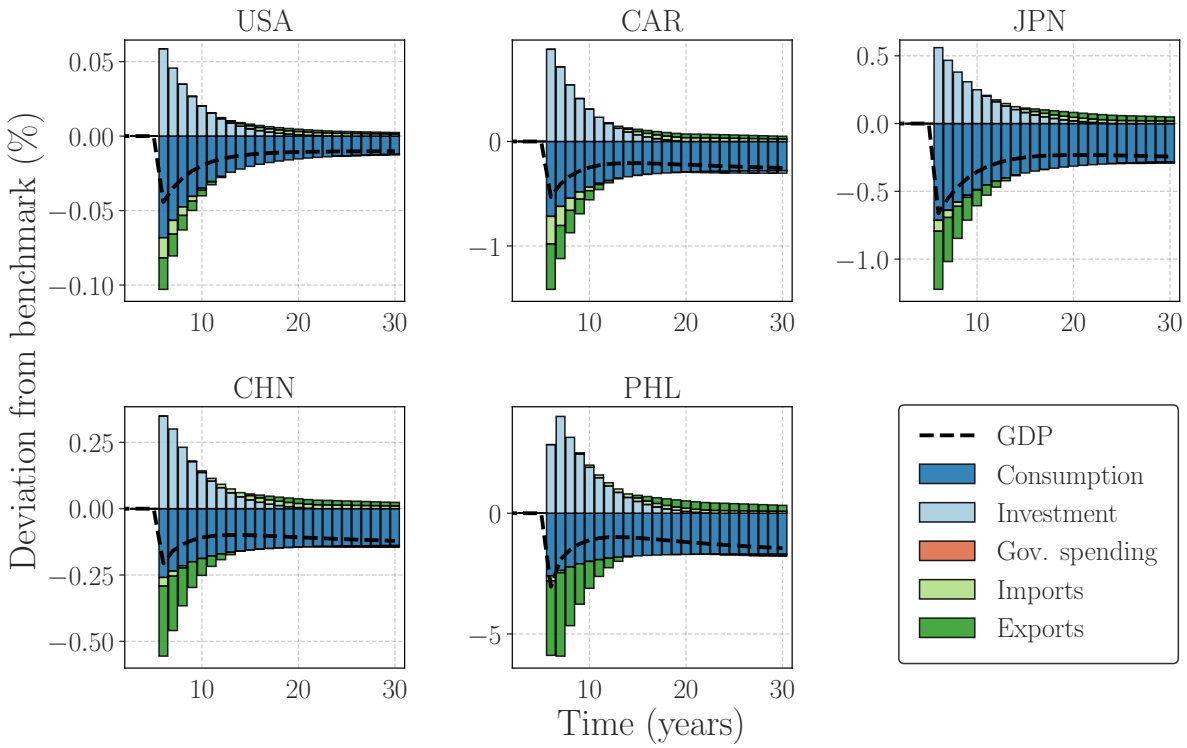

Figure 3: Impulse response to a single cyclone shock. The magnitude of the shock for all countries is one standard deviation above the regional mean, as described in Table 1. The change in GDP is the sum of changes in aggregate investments, consumption, government expenditure, and the trade balance. All values are relative to a benchmark economy that grows on a balanced growth path without shocks.

years in the Philippines, whereas the U.S. already reinvests the lost capital amount in the first post-disaster period. However, compared to the benchmark economic trajectory that evolves without interruptions, the catch-up recovery period can take up to several decades. Although the aggregate capital stock eventually reaches the reference trajectory, households spread the required additional investments over multiple years to avoid a drastic drop in consumption. As a result, the consumption (and GDP) levels remain permanently below the reference path in all regions. The long-run gap is 0.01% in the US, but up to 1.6% in the Philippines.

That the recovery back to the pre-disaster growth path can take decades might sound surprisingly slow. In reality, however, several factors can contribute to long recovery times.

The first is the limited reconstruction capacity. With insufficient financial resources, a rapid reconstruction can only come with a sudden drop in consumption, prolonging the recovery. Technical limitations, such as the lack of a sufficient reconstruction workforce, are also possible. Moreover, business cycles can further amplify the effects, particularly if the disaster strikes during a high cycle where available resources are already scarce (Hallegatte & Przyluski, 2010). There can also be significant production factor rigidity, especially between-sector capital immobility, that complicates reconstruction efforts. The long recovery times are a common finding both in empirical works (Hsiang & Jina, 2014) and studies based on numerical general equilibrium simulations (Gertz et al., 2019).

Governments usually assume an active role in the disaster aftermath. Yet changes in public demand are absent from the results shown in Figure 3. Since the cyclone impacts in our framework occur solely through losses in capital stock, the primary recovery mechanism is reinvesting. However, our numerical model makes no distinction between the private sector and government investments. Therefore, the numerical results we present on post-disaster aggregate investment levels include the increased public investment demand. Although our framework is flexible enough to consider additional transfer schemes from the government to households (Gertz et al., 2019), we ignore them since the shock process does not automatically trigger any. Introducing these measures would require additional ad-hoc assumptions on government payouts. In reality, however, transfers such as medical payments and unemployment support can significantly increase in response to disaster events (Deryugina, 2017).

Finally, disasters' consequences unquestionably go beyond their impacts on physical assets and direct loss of lives. In addition, disasters can cause traumatic injuries, stress, or diseases that have long-lasting effects on welfare and productivity. However, these effects are likely to vary depending on the local institutions and the type of disaster. As this paper focuses on constructing a globally consistent modeling framework, we omit these effects from the numerical model but acknowledge that their unmeasured cost can be substantial.

3.2 Cumulative effect of recurring cyclone shocks

Whereas the previous section illustrated the model dynamics, we now turn to the paper's main results of quantifying the long-run cumulative cyclone impacts. We randomly draw annual capital depreciation shocks from the augmented disaster event pool constructed in Section 2.1. We run 500 Monte Carlo simulations of the economic model for each region and provide aggregate results over a 30-year period.

When cyclone shocks are frequent and random, the economy is constantly adjusting to new conditions. Capital depreciation is therefore always above its natural level, hampering growth. Figure 4 shows the cumulative impact on the aggregate consumption levels. In the US, where direct cyclone damages typically only occur in specific regions, the cyclone-induced consumption drop is approximately 0.3% after 30 years of simulation. However, the reduction can be significantly greater for more thoroughly exposed regions. For instance, consumption in the Caribbean islands is more than 3% below the baseline level, whereas, in the Philippines, the long-run reduction exceeds 20%.

Compared to prior works, the magnitude of the results appears reasonable. For instance, Anttila-Hughes & Hsiang (2013) find that typhoon exposure in the Philippines leads to an approximately 7% drop in the next year's household expenditure. On the other hand, the U.S. Congressional Budget Office estimates the country's annual hurricane damages at 0.16% of GDP (CBO, 2016).

Appendix D illustrates the results for additional economic variables. Investment levels are consistently above the no-disaster baseline trajectory for all regions, reflecting the dynamics explained in the stylized single-shock scenarios above. Similarly, industry output and capital intensity remain consistently below the reference values for the entire simulation horizon.

Notably, compared to the changes in aggregate consumption and investments, the impacts on GDP appear relatively small. For instance, the long-run GDP in the U.S. is only 0.1% below the reference growth trajectory, compared to a drop of 0.3% in consumption. The difference highlights that the long-term welfare implications of tropical cyclones are likely to

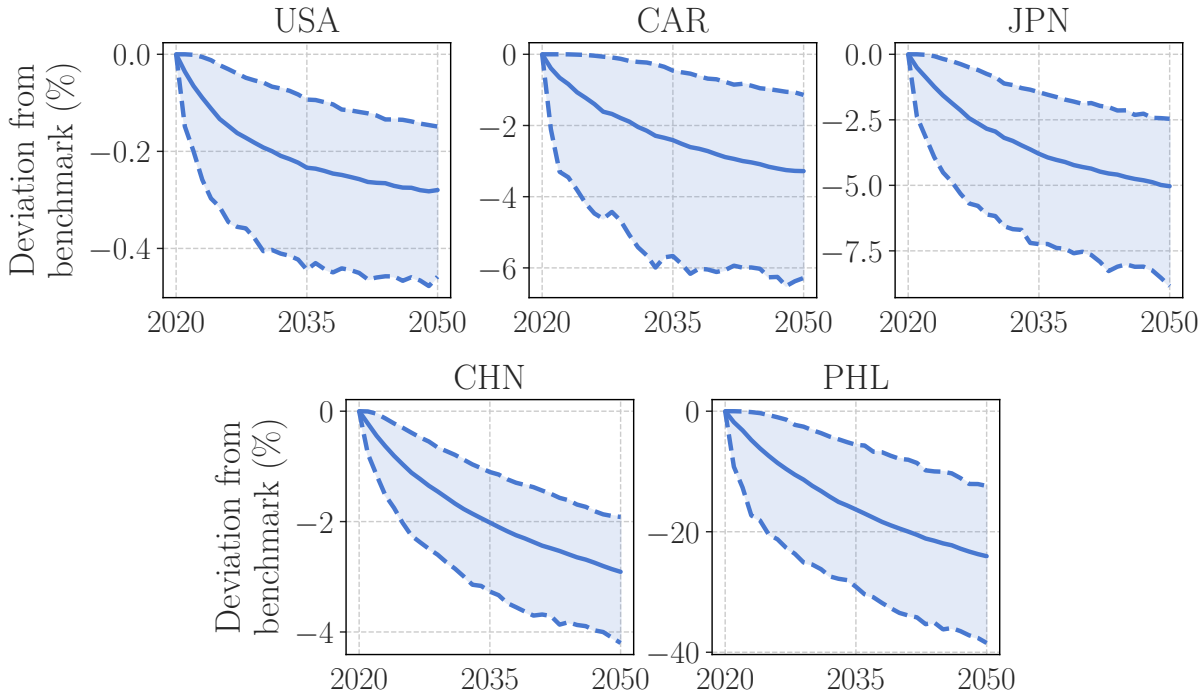

Figure 4: Change in aggregate consumption by region with recurring cyclone shocks. The solid lines represent the means of 500 Monte Carlo runs. The shaded areas denote simulations between the 5th and 95th percentiles. All values are relative to benchmark economies that grow on a steady-state path without shocks

be higher than what the GDP impacts alone might suggest. Mohan et al. (2018) also find similar results, where collapsing the cyclone effects to only GDP masks the heterogeneous impacts they might have on macroeconomic activity through changes in consumption, investment, and trade patterns. Nevertheless, the unambiguous finding here is that cyclone activity negatively affects GDP, consumption, and welfare in all regions. In terms of equivalent variation, taking cyclone activity into account reduces welfare by 0.35% in the US, 4.25% in the Caribbean islands, 6.2% in Japan, 3.4% in China, and 30.3% in the Philippines.

3.3 Productivity gains from specialization

Our regional sample consists of heterogeneous countries in terms of size and economic structure. It is therefore important to consider alternative assumptions regarding the underlying drivers of growth as an explanation for varying disaster effects. Different growth mecha-

nisms might allow, for instance, some countries to exhibit a post-disaster growth spurt due to "build back better" dynamics. In contrast, others may never recover to their original growth trend. [2] The capital structure is also likely to play a role. Richer economies might have a higher share of knowledge capital, less susceptible to natural disasters, attenuating the overall negative cyclone impacts.

We model the endogenous productivity gains with a simple model reparameterization. Instead of considering capital only as the physical stock, we make a broader interpretation of a capital composite that includes both the physical stock and the immaterial knowledge capital. Intermediate firms can invest in new sector-specific capital varieties. The varieties are imperfectly substitutable, such that the intermediate firms make positive profits due to a monopoly mark-up. Similarly to the growth dynamics in Romer (1990), firms investing in new varieties receive a perpetual blueprint for their product. Compared to the previous section, where growth is solely due to physical capital accumulation, there is now an additional incentive for conducting R&D investments. The positive spillovers from specialization, on the other hand, enhance the overall economic growth rate.

We simulate the economies with the same shock realizations as in the previous section but now turn on the endogenous gains from specialization. We again use 500 Monte Carlo runs and report the results after 30 years of simulation. The resulting growth trajectories vary significantly compared to the previous section, as summarized in Table 2. Overall, the endogenous growth engine substantially dampens the negative impacts of repetitive cyclone events. Under gains from specialization, post-disaster investments increase more than under the standard case. As a result, the capital stock, although damaged by the same amount, gets rebuilt faster, leading to lower capital losses in the long run. The existing capital stock is also more productive, affording a faster reconstruction and limiting the overall drop in consumption and welfare.

For most regions, the GDP reduction after 30 years of cyclone activity is more than

[2] For a thorough discussion on the hypotheses regarding possible post-disaster growth trends, see Hsiang & Jina (2014).

	USA	CAR	JPN	CHN	PHL
ΔConsumption	-23.18	-24.50	-26.30	-22.30	-17.21
ΔInvestments	0.60	7.72	24.60	14.80	51.73
ΔCap. intensity	-7.25	-4.22	-6.55	-5.73	-12.96
ΔCapital Stock	-15.45	-24.88	-25.20	-24.67	-44.90
ΔIndustry output	-45.54	-66.04	-63.01	-59.73	-84.22
ΔGDP	-45.03	-57.16	-56.73	-59.24	-87.95
ΔWelfare	-16.28	-20.40	-20.45	-17.87	-14.77

Table 2: Change in mean tropical cyclone impacts after 30 years of simulation under endogenous gains from specialization. All values denote percentage change relative to the cyclone impacts in Section 3.2. For instance, compared to the scenario without productivity gains, aggregate long-term consumption drop in the U.S. is 23.18% smaller, the reduction in capital stock 15.45% smaller, and the increase in investments is 0.60% larger. Welfare impacts are measured in terms of Hicksian equivalent variation.

50% smaller than under the standard scenario. The consumption losses are between 17% to 26% smaller than before, depending on the region. For extreme shock realizations, GDP impacts under endogenous productivity gains can even become temporarily positive for the most affected regions, driven by the higher investment levels and increasing capital returns. However, even under these extreme realizations, the overall consumption impact remains negative. GDP only appears higher as the destroyed capital stocks are not measured in GDP, whereas the reconstruction efforts are. Even with gains from specialization, the long-run average GDP impacts remain negative for all regions.

3.4 Effects of climate change

Climate change likely increases the intensity and the frequency of weather-related extreme events (IPCC, 2020). At the same time, economic growth and coastal development can increase future cyclone impacts by increasing the value of exposed assets (Gettelman et al., 2018). For instance, the U.S. Congressional Budget Office estimates the country's hurricane damages to rise from the current levels of USD 28 billion per year to USD 39 billion by

2075, attributing half of the increase to climate change and another half to further coastal development CBO (2016). Therefore, in the final scenario, we study how our framework's main long-run economic variables react to the assumptions on future climate trajectories.

In the following, we extend our model horizon from 30 to 80 years and simulate up to the year 2100 for the climate change impacts to take effect. We run the model in ten-year increments to compensate for the resulting increase in computational cost. We consider two possible greenhouse gas concentration pathways: the RCP4.5 with intermediate emissions and the high-emission RCP8.5 scenario. We calibrate a new damage distribution for each region and concentration scenario by tuning the cyclone intensity and frequency values based on Knutson et al. (2015). Appendix F documents the steps in more detail.

To ensure that the economic growth model is also consistent with the RCP scenarios, we implement a carbon tax on both the baseline economy and counterfactual simulations. As a result, the emissions from our simulated economic trajectories approximately match those used in the disaster impact estimation. That is, the percent change we show is the comparison between the value of an economic variable in 2100 under a growth scenario (without productivity gains from capital variety) with a carbon tax and the distribution of cyclones damages of the current climate (we call it the benchmark growth path) and the same growth and tax scenario but with the cyclones damages modified by climate change (RCP4.5 or 8.5). This way, the economic conditions are the same under the benchmark and the climate change growth paths. We isolate the sole effect of the change in the cyclone distribution. The initial estimates of the tropical cyclone damages are the ones of Table 1.[3] We conduct 100 Monte Carlo runs for each climate change scenario, randomly drawing shocks in each period as in the previous section.

Table 3 reports the main results at year 2100. The first thing to note is the regional variation in the cyclone damage statistics. In the RCP4.5 scenario, the cyclone intensity in the North Atlantic basin (Caribbean Islands and the U.S. Atlantic coast) increases by 4.5%,

[3]We provide details on the new cyclone distribution under the two RCPs and in all our regions of study in Appendix F.

whereas there is no significant change in cyclone frequency (Knutson et al., 2015). As a result, in our framework, the mean cyclone damage $\bar{\delta}_{TC}$ increases both for the U.S. and the Caribbean Islands. For the Northwestern Pacific Ocean basin (China, Japan, Philippines), on the other hand, the cyclone frequency falls by 34.5%, but the intensity increases by 5.5%. These counter-acting factors first increase the mean damage in the corresponding regions until the year 2060 before lowering it for the next decades up to 2100. Therefore, the results of the RCP4.5 scenario for the pacific regions should be interpreted with caution. They hide non-linearities over the whole period 2020-2100.

For the RCP8.5 scenario, the estimated change in cyclone intensity is based on a linear interpolation from Knutson et al. (2015) using relative radiative forcings as scaling terms. We use Emanuel (2013) for the changes in cyclone frequency. In RCP8.5, both the frequency and intensity of cyclones increase in all considered ocean basins, leading to large increases in the projected damages in our economic model. Table 3 shows particularly striking results in the North Pacific basin where this increase is the largest. China, which would suffer less from cyclones under RCP4.5 than under the current the climate, bears a change in consumption losses that is close to ten times larger than the U.S. under RCP8.5. In RCP8.5, just like in RCP4.5, Japan endures the largest decrease in its welfare due to climate change.

All in all, the comparison of results from both climate scenarios shows non-linearities in the climate system to the climate change process. The comparison emphasizes that different regions may have to adapt differently according to the future state of the climate.

Statistics (% change)	USA	CAR	JPN	CHN	PHL
	RCP4.5				
Mean damage, $\bar{\delta}_{TC}$	30.16	24.03	-9.73	-12.66	-13.47
Std. of damages, σ_{TC}	25.94	18.72	5.86	-1.22	-2.18
Consumption	-0.10	-1.18	-0.06	0.32	-0.31
Welfare	-0.05	-0.78	-1.87	0.28	-1.11
Capital stock	-0.85	-1.07	-1.87	0.56	0.58
GDP	-0.02	-0.16	-0.48	0.13	-3.07
	RCP8.5				
Mean damage, $\bar{\delta}_{TC}$	112.92	87.95	166.83	151.50	126.55
Std. of damages, σ_{TC}	93.11	66.39	115.51	103.22	81.92
Consumption	-0.19	-2.10	-7.10	-1.74	-5.90
Welfare	-0.11	-1.78	-4.12	-1.43	-3.64
Capital stock	-0.96	-5.95	-25.95	-6.42	-24.10
GDP	-0.08	-0.83	-3.11	-0.46	-1.76

Table 3: Change of tropical cyclone impacts in 2100 under different climate scenarios compared to estimates under constant climate. Welfare impacts are measured in terms of Hicksian equivalent variation.

4 Discussion

We have constructed a modeling framework to represent probabilistic, region-specific cyclone damage functions in a dynamic economic growth model. That enables us to isolate how the impact of tropical cyclone strikes affects economic variables over time in general equilibrium. The chapter's main goal was to set up a globally consistent modeling framework. However, several possible extensions remain for studying additional cyclone impact channels or the role of public policies in disaster impact management.

First, we have excluded the role of adaptation. In our model, local adaptation measures could affect either the cyclone impact function (for instance, the construction of sea walls, mangrove restoration, or the implementation of new building codes) or the distribution of exposed assets (such as spatial planning in high-risk areas), and therefore have interesting broader impacts in the economy.

In our coupled system, tropical cyclones only enter the economy through damages on

capital stock. In reality, cyclone impacts are much more complex. Disaster strikes might reduce the economy's total factor productivity via, say, electricity blackouts (Bakkensen & Barrage, 2018) or business interruptions (Gertz et al., 2019). Moreover, there are externalities that are not directly captured by the general equilibrium response. For instance, a drop in post-disaster quality of public services might make attracting workers more difficult, directly affecting the recovery period dynamics (Hallegatte & Vogt-Schilb, 2016).

Throughout, we have considered countries as the units of regional aggregation. With detailed enough economic accounts, it is possible use even higher regional detail. For instance, Carrera et al. (2015) use a sub-national model to study flood impacts in Italy, and Gertz et al. (2019) use a numerical general equilibrium model calibrated to a single city. This might better allow studying local questions such as labor reallocations or comparing adaptation alternatives.

Finally, we acknowledge some caveats. First, by design, our model economy is always in equilibrium. This might be unrealistic especially in the time periods directly after a disaster where bottlenecks and misallocations are likely to happen in all markets. That might make the early stages of the recovery path in our model overly optimistic, ignoring some of the real-world rigidities. We also assume that the regional distribution of exposed assets remains constant throughout the simulation periods. In reality, there might be a considerable shifts if people and firms leave the most exposed areas or with gradual urban expansion. We have also explicitly focused on tropical cyclone impacts, although the simultaneous effects from cyclones, storm surges, and on the long term even sea level rise, might give a more complete picture of the disaster impacts. The wind impact model parameterization in Eq. (2) also relies on data solely from the US, and might not be directly applicable to other regions.

5 Conclusion

We develop a methodology for estimating the long-run economic impacts of tropical cyclones. Our framework features a dynamic general equilibrium economic growth model and a probabilistic disaster impact model. Our coupled system allows us to consider region-specific damage functions and post-disaster recovery profiles. We focus on the effects of cyclone strikes that enter the economy through damages to capital stock.

We apply our framework to five regions: the US, Caribbean islands, Japan, China, and the Philippines. The general findings are similar for all regions. Cyclone shocks harm GDP, consumption, and welfare as they increase capital depreciation, thereby forcing higher investments for reconstruction. After 30 years of simulation, the aggregate capital stock in the U.S. is 0.5% smaller compared to a no-shock baseline path. In the Philippines, which is the most affected region, the difference is almost 13%. Consistent with previous literature, the recovery period after a cyclone shock towards the original steady-state growth path is long and can take up to decades. Our results also highlight the need to disentangle GDP and welfare impacts. The GDP effects often appear artificially small since they aggregate cyclones' many heterogeneous macroeconomic impacts with opposite signs.

Assumptions on the economic growth engine and future climate change affect the long-run numerical results but do not change the overall qualitative findings. When endogenous productivity gains from specialization drive growth, cyclone impacts are smaller but still unambiguously negative. Under the RCP4.5 climate change scenario, cyclone damages increase in the North Atlantic Ocean basin (the US, Caribbean islands) but fall slightly in the Northwestern Pacific basin (China, Japan, the Philippines). Under a high-emission scenario (RCP8.5), cyclone damages increase in all regions from the current climate conditions.

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Appendices

A Economic growth model

We employ a dynamic, multi-regional, and multi-sectoral numerical general equilibrium model following Bretschger et al. (2011) and Bretschger et al. (2017).

A.1 Production

In each region, we model the economy's production structure as the interaction between three agents: *i*) final good producers, *ii*) producers of intermediate goods, and *iii*) producers of intermediate composites. The markets for the final goods and intermediate composites are perfectly competitive, whereas the market for intermediate goods can also be monopolistic. Figure A.1 provides an overview of the nested production structure.

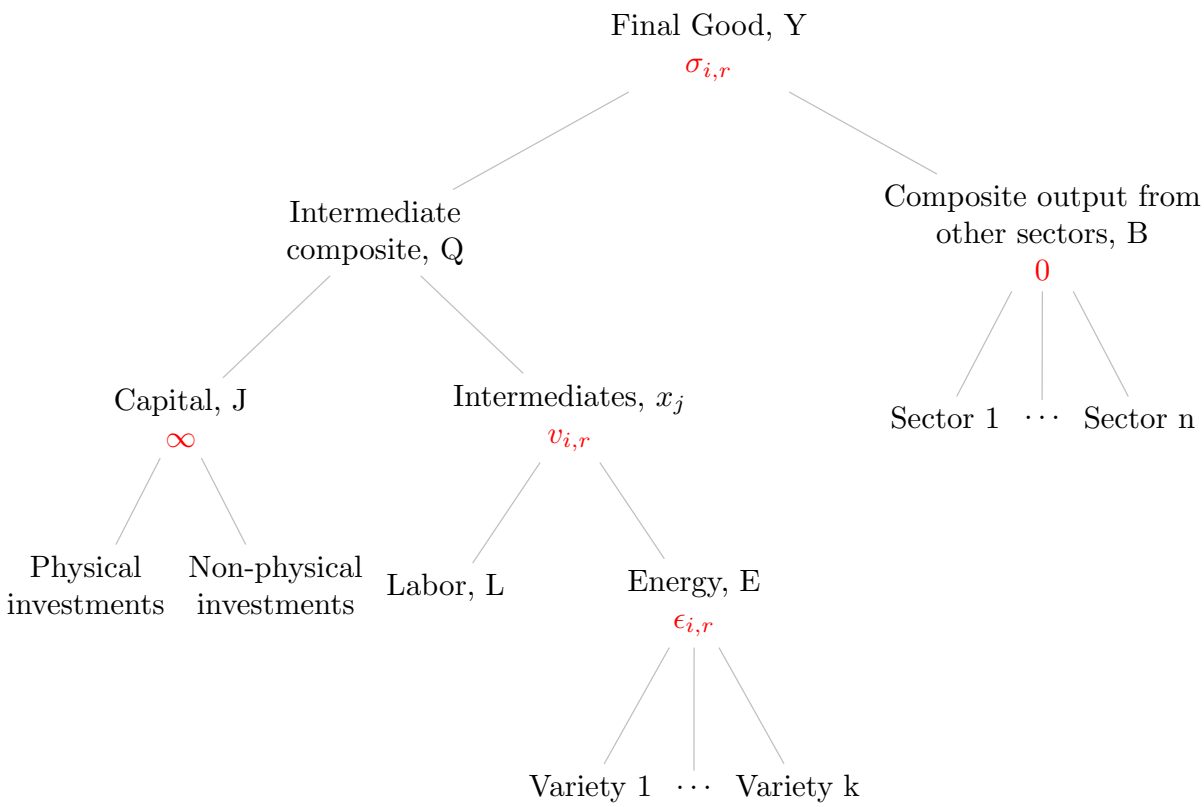

Figure A.1: Production structure of the economy. Substitution elasticity within a sub-nest is highlighted in red.

Final good production

The final good producers in sector i, region r, and time t produce output $Y_{i,r,t}$ according to the following constant elasticity of substitution (CES) production function:

$$Y_{i,r,t} = \left[\alpha_{i,r} Q_{i,r,t}^{\frac{\sigma_{i,r}-1}{\sigma_{i,r}}} + (1-\alpha_{i,r}) B_{i,r,t}^{\frac{\sigma_{i,r}-1}{\sigma_{i,r}}} \right]^{\frac{\sigma_{i,r}}{\sigma_{i,r}-1}}. \tag{A.1}$$

Above, $Q_{i,r,t}$ is the sector-specific composite intermediate good. $B_{i,r,t}$ denotes the composite final good from all other sectors needed for producing i, capturing how different sectors (and regions) link through a complex network of value chains. Outputs from different sectors are assembled to $B_{i,r,t}$ according to a Leontief-type production function, that is, in fixed proportions. Share parameters $\alpha_{i,r}$ determine the value shares between $Q_{i,r,t}$ and $B_{i,r,t}$ in the production function. The elasticity of substitution between the two types of inputs is $\sigma_{i,r}$. All elasticity and share parameters are sector- and region-specific.

In each sector, the final good producer maximizes profits in a perfectly competitive market according to:

$$\max_{Q_{i,r,t}, B_{i,r,t}} p^Y_{i,r,t} Y_{i,r,t} - p^Q_{i,r,t} Q_{i,r,t} - p^B_{i,r,t} B_{i,r,t}, \text{ w.r.t A.1}, \tag{A.2}$$

where $p^Y_{i,r,t}$, $p^Q_{i,r,t}$ and $p^B_{i,r,t}$ denote the prices of final goods, intermediate composite, and other inputs, respectively. Solving Eq. (A.2) and combining the resulting optimal demand functions for $Q_{i,r,t}$ and $B_{i,r,t}$ yields the following condition for the optimal input use:

$$\frac{Q_{i,r,t}}{B_{i,r,t}} = \left(\frac{\alpha_{i,r}}{1-\alpha_{i,r}} \right)^{\sigma_{i,r}} \left(\frac{p^B_{i,r,t}}{p^Q_{i,r,t}} \right)^{\sigma_{i,r}}. \tag{A.3}$$

According to Eq. (A.3), an increase in the price of one input type will increase the share of the other input in the optimal bundle. For most of the goods, we assume that the substitution elasticity $\sigma_{i,r}$ is below unity, which implies imperfect substitutability between different input types.

Intermediate composite production

In the second step of the production nest, producers of a sector-specific intermediate composite assemble their output $Q_{i,r,t}$ by combining different varieties of individual intermediate

goods according to a standard Dixit-Stiglitz CES production function:

$$Q_{i,r,t} = \left[\int_{j=0}^{J_{i,r,t}} x_{j,i,r,t}^{\kappa} dj \right]^{\frac{1}{\kappa}}, \tag{A.4}$$

where $x_{j,i,r,t}$ denotes the jth type of intermediate good variety that is available in sector i. $J_{i,r,t}$ denotes the sector-specific capital stock. We treat new innovations (that is, new varieties of $x_{j,i,r,t}$) as new varieties of capital, so new types of $x_{j,i,r,t}$ also imply an expansion in the capital stock. This specification gives us two channels through which the intermediate sector can induce growth in the overall economy. One is to produce a larger amount of any single variety $x_{j,i,r,t}$ by employing more labor and energy. The other is to expand the number of available varieties through investments in the sector-specific capital stock. The parameter κ measures the substitutability between different varieties, or equivalently, the gains from specialization. Setting $0 < \kappa < 1$ allows the increasing number of varieties to enhance final sector productivity in an endogenous manner (Romer, 1990), whereas $\kappa = 1$ switches off these productivity gains.

The producer of the intermediate good composite $Q_{i,r,t}$ maximizes profits on a competitive market, taking all prices as given, and solving:

$$\max_{x_{j,i,r,t}} p_{i,r,t}^{Q} Q_{i,r,t} - \int_{j=0}^{J_{i,r,t}} p_{j,i,r,t}^{x} \, x_{j,i,r,t} \, dj, \text{ w.r.t A.4}, \tag{A.5}$$

where $p_{j,i,r,t}^{x}$ is the price of intermediate varieties. Solving the optimization problem in Eq. (A.5) determines the optimal demand for $x_{j,i,r,t}$ as:

$$x_{j,i,r,t} = \left(\frac{p_{i,r,t}^{Q}}{p_{j,i,r,t}^{x}} \right)^{\frac{1}{1-\kappa}} Q_{i,r,t}. \tag{A.6}$$

From here onwards, we assume that all varieties of the sector-specific intermediate good are perfectly symmetrical, i.e. $x_{j,i,r,t} = x_{i,r,t}$.

Intermediate good production

As described in Eq. (A.4), the amount, variety, and substitutability between different intermediate goods determine the expansion of each production sector i. We assume that each intermediate variety $x_{i,r,t}$ is first invented, and then produced, by a single firm that receives a perpetual patent at the moment of invention. Therefore, the growth rate of the overall economy depends on the decisions of profit-seeking intermediate firms. To describe these intermediate firms in full, we need to describe both their optimal output decision for the

already invented varieties, as well as their incentives to innovate new varieties.

i) Optimal output of existing varieties

To produce one unit of output, the intermediate good producer combines two types of inputs, labor $L_{i,r,t}$ and energy $E_{i,r,t}$, according to the following CES technology:

$$x_{i,r,t} = J_{i,r,t} \left[\lambda_{i,r} L_{i,r,t}^{\frac{v_{i,r}-1}{v_{i,r}}} + (1-\lambda_{i,r}) E_{i,r,t}^{\frac{v_{i,r}-1}{v_{i,r}}} \right]^{\frac{v_{i,r}}{v_{i,r}-1}}, \tag{A.7}$$

where $\lambda_{i,r}$ denote the value share parameters and $v_{i,r}$ the substitution elasticities. From Eq. (A.7), there are within-sector spillover effects from the expanding capital stock $J_{i,r,t}$. We assume the supply of labor to be inelastic throughout the modeling horizon, mobile between sectors within a country, but immobile between countries. The energy aggregate $E_{i,r,t}$, on the other hand, is combined from a variety of K available energy sources according to:

$$E_{i,r,t} = \left[\sum_{k \in K} \phi_{k,i,r} (Z_{k,i,r,t})^{\frac{\epsilon_{i,r}-1}{\epsilon_{i,r}}} \right]^{\frac{\epsilon_{i,r}}{\epsilon_{i,r}-1}}. \tag{A.8}$$

We denote the amount of every energy input $k \in K$ by $Z_{k,i,r,t}$, and the respective price by $p^Z_{k,r,t}$. The output decision of the intermediate monopoly can be derived from two parts. First, it chooses an optimal bundle of labor and energy inputs under profit-maximizing conditions of a perfectly competitive market:

$$\max_{L_{i,r,t}, Z_{k,i,r,t}} \psi^x_{i,r,t} x_{i,r,t} - w_{r,t} L_{i,r,t} - \sum_k p^Z_{k,r,t} Z_{k,i,r,t}, \tag{A.9}$$

where $\psi^x_{i,r,t}$ is the price that would prevail under a perfectly competitive market. The firm, however, exploits its monopoly power in the output market and sets the optimal output price under:

$$\max_{p^x_{i,r,t}} p^x_{i,r,t} x_{i,r,t} - \psi^x_{i,r,t} x_{i,r,t}, \tag{A.10}$$

taking the demand for $x_{i,r,t}$ in Eq. (A.6) as given. Thus, it sets prices according to:

$$p^x_{i,r,t} = \frac{1}{\kappa}\psi^x_{i,r,t}, \tag{A.11}$$

making profits of:

$$\pi_{i,r,t} = (1-\kappa)p^x_{i,r,t}x_{i,r,t}. \tag{A.12}$$

This brings us to an alternative definition of the substitutability term κ: as the individual intermediate goods $x_{i,r,t}$ are imperfect substitutes, and the intermediate good producers compete in a monopolistic market with an output price $p^x_{i,r,t}$ and mark-up $\frac{1}{\kappa}$, we can consider $(1-\kappa)$ as the profit fraction of revenues from the intermediate composite sector going to the households that own the firms.

ii) Investments to new varieties

The model makes a distinction between physical and non-physical capital, which together make up the sector-specific capital composite $J_{i,r,t}$. Firms conduct innovation by investing an amount $I_{i,r,t}$ to this composite capital good. Access to the investment market is unrestricted. This implies that new innovations occur until the marginal cost of investments to the composite capital is equal to the firm's value so that no real profits remain. We follow the approach of Romer (1990) where the knowledge capital from the innovation process is non-rival but partially excludable with the use of patents. The equation of motion of the capital stock is:

$$J_{i,r,t+1} = I_{i,r,t} + (1-\delta_{i,r,t})J_{i,r,t}, \tag{A.13}$$

with $\delta_{i,r,t}$ denoting the capital depreciation rate. The depreciation parameter has a particular role for our work as it depends both on the baseline depreciation rate and the exposure to cyclones that varies by year and region.

Finally, the capital accumulation process requires introducing a no-arbitrage condition. New firms (capital varieties) emerge as a result of the household investment. In equilibrium, households must be indifferent between investing in a new firm and to a riskless loan with return $r_{i,r,t}$. As in standard endogenous growth models based on expanding input varieties, the value of the monopolist firm, that is, the value of owning a technology blueprint, is equal to the discounted value of all future profits. In our setting, this is also equal to the cost of investing to a new firm. We can write the relationship between the new firm value

$V_{i,r,t}$, instantaneous profits $\pi_{i,r,t}$, and the interest rate as $r_{i,r,t}$ with the following asset value equation: [4]

$$\pi_{i,r,t} + \Delta V_{i,r,t} = r_{i,r,t} V_{i,r,t}, \tag{A.14}$$

where $\Delta V_{i,r,t}$ denotes the change in firm value. We can then extend Eq. (A.14) by writing:

$$\underbrace{\pi_{i,r,t}}_{\text{Direct return}} + \underbrace{\frac{p^J_{i,r,t+1}}{1+r_{i,r,t}} - p^J_{i,r,t}}_{\substack{\text{Time } t \text{ present value} \\ \text{of the capital gain}}} - \underbrace{\delta_{i,r,t} p^J_{i,r,t}}_{\substack{\text{Value lost to} \\ \text{depreciation}}} = \underbrace{r_{i,r,t}}_{\substack{\text{Interest rate of} \\ \text{a riskless loan}}} \times \underbrace{V_{i,r,t}}_{\substack{\text{Firm value =} \\ \text{investment cost}}}, \tag{A.15}$$

where p^J_t is the price of capital. The intermediate good producer borrows from households to pay the innovation activities in advance. We can also re-write the sectoral profits from Eq. (A.12) as:

$$\pi_{i,r,t} = \underbrace{(1-\kappa)}_{\substack{\text{Monopoly} \\ \text{profit share}}} \underbrace{p^Q_{i,r,t} Q_{i,r,t}}_{\substack{\text{Sectoral} \\ \text{revenue}}} / \underbrace{J_{i,r,t}}_{\substack{\text{Number of} \\ \text{varieties}}}. \tag{A.16}$$

Inserting Eq. (A.16) into Eq. (A.15) then yields the expression for equilibrium interest rates, and thus completes the no-arbitrage condition.

A.2 International trade

Our baseline dataset contains economic accounts of 129 regions, covering most of the global economy. Representing how different countries interact through international trade is, therefore, a central feature of our underlying general equilibrium model, and an important determinant of how countries can adapt to economic shocks.

All final sectors in the economy are open to international trade. That is, all producers can employ both domestically produced and imported inputs, and consumers can purchase both domestic and imported consumption goods. To give more structure to the representation of international trade, we follow the Armington approach (Armington, 1969), which is a standard assumption in the numerical general equilibrium literature. With this approach, the suppliers of the final good use both domestically produced goods and imported goods, and use them as inputs in creating an Armington aggregate good, which is the final good demanded in the economy. The domestic and imported inputs are combined with an elasticity of substitution less than one so that they function as imperfect substitutes. Intuitively, this means that consumers in any country can prefer domestically produced goods over imports

[4] For details on deriving the relationship, see e.g. Acemoglu (2009) Ch. 13.

varieties. More importantly, this allows for a realistic description of international trade, where any production sector in any region can simultaneously be an exporter and an importer of the same good, which is what we also observe in the real economies.

More formally, denoting domestic sectoral production in region r by $D_{i,r,t}$ and imports from region s to r by $M_{i,s,r,t}$, the Armington aggregate is given by:

$$A_{i,r,t} = \left(\zeta_{i,r} D_{i,r,t}^{\frac{\eta_{i,r}-1}{\eta_{i,r}}} + (1-\zeta_{i,r}) \left(\left[\sum_{s \neq r} m_{i,s,r} M_{i,s,r,t}^{\frac{\phi_{i,r}-1}{\phi_{i,r}}} \right]^{\frac{\phi_{i,r}}{\phi_{i,r}-1}} \right)^{\frac{\eta_{i,r}-1}{\eta_{i,r}}} \right)^{\frac{\eta_{i,r}}{\eta_{i,r}-1}}, \tag{A.17}$$

where we denote by $\zeta_{i,r}$ the share of domestic goods, and by $m_{i,s,r}$ the share parameters of different regions in the basket of imports. Parameters $\eta_{i,r}$ and $\phi_{i,r}$ are the respective substitution elasticities. With $p^A_{i,r,t}$ being the price of the Armington composite, and $p^Y_{i,r,t}$ the price of the domestic output, the profit maximization the final suppliers face is then:

$$\max_{D_{i,r,t}, M_{i,s,r,t}} p^A_{i,r,t} A_{i,r,t} - p^Y_{i,r,t} D_{i,r,t} - \sum_{s \neq r} p^A_{i,s,t} M_{i,s,r,t}. \tag{A.18}$$

We allow countries to run either trade surpluses or deficits, as also observed in the baseline dataset.

A.3 Preferences

For each region, we assume an infinitely lived, forward-looking representative household. The representative household derives utility from consumption according to a standard constant intertemporal elasticity of substitution function:

$$U = \sum_{t=0}^{\infty} \left[\frac{1}{1+\rho} \right]^t \frac{C_{r,t}^{1-\theta} - 1}{1-\theta}, \tag{A.19}$$

where ρ denotes the time discounting parameter and θ the inverse of the intertemporal elasticity of substitution. As the economy consists of multiple production sectors, $C_{r,t}$ is a CES aggregate of the sector-specific consumption goods. Figure A.2 illustrates the nested consumption structure.

The household also owns all firms in the economy, so its budget reads:

$$p^C_{r,t} C_{r,t} = w_{r,t} L_{r,t} - T_{r,t} - \sum_i p^J_{i,r,t+1} J_{i,r,t+1} + \sum_i (1 + r_{i,r,t}) p^J_{i,r,t} J_{i,r,t}, \tag{A.20}$$

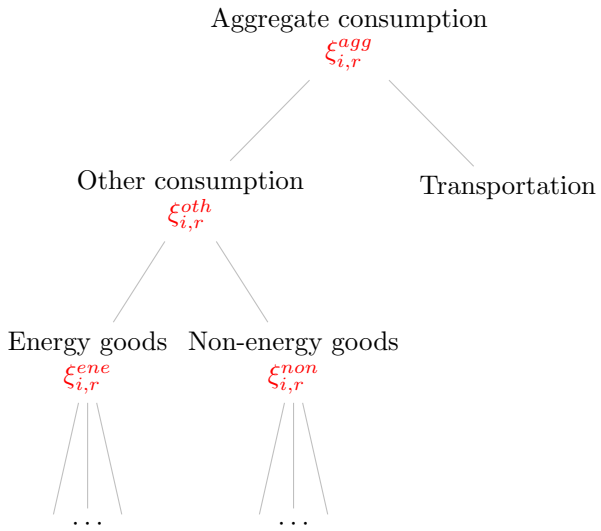

Figure A.2: Nested consumption structure. The substitution elasticity value within a sub-nest is highlighted in red.

where $w_{r,t}$ denotes the wage rate, $T_{r,t}$ a lump-sum tax which ensures the public budget to remain balanced, and $p^C_{r,t}$ is the price for the consumption aggregate.

A.4 Calibration details

Our model calibration follows closely the steps outlined in Lau et al. (2002) and Paltsev (2004). The key goal of the calibration process is to use the GTAP dataset as a static snapshot of the economy, and extrapolate—using a set of exogenous parameter assumptions—a balanced growth path on which all sectors, and therefore also all regional economies, grow at the same rate.

The household's problem involves maximizing the stream of utility over time in Eq. (A.19). The optimization is subject to the the economy's production function $F(K_t, L_t)$, a resource constraint $F(K_t, L_t) = I_t + C_t$ dividing the output between consumption and investment, and the capital stock law of motion from Eq. (A.13). Assuming constant returns to scale and perfectly competitive markets, we can derive the following price relationships from the first-order optimality conditions (Paltsev, 2004):

$$p_t = \left[\frac{1}{1+\rho}\right]^t \frac{\partial U(C_t)}{\partial C_t}, \tag{A.21}$$

$$p_t^K = p_t \frac{\partial F(K_t, L_t)}{\partial K_t} + (1-\delta) p_{t+1}^K, \tag{A.22}$$

$$p_t = p_{t+1}^K. \tag{A.23}$$

We can interpret these values as p_t being the price of output, $p_t \frac{\partial F(K_t,L_t)}{\partial K_t} := R_t$ the rental rate of capital, that is, the value of the marginal product, and p_t^K the price of buying one new unit of capital. This distinction between capital stocks and capital services is central to the modeling approach: households own the stock, invest by buying new units of capital, and rent the capital to firms at the rate R_t.

Assuming a baseline interest rate $\bar{r}$, the calibration makes use of a declining reference price trajectory $p_t^{\text{ref}} = (1/(1+\bar{r}))^t$. Then, for all prices in the model, and for any arbitrary time instance τ, we have that:

$$p_{\tau+1} = \frac{p_\tau}{1+\bar{r}}. \tag{A.24}$$

We can use the reference price path to further highlight the distinction between the capital rental and purchase prices. Combining Eq. (A.24) and (A.22) gives:

$$R_t = p_t^K \left(1 - \frac{1-\delta}{1+\bar{r}}\right), \tag{A.25}$$

which states that the capital rental price R_t is equal to the price of buying a new capital unit, subtracting the discounted value of the depreciated stock in the subsequent time period. Further normalizing $p_0 = 1$ allows us to write the first-period rental rate as $R_0 = \delta + \bar{r}$.

The benchmark GTAP data does not provide the capital stock values directly but only the base year capital earnings, denoted with V_0^K. Using $V_t^K := R_t K_t$ and the base year rental rate from above, we can derive the initial capital stock as $K_0 = V_0^K/(\delta + \bar{r})$. The next task is to calibrate the initial investments on balanced growth path. Assuming a constant capital stock growth rate γ_K, we can write the next period capital stock either as in Eq. (A.13) or with $K_{t+1} = (1+\gamma_K)K_t$. Combining the two equations gives $I_t = (\gamma_K + \delta)K_t$, such that on a balanced growth path the annual investment level must cover both the capital growth rate and depreciation. Plugging in the definition of K_0 from before gives:

$$I_0 = (\gamma_K + \delta)K_0. \tag{A.26}$$

The calibration process so far follows the standard conventions of numerical general

equilibrium modeling. In our setting, however, the possibility to consider productivity gains from specialization requires some additional steps. When the gains from specialization are active, we assume that the size of the capital stock directly corresponds to the number of capital varieties. Moreover, the different varieties are imperfect substitutes, determined by the substitution elasticity parameter κ. The imperfect substitutability then creates monopoly rents and additional incentives for investing. The growth rate of output γ_Y then depends on two factors: an exogenously specified capital growth rate γ_K and an endogenous growth part determined by κ. The relationship between these parameters satisfies:

$$1 + \gamma_Y = (1 + \gamma_K)^{\frac{1}{\kappa}}. \tag{A.27}$$

Whenever $0 < \kappa < 1$, the output growth rate γ_Y exceeds the capital growth rate γ_K. To make this difference in growth rates compatible with the balanced growth path, and to avoid situations where investments grow faster than the actual stock of capital, we also make the base depreciation rate time-dependent. This assumption is necessary for the balanced growth path to exist, but there is also an appealing intuition behind the adjustment. Namely, as the economies develop further, their capital stock grows more specialized and more susceptible to depreciation. The base depreciation rate is:

$$\delta_{r,t} = \left(\frac{1+\gamma_Y}{1+\gamma_K}\right)^t \delta_{r,0} + \gamma_K \left(\left(\frac{1+\gamma_Y}{1+\gamma_K}\right)^t - 1\right), \tag{A.28}$$

which collapses to a constant value when $\kappa = 1$ and the gains from specialization are switched off.

Finally, to obtain the baseline consumption growth rate $g_r = \frac{C_{r,t+1}}{C_{r,t}}$ on the balanced growth path calibration, we can maximize Eq. (A.19) with respect to Eq. (A.20) to obtain the standard Keynes-Ramsey rule:

$$g_r \equiv \left[\frac{1+\bar{r}}{1+\rho}\right]^{\frac{1}{\theta}}. \tag{A.29}$$

According to Eq. (A.29), a higher interest rate $\bar{r}$ boosts growth by inducing more saving, whereas a higher discount rate ρ gives incentives to present consumption, therefore reducing the rate of growth. A higher intertemporal substitution elasticity $1/\theta$ also increases growth rates, as the households become more willing to tolerate consumption variability in response to interest rate changes. In our setting, Eq. (A.29) also implicitly pins down the temporal

discount rate ρ.

A.5 Numerical implementation

We follow Mathiesen (1985) and formulate the general equilibrium economy as a mixed complementary problem (MCP). The formulation includes three types of inequality constraints: market-clearing conditions, zero profit conditions, and income balance conditions. Each equilibrium condition f has a complementary variable z, such that the following conditions always hold: $f(z) \geq 0, z \geq 0, z^T f(z) = 0$. For instance, we can write the market-clearing condition as $f(p) = S(p) - D(p)$, where we use the price level p as the complementary variable, and supply and demand functions S and D, respectively. When the market clears, $f(p) = 0$ and the equilibrium prices are positive. If supply exceeds demand, however, the complementary variable (prices) become zero. Similarly for the zero-profit conditions, the complementary variable is the output level. As long as sectoral profits are non-negative, the output level is positive. With negative profits, however, firms exit the market and the output becomes zero.

Although the theoretical model considers an infinite time horizon, the numerical implementation requires using a finite approximation. This introduces the risk of horizon-effects affecting the equilibrium outcome as we approach the terminal period. To remedy the risk around the terminal period, we employ the method from Lau et al. (2002). This method imposes an additional constraint on capital accumulation at the terminal period T to approximate the infinite horizon equilibrium. We introduce the post-terminal capital stock as an additional variable and require that the growth rate of investments in the terminal period mirror the output growth rate:

$$\frac{I_T}{I_{T-1}} = \frac{Y_T}{Y_{T-1}}. \tag{A.30}$$

That is, we only fix the growth rate of investments, and do not have to fix the actual growth rate, nor the terminal level, of capital stock. To further reduce terminal effects, we discard the last two decades of simulation from the results.

We use the programming language GAMS (General Algebraic Modeling System) as well as the MPSGE (Mathematical Programming System for General Equilibrium, Rutherford (1999)) sub-system to implement the economic model. To solve the model, use the PATH numerical solver Ferris & Munson (2000).

B Aggregation of regions, sectors, and production factors

Aggregate region	GTAP region
USA	United States of America
Japan	Japan
Philippines	Philippines
Caribbean	Rest of Caribbean [1]
China	China, Hong Kong
Rest of the World	Australia, New Zealand, Rest of Oceania, Republic of Korea, Mongolia, Taiwan, Rest of East Asia, Cambodia, Indonesia, Lao PDR, Malaysia, Singapore, Thailand, Viet Nam, Rest of Southeast Asia, Bangladesh, India, Nepal, Pakistan, Sri Lanka, Rest of South Asia, Canada, Mexico, Rest of North America, Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America, Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom, Switzerland, Norway, Rest of European Free Trade Association, Albania, Bulgaria, Belarus, Croatia, Romania, Russian Federation, Ukraine, Rest of Eastern Europe, Rest of Europe, Kazakhstan, Kyrgyzstan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia, Bahrain, Iran, Israel, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Rest of Western Asia, Egypt, Morocco, Tunisia, Rest of North Africa, Cameroon, Côte d'Ivoire, Ghana, Nigeria, Senegal, Rest of Western Africa, Rest of Central Africa, South Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, Namibia, South Africa, Rest of South African Customs Union, Rest of the World

[1] Includes: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, British Virgin Islands, Cayman Islands, Cuba, Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Montserrat, Netherlands Antilles, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and Grenadines, Trinidad and Tobago, Turks and Caicos Islands, Virgin Islands.

Table B.1: Aggregation of countries and regions.

Aggregate variable	GTAP variable
Goods and sectors	
Manufacturing	Textiles, Wearing apparel, Leather products, Wood products, Motor vehicles, Other transport equipment, Water, Construction, Paper products, publishing, Chemical, rubber, plastic products, Minerals, Ferrous metals, Other metals, Metal products, Electronic equipment, Other machinery and equipment, Other manufactures
Services	Trade, Communication, Financial services, Insurance, Business services, Recreation, Dwellings, Public Administration, Defense, Education, Health
Transport	Water transport, Air transport, Other transport
Agriculture	Paddy rice, Wheat, Cereal grains, Vegetables, fruits, nuts, Oil seeds, Sugar cane, sugar beet, Plant-based fibers, Other crops, Bovine cattle, Other animal products, Raw milk, Wool, Forestry, Fishing, Bovine meat products, Other meat products, Vegetable oils and fats, Dairy products, Processed rice, Sugar, Other food products, Beverages and tobacco
Electricity	Electricity
Coal	Coal
Natural gas	Gas, Gas manufacture, distribution
Crude oil	Oil
Refined oil	Petroleum, coal products
Factors of production	
Resources	Land, Natural resources
labor	Skilled labor, Unskilled labor
Capital	Capital

Table B.2: Aggregation of sectors and production factors.

C Main parameter values

Parameter	Description	Value
Elasticities of substitution for production activities		
$\sigma_{i,r}$	Intermediate composite Q and inputs B from other sectors	0.5
$v_{i,r}$	Labor L and energy E in intermediate good production	1.0
$\epsilon_{i,r}$	Energy type Z in the energy aggregate	0.5
$\eta_{i,r}$	Imports and domestic goods	$\in [1.9, 6.0]$
$\phi_{i,r}$	Import regions	$\in [3.8, 12]$
κ	Intermediate varietes	$\in \{1.0, 0.86\}$
Elasticities of substitution for private consumption		
$\xi_{i,r}^{agg}$	Transportation and other consumption goods	1.0
$\xi_{i,r}^{oth}$	Energy and non-energy consumption goods	0.25
$\xi_{i,r}^{ene}$	Energy varieties	0.4
$\xi_{i,r}^{non}$	Non-energy consumption goods	0.25
Other parameters		
$1/\theta$	Intertemporal elasticity of substitution	0.5
$\delta_{i,r,t}$	Baseline capital depreciation	0.07
$\bar{r}$	Baseline nominal interest rate	0.05
γ_K	Capital growth rate	0.02

Table C.3: Default parameter values used in numerical simulations. Based on Paltsev et al. (2005); Hasanov (2007); Narayanan et al. (2012); Bretschger et al. (2017).

D Additional results

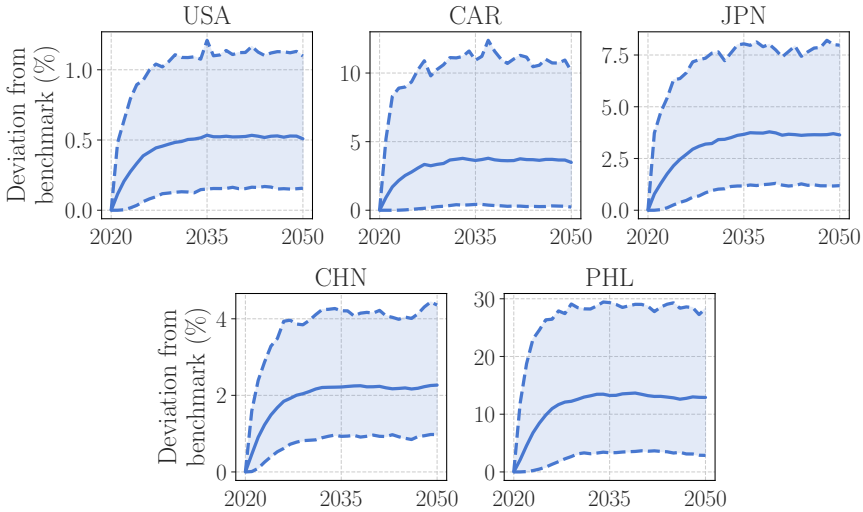

Figure D.3: Aggregate investment levels by country over 30 years of tropical cyclone activity. We compare the levels under years of cyclone activity to a benchmark scenario where the economy would grow on a balanced growth path, without any cyclones. The bold lines represent the means of the 500 Monte Carlo simulations.

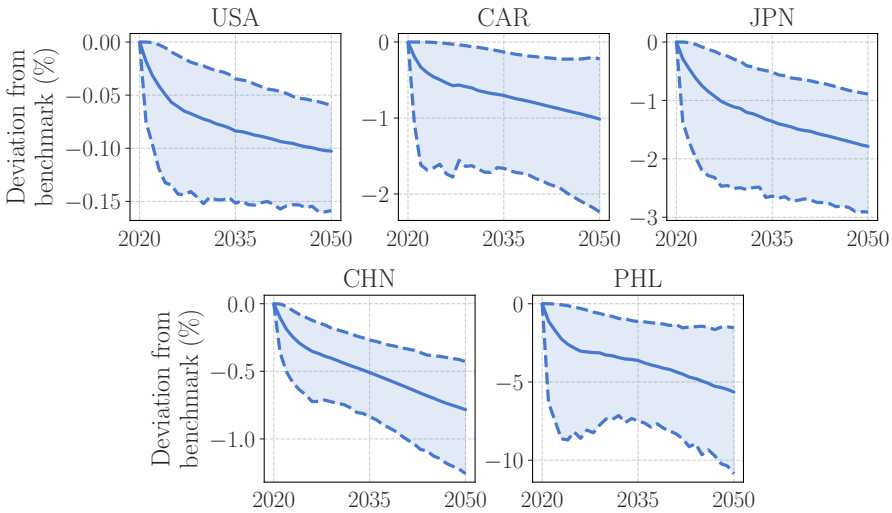

Figure D.4: GDP levels by country over 30 years of tropical cyclone activity. We compare the levels under years of cyclone activity to a benchmark scenario where the economy would grow on a balanced growth path, without any cyclones. The bold lines represent the means of the 500 Monte Carlo simulations.

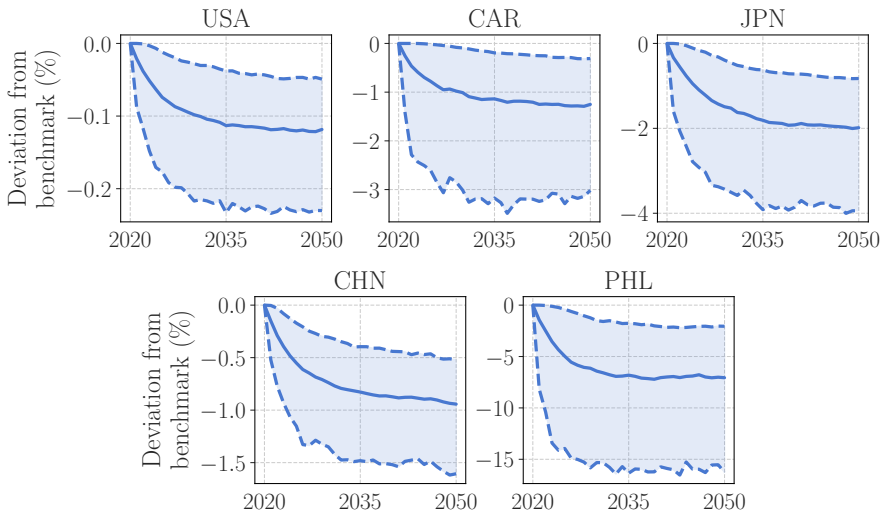

Figure D.5: Aggregate industry output levels levels by country over 30 years of tropical cyclone activity. We compare the levels under years of cyclone activity to a benchmark scenario where the economy would grow on a balanced growth path, without any cyclones. The bold lines represent the means of the 500 Monte Carlo simulations.

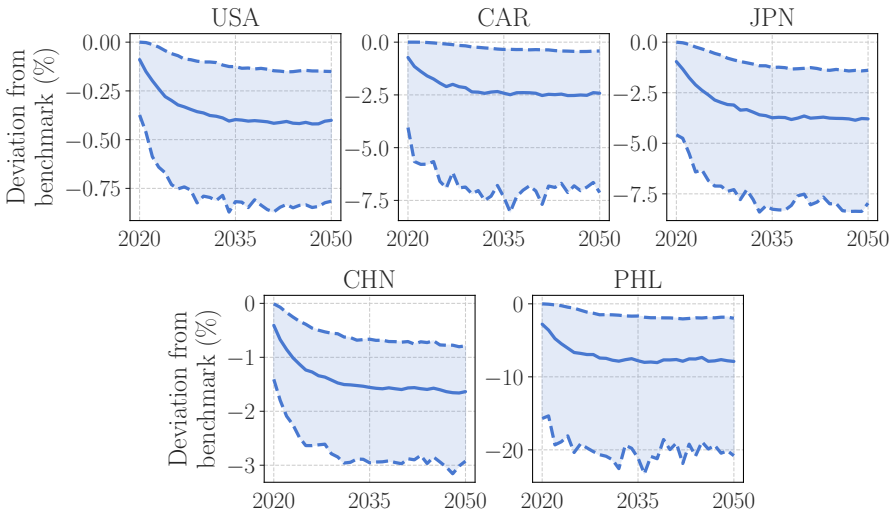

Figure D.6: Aggregate capital intensity by country over 30 years of tropical cyclone activity. We compare the levels under years of cyclone activity to a benchmark scenario where the economy would grow on a balanced growth path, without any cyclones. The bold lines represent the means of the 500 Monte Carlo simulations.

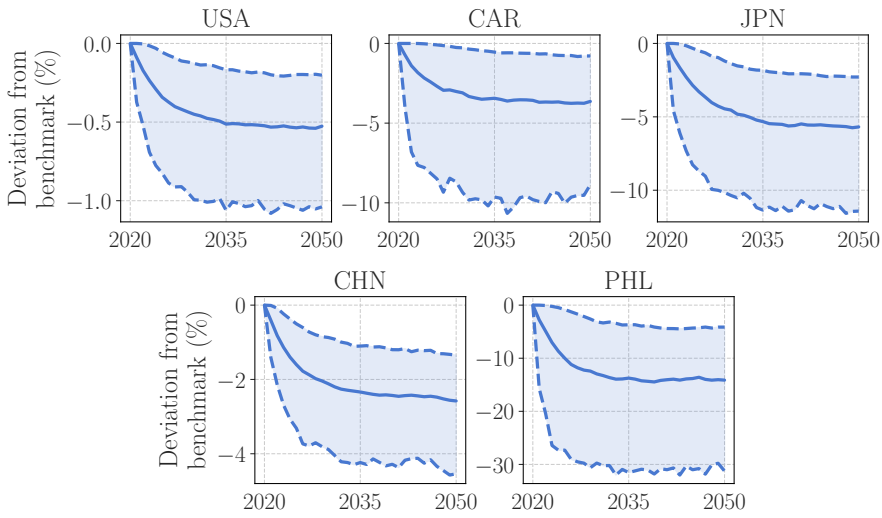

Figure D.7: Aggregate capital stock level by country over 30 years of tropical cyclone activity. We compare the levels under years of cyclone activity to a benchmark scenario where the economy would grow on a balanced growth path, without any cyclones. The bold lines represent the means of the 500 Monte Carlo simulations.

E Cyclone simulation

Figure E.8 shows the fit between the new synthetic years and the historical ones. We use the methodology of section 2.1 to compute the damage caused by tropical cyclones. The synthetic years and the historical ones have a quite similar empirical cumulative distribution function. Table 1 of section 2.1 shows that the mean and the standard deviation of damages from the historical years stay close to the ones of the synthetic years. Figure E.8 reflects how yearly cyclone activity may differ from the 70 years we have on records so far.

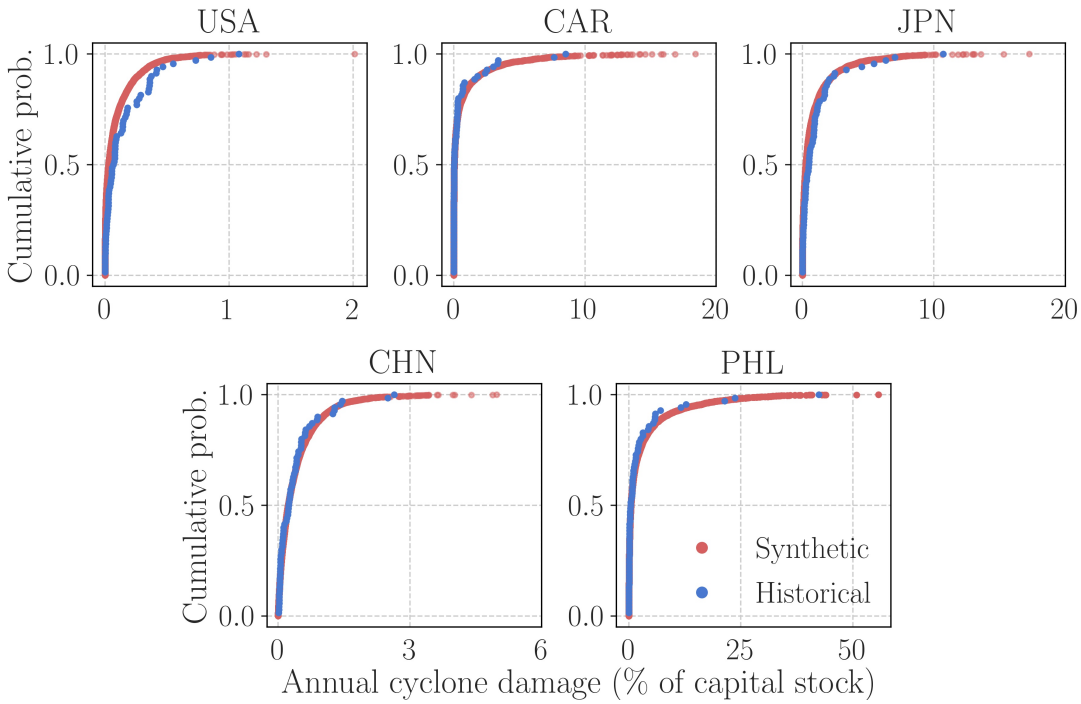

Figure E.8: Probability estimates of tropical cyclone damages from the historical years versus the synthetic years under constant climate conditions.

F Cyclone simulation with climate change

The simulation of cyclones under climate change follows similar steps to the simulation without climate change. The main differences come from the fact that we need to change the occurrence rate of the cyclones (the frequency) and the damage that each cyclone may cause (the intensity).

We start from the historical tracks to again extend our sample to synthetic years. We use 2020 as a starting and reference year for climate change. We generate a new pool of 5,070 synthetic years of damages for every 10-years steps from 2025 to 2095. The pool of damages we compute for the year 2025 corresponds to our damage estimates for the 2020-2030 period. At each step, we use CLIMADA to compute the change in intensity of the cyclones. CLIMADA relies on Knutson et al. (2015) as a reference for its climate change scenario. Knutson et al. (2015) use a dynamical downscaling of models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) under the RCP4.5 scenario to project tropical cyclone activity for the years 2081–2100. Knutson et al. (2015) present results only for the RCP4.5 scenario. CLIMADA interpolates other RCP scenarios from the RCP4.5 values according to the relative radiative forcing of each scenario. This interpolation allows us to get estimates of the intensity of cyclones under RCP8.5.

Similar to the simulation without climate change, we proceed to the creation of synthetic years. We need to adapt the Poisson parameter that represents the frequency of cyclones. In their late twenty-first century projections, Knutson et al. (2015) find no significant change in tropical cyclones' frequency in the North Atlantic basin. They find, however, a statistically significant change in tropical cyclones' frequency in the Northwestern Pacific basin of -34.5% on average overall cyclone categories. We use these results and do not adjust the average number of cyclones per year in the Caribbean islands and the USA. We specify, however, the -34.5% change in frequency for countries in the Northwestern Pacific basin by 2090. We interpolate the occurrence rate linearly at each decadal step from 2025 to 2095. We assume the same frequency of cyclones in 2100 as in 2095.

Since Knutson et al. (2015) have no estimates for the change in frequency for the RCP8.5 scenario, we take Emanuel (2013) as a reference. Emanuel (2013) also downscales models from CMIP5 to project tropical cyclone activity for the late twenty-first century. Emanuel (2013) assumes an RCP8.5 scenario. His results complement the ones of Knutson et al 2015. But Emanuel (2013) reports his results globally. He finds an increase in cyclone frequency of $10 - 40\%$ globally depending on models of the CMIP5. According to Emanuel (2013), this increase is mostly concentrated in the Northwestern Pacific basin but also present in the North Atlantic basin. We take a conservative calibration of 5% and 10% increase in cyclone frequency for the North Atlantic and Northwestern Pacific basin respectively.

F.1 RCP4.5

Figure F.9 shows the cumulative distribution of damages from the synthetic years without climate change, with 2020 as reference climate, versus the synthetic yearly damages in 2100 under an RCP4.5 scenario. The intensity of the damages in the North Atlantic basin increases by 4.5% in 2100 compared to the present day's climate. In the Northwestern Pacific region, although the intensity of cyclones in this region increases by 5-7%, their frequency decreases by 16-30%.

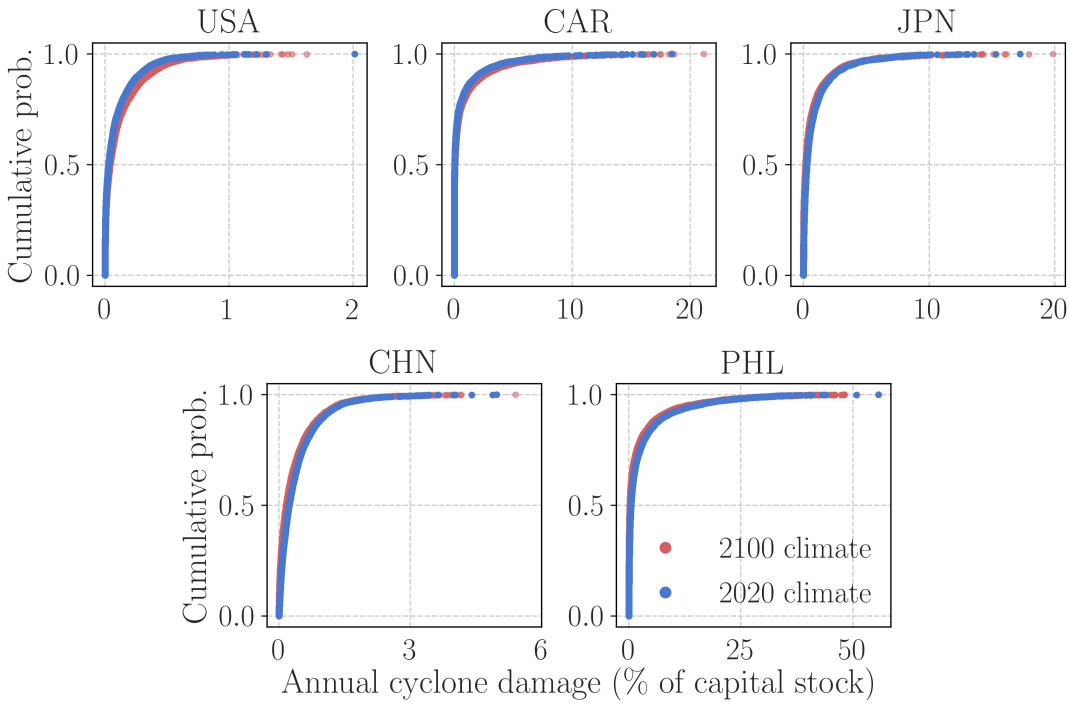

Figure F.9: Probability estimates of cyclone damages under in 2020 versus their potential damages in 2100 under the RCP4.5 scenario.

F.2 RCP8.5

Figure F.10 shows the cumulative distribution of damages from the synthetic years without climate change, with 2020 as reference climate, versus the synthetic yearly damages in 2100 under an RCP8.5 scenario. For all regions, we see an increase in the mean and standard deviation of damages. Under the RCP8.5, both the intensity and the frequency of the cyclone increase in both the North Atlantic and the Northwestern Pacific basin.

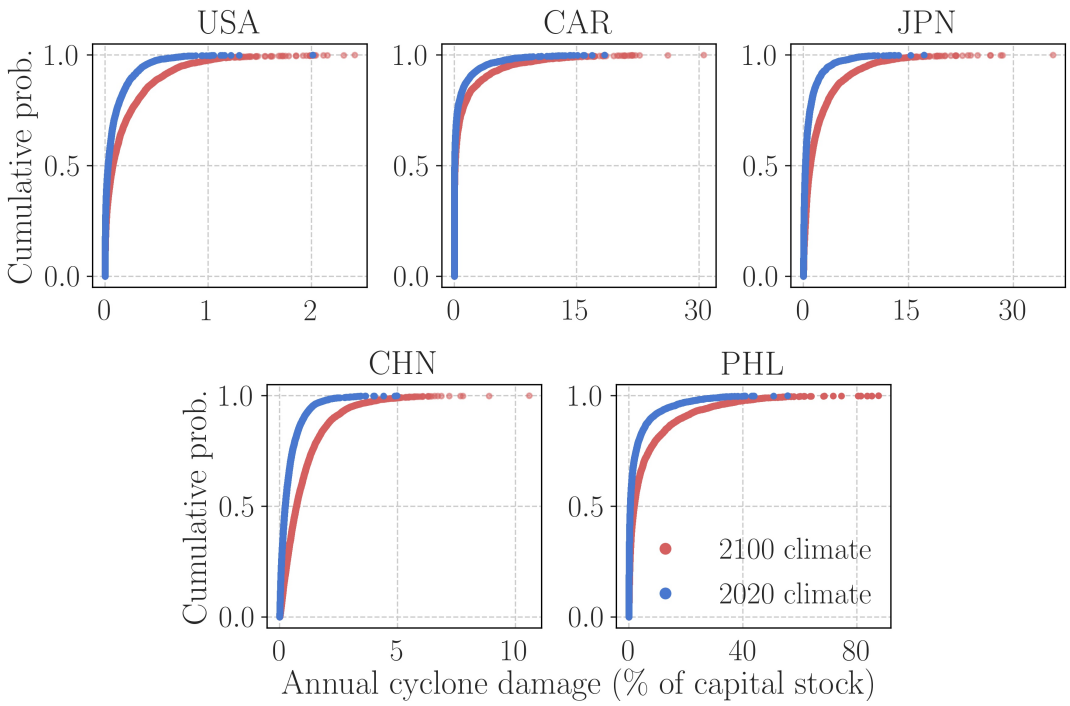

Figure F.10: Probability estimates of cyclone damages under in 2020 versus their potential damages in 2100 under the RCP8.5 scenario.

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