Connecting Climate Impact Assessments and Economic Growth Theory: the Case of Tropical Cyclones

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July 20, 2020
PRELIMINARY DRAFT

Abstract

The economic literature suggests that differences in countries' in economic growth can be partially explained by their respective exposure to natural catastrophes. The integration of damages from natural catastrophes in economic models, however, may be improved. We propose a new methodology in that direction, which consists in combining a general equilibrium model of economic growth with a probabilistic disaster impact model. We focus on tropical cyclones (TC) and use a 10×10 km spatial distribution of economic assets in two regions of the world, the US and the Caribbean islands, in order to evaluate their respective exposure to TC. From these estimates, we analyze and quantify the intertemporal effects that result from the modified growth path of the two economies after a year of TC activity. We find both a short-term reconstruction boom as well as a long-run recovery path. We show that the type of economic growth specification, either exogenous or endogenous, can have large impacts on the results. This aspect is often overlooked in the literature and helps to better explain why countries might differ in their immediate response to TC shocks as well as in their post-disaster growth trajectories. On a policy-maker perspective, such results can also be useful to better understand the impact of TC on welfare.

Keywords: Tropical Cyclones, Climate, Growth, Numerical Solutions

JEL Codes: C63, O11, Q54

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1 Introduction

Tropical cyclones (TC) are certainly among the costliest natural catastrophe events (Bevere et al., 2011), widely spread across the world, affecting economies of heterogeneous sizes and GDP levels. Their direct impacts, moreover, could increase significantly in the future, driven both by the development of exposed coastal regions (Gettelman et al., 2018) as well as their possible change in intensity and frequency due to climate change (Field et al., 2012).

Estimating the economic impacts of tropical cyclones is an active, yet inconclusive field of research. The economic literature shows that growth impacts can be either positive during the immediate reconstruction boom, or if the risk of future strikes induces more contemporary precautionary savings. On the other hand, frequently affected areas can be permanently trapped in a lower growth trajectory due to the destruction of productive assets, business interruptions, and loss of lives. The results vary across regions and types of economies. Agriculture-based countries are likely to be much more vulnerable to cyclone shocks than richer, service-based economies. In economic studies, long-run impact estimates are always sensitive to the underlying assumptions of growth mechanisms. A possible approach, more commonly taken in the environmental and geoscientific studies looking for economic estimates of natural catastrophe events, is to rely on pre-defined exogenous growth scenarios (Narita et al., 2009; Mendelsohn et al., 2012). These studies often have more precise estimates of the damage function(s), but for the most affected regions, cyclone shocks are likely to be an endogenous determinant of future growth.

Our goal in this paper is to study the growth impacts of tropical cyclones, taking advantage of tools from both the economic and the environmental sciences literature. First, we employ a probabilistic disaster impact model (Aznar Siguan & Bresch, 2019) that is based on both historical satellite data as well as synthetic cyclone tracks to estimate a proxy capital destruction following each event. The model is global in geo-coverage and has a high spatial resolution, allowing us to derive realistic region-specific damage functions. To keep track of the indirect and long-run effects, we feed these direct damage estimates into a dynamic, multi-sectoral general equilibrium growth model similar to the one used in Bretschger et al. (2017). We use the model to study two types of growth dynamics: a Ramsey (1928) style exogenous growth engine, as well as a Romer (1990) style endogenous growth specification based on the expanding varieties of goods and gains from specialization. We calibrate the growth model using the Global Trade Analysis Project (GTAP) dataset. The dataset gives a globally consistent sectoral breakdown of economic activities, as well as bilateral trade flows. We report our results for the US and the Caribbean islands. These regions are regularly exposed to tropical cyclones, and allow us to study two economies that are very different in size, structure, and overall cyclone exposure.

Our results quantify the country-specific disaster impacts, as well as the long-run recovery path. Intuitively, our results show a spike in aggregate investment directly after the impact. Converging back to the benchmark growth path is relatively slow, and can take several decades. For many economic variables, such as the aggregate output and aggregate consumption, the post-disaster trajectory remains below the benchmark for the entire modeling period, never catching up the original levels. Allowing for an endogenous growth engine incentivizes more investments at the disaster impact, bringing a smaller post-disaster output slump and a faster recovery, as firms have additional profit incentives and scale benefits from investing.

Related Literature

Quantifying the broad economic impacts of natural disasters is an active field of ongoing research. Empirical studies focusing on the short-term implications of cyclone strikes usually disentangle economic output by sectors. They often find a negative impact of tropical cyclones on sectors such as agriculture and a positive impact for the industry. Empirically examining the economic gains and losses from hurricane Hugo in South Carolina, Guimaraes et al. (1993) find that the economic gains due to an increase in activity, mainly in construction and retail, did not compensate for the unreimbursed wealth losses to public utilities, forestry and agriculture. Loayza et al. (2012) find that growth in the agricultural and service sectors are negatively affected by storms. The industrial sector, however, is positively affected if wind speeds remain below a certain threshold. For severe storms above that threshold, the impacts are negative in all sectors. Hsiang (2010) provides more detailed results disentangling seven different sectors in the economy. He finds clear evidence that in the short term (≤ 3 years), TCs have positive effects on the construction industry and negative effects in retail, tourism, and agriculture. We find similar short term effects with a boom in investments and output in the first post-disaster periods as the economy tries to compensate the losses from the TC shock.

The literature on long-term impacts of a TC event on the economy is more disparate. One strand of empirical studies advocates that destruction caused by natural disasters is positive for GDP growth. For Skidmore & Toya (2002), frequent climatic disasters drive economies from physical capital towards human capital accumulation, increasing total factor productivity (TFP) and growth in the long run. Crespo Cuaresma et al. (2008), however, find that a "creative destruction" effect of climatic disasters only occurs for countries that are developed enough.

Differences in countries' level of development may appear as an important factor of the effect of TC activity on growth as Noy (2009) and Berlemann & Wenzel (2018) argue. For Berlemann & Wenzel (2018), more developed countries may benefit slightly from tropical storms whereas developing countries are negatively affected. Studies by Hsiang & Jina (2014, 2015), however, find a systematic negative impact of tropical cyclones on GDP growth. According to their analysis, a single shock drags economic growth for about twenty years. In Hsiang & Jina (2014), a frequent occurrence of shocks makes it impossible to catch up the initial trend of GDP per capita growth. Our results are very similar to those in Hsiang & Jina (2014), suggesting that the economy needs several decades to fully recover from a single shock, and that frequently affected areas can be permanently trapped in a lower growth path due to the impact of TC.

Contrary to many previous studies, Hsiang & Jina (2014) also find no evidence that either the level of development or the size of the economy matters in how different countries react to TC strikes. But TCs may hit developed and developing countries differently for several reasons, such as lower quality of institutions, lower insurance cover, and lower levels of education (Toya & Skidmore, 2007; Noy, 2009). Developing countries also have a larger share of agriculture — a sector especially vulnerable to TCs — and stronger linkages between agriculture and non-agricultural sectors than more developed economies (Johnston & Mellor, 1961; Schultz et al., 1964). This higher dependence on agriculture may also explain why smaller economies tend to be more vulnerable than larger countries when exposed to cyclones of similar intensity (Noy, 2009). Finally, Noy (2009) also shows that an economy open to international trade is better able to withstand a disaster shock. Our results suggest that long-term economic differences between countries of various development levels also arise from their different growth dynamics — a Ramsey growth model may better represent an economy in its earlier stages of development than a Romer specification — and the type of capital that constitutes this economy. As discussed in Strulik & Trimborn (2019), the impact of a natural disaster strike on GDP will depend heavily on whether it destroys mainly productive capital stocks or durable consumption goods, such as cars and appliances.

The main reason for the discrepancies found in the literature on natural disaster impacts at the macro-level is the use of different estimation techniques. Some studies use cross-country data on TCs, such as the one by Skidmore & Toya (2002), whereas others use panel data Hsiang & Jina (2015)[1]. Results from previous studies are also difficult to compare as they do not all use the same database: the EM-DAT [2] for Skidmore & Toya (2002); Toya & Skidmore (2007); Crespo Cuaresma et al. (2008); Narita et al. (2009); Noy (2009); Loayza et al. (2012) and the International Best Track Archive for Climate Stewardship (IBTrACS) database [3] for Hsiang & Jina (2014, 2015) and Berlemann & Wenzel (2018). The EM-DAT

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[1] See Bakkensen & Barrage (2018) for a detailed discussion on economic interpretations of the different empirical techniques.

[2] For more information on the EM-DAT database, see https://www.emdat.be/.

[3] Knapp et al. (2010).

database contains data on various natural disasters and includes estimates of their monetary damages. The IBTrACS database, on the other hand, provides a global satellite-based repository of annual storm tracks. We use data from the IBTrACS database in our damage estimates to avoid possible measurement errors present in the EM-DAT database as pointed out by Strobl (2012).

Most of the studies discussed above use empirical methods to estimate the economic consequences of different natural disasters. Another strand of the literature takes a simulation-based approach, and employs either input-output (IO) models or numerical general equilibrium models to quantify natural disaster impacts [4]. Both types of simulation models are based on Social Accounting Matrices (SAM), that provide a detailed, but static, description of economic activity between different sectors in different regions. Both models are well-suited for assessing the indirect disaster impacts, as the shock to one sector in a given area dissipates according to the intertwined material flows of the global economy. Hallegatte (2008), for instance, reports that looking only at direct disaster impacts (such as replacement of lost assets) can greatly underestimate the total impacts, as the indirect impacts (such as business interruption) increase non-linearly with direct losses.

Applied general equilibrium models are similar to IO models in many respects, but provide some additional flexibility by including mechanisms such as active price adjustment and input substitution possibilities for producers when the shock occurs. The rigidities of IO models fit well the modeling of short-term responses and production bottlenecks immediately after a disaster (up to weekly and monthly detail). Applied general equilibrium models — such as the one we use here — are better suited for quantifying the medium and long-run economic implications of natural disasters, spanning from one year to multiple decades.

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[4] See Botzen 2019 for a recent, general overview of the literature.

2 Data

Our study combines data from four different main sources. For the cyclone impact component, we need data about the hazard (the tracks and wind speeds of historical cyclones), as well as the exposures (the spatial distribution of vulnerable physical assets). The multi-sector economic growth model, on the other hand, needs national accounts data to describe the international input-output structure of the world economy, as well as elasticity estimates to capture the reaction of economic agents within the model to a cyclone shock. For all disaster impact computations and cyclone data manipulations, we use the open-source and open-access CLIMADA (Climate Adaptation) platform (Aznar Siguan & Bresch, 2019). Below we describe all of these data sources in details.

2.1 Hazard data

For the tropical cyclone data, we use the IBTrACS database (Knapp et al., 2010) by the US National Oceanic and Atmospheric Administration (NOAA). We focus on cyclones in the North Atlantic basin, as our countries of interest for the economic analysis are the United States and the Caribbean countries[5]). The IBTrACS database allows us to analyze the path of each historical cyclone with a spatial resolution of approximately 10×10 km and the maximum sustained wind speed of the cyclones throughout the period from 1950. However, we only use data from 1965 to 2019 in order to improve the quality of estimates and reduce wind speed uncertainty to about 20 knots[6]. Within this historical time frame and limiting the geographic area to the North Atlantic basin, we have a set of 906 observed tropical cyclone tracks that we show in Figure 1.

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[5] See Table 4.

[6] The uncertainty is of 30 knots prior 1965 and reduces progressively to 7 knots in the 2000's to today, following the improvements in satellite coverage and measurement accuracy.

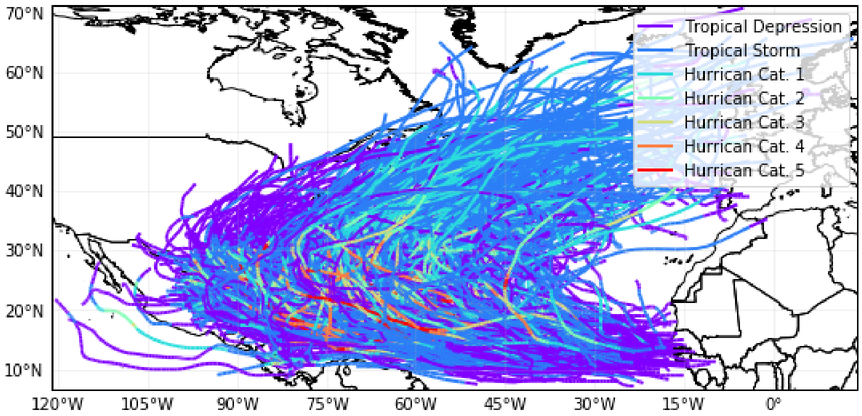

Figure 1: Tropical cyclones in the North Atlantic basin in years 1965-2019

We use the historical tracks to build a set of synthetic tracks for probabilistic future estimates. For each historical observation, we construct 50 synthetic counterparts as random walk processes under parameters controlling their distance from the original tracks. The synthetic tracks inherit several features from their historical counterparts, such as changes in wind speeds on landfall. Later, we combine the historical and synthetic tracks and create a probabilistic wind field model to calculate the annual average damages caused by TC activity.

2.2 Exposure data

Having constructed the probabilistic wind field model from the historical and synthetic cyclone tracks, we then need to estimate how physical assets are globally distributed in order to translate the cyclone wind field intensities into economic damages in monetary units. For this we use the *LitPop* model (Eberenz et al., 2019), which combines weighted global night light intensities and gridded global population accounts to obtain a globally consistent estimate of the spatial asset distribution.

The night-time light intensity data comes from the NASA's Black Marble night-time light suite (Román et al., 2018), available at a global resolution down to roughly 500 meters. Our base year for the night-time light data is 2016. The use of satellite imagery is convenient in particular for their public availability, global spatial coverage and a frequent update schedule. However, as noted in Eberenz et al. (2019), there are some known caveats in using satellite light intensities as a proxy for economic activity. First, since the night-time luminosity of any pixel can only be described on a 256-step range (from 0 to 255), the most intensively illuminated pixels are likely to be saturated to the maximum value. In addition, bright pixels might leak light to their adjacent pixels, and therefore inflate their brightness relative to the actual levels.

In order to overcome some of these issues, we supplement the light intensity data with global population data from the Gridded Population of the World (GPW) database (Center for International Earth Science Information Network, 2016). It provides globally disaggregated population counts with a resolution down to 1×1 km. Applying weights m and n for population and night-time light intensity respectively, the share of the physical assets (A_i) in each pixel i out of N total pixels for a given country is given by:

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

We give equal weights to the light intensity and population data, and use $n = 1$ and $m = 1$. Finally, we need to choose the economic (monetary) indicator that we distribute according to the pixel level LitPop proportions. Ultimately, we will model TC damages as destroyed capital stock. Therefore, we use as our indicator the produced capital stock, obtained from the World Bank wealth accounts data[7]. It includes an array of different physical capital types, such as machines, buildings, equipment, and urban land in constant 2014 USD. The value of physical capital in each pixel is then the product of the country's total capital stock value and the LitPop pixel-specific share as defined above.

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[7] Source: https://datacatalog.worldbank.org/dataset/wealth-accounting

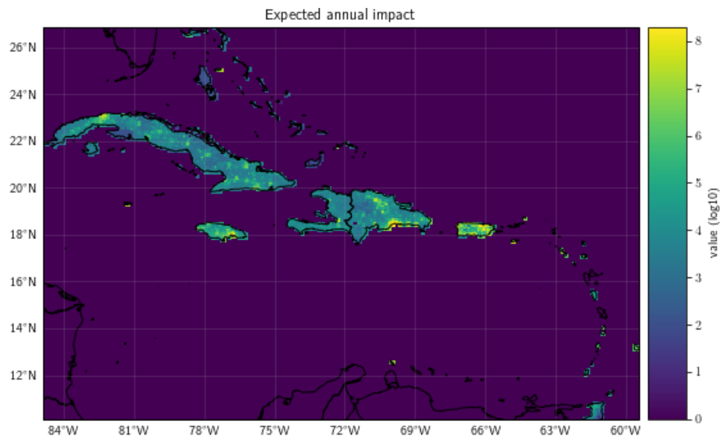


Figure 2: Expected annual impact (in USD) from TC in the Caribbean

Having the exposure data that we describe above and the TC data that we describe in Section 2.1, we can visualize the expected annual impact (in USD) caused by TC activity. In Figure 2 we represent such data for the Caribbean islands. We see that most of the expected damages concentrates around cities — since this is where most of the produced capital is concentrated — such as the Dominican Republic capital city Santo Domingo geo-located at about (71°W,18°N)

2.3 Economic accounts

Our numerical simulations focus on the TC impacts in the US and the Caribbean islands. The simulations provide an interesting comparison for our model, since both regions are frequently exposed to damages from tropical cyclones, but vary drastically in the structure of their economies and their adaptation capabilities. However, since the CLIMADA disaster impact model operates on a global scale, we also keep our economic model component flexible for different regional configurations.

For the economic data, we use the Global Trade Analysis Project (GTAP) database (Aguiar et al., 2016). It provides a unified base year dataset for 129 regions and 57 commodities, which gives us the flexibility to consider a range of countries and industrial sectors that are exposed to tropical cyclones. This level of regional and sectoral detail, however, is too extensive for most modeling applications. Therefore, we aggregate the data further, as specified in Table 3 (for industrial sectors) and in Table 4 (for regions) in Appendix B. The GTAP dataset provides information on international trade flows and the input-output structure both on a national and an international level. This allows us to study in our numerical general equilibrium model, how the destruction of capital in one region affects prices and demand in different sectors, and how such a change affects other regions through the interlinkage of service and material flows.

In addition to the dollar-valued economic data from GTAP, our model calibration requires various sector- and region-specific elasticity values. The elasticities for demand and the substitution between different intermediate inputs in production are the most important parameters for our analysis. We use the elasticity estimates from the MIT Economic Projection & Policy Analysis (EPPA) model (Paltsev et al., 2005), as described in table 1 in appendix A.

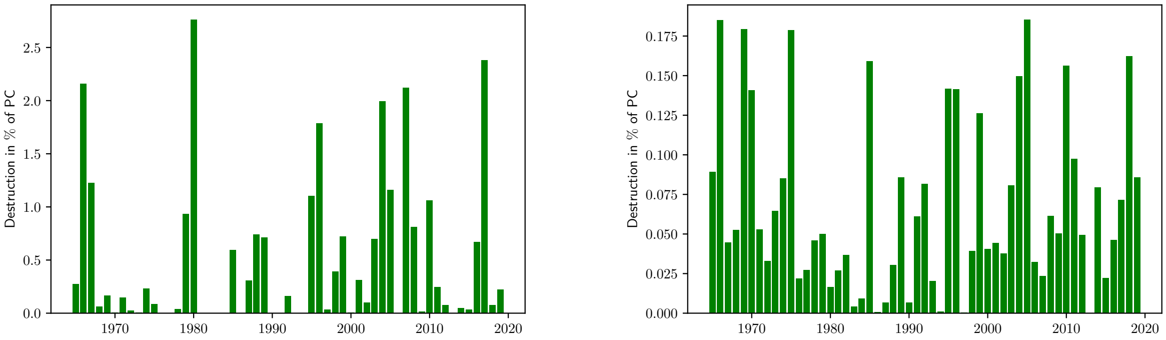
3 Methods

3.1 Computation of cyclone damages

We compute annual average damage for the period from historical data and a set of fifty synthetic tracks from simulations. The synthetic tracks help to develop a better measure of probabilistic annual average damage. Hence, we have damage estimates that correspond to a mean fractional loss of produced capital for each year at each spatial location.

Wind speed of each storm is converted to a fractional loss of the produced capital value at each location based on the cyclone's path. The damage function is taken from Emanuel (2011). The fraction of capital damaged by storm j at location i, δ_{ij} varies as the cube of the wind speed over a threshold value:

$$\delta_{ij} = \frac{v_{ij}^3}{1 + v_{ij}^3}, \tag{1}$$



(a) Caribbean islands (b) United States

Figure 3: History of TC damages in the Caribbean islands and the US in % of capital destroyed

where,

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

Similar to Emanuel (2011), we take the wind speed in m/s below which there is no damage $V_{thresh} = 25.7m/s$. We take $V_{half} = 74.7m/s$, the wind speed at which 50% of the capital value is lost from Sealy & Strobl (2017), which roughly corresponds to the one used by Emanuel (2011). These values are calibrated for the US. In this respect, our damage computation for the Caribbean is conservative. In Figure 3 are the histories and histograms of TC damages in the Caribbean islands (Figure 1.a) and in the US (Figure 1.b). We observe that a higher proportion of produced capital is destroyed in the Caribbean islands. Note, however, that TC destroys produced capital in the US with a higher frequency. Among the 906 historical TC in the NA basin from 1965 to 2019, 22.93% damage the US whereas only 11.52% cause destruction in the Caribbean islands.

3.2 Model used in the numerical simulations

We employ a dynamic, multi-regional and multi-sectoral numerical general equilibrium model similar to Bretschger et al. (2011a) and Bretschger et al. (2017). The specification of the growth dynamics is flexible: it can be used either as a standard Ramsey-type exogenous growth model, or alternatively with a Romer-style endogenous growth engine (Romer, 1990). With endogenous growth, the growth rate of the economy is determined by the gradual expansion in the available variety of intermediate goods. The broader variety of intermediate inputs increases productivity through gains from specialization. The time horizon of the theoretical model formulation is infinite with discrete increments, but solved for a finite number of periods in the numerical implementation. We next describe the model step-by-step, starting with the production structure.

3.2.1 Production

In each region, we model the production structure of the economy as the interaction between three types of agents: *i*) final good producers, *ii*) producers of sector-specific intermediate composites, as well as *iii*) the producers of intermediate goods. The markets for the final goods and the intermediate composite are perfectly competitive, whereas the intermediate good producers compete under a monopolistic setting. Figure 4 below presents an overview of the nested production structure.

Final good producers

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

$$Y_{i,r,t} = \left[\alpha_{i,r} Q_{i,r,t}^{\frac{\sigma_{i,r}-1}{\sigma_{i,r}}} + (1-\alpha_{i,r}) B_{i,r,t}^{\frac{\sigma_{i,r}-1}{\sigma_{i,r}}} \right]^{\frac{\sigma_{i,r}}{\sigma_{i,r}-1}}, \tag{3}$$

where $Q_{i,r,t}$ is the sector-specific composite of intermediate goods. $B_{i,r,t}$ denotes the composite output of final goods from all sectors that are needed as inputs for producing i. It therefore captures how different sectors (and regions) are interlinked through their complex

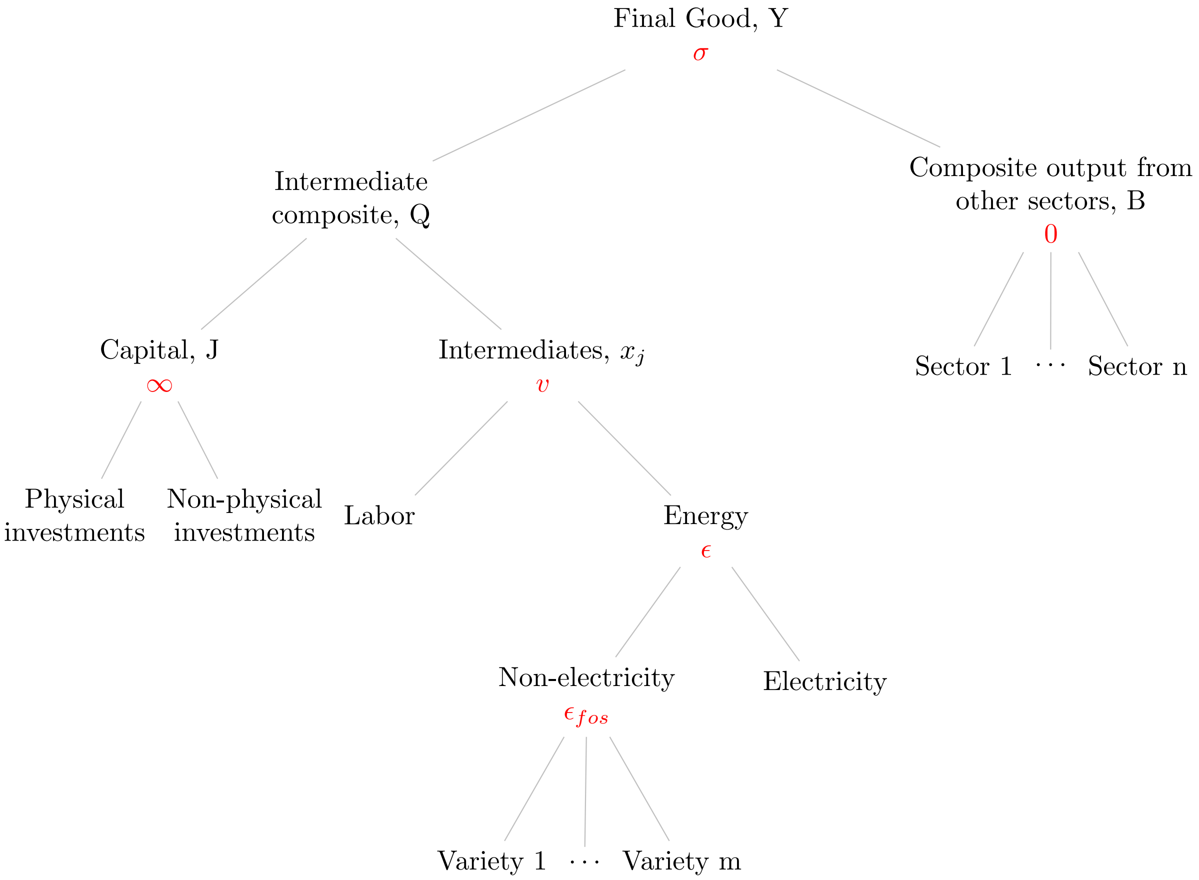


Figure 4: Production structure of the economy

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. The value shares of $Q_{i,r,t}$ and $B_{i,r,t}$ in the production function are determined by share parameters $\alpha_{i,r}$ and $1-\alpha_{i,r}$ respectively, and the elasticity of substitution between the two types of inputs is given by $\sigma_{i,r}$. Both parameters are also sector- and region-specific. The parameter values used in the numerical simulations are available in the appendix.

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

$$\max_{Q_{i,r,t},B_{i,r,t}} p^Y_{i,r,t} Y_{i,r,t} - p^Q_{i,r,t} Q_{i,r,t} - p^B_{i,r,t} B_{i,r,t}, \text{ w.r.t (3)}, \tag{4}$$

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 equation (4), 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:

$$\frac{Q_{i,r,t}}{B_{i,r,t}} = \left(\frac{\alpha_{i,r}}{1-\alpha_{i,r}}\right)^{\sigma_{i,r}} \left(\frac{p^B_{i,r,t}}{p^Q_{i,r,t}}\right)^{\sigma_{i,r}} . \tag{5}$$

According to Equation (5), an increase in the price of one input type will increase the share of the other input in the optimal bundle. Finally, for most goods, we are assuming the substitution elasticity $\sigma_{i,r}$ below unity, which implies imperfect substitutability between different types of inputs.

Production of intermediate composites

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:

$$Q_{i,r,t} = \left[\int_{j=0}^{J_{i,r,t}} x^{\kappa}_{j,i,r,t} dj\right]^{\frac{1}{\kappa}} , \tag{6}$$

where $x_{j,i,r,t}$ denotes the j^{th} type of intermediate good variety that is available in sector i. $J_{i,r,t}$ is the sector-specific capital stock. Importantly, 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 then gives us two channels through which the intermediate sector can induce growth in the overall economy: by producing a larger amount of any single variety $x_{j,i,r,t}$ by employing more labour and energy, or by expanding the number of available varieties through investing to the sector-specific capital stock $J_{i,r,t}$. Equation (6) therefore determines the growth rate for each sector through these two channels. The parameter κ measures the substitutability between different varieties $x_{j,i,r,t}$ (or equivalently, the gains from specialization), and is formally defined as $\kappa = (\sigma_Q - 1)/\sigma_Q$, where we assume $\sigma_Q > 1$ for the endogenous growth specification. Note that if we set $\kappa = 1$, the model in effect collapses to a standard, Ramsey-type exogenous growth model.

The producers of the intermediate good composite $Q_{i,r,t}$ maximize profits on a competitive market, taking all prices as given. They then solve:

$$\max_{x_{j,i,r,t}} p^Q_{i,r,t} Q_{i,r,t} - \int_{j=0}^{J_{i,r,t}} p^x_{j,i,r,t} x_{j,i,r,t} dj, \text{ w.r.t (6),} \tag{7}$$

where we denote by $p^x_{j,i,r,t}$ the price of each intermediate varieties. Solving the optimization problem in equation (7) determines the optimal demand for $x_{j,i,r,t}$ to be:

$$x_{j,i,r,t} = \left(\frac{p^Q_{i,r,t}}{p^x_{j,i,r,t}} \right)^{\frac{1}{1-\kappa}} Q_{i,r,t}. \tag{8}$$

From now on, we assume that all varieties of the sector-specific intermediate good are perfectly symmetrical, so we can simplify notation by writing $x_{j,i,r,t} = x_{i,r,t}$.

Production of intermediate goods

As described in equation (6), what determines the expansion of each production sector i are the amount, variety, and substitutability of different intermediate goods. Moreover, 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. In order to describe these intermediate firms in full, we need to describe their incentives to innovate new varieties, as well as their optimal output decision for the already invented varieties, separately.

i) Capital investments to new varieties

Our model consists of two types of capital, as depicted in Figure 4: physical and nonphysical, which together make up the sector-specific capital composite $J_{i,r,t}$. Firms conduct innovation by investing to this composite capital good, and we denote these investments by $I_{i,r,t}$. Access to the investment market is unrestricted. This implies that new innovations occur until the marginal cost of investment is equalized with the firm value, so that there are no real profits remaining. We follow the approach in 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:

$$J_{i,r,t+1} = I_{i,r,t} + (1 - \bar{\delta}_t) J_{i,r,t}, \tag{9}$$

with $\bar{\delta}_t$ denoting the total depreciation rate. We also introduce a no-arbitrage condition, where the total gains and losses from investing to a new innovation (profits, capital gains, and depreciation) must equal the return of a riskless loan. Intermediate good producers borrow from households in order to pay for their innovation activities in advance. Then, in equilibrium, we must have that the stream of discounted profits is equal to the sum borrowed by intermediate producers.

ii) Optimal output of new varieties

In order to produce one unit of output, the intermediate good producers combine two types of inputs, labour $L_{i,r,t}$ and energy $E_{i,r,t}$, according to the following CES technology:

$$x_{i,r,t} = J_{i,r,t} \left[\lambda_{i,r} L_{i,r,t}^{\frac{v_{i,r}-1}{v_{i,r}}} + (1 - \lambda_{i,r}) E_{i,r,t}^{\frac{v_{i,r}-1}{v_{i,r}}} \right]^{\frac{v_{i,r}}{v_{i,r}-1}}. \tag{10}$$

An important thing to note from Equation (10) is that there are within-sector spillover effects from the expanding capital stock $J_{i,r,t}$. We assume labour $L_{i,r,t}$ to be in inelastic supply 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:

$$E_{i,r,t} = \left[\sum_{k \in K} \phi_{k,i,r} (Z_{k,i,r,t})^{\frac{\epsilon_{i,r}-1}{\epsilon_{i,r}}} \right]^{\frac{\epsilon_{i,r}}{\epsilon_{i,r}-1}}. \tag{11}$$

The output decision of the intermediate monopoly can be derived from two parts. First, it chooses an optimal bundle of labour and energy inputs as if it were maximizing profits in a perfectly competitive market:

$$\max_{L_{i,r,t}, Z_{k,i,r,t}} \psi^x_{i,r,t} x_{i,r,t} - w_{r,t} L_{i,r,t} - \sum_k p^Z_{k,r,t} Z_{k,i,r,t}, \tag{12}$$

where we can interpret $\psi^x_{i,r,t}$ as the price that would prevail under a perfectly competitive market. We denote the amount of every energy input $k \in K$ by $Z_{k,i,r,t}$, and the respective price by $p^Z_{k,r,t}$. In addition, however, the firm will exploit its monopoly power in the output market and set the optimal output price by solving:

$$\max_{p^x_{i,r,t}} p^x_{i,r,t} x_{i,r,t} - \psi^x_{i,r,t} x_{i,r,t}, \tag{13}$$

taking the demand for $x_{i,r,t}$ in equation (8) as given. Thus, it will set prices according to:

$$p^x_{i,r,t} = \frac{1}{\kappa} \psi^x_{i,r,t}, \tag{14}$$

with profits then being equal to:

$$\pi_{i,r,t} = (1-\kappa) p^x_{i,r,t} x_{i,r,t}. \tag{15}$$

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 $p^x_{i,r,t}$, we can in fact consider $\frac{1}{\kappa} - 1$ as the optimal mark-up term on top of the marginal production cost of the good.

3.2.2 Preferences

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

$$U = \sum_{t=0}^{\infty} \left[\frac{1}{1+\rho} \right]^t \frac{C_{r,t}^{1-\theta} - 1}{1-\theta}, \tag{16}$$

where ρ denotes the time discounting parameter and θ the inverse of the intertemporal elasticity of substitution. Remembering that households also own all firms in the economy, we can write the budget constraints as:

$$p_{r,t}^{C} C_{r,t} = w_{r,t} L_{r,t} - T_{r,t} - \sum_i p_{i,r,t+1}^{J} J_{i,r,t+1} + \sum_i (1 + r_{i,r,t}) p_{i,r,t}^{J} J_{i,r,t}, \tag{17}$$

where $w_{r,t}$ denotes the wage rate, and $T_{r,t}$ a lump-sum tax which ensures the public budget to remain balanced. Maximizing (16) with respect to (17) gives the optimal consumption growth rate $g = \frac{C_{t+1}}{C_t}$ according to the standard Keynes-Ramsey rule:

$$g_C \equiv \left[\frac{1 + r_{t+1}}{1+\rho} \frac{p_t^C}{p_{t+1}^C} \right]^{\frac{1}{\theta}}. \tag{18}$$

According to Equation (18), higher interest rate r boosts growth by inducing more saving, whereas a higher discount rate ρ gives incentives to present consumption, therefore reducing the rate of growth.

3.3 International trade

Our baseline dataset contains economic accounts of 129 regions, covering most of the global economy. Also our model assumes the interaction of several countries through international trade. This channel will be an important determinant of how countries can adapt to a variety of economic shocks.

All final sectors in the economy are open to international trade. That is, all producers can employ both domestic 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 more than imports. 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 goods, which is what we also observe in the real economies.

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

$$A_{i,r,t} = \left(\zeta_{i,r} D_{i,r,t}^{\frac{\eta_{i,r}-1}{\eta_{i,r}}} + (1-\zeta_{i,r}) \left(\left[\sum_{s \neq r} m_{i,s,r} M_{i,s,r,t}^{\frac{\phi_{i,r}-1}{\phi_{i,r}}} \right]^{\frac{\phi_{i,r}}{\phi_{i,r}-1}} \right)^{\frac{\eta_{i,r}-1}{\eta_{i,r}}} \right)^{\frac{\eta_{i,r}}{\eta_{i,r}-1}}, \tag{19}$$

where we denote by $\zeta_{i,r}$ the share of domestic goods, and by $m_{i,s,r}$ the share parameters of regions in the basket of imports. $\eta_{i,r}$ 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 good producers face is then:

$$\max_{D_{i,r,t}, M_{i,s,r,t}} p^A_{i,r,t} A_{i,r,t} - p^Y_{i,r,t} D_{i,r,t} - \sum_{s \neq r} p^A_{i,s,t} M_{i,s,r,t}. \tag{20}$$

Finally, the model closure allows countries to run either trade surpluses or deficits, as also observed in the baseline dataset.

3.4 Calibration

Our model calibration follows closely the steps outlined in Paltsev (2004). The key goal of the calibration process is to use the GTAP dataset described in Section 2.3 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 social accounting matrices (SAM) obtained from the GTAP dataset report the values — prices times quantities — of economic transactions in millions of US dollars. However, for our general equilibrium analysis, we have disentangled the value flows into prices and quantities. The general approach in the applied general equilibrium literature, which we also follow here, is to normalize base year prices to unity. This maps the values reported in the SAM directly to reference quantities, which we then use in our simulations.

We will exploit the features of the balanced growth path, and explicitly write out the reference price and quantity paths for each region. We first assume a constant interest rate $r = 0.02$, thus, all prices in the economy evolve according to $p_t = p_0 \left(\frac{1}{1+r}\right)^t$. Similarly, we assume an annual growth rate of capital of $g_J = 0.02$, and the reference quantity path for capital becomes $(1 + g_J)^t$. Finally, we assume a constant baseline depreciation rate $\delta = 0.07$, that is, excluding the additional depreciation induced by the tropical cyclones. Regarding Equation (9), we can then describe the evolution of the capital stock by $J_{t+1} = (1 + g_J)J_t$. Combining these two equations gives us the condition for investment demand as $I_t = (g_J + \delta)J_t$. That is, on a balanced growth path, the investments must exactly account for the growth rate, as well as the depreciation rate, of the economy. We can write a similar condition for the supply side as well, by first noting that households are also the sole owners of the capital stocks, and can choose to rent it to firms as capital services. Then, in equilibrium, they should be indifferent between borrowing to other households (at rate r), and renting to firms. However, since capital wears out in use, the rental rate paid by firm must also be adjusted. The rental rate is then given by $r + \delta$. With these assumptions, we get a benchmark growth rate of the economy of roughly 2%.

Despite the theoretical model being formulated for an infinitely-lived representative agent, the numerical solution must be approximated using a finite number of time periods. This brings the risk of horizon-effects affecting the equilibrium outcome as we approach the terminal period. We therefore employ the method from Lau et al. (2002), to solve for the infinite horizon equilibrium by imposing additional constraints for the terminal period T capital accumulation in the numerical solution. More specifically, 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:

$$\frac{I_T}{I_{T-1}} = \frac{Y_T}{Y_{T-1}}. \tag{21}$$

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.

3.5 Solving the model

The model equilibrium, given our initial database, and calibration to a balanced growth path, is given by a vector of prices and quantities such that firms maximize their profits, the representative agent maximizes intertemporal utility with respect to a budget constraint, and the adjustment of prices clears all markets. The model is calibrated in the absence of any shocks, and tropical cyclones are then added to the analysis as counterfactual experiments.

As shown by Mathiesen (1985), we can model such a general equilibrium economy as a mixed complementary problem (MCP) through three types of inequality constraints: market clearing conditions, zero profit conditions, as well as income balance conditions. Each equilibrium condition f has a complementary variable x, such that $f(x) \geq 0, x \geq 0, x^T f(x) = 0$. For instance, denoting supply and demand by S and D, respectively, and price by p, we can write market clearing conditions $f(p) = S(p) - D(p)$. Then, only when the market perfectly clears, will the equilibrium price be positive. If supply exceeds demand, however, the complementary variable (price) will be zero. Similarly, the zero profit condition is combined with a complementary variable output. The output will be positive as long as the profits are non-negative, and zero otherwise.

The economic model is implemented using a high-level programming language GAMS (General Algebraic Modeling System, Rosenthal 2013), as well as the MPSGE (Mathematical Programming System for General Equilibrium, Rutherford (1999)) sub-system. The model is solved using the PATH solver Ferris & Munson (2000).

3.6 Solution algorithm for unanticipated shocks

3.6.1 Cyclones increase the depreciation rate of capital

A natural disaster affects the economy in more ways than can be described in a single model, and we must therefore choose the most important channels to include the analysis. One of the key point here is the formulation of shocks either as targeting the stock or the flow variables of the economy. The standard approach in the integrated assessment modeling literature is to formulate climate-related damages as losses in the level of current gross final output flow Y — see e.g. Nordhaus (2010). As pointed out in Dietz & Stern (2015), however, this simplistic approach does not properly capture the long-term impacts that climate change might have on growth rates. We follow Dietz & Stern (2015) and model the economic shocks from tropical cyclones as changes in the capital depreciation rate, which reduces capital stocks, and also brings long-lasting impacts on the determinants of growth rates.

A higher depreciation rate affects the economy in two ways. First, with lower contemporary capital stock, the production capabilities are lower. Hence, current output also drops. Second, with a higher depreciation rate, more resources are needed to maintain even the existing stock of capital, with less resources being devoted to new innovations, thus reducing the rate of growth.

3.6.2 An algorithm to isolate the effect of TC shocks

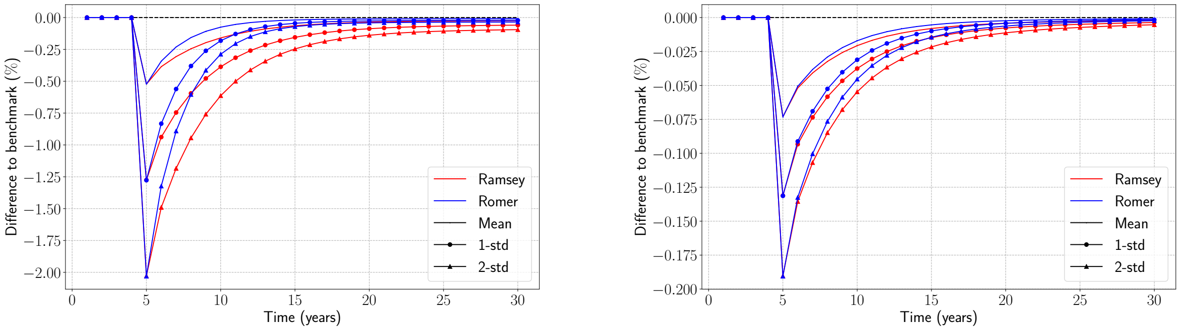
Numerical general equilibrium models can well capture the multi-sectoral adjustment of prices after a disaster occurs. Unfortunately, in such models the representation of information is rather restricted. Models such as Bretschger et al. (2011b) assume agents to have perfect foresight of the whole economy, which may exaggerates their ability to prepare for any future shocks. Assuming perfect-foresight would be a poor approximation to study the impact TC strikes because of the high variance in the damages they cause. Even if the cyclone shocks were drawn randomly in the simulation, the agents in a deterministic and perfect foresight model would perfectly anticipate the timing and severity of their occurrence.

An alternative is to formulate the model as a recursive economy, such as the standard EPPA model (Paltsev et al., 2005), which gives the agents in the model zero foresight about the future. However, also the recursive approach has its limitations. Especially in areas with frequently occurring disasters, the agents have some anticipations on the future disastrous events. A recursive approach also assumes that agents only optimize within a single period, and subsequent periods are linked by typically fixing an exogenous savings rate. This assumption represents poorly the empirical findings on anticipation and rebuilding efforts related to natural disasters (Hsiang, 2010; Loayza et al., 2012).

The economic reality may lie somewhere in between these two approaches. In order to remedy this issue while focusing on the impact of TC strikes on the economy, we choose an algorithm that maintains the perfect foresight over all economic variables, but treats the actual disaster realizations as unanticipated shocks. In order to model an unanticipated disaster occurring at time τ, we first solve for a reference equilibrium path from the initial time period t_0 to the terminal period T, such that $t_0 < \tau < T$. From the reference equilibrium, we then take the time τ state variables and construct a new set of initial values. In the newly constructed sub-model from τ to T, the shock then occurs in the first period of the simulation, with no chance of anticipation for the agents. We then 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 approach produces the same numerical results as only simulating for the reference equilibrium path.

4 Quantitative analysis

In the figures below, we analyze the economy's reaction to a single year of tropical cyclones activity. We compare the reactions of an economy with an endogenous growth mechanism to an economy growing exogenously. The size of the shock depends on the historical distribution TC damages in each region as we explain in previous sections. We generate the shock at year five. In order to have precise estimates of the impact of a potential year of TC damages to the economy, we analyze three possible scenarios, *1)* the economy undergoes a year of TC of average intensity, *2)* the economy undergoes a year of TC of intensity one standard deviation above the average and *3)* the economy undergoes a year of TC pf intensity two standard deviation above the average.



(a) Caribbean islands

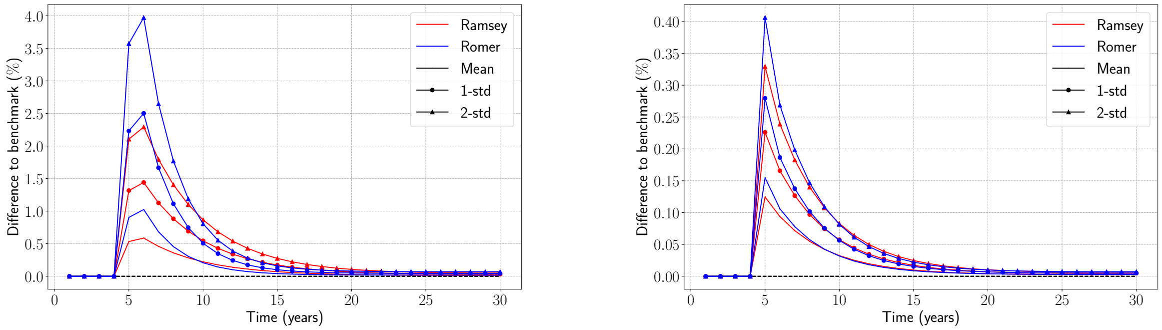
(b) United States

Figure 5: Impact on the aggregate capital stock

In our standard exogenous growth model à la Ramsey, a shock that destroys capital (Figure 5) triggers immediate investments (Figure 6) and savings (Figure 7) in order to replace the capital destroyed. This brings an immediate boost to output (Figure 8) that other studies commonly observe.

In all cases, the impacts measured as percentage difference to the benchmark case without TC, the Caribbean islands undergo a much larger shock to their economy than the US. The short-term quantitative economic divergence between the two regions following a one-year TC activity is even more striking than their relative initial exposures to TC destruction that we represent in Figure 3. The long-run consequences, however, diverge, especially under the endogenous growth set-up.

In a Romer-type economy, the growth rate is determined by the total stock of capital. Therefore, a sudden loss of this capital (Figure 5) implies a lower post-disaster growth of output in the mid-term. In the long run, however, the capital stock is re-built (Figure 5) so the difference in growth rates of output is caught up. We see the catch-up effect in growth rates in the graphs since the lines representing the aggregate output level become parallel to their benchmark level (Figure 8).

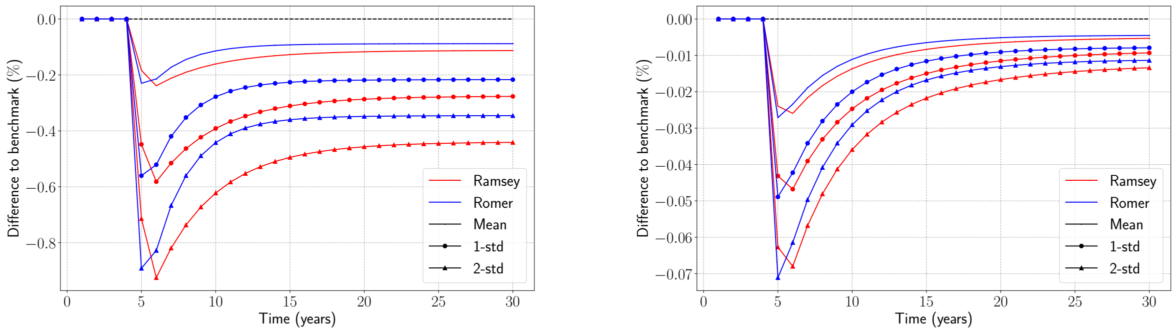


(a) Caribbean islands

(b) United States

Figure 6: Impact on the aggregate investment

In the economic accounts of the US, there is a lot more productive capital than in the Caribbean economy in proportion of their respective amount of total capital. Hence, a lot more productive capital gets destroyed in the US compared to the type of capital destroyed in the Caribbean. The productive type of capital represents the one that is directly used to produce output whereas other types of capital such as houses and other durable goods do not directly enter production. Again, since in a Romer-type economy, the growth rate is determined by the total stock of (productive) capital, the long-run impact on output under endogenous growth is more pronounced for the US Figure (8). Such pattern in our endogenous growth set-up is similar to the one Strulik & Trimborn (2019) describe. For Strulik & Trimborn (2019), the impact of natural disasters is positive on output if the disasters mainly destroy durable goods. They argue that households want to replace their damaged goods rapidly, and no production opportunities are lost, causing a spike in output. This is what we observe in the Caribbean case. On the contrary, it is not the case for the US since the disasters destroy a lot of productive capital.

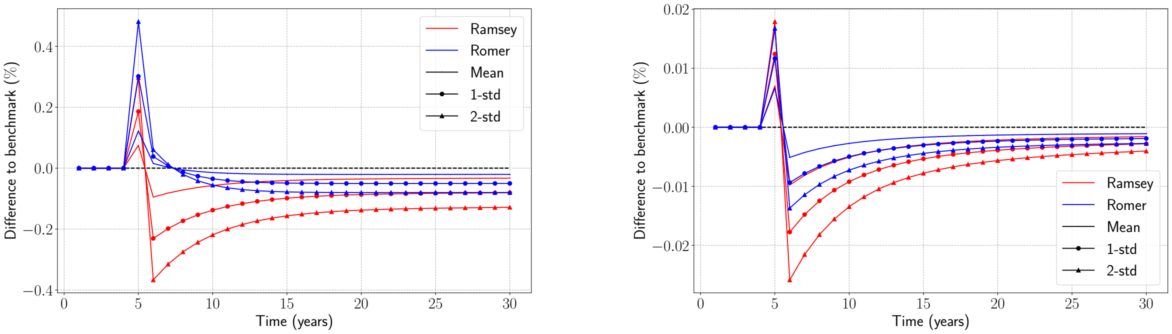


(a) Caribbean islands

(b) United States

Figure 7: Impact on the aggregate consumption

Although the capital stock recovers faster with endogenous growth than in a Ramsey-type economy, in both cases, there is a gap that remains at the output level relative to the benchmark economy. This is consistent with the findings of Hsiang & Jina (2014) which shows that after even a single TC destruction event, the national income do not recover within twenty years relative to their pre-disaster trend. This non-recovery to the trend is even more pronounced for an economy growing with a Ramsey growth engine. An neoclassical growth model à la Ramsey better model the engine of growth of developing economies. With this respect, our results go along the other ones in the literature finding stronger effects of TC strikes on poorer countries (Noy, 2009; Berlemann & Wenzel, 2018). Note that in order to see an output growth boost, the economy would need to have a Schumpeterian creative destruction growth dynamics as in Crespo Cuaresma et al. (2008) where the capital destroyed is replaced by better and more productive capital.



(a) Caribbean islands

(b) United States

Figure 8: Impact on the aggregate output

Consumption in Figure 7 remains below the benchmark levels. First, there is a negative shock on consumption due to the increase investments (Figure 6) in order to start re-building the capital stock. The initial drop in consumption with endogenous growth is more pronounced, but recovery is faster since the capital stock re-builds faster (Figure 5) by virtue of the increasing returns to scale advantage of a Romer economy over a Ramsey economy.

5 Conclusion

In this paper, we combine a multi-sectoral dynamic general equilibrium model with a probabilistic natural disaster impact model to estimate the economic consequences of tropical cyclones. We model the disaster impacts as destruction of the capital stock, and present the results for the US and the Caribbean islands, two frequently affected regions. Our simulation framework confirms — and quantifies — numerous findings from the existing literature: the surge in aggregate investment and output during the reconstruction phase, and a slow convergence back towards the benchmark growth path. For large shocks, the economy can be permanently trapped in a lower growth trajectory. In addition, our results highlight the role of growth dynamics in simulating rare natural disaster impacts. For an endogenous Romer-type growth specification, economies respond faster to restore the destroyed capital stock, and the post-disaster drop in output remains smaller than under a Ramsey-type exogenous assumption of growth.

Our model combination allows us to represent regional economies and region-specific probabilistic damage functions in high detail. Our approach also presents the advantage of isolating the effect of TC in order to be able to capture their effects *via* different channels despite the complexity of general equilibrium analysis. But some caveats remain. Assuming the economy to settle in an equilibrium right after the shock occurs is optimistic, in particular for small regions that might see a significant share of their GDP being wiped away in a single disastrous cyclone. Also, we do not treat the role of agriculture. This sector is more vulnerable to TC and in economies like the Caribbean islands, agriculture still contributes to a large part to the global economic activity. Such regions might then be more severely hit by cyclones than what we estimate here. We leave this issues for future work.

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Appendices

A Parameter values used in the numerical simulations

Model parameters			
Param.	Description	Value	GAMS code
Elasticities of substitution for production activities			
σ	Intermediate composite Q and inputs B from other sectors	0.5	esub(i,r)
v	Labour and energy in intermediate good production	1	sigma(g,r)
v_{trn}	Labour and energy in transport sector intermediate good production	0.95	sigma("trn",r)
ϵ	Electricity and non-electricity for intermediate goods production	0.5	sigma_enoe(g,r)
ϵ_{fos}	Types of non-electricity energy in intermediate production	1	sigma_en(g,r)
κ	Intermediate varieties	0.86	kappa
Elasticities of substitution for consumption			
$1/\theta$	Intertemporal elasticity of substitution	0.5	sigma
σ_c	Non-energy goods in consumption	0.25	sigma_c(g,r)
$\sigma_{e,f}$	Energy goods in consumption	0.40	sigma_ef(g,r)
$\sigma_{e,c}$	Energy and non-energy goods in consumption	0.45	sigma_ec(g,r)
$\sigma_{c,t}$	Transport and non-transport goods in consumption	1	sigma_ct(g,r)
$\sigma_{c,l}$	Consumption and leisure	1	sigma_cl(g,r)

Table 1: Description and values of the parameters used in the simulations

Model variables	
Variable	Description
Sets	
i	Commodities / sectors
j	Intermediate varieties
r	Regions
f	Factors of production
Quantity variables	
$Y_{i,r,t}$	Final good
$Q_{i,r,t}$	Intermediate composite
$X_{i,r,t}$	Intermediate goods
$J_{i,r,t}$	Capital stock
$I_{i,r,t}$	Investment
$C_{r,t}$	Aggregate consumption
$A_{i,r,t}$	Armington good

Table 2: Description the variables used in the economic model

B Mapping of regions and economic sectors

Label	Description	GTAP sectors
Goods and sectors		
MAN	Manufacturing	Minerals, Textiles, Wearing apparel, Leather products, Wood products, Motor vehicles, Transport equipment, Machinery, Manufactures, Water, Construction, Paper, Chemicals, Minerals, Ferrous metals, Other metals, Metal products
SER	Services	Trade, Communication, Financial services, Insurance, Business services, Recreation, Dwellings, Public services
TRN	Transport	Water transport, Air transport, Other transport
AGR	Agriculture	Paddy rice, Wheat, Ceral grains, Vegetables, Oil seeds, Sugar cane, Plant-based fibers,Other crops, Bovine cattle, Other animal products, Raw milk, Wool, Forestry, Fishing, Bovine meat products, Vegetable oils, Dairy products, Processed rice, Sugar, Other food products, Beverages and tobacco
ELE	Electricity	Electricity, Electricity equipment
ENE	Other energy	Petroleum, Crude oil, Gas, Coal, Gas Distribution
Factors of production		
RES	Resources	Land, Natural resources
LAB	Labour	Skilled labour, Unskilled labour
CAP	Capital	

Table 3: Mapping of sectors and factors of production

Region	Countries
USA	United States of America
Caribbean	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
China	China, Hong Kong
Europe	France, Germany, Italy, Turkey, United Kingdom, Austria, Belgium, Denmark, Finland, Greece, Ireland, Luxemburg, Netherlands, Portugal, Spain, Sweden, Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Bulgaria, Cyprus, Switzerland, Norway
ROW	Rest of the World

Table 4: Mapping of countries and regions