Do Disasters Affect Growth? A Macro Model-Based Perspective on the Empirical Debate

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Abstract

A growing literature has sought to quantify the impacts of natural disasters on economic growth, but has found seemingly contradictory results, ranging from positive to very large negative effects. This paper brings a novel macroeconomic model-based perspective to the data. We present a stochastic endogenous growth model where individual regions face uninsurable cyclone risks to human and entrepreneurial capital, building on the tools developed in the incomplete markets macroeconomics literature (Krebs, 2003, Angeletos, 2007). Our model can reconcile key divergent results from prior empirical studies, as they measure different elements of the overall impact of disasters on growth: (1) Higher disaster *risk* can increase growth by increasing (precautionary) savings, whereas disaster *strikes* induce (potentially persistent) output losses, in line with the empirical evidence of positive growth effects in cross-sectional analyses (e.g., Skidmore and Toya, 2002) but negative impacts in panel studies (e.g., Hsiang and Jina, 2015a). We explore a combined two-step estimation to assess the overall impact of cyclones on growth, which - on average - appears to lie in between. (2) Competing measures of cyclone risk - average capital destruction, fatalities, or storm intensity - can be related to growth in opposite ways, again in line with the literature (e.g., Hsiang and Jina, 2015b vs. Skidmore and Toya, 2002). Intuitively, long-run growth depends on the level and composition of investments across different assets, which, in turn, depend differentially on the vector of expected damages to all capital goods. (3) Finally, we show that disaster risk can have opposite effects on growth and welfare.

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1 Introduction

How do natural disasters affect economic growth? A rich empirical literature continues to analyze this question, but has come to seemingly contradictory conclusions, ranging from positive \to very large negative impacts of disasters on growth. While the direct costs of natural disasters are well-established to be large (Bakkensen and Mendelsohn, 2016; Ranson et al., 2014) and increasing due to global changes (Mendelsohn et al., 2012; Nordhaus, 2010), the macroeconomic consequences of disasters thus remain an open question. Resolving this question is arguably important as both the adaptation to and valuation of changes in disaster risks - such as due to climate change - require a detailed understanding of disaster impacts' magnitudes and mechanisms.

This paper brings a novel macroeconomic model-based perspective to the data in order to reconcile and build upon the empirical literature on disasters and growth. Despite its importance and richness, this literature currently features two main gaps. First, the empirical growth literature has found a range of seemingly contradictory results, ranging from positive impacts (e.g., Skidmore and Toya, 2002) to extremely large negative effects (Hsiang and Jina, 2015, "HJ"). These differences have yet to be reconciled, and it remains unclear how competing empirical settings and methodologies impact the results. The second key gap is the lack of connection between empirical work with macroeconomic growth models. As HJ note, it is difficult to compare empirical estimates without the context of a growth model. While there have been some important recent advances in the theory of disasters and growth (e.g., Akao and Sakamoto, 2014; Ikefuji and Horii, 2012), these works have pursued limited empirical connections, and/or employ models with a different focus.[1] This paper takes advantage of the tools developed in the literature on incomplete markets and growth (e.g., Angeletos, 2007; Krebs, 2003) to develop a structural perspective on disasters and growth. We seek to inform both gaps by developing a macroeconomic stochastic endogenous growth model of disaster risk and impacts, where individual regions face uninsurable idiosyncratic cyclone risks to their human and entrepreneurial capital.[2] We then use the model to re-evaluate the literature and the data through a structural lens.

The main result is that the model can reconcile some key divergent results from prior empirical studies, as they measure different elements of the overall impact of natural disasters on growth: (1) Higher hurricane *risk* can increase growth by increasing (precautionary) savings rates, whereas hurricane *strikes* induce (potentially persistent) output losses. Consequently, we should potentially expect cross-sectional studies of cyclone risk and long-run growth (e.g., Skid-

[1] For example, Akaho and Sakamoto (2014) employ a single-region model focusing on aggregate shocks, whereas we focus on idiosyncratic uninsurable disaster risks to regions within a larger economy. Ikefuji and Horii's (2012) focus on endogenous disaster risk from pollution and growth.

[2] We use tropical cyclones ("hurricanes") as natural disaster. Previous literature has shown heterogeneous impacts of disasters on growth, making the focus on a specific category desirable. Cyclones are large, frequent, and well-recorded for many years. The growth impacts of other types of disasters are left for future work.

more and Toya, 2002) to find opposite results from panel fixed-effects studies identifying the impact of cyclone *strikes*, as is indeed the case. While competing empirical approaches identify different aspects of the growth question, neither cross-sectional nor panel fixed-effects specifications may thus be individually sufficient to capture the overall effect of disasters on growth. We explore a two-step estimation procedure that seeks to adjust directly for the dependence of countries' average growth rates on cyclone risk. We empirically find that average growth in a world without cyclone *strikes* is positively associated with cyclone *risk*, in line with the model. Our best estimate of the *overall* impact of cyclones on growth lies between the large negative cumulative effect of strikes and the positive effect of risk. (2) Alternative measures of cyclone risk - such as average damages to physical versus human capital, or average storm intensity - can be related to growth in opposite ways. Consequently, we should expect cross-sectional studies employing different measures to find different results, as is indeed the case. For example, Hsiang and Jina (2015b) document a negative relationship between average cyclone-induced capital depreciation and long-run growth, whereas Skidmore and Toya's (2002) find a positive association between the average number of disasters and growth. In our model, long-run growth depends on the level and composition of households' investments in assets with different productivities and disaster vulnerabilities. A decline in the expected returns to investments in, e.g.,. human capital due to higher expected cyclone damages can thus increase investment in other, potentially more productive (but riskier) assets, such as entrepreneurial capital, increasing growth. While empirical studies using different individual cyclone risk measures identify different elements of growth impacts, our model suggests that the overall impact of cyclone risk on growth depends on the entire vector of expected damages, as well as impact variance and covariance measures, which have seldom been included in empirical studies. (3) Finally, we show that cyclone risk can have opposite effects on growth and welfare. That is, the growth impacts of cyclone risks may not be of the same sign as the welfare impact of those risks. Consequently, joint advances in theory, data, and empirics will likely be neeed to improve our understanding of these environment-economy interactions.

The paper is structured as follows. Section 2 reviews the relevant empirical and theoretical disaster growth literatures. Section 3 presents our model setup, predictions for cyclones and long-run growth, transitional impacts, and implications for the empirical literature. Section 4 presents our empirical methodology, data, and results. We conclude in Section 5 and present the Appendix in Section 6.

2 Disasters and Growth Literature

A growing area of literature exists to identify and explain the impacts of natural disasters on human communities. Broadly, empirical literature aims to identify the impact of natural disasters on direct and indirect losses as well as broader macroeconomic impacts. Motivated by our model, we include direct impact studies in our review, as they represent damages to physical and human capital that endogenously generate growth impacts through changes in the capital stock as well as investment behavior.

2.1 Empirical Approaches

Extensive literature exists analyzing the impacts of natural disasters on direct losses and economic growth (Cavallo and Noy, 2011; Kousky, 2014). First, new and growing literature analyzes the impact of exogenous disaster shocks on economic growth, with a range of conclusions. Using a cross-sectional approach, Skidmore and Toya (2002) find that countries with higher frequencies of disasters have, on average, higher average economic growth rates. This is driven by climatic events, whereas geologic events, such as earthquakes, are negatively correlated with growth. Noy (2009) empirically analyzes the impact of endogenous and exogenous variables on the annual growth rate using a panel of 109 countries using the Hausman-Taylor estimator (1981). Using a month of disaster onset normalization, they find that only damages impact the growth rate and not fatalities or number of individuals affected. The analysis does not analyze the impact of long-run disaster risk, as does Skidmore and Toya, instead looking at the contemporaneous impacts of a disaster on economic growth. Hsiang and Jina (2015) use a panel fixed effects specification to analyze the impact of disasters lagged up to twenty years on current growth. They also perform simulations to model counter-factual growths rates, if no hurricanes had ever occurred. They conclude that hurricanes have a minor but persistent impact on growth. Once integrated over time, these losses become very large. Similar to Noy, Hsiang and Jina control for the long-run cyclone risk in their empirical specification, identifying off of individual shocks.

In a similar spirit, Cavallo, Galiani, Noy, and Pantano (2013) use synthetic control to construct counter-factual no-disaster growth rates of countries impacted by disasters. They find that only the most extreme disasters have negative growth impacts in both the short and long runs. However, significant political revolutions is an important variable that, once included, wash away the negative impact of disasters on growth. Hochrainer (2009) also uses counter-factual analysis, finding that disaster impacts are negative but small, with larger shocks leading to larger impacts. He also analyzes factors that increase vulnerability to macroeconomic losses, finding that less aid or remittances increases harm. Loayza, Olaberria, Rogolini, and Christiansen (2009) find that disasters have heterogeneous impacts across disaster types and sectors, with some small dis-

asters triggering positive growth impacts. However, large disasters only have negative impacts. Lastly, they find that developing countries are more sensitive to natural disaster impacts. Using a vector autoregressive approach, Fomby, Ikeda, and Loayza (2013) finds similar results. Strobl (2011) conducts a careful analyses of the impact of hurricane strikes on county-level growth in the United States. He finds that the average impact of a landfall on growth is -0.45 percentage points, however one quarter of that impact is due to migration of richer individuals. Strobl does not find any impacts at the state or national level, nor negative long run impacts. Therefore, the empirical growth literature, taking very different approaches, finds a wide range of results. No attempts have been made to reconcile these findings. Klomp and Valckz (2014) conduct a meta-analysis and find a negative impact of disasters on growth, but note that this could be, in part, due to publication bias. Lazzaroni and van Bergeijk (2014) find similar results in their meta-analysis of 64 primary studies.

Underpinning macroeconomic growth are the stocks of both human and physical capital. Thus, much of the literature on the direct and indirect impacts of natural disasters also usefully informs determinants of macroeconomic growth impact channels. Concerning physical capital, Leiter, Oberhofer, and Raschky (2009) use a difference-in-difference approach and find that flood-hit companies have, on average, higher growth in assets and employment, relative to non-flooded firms. These affects are concentrated among firms with more intangible assets. Mechler (2009) analyzes nontraditional national accounting metrics, including savings rates, to model post-disaster consumption, finding that poorer countries are most hit by capital stock losses, whereas richer countries rely more on human capital and technology to mitigate disasters. Multiple studies analyze determinants of direct damages from natural disasters (Bakkensen and Mendelsohn, 2016; Toya and Skidmore, 2007; Kellenberg and Mobarak, 2007; Fankhauser and McDermott, 2013; Nordhaus, 2010) including the underlying risk rate (Hsiang and Narita, 2012; Schumacher and Strobl, 2011). In addition, Conte and Kelly (2016) find that the distribution of property losses can have fat tails, which is explained by property location and not distributions of hurricane strength or damages across individual properties. All together, these findings inform policy and risk reduction strategies.

The impacts of natural disasters on human capital is a question of fundamental importance. Growing literature analyzes the impact of disasters on fatalities (Kahn, 2005). While extensive literature in public health, psychology, sociology, and economics analyze the impacts of singular events or a few case studies on a variety of specific impacts, few papers analyze these impacts through the lens of a macroeconomic model. Clear negative consequences results from natural disasters, including death and injury as well as reductions in nutrition, education, health, and income-generation. These impacts are most concentrated in developing countries. However, the empirical and theoretical impacts are ambiguous in terms of duration of consequences, as well

as potential general equilibrium impacts that could increase investment or returns to human capital, relative to physical capital, under natural disasters (Baez, de la Fuente, and Santos, 2010). Antilla-Hughes and Hsiang (2012) find that income loss and infant mortality in the year following a disaster are much larger than direct losses and fatalities. Hallegatte (2015) also finds that indirect "ripple effects" are important, but can be either negative or positive. Toya, Skidmore, and Robertson (2012) use disasters as an exogenous instrument for human capital shocks, to isolate the growth impacts. Cuaresma (2010) find a negative relationship between geologic disasters and schooling. However, knowledge gaps remain, including the extent to which impacts are long term, as well as the ultimate growth impacts from human capital shocks (Baez, de la Fuente, and Santos, 2010).

Lastly, disasters can impact knowledge, policy, and trade. Using both cross-sectional and panel techniques, Cuaresma, Hlouskova, and Obersteinter (2008) find a positive relationship between the underlying risk of disasters and knowledge spillovers taking place between developed and developing countries. They find that this is evidence of creative destruction. Popp (2006) reviews the literature and finds that disasters' impact on technology has a qualitatively ambiguous impact on economic growth. Gassebner, Keck, and Teh (2010) find that disasters reduce both imports and exports in a struck country, with reductions greatest in smaller or non-democratic states. Noy and Nualsri (2011) analyze the fiscal impacts of disasters and Deryugina (2011) finds that the indirect and fiscal costs of hurricanes outweigh the direct losses.

2.2 Theoretical Approaches

While the theoretical literature focusing explicitly on the impacts of natural disasters on output and growth is "still in its infancy" (Ikefuji and Horii, 2012), we build on its important recent advances. Most closely related to our approach, Ikefuji and Horii (2012) present an endogenous model in the Uzawa-Lucas tradition, where individual regions are subject to hurricane shocks to physical and human capital. The focus of their paper is on pollution taxation and growth, as pollution affects disaster risk in their framework. They consider the potential implications of uninsurable human - but not physical - capital risk on long-run growth. In addition, their model is not brought to data. Akao and Sakamoto (2014) present a two-sector endogenous growth model with different disaster shock processes, and studies the channels through which these affect long-run growth. Their approach is complementary to our study as it focuses on aggregate shocks in a single-region model, whereas our framework models uninsurable shocks to individual regions in an incomplete markets endogenous growth model. Akao and Sakamoto's focus is moreover theoretical, whereas we focus on connecting our model to the data and to empirical methodologies. Noy and Nualsri (2007) analyze the impact of changes in growth model

assumptions on predictions of the impact of natural disasters while testing these predictions empirically. McDermott, Barry, and Tol (2014) study the impact of capital markets to mitigate the harmful growth impacts of natural disasters. Finally, Kousky, Luttmer, and Zeckhauser (2007) analyze the interaction between private capital markets and public hazard protection, but do not empirically quantify their results.

In addition to theoretical models, several papers develop quantitative estimates of disaster impacts. Albala-Bertrand (1993) develops a growth-accounting framework for disaster impacts, finding that capital losses from a disasters do not greatly impact growth. Hallegatte and Dumas (2009) develop a dynamic growth model in a disequilibrium setting to analyze direct and indirect disaster impacts. Rose (2004) highlights the importance of computable general equilibrium models in the study of natural disasters. Finally, Narita, Tol, and Anthoff (2010) develop an integrated assessment model to analyze hurricane costs.

We seek to add to this literature by bringing in analytic tools that have been developed for the study of incomplete markets and their macroeconomic implications. A rich literature in macroeconomics first studied the implications of idiosyncratic (uninsurable) labor income risk, which was found to increase aggregate savings and growth (e.g., Bewley, 1977; Ayiagari, 1994; Huggett, 1997, Smith and Krusell, 1998). More recently, Angeletos (2007) extended this framework to consider uninsurable investment risk, finding that it can increase or decrease growth depending on preferences and the private (risky) capital share. Finally, most directly related to our approach, Krebs (2003a,b; 2006) presents an endogenous growth framework with uninsurable risk to human capital. Krebs' approach is motivated based on the idea that households within a modern macroeconomy face idiosyncratic job separation risks, which can damage their human capital. We apply this framework to a different context: the idiosyncratic risk to human capital faced by different regions in countries at risk for hurricane strikes. Krebs' (as well as Ikefuji and Horii's) frameworks assume all physical capital is risk-free or fully diversified. For our setting - where developing nations suffer substantial hurricane risks - this approach seems insufficient. We consequently extend Krebs' (2003b) model to incorporate entrepreneurial or privately held local capital that is subject to uninsurable hurricane risks. Krebs (2003a) briefly illustrates such an extension of his model, but assumes that human and entrepreneurial capital shocks are uncorrelated. Naturally, this assumption is inappropriate for the study of hurricane risk, where these shocks are likely positively correlated. Our model thus (i) formally extends Krebs' (2003a,b) framework to a setting with entrepreneurial and human capital with correlated shocks, and (ii) applies this framework to evaluate hurricane risk and strike impacts on economic growth.

3 An Endogenous Growth Model of Disaster Impacts

3.1 Setup

The model economy features a unit mass of households $i \in [0,1]$ that is spread across a continuum of locations (as in Ikefuji and Horii, 2012). There are two types of production: First, a unit mass of "corporate" firms $j \in [0,1]$ rent capital k_{jt} and human capital n_{jt} in a competitive financial market to produce output y_{jt} with constant returns to scale technology:

$$y_{1jt} = A_1 k_{jt}^{\alpha} n_{jt}^{1-\alpha} \tag{1}$$

Second, there is "entrepreneurial" production that relies on local capital owned by the representative household in region i to produce output y_{2it} :

$$y_{2it} = A_2 k_{2it}$$

Households can thus invest in three types of assets: their human capital h_{it} and their financial capital s_{it}, both of which are supplied to formal firms, and private capital k_{2it}, which is used for local/entrepreneurial production. As we assume a closed economy, the aggregate corporate capital stock is given by $K_{1t} = \int k_{1jt} dj = \int s_{it} dj$. Analogously defining aggregate human capital via $H_t = \int h_{it} di$, aggregate output from firms can be written as:

$$Y_{1t} \equiv \int y_{1jt} dj = A_1 K_{1t}^{\alpha} {H_t}^{1-\alpha} \tag{2}$$

Disaster strikes can damage all three types of capital. Importantly, our analysis focuses on the (interesting) case where households cannot properly insure against risks to their human and private capital. In contrast, even though one can also consider cyclone damages to physical capital installed at firm j, this risk is diversified across the macroeconomy (if shocks are independently and identically distributed across locations). That is, if households' financial assets are invested across the economy, then idiosyncratic local damages to firms' capital stocks do not affect the aggregate return to these assets. Financial assets s_{it} are thus effectively a risk-free asset.

3.2 Firms

Each firm j rents human and physical capital in competitive markets. The firm pays households gross return R_{ht} for their provision of human capital (efficiency units of labor services provided), and pays R_{k1t} plus depreciation as return on financial capital. We assume that cyclone shocks to firms take the form of an additive increase in the depreciation rate by $\eta_{jt}^{k_1} \sim \ln N(\mu_{k1}, \sigma_{k1}^2)$.

The assumption of log-normality is motivated twofold. First, as shown in the Appendix, a log-normal distribution fits the data on average cyclone capital destruction rates well. Second, for the uninsurable cyclone risks endured by households (described below), log-normality permits a direct mapping from expected utility maximization to a portfolio choice problem to characterize the households' optimal investment as a function of cyclone risk. For firms in the formal sector, however, as storm risks are identically and independently, the risk-neutral firm's expected profit maximization problem is given by:

$$\max_{k_{1jt},n_{jt}} (A_1 k_{1jt}^{\alpha} n_{jt}^{1-\alpha}) - R_{ht} n_{jt} - (R_{k1t} + \delta_{k1} + \mu_{k1}) k_{1jt}$$

We assume full mobility of labor and capital across locations (within a country). Consequently, factor rates of return are equated across regions, and the firm's first-order conditions are thus standard:

$$\begin{aligned} R_{ht} &= (1-\alpha) A_1 \left(\frac{n_{jt}}{k_{1jt}} \right)^{-\alpha} \\ R_{k1t} + \delta_k + \mu_{k1} &= (\alpha) A_1 \left(\frac{n_{jt}}{k_{1jt}} \right)^{1-\alpha} \end{aligned} \tag{3}$$

Since (3) holds for all firms, we can also express equilibrium factor prices in terms of the aggregate human-corporate capital ratio $\widetilde{h_t} \equiv \frac{H_t}{K_{1t}}$:

$$\begin{aligned} R_{ht} &= (1-\alpha) A_1 (\widetilde{h_t})^{-\alpha} \\ R_{k1t} + \delta_k + \mu_{k1} &= (\alpha) A_1 (\widetilde{h_t})^{1-\alpha} \end{aligned} \tag{4}$$

Note that equations (4) define $R_{ht} = R_h(\widetilde{h_t})$ and $R_{kt} = R_{k1}(\widetilde{h_t})$.

3.3 Households

The representative household in region i maximizes his expected lifetime utility by choosing state-contingent plans for consumption c_{it} and his investments in financial (x_{sit}), human (x_{hit}), and private (x_{k2it}) capital. In particular, he solves:

$$\max E_0 \sum_{t=0}^{\infty} \beta^t U(c_{it})$$

subject to constraints:

$$\begin{aligned} c_{it} + x_{st} + x_{ht} + x_{kt} &= s_{it}R_{k1t} + h_{it}R_{ht} + \underbrace{(A_2 k_{2it})}_{=y_{2it}} \\ h_{it+1} &= (1 - \delta_h - \eta_{it}^h)h_{it} + x_{hit} \\ s_{it+1} &= s_{it} + x_{sit} \\ k_{2it+1} &= (1 - \delta_{k2} - \eta_{it}^{k_2})k_{2it} + x_{k2it} \\ & \quad h_{i0}, s_{i0}, k_{20} \text{ given} \end{aligned}$$

where η_{it}^h and $\eta_{it}^{k_2}$ denote the (jointly lognormally distributed) shocks to depreciation from storms. As shown in the Appendix, a log-normal distribution appears to provide a good fit for damage data. In contrast to Krebs (2003a), we do not assume that η_{it}^h and η_{it}^{k2} are independent, as both damage shocks originate from natural disasters in our setting, and are thus almost surely positively correlated. For example, later we consider the case where there is an underlying hurricane strength random variable $\varepsilon_{it} \sim \ln N(\mu_\varepsilon, \sigma_\varepsilon^2)$ and where damage ratios are proportional to hurricane strength: $\eta_{it}^h = \xi^h \varepsilon_{it}$ and $\eta_{it}^{k2} = \xi^{k2}\varepsilon_{it}$. In this case, $cov(\eta_{it}^h, \eta_{it}^{k2}) = \xi^h \xi^{k_2} \sigma_\varepsilon^2 > 0$.

We now define some helpful notation and re-write the household's problem in order to facilitate the analysis. Let $\widetilde{h_{it}}$ denote the household's human-financial capital ratio:

$$\widetilde{h_{it}} \equiv \frac{h_{it}}{s_{it}}$$

The share of human capital in the household's asset allocation to firms is then given by:

$$\theta_{hit} \equiv \frac{h_{it}}{s_{it} + h_{it}} = \frac{\widetilde{h_{it}}}{1 + \widetilde{h_{it}}} = \theta_h(\widetilde{h}_{it})$$

Next, let Θ_{k2it} denote the share of the household's *total wealth* invested in private capital:

$$\Theta_{k2it} \equiv \frac{k_{2it}}{s_{it} + h_{it} + k_{2it}}$$

The household's overall return on his assets in period t can thus be written as:

$$\begin{aligned} r_{it} &= r(\widetilde{h_{it}}, \Theta_{k2it}, \widetilde{h}_t, \eta_{it}^h, \eta_{it}^{k2}) \\ &= [(1 - \Theta_{k2it})(1 - \theta_h(\widetilde{h}_{it}))R_{k1t} + \theta_h(\widetilde{h}_{it})(R_{ht} + 1 - \delta_h - \eta_{it}^h) + \Theta_{k2it}(A_2 + 1 - \delta_{k2} - \eta_{it}^{k_2})] \end{aligned} \quad (5)$$

It is now straightforward to write the household's budget constraint in terms of the evolution

of his wealth $w_{it} \equiv s_{it} + h_{it} + k_{2it}$:

$$w_{it+1} = [1 + r(\widetilde{h_{it}}, \Theta_{k2it}, \widetilde{h}_t, \eta^h_{it}, \eta^{k2}_{it})]w_{it} - c_{it} \tag{6}$$

Following Krebs (2003a, 2003b, 2006) we now construct a stationary equilibrium where aggregate returns are defined by $R_{ht} = R_h = R_h(\widetilde{h})$ and $R_{k1t} = R_{k1} = R_{k1}(\widetilde{h})$, and where the aggregate human-physical corporate capital ratio is thus constant. The agent's problem can then be written recursively as:

$$V(w_i, \widetilde{h}_i, \Theta_{k2i}, \eta^h_i, \eta^{k2}_i) = \max u(c_i) + \beta E[V(w'_i, \widetilde{h}'_i, \Theta'_{k2i}, \eta^{h\prime}_i, \eta^{k2\prime}_i)] \tag{7}$$

subject to the law of motion (6).[3]

Proposition 1 *Assume preferences are of the CES form:*

$$u(c_i) = \frac{c_i^{1-\gamma}}{1-\gamma} \tag{8}$$

The solution to the household's problem then involves (i) a constant consumption-wealth ratio $\widetilde{c}$ *(ii) a constant human-to-financial capital ratio* $\widetilde{h}_i$*, and (iii) a constant entrepreneurial capital-to-wealth ratio* $\widetilde{\theta_{k2i}}$*, defined by:*

$$\widetilde{c} = 1 - (\beta E[(1 + r(\widetilde{h}_i, \widetilde{\theta_{k2i}}, \eta^{h\prime}_i, \eta^{k2\prime}_i))^{1-\gamma}])^{\frac{1}{\gamma}} \tag{9}$$

$$0 = \beta E\left[\frac{\{(\widetilde{r_h} - \eta^{h\prime}_i) - (1 - \Theta'_{k2i})R_{k1}\}}{(1 + r(\widetilde{h_i}', \Theta'_{k2i}, \eta^{h\prime}_i, \eta^{k2\prime}_i))^{\gamma}(1 + \widetilde{h_i}')^2}\right] \tag{10}$$

$$0 = \beta E\left[\frac{\{(\widetilde{r_{k2}} - \eta^{k_2\prime}_i) - (1 - \theta_h(\widetilde{h}'_i))R_{k1}\}}{(1 + r(\widetilde{h_i}', \Theta'_{k2i}, \eta^{h\prime}_i, \eta^{k2\prime}_i))^{\gamma}}\right] \tag{11}$$

Proof: See Appendix. Intuitively, the optimal consumption-to-wealth ratio $\widetilde{c}$ follows from the household's Euler Equation, whereas equations (10) and (11) express no-arbitrage conditions based on the expected excess returns to human capital and entrepreneurial capital, respectively, above and beyond the risk-free rate R_{k1}.

Given the result for $\widetilde{c} = c_{it}(1+r_{it})w_{it}$, and by the law or large numbers, aggregate consumption growth in this economy is equal to expected local consumption growth (see Krebs, 2003b). In our setting, this is given by:

$$\frac{C_{t+1}}{C_t} = E\left[\frac{c_{it+1}}{c_{it}}\right] = (1 - \widetilde{c})(1 + E[r(\widetilde{h_i}', \Theta'_{k2i}, \eta^{h\prime}_i, \eta^{k2\prime}_i) \qquad \text{(Growth_C)}$$

[3] Note that we do assume that hurricane shocks are independently distributed across time.

This expression allows us to preview the two main channels through which hurricane risk affects growth in this model. Note that we provide a formal statement and proof of these effects below after describing households' optimal asset allocations.

Remark 1 *Hurricane risk affects growth rates through two channels (Informal Statement):*

1. *(Precautionary) Savings Effect: Uninsurable hurricane risk affects the household's overall savings rate out of wealth $\widetilde{c}$ (via 9). If hurricane risk increases overall savings, then observed consumption growth will be higher in economies with larger hurricane risk, ceteris paribus.*

2. *Rate of Return Effect: Uninsurable hurricane risk affects expected returns on the household's investments in human and entrepreneurial capital. If hurricane risk reduces expected returns to investment, then observed consumption growth will be lower in economies with larger risks, ceteris paribus.*

3. *The overall effect of hurricane risks on growth are thus ambiguous despite the fact that the effect of a hurricane strike on consumption growth is unambiguously negative.*[4]

3.4 Cyclone Risk, Investment, and Growth

In order to provide concrete insights on the growth impacts of disaster risk it is necessary to assess the effect of this risk on households' investment decisions, and thus the overall expected return on their portfolios. In particular, we want to understand how destructive risks to human and entrepreneurial capital affect the household's decision to invest in different assets, as these affect economic growth differently.

We have already demonstrated that the consumption-wealth ratio is constant in the present model (Proposition 1). A fundamental insight from the literature (e.g., Krebs, 2003a,b) is that the household's investment decision in this kind of setting can be solved as a portfolio choice problem. In our model, due to the assumptions of power utility and log-normal returns on risky assets, we can specifically cast this problem as a mean-variance analysis portfolio choice problem (see, e.g., Campbell and Viceira, 2001). In particular, as is standard, we will first characterize how the household allocates resources among the two risky assets (h_{it}, k_{2it}), and then consider how he spreads his resources between the optimized risky portfolio and risky-free financial capital. Let $\omega_{k2} \equiv k_{2it}/(h_{it} + k_{2it})$ denote the share of private capital k_{2it} in the household's risky asset

[4] To see the latter, note first that: $c_{it} = \widetilde{c}(1+r_{it})w_{it}$. As per (5), the realization of a hurricane *strike* ($\eta_{it}^{k_2} \geq 0$, $\eta_{it}^{h} \geq 0$) reduces the contemporaneous return $1 + r_{it}$. Consequently, consumption in period t is reduced by the disaster. Consumption growth between periods $t-1$ and t is thus also lower than normal.

portfolio (k_{2it}, h_{it}). The mean-variance efficient risky portfolio then maximizes the Sharpe ratio:

$$\max_{\omega_{k2}} \frac{E(r_{rp}) - R_{k1}}{\sigma_p}$$

where $E(r_{rp})$ is the expected return on the risky portfolio,

$$E(r_{rp}) = \omega_{k2}\widetilde{r_2} + (1 - \omega_{k2})\widetilde{r_h}$$

with standard deviation:

$$\sigma_{rp} = [\omega_{k2}^2\sigma_{k2}^2 + (1 - \omega_{k2})^2\sigma_h^2 + 2\omega_{k2}(1 - \omega_{k2})\rho_{h,k2}\sigma_h\sigma_{k2}]^{\frac{1}{2}}$$

where σ_{k2}^2 and σ_h^2 are the standard deviations of private and human capital, respectively, where $\widetilde{r_{k2}} = R_{k2} - \delta_{k2} - \mu_{k2}$ and $\widetilde{r_h} = R_h - \delta_h - \mu_h$ denote expected returns on private and human capital, and where $\rho_{h,k2}$ denotes the correlation between the shocks to human and entrepreneurial capital. As is well-known, the solution to this form of optimization problem is given by:

$$\omega_{k2}^* = \frac{(\widetilde{r_{k2}} - r_{k1})\sigma_h^2 - (\widetilde{r_h} - r_{k1})cov(\eta^h, \eta^{k2})}{(\widetilde{r_{k2}} - r_{k1})\sigma_h^2 + (\widetilde{r_h} - r_{k1})\sigma_{k2}^2 - [(\widetilde{r_{k2}} - r_{k1}) + (\widetilde{r_h} - r_{k1})]cov(\eta^h, \eta^{k2})} \tag{12}$$

with $cov(\eta^h, \eta^{k2}) = \rho_{h,k2}\sigma_h\sigma_{k2}$. It should be noted that expression (12 only defines optimal investment shares in entrepreneurial capital ω_{k2}^* implicitly, as equilibrium returns depend on households' investment behaviors. However, (12) can be used to derive some informal insights into how cyclone risks affect investment. For example, in the unrealistic but illustrative case where shocks to physical and human capital are uncorrelated ($cov(\eta^h, \eta^{k2}) = 0$), we see that the optimal investment share in entrepreneurial capital ω_{k2}^* is increasing in the expected excess returns to entrepreneurial capital relative to risk-free capital $(\widetilde{r_{k2}} - r_{k1})$, holding all else equal. Conversely, the entrepreneurial capital investment share is decreasing in the expected excess returns to human capital $(\widetilde{r_h} - r_{k1})$, ceteris paribus. The attractiveness of human capital as alternative investment moreover increases, the riskier entrepreneurial capital is (higher σ_{k2}^2), and vice versa. In the fully general case, the effects of cyclone risk parameters on investment depend on additional factors such as the magnitude of the covariance between cyclone risks to human and physical capital relative to the riskiness to these individual assets. In order to derive more formal insights, we thus proceed to characterize the rest of households' investment decision problem.

Let ω_{rp} denote the fraction of the household's wealth invested in the risky portfolio, such that $(1 - \omega_{rp})$ corresponds to the fraction of wealth invested in risk-free financial capital. The

optimal ω_{rp} solves:

$$\max_{\omega_{rp}} E(r_p) - \frac{1}{2}\gamma\sigma_p^2$$

where γ is the coefficient of relative risk aversion for our utility function 8), and subject to constraints:

$$\begin{aligned} E(r_p) &= (1-\omega_{rp})r_{k1} + \omega_{rp}E(r_{rp}) \\ \sigma_p^2 &= \omega_{rp}^2\sigma_{rp}^2 \end{aligned}$$

The optimality conditions yield:

$$\omega_{rp}^* = \frac{E(r_{rp}) - r_{k1}}{\gamma\sigma_{rp}^2} \tag{13}$$

Together, (12) and (13) define the optimal overall shares of wealth invested in private capital $\Theta_{k_{2i}}$, human capital, and financial capital, respectively:

$$\begin{aligned} \Theta_{k2i} &= \omega_{rp}\omega_{k2} = \text{Private capital share} \\ (1-\Theta_{k2i})\theta_h(\widetilde{h}_{it}) &= \omega_{rp}(1-\omega_{k2}) = \text{Human capital share} \\ (1-\Theta_{k2i})(1-\theta_h(\widetilde{h}_{it})) &= (1-\omega_{rp}) = \text{Financial capital share} \end{aligned}$$

Note that this system of equations provides two equations in two unknowns (Θ_{k2i}, $\widetilde{h}_i$):

$$\begin{aligned} \Theta_{k2i} - \omega_2\omega_{rp} &= 0 \\ (1-\Theta_{k2i})\theta_h(\widetilde{h}_i) - \omega_{rp}(1-\omega_2) &= 0 \end{aligned} \tag{14}$$

One can use the Implicit Function Theorem to derive comparative statics on the equilibrium relationships between cyclone damage risk and the optimal investment variables Θ_{k2i}, $\widetilde{h}_i$. These variables, in turn, pin down the effect of storm risk on expected rates of return and thus on aggregate consumption growth as per $(Growth_C)$. Since it is not generally possible to sign these comparative statics in the fully general case presented thus far, we proceed in two ways. First, we impose some basic structure on the relationship between η^h and η^{k2} and underyling storm risks and derive predictions for for the effects of changes in the cyclone risk variance for certain subsets of the parameter space. Second, we provide results from a numerical example to illustrate possible effects of changes in average damages.

3.4.1 Cyclone Variability and Long-Run Growth

Assumption 1: *Disaster damages to human and physical capital are each proportional to a fundamental hurricane strength measure* $\varepsilon_{it} \sim \ln N(\mu_\varepsilon, \sigma_\varepsilon^2)$ *(iid over time and space), with:*

$$\begin{aligned} \eta_{it}^h &= \xi^h \varepsilon_{it} \\ \eta_{it}^{k2} &= \xi^{k2} \varepsilon_{it} \end{aligned}$$

Assumption 1 implies that damage risks are linked to underlying storm risks as follows: $cov(\eta_{it}^h, \eta_{it}^{k2}) = \xi^h \xi^{k_2} \sigma_\varepsilon^2 > 0$, $\sigma_h^2 = var(\eta_{it}^h) = (\xi^h)^2 \sigma_\varepsilon^2$, and $\sigma_{k2}^2 = var(\eta_{it}^{k2}) = (\xi^{k2})^2 \sigma_\varepsilon^2$. In order to derive unambiguous comparative statics on the effects of cyclone risk σ_ε^2 on the growth-relevant variables (Θ_{k2i}, $\widetilde{h}_i$), we further have to partition the parameter space into different cases. We focus on the most empirically relevant case:

Case 1: $\xi^{k_2} > \xi^h$, implying that entrepreneurial capital is more vulnerable to storms of a given intensity than human capital.

Next, we assume that households cannot short-sell human nor entrepreneurial capital.[5] In order to ensure that the household's optimal risky investment share is interior, we further make Assumption 2: *The excess return to human capital satisfies:* $0 < \widetilde{r_h} - r_{k1} < \sigma_\varepsilon^2 \gamma [\xi^h]^2$. Intuitively, this condition ensures that the household is willing to invest in human capital, but that the excess returns are not so large (relative to the risks) so as to push the household to a corner solution of only wanting to invest in human capital. Finally, for points (3)-(6) of Proposition 2 below, we additionally impose Assumption 3: $(1-\alpha) < \frac{\widetilde{h}}{1+\widetilde{h}}$.

In Case 1, given Assumptions (1)-(3), one can then use the Implicit Function Theorem on (14) to demonstrate the following:

Proposition 2 *A (mean-preserving) increase in cyclone risk* $\sigma_\varepsilon^{2\prime} > \sigma_\varepsilon^2$ *leads to the following economic outcomes:*

1. *A decreased human-financial capital ratio:*

$$\frac{d\widetilde{h}}{d\sigma_\varepsilon^2} < 0$$

2. *A lower equilibrium return on corporate capital* $R_{k1}(\widetilde{h}') < R_{k1}(\widetilde{h})$ *and a higher equilibrium (gross) return on human capital* $R_h(\widetilde{h}') > R_h(\widetilde{h})$ *(as per equation (4)).*

[5] Given Assumption 1 and Case 1, this restriction will be binding as the damage shocks are perfectly correlated. Consequently, in Case 1, the risk-minimizing portfolio would - in theory - involve the short-selling of entrepreneurial capital. As we do not permit such short-sales, the household will not want to invest in entrepreneurial capital in this particular case ($\Theta_{k2}^* = 0$), investing only in human and financial assets.

3. *A lower expected return on the household's asset portfolio:* $E[r(\widetilde{h_i}', \Theta'_{k2i}, \xi^h \varepsilon_{it}, \xi^{k2} \varepsilon_{it})] < E[r(\widetilde{h_i}, \Theta_{k2i}, \xi^h \sigma_\varepsilon^2, \xi^{k2} \sigma_\varepsilon^2)]$ *(as per equation (5) in combination with points (1)-(3))* $\Rightarrow$ *Rate of Return Effect*

4. *A lower, equal, or higher consumption-out-of-wealth ratio, depending on the coefficient of relative risk aversion:*

   - $\widetilde{c} > \widetilde{c}'$ *if* $\gamma < 1$
   - $\widetilde{c} = \widetilde{c}'$ *if* $\gamma = 1$ *(logarithmic preferences)*
   - $\widetilde{c} > \widetilde{c}'$ *if* $\gamma > 1$

   This result implies that the savings rate out of wealth $(1 - \widetilde{c}')$ *increases in response to larger cyclone risks if* $\gamma > 1 \Rightarrow$ *Precautionary Savings Effect.*

5. *Larger cyclone risk can increase, leave unaffected, or decrease consumption growth (and thus output growth). Whether growth is increasing or decreasing in cyclone risk depends on whether the Precautionary Savings Effect outweighs the Rate of Return Effect as per equilibrium consumption growth:*

$$\frac{C_{t+1}}{C_t} = E\left[\frac{c_{it+1}}{c_{it}}\right] = (1 - \widetilde{c}')(1 + E[r(\widetilde{h_i}', \Theta'_{k2i}, \xi^h \varepsilon'_{it}, \xi^{k2} \varepsilon'_{it}) \tag{15}$$

6. *Larger cyclone risk unambiguously decreases welfare:*

$$E_0 \sum_{t=0}^{\infty} \beta^t \frac{c_{it}^{1-\gamma}}{1-\gamma} \leq E_0 \sum_{t=0}^{\infty} \beta^t \frac{c_{it}'^{1-\gamma}}{1-\gamma} \tag{16}$$

   Consequently, cyclone risk can affect economic growth and welfare in opposite ways.

Proof: Use the Implicit Function Theorem on (14) with the Case 1 assumptions and refer to other key equations as per the Proposition. Note that the last point on welfare follows from the fact that, as noted by Krebs (2003) one can combine (15) and (16) to express expected lifetime utility, which in our case yields $E_0 \sum_{t=0}^{\infty} \beta^t \frac{c_{it}^{1-\gamma}}{1-\gamma} = \frac{c_{i0}^{1-\gamma}}{(1-\gamma)(1-\beta E[(1+(1-\widetilde{c})r(\widetilde{h}_{it+1}, \Theta_{k2it+1}, \xi^h \varepsilon_{it}, \xi^{k2} \varepsilon_{it}))^{1-\gamma}]}$ with $c_{i0} = \widetilde{c}[1 + r(\widetilde{h_{i0}}, \Theta_{k2i0}, \xi^h \varepsilon_{i0}, \xi^{k2} \varepsilon_{i0}]w_{i0}$ where the initial values in the return are all given by assumption.

3.4.2 Average Cyclone Destruction Measures and Long-Run Growth

As with cyclone variability, the effects of average cyclone damages on long-run growth are theoretically ambiguous. We thus provide numerical results for an illustrative calibration of the model. We emphasize that, at this stage, the calibration serves only as an example to illustrate *qualitative* differences that can arise in the effects of different average cyclone damage measures on long-run growth.[6] We use World Bank Development Indicators data to estimate countries' approximate aggregate capital stocks (assuming a capital share of 30%, average depreciation of 10%, and a rate of return of 5%) and populations (1960-2015). We then use EM-DAT data[7] from the International Disaster Database at the Center for Research on Epidemiology of Disasters (CRED) on the value of direct damages to calculate the fraction of the aggregate capital stock destroyed by country-year. In order to approximate human capital destruction, we compute the fraction of the population killed by cyclones in each country-year. We then compute the means, variances, and co-variance of these variables across country-years in our data. Finally, we adopt preference parameters in line with standard values in macroeconomics, and assume illustrative values for productivity in corporate and entrepreneurial production (pinning down excess returns). The resulting parameters are listed in Table 1:

$\mu_{k2} = 2.14\%$	$\sigma_{k2} = 9.67\%$	$(\widetilde{r_2} - r_{k1}) = 3.5\%$
$\mu_h = 0.0047\%$	$\sigma_h = 0.03\%$	$(\widetilde{r_h} - r_{k1}) = 0.0004\%$
$\gamma = 1$ (log)	$\beta = 0.96$	$\rho_{h,k2} = 0.34$

Table 1: Toy Calibration Parameters

At these parameter values, the household invests 36% of his wealth in entrepreneurial capital. The excess return on these investments (3.5%) is very high compared to human capital (0.0004%); however, the riskiness of entrepreneurial capital investments is also higher, implying a standard mean-variance tradeoff. This economy could grow faster if households invested more in entrepreneurial capital. The effects of cyclone risks on growth thus depend in part on how they affect households' propensity to invest in entrepreneurial capital. We consider the effect on the long-run growth rate of changing mean cyclone damages μ_{k2} and μ_h each by $\pm 50\%$ and ± 25, respectively. Intuitively, an increase in the average storm damage to a given asset implies a ceteris paribus reduction in the excess returns to investing in that asset.

[6] A quantitatively meaningful calibration of the model is work in progress.

[7] While EM-DAT data suffer from well-known limitations, such as selective reporting of disasters and damages, for the purposes of this toy calibration these are not important.

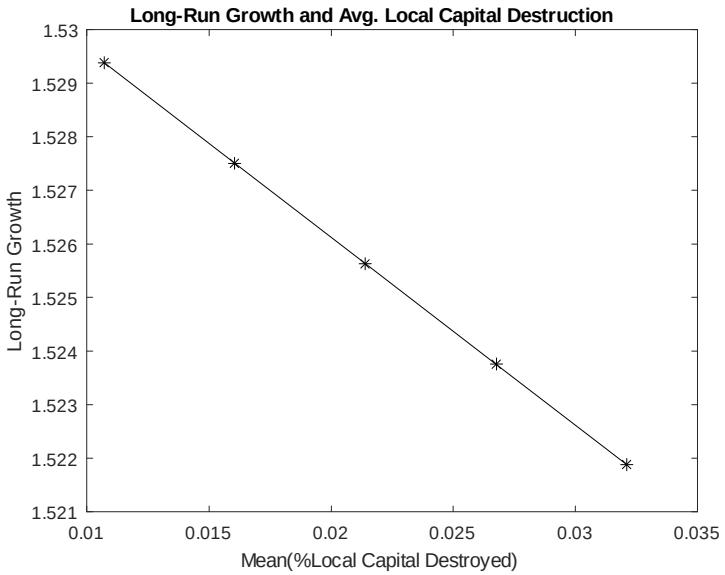


Figure 1: Long-Run Growth and Avg. Local Capital Destruction

First, we find that growth is decreasing in the average destruction to entrepreneurial capital μ_{k2}. This result is in line with findings of, e.g., Hsiang and Jina (2015b), who document a negative cross-sectional relationship between cyclone-induced capital depreciation and average growth rates. Intuitively, this is because an increase in entrepreneurial capital losses μ_{k2} decreases the returns to the economy's most productive (marginal) investment, thus lowering overall growth.

In contrast, we find the opposite for damages to human capital, as shown in Figure 2:

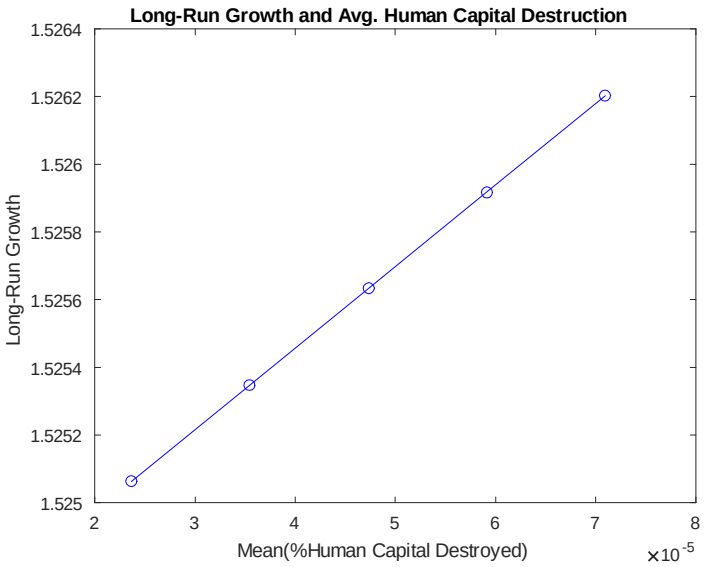


Figure 2: Long-Run Growth and Avg. Human Capital Destruction

We find that growth is increasing in the average destruction of human capital μ_h. Intuitively, this is because larger expected damages decrease the relative attractiveness of human capital as an investment, holding all else equal. Consequently, some of the household's risky investments shifts to entrepreneurial capital, which has a higher excess return, thus increasing overall growth.[8]

While the quantitative results of this numerical exercise are sensitive to the parameter assumptions, the central qualitative result is as follows:

Result Average cyclone damages to physical vs. human capital can affect long-run growth in opposite ways.

Importantly, this result appears consistent with the empirical evidence. For example, Hsiang and Jina (2015b) find a negative cross-sectional relationship between average capital depreciation from cyclones and long-run growth. In contrast, Skidmore and Toya (2002) find a positive cross-sectional relationship between the average number of disasters and growth.[9] Some panel studies have also documented different growth impacts of disaster damages versus fatalities (e.g., Noy, 2009). However, these results are not directly comparable as the structural impact of disaster realizations is fundamentally different from the effects of cyclone risks. The next Section formalizes this point.

[8] As with Proposition 2, this growth increase need not be welfare-increasing.

[9] In our model, a change in the number or intensity of cyclones could affect growth positively or negatively depending on whether it translates into larger average physical or human capital damages.

3.5 Disaster Strikes and Observed Growth

Thus far our analysis has focused on the effects of hurricane *risk* on growth, corresponding empirically most closely to cross-sectional analyses. This section compares and contrasts these growth impacts to those we would expect to observe in the data after an actual hurricane *strike*.

3.5.1 Immediate Growth Impacts

Moving from expected local growth in (15) to realized local growth immediately yields the following results:

Result An above-average hurricane *shock (strike* $\overline{\varepsilon}_{it} > \mu_{\varepsilon}$*)* decreases contemporaneous local growth unambiguously.

This result follows immediately from applying a positive hurricane shock $\overline{\varepsilon}_{it} > \mu_{\varepsilon}$ to realized growth:

$$\frac{c_{it}}{c_{it-1}} = (1-\widetilde{c})(1+r(\widetilde{h}_i, \Theta'_{k2i}, \xi^h\overline{\varepsilon}_{it}, \xi^{k2}\overline{\varepsilon}_{it})) < E_{t-1}[\frac{c_{it}}{c_{it-1}}]$$

This result has two main empirical implications. First, the model predicts that *only above-average disaster realizations lead to below-average growth.* This prediction is in line with numerous empirical studies that have found that it is mainly large disasters that induce negative growth impacts (e.g., Hochrainer, 2009). Importantly, however, a below-average disaster could be estimated to yield higher or lower growth depending on the counterfactual against which it is measured.[10]

The second main empirical implication of this result, coupled with Proposition 2, is that *hurricane risk can increase growth even when hurricane strikes unambiguously decrease growth.* Consequently, we argue that the positive cross-sectional association between disaster risk and growth discovered by Skidmore and Toya (2002) need not be at odds with results from panel regressions that find large, negative cyclone *strike* effects.[11]

3.5.2 Medium-Run Growth Impacts

Our benchmark model yields two main predictions for the transitional impacts after an above-average disaster shock. First, the contemporaneous growth rate returns to its balanced growth

[10] In particular, a below-average storm season will yield higher than average growth when measured against average growth in a given location. However, when measured against a counterfactual with no storm realizations, then a below-average storm season will lead to losses.

[11] Although not formally developed, our model would also predict that both types of growth impacts are greatly diminished in countries with developed insurance markets, again suggesting that differences in results obtained by studies focused on, e.g., the U.S. only (e.g., Strobl, 2011) versus those focused on the world (e.g., Hsiang and Jina, 2015) need not imply a contradiction.

path level after one period. Second, however, the loss in the output level is persistent, and the economy remains on a permanently lower output level path after the disaster. Notably, these results are broadly in line with the empirical findings of Hsiang and Jina (2015), who find that contemporaneous growth rates return to normal after a number of years, but that the cumulative output losses in the transition are not recovered.[12]

Figures 3 and 4 illustrate how output level and growth rates diverge, respectively, after an above-average disaster strike in the toy model calibration.

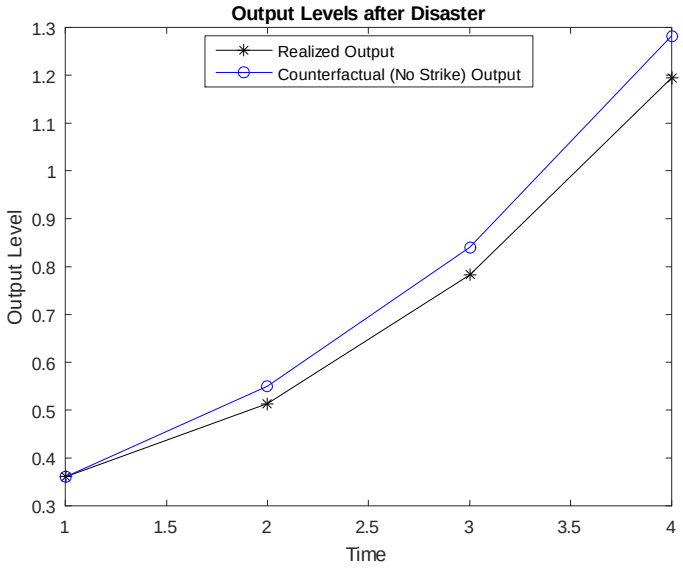


Figure 3: Output Levels after Disaster

[12] The central difference is that our model predicts a return to balanced growth after one period, whereas HJ find that the transition takes multiple years. This difference could be reconciled either by interpreting our model period as a decade, or by introducing capital adjustment costs or frictions that slow down the recovery of contemporaneous growth rates.

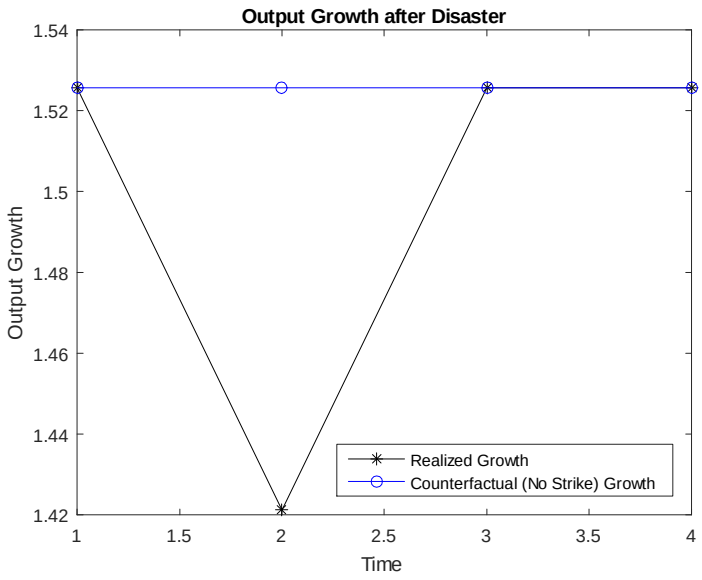


Figure 4: Output Growth after Disaster

As can be seen in Figure 4, the sum of the disaster's contemporaneous growth impacts - HJ's main cumulative impact measure - is negative. Consequently, even though contemporaneous growth rates are not affected by disaster *strikes* in the medium or long-run, the output level remains permanently lower after the disaster strike (Figure 1).

It is useful to compare these transitional predictions to those of a standard Solow growth model. As shown below, the Solow model yields different predictions, namely that output growth will temporarily increase after a disaster as the economy rebuilds and transitions back to its balanced growth path. While this prediction does not seem to align with the empirical evidence such as presented by Hsiang and Jina (2015) and in the case of tropical cyclones, it is a central benchmark for comparison.

3.5.3 One-Time Hurricane Strike Illustration in the Solow Growth Model

This section derives transitional impact predictions for a one-time unanticipated disaster realization in a simple, single-region mode with exogenous but convex growth. We further impose the standard assumptions well-known to permit closed-form solution of the dynamic model. Aggregate output Y_t, is produced from capital K_t, labor L_t, and labor efficiency (technology) level A_t via a constant returns to scale (CRS) technology:

$$Y_t = F(K_t, A_t L_t) \tag{17}$$

We assume that this economy is on a balanced growth path (BGP) at time $t = 0$, and study the effects of an unanticipated one-time hurricane strike at time $t = 1$. The storm decreases the capital level by fraction $1 - \zeta^K$ and damages effective labor by fraction $1 - \zeta^{AL}$, with $\zeta_j \in (0, 1]$ for $j = K, AL$. Consequently, period 1 output is given by:

$$Y_1 = F(\zeta^K K_1, \zeta^{AL} A_1 L_1) \tag{18}$$

Given the assumption of CRS, we can express (17) in terms of output per efficiency unit of labor $y_t \equiv \frac{Y_t}{A_t L_t} = f(k_t)$ where $k_t \equiv \frac{K_t}{A_t L_t}$. Next, assume that the population is constant and normalized to $L_t = \overline{L} = 1 \ \forall t$. Further assume Cobb-Douglas technology:

$$y_t = k_t^{\alpha}$$

Finally, in order to obtain closed-form solutions, impose the standard simplifying assumptions that (i) the representative household has logarithmic preferences over consumption C_t, seeking to maximize lifetime utility:

$$\sum_{t=0}^{\infty} \beta^t U(C_t) = \sum_{t=0}^{\infty} \beta^t \ln(C_t)$$

and (ii) that capital depreciates fully in each model period. As is well-known and easy to show, the savings rates that solves the representative household's problem is constant (even in the face of the hurricane shock) and defined by:

$$k_{t+1} = \alpha \beta y_t$$

The assumption that the economy begins on a balanced growth path equivalently implies that the economy's initial level of capital per efficiency unit of labor k_0 is equal to its steady-state value $k^* = (\alpha\beta)^{\frac{1}{1-\alpha}}$. The growth rate of capital per efficiency unit of labor in the initial (BGP) period is thus equal to zero, $g_{k^*} = 0$. Naturally, this implies that the aggregate capital growth rate g_K equals the rate of technological progress g_A $(= \frac{A_{t+1}}{A_t} - 1)$.[13]

[13] To see this, note that:

$$\begin{aligned} k_1 &= k_0 \\ \left(\frac{K_1}{A_1}\right) &= \left(\frac{K_0}{A_0}\right) \\ \left(\frac{K_1}{K_0}\right) &= 1 + g_K = \left(\frac{A_1}{A_0}\right) = 1 + g_A \end{aligned}$$

Immediate Disaster Impacts Assume now that disaster strikes as outlined above in (18). Define the hurricane impact factor on capital per efficiency unit of labor as:

$$\zeta \equiv (\zeta^{k}(\zeta^{AL})^{\frac{1-\alpha}{\alpha}})$$

Output at time 1 is then given by:

$$\begin{aligned} y_1 &= (\zeta \cdot k_1)^{\alpha} \\ &= \zeta^{\alpha} k_0^{\alpha} \\ &= \zeta^{\alpha} y_0 \end{aligned} \tag{19}$$

where the second equation follows from the fact that we observe this economy beginning with capital at its steady-state value, implying that $k_0 = k_1$. Consequently, the observed growth in output per efficiency unit of labor between $t = 0$ and $t = 1$, $g_{y,0,1}$ is given by:

$$g_{y,0,1} \equiv \frac{y_1 - y_0}{y_0} = (\zeta^{\alpha} - 1) \tag{20}$$

Finally, these effects can be mapped back to the levels (aggregate or per capita) that an econometrician would observe in the data. Noting that $Y_t = y_t A_t$ we can solve for the aggregate or per capita output growth rate in the hurricane impact period as:

$$\begin{aligned} g_{Y,0,1} &\equiv \frac{Y_1 - Y_0}{Y_0} = [\zeta^{\alpha}(1 + g_A) - 1] \\ &= \text{Contemporaneous growth impact} \end{aligned} \tag{21}$$

Medium-Run Disaster Impacts Next, we consider how output continues to evolve after the storm. As the household's optimal savings rate remains a constant fraction $\alpha\beta$ of realized output, total investment in the new capital stock for period 2 is given by:

$$k_2 = \alpha\beta y_1$$

Output per efficiency unit of labor in period 2 thus equals:

$$y_2 = k_2^{\alpha} = (\alpha\beta)^{\alpha} y_1^{\alpha} = (\alpha\beta)^{\alpha}(\zeta^{\alpha} y_0)^{\alpha}$$

where the last equation follows from (19). It is easy to show that the observed aggregate

output growth rate between periods 2 and 1 will then be given by:

$$g_{Y,1,2} = \frac{Y_2 - Y_1}{Y_1} = \left[\zeta^{\alpha(\alpha-1)}(1+g_A) - 1\right]$$

The contemporaneous hurricane damages ζ thus continue to affect the observed output growth rate. Perhaps surprisingly, however, growth in the period after the disaster is *increasing* in the fraction of effective capital destroyed $(1-\zeta)$. That is, $\frac{\partial g_{Y,1,2}}{\partial \zeta} < 0$, implying that growth is decreasing in the fraction of capital left after the storm, ζ. Intuitively, this is because of investment as the economy rebuilds, and specifically because capital is accumulating more quickly than it is depreciating as the economy begins to return to its balanced growth path.

We visualize these transitions by calibrating the model for parameter values $\alpha = 0.3$, $\beta = 0.98$, normalize $A_0 = L = 1$, assume $g_A = 2\%$ per year, and consider a benchmark storm whose immediate impact is to decreases effective capital by 10% ($\zeta = 0.9$). Figure 5 displays the evolution of GDP levels in the economy hit by the storm in year 2 (solid line with stars) compared to counterfactual GDP had no storm occurred (dashed line with circles).

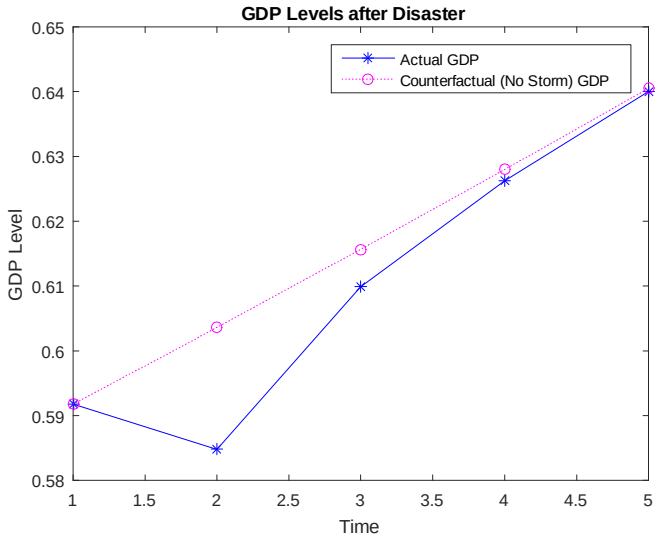


Figure 5: GDP Levels after Disaster

The storm decreases GDP immediately when it strikes (period 2), but continues to have a negative effect on GDP levels (relative to the counterfactual) as it takes time for the capital stock to re-accumulate to its steady-state level. The cumulative effect of the storm on consumption *levels* is thus unambiguously negative, although contemporaneous effects decline over time. In contrast, Figure 6 plots observed versus counterfactual output *growth* rates:

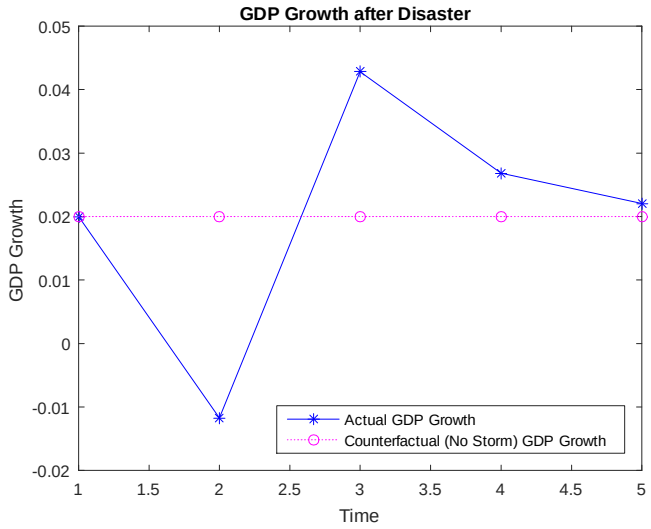


Figure 6: GDP Growth after Disaster

Intuitively, growth initially falls due to the capital destruction associated with the disaster, but rebounds as capital stocks re-accumulate to balanced growth path levels.[14] In this model, the sum of growth impacts over time - again, HJ's cumulative damage measure - would come out to zero. That is, there are periods of higher growth after the disaster that compensate for the initial loss, thus also allowing output levels to return to their baseline trajectory. Though different from our model's predictions and HJ's empirical findings, the Solow framework is an important benchmark illustrating how alternative growth models can yield different predictions for transitional impacts after disasters.

4 Empirical Analysis

The theoretical model and results presented thus far raise a number of empirical questions and challenges. In this section, we connect some of these questions back to the data and to established empirical estimation frameworks.

[14] From a simple growth accounting perspective:

$$\begin{aligned} g_{Y^{BGP}} &= g_{Y_1} = \alpha(g_A) + (1-\alpha)g_A = g_A \\ g_{Y_2} &= \underbrace{\alpha g_{K2}}_{<0 \text{ due to storm}} + (1-\alpha)g_A < g_A \\ g_{Y_3} &= \underbrace{\alpha g_{K_3}}_{>g_A>0 \text{ due to capital re-accumulation}} + (1-\alpha)g_A > g_A > 0 \end{aligned}$$

First, our model implies that underlying disaster risk affects growth differently than disaster realizations (strikes). In line with this prediction, empirical studies identifying the impacts of disaster strikes using panel data models (e.g., Hsiang and Jina, 2015) have often found different results than cross-sectional studies estimating the effects of disaster risk (e.g., Skidmore and Toya, 2002). For researchers interested in understanding the *overall* impacts of changing cyclone distributions on growth, neither approach may thus be individually sufficient. In particular, fixed effects panel estimation can causally identify the impact of individual disaster strikes on growth. However, the estimated country fixed effects - representing average growth in the absence of cyclone realizations - will depend on the underlying country risk rate. Consequently, in order to project the growth impacts of changes in cyclone *distributions* - such as from climate change - both the projected cyclone realizations and countries' average growth rates in the absence of disasters have to be adjusted.

We thus explore a two-step combined panel-cross sectional estimation framework that seeks to account directly for the endogeneity of countries' long-run average growth rates (absent disaster strikes) to cyclone risk. The first stage runs a panel fixed effects model in the spirit of HJ. The second stage provides a cross-sectional average growth decomposition that specifically regresses the fixed effects from the first stage on cyclone risk and other relevant control variables. We then re-estimate the impact of historical cyclones on growth by cleaning out both the negative impact of disaster strikes and the positive impact of the underlying risk rate.

We further explore the prediction of our model that market incompleteness (lack of insurance) is a central driver of disaster risk impacts on growth. We provide suggestive evidence that this mechanism is at play by interacting a proxy for financial market development - total domestic credit provided by the financial sector as a percentage of GDP - with our cyclone risk metrics. The subsections below present our empirical methodology, data sources, results, and discussion.

4.1 Empirical Methodology

In this section, we discuss our empirical approach. Step 1 estimates the effect of cyclone strikes on growth in a panel fixed effect specification in the spirit of Hsiang and Jina (2015), using observations in a country-year panel and the Ordinary Least Squares estimator:

$$G_{i,t} = \sum_{L=0}^{20} [\beta_L \times S_{i,t-L}] + \gamma_i + \delta_t + \theta_i \times t + \epsilon_{i,t} \tag{22}$$

where $G_{i,t}$ is real GDP per capita growth for county i in year t and $S_{i,t}$ is a variable describing cyclone exposure within country i in year t. Twenty years of lags are included to capture any potential persistence in impacts, following HJ. The model includes country fixed effects (γ_i),

year fixed effects (δ_t), and country-specific trends ($\theta_i \times t$).[15] The growth impacts from individual years of cyclone landfalls are found in the β_L estimated coefficients, which represent the extent to which GDP growth is and continues to be affected after a landfall. From this model, we can estimate (counterfactual) country growth rates without cyclone strikes, $\widehat{G_{i,t}}^{NS}$ from the following equation:

$$\widehat{G_{i,t}}^{NS} = \sum_{L=0}^{20} [\hat{\beta_L} \times 0] + \hat{\gamma_i} + \hat{\delta_t} + \hat{\theta_i} \times t \tag{23}$$

where the estimated coefficients from equation 22 are used and previous cyclone strikes are assumed to be zero.

Next, we note that the impact of cyclone risk on growth is subsumed by γ_i and θ_i, the country fixed effects in equation (22). In order to decompose its relationship with long-run cyclone risks, we first estimate the average growth rate in the absence of cyclone strikes, $\overline{\widehat{G_{i,t}}}$, from the panel estimation using the following equation:

$$\overline{\widehat{G_{i,t}}} = \widehat{\gamma_i} + (\widehat{\theta_i} \times \bar{t}) \tag{24}$$

where $\widehat{\gamma_i}$ is the estimated country fixed effect and $\widehat{\theta_j}$ is the estimated country trend from equation (22) above.[16] Step 2 of our approach estimates the following cross-sectional model:

$$\overline{\widehat{G_{i,t}}} = \widetilde{\alpha} + \widetilde{\lambda_1} L_i + X_i \times \beta + \widetilde{\delta_{Ri}} + \epsilon_i \tag{25}$$

We regress estimated average growth rates on the underlying cyclone risk characteristics in country i, L_i, relevant control variables, X_i, and a regional fixed effect, $\widetilde{\delta_{Ri}}$. In addition, and motivated by the theoretical model, we include landfall variance, V_i, in some specifications to further describe the risk distribution. The dependent variable is estimated from Step 1 and therefore may have measurement error. This will not bias our estimated coefficients, but will lead to inefficient estimates with larger standard errors (Hausman, 2001). Therefore, we bootstrap our standard errors and, in other specifications, employ robust standard errors, to correct for this inefficiency (Lewis and Linzer, 2005).

Finally, in order to gauge the overall impact of cyclones on economic growth, we estimate each countr's no-cyclones counterfactual growth rate, $\widehat{G_{i,t}}^*$, by subtracting underlying *risk* impact from the *no-strikes* growth estimates $\widehat{G_{i,t}}^{NS}$ obtained in the first stage:

$$\widehat{G_{i,t}}^* = \widehat{G_{i,t}}^{NS} - \widehat{\widetilde{\lambda_1}} L_i \tag{26}$$

[15] Guided by our theoretical model, we do not use an autoregressive specification, as this would change the interpretation of the fixed effects.

[16] The country trend is multiplied by the average year, $\bar{t}$, for every country in our sample, to estimate its average growth rate over its time in the panel.

Note that based on the previous literature, we expect $\widehat{\lambda_1} > 0$. We can then compare (i) estimated observed growth with (ii) *no-strikes* growth and (iii) *no-cyclones* (neither strikes nor risk) growth.

Lastly, we explore the ability of financial markets to attenuate the growth impacts of cyclone risk. To do so, we interact *total domestic credit provided by the financial sector as a percentage of GDP* with our cyclone risk variables in equation (25). If the coefficients are of the opposite sign of the un-interacted risk variable, this is consistent with financial market development mitigating the impact of disaster risk, in line with the theoretical model.

4.1.1 Data

Three types of data are the cornerstones of the empirical disaster growth impacts literature: growth data, disaster shock data, and other relevant control variables. We discuss each, in turn.

We collect all available data on economic growth for all countries from 1960 to 2014 from the World Bank's World Development Indicators (WDI) database. We also consider growth data from the Penn World Table as a robustness check.

Cyclone data come from the International Best Track Archive for Climate Stewardship (IBTrACS) and include individual track information such as wind speed, minimum sea level pressure, latitude, and longitude. We process the data to generate country-year and average country-level statistics on annual landfalls (count, maximum wind speed observed, sum of maximum wind speeds per landfall) as well as long run risk. This is in the spirit of Hsiang and Jina (2015) as well as Skidmore and Toya (2002). HJ build the LICRICE model, which takes the underlying hurricane tracks from IBTrACS and estimates the two-dimensional wind speed structure. Hsiang (2011) notes that the LICRICE model is a two-step process. First, the radius of maximum wind is estimated using a linear combination of wind speed and latitude. Second, the wind speed within the radius is estimated using the wind direction and forward speed of the storm. Ultimately, the wind speed data are aggregated up to the country-year level using spatial area weighting. The maximum wind speed, as well as the dissipated energy (the cube of the wind speed summed over time the hurricane is over a country) are two relevant outputs of the LICRICE technique. Since LICRICE is not publicly available, we are unable to know how close our variables are to LICRICE. However, we find qualitatively consistent results. Similar to HJ, we are most confident of the hurricane data after the satellite era begins in 1970.

We also find that early records in IBTrACS often do not have wind speeds affiliated with the historical records when clearly a windy storm exists. Thus, we run the data two ways: 1) We estimate the results without interpolating wind speeds. This will lead to an attenuation bias because the measurement error will often underestimate wind speeds. 2) We approximate wind speeds using the following assumptions, in the following order: a) interpolate missing wind speeds

from temporally neighboring observed records from the same storm, b) using observed pressure readings at the same time as unobserved wind readings using the approach from Atkinson and Holliday (1977), c) based on the categorized value of the storm, and d) for a small minority of observations for which the previous three approaches did not work, we assumed wind speeds of 25 knots. We find our results to be much more significant after this correction for the missing wind speed data.

The main challenge in estimating our second-step cross-sectional specification is that cyclone risks are not randomly distributed across space, but are likely correlated with other factors that may influence growth. In particular, we would want to control for any exogenous factors that correlate with cyclone risk such as geography (Sachs and Warner, 1997; Hall and Jones, 1996) or institutions during early development (Acemoglu, Johnson, Robinson, 2001). Similar to Skidmore and Toya, we thus include geographic variables such as latitude and continent controls (Barro and Lee, 1994). Geographic variables are from Portland State University's Country Geography Data set. We further use Transparency International's Corruption Perception Index to proxy for institutional quality. Lastly, our financial markets development proxy and other societal controls are from the World Bank's WDI.

4.2 Empirical Findings

This section presents the empirical results. First, Table 2 provides results from the first stage panel fixed effects estimation (22). The results are consistent with those of HJ, indicating negative and persistent impacts of cyclone strikes on output levels (i.e., temporary but cumulatively negative impacts on growth rates). Column 1 reports the growth impact of contemporaneous and lagged maximum annual hurricane wind speed. Column 2 is identical but uses the sum of cyclone energy (wind speed cubed and summed over the lifetime of the storm over a given country) in a given country-year. The country-year observations occur from 1970-2015, with lagged hurricane characteristics going back until 1950. In these main results, we used the interpolated wind speeds described in the data section. The results are qualitatively similar, except less precisely estimated, if we use the data with values of zero for missing wind speeds. Overall, the results are more strongly consistent with the finding that hurricane strikes have a negative and durational impact. All specifications include country and time fixed effects as well as country-year trends.

Table 3 presents the cumulative sum and significance of the estimated cyclone strike coefficients across five, ten, fifteen, and twenty years following a landfall, corresponding to maximum annual wind speed in Columns 2 and 3, and cyclone energy in Columns 4 and 5. We calculate the cumulative significance using the F-Test. We find that the Wind Sum model (Table 2 Column 1) performs the best, and therefore we employ that specification for the second stage of our

Table 2: Hurricane Strikes in Panel Fixed Effects Regressions

	(1)	(2)
Dependent Variable	GDP PC Growth	GDP PC Growth
Hurricane Variable	Max Wind	Energy
Years	1970-2015	1970-2015
Hurricane t	-0.00220	-9.22e-08*
	(0.00455)	(5.41e-08)
Hurricane t-1	-0.00134	1.95e-08
	(0.00382)	(5.03e-08)
Hurricane t-2	-0.00420	-4.22e-08
	(0.00382)	(4.90e-08)
Hurricane t-3	-0.00163	-5.53e-08
	(0.00409)	(4.93e-08)
Hurricane t-4	-0.00379	4.29e-09
	(0.00376)	(4.55e-08)
Hurricane t-5	-0.00188	-8.44e-08
	(0.00392)	(5.21e-08)
Hurricane t-6	-0.00478	-7.17e-08
	(0.00395)	(4.71e-08)
Hurricane t-7	0.00164	-3.73e-08
	(0.00389)	(5.95e-08)
Hurricane t-8	-0.00686	-6.14e-08
	(0.00472)	(5.56e-08)
Hurricane t-9	0.00336	3.92e-08
	(0.00378)	(5.27e-08)
Hurricane t-10	-0.00727*	-6.69e-08
	(0.00377)	(5.60e-08)
Hurricane t-11	-0.00597	-1.04e-07*
	(0.00391)	(5.85e-08)
Hurricane t-12	-0.00496	-1.83e-08
	(0.00389)	(6.02e-08)
Hurricane t-13	0.00322	-9.25e-09
	(0.00390)	(5.91e-08)
Hurricane t-14	-0.00514	-1.63e-08
	(0.00452)	(7.10e-08)
Hurricane t-15	-0.00243	-6.05e-08
	(0.00465)	(6.45e-08)
Hurricane t-16	-0.00535	-9.57e-08*
	(0.00441)	(5.77e-08)
Hurricane t-17	-0.00171	-8.13e-10
	(0.00449)	(5.98e-08)
Hurricane t-18	0.00439	1.09e-07
	(0.00438)	(8.19e-08)
Hurricane t-19	-0.000989	8.15e-08
	(0.00506)	(7.41e-08)
Hurricane t-20	0.00120	5.73e-08
	(0.00415)	(6.04e-08)
Country FE	Y	Y
Year FE	Y	Y
Country-Year Trend	Y	Y
Observations	7,348	7,348
R-squared	0.268	0.268

Robust standard errors in parentheses
** p<0.01, ** p<0.05, * p<0.1

empirical analysis.

Table 3: Hurricane Strike Cumulative Impacts

Lags	Max Wind Coefficient Sum	Max Wind P-Values	Energy Coefficient Sum	Energy P-Values
5	-0.015	0.1902	-1.58E-07	0.0862
10	-0.022	0.0831	-3.56E-07	0.0284
15	-0.037	0.0348	-4.61E-07	0.0151
20	-0.039	0.0851	-2.14E-07	0.1369

4.2.1 Cyclone Risk and Strikes: Growth Decomposition

We next estimate average country growth in the absence of cyclone *strikes* through the fixed effects estimated in the panel regression as per equation (23). We use Column 1 from Table 2 to extract the estimated parameters. We then regress the estimated growth rate on relevant cyclone risk variables and controls as per equation 25, including the Corruption Perception Index (CPI), latitude, additional control variables found in Skidmore and Toya (2002), and, in some specifications, region fixed effects. Table 4 presents the results. In line with the theoretical model, we find that countries' average growth rates in the absence of strikes are still a function of underlying cyclone risk. In particular, growth appears positively and significantly associated with average cyclone risk (measured as maximum wind speed), in line with Skidmore and Toya (2002). The results remain strongly significant and stable in the point estimate across all seven specifications. Driven by our model, we also include the variance of annual maximum wind in Columns 6 and 7. We find that the sign is as expected, and opposite of the average wind, but imprecisely estimated. This is likely due to the multicollinearity between the mean and variance of wind speed in the data. Overall, the results are consistent with the central implication of our model that changes in cyclone distributions - such as from climate change - will have two effects on growth. On the one hand, more intense or frequent disaster realizations will lead to larger, persistent output losses. On the other hand, households will respond to this change by adjusting their savings behavior to account for these risks. The net effect on observed output growth is thus ex-ante ambiguous.

Finally, Table 5 presents our estimates of (i) average observed growth, (ii) no-strikes growth, and (iii) *no-cyclones* (neither strikes nor risk) growth as per equation (26). To estimate the overall impact of cyclones on growth, one must account for both the effects of strikes and risk in the counterfactual comparison. In Table 5, Columns 2 and 8 present our estimated average country

Table 4: Average Growth Decomposition

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent Variable	$\overline{\widehat{G_{i,t}}}$	$\overline{\widehat{G_{i,t}}}$	$\overline{\widehat{G_{i,t}}}$	$\overline{\widehat{G_{i,t}}}$	$\overline{\widehat{G_{i,t}}}$	$\overline{\widehat{G_{i,t}}}$	$\overline{\widehat{G_{i,t}}}$
Average Max Wind	0.0203***	0.0230***	0.0184***	0.0213***	0.0195***	0.0216**	0.0213**
	(0.00686)	(0.00737)	(0.00695)	(0.00503)	(0.00731)	(0.00904)	(0.00926)
Variance Max Wind						-5.01e-05	-0.000348
						(0.00117)	(0.00123)
Absolute Latitude		-0.00362	-0.00168	-0.0458	-0.0225	-0.0452	-0.0164
		(0.0462)	(0.0297)	(0.0388)	(0.0501)	(0.0409)	(0.0501)
Corruption Perception Index		0.0582*	0.0248	0.0450*	0.0173	0.0448*	0.0158
		(0.0329)	(0.0254)	(0.0233)	(0.0227)	(0.0230)	(0.0255)
Ln Initial GDP				-0.202	-0.199	-0.204	-0.205
				(0.443)	(0.483)	(0.397)	(0.424)
Avg Education Labor Force				-0.0689*	-0.0549*	-0.0691***	-0.0562**
				(0.0372)	(0.0303)	(0.0226)	(0.0232)
Avg Birth Rate				-0.107*	-0.119	-0.108*	-0.118*
				(0.0598)	(0.0807)	(0.0545)	(0.0662)
Avg Capital Formation				0.0691	0.0778	0.0690	0.0789
				(0.0734)	(0.0905)	(0.0655)	(0.0702)
Avg Gov Consumption				0.0727	0.0553	0.0732	0.0603
				(0.0785)	(0.0901)	(0.0611)	(0.0653)
Avg Trade				0.00323	0.00249	0.00319	0.00247
				(0.0118)	(0.0115)	(0.0108)	(0.0108)
Ln Land Area				-0.270	-0.383	-0.273	-0.414
				(0.241)	(0.279)	(0.251)	(0.284)
Ln Population				0.571	0.509	0.574	0.537
				(0.518)	(0.520)	(0.459)	(0.478)
Ln Urbanization				0.549	0.726	0.557	0.758
				(0.721)	(0.834)	(0.743)	(0.784)
Pct Tropical				-0.175	-0.416	-0.148	-0.252
				(1.381)	(1.542)	(1.415)	(1.525)
Constant	3.082***	0.183	3.234***	0.654	4.075	0.659	3.841
	(0.434)	(0.783)	(0.810)	(6.861)	(7.599)	(6.773)	(7.358)
Region FE	N	N	Y	N	Y	N	Y
Observations	203	149	149	81	81	81	81
R-squared	0.017	0.064	0.106	0.464	0.539	0.464	0.540

Bootstrapped SE in parentheses
** p<0.01, ** p<0.05, * p<0.1

growth rates.[17] Columns 3 and 9 present the no-strikes counterfactual that does not remove the growth bump from the underlying risk. While these columns correctly estimate counterfactual growth without cyclone strikes, they do not estimate a no-cyclone world. Columns 4 and 10 calculate the impact of strikes on average growth. Columns 5 and 11 estimate the counterfactual comparison of each country with no cyclone strikes or risk. Columns 6 and 12 present the overall impact of cyclones (strikes plus risk) on average growth.

We find that careful consideration of the appropriate counterfactual matters greatly. For example, analyzing the impact of strikes alone will lead to an overestimate of the negative impacts of cyclones. Similarly, only identifying the impact of the underlying cyclone risk rate will lead to an underestimate of the true impact of cyclones on growth. The truth is in between. Overall, we find that, conditional on ever experiencing cyclones, the strike-only approach will estimate an average cyclone impact of -0.72 percentage points from the annual growth rate. However, once the increase in growth due to long run cyclone risk is accounted for, the estimated average growth impact is a -0.09 percentage point reduction form the annual growth rate. Thus, focusing on strikes, alone, will overestimate losses by a significant amount. Similarly, only focusing on the underlying risk rate, and conditional on having hurricanes, would indicate that cyclones positively impact growth by 0.63 percent per year, on average. While these are preliminary results, they highlight the need for both factors to be included in impact estimates.

Cyclones and Risk Reduction: Credit Lastly, we present some suggestive evidence to empirically test the model's prediction that financial markets can attenuate the impacts of cyclone risk on growth.[18] We do so by interacting a proxy for financial market development - total domestic credit provided by the financial sector as a percentage of GDP - with cyclone risk variables. Though imprecisely estimated in most specifications, the interaction between average cyclone risk and financial market development is negative, suggestively consistent with the hypothesis that market completeness mitigates the effects of cyclone risk on growth.[19]

[17] For transparency, we present the raw numbers. Alternatively, we could calculate the percent change in the values and then apply them back to the observed (historical) growth rates.

[18] McDermott, Barry, and Tol (2014) explore the effect of financial market development on the growth impact of disaster *strikes* in a panel estimation, finding a significant protective effect. Our model implies that the underlying mechanisms rendering financial markets beneficial in disaster strike recovery likely differs from the effect on long-run growth (via changes in investment patterns). We hope to explore this question more formally in the future.

[19] In current work we are exploring other financial market and insurance availability proxies, as well as other cyclone risk interactions, to test the strength and robustness of these results.

Table 5: Strike and Cyclone Growth Impacts

Country	Estimated Avg Growth (%)	No-Strikes Growth (%)	Strike Impact (%)	No-Cyclones Growth (%)	Cyclone Impact (%)	Country	Estimated Avg Growth (%)	No-Strikes Growth (%)	Strike Impact (%)	No-Cyclones Growth (%)	Cyclone Impact (%)
AFG	3.40	3.40	0.00	3.40	0.00	LBY	2.70	2.70	0.00	2.70	0.00
AGO	2.83	2.83	0.00	2.83	0.00	LCA	2.65	2.97	-0.31	2.69	-0.04
ALB	4.02	4.02	0.00	4.02	0.00	LIE	3.13	3.13	0.00	3.13	0.00
ARE	-1.66	-1.66	0.00	-1.66	0.00	LKA	4.95	5.44	-0.49	5.05	-0.10
ARG	2.60	2.60	0.00	2.60	0.00	LSO	3.57	3.57	0.00	3.57	0.00
ARM	3.30	3.30	0.00	3.30	0.00	LTU	6.60	6.60	0.00	6.60	0.00
ATG	2.77	3.30	-0.53	3.09	-0.32	LUX	2.97	2.97	0.00	2.97	0.00
AUS	2.26	6.43	-4.17	2.78	-0.52	LVA	7.04	7.04	0.00	7.04	0.00
AUT	2.24	2.24	0.00	2.24	0.00	MAC	6.31	6.31	0.00	6.31	0.00
AZE	2.11	2.11	0.00	2.11	0.00	MAR	3.44	3.44	0.00	3.40	0.03
BDI	0.09	0.09	0.00	0.09	0.00	MCO	2.89	2.89	0.00	2.89	0.00
BEL	2.04	2.04	0.00	2.04	0.00	MDA	1.50	1.50	0.00	1.50	0.00
BEN	1.77	1.77	0.00	1.77	0.00	MDG	-0.54	2.63	-3.17	0.51	-1.05
BFA	3.03	3.03	0.00	3.03	0.00	MDV	6.77	6.77	0.00	6.77	0.00
BGD	4.05	5.37	-1.32	4.12	-0.07	MEX	1.32	5.93	-4.62	2.07	-0.75
BGR	3.46	3.46	0.00	3.46	0.00	MHL	1.86	1.86	0.00	1.86	0.00
BHR	1.08	1.08	0.00	1.08	0.00	MKD	1.04	1.04	0.00	1.04	0.00
BHS	0.83	2.26	-1.43	1.06	-0.23	MLI	2.06	2.06	0.00	2.06	0.00
BLR	3.05	3.05	0.00	3.05	0.00	MMR	7.17	8.48	-1.31	7.51	-0.35
BLZ	3.33	3.58	-0.25	2.71	0.62	MNE	1.91	1.91	0.00	1.91	0.00
BMU	1.49	1.49	0.00	1.45	0.04	MNG	4.54	4.54	0.00	4.52	0.02
BOL	2.41	2.41	0.00	2.41	0.00	MOZ	4.35	5.76	-1.41	4.73	-0.37
BRA	2.38	2.38	0.00	2.30	0.07	MRT	1.73	1.73	0.00	1.73	0.00
BRB	1.49	1.49	0.00	1.43	0.06	MUS	4.43	4.43	0.00	4.35	0.07
BRN	-0.18	-0.18	0.00	-0.21	0.02	MWI	1.90	1.90	0.00	1.88	0.02
BTN	6.27	6.27	0.00	6.27	0.00	MYS	4.31	4.39	-0.08	4.28	0.03
BWA	4.50	4.56	-0.05	4.54	-0.04	NAM	2.17	2.23	-0.05	2.21	-0.04
CAF	-1.18	-1.18	0.00	-1.18	0.00	NCL	2.05	4.30	-2.25	3.15	-1.10
CAN	2.13	3.97	-1.84	2.02	0.11	NER	0.63	0.63	0.00	0.63	0.00
CHE	1.73	1.73	0.00	1.73	0.00	NGA	2.97	2.97	0.00	2.97	0.00
CHI	1.04	1.04	0.00	1.04	0.00	NIC	1.38	2.38	-1.00	1.55	-0.17
CHL	4.03	4.03	0.00	4.03	0.00	NLD	2.09	2.09	0.00	2.09	0.00
CHN	9.50	13.08	-3.58	9.50	-0.01	NOR	2.35	2.35	0.00	2.32	0.02
CIV	0.37	0.37	0.00	0.37	0.00	NPL	3.27	3.27	0.00	3.25	0.02
CMR	1.21	1.21	0.00	1.21	0.00	NZL	1.58	2.79	-1.20	2.24	-0.65
COG	1.79	1.79	0.00	1.79	0.00	OMN	1.00	1.45	-0.45	1.15	-0.14
COL	2.85	3.23	-0.38	3.14	-0.29	PAK	2.70	2.95	-0.24	2.59	0.12
COM	0.53	0.53	0.00	0.43	0.10	PAN	4.17	4.17	0.00	4.13	0.04
CPV	5.93	5.89	0.05	5.77	0.16	PER	3.03	3.03	0.00	3.03	0.00
CRI	3.18	3.18	0.00	3.16	0.02	PHL	2.76	6.68	-3.92	2.97	-0.21
CUB	3.99	5.20	-1.21	3.36	0.63	PLW	-0.20	-0.17	-0.03	-0.26	0.05
CYM	2.77	2.77	0.00	2.71	0.06	PNG	2.44	2.84	-0.39	2.52	-0.07
CYP	2.45	2.45	0.00	2.45	0.00	POL	4.33	4.33	0.00	4.33	0.00
CZE	2.16	2.16	0.00	2.16	0.00	PRI	1.75	2.49	-0.73	2.12	-0.37
DEU	2.28	2.28	0.00	2.28	0.00	PRT	2.23	2.22	0.00	1.99	0.24
DJI	-0.40	-0.40	0.00	-0.40	0.00	PRY	2.74	2.74	0.00	2.74	0.00
DMA	3.33	3.47	-0.13	3.31	0.02	PYF	0.70	0.70	0.00	0.70	0.00
DNK	1.75	1.75	0.00	1.75	0.00	QAT	1.38	1.38	0.00	1.38	0.00
DOM	4.30	4.80	-0.49	3.83	0.47	ROM	2.48	2.48	0.00	2.48	0.00
DZA	1.76	1.76	0.00	1.73	0.02	RUS	0.40	2.37	-1.97	0.52	-0.12
ECU	2.32	2.32	0.00	2.32	0.00	RWA	3.85	3.85	0.00	3.85	0.00
EGY	3.09	3.09	0.00	3.09	0.00	SAU	1.28	1.52	-0.24	1.49	-0.22
ERI	3.38	3.38	0.00	3.38	0.00	SDN	3.45	3.45	0.00	3.45	0.00
ESP	1.78	2.10	-0.32	2.00	-0.22	SEN	1.27	1.27	0.00	1.18	0.09
EST	6.69	6.69	0.00	6.69	0.00	SGP	4.64	4.64	0.00	4.64	0.00
ETH	3.85	3.85	0.00	3.85	0.00	SLB	1.56	1.95	-0.39	1.43	0.13
FIN	2.26	2.26	0.00	2.26	0.00	SLE	2.47	2.47	0.00	2.47	0.00
FJI	1.84	2.70	-0.87	1.97	-0.14	SLV	2.17	2.17	0.00	2.17	0.00
FRA	1.85	1.85	0.00	1.80	0.05	SMR	3.02	3.02	0.00	3.02	0.00
FSM	1.36	1.42	-0.06	1.38	-0.02	SOM	2.24	2.76	-0.51	2.62	-0.38
GAB	0.80	0.80	0.00	0.80	0.00	SRB	3.74	3.74	0.00	3.74	0.00
GBR	2.11	2.67	-0.56	2.42	-0.31	SSD	4.78	4.78	0.00	4.78	0.00
GEO	2.55	2.55	0.00	2.55	0.00	STP	2.30	2.30	0.00	2.30	0.00
GHA	3.23	3.23	0.00	3.23	0.00	SUR	2.07	2.07	0.00	2.07	0.00
GIN	0.95	0.95	0.00	0.93	0.02	SVK	4.69	4.69	0.00	4.69	0.00
GMB	0.90	0.90	0.00	0.88	0.02	SVN	3.84	3.84	0.00	3.84	0.00
GNB	0.82	0.82	0.00	0.80	0.02	SWE	2.26	2.26	0.00	2.26	0.00
GRC	1.11	1.11	0.00	1.11	0.00	SYC	3.34	3.34	0.00	3.34	0.00
GRD	3.17	3.46	-0.30	3.32	-0.15	SYR	1.76	1.76	0.00	1.76	0.00
GRL	2.02	2.02	0.00	1.95	0.07	TCD	3.42	3.42	0.00	3.42	0.00
GTM	2.10	2.33	-0.23	1.64	0.46	TGO	0.91	0.91	0.00	0.91	0.00
GUY	3.18	3.18	0.00	3.18	0.00	THA	4.55	5.92	-1.38	4.82	-0.27
HKG	4.15	4.15	0.00	4.15	0.00	TJK	-0.17	-0.17	0.00	-0.17	0.00
HND	2.44	2.79	-0.35	2.11	0.32	TKM	3.94	3.94	0.00	3.94	0.00
HTI	-1.63	-1.31	-0.33	-2.12	0.49	TON	2.14	2.24	-0.10	2.09	0.05
HUN	2.72	2.72	0.00	2.72	0.00	TTO	3.39	3.57	-0.17	3.46	-0.07
IDN	4.66	4.92	-0.26	4.56	0.09	TUN	3.21	3.21	0.00	3.21	0.00
IMY	5.71	5.92	-0.21	5.88	-0.17	TUR	3.26	3.26	0.00	3.26	0.00
IND	5.42	7.73	-2.31	5.73	-0.31	TUV	2.86	2.86	0.00	2.86	0.00
IRL	3.83	4.16	-0.33	3.91	-0.09	TZA	2.64	2.64	0.00	2.60	0.04
IRN	1.70	1.70	0.00	1.70	0.00	UGA	3.41	3.41	0.00	3.41	0.00
IRQ	5.36	5.36	0.00	5.36	0.00	UKR	-0.29	-0.29	0.00	-0.29	0.00
ISL	2.39	2.47	-0.08	2.33	0.06	URY	3.44	3.44	0.00	3.44	0.00
ISR	2.95	2.95	0.00	2.95	0.00	USA	1.80	6.07	-4.27	2.31	-0.50
JAM	0.66	1.41	-0.75	1.11	-0.46	VCT	3.48	3.48	0.00	3.44	0.04
JPN	2.41	5.56	-3.16	2.23	0.17	VIR	7.95	9.12	-1.18	8.97	-1.02
KAZ	2.12	2.12	0.00	2.12	0.00	VNM	5.50	8.14	-2.64	5.82	-0.32
KEN	1.76	1.76	0.00	1.76	0.00	VUT	0.86	2.79	-1.93	1.86	-1.00
KGZ	1.08	1.08	0.00	1.08	0.00	WBG	4.79	4.79	0.00	4.79	0.00
KHM	5.30	6.56	-1.26	5.85	-0.55	WSM	2.67	2.55	0.11	2.37	0.29
KIR	0.67	0.67	0.00	0.67	0.00	YEM	1.43	1.56	-0.13	1.50	-0.07
KOR	5.61	7.48	-1.87	5.88	-0.27	ZAR	-0.59	-0.59	0.00	-0.59	0.00
KWT	-0.86	-0.86	0.00	-0.86	0.00	ZWE	0.83	1.22	-0.39	1.11	-0.28

Table 6: Hurricane and Risk Reduction: Credit

	(1)	(2)	(3)	(4)
Dependent Variable	Avg Growth	Avg Growth	Avg Growth	Avg Growth
Avg Max Wind	0.0374***	0.0477***	0.0365***	0.0339***
	(0.0137)	(0.0136)	(0.0102)	(0.0100)
Avg Credit	-0.000261	-0.00276	0.00446	-0.00300
	(0.00581)	(0.00526)	(0.00488)	(0.00468)
Avg Max Wind X Avg Credit	-6.80e-06	-3.71e-05	-0.000133*	-9.49e-05
	(9.82e-05)	(7.90e-05)	(7.88e-05)	(7.44e-05)
Abs Latitude		0.0182		0.0148
		(0.0231)		(0.0163)
Corruption Perception Index		0.00646		0.0174
		(0.0166)		(0.0147)
Constant	1.341***	0.593	0.604	2.152***
	(0.502)	(0.493)	(0.598)	(0.602)
Region FE	N	N	Y	Y
Observations	112	87	92	87
R-squared	0.055	0.107	0.164	0.188

Robust SE in parentheses
** p<0.01, ** p<0.05, * p<0.1

5 Conclusion

A growing body of empirical work has sought to quantify the impacts of natural disasters on economic growth. To date, this literature has found seemingly contradictory results, ranging from positive effects to very large negative impacts. This paper brings a novel macroeconomic model-based perspective to the data in order to reconcile and build upon these findings. Taking advantage of the tools developed in the literature on incomplete markets and macroeconomic outcomes (Krebs, 2003, 2006), we present a stochastic endogenous growth model where individual regions face uninsurable cyclone risks to human and entrepreneurial capital. The first central result is that the model can reconcile some key divergent results from prior empirical studies as they measure different elements of the overall impact of natural disasters on growth: (1) Higher hurricane *risk* can increase growth by increasing (precautionary) savings rates, whereas hurricane *strikes* induce (potentially persistent) output losses. These results are in line with differences in empirical results of, e.g., the positive cross-sectional impact estimates of Skidmore and Toya (2002) versus the negative cyclone strike impacts documented in panel estimation by Hsiang and Jina (2015). While competing empirical approaches identify different aspects of the growth question, neither cross-sectional nor panel fixed-effects specifications may thus be individually sufficient to capture the overall effect of disasters growth. We explore a two-step combined estimator that seeks to adjust directly for the dependence of countries' average growth rates on cyclone risk. We empirically find that average growth (in a world without cyclone *strikes*) is positively associated with cyclone *risk*, in line with the model. Based on these results we find that the *overall* impact of cyclones on growth lies between the large negative cumulative effect of strikes and the positive effect of risk. (2) We find that competing measures of cyclone risk - specifically average damages to physical versus human capital, or average storm intensity - can be related to growth in opposite ways. This result is in line with, e.g., Hsiang and Jina's (2015b) finding that average cyclone-induced capital depreciation is negatively associated with long-run growth, in contrast with Skidmore and Toya's (2002) finding that the average number of disasters is positively associated with long-run growth. The intuition for our result is as follows. Long-run growth depends on the level and composition of households' investments in assets with different productivities and cyclone vulnerabilities. A decline in the expected returns to investments in, e.g., human capital due to higher expected cyclone damages can thus increase investment in other, more productive (albeit riskier) assets, such as entrepreneurial capital, increasing growth. Again, empirical studies using different average cyclone risk measures estimate different aspects of the overall growth impacts. However, our model implies that the overall impact of cyclone risk on growth depends on the entire vector of different assets' returns, average damages, as well as cyclone risk variance and covariance measures, which have seldom been included in empirical

studies. (3) Finally, we show that cyclone risk can have opposite effects on growth and welfare. For example, an increase in cyclone risk can increase growth by strengthening precautionary savings motives, but this change will unambiguously decrease welfare. While this ambiguity is known in the macroeconomics incomplete markets literature (e.g., Krebs, 2003, 2006; Angeletos, 2007), we demonstrate its relevance for the environmental literature seeking to map reduced form output growth impact estimates into welfare. In particular, this result highlights the importance of decomposing output growth changes into underlying changes in savings rates, productivity, etc. in order to inform such a mapping.

In summary, our model can both reconcile and contextualize key results from the empirical literature on disasters and economic growth. We argue that this rich literature has carefully identified different elements of disaster growth impacts (e.g., risk versus strikes). However, through the lens of a macroeconomic model, the pieces of the puzzle can be assembled to inform a more comprehensive understanding of the impact of disasters on growth, and to highlight the key empirical challenges that remain open. Overall, our results highlight the potential value of joint advances in theory and empirics to improve our understanding of environment-economy interactions.

6 Appendix

6.1 Lognormal Distribution Fit for Cyclone Damages

In order to gauge the plausibility of a log-normal distribution of cyclone-induced shocks to the depreciation of human and physical capital, we obtain EM-DAT data from the International Disaster Database at the Center for Research on Epidemiology of Disasters (CRED). These data provide both the value of direct damages and total fatalities. We then obtain World Bank Development Indicators data on countries' real GDP and populations over time (for all available countries and years from 1960-2014). We approximate countries' capital stocks by assuming a marginal product of capital of $r = 5\%$, a uniform depreciation rate of 10% and a capital share in output of 30%. We then calculate the fraction of the capital stock destroyed, and the fraction of human capital destroyed (i.e., population killed) by cyclones in each country-year. Figures A1 and A3 plot the histogram for these variables conditional on damages being positive. Figures A2 and A4 plot the histogram of the logarithm of these variables, along with a normal distribution fit line. Both variables appear well-approximated by a log-normal distribution.

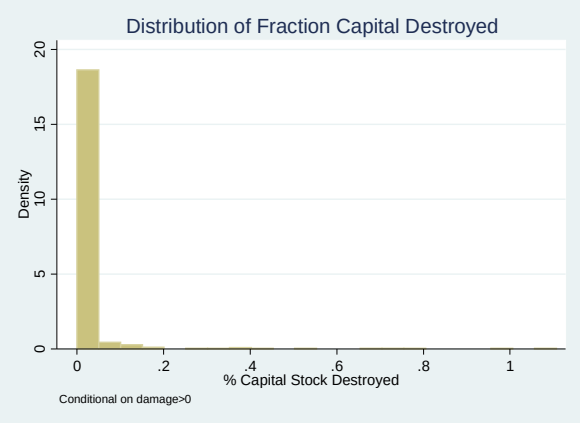


Figure A1

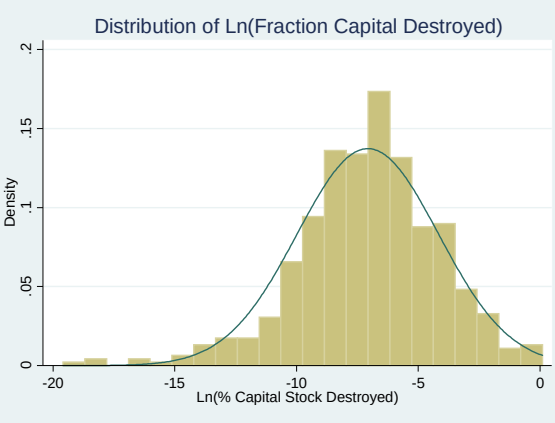


Figure A2

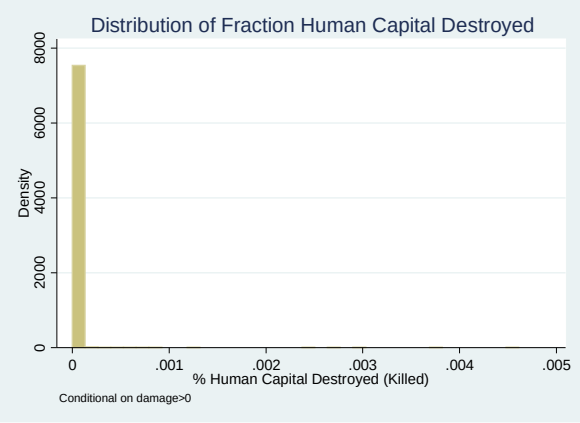


Figure A3

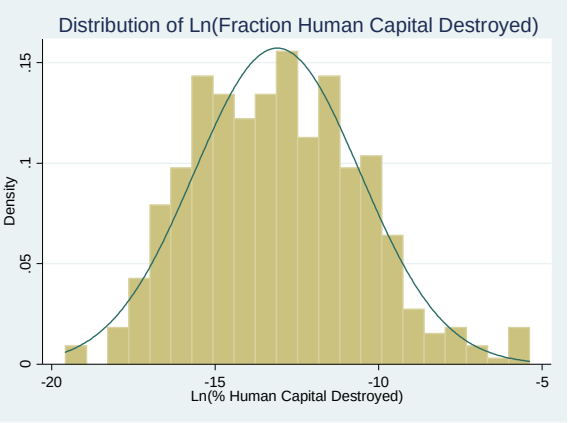


Figure A4

6.2 Proof of Proposition 1

The household's recursive dynamic optimization problem is given by:

$$V(w_i, \widetilde{h}_i, \Theta_{k2i}, \eta_i^h, \eta_i^{k2}) = \max u(c_i) + \beta E[V(w_i', \widetilde{h}_i', \Theta_{k2i}', \eta_i^{h\prime}, \eta_i^{k2\prime})] \tag{27}$$

subject to:

$$w_i' = [1 + r(\widetilde{h}_i, \Theta_{k2i}, \eta_i^h, \eta_i^{k2})]w_i - c_i \tag{28}$$

where:

$$\begin{aligned} & r(\widetilde{h}_i, \Theta_{k2i}, \eta_i^h, \eta_i^{k2}) \\ = \; & [(1-\Theta_{k2i})(1-\theta_h(\widetilde{h}_i))R_{k1} + \theta_h(\widetilde{h}_i)(R_h + 1 - \delta_h - \eta_i^h) + \Theta_{k2i}(A_2 + 1 - \delta_{k2} - \eta_i^{k_2})] \end{aligned}$$

First, substituting (28) into (27) and taking the FOCs for c_i, $\widetilde{h}_i$, and Θ_{k2i}, respectively, yields:

$$\begin{aligned} u'_{c_i} &= \beta E V'_{w'} \\ 0 &= \beta E V'_{\widetilde{h}_i'} \\ 0 &= \beta E V'_{\Theta'_{k2i}} \end{aligned} \tag{29}$$

Second, we substitute in the decision rules $c_i = g(w_i, \widetilde{h}_i, \Theta_{k2i}, \eta_i^h, \eta_i^{k2})$, $\widetilde{h}'_i = f(w_i, \widetilde{h}_i, \Theta_{k2i}, \eta_i^h, \eta_i^{k2})$, $\Theta'_{k2i} = v(w_i, \widetilde{h}_i, \Theta_{k2i}, \eta_i^h, \eta_i^{k2})$ and derive the Beinveniste-Scheinkman conditions:

$$\begin{aligned} V'_w &= \beta E[V'_{w'}[1 + r(\widetilde{h}_i, \Theta_{k2i}, \eta_i^h, \eta_i^{k2})]] \\ V'_{\widetilde{h}_i} &= \beta E[V'_{w'}\{(1-\Theta_{k2i})(-1)(1+\widetilde{h}_i)^{-2}R_{k1} + (1+\widetilde{h}_i)^{-2}(R_h + 1 - \delta - \eta_i^h)\}w_i] \\ V'_{\Theta_{k2i}} &= \beta E[V'_{w'}\{(-1)(1-\theta_h(\widetilde{h}_i))R_{k1} + (A_2 + 1 - \delta_{k2} - \eta_i^{k_2})\}w_i] \end{aligned}$$

Substituting out based on the FOCs (29) yields:

$$\begin{aligned} V'_w &= u'_{c_i}[1 + r(\widetilde{h}_i, \Theta_{k2i}, \eta_i^h, \eta_i^{k2})] \\ V'_{\widetilde{h}_i} &= u'_{c_i}\{(1-\Theta_{k2i})(-1)(1+\widetilde{h}_i)^{-2}R_{k1} + (1+\widetilde{h}_i)^{-2}(R_h + 1 - \delta - \eta_i^h)\}w_i \\ V'_{\Theta_{k2i}} &= u'_{c_i}\{(-1)\theta_h(\widetilde{h}_i)R_{k1} + (A_2 + 1 - \delta_{k2} - \eta_i^{k_2})\}w_i \end{aligned}$$

Next, iterating forward provides:

$$\begin{aligned} V'_w &= u'_{c'_i}[1 + r(\widetilde{h}_i{}', \Theta'_{k2i}, \eta_i^{h\prime}, \eta_i^{k2\prime})] \\ V'_{\widetilde{h}_i} &= u'_{c_{i'}}\{(1-\Theta'_{k2i})(-1)(1+\widetilde{h}_i{}')^{-2}R_{k1} + (1+\widetilde{h}_i{}')^{-2}(R_h + 1 - \delta - \eta_i^{h\prime})\}w'_i \\ V'_{\Theta_{k2i}} &= u'_{c'_i}\{(-1)(1-\theta_h(\widetilde{h}_i{}'))R_{k1} + (A_2 + 1 - \delta_{k2} - \eta_i^{k_2\prime})\}w'_i \end{aligned}$$

Next, substituting back into the consumer's optimality conditions yields the following Euler equation and no-arbitrage conditions, respectively:

$$u'_{c_i} = \beta E[u'_{c'_i}[1 + r(\widetilde{h}_i{}', \Theta'_{k2i}, \eta_i^{h\prime}, \eta_i^{k2\prime})]] \tag{30}$$

$$0 = \beta E[u'_{c_{i'}}\{(1-\Theta'_{k2i})(-1)(1+\widetilde{h}_i{}')^{-2}R_{k1} + (1+\widetilde{h}_i{}')^{-2}(R_h + 1 - \delta - \eta_i^{h\prime})\}w'_i] \tag{31}$$

$$0 = \beta E[u'_{c'_i}\{(-1)(1-\theta_h(\widetilde{h}_i{}'))R_{k1} + (A_2 + 1 - \delta_{k2} - \eta_i^{k_2\prime})\}w'_i] \tag{32}$$

Finally, (i) applying our assumed utility function , (ii) defining mean returns $\widetilde{r_{k2}} \equiv A_2 + (1 - \delta_{k2})$ and $\widetilde{r_h} = R_h + (1 - \delta_h)$, (iii) invoking the budget constraint $w_i' = (1 + r(\widetilde{h_i}, \Theta_{k2i}, \eta_i^h, \eta_i^{k2}))w_i - c_i$ and $c_i' = \widetilde{c}(1 + r')w'$, and rearranging yields:

$$\widetilde{c} = 1 - (\beta E[(1 + r(\widetilde{h_i}', \Theta_{k2i}', \eta_i^{h\prime}, \eta_i^{k2\prime}))^{1-\gamma}])^{\frac{1}{\gamma}} \tag{33}$$

$$0 = \beta E\left[\frac{\{(\widetilde{r_h} - \eta_i^{h\prime}) - (1 - \Theta_{k2i}')R_{k1}\}}{(1 + \widetilde{h_i}')^2(1 + r(\widetilde{h_i}', \Theta_{k2i}', \eta_i^{h\prime}, \eta_i^{k2\prime}))^{\gamma}}\right] \tag{34}$$

$$0 = \beta E\left[\frac{\{(\widetilde{r_{k2}} - \eta_i^{k_2\prime}) - (1 - \theta_h(\widetilde{h_i'}))R_{k1}\}}{(1 + r(\widetilde{h_i}', \Theta_{k2i}', \eta_i^{h\prime}, \eta_i^{k2\prime}))^{\gamma}}\right] \tag{35}$$

Our three unknowns $(\widetilde{c}, \Theta_{k2i}', \widetilde{h_i'})$ are thus defined by equations (33)-(35). Importantly, they do not depend on wealth nor on the current hurricane shock, but only on the (time-invariant) expectations over future realizations. □.

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