Climate Shocks, Cyclones, and Economic Growth: Bridging the Micro-Macro Gap

Online Appendix

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1 Theoretical Derivations

1.1 Stationary Equilibrium Growth

This section derives the paper's equations defining equilibrium growth (6-8), following the approach in Krebs (2003a,b). Country subscripts j are omitted for legibility. First, note that the household's problem can be written in recursive form as:

$$V(w,\widetilde{k},\varepsilon) = \max u(c) + \beta E[V(w',\widetilde{k}',\varepsilon')] \tag{1}$$

subject to:

$$w' = w[1 + r(\widetilde{k},\varepsilon)] - c \tag{2}$$

where $r(.)$ is as defined in paper equation (5). Substituting (2) into (1) and taking the first-order conditions (FOCs) for c and $\widetilde{k}$ yields:

$$\begin{aligned} u'_c &= \beta E[V'_{w'}] \\ 0 &= \beta E[V'_{\widetilde{k}'}] \end{aligned} \tag{3}$$

Next, substituting in the decision rules $c = g(w,\widetilde{k},\varepsilon)$ and $\widetilde{k}' = f(w,\widetilde{k},\varepsilon)$ yields the Benveniste-Scheinkman conditions:

$$\begin{aligned} V'_w &= \beta E[V'_{w'}[(1 + r(\widetilde{k},\varepsilon)]] \\ V'_{\widetilde{k}} &= \beta E[V'_{w'} w \left\{ \frac{[R^k(\varepsilon) - \overline{\delta^k} - (1-\pi)\eta^k(\varepsilon)] - [R^h(\varepsilon) - \overline{\delta^h} - (1-\pi)\eta^h(\varepsilon)]}{(1+\widetilde{k})^2} \right\}] \end{aligned}$$

Substituting based on (3) and iterating forward then yields the Euler equation and no-arbitrage condition, respectively:

$$u'_c = \beta E[u'_{c'}[(1 + r(\widetilde{k}',\varepsilon')]] \tag{4}$$

$$0 = \beta E[u'_{c'} w' \left\{ \frac{[R^k(\varepsilon') - \overline{\delta^k} - (1-\pi)\eta^k(\varepsilon')] - [R^h(\varepsilon') - \overline{\delta^h} - (1-\pi)\eta^h(\varepsilon')]}{(1+\widetilde{k}')^2} \right\}] \tag{5}$$

Next, invoking the assumed utility function $u(c) = \frac{c^{1-\gamma}}{1-\gamma}$, the budget constraint (2), and the fact that $c' = \widetilde{c}[1 + r(\widetilde{k}',\varepsilon')]w'$ (where $\widetilde{c} \equiv 1 - \widetilde{s}$ denotes the consumption-out-of-wealth ratio), substitution and rearranging in (4) yields the desired result that:

$$\widetilde{s} = 1 - \widetilde{c} = \left(\beta E[(1 + r(\widetilde{k}',\varepsilon'))^{1-\gamma}]\right)^{\frac{1}{\gamma}} \tag{6}$$

The same substitutions allow us to factor out as pre-determined terms $\widetilde{c}$ and $w' = (1+r)w - c$ in (5), yielding the desired condition:

$$0 = \beta E[\frac{\left\{[R^k(\varepsilon') - \overline{\delta^k} - (1-\pi)\eta^k(\varepsilon')] - [R^h(\varepsilon') - \overline{\delta^h} - (1-\pi)\eta^h(\varepsilon')]\right\}}{(1+\widetilde{k}')^2(1 + r(\widetilde{k}',\varepsilon'))^{\gamma}}] \tag{7}$$

Finally, the expression for average growth can be derived by again invoking $w' = [1+r(\widetilde{k},\varepsilon)]w - c$ and $c' = \widetilde{c}[1+r(\widetilde{k}',\varepsilon')]w'$. First, note that the definition of $\widetilde{c}$ implies that:

$$\begin{aligned} \widetilde{c} &= \frac{c}{[1+r(\widetilde{k},\varepsilon)]w} \\ &\rightarrow \quad 1-\widetilde{c} = \frac{[1+r(\widetilde{k},\varepsilon)]w - c}{[1+r(\widetilde{k},\varepsilon)]w} \end{aligned} \tag{8}$$

Consequently, expected growth can readily be shown to equal paper equation (8), as desired:

$$\begin{aligned} E\left[\frac{c'}{c}\right] &= E\left[\frac{\widetilde{c}[1+r(\widetilde{k}',\varepsilon')]w'}{c}\right] = E\left[\frac{\widetilde{c}[1+r(\widetilde{k}',\varepsilon')]\{[1+r(\widetilde{k},\varepsilon)]w-c\}}{c}\right] \\ &= (1-\widetilde{c})(1+E[r(\widetilde{k}',\varepsilon')]) = (\widetilde{s})(1+E[r(\widetilde{k}',\varepsilon')]) \end{aligned}$$

1.2 Proposition 1

Proposition 1: Cyclone Risk and Avg. Growth *An increase in cyclone risk has a theoretically ambiguous effect on average growth:*

$$\frac{d\overline{g}}{d\mu_\varepsilon} \lesseqgtr 0$$

Proof: We demonstrate the possibility of both positive and negative effects of cyclone risk on average growth by construction. In order to maintain analytic transparency, we present a simple parameterization where, each period, there is just a binary probability ϕ that a cyclone occurs with intensity $\varepsilon_t = \overline{\varepsilon}$, whereas, with probability $1-\phi$, no cyclone occurs ($\varepsilon_t = 0$). The mean disaster realization is thus $\mu_\varepsilon = \phi\overline{\varepsilon}$. For clarity, we also separate the average depreciation term $\overline{\delta_k}$ back into its underlying components: $\overline{\delta_k} = \delta_k + \pi\mu^k = \delta_k + \pi\phi\eta^k(\overline{\varepsilon})$, and analogously for human capital. In this setting, expressions (6) and (7) become:

$$\begin{aligned} \widetilde{s} &= \beta^{\frac{1}{\gamma}} \left[\phi \left\{ (1 + \left[\begin{array}{c} \omega_k(\widetilde{k})[R_k(\widetilde{k}) - \delta_k - \pi\phi\eta^k(\overline{\varepsilon}) - (1-\pi)\eta^k(\overline{\varepsilon})] \\ +(1-\omega_k(\widetilde{k}))[R_h(\widetilde{k}) - \delta_h - \pi\phi\eta^h(\overline{\varepsilon}) - (1-\pi)\eta^h(\overline{\varepsilon})] \end{array} \right]^{1-\gamma} \right\} \right. \\ & \left. +(1-\phi)\left\{ (1 + \left[\omega_k(\widetilde{k})[R_k(\widetilde{k}) - \delta_k - \pi\phi\eta^k(\overline{\varepsilon})] + (1-\omega_k(\widetilde{k}))[R_h(\widetilde{k}) - \delta_h - \pi\phi\eta^h(\overline{\varepsilon})] \right])^{1-\gamma} \right\} \right]^{\frac{1}{\gamma}} \end{aligned} \tag{9}$$

$$\phi \left[\frac{\left[R_k(\widetilde{k}) - \delta_k - \pi\phi\eta^k(\bar{\varepsilon}) - (1-\pi)\eta^k(\bar{\varepsilon})\right] - \left[R_h(\widetilde{k}) - \delta_h - \pi\phi\eta^h(\bar{\varepsilon}) - (1-\pi)\eta^h(\bar{\varepsilon})\right])}{(1+\widetilde{k})^2(1+\left[\omega_k(\widetilde{k})[R_k(\widetilde{k}) - \delta_k - \eta^k(\bar{\varepsilon})(\pi\phi+1-\pi)] + (1-\omega_k(\widetilde{k}))[R_h(\widetilde{k}) - \delta_h - \eta^h(\bar{\varepsilon})(\pi\phi+1-\pi)]\right]} \right.$$

$$\left. +(1-\phi)\left[\frac{\left[R_k(\widetilde{k}) - \delta_k - \pi\phi\eta^k(\bar{\varepsilon})\right] - \left[R_h(\widetilde{k}) - \delta_h - \pi\phi\eta^h(\bar{\varepsilon})\right]}{(1+\widetilde{k})^2\cdot(1+\left[\omega_k(\widetilde{k})[R_k(\widetilde{k}) - \delta_k - \pi\phi\eta^k(\bar{\varepsilon})] + (1-\omega_k(\widetilde{k}))[R_h(\widetilde{k}) - \delta_h - \pi\phi\eta^h(\bar{\varepsilon})]\right])^\gamma}\right] = 0$$

While it is *possible* to apply the implicit function theorem to (9)-(10) to derive analytic expressions for $\frac{d\widetilde{k}}{d\bar{\varepsilon}}$, $\frac{d\widetilde{s}}{d\bar{\varepsilon}}$, and thus ultimately $\frac{d\bar{g}}{d\bar{\varepsilon}}$, we have not found these expressions to be instructive. We therefore analytically illustrate the possibility of higher average growth due to higher storm risk in the simplest possible case where human and physical capital are perfectly symmetric. That is, assume that both types of capital are equally vulnerable to cyclone damages $\eta^k(\varepsilon_t) = \eta^h(\varepsilon_t) \equiv \eta(\varepsilon_t)$, enter production symmetrically (with Cobb-Douglas exponents $\alpha = 1-\alpha = 0.5$), and have equal baseline depreciation rates $\delta_k = \delta_h \equiv \delta$. In this case, it is straightforward to show that the optimal capital share equation (10) is solved by $\widetilde{k}^* = 1$, implying equal optimal investment in both types of capital in stationary equilibrium. The optimal savings rate (9) in the symmetric setting then reduces to:

$$\begin{aligned} \widetilde{s} &= \left(\beta E[(1+r(\widetilde{k}',\varepsilon'))^{1-\gamma}]\right)^{\frac{1}{\gamma}} \\ &= \beta^{\frac{1}{\gamma}}\left[\phi\left\{(1+\frac{A}{2}-\delta-\eta(\bar{\varepsilon})(\pi\phi+1-\pi))^{1-\gamma}\right\} + (1-\phi)\left\{(1+\frac{A}{2}-\delta-\pi\phi\eta(\bar{\varepsilon}))^{1-\gamma}\right\}\right]^{\frac{1}{\gamma}} \end{aligned} \quad (11)$$

where A denotes total factor productivity. Here, the impact of a change in storm risk on optimal savings depends only on its direct effect in (11), and is given by:[1]

$$\frac{d\widetilde{s}}{d\bar{\varepsilon}} = \beta\cdot[\widetilde{s}]^{1-\gamma}\cdot\frac{1}{\gamma}\phi(1-\gamma)(1+r(\bar{\varepsilon}))^{-\gamma}\cdot(-1)\frac{\partial\eta}{\partial\bar{\varepsilon}} \quad (12)$$

where the portfolio return in case of a storm $r(\bar{\varepsilon}) = \frac{A}{2} - \delta - \pi\phi\eta(\bar{\varepsilon}) - (1-\pi)\eta(\bar{\varepsilon})$ and $\widetilde{s}$ are both as in (11).

Since depreciation damages are assumed to be increasing in storm intensity ($\frac{\partial\eta}{\partial\bar{\varepsilon}} > 0$), expression (12) immediately shows that the equilibrium savings rate is increasing in average storm intensity if $\gamma > 1$, unaffected by storm risk if $\gamma = 1$ (logarithmic preferences), and decreasing in

[1] That is, there is no additional indirect effect via a change in $\widetilde{k}$.

storm risk if $\gamma < 1$:[2]

$$\frac{d\widetilde{s}}{d\overline{\varepsilon}} = \begin{cases} > 0 & \text{if } \gamma > 1 \\ = 0 & \text{if } \gamma = 1 \\ < 0 & \text{if } \gamma < 1 \end{cases} \tag{13}$$

The corresponding change in average growth due to storm risk is then given by:

$$\frac{d\overline{g}}{d\overline{\varepsilon}} = \frac{d\widetilde{s}}{d\overline{\varepsilon}}(1 + E[r(\varepsilon')]) + (\widetilde{s})\frac{d(1 + E[r(\varepsilon')])}{d\overline{\varepsilon}} \tag{14}$$

where $\frac{d\widetilde{s}}{d\overline{\varepsilon}}$ is given by (12), $\widetilde{s}$ remains defined by (11), and:

$$\begin{aligned} E[r(\varepsilon')] &= \frac{A}{2} - \delta - \pi\phi\eta(\overline{\varepsilon}) - \phi(1-\pi)\eta(\overline{\varepsilon}) = \frac{A}{2} - \delta - \phi\eta(\overline{\varepsilon}) \\ \frac{d(1 + E[r(\varepsilon)])}{d\overline{\varepsilon}} &= -\phi\frac{\partial\eta}{\partial\overline{\varepsilon}} \end{aligned} \tag{15}$$

To complete the characterization of $\frac{d\overline{g}}{d\overline{\varepsilon}}$, we assume the same functional form for $\eta(\overline{\varepsilon})$ as in the empirical part of the paper:

$$\eta(\overline{\varepsilon}) = \xi_1(\overline{\varepsilon})^{\xi_2} \tag{16}$$

Utilizing (16), (15), and (12) in (14) and rearranging then implies that:

$$\begin{aligned} \frac{d\overline{g}}{d\overline{\varepsilon}} &= (\widetilde{s})[(-1)\phi\xi_1\xi_2(\overline{\varepsilon})^{\xi_2-1}] \\ &\cdot \left[\beta[\widetilde{s}]^{-\gamma}\frac{1}{\gamma}\phi(1-\gamma)\left[1 + \frac{A}{2} - \delta - \pi\phi\xi_1(\overline{\varepsilon})^{\xi_2} - (1-\pi)\xi_1(\overline{\varepsilon})^{\xi_2}\right]^{-\gamma}(1 + \frac{A}{2} - \delta - \phi\xi_1(\overline{\varepsilon})^{\xi_2}) + 1\right] \end{aligned}$$

where $\widetilde{s}$ remains defined by (11). Consequently,

$$\begin{aligned} & sign(\frac{d\overline{g}}{d\overline{\varepsilon}}) \\ = \;& (-1)sign\left\{\beta[\widetilde{s}]^{-\gamma}\frac{1}{\gamma}\phi(1-\gamma)\left[1 + \frac{A}{2} - \delta - \xi_1(\overline{\varepsilon})^{\xi_2}(\pi\phi + 1 - \pi)\right]^{-\gamma}(1 + \frac{A}{2} - \delta - \phi\xi_1(\overline{\varepsilon})^{\xi_2}) + 1\right\} \end{aligned} \tag{17}$$

It immediately follows from (17) that, within the realm of permissible parameter values (where depreciation does not exceed 100 percent even in case of a storm), *average growth is unambiguously decreasing in storm risk whenever* $\gamma \leq 1$.

In contrast, if agents are sufficiently risk averse with $\gamma > 1$, average growth may be increasing

[2] This conclusion follows from the fact that all terms in (12) are positive except for $\left[\frac{-\partial\eta(.)}{\partial\overline{\varepsilon}}\right]$, which is negative, and $(1-\gamma)$, whose sign consequently determines the overall sign of (12).

in storm risk. Figure A1 showcases this possibility by displaying average growth as a function of average storm risk $\mu_\varepsilon = \phi\bar{\varepsilon}$ (while varying $\bar{\varepsilon}$) for different values of γ (for example calibration $\beta = 0.985,\ A = 1,\ \phi = 0.1,\ \delta = .1,\ \xi_1 = 0.5,\ \xi_2 = 2$):

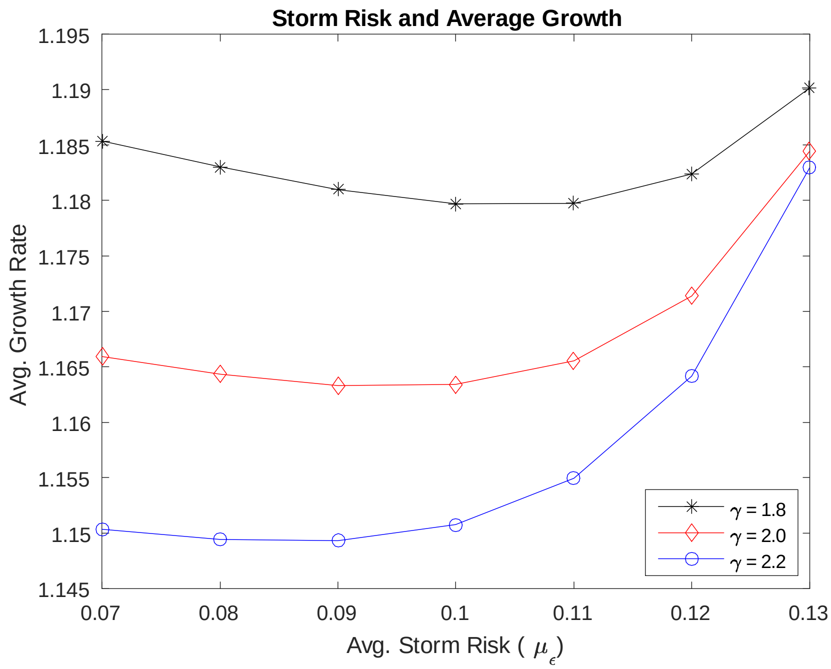

Figure A1

Figure A1 demonstrates that the $\frac{d\bar{g}}{d\bar{\varepsilon}}$ may be ambiguous in sign not only across but even *within* calibrations, depending on the level of baseline storm risk at which it is evaluated. This demonstrates the theoretical ambiguity claim of Proposition 1.

1.3 Corollary 1

Proposition 1 establishes that an increase in cyclone risk can increase average growth. In order to prove Corollary 1, it is thus sufficient to demonstrate that the increase in cyclone risk in those cases results in a decline in welfare. Following the same approach as Krebs (2003b), one can re-write household lifetime utility (again omitting country j subscripts for legibility and focusing on the relevant case with $\gamma > 1$) as:

$$\begin{aligned} U_0 &\equiv E_0 \sum_{t=0}^{\infty} \beta^t \frac{c_t^{1-\gamma}}{1-\gamma} \qquad (18) \\ &= \frac{c_0^{1-\gamma}}{1-\gamma} + \beta \frac{E_0[\{c_0 g(\widetilde{k},\varepsilon)\}^{1-\gamma}]}{1-\gamma} + \beta^2 \frac{E_0[\{c_0 g(\widetilde{k},\varepsilon) g(\widetilde{k},\varepsilon)\}^{1-\gamma}]}{1-\gamma} \ldots \end{aligned}$$

where initial consumption $c_0 = (1-\widetilde{s})(1+r(\widetilde{k}_0, \varepsilon_0))w_0$ is pre-determined (since h_0, k_0, and ε_0 are given) except for the equilibrium savings rate $\widetilde{s}$, and $g(.)$ is the consumption growth factor $g_t \equiv \frac{c_t}{c_{t-1}} = (\widetilde{s})[1+r(\widetilde{k}, \varepsilon_t)]$. Given the assumption of independently distributed shocks and following Krebs (2003b) one can write (18) as:

$$E_0 \sum_{t=0}^{\infty} \beta^t \frac{c_t^{1-\gamma}}{1-\gamma} = \frac{c_0^{1-\gamma}}{(1-\gamma)(1-\beta E_0[g(\widetilde{k}, \varepsilon)^{1-\gamma}])} \tag{19}$$

For the simple setting studied in Proposition 1, (19) becomes:

$$U_0 = \frac{c_0^{1-\gamma}}{(1-\gamma)(1-\beta\left\{\phi g(\overline{\varepsilon})^{1-\gamma} + (1-\phi) g(0)^{1-\gamma}\right\})}$$

where $g(\varepsilon) = (\widetilde{s})\left[1 + \frac{A}{2} - \delta - \pi\phi\xi_1(\overline{\varepsilon})^{\xi_2} - (1-\pi)\xi_1(\varepsilon)^{\xi_2}\right]$. Differentiating U_0 with respect to $\overline{\varepsilon}$ then yields:

$$\begin{aligned} \frac{dU_0}{d\overline{\varepsilon}} &= \frac{(1-\widetilde{s})^{-\gamma}(-\frac{d\widetilde{s}}{d\overline{\varepsilon}})[(1+r(\widetilde{k}_0, \varepsilon_0))w_0]^{1-\gamma} + (1-\widetilde{s})^{1-\gamma}[(1+r(\widetilde{k}_0, \varepsilon_0))w_0]^{-\gamma} \cdot \left(-\pi\phi\xi_1\xi_2(\overline{\varepsilon})^{\xi_2-1}\right)}{(1-\beta\left\{\phi g(\overline{\varepsilon})^{1-\gamma} + (1-\phi) g(0)^{1-\gamma}\right\})} \\ &+ \frac{(-1)c_0^{1-\gamma}}{\left[(1-\gamma)(1-\beta\left\{\phi g(\overline{\varepsilon})^{1-\gamma} + (1-\phi) g(0)^{1-\gamma}\right\}\right]^2}[\Delta] \end{aligned} \tag{20}$$

where:

$$\begin{aligned} \Delta &= (1-\gamma)^2\beta\left[\phi g(\overline{\varepsilon})^{-\gamma}\frac{dg(\overline{\varepsilon})}{d\overline{\varepsilon}} + (1-\phi)g(0)^{-\gamma}\frac{dg(0)}{d\overline{\varepsilon}}\right] \\ \frac{dg(\overline{\varepsilon})}{d\overline{\varepsilon}} &= \frac{d\widetilde{s}}{d\overline{\varepsilon}}\left[1 + \frac{A}{2} - \delta - \pi\phi\xi_1(\overline{\varepsilon})^{\xi_2} - (1-\pi)\xi_1(\overline{\varepsilon})^{\xi_2}\right] + \widetilde{s}\left[-\pi\phi\xi_1\xi_2(\overline{\varepsilon})^{\xi_2-1} - (1-\pi)\xi_1\xi_2(\overline{\varepsilon})^{\xi_2-1}\right] \\ \frac{dg(0)}{d\overline{\varepsilon}} &= \frac{d\widetilde{s}}{d\overline{\varepsilon}}\left[1 + \frac{A}{2} - \delta - \pi\phi\xi_1(\overline{\varepsilon})^{\xi_2}\right] + \widetilde{s}\left[-\pi\phi\xi_1\xi_2(\overline{\varepsilon})^{\xi_2-1}\right] \end{aligned}$$

For the relevant case where $\gamma > 1$, we have already shown that $\frac{d\widetilde{s}}{d\overline{\varepsilon}} > 0$, so that the first part in (20) is unambiguously negative. If the parameters are such that $\frac{dg(\overline{\varepsilon})}{d\overline{\varepsilon}} > 0$ and $\frac{dg(0)}{d\overline{\varepsilon}} > 0$, this is sufficient to ensure that the second line in (20) is also negative as it then follows that $\Delta > 0$, and, consequently, that the welfare effects of cyclone risk increases are negative. Intuitively, $\frac{dg(\overline{\varepsilon})}{d\overline{\varepsilon}} > 0$ if the precautionary savings effect is sufficiently strong to dominate the direct depreciation effect even during cyclone events. However, the present focus on areas of the parameter space where *average* growth impacts are positive (i.e., $\frac{d\overline{g}}{d\overline{\varepsilon}} = \phi\frac{dg(\overline{\varepsilon})}{d\overline{\varepsilon}} + (1-\phi)\frac{dg(0)}{d\overline{\varepsilon}} > 0$) is not sufficient to guarantee that $\frac{dg(\overline{\varepsilon})}{d\overline{\varepsilon}} > 0$. While it is less analytically transparent in this case to show that $\frac{dU_0}{d\overline{\varepsilon}} < 0$, intuitively cyclone risk increases should always be welfare-decreasing as households could have chosen to save more and throw away more of their income (representing higher insurance premia) even in the absence of such risk increases, if this would make them better off. In order to formally demonstrate that such welfare declines can exist in the same settings giving rise to positive growth effects, we resort to a numerical evaluation of (19) at the same parameters as in Figure A1 ($\beta = 0.985$, $A = 1$, $\phi = 0.1$, $\delta = .1$, $\xi_1 = 0.5$, and $\xi_2 = 2$, evaluated variably for initial conditions $\varepsilon_0 = 0$ or $\varepsilon_0 = \overline{\varepsilon}$). Figure A2 shows that welfare declines with cyclone risk, even in the area of the parameter space where output growth increases.

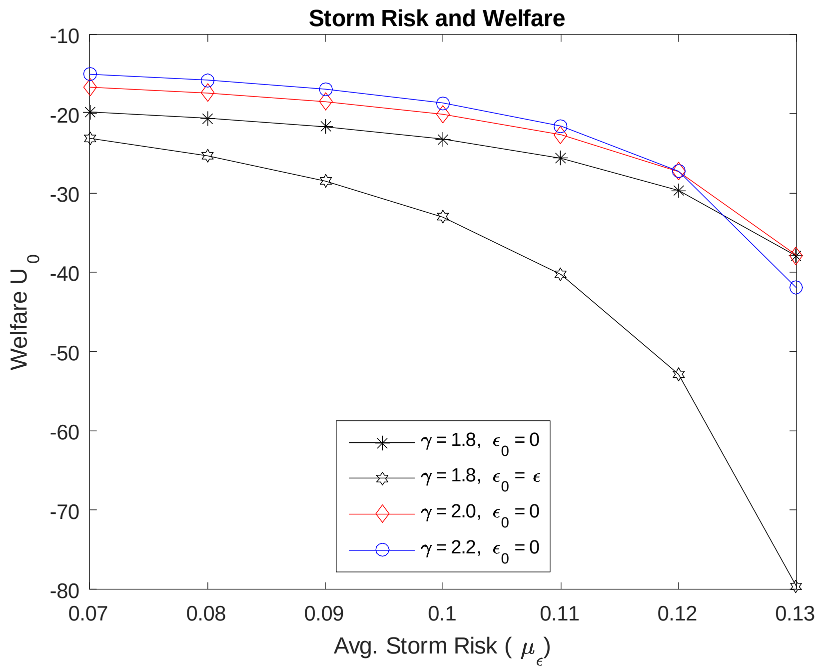

Figure A2

To summarize, we have shown that, in the same setup used in Proposition 1 to illustrate the possibility of a positive effect of cyclone risk on output growth, the effect of an increase in cyclone risk on welfare is negative. Consequently, we have shown that cyclone risk may affect output growth and welfare in opposite ways.

1.4 Proposition 2

The claims of Proposition 2 follow from (i) the equation for realized growth in stationary equilibrium (paper eqn. 9) with the definition of portfolio returns (paper eqn. 5) substituted in:

$$g_{j,t} = \frac{c_{j,t}}{c_{j,t-1}} = (\widetilde{s}_j)[1 + \omega_k(\widetilde{k}_j)\{R_j^k(\widetilde{k}) - \overline{\delta_j^k} - (1-\pi_j)\eta_j^k(\varepsilon_{j,t})\} + (1-\omega_k(\widetilde{k}_j))\{R_j^h(\widetilde{k}) - \overline{\delta_j^h} - (1-\pi_j)\eta^h(\varepsilon_{j,t})\}] \tag{21}$$

Claims (1)-(2) focus on the case where financial markets are incomplete ($\pi_j < 1$):

1) Cyclone realizations have a negative effect on contemporaneous growth ($\frac{dg_{j,t}}{d\varepsilon_{j,t}} < 0$*).*

This claim follows directly from differentiating (21):

$$\frac{dg_{j,t}}{d\varepsilon_{j,t}} = (\widetilde{s}_j)(1-\pi_j)(-1)\left[\omega_k(\widetilde{k}_j)\frac{\partial\eta_j^k}{\partial\varepsilon_{j,t}} + (1-\omega_k(\widetilde{k}_j))\frac{\partial\eta_j^h}{\partial\varepsilon_{j,t}}\right] < 0 \tag{22}$$

2) Cyclone realizations have a persistently negative effect on output levels in the sense that there is no compensating positive growth rebound after the storm ($\sum_{j=0}^{L} \frac{dg_{t+j}}{d\varepsilon_{j,t}} < 0$*).*

This statement follows from the AK-nature of the model. In particular, the contemporaneous growth rate (21) returns to baseline levels following the disaster realization, so that $\frac{dg_{j,t+l}}{d\varepsilon_{j,t}} = 0$ for $l > 0$. Adding up these terms with (22) thus yields the desired result that $\sum_{l=0}^{L} \frac{dg_{t+l}}{d\varepsilon_{j,t}} < 0$.

Finally, claim (3) pertains to the case where financial markets are complete ($\pi_j = 1$). In this case, all cyclone damages would insured (i.e., contained in $\overline{\delta_j^m}$, $m = k, h$) and $\varepsilon_{j,t}$ would vanish from equation (21). Consequently, cyclone realizations $\varepsilon_{j,t}$ would not affect growth realizations if $\pi_j = 1$, showing the desired result that $\frac{dg_{j,t}}{d\varepsilon_{j,t}}|_{\pi_j=1} = 0$.

2 Empirical Analysis: Details and Robustness

2.1 TFP Robustness

2.1.1 Varying Lag Lengths

Table A1 presents results for the benchmark TFP specification across varying cyclone impact lag lengths, along with Akaike/Bayesian Information Criteria (AIC/BIC).

Table A1: TFP Impacts at Varying Lag Lengths								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
MaxWind_t	-0.570**	-0.644**	-0.690**	-0.735**	-0.803*	-0.795*	-0.773*	-0.762
	(0.265)	(0.300)	(0.324)	(0.337)	(0.414)	(0.425)	(0.460)	(0.529)
MaxWind_{t-1}	-0.552***	-0.636***	-0.675***	-0.720***	-0.750**	-0.798**	-0.759*	-0.744
	(0.197)	(0.240)	(0.258)	(0.271)	(0.301)	(0.379)	(0.411)	(0.491)
MaxWind_{t-2}		-0.605*	-0.653*	-0.694*	-0.722*	-0.729*	-0.731	-0.697
		(0.314)	(0.343)	(0.355)	(0.386)	(0.416)	(0.497)	(0.568)
MaxWind_{t-3}			-0.759*	-0.800*	-0.812*	-0.823*	-0.806*	-0.876
			(0.400)	(0.410)	(0.421)	(0.440)	(0.470)	(0.626)
MaxWind_{t-4}				-0.695**	-0.727**	-0.719**	-0.699*	-0.688
				(0.280)	(0.312)	(0.331)	(0.374)	(0.453)
MaxWind_{t-5}					-0.617**	-0.628*	-0.588	-0.572
					(0.303)	(0.338)	(0.380)	(0.462)
MaxWind_{t-6}						-0.490*	-0.462	-0.432
						(0.286)	(0.343)	(0.434)
MaxWind_{t-7}							-0.329	-0.309
							(0.340)	(0.439)
MaxWind_{t-8}								-0.297
								(0.417)
Obs.	5,787	5,686	5,585	5,484	5,383	5,281	5,179	5,076
Adj. R^2	0.970	0.970	0.971	0.971	0.972	0.972	0.972	0.973
AIC	-8416	-8378	-8340	-8304	-8244	-8173	-8112	-8024
BIC(n=N)	-8122	-8079	-8029	-8013	-7921	-7871	-7824	-7737
BIC(n=#Clusters)	-8285	-8244	-8201	-8174	-8099	-8036	-7982	-7894

Table presents results of regression of natural log of countries' TFP $\ln(A_{j,t})$ on a constant, country fixed-effects, year fixed-effects, country-specific linear time trends, and cyclone intensity in max. wind speed/km^{2}for various lags. Standard errors are heteroskedasticity-robust and clustered at the country level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

The results are generally similar across lag lengths, but cease to be precisely estimated as more observations are excluded at higher lag lengths. The information criteria also imply that lower lag lengths are preferred.

2.1.2 HP-Filtering

Table A2 shows TFP results based on HP-filtering of each country's TFP series (using annual smoothing parameter $\lambda = 6.25$), and regressing the natural logarithm of the cyclical components, $\ln(\overline{TFP_{j,t}})$ on year fixed-effects and cyclone measures $\varepsilon_{j,t}$ (with robust errors $\epsilon_{j,t}$ clustered at the country-level).

$$\ln(\overline{TFP_{j,t}}) = \delta_t + \sum_{l=0}^{L} \beta^{A}_{1+l} \varepsilon_{j,t-l} + \epsilon_{j,t}$$

Table A2: HP-Filtered TFP Impacts

	(1)		(2)
Dep. Variable:	$\ln(\overline{TFP_{j,t}})$		$\ln(\overline{TFP_{j,t}})$
MaxWind_t	-1.276	Energy_t	-0.00818
	(5.223)		(0.00684)
MaxWind_{t-1}	-28.28***	Energy_{t-1}	-0.00762*
	(3.216)		(0.00389)
MaxWind_{t-2}	-108.8*	Energy_{t-2}	-0.00226
	(60.31)		(0.00201)
MaxWind_{t-3}	3.535	Energy_{t-3}	-0.00619
	(5.626)		(0.00727)
MaxWind_{t-4}	-1.838	Energy_{t-4}	-0.00184
	(2.642)		(0.00342)
MaxWind_{t-5}	-0.311	Energy_{t-5}	0.00138
	(1.759)		(0.00159)
MaxWind_{t-6}	-60.71	Energy_{t-6}	-0.00155
	(37.64)		(0.00269)
Obs.	2,678		2,678
Adj. R^2	0.0555		0.0557

Table presents regression of natural log of cyclical component of TFP (based on HP filtering with $\lambda = 6.25$) on a constant, year fixed-effects and cyclone intensity for either max. wind speed/km^2 (Col. 1) or energy/km^2 (sum of max. wind speeds cubed) (Col 2). Standard errors are heteroskedasticity-robust and clustered at the country level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

2.2 Cyclone Intensity Monte Carlo Simulation Details

First, we use the Emanuel et al.'s (2008) cyclone frequency data to estimate the projected mean number of storms making landfall in each country j under the future climate T_{2090}.[3] Next we assume a Poisson distribution of cyclone counts (Emanuel, 2013) to randomly sample the

[3] Specifically, we compute the relative increase in the number of landfalls in the synthetic track data between present and future conditions, and apply this increase (e.g., +5%) to each country's observed mean landfall count (1970-2015) in the actual historical data.

number of storms making landfall in each country j per year under the future climate (taking $n = 5,000$ draws from the Poisson($\#landfalls_j | T_{2090}$) distribution for each country j). Third, for each draw of a *number* of storms making landfall in country j, we then randomly sample storm characteristics (e.g., maximum wind speed) from one of the 3,000 synthetic tracks per basin[4] in the Emanuel data (with replacement). This process thus generates random draws over *annual* cyclone realizations $\varepsilon_{j,2090}$, including years without storms. This process captures changes in expected future intensity driven both by changes in the number and characteristics of storms. Finally, we then fit appropriate distributions for each cyclone variable in each country. The resulting parameter estimates for each country are listed below.

2.3 Country-Level Results: Expected Cyclone Impacts

Tables 1-4 below display country-level results for expected 2090-2100 annual damages to TFP, physical capital, and human capital (%/year), along with the estimated Weibull distribution parameters for each country's 2080-2100 annual maximum wind speed distribution (based on Emanuel et al.'s (2008) synthetic cyclone tracks for IPCC A1B scenario).

3 Calibration Details

3.1 DICE Damage Functions

This section describes the derivation of the climate change damage function coefficients in Table 4 based on the results of Table 3, which represent *total* expected cyclone depreciation. Holding socioeconomic factors constant, total future cyclone depreciation reflects a combination of baseline impacts and warming damages: $\delta^{Total}(T_\tau) = \bar{\delta}^{\text{Base}} + \delta^{\text{Additional}}(T_\tau)$. First, given the scientific literature's common finding of linearity in the global cyclone intensity-temperature relationship (see, e.g., Holland and Bruyere, 2014), we linearly interpolate from T_{2090} and specify $\delta^{\text{Additional}}(T_\tau) = \alpha T_\tau$.Table 3 provides pairs of 'observations' of total damages at current and future climates that we thus use to solve for slope parameters α via:

$$\alpha = \frac{\delta^{Total}(T_{2090}) - \delta^{Total}(T_{2015})}{(T_{2090} - T_{2015})} \tag{23}$$

The synthetic cyclone tracks from Emanuel et al. (2008) underlying our T_{2090} simulations reflect the IPCC's A1B emissions scenario, which different climate models estimate to result (on average) in $2.8°C$ warming over 1980-99 temperatures by 2100 (IPCC, 2007). Based on Hawkins et al.'s

[4] 5,000 tracks were used in the North Atlantic Ocean.

Table 1: Country-Level Expected Future Damages, Part I

	TFP	Physical Capital		Weibull Coefficients	
		$\widehat{\xi^k_{j,2015}}$	$\widehat{\xi^k_{j,2095}}$	Scale	Shape
Anguilla	3.70061		8.12E-07	62.39823	1.95567
Netherlands Antilles	0.27462			27.17427	1.70656
American Samoa	3.68957			70.25259	1.882526
Antigua and Barbuda	1.07257	0.000129	8.65E-07	61.74667	1.788226
Australia	0.00004	1.02E-05	3.28E-07	69.9772	3.699924
Bangladesh	0.00166	0.000407	4.93E-05	50.36693	3.188151
The Bahamas	0.02920	8.46E-05	6.73E-07	70.83424	2.275997
Belize	0.01320	0.000379	0.000018	67.84988	2.254345
Bermuda	19.30000	8.31E-06	4.84E-08	63.11744	2.076133
Barbados	1.09439	0.000523	4.56E-06	58.98309	1.375166
Brunei	0.02430	8.33E-11	9.66E-14	29.73408	165.8734
Cambodia	0.00116	0.000353	6.06E-05	47.38866	2.782336
Canada	0.00002	1.33E-05	4.29E-07	43.90576	4.104966
China	0.00004	5.46E-05	3.42E-06	80.92273	6.613148
Colombia	0.00008	6.01E-05	3.33E-06	19.80464	1.462793
Comoros	0.30800	0.048813	0.000302	77.45757	2.906959
Cape Verde	0.06934	0.000978	6.34E-06	32.56799	5.854458
Costa Rica	0.00240	0.000114	3.04E-06	27.16065	1.208993
Cuba	0.00346			84.40723	2.502704
Dominica	0.50189	0.000887	0.000011	47.39346	1.511694
Dominican Republic	0.00717	0.000153	3.39E-06	76.6973	2.449758
Fiji	0.01420	0.000377	3.33E-06	57.3049	1.969591
F.S. Micronesia	1.50483			51.17152	1.315246
United Kingdom	0.00061	2.31E-05	6.03E-07	30.94393	8.530496
Guadeloupe	0.22400			56.07433	1.567775
Grenada		0.000625	6.02E-06	32.13932	1.74645
Greenland	0.00007			31.60629	10.46832
Guatemala	0.00231	0.000226	2.32E-05	57.32832	2.566435
Guam	0.84800			62.04909	1.495241
Honduras	0.00180	0.000293	6.45E-05	46.12234	1.870335
Haiti	0.00976	0.002637	0.000259	61.80358	2.254183
Indonesia	0.00010	6.53E-05	1.47E-06	41.84531	1.442086
Isle of Man	0.48700			29.40475	14.39998
India	0.00010	0.000074		71.58994	3.252822
Ireland	0.00221	7.78E-06	2.02E-07	31.49372	10.15739
Jamaica	0.02260	0.000493	2.18E-05	55.68285	1.610694
Japan	0.00086	2.38E-05	7.72E-07	69.43372	4.916136
Malaysia	0.00098	0.00007	1.35E-07	73.23889	2.410471
Martinique	0.36669			63.59187	1.493702
Mauritius	0.17829	0.000144	2.51E-07	57.10426	2.084171
Mayotte	1.20088			72.92911	2.276155

Table 2: Country-Level Expected Future Damages, Part II

	TFP	Physical Capital		Weibull Coefficients	
		$\widehat{\xi^k_{j,2015}}$	$\widehat{\xi^k_{j,2095}}$	Scale	Shape
Madagascar	0.00065	0.000419	0.0001	86.05257	3.391796
Mexico	0.00024	7.31E-05	1.87E-06	103.1179	5.789748
Montserrat	3.43000		9.41E-07	59.4275	1.702788
Morocco	0.00042	0.000117	3.49E-06	36.28765	9.171823
Mozambique	0.00043	0.000341	0.000104	76.76399	2.581144
Myanmar	0.00033	0.000132	1.42E-05	48.53157	3.236179
N. Mariana Islands	3.18783			52.52581	1.63415
New Caledonia	0.01192			48.19364	2.840558
New Zealand	0.00068	0.000029	9.25E-07	39.02092	6.137892
Nicaragua	0.00192	0.000302	6.47E-05	56.19756	1.806228
Niue	1.57794			64.06889	2.668067
North Korea	0.00136			36.08171	6.288256
Oman	0.00078	1.96E-05	2.10E-07	54.44291	2.925709
Pakistan	0.00024	0.000113	1.44E-05	47.38592	3.028682
Philippines	0.00178	0.000214	4.90E-06	108.2431	6.122329
Palau	0.79432			41.29496	1.681971
Papua New Guinea	0.00059			61.22783	1.986449
Puerto Rico	0.02990			61.44781	1.863509
Portugal	0.00196	6.56E-05	2.09E-06	39.45657	3.486135
Reunion	0.12300			61.86412	2.573926
Russia	0.00001	5.63E-05	1.20E-06	39.30797	4.519351
Samoa	0.10633			48.36356	1.689022
Saudi Arabia	0.00008	8.39E-06	9.08E-08	30.94611	10.31276
Solomon Islands	0.01240			58.20658	1.327752
Somalia	0.00044			63.08085	2.622298
South Korea	0.00228	2.76E-05	8.78E-07	47.61918	4.480676
Sri Lanka	0.00267	0.00015	1.18E-06	38.89352	1.787039
St. Kitts & Nevis	1.70099	0.00014	9.14E-07	63.17972	1.785639
St. Lucia	0.80530	0.000783	7.95E-06	57.82529	1.58214
St. Pierre & Miquelon	0.54131			33.62694	5.488935
St. Vincent & Grenadines	1.06249	0.0011	1.11E-05	54.46851	1.283157
Turks and Caicos	1.57200	0.001701	1.53E-05	57.86029	1.733655
Thailand	0.00065	8.74E-05	4.55E-07	76.16127	2.255309
East Timor	0.01138			39.67458	2.925687
Tonga	0.95183			54.87697	2.723092
Trinidad and Tobago	0.02910	3.97E-05	2.37E-07	28.78744	1.608998
Tanzania	0.00033	0.000182	6.57E-05	69.84156	3.18917
USA	0.00006	0.000526	0.000526	122.5129	5.960866
Venezuela	0.00012	6.25E-05	1.36E-06	23.78803	1.421359
British Virgin Islands	6.56492	0.000067	3.92E-07	59.44067	1.909729
U.S. Virgin Islands	1.54233			61.84608	1.802403
Vietnam	0.00129	0.000227	9.63E-06	91.48033	4.488925
Vanuatu	0.02965			56.72905	2.485984
Wallis & Futuna	5.35447			66.98585	2.234975
Yemen	0.00049	0.000177	0.000076	50.1893	3.154574

Table 3: Country-Level Results, Part III
Expected Fatalities (Fraction of Pop.)

	$\widehat{\xi^h_{j,2015}}$	$\widehat{\xi^h_{j,2095}}$
Anguilla		6.96E-07
Antigua and Barbuda	1.51E-05	5.56E-07
Australia	7.76E-08	6.04E-08
Bangladesh	2.99E-06	4.41E-07
The Bahamas	2.24E-06	2.33E-07
Belize	5.65E-06	7.29E-07
Bermuda	6.39E-06	1.03E-07
Barbados	4.36E-05	1.58E-06
Brunei	1.33E-11	4.12E-13
Cambodia	2.39E-06	4.03E-07
Canada	6.12E-08	5.45E-08
China	1.04E-07	7.16E-08
Colombia	1.44E-07	8.24E-08
Comoros	0.000832	1.71E-05
Cape Verde	2.32E-05	8.47E-07
Costa Rica	9.89E-07	2.11E-07
Dominica	4.73E-05	2.13E-06
Dominican Republic	2.04E-06	3.17E-07
Fiji	5.78E-06	3.80E-07
United Kingdom	2.45E-07	1.07E-07
Grenada	0.000044	1.75E-06
Guatemala	1.90E-06	4.05E-07
Honduras	2.26E-06	5.12E-07
Haiti	2.63E-05	3.64E-06
Indonesia	1.87E-07	8.09E-08
India	2.44E-07	
Ireland	2.97E-07	9.95E-08
Jamaica	8.63E-06	9.50E-07
Japan	2.81E-07	1.21E-07
Morocco	5.66E-07	1.43E-07
Madagascar	2.57E-06	5.44E-07
Mexico	2.66E-07	1.09E-07
Myanmar	6.24E-07	1.71E-07
Mozambique	2.02E-06	4.95E-07
Montserrat		7.55E-07
Mauritius	7.55E-06	1.97E-07
Malaysia	4.34E-07	7.98E-08

Table 4: Country-Level Results, Part IV
Expected Fatalities (Fraction of Pop.)

	$\widehat{\xi^h_{j,2015}}$	$\widehat{\xi^h_{j,2095}}$
Nicaragua	2.37E-06	5.28E-07
New Zealand	2.68E-07	1.20E-07
Oman	2.56E-07	8.67E-08
Pakistan	4.93E-07	1.52E-07
Philippines	1.65E-06	2.39E-07
Portugal	5.53E-07	1.91E-07
Russia	4.80E-08	4.85E-08
Saudi Arabia	9.55E-08	5.85E-08
Saint Kitts and Nevis	1.98E-05	6.37E-07
South Korea	4.33E-07	1.54E-07
Saint Lucia	5.23E-05	2.07E-06
Sri Lanka	1.35E-06	1.69E-07
Turks and Caicos Islands	0.000124	4.03E-06
Thailand	4.67E-07	1.00E-07
Trinidad and Tobago	1.38E-06	1.46E-07
Tanzania	9.37E-07	2.57E-07
United States of America	8.74E-08	6.51E-08
Saint Vincent and the Grenadines	7.57E-05	2.75E-06
Venezuela	1.61E-07	8.26E-08
British Virgin Islands	2.08E-05	4.57E-07
Vietnam	1.58E-06	2.58E-07
Yemen	9.56E-07	3.60E-07

(2017) estimates that warming between 1986-2005 and 2015 was $0.45°$ to $0.2°C$, we thus have $T_{2090} - T_{2015} \approx 2.35°C$.

Given that global temperatures in 2015 were already around $1°C$ above pre-industrial levels, one additional question is whether to treat current cyclone patterns as already having been affected by this warming. A recent review by GFDL "conclude[s] that despite statistical correlations between SST [sea-surface temperatures] and Atlantic hurricane activity in recent decades, it is premature to conclude that human activity – and particularly greenhouse warming – has already caused a detectable change in Atlantic hurricane activity" (GFDL, 2018). In particular, they argue that, while a trend can be observed in recent years, over a longer time horizon back to the 1880s, one fails to detect a significant trend in cyclones (concurrent with the observed trend in warming) once observational biases are adjusted. In this case, the damage function would apply only to warming over the DICE model base year (2015), so that $\delta^{\text{Additional}}(T_t) = \alpha(T_t - T_{2015})$ (for $T_t > T_{2015}$). On the other hand, if anthropogenic warming has already been affecting cyclone patterns, the damage function is defined over warming since pre-industrial level as for other damages in DICE. Since both our overall global impact estimates and the difference between these scenarios are already small, we focus on the latter case where $\delta^{\text{Additional}}(T_t) = \alpha(T_t)$.

We thus back out annual impact coefficients via (23). For example, the benchmark TFP impact coefficient is calculated via:

$$\widehat{\alpha_A} = \frac{(.001048) - (.000355)}{2.35} = .000295$$

The remaining parameters in Table 4 are computed analogously.

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