Supporting Information

Hsiang 10.1073/pnas.1009510107

SI Appendix

In the main article, it was shown that variations in surface temperature and cyclone energy significantly impacted production in several industries in the Caribbean and Central America. This *SI Appendix* contains additional tables cited in the main text, as well as details on data and statistical methods.

Note that for reading regression tables, each column displays coefficients (and SEs in brackets) from a single, multivariate regression unless otherwise specified. The atmospheric variable corresponding to each coefficient is listed in the leftmost column.

S1. Data. Table S1 contains summary statistics for the primary variables used in the analysis.

Countries. Included in this study are Anguilla, Aruba, the Bahamas, Barbados, Belize, the British Virgin Islands, the Cayman Islands, Costa Rica, Cuba, Dominica, Dominican Republic, Antigua and Barbuda, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, the Netherlands Antilles, St. Lucia, Montserrat, Nicaragua, Panama, Puerto Rico, St. Kitts and Nevis, St. Vincent and the Grenadines, Trinidad and Tobago, and the Turks and Caicos Islands. Note that not all countries are independent states for all or any of the years in the sample.

Temperature. Observations are extracted from gridded reanalysis estimates from the NOAA NCEP-NCAR Climate Data Assimilation System I (1). Temperature is spatially averaged over each country.

Rainfall. Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) estimates of rainfall are preferred because they merge available gauge readings with satellite data. When CMAP observations are unavailable, they are replaced by CPC's Climate Anomaly Monitoring System (CAMS) observations that interpolate gauge readings only. When combined, rainfall estimates are available for the period 1950–2007. Like temperature, spatial averages are used.

Cyclones. Storm trajectories and intensities are taken from the HURDAT Best Track database (2), with the wind field of each storm numerically reconstructed to estimate the "storm experience" of individuals on the ground. This reconstruction is implemented with the Limited Information Cyclone Reconstruction and Integration for Climate and Economics (LICRICE) model, which uses statistical relationships about key parameters to rebuild storm structures using information collected before the satellite era.

The radius of maximum wind is predicted using a linear function of latitude and maximum wind speed (3), even when satellite data are available for statistical consistency. The field of absolute surface wind speed is estimated by combining azimuthal winds and the translational velocity of the storm. An example wind-speed function is pictured in Fig. 1*A*.

Holding constant surface wind speed and drag (and thus the working rate), cyclone energy dissipation at a fixed location will increase when a storm remains over that location longer. For this reason, power dissipation must be multiplied by the length of time a storm spends at a location, which is inversely proportional to the storm's translational speed. The translational speed of a storm's center is calculated for each 6-h interval of the Best Track record and then smoothed once with a 1-2-1 filter to prevent large jumps in storm velocity. Fig. S1 plots an example field of total estimated energy dissipation for all points in the region during 2004.

All else equal, larger countries have more total energy dissipated over them, so energy dissipation is normalized by a country's area. Thus, the measure of energy dissipation is an energy dissipation *density* that describes the expected quantity of energy dissipated over a square kilometer conditional only on the year and the country containing that square.

The cyclone energy density C is an annual estimate, so it is summed over all storms affecting country i in year t,

$$C_{it} = \frac{\kappa}{A_i} \sum_{z \in i} \sum_{s \in t} \frac{V_s^{wind}(z)^3}{V_s^{storm}},$$

where V^{storm}_s is the translational velocity of the center of a storm indexed by s, $V^{wind}_s(z)$ is the velocity of wind at grid cell z, A_i is the area of country i, and κ is a constant capturing drag and the density of air. This measure is analogous to a density of *accumulated cyclone energy* (ACE), a commonly used alternative measure (4).

Economic output. National statistical agencies, government ministries, central banks, and other international institutions provide national accounts data to the United Nations where they are standardized into estimates of annually averaged production for 28 countries from 1970 to 2007 (5). Details on the methodology for data estimation can be found at data.un.org.

Tourism. *Tourism receipts* are the income earned by destination countries from visitors' consumption across multiple industries (lodging, transport, food, etc.) (6). It excludes income related to international transport contracted by residents of other countries. The data are maintained by the Secretariat of the United Nations World Tourism Organization (UNWTO); details are at unwto.org. Tourism data are available for 25 countries for the shorter period 1995–2006.

S2. Methods. The objective of this study is to empirically determine if the production of value in individual industries has any statistical dependence on interannual variations in the state of the local atmosphere. Previous work used a cross-sectional approach where patterns in production are correlated with the *average* state of the local atmosphere (7–9). A critique of this approach is that the average state of the atmosphere (a fixed parameter) may be correlated with other fixed parameters (for example, altitude) that may themselves directly affect patterns of production (9). This is the *omitted-variables problem*: Without describing all fixed variables affecting an outcome, statistical inference on any single fixed variable may be biased (10). Because it is impossible to characterize this full set of fixed variables, this study removes all fixed differences between countries and only examines correlations with dynamic variations. The average atmospheric states of any two countries are never compared here. Instead, the influence of the atmosphere on production is identified by looking at the response of production to perturbations in the atmospheric state around its mean value. This should only compare a country to itself at different points in time when it is experiencing a different atmospheric state. Whereas each country may respond slightly differently to atmospheric variations, a collection of countries is analyzed as if they responded identically to increase statistical power, producing a single estimate (β) for the "average effect" of atmospheric conditions on production within that collection. If the effects differ dramatically between countries, this average effect will not describe the true structure of the relation well. For this reason, analysis is restricted to a small region where atmospheric variations and productive processes share reasonable commonalities.

For industry j, let production of value be some function

$$V_{it}^j = f^j(V_{i,t-1}^j, t, X_i, C_{it}, R_{it}, T_{it}) + \varepsilon_{it}^j, \quad \textbf{[S1]}$$

where $\mathbf{V}_{i,t-1}{}^j$ is a vector of historical production; $\mathbf{X_i}$ is some vector of fixed country-specific traits; and $\mathbf{C_{it}}$, $\mathbf{R_{it}}$, and $\mathbf{T_{it}}$ are vectors of historical incidence of cyclones, rainfall, and surface temperature, respectively. Atmospheric variations that impact production at time t may include events from the recent past. Time t enters $f^j(\ldots)$ directly for three reasons: (*i*) there may be trends in productive output due to technological innovations that occur gradually over time, (*ii*) production in a given industry may be expanding over time due to economic growth, or (*iii*) specific years may be "abnormal" for reasons unrelated to atmospheric processes, such as large variations in world commodity prices. ε describes variations in output not explained by the data.

Eq. **S1** can be approximated by a Taylor-series expansion in which nonlinear terms are dropped (except a t^2 term, which is kept). The following linear approximation for f^j is estimated,

$$V_{it}^j \approx \rho_1^j \times V_{i,t-1}^j + \rho_2^j \times V_{i,t-2}^j + \gamma_i^j \times t + \delta_i^j \times t^2 + \eta_t^j + \mu_i^j + \sum_{L=0}^{\tau}\left[\beta_C^{jL} \times C_{i,\,t-L} + \beta_R^{jL} \times R_{i,\,t-L} + \beta_T^{jL} \times T_{i,\,t-L}\right] + \varepsilon_{it}^j \quad \textbf{[S2]}$$

by applying ordinary least squares to the data. The variables of interest are the parameters denoted by β, the derivatives of production with respect to atmospheric fluctuations. The terms lagged by L measure the impact of events from previous years, up to some maximum lag τ. If τ is larger than the actual number of historical years that affect production at t, the estimates for β will be consistent (10) ($\tau = 5$ for all industries in all estimates unless otherwise noted). Each industry in each country is assumed to have a mean output that varies smoothly in time. This variation is thought to be different for each country, as different economies will expand in different industries at different rates: γ_i and δ_i describe these changes over time. If a certain year has unusual properties that affect all of the countries in the sample (for example, world oil prices are high), then this variation will be captured in the estimate of η_t. This term is an additive constant that is common to all countries in the data, but only added for a single year. μ_i is a constant term that is unique to each country. This term is critical because countries will have different baseline levels of production in different industries for reasons unrelated to variations in atmospheric processes. This term captures all static differences between production levels in countries described earlier as dependent on $\mathbf{X}_i$. The autocorrelation coefficients ρ_{1-2} describe the extent to which output in year t (relative to the trends described by γ_i and δ_i) is correlated with the previous year's output, holding all environmental variables fixed. Because the sum $\rho_1 + \rho_2$ is large (but always less than unity), controlling for these lagged dependent variables is essential to avoiding spuriously large estimates of β. However, because ρ_{1-2} may be underestimated by Eq. **S2**, a model in "first differences" that constrains $\rho_1 = 1$ (it assumes V has a unit root) is also estimated as a robustness check (see below).

The model in Eq. **S2** is equivalent to writing the model in terms of detrended "anomalies" of economic and weather variables (as is often done in the climate sciences). The two models produce identical estimates for the β's (11).

The omitted variables problem also applies to dynamic variables, such as temperature anomalies. If the dynamic variation of two variables is correlated and both affect production, the exclusion of one from Eq. **S2** will produce biased estimates of β for the other (10). Previous literature established correlations between cyclogenesis, cyclone intensity, surface temperatures, and rainfall (12–14). Of particular concern is the contamination of the estimated impact of surface temperature by tropical cyclones. "Potential intensity theory" (15, 16) predicts that the maximum attainable intensity of cyclones will be determined by local sea surface temperatures (holding other atmospheric variables fixed). Empirically, variations in the number and intensity of extremely intense hurricanes are well predicted by local sea surface temperatures (17, 18). If intense hurricanes dominate the magnitude of economic responses, as suggested by Nordhaus (2006) for capital damages in the United States (19), then a small number of cyclones may seriously contaminate the estimated response of industries to surface temperatures. This bias may occur even if the correlation between surface temperatures and cyclones is weak, should the response to cyclones be nonlinear and the response to surface temperatures be small.

Table S9 displays the correlation coefficients (ρ) between anomalies C', T', and P'. When integrated over countries, cyclone energy dissipation is only weakly positively correlated with surface temperature ($\rho = 0.08$) and weakly negatively correlated with rainfall ($\rho = -0.04$). Temperature and rainfall are weakly negatively correlated ($\rho = -0.14$). Table S10 demonstrates that when the effects of temperature or cyclones are estimated alone, they do not differ substantially from their values when they are estimated simultaneously. Thus, it appears that in the region studied, regressions on temperature without controlling for rainfall and cyclones would have revealed similar estimates. However, such a study would have left the interpretation of these coefficients ambiguous. It would be unclear whether the included variable was directly affecting production or appeared to affect production because an excluded variable actually affected production. Using the approach of this study, it is possible to attribute the estimated impact of surface temperatures to direct impacts of local thermal energy (enthalpy) and not to the secondary process associated with surface heating: intense tropical cyclones. In the Caribbean Basin, cyclones are likely the most economically significant form of correlated environmental variation. However, different regions around the world exhibit a variety of environmental variations that are correlated with surface heating and that have plausible economic significance. The environmental variables included in this study are limited to measures of major processes in the local atmosphere and may not be comprehensive insofar as environmental variation in the region is concerned (e.g., earthquakes).

Table S9 also displays correlations between variables in year t and the previous year $t-1$. Following quadratic detrending, C' ($\rho = 0.10$), T' ($\rho = 0.55$), and R' ($\rho = 0.49$) still all exhibit serial correlation. As production is also autocorrelated, there is potential for spurious correlations between weather variations and economic output. Thus, an important check on the main results is to estimate the effect of weather changes on *changes in output*, rather than output itself. If output is an integrated process of order one, differencing output between periods will produce a stationary time series that should not lead to spurious correlations. As mentioned in the main text, results from the model

$$V_{it}^j - V_{i,t-1}^j = \eta_t^j + \mu_i^j + \sum_{L=0}^{\tau}\left[\beta_C^{jL} \times C_{i,t-L} + \beta_R^{jL} \times R_{i,t-L} + \beta_T^{jL} \times T_{i,t-L}\right] + \varepsilon_{it}^j \quad \textbf{[S3]}$$

are estimated and listed in Table S4 and Table S5 in the columns marked "Δ_{t-1}." The values for β estimated by this model remain highly significant for the relationships highlighted in the main text. In fact, the coefficients estimated for Eq. **S3** are actually larger than those estimated for Eq. **S2** for *total production*, *wholesale*, *retail*, *restaurants and hotels*, and *other services*.

Eqs. **S2** and **S3** relate annually averaged temperature to production. In the main text, Eq. **S2** is modified to decompose the seasonal contributions ($L = 0$ only) to this annual average,

$$V_{it}^{j} = \beta_T^{j,DJF} \times T_{it}^{DJF} + \beta_T^{j,MAM} \times T_{it}^{MAM} + \beta_T^{j,JJA} \times T_{it}^{JJA} + \beta_T^{j,SON} \times T_{it}^{SON} + g(\mathbf{V}_{i,t-1}^{j}, t, \mathbf{C}_{it}, \mathbf{T}_{it}, \mathbf{R}_{it}), \quad \textbf{[S4]}$$

where $g(\ldots)$ contains all of the terms ($\tau = 1$) of Eq. **S2** except the $L = 0$ term for temperature. The superscripts indicate the average surface temperature over 3 mo: December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON). Table 2 in the main text presents these seasonal coefficients for all industries.

To test whether average or extreme temperatures are driving reductions in productivity, the relative impact of extremely warm days is compared with the impact of "normal" days. If high temperatures affect productivity more than average temperatures, then incremental changes in temperature will affect production more at higher temperatures than the same incremental changes in temperature at average temperatures. This will produce nonlinearities in the response of productivity to surface temperature, with the response function becoming steeper at high temperatures if they have larger impacts on production. To detect such nonlinearity, it may be insufficient to examine only the impact of annually or seasonally averaged surface temperatures. To estimate the structure of nonlinear production responses to temperature, the response to daily average temperature is estimated.

To construct such an estimate, let $\tilde{P}(T_d)$ be a continuous function describing production as a function of temperature T on day d,

$$\tilde{P}(T_d) = \tilde{P}(T_0) + \int_{T_0}^{T_d} \frac{\partial \tilde{P}}{\partial T}\, dT,$$

which is approximated by a piecewise linear function $\bar{P}$,

$$\bar{P}(T_d) = \bar{P}(T_0) + \sum_{k=1}^{N} \beta_k D_k(T_d), \quad \textbf{[S5]}$$

where β_k is the slope of the kth linear segment, and

$$D_k(T_d) = \int_{\underline{x}_k}^{\bar{x}_k} \mathbf{1}[T_d \le x]dx,$$

where $\mathbf{1}[\ldots]$ is equal to one if the statement in the brackets is true and zero otherwise. Here, $\underline{x}_k$ is the lower-valued limit of the kth segment and $\bar{x}_k$ is the higher-valued limit of that segment.

If $\tilde{P}$ is *assumed* to be a function that is independent of the day of the year, then $\bar{P}$ can still be recovered if daily temperature observations and *only* annual production observations are available. (Schlenker and Roberts test this assumption and the assumption of piecewise linearity, and they find them both to be reasonable for primary crops in the United States) (20). Under these assumptions, annual production P_t in year t is then

$$P_t = \sum_{d\in t} \bar{P}(T_d) = \sum_{d\in t}\left[\bar{P}(T_0) + \sum_{k=1}^{N} \beta_k D_k(T_d)\right] = P_0 + \sum_{k=1}^{N} \beta_k \cdot \left[\sum_{d\in t} D_k(T_t)\right]$$

by substitution of Eq. **S5** and interchanging the order of summation. The bracketed term $[\sum_{d\in t} D_k(T_t)]$ is constructed for each year using daily temperature observations for each of the N segments. This term is in units of "degree days," as it is referred to in the literature (20).

Fig. 5*A* in the main text is constructed by estimating such an equation for $n = 3$ segments with boundaries at 27 and 29 °C. The following equation is estimated with ordinary least squares,

$$V_{it}^{j} = \beta_1^{j}\left[\sum_{d\in t} D_1(T_d)\right] + \beta_2^{j}\left[\sum_{d\in t} D_2(T_d)\right] + \beta_3^{j}\left[\sum_{d\in t} D_3(T_d)\right] + g(\mathbf{V}_{i,t-1}^{j}, t, \mathbf{C}_{it}, \mathbf{T}_{it}, \mathbf{R}_{it}),$$

where $g(\ldots)$ is the same as in Eq. **S4**. Here, the subscript d denotes daily observations and t yearly observations. The estimated coefficients β_1^{j} – β_3^{j} are the slopes of the segments in Fig. 5*A* (main text) and are tabulated with their SEs in Table S6.

S3. Weather Impact Reductions with Higher Income. In the discussion of the main article, it was noted that as countries become wealthier, they may become better able to cope with environmental changes (21–23). Within this sample of countries, the response to temperature changes and cyclones can be modeled as linear functions of income. This is implemented by "interacting" income and temperature or income and cyclone exposure in the statistical model. For this procedure, a new variable is constructed by multiplying temperature by income, so that the effect of temperature becomes a linear function of income ($\tilde{\beta} + \tilde{\zeta} \times \text{income}$). However, because income in any year is also affected by temperature in that year, income levels observed 3 y earlier are used in constructing the "interaction variable." The new model for temperature impacts becomes

$$V_{it}^{j} = \tilde{\beta}_T^{j,SON} \times T_{it}^{SON} + \tilde{\zeta}_T^{j,SON} \times \left[T_{it}^{SON} \times income_{i,t-3}\right] + \omega \times income_{i,t-3} + g(\mathbf{V}_{i,t-1}^{j}, t, \mathbf{C}_{it}, \mathbf{R}_{it}, \mathbf{T}_{it}). \quad \textbf{[S6]}$$

If increases in income make countries more susceptible to temperature impacts, than the estimated values for $\tilde{\zeta}$ should be negative; and if increases in income make countries more resilient to temperature changes, then $\tilde{\zeta}$ should be positive. Table S7 presents the estimated values of $\tilde{\beta}$ and $\tilde{\zeta}$ for SON temperature using models analogous to Eqs. **S2** and **S3**. The structure across these estimates is not entirely consistent. However, for temperature-sensitive industries other than *transport and communications* it appears that increases in income generally increase resilience to high temperatures. The disagreement in coefficients and significance levels for the two statistical models suggests the need for additional analysis to determine what models are appropriate for modeling adaptation. Table S8 presents analogous results for tropical cyclones. Again, these results are suggestive that higher income countries experience smaller losses to cyclones (in percentage of current income); however, they are not entirely compelling. One concern is that those sectors with significant, positive-valued interaction terms are not those sectors identified in the main text as most vulnerable to cyclones. A related concern is that several industries that are vulnerable to cyclones do not exhibit significant interaction terms. Thus, it is only with strong caution that these results can be taken as suggestive evidence that increases in income generally reduce productive vulnerability to weather shocks. Future work will focus on understanding this relationship better.

1. Kalnay E, et al. (1996) The NCEP/NCAR 40-year reanalysis project. *Bull Am Meteorol Soc* 77:437–471.
2. McAdie, et al. (2009) *Tropical Cyclones of the North Atlantic Ocean, 1851–2006* (National Climatic Data Center, Asheville, NC). Available at http://www1.ncdc.noaa.gov/pub/data/hcs/HCS6-2_web.pdf. Accessed January 15, 2010.
3. Kossin J, et al. (2007) Estimating hurricane wind structure in the absence of aircraft reconnaissance. *Weather Forecast* 22:89–101.
4. Bell GD, et al. (2000) Climate assessment for 1999. *Bull Am Meteorol Soc* 81:1328.
5. National Accounts Statistics (2007) *Main Aggregates and Detailed Tables, 2007* (United Nations, New York).
6. United Nations World Tourism Organization (2008) *International Recommendations for Tourism Statistics* (United Nations, New York).
7. Nordhaus WD (2006) Geography and macroeconomics: New data and new findings. *Proc Natl Acad Sci USA* 103:3510–3517.
8. Dell M, Jones BF, Olken BA (2009) Temperature and income: Reconciling new cross-sectional and panel estimates. *Am Econ Rev Pap Proc* 99:198–204.
9. Tol RSJ (2009) The economic effects of climate change. *J Econ Perspect* 23:29–51.
10. Greene WH (2003) *Econometric Analysis* (Prentice Hall, Englewood Cliffs, NJ), 5th Ed.

11. Frisch R, Waugh FV (1933) Partial time regressions as compared with individual trends. *Econometrica* 1:387–401.
12. Mann ME, Emanuel KA (2006) Atlantic hurricane trends linked to climate change. *Eos* 87:233.
13. Camargo SJ, Sobel AH, Barnston AG, Emanuel KA (2007) Tropical cyclone genesis potential index in climate models. *Tellus* 59A:428–443.
14. Rosenzweig C, Hillel D (2008) *Climate Variability and the Global Harvest: Impacts of El Niño and Other Oscillations on Agro-Ecosystems* (Oxford Univ Press, London).
15. Bister JC, Emanuel KA (1998) Dissipative heating and hurricane intensity. *Meteorol Atmos Phys* 65:233–240.
16. Emanuel KA (1991) The theory of hurricanes. *Annu Rev Fluid Mech* 23:179–196.
17. Emanuel KA (1999) Thermodynamic control of hurricane intensity. *Nature* 41:665–669.
18. Elsner JB, Kossin JP, Jagger TH (2008) The increasing intensity of the strongest tropical cyclones. *Nature* 455:92–95.
19. Nordhaus WD (2006) *The Economics of Hurricanes in the United States. NBER Working Paper 12813* (National Bureau of Economic Research, Cambridge, MA).
20. Schlenker W, Roberts MJ (2009) Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proc Natl Acad Sci USA* 106: 15594–15598.
21. Parry M, Canziani O, Palutikof J, van der Linden P, Hanson C, eds (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK).
22. Stern N, et al. (2006) *Stern Review: The Economics of Climate Change* (Cambridge Univ Press, Cambridge, UK).
23. Dell M, Jones BF, Olken BA (2008) *Climate Change and Economic Growth: Evidence from the Last Half Century. NBER Working Papers 14132* (National Bureau of Economic Research, Cambridge, MA).

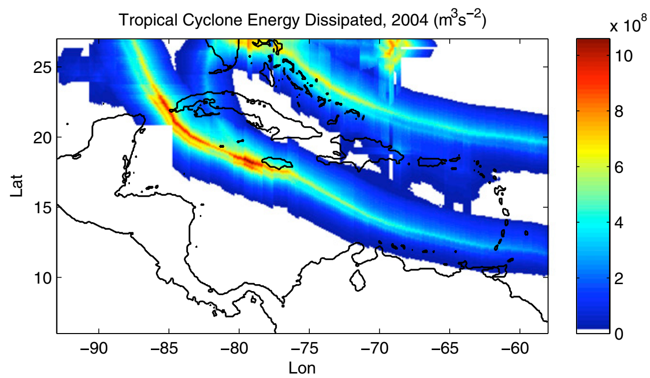

Fig. S1. An example of the computed energy dissipated by tropical cyclones for a single year (2004) using the Limited Information Cyclone Reconstruction and Integration for Climate and Economics (LICRICE) model.

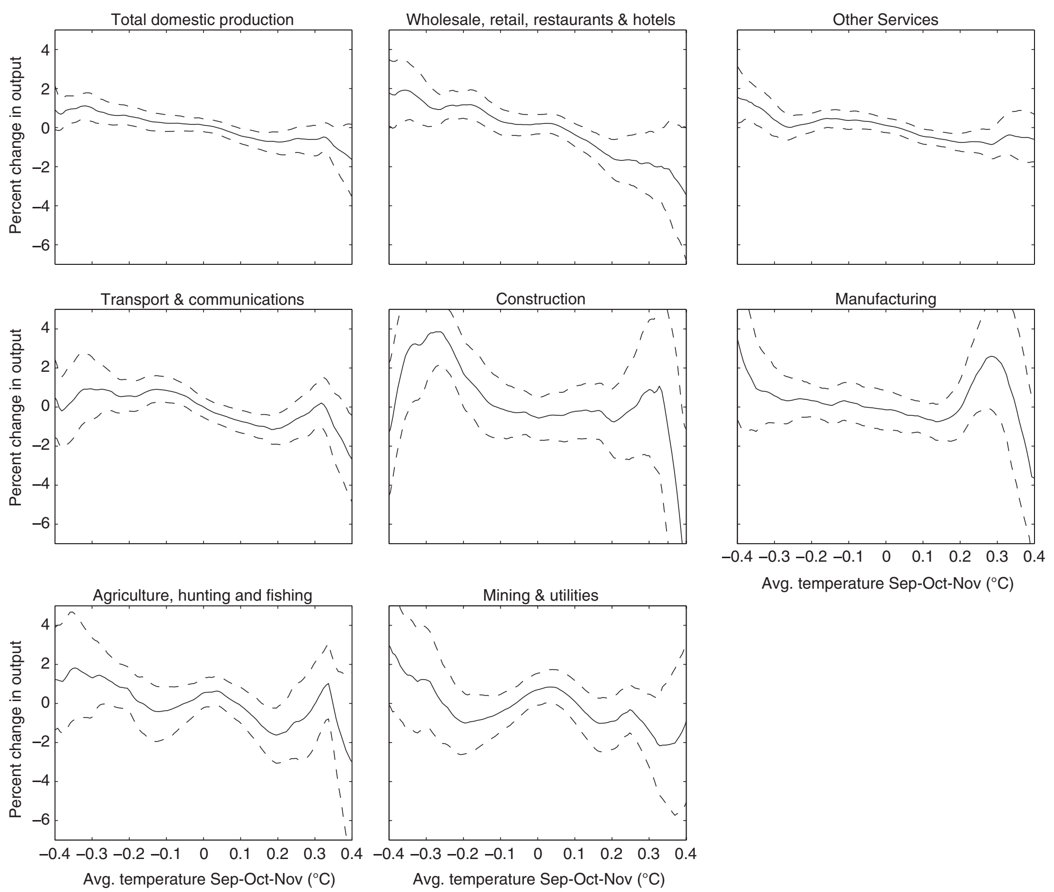

Fig. S2. Same as Fig. 4*A* in the main text, but for all industries. Dashed lines are bootstrapped 90% confidence intervals using 10,000 resamples.

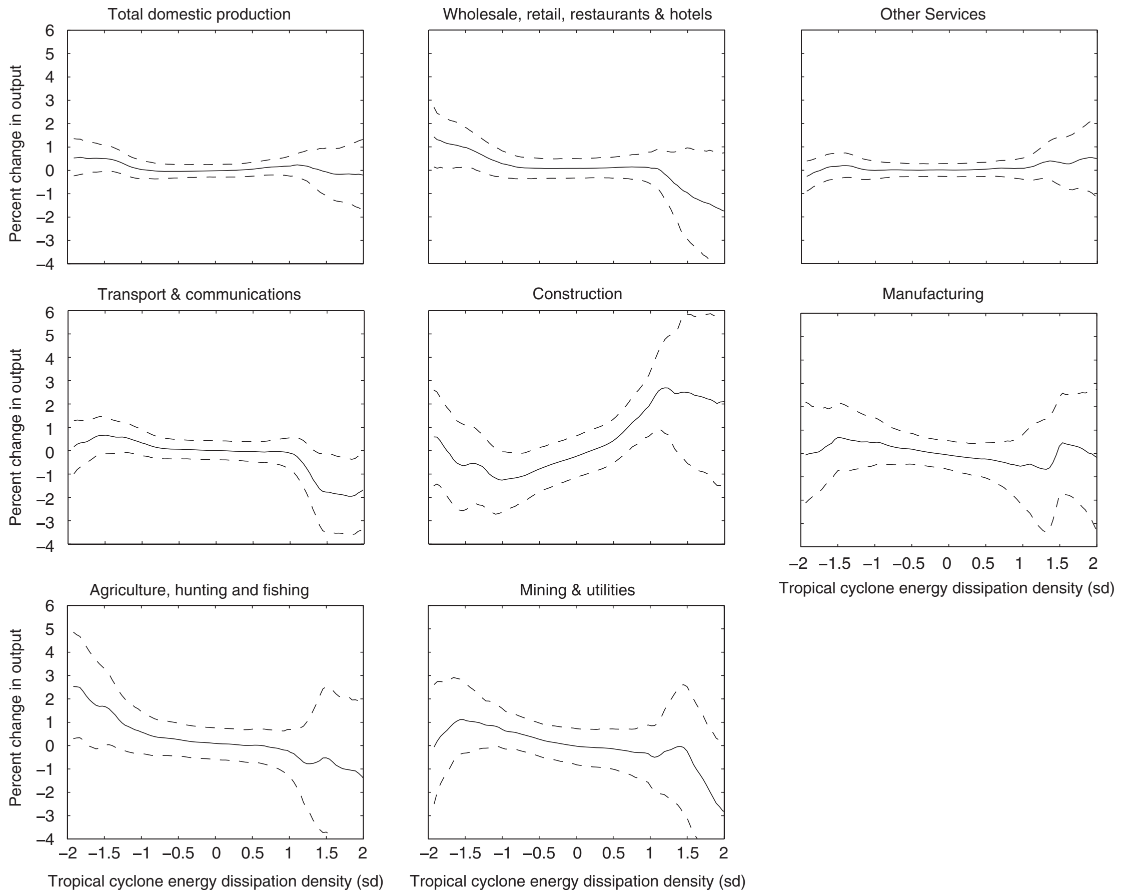

Fig. S3. Same as Fig. 4*B* in the main text, but for all industries. Dashed lines are bootstrapped 90% confidence intervals using 10,000 resamples.

Table S1. Sample sizes and summary statistics

Variable	*N*	Countries	Years	Units	Mean	SD	Min	Max
Temperature (*T*), annual	1,789	31	1950–2007	°C	26.73	0.33†	22.55	28.59
Sep–Oct–Nov (SON) only	1,824	31	1950–2007	°C	27.45	0.36†	21.75	29.80
Tropical cyclone energy (*C*)	1,767	31	1950–2006	10^9 $m^3 \cdot s^{-2}$	0.0302	0.0784	0	1.0299
Rainfall (*R*)	1,786	31	1950–2007	mm/mo	105.58	42.67†	11.75	300.51
Total production	1,060	28	1970–2007	2,000 US$	6,678.24	8,679.33	297.38	64,630.30
Wholesale, retail, hotels and restaurants	1,060	28	1970–2007	% of total production	20.40	6.96	5.72	48.47
Other services	1,052	28	1970–2007	% of total production	35.02	9.76	14.15	60.72
Transport and communications	1,060	28	1970–2007	% of total production	10.70	4.69	1.74	27.02
Construction	1,060	28	1970–2007	% of total production	7.38	3.64	0.85	32.89
Manufacturing	1,060	28	1970–2007	% of total production	11.98	9.35	0.64	43.28
Agriculture, hunting and fishing	1,052	28	1970–2007	% of total production	10.46	9.18	0.34	46.88
Mining and utilities	1,052	28	1970–2007	% of total production	4.17	4.12	0.00	31.48
Tourism receipts	287	24	1995–2006	Current US$	7.67*E*8	8.01*E*8	4.20*E*7	3.79*E*9

†Demeaned by country.

Table S2. Comparing the effects of annual-average and SON-average temperatures

	Total production		Wholesale, retail, restaurants and hotels		Other services		Transport and communications	
	SON	AVG	SON	AVG	SON	AVG	SON	AVG
$Temp_t$	−2.65%***	−2.50**	−5.41***	−6.13***	−2.21**	−2.16**	−3.24**	−2.16
	[0.87]	[1.01]	[1.47]	[1.68]	[0.90]	[1.07]	[1.39]	[1.70]
$Temp_{t-1}$	−0.19	0.17	−1.11	0.69	0.79	0.82	−1.57	−0.72
	[0.70]	[1.00]	[1.10]	[1.54]	[0.69]	[1.00]	[1.16]	[1.41]
Observed	968	968	968	968	968	968	964	964
	Construction		Manufacturing		Agriculture, hunting and fishing		Mining and utilities	
	SON	AVG	SON	AVG	SON	AVG	SON	AVG
$Temp_t$	−5.51*	−0.55	0.70	1.41	−0.97	−0.76	0.67	−4.24*
	[3.07]	[3.12]	[2.08]	[2.61]	[2.33]	[2.48]	[2.09]	[2.44]
$Temp_{t-1}$	−3.13	1.41	−0.57	−1.86	−1.21	−1.83	−1.70	−1.74
	[2.34]	[3.87]	[1.62]	[2.29]	[1.89]	[2.27]	[1.96]	[2.86]
Observed	968	968	958	958	968	968	955	955

***$P < 0.01$, **$P < 0.05$, *$P < 0.1$. SEs (in brackets) account for spatial correlation (uniformly weighted up to 300 km) and country-specific serial correlations using a Bartlett window of 5 y. Units: % output, 1 °C.

Table S3. Falsification test: the effect of future weather on current production

	Total production	Wholesale, retail, restaurants and hotels	Other services	Transport and communication
$Temp^{SON}_{t+1}$	−0.7%	−0.2	−1.0	−1.2
	[0.8]	[1.3]	[0.8]	[1.3]
$Cyclones_{t+1}$	0.1	−0.1	0.1	−0.1
	[0.2]	[0.2]	[0.1]	[0.2]
	Construction	Manufacturing	Agriculture, hunting and fishing	Mining and utilities
$Temp^{SON}_{t+1}$	−3.9	−0.8	−5.4**	−0.6
	[2.5]	[2.0]	[2.3]	[2.1]
$Cyclones_{t+1}$	0.1	−0.2	0.1	−0.2
	[0.5]	[0.3]	[0.4]	[0.3]

***$P < 0.01$, **$P < 0.05$, *$P < 0.1$. SEs (in brackets) account for spatial correlation (uniformly weighted up to 300 km) and country-specific serial correlations using a Bartlett window of 5 y. Model includes regressors from the "true" model in Eq. **1**. Each coefficient is a separate regression. Units for temperature coefficients, % output per 1 °C; cyclone coefficients, % output per 1 SD in cyclone energy dissipated.

Table S4. Robustness of main results

	Total production					Wholesale, retail, restaurants and hotels				
	Δ from trend			Δ_{t-1}	Δ_{trend}	Δ from trend			Δ_{t-1}	Δ_{trend}
$Temp_t^{SON}$	−2.5%***	−2.7***	−2.2***	−2.9***	−2.8***	−4.3***	−5.4***	−4.6***	−5.0***	−5.5***
	[0.8]	[0.9]	[0.8]	[0.8]	[0.9]	[1.4]	[1.5]	[1.3]	[1.2]	[1.9]
$Temp_t^{SON}$	0.3	−0.2	0.6	−0.8	−0.6	−1	−1.1	0.2	−1.2	−1.8
	[0.7]	[0.7]	[0.8]	[0.7]	[0.7]	[1]	[1.1]	[1.1]	[1]	[1.2]
$Cyclones_t$	−0.3	−0.4	−0.3	−0.3	−0.3	−0.7*	−0.8**	−0.7**	−0.9**	−0.4
	[0.2]	[0.2]	[0.2]	[0.2]	[0.4]	[0.3]	[0.3]	[0.3]	[0.4]	[0.6]
$Cyclones_{t-1}$	0.3*	0.2	0.4	0.2	0.2	−0.1	−0.3	0	−0.3	−0.1
	[0.2]	[0.2]	[0.2]	[0.2]	[0.2]	[0.3]	[0.3]	[0.4]	[0.4]	[0.4]
$Cyclones_{t-2}$		−0.3	−0.2	−0.2	−0.2		−0.2	0	−0.3	−0.1
		[0.2]	[0.3]	[0.2]	[0.3]		[0.3]	[0.3]	[0.3]	[0.3]
Lags	1	5	5	5	5	1	5	5	5	5
FE and YE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Country trends	Y	Y	N	N	Y	Y	Y	N	N	Y
Trend breaks	N	N	N	N	Y	N	N	N	N	Y
Observed	972	968	968	996	968	972	968	968	996	968

	Other services					Transport & communications				
	Δ from trend			Δ_{t-1}	Δ_{trend}	Δ from trend			Δ_{t-1}	Δ_{trend}
$Temp_t^{SON}$	−2.2***	−2.2**	−1.9**	−3.2***	−2.5*	−3.5***	−3.2**	−2.9**	−2.8**	−3*
	[0.8]	[0.9]	[0.8]	[0.8]	[1.3]	[1.3]	[1.4]	[1.3]	[1.2]	[1.7]
$Temp_t^{SON}$	1	0.8	1.4	0.4	0.4	−0.3	−1.6	−0.8	−1.9	−2
	[0.6]	[0.7]	[0.7]	[0.7]	[1]	[1.1]	[1.2]	[1.2]	[1.2]	[1.2]
$Cyclones_t$	−0.2	−0.2	−0.1	−0.1	−0.2	−0.3	−0.5	−0.5	−0.5*	−0.4
	[0.1]	[0.2]	[0.2]	[0.2]	[0.3]	[0.3]	[0.3]	[0.3]	[0.3]	[0.7]
$Cyclones_{t-1}$	0.3**	0.3	0.4**	0.3	0.3	0.4*	0.2	0.3	0.3	0.3
	[0.2]	[0.2]	[0.2]	[0.2]	[0.2]	[0.2]	[0.3]	[0.3]	[0.3]	[0.4]
$Cyclones_{t-2}$		0	0	0.1	0.1		−0.6**	−0.6**	−0.7**	−0.5
		[0.1]	[0.1]	[0.1]	[0.3]		[0.2]	[0.2]	[0.2]	[0.6]
Lags	1	5	5	5	5	1	5	5	5	5
FE and YE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Country trends	Y	Y	N	N	Y	Y	Y	N	N	Y
Trend breaks	N	N	N	N	Y	N	N	N	N	Y
Observed	972	968	968	996	968	968	964	964	992	964

Models denoted "Δ from trend" or "Δ_{trend}" are regressions of ln(output) that control for two lagged values of ln(output) and quadratic country-specific time trends, when noted. Models denoted "Δ_{t-1}" use a dependent variable that is $\ln(\text{output})_t - \ln(\text{output})_{t-1}$ and do not control for deterministic trends. In all models, for each industry, country-specific constants and year-specific constants [so-called "fixed effects" (FE) and "year effects" (YE)] are estimated ("FE and YE"). In the model with "trend breaks," only linear country-specific trends are included but two country-specific trend breaks are estimated for the largest cyclone events experienced by each country. ***$P < 0.01$, **$P < 0.05$, *$P < 0.1$. SEs (in brackets) account for spatial correlation (uniformly weighted up to 300 km) and country-specific serial correlations using a Bartlett window of 5 y. Units for temperature coefficients: % output per 1 °C. Cyclone coefficients: % output per 1 SD in cyclone energy dissipated.

Table S5. Robustness of main results continued

	Construction					Manufacturing				
	Δ from trend			Δ_{t-1}	Δ_{trend}	Δ from trend			Δ_{t-1}	Δ_{trend}
Temp_t^{SON}	−3.6%	−5.5*	0.4	−2.8	−7.9*	0.1	0.7	0.7	−0.3	0.7
	[2.9]	[3.1]	[3]	[2.7]	[4.3]	[2]	[2.1]	[2.1]	[2]	[2.9]
Temp_{t-1}^{SON}	−1	−3.1	2.5	0.5	−5	−0.5	−0.6	−1.1	−1.6	−0.3
	[2.4]	[2.3]	[2.5]	[2.5]	[3]	[1.6]	[1.6]	[1.6]	[1.6]	[2.4]
Cyclones_t	1.2*	0.9	1.6**	1.4**	1	0	−0.3	−0.1	−0.1	−1.2
	[0.7]	[0.7]	[0.6]	[0.6]	[1.4]	[0.5]	[0.5]	[0.5]	[0.5]	[1.2]
Cyclones_{t-1}	1.4**	1.3*	1.5**	1.4**	1.2	0.1	0	0.2	0.1	−0.8
	[0.7]	[0.7]	[0.7]	[0.7]	[1.1]	[0.4]	[0.3]	[0.4]	[0.4]	[1.0]
Cyclones_{t-2}		−0.9	−0.9	−1.3	−0.6		−1.2**	−0.9	−0.9*	−2.1
		[0.8]	[0.9]	[1]	[0.9]		[0.6]	[0.5]	[0.5]	[1.5]
Lags	1	5	5	5	5	1	5	5	5	5
FE and YE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Country trends	Y	Y	N	N	Y	Y	Y	N	N	Y
Trend breaks	N	N	N	N	Y	N	N	N	N	Y
Observed	972	968	968	996	968	962	958	958	987	958

	Agriculture, hunting and fishing					Mining and utilities				
	Δ from trend			Δ_{t-1}	Δ_{trend}	Δ from trend			Δ_{t-1}	Δ_{trend}
Temp_t^{SON}	−1.7	−1	−3.3	−2	−0.3	0.5	0.7	2.2	0.5	2.3
	[1.9]	[2.3]	[2.2]	[2.1]	[2.2]	[2]	[2.1]	[1.8]	[2]	[3.7]
Temp_{t-1}^{SON}	−0.8	−1.2	−2.7	−2.2	−1.9	−2	−1.7	−0.9	−1.2	−0.1
	[2]	[1.9]	[1.8]	[1.9]	[2.7]	[1.8]	[2]	[1.8]	[1.9]	[3.1]
Cyclones_t	−1.1***	−1.3***	−1.6***	−1.8***	−1.4***	−0.8**	−0.9**	−0.6	−0.9**	−0.5
	[0.3]	[0.3]	[0.3]	[0.4]	[0.8]	[0.3]	[0.4]	[0.4]	[0.4]	[0.8]
Cyclones_{t-1}	−0.8**	−0.8**	−0.7**	−0.6*	−1.2*	−0.1	−0.3	0.1	0.1	−0.2
	[0.3]	[0.4]	[0.3]	[0.4]	[0.7]	[0.3]	[0.3]	[0.3]	[0.4]	[0.6]
Cyclones_{t-2}		−0.7	−0.2	−0.2	−1.3		−0.1	0.4	0.3	0.2
		[0.6]	[0.6]	[0.6]	[1.2]		[0.4]	[0.4]	[0.4]	[0.6]
Lags	1	5	5	5	5	1	5	5	5	5
FE and YE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Country trends	Y	Y	N	N	Y	Y	Y	N	N	Y
Trend breaks	N	N	N	N	Y	N	N	N	N	Y
Observed	972	968	968	996	968	959	955	955	985	955

Models denoted "Δ from trend" or "Δ_{trend}" are regressions of ln(output) that control for two lagged values of ln(output) and quadratic country-specific time trends, when noted. Models denoted "Δ_{t-1}" use a dependent variable that is $\ln(\text{output})_t - \ln(\text{output})_{t-1}$ and do not control for deterministic trends. In all models, for each industry, country-specific constants and year-specific constants [so-called "fixed effects" (FE) and "year effects" (YE)] are estimated ("FE and YE"). In the model with "trend breaks," only linear country-specific trends are included but two country-specific trend breaks are estimated for the largest cyclone events experienced by each country. ***$P < 0.01$, **$P < 0.05$, *$P < 0.1$. SEs (in brackets) account for spatial correlation (uniformly weighted up to 300 km) and country-specific serial correlations using a Bartlett window of 5 y. Units for temperature coefficients: % output per 1 °C. Cyclone coefficients: % output per 1 SD in cyclone energy dissipated.

Table S6. Nonlinear response to daily mean surface temperature [%Δ/+1 °C in bin]

	Total production	Wholesale, hotels	Other services	Transport and communication
$\text{Temp}_t^{SON} < 27$ °C	−2.9**	−2.7	−1.4	−3.1
	[1.4]	[2.4]	[1.3]	[2.1]
27 °C $< \text{Temp}_t^{SON} < 29$ °C	−2.1*	−3.9**	−2.0	−3.7**
	[1.1]	[1.8]	[1.2]	[1.7]
29 °C $< \text{Temp}_t^{SON}$	−4.4*	−4.5	−4.1*	−9.6**
	[2.5]	[4.4]	[2.4]	[4.2]
Observed	973	973	973	969

***$P < 0.01$, **$P < 0.05$, *$P < 0.1$. SEs (in brackets) account for spatial correlation (uniformly weighted up to 300 km) and country-specific serial correlations using a Barlett window of 5 y. Units: % output per 1 °C.

Table S7. Effect of temperature on production for different income levels

	Total production		Wholesale, retail, restaurants and hotels		Other services		Transport and communications	
	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}
$Temp_t^{SON}$	−4.2%	−11.9***	−9.4	−16.9***	−6.5	−12.4***	11.8*	−3.2
	[4.2]	[3.5]	[9.9]	[5.0]	[4.7]	[4.0]	[6.8]	[6.1]
$Temp_t^{SON}$× ln(income)	0.3	1.2***	0.6	1.6***	0.6	1.3***	−1.7**	0.0
	[0.5]	[0.4]	[1.1]	[0.6]	[0.6]	[0.5]	[0.8]	[0.7]
Observed	806	806	806	806	806	806	806	806
	Construction		Manufacturing		Agriculture, hunting and fishing		Mining and utilities	
	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}
$Temp_t^{SON}$	−28.0*	−37.6***	−14.7	−5.7	1.8	−1.4	17.4*	−8.5
	[15.4]	[8.7]	[11.0]	[5.0]	[12.6]	[7.6]	[9.9]	[11.6]
$Temp_t^{SON}$ × ln(income)	3.0	4.3***	1.8	1.0	−0.3	0.1	−1.9	1.4
	[1.9]	[0.9]	[1.4]	[0.6]	[1.5]	[0.8]	[1.1]	[1.4]
Observed	806	806	802	804	806	806	802	804

Models denoted "Δ from trend" or "Δ_{trend}" are regressions of ln(output) that control for two lagged values of ln(output) and quadratic country-specific time trends. Models denoted "Δ_{t-1}" use a dependent variable that is $\ln(\text{output})_t - \ln(\text{output})_{t-1}$ and do not control for deterministic trends. ln(income) for the average country in the sample is 8.0 ± 1.0 (SD). The minimum is 5.4 (Haiti, 2004), the maximum is 10.8 (British Virgin Islands, 2007). $***P < 0.01$, $**P < 0.05$, $*P < 0.1$. SEs (in brackets) account for spatial correlation (uniformly weighted up to 300 km) and country-specific serial correlations using a Bartlett window of 5 y.

Table S8. Effect of cyclones on production for different income levels

	Total production		Wholesale, retail, restaurants and hotels		Other services		Transport and communications	
	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}
$Cyclones_t$	−6.9***	−3.6	−10.4**	−7.0*	−4.9***	−1.9	−8.9***	−5.9***
	[2.7]	[2.7]	[4.3]	[3.7]	[1.7]	[2.0]	[2.8]	[2.3]
$Cyclones_{t-1}$	−0.7	1.7	−3.4	−0.2	−0.8	1.7	−3.5	0.2
	[1.9]	[1.7]	[4.5]	[4.3]	[1.7]	[1.5]	[2.2]	[2.1]
$Cyclones_t \times \ln(\text{income})_{t-3}$	0.8**	0.4	1.1**	0.7*	0.5**	0.2	1.0***	0.6**
	[0.3]	[0.3]	[0.5]	[0.4]	[0.2]	[0.2]	[0.3]	[0.3]
$Cyclones_{t-1} \times \ln(\text{income})_{t-3}$	0.1	−0.2	0.4	0.0	0.1	−0.2	0.4*	0.0
	[0.2]	[0.2]	[0.5]	[0.5]	[0.2]	[0.2]	[0.2]	[0.2]
Observed	806	806	806	806	806	806	806	806
	Construction		Manufacturing		Agriculture, hunting and fishing		Mining and utilities	
	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}	Δ_{trend}	Δ_{t-1}
$Cyclones_t$	−1.0	5.7	−8.0	−2.3	−8.7	−6.1	−1.6	−2.5
	[5.0]	[3.9]	[4.9]	[4.1]	[5.4]	[4.3]	[4.5]	[3.2]
$Cyclones_{t-1}$	6.0	9.3*	−0.7	4.6	−9.6**	−5.1	2.4	3.0
	[5.3]	[5.1]	[3.1]	[3.6]	[3.8]	[4.2]	[4.6]	[2.3]
$Cyclones_t \times \ln(\text{income})_{t-3}$	0.2	−0.5	0.9	0.3	0.8	0.5	0.1	0.2
	[0.6]	[0.4]	[0.5]	[0.5]	[0.6]	[0.5]	[0.5]	[0.4]
$Cyclones_{t-1} \times \ln(\text{income})_{t-3}$	−0.6	−0.9	0.1	−0.5	1.0**	0.5	−0.3	−0.3
	[0.6]	[0.6]	[0.3]	[0.4]	[0.4]	[0.5]	[0.6]	[0.3]
Observed	806	806	802	804	806	806	802	804

Models denoted "Δ from trend" or "Δ_{trend}" are regressions of ln(output) that control for two lagged values of ln(output) and quadratic country-specific time trends. Models denoted "Δ_{t-1}" use a dependent variable that is $\ln(\text{output})_t - \ln(\text{output})_{t-1}$ and do not control for deterministic trends. ln(income) for the average country in the sample is 8.0 ± 1.0 (SD). The minimum is 5.4 (Haiti, 2004), and the maximum is 10.8 (British Virgin Islands, 2007). $***P < 0.01$, $**P < 0.05$, $*P < 0.1$. SEs (in brackets) account for spatial correlation (uniformly weighted up to 300 km) and country-specific serial correlations using a Bartlett window of 5 y.

Table S9. Correlation coefficients between residuals (anomalies) of atmospheric variables

	C'_t	C'_{t-1}	T'_t	T'_{t-1}	R'_t	R'_{t-1}
Cyclones (C'_t)	1					
C'_{t-1}	0.1015	1				
Temperature (T'_t)	0.0753	0.0454	1			
T'_{t-1}	0.1127	0.0892	0.5517	1		
Rainfall (R'_t)	−0.0376	−0.1055	−0.1428	−0.1575	1	
R'_{t-1}	−0.1073	−0.0426	−0.2766	−0.1309	0.4911	1

Table S10. Comparing models for the effect of SON temperature (TSON) and cyclones (*C*) on production

	Total production				Wholesale, retail, restaurants and hotels				Other services				Transport and communications			
	Δ off trend		Δ off $t-1$		Δ off trend		Δ off $t-1$		Δ off trend		Δ off $t-1$		Δ off trend		Δ off $t-1$	
T_t^{SON}	−2.8%***	−2.7***		−2.9***	−5.2***	−5.4***		−5.0***	−2.4***	−2.2***		−3.2***	−3.4**	−3.2**		−2.8**
	[0.8]	[0.9]		[0.8]	[1.4]	[1.5]		[1.2]	[0.9]	[0.9]		[0.8]	[1.3]	[1.4]		[1.2]
T_{t-1}^{SON}	−0.1	−0.2		−0.8	−0.9	−1.1		−1.2	0.7	0.8		0.4	−0.9	−1.6		−1.9
	[0.7]	[0.7]		[0.7]	[1.1]	[1.1]		[1.02]	[0.7]	[0.7]		[0.7]	[1.1]	[1.2]		[1.2]
C_t		−0.4	−0.1	−0.3		−0.8**	−0.7**	−0.9**		−0.2	−0.01	−0.1		−0.5	−0.3	−0.5*
		[0.2]	[0.2]	[0.2]		[0.3]	[0.3]	[0.4]		[0.2]	[0.2]	[0.2]		[0.4]	[0.3]	[0.3]
C_{t-1}		0.2	0.2	0.2		−0.3	−0.3	−0.3		0.3	0.3	0.3		0.3	0.4	0.3
		[0.2]	[0.2]	[0.2]		[0.3]	[0.4]	[0.4]		[0.2]	[0.2]	[0.2]		[0.3]	[0.3]	[0.3]
C_{t-2}		−0.3	−0.2	−0.2		−0.2	−0.3	−0.3		−0.0	0.1	0.1		−0.6**	−0.6**	−0.7***
		[0.3]	[0.2]	[0.2]		[0.3]	[0.3]	[0.3]		[0.1]	[0.1]	[0.1]		[0.2]	[0.2]	[0.2]
Observed	1,008	968	1,008	996	1,008	968	1,008	996	1,008	968	1,008	996	1,004	964	1,004	992

	Construction				Manufacturing				Agriculture, hunting and fishing				Mining and utilities			
	Δ off trend		Δ off $t-1$		Δ off trend		Δ off $t-1$		Δ off trend		Δ off $t-1$		Δ off trend		Δ off $t-1$	
T_t^{SON}	−5.9**	−5.5*		−2.8	−0.4	0.7		−0.3	−1.7	−1.0		−2.1	1.0	0.7		0.5
	[2.8]	[3.1]		[2.7]	[1.9]	[2.1]		[2.0]	[2.0]	[2.3]		[2.1]	[2.0]	[2.1]		[2.0]
T_{t-1}^{SON}	−2.7	−3.1		0.5	−0.7	−0.6		−1.6	−0.7	−1.2		−2.3	−1.6	−1.7		−1.2
	[2.3]	[2.3]		[2.6]	[1.6]	[1.6]		[1.6]	[1.9]	[1.9]		[1.9]	[1.9]	[2.0]		[1.9]
C_t		1.0	1.7***	1.4**		−0.3	−0.0	−0.1		−1.3***	−1.5***	−1.8***		−0.9**	−0.7**	−0.9**
		[0.7]	[0.7]	[0.6]		[0.5]	[0.5]	[0.5]		[0.3]	[0.4]	[0.4]		[0.4]	[0.4]	[0.4]
C_{t-1}		1.3*	1.5**	1.4**		−0.0	0.3	0.2		−0.8**	−0.7*	−0.6*		−0.3	0.2	0.1
		[0.7]	[0.7]	[0.7]		[0.3]	[0.4]	[0.4]		[0.4]	[0.4]	[0.4]		[0.3]	[0.4]	[0.4]
C_{t-2}		−0.9	−1.2	−1.3		−1.2**	−0.9*	−0.9**		−0.7	−0.2	−0.2		−0.1	0.3	0.3
		[0.8]	[1.0]	[1.0]		[0.6]	[0.5]	[0.5]		[0.6]	[0.5]	[0.6]		[0.4]	[0.4]	[0.4]
Observed	1,008	968	1,008	996	998	958	999	987	1,008	968	1,008	996	995	955	997	985

Models denoted "Δ off trend" are regressions of ln(output) that control for two lagged values of ln(output) and quadratic country-specific time trends. Models denoted "Δoff $t-1$" use a dependent variable that is $\ln(\text{output})_t - \ln(\text{output})_{t-1}$ and do not control for deterministic trends. $***P < 0.01$, $**P < 0.05$, $*P < 0.1$. SEs (in brackets) account for spatial correlation (uniformly weighted up to 300 km) and country-specific serial correlations using a Bartlett window of 5 y. Units for temperature coefficients: % output per 1 °C. Cyclone coefficients: % output per 1 SD in cyclone energy dissipated.