Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America

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Understanding the economic impact of surface temperatures is an important question for both economic development and climate change policy. This study shows that in 28 Caribbean-basin countries, the response of economic output to increased temperatures is structurally similar to the response of labor productivity to high temperatures, a mechanism omitted from economic models of future climate change. This similarity is demonstrated by isolating the direct influence of temperature from that of tropical cyclones, an important correlate. Notably, output losses occurring in nonagricultural production (–2.4%/+1 °C) substantially exceed losses occurring in agricultural production (–0.1%/+1 °C). Thus, these results suggest that current models of future climate change that focus on agricultural impacts but omit the response of workers to thermal stress may underestimate the global economic costs of climate change.

economic growth | climate | ergonomics | weather impacts | hurricanes

Understanding what drives and constrains economic growth is a classical problem in economics (1–4). Whereas the relationship between environmental conditions and economic performance is debated (4–12) it is central to cost-benefit analyses of environmental policies, such as the global regulation of greenhouse gases (13–18). In this study, the economic histories of geographically and economically similar Caribbean and Central American countries are analyzed to understand whether year-to-year variations in surface temperature and tropical cyclones (hurricanes and tropical storms) could be responsible for country-level economic fluctuations. The central finding is that short-term increases in surface temperature are associated with large reductions in economic output across a set of industries previously considered "not vulnerable" to climate changes. A temporary 1 °C increase in surface temperature is associated with contemporaneous 2.5% reductions in economic output.

Recent work by Dell, Jones, and Olken (19) and Jones and Olken (20) observes similar magnitude losses in, respectively, total production (−1.1%/+1 °C) and exports (–2.0%/+1 °C to –5.7%/+1 °C) for a larger and more heterogenous sample of countries. They hypothesize that this response may be driven by (*i*) a temperature-sensitive agricultural sector that in turn has repercussions for the entire economy and/or (*ii*) the response of human labor to thermal stress. This second mechanism has largely been dismissed by modelers of future climate change in favor of the first one (for a review and discussion, see Tol, ref. 14). However, this study suggests that it is implausible for agricultural temperature responses to directly or indirectly drive the observed economy-wide variations in these Caribbean-basin countries.

In the sample of countries examined here, the total value of temperature-related losses in nonagricultural industries exceed the (statistically insignificant) losses of agricultural industries by a factor of 29. Three of six nonagricultural industries suffer large and robust reductions in annual output that are dominated by temperatures experienced during the hottest season and are nonlinear in temperatures during that season. The magnitude, structure, and coherence of these responses support the hypothesis that the underlying mechanism is a reduction in the productivity of human labor when workers are exposed to thermal stress. The ergonomics and physiology of thermal stress in humans is well studied (21–26), but has been absent from previous integrated assessments of global climate change impacts (13–18).

To isolate the direct economic impact of local thermal conditions, the impacts of correlated atmospheric processes must also be accounted for. Because temperatures in the tropical Atlantic and local tropical cyclone activity have been correlated since 1950 (27–30), the economic impact of tropical cyclones must be estimated and removed from the estimated effect of temperature. If correlations in temperature and output were measured without accounting for the impact of cyclones, it would be difficult to know whether local thermal conditions were directly responsible for reductions in output or if the correlation simply measured the effect of cyclones on output by proxy. To measure the impact of cyclones so it may be separated from the impact of temperature, wind-field histories for every storm passing through the region are numerically reconstructed (Fig. 1*A*). Energy dissipation per square meter is then computed for each location in the region (Fig. 1*B* and Fig. S1) and spatially averaged over each country for every year (*Methods*). When this measure of cyclone incidence is compared with raw economic data (for example, Fig. 1*C*), it is clear that cyclones are a major factor in some economic processes and must be accounted for. Annual rainfall is also controlled for in all of the statistical models; however, the results are not presented here (available on request).

Transient production losses associated with tropical cyclones exhibit an entirely different structure from those associated with temperature and are most strongly exhibited in agriculture and tourism, the two sectors where adaptation via geographic relocation is plausibly the most costly. In contrast, the construction industry expands production in response to cyclones, probably due to its role in reconstruction. Whereas an economic response to temperature changes only appears contemporaneously with temperature fluctuations, the direct impacts of cyclones may persist for several years.

Annual longitudinal data from 28 countries in Central America and the Caribbean (1970–2006; *SI Appendix S1* and Table S1) are analyzed with multiple regression analyses that simultaneously control for precipitation, average country-level differences in production for each industry, country-industry time trends in production, and year-level shocks to regional-industry production (*Methods* and *SI Appendix S2*). Throughout this study the effects of temperature and cyclones are estimated simultaneously; however, they are presented in sequence for clarity.

Temperature Impacts

Annual average temperatures are associated with statistically significant reductions in total domestic output and the outputs for

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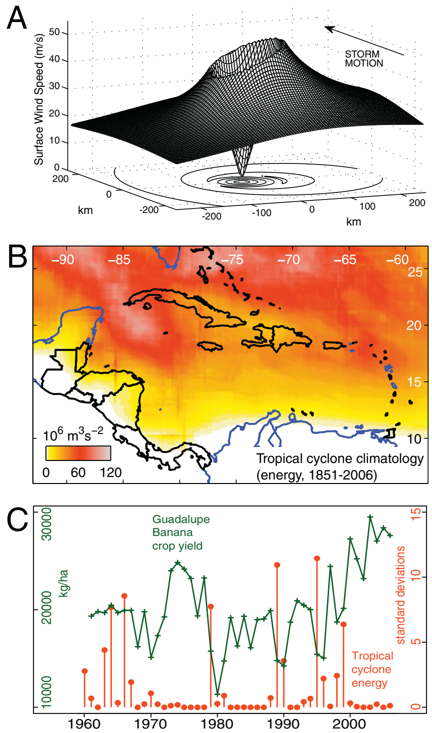

Fig. 1. Estimating tropical cyclone exposure and impacts. (*A*) An example of idealized surface wind speed function used to reconstruct the distribution of cyclone energy dissipated for each storm (contours reflect the overlying surface). The direction of wind flow is irrelevant to energy dissipation, so azimuthal flow is combined with the translational velocity of the storm (arrow) generating the observed asymmetry in the wind speed field about the storm's vector of motion. (*B*) The average density of tropical cyclone wind energy annually dissipated throughout the Caribbean Basin over the period 1851–2006. Countries included in this study are black, and those excluded are blue. Inclusion is based only on geographical extent and the availability of economic data. (*C*) An example of economic impacts: banana crop yield (green) (source: FAOSTAT) and annual tropical cyclone energy dissipation (orange) in Guadeloupe.

three of six nonagricultural industries. These results are presented in Table 1 and they suggest that it is implausible for agricultural losses to drive these economy-wide responses in the Caribbean and Central America. First, the statistically significant responses of *wholesale*, *retail*, *restaurants and hotels* (−6.1%/+1 °C), *mining and utilities* (−4.2%/+1 °C), and *other services* (−2.2%/+ 1 °C) are substantially larger than the estimated (statistically insignificant) response of *agriculture*, *hunting*, *and fishing* (−0.8%/+1 °C) when measured in percentage points. Second, these responses dwarf the losses in agriculture further if they are measured in terms of their

Table 1. Effect of annual average surface temperature on production (1970–2006)

Industry	%Δ/+1 °C	SE	% output
Total production	−2.5%**	[1.0]	—
Wholesale, retail, restaurants and hotels	−6.1%***	[1.7]	20.4
Other services	−2.2%**	[1.1]	35.0
Transport and communications	−2.2%	[1.7]	10.7
Construction	−0.6%	[3.1]	7.4
Manufacturing	+1.4%	[2.6]	12.0
Agriculture, hunting and fishing	−0.8%	[2.5]	10.5
Mining and utilities	−4.2%*	[2.4]	4.2

***$P < 0.01$, **$P < 0.05$, *$P < 0.1$.

"economic size." The last column of Table 1 lists the average contribution of each industry to total production. *Wholesale*, *retail*, *restaurants and hotels*, and *other services* together constitute 55.4% of value added in the region's average economy, compared with the 10.5% represented by agriculture. Thus, production losses in the two former industries account for –2.0%/+1 °C in the economy-wide losses of –2.5%/+1 °C. This response is more than 20-fold the losses in *agriculture*, *hunting*, *and fishing*, estimated at –0.1%/+1 °C in economy-wide losses.

The sheer scale of the economic response to temperature suggests it cannot be driven by agriculture alone, and the centrality of labor to production in *wholesale*, *retail*, *restaurants and hotels*, and *other services* is suggestive that ergonomic considerations may be important. However, additional evidence substantially strengthens the case for ergonomic impacts. Metaanalyses of >150 laboratory and observational ergonomic studies agree that most forms of human performance deteriorate under levels of thermal stress beyond a threshold (21–26). Thus, performance losses appear to be nonlinear, with little or no performance loss from temperature increases in moderate temperature regimes and large performance losses associated with temperature increases in high temperature regimes. If the economic responses to annual average temperature are driven by performance losses, then they should be similarly nonlinear and driven primarily by high temperatures. Two techniques are used to detect the presence of this nonlinearity. First, the effect of annual average temperature is decomposed into four seasonal contributions: December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON). If the economic response to temperature is nonlinear and in agreement with ergonomic studies, temperature changes during the hottest season (SON in this region) should have a larger economic impact than temperature changes in other seasons. Second, spline regressions on degree days are used to look for nonlinearities within this hottest season.

In all industries except *mining and utilities* and *manufacturing*, temperature increases during SON (the hottest season) are associated with the largest reductions in production. Each column in Table 2 presents coefficients for seasonal average temperatures that are estimated simultaneously. Most of the production losses associated with increased annual average temperatures are due to temperature increases in SON. The effects of temperature changes during all other seasons are not statistically different from zero (except one coefficient for *mining and utilities*). This seasonal structure is consistent with the hypothesis that production losses are nonlinear in temperature, with production dropping most strongly at the highest temperatures. Furthermore, the coefficients for SON temperature are more precise than those for annual temperature (Table S2). This feature suggests that annual average temperatures served as a noisy measure of SON temperature for the results in Table 1 and that SON temperature is the measure most strongly associated with economic output. Therefore, for statistical parsimony, SON temperature is used as the sole predictor of output unless otherwise noted. (Because the response of *mining and utilities* to DJF temperature appears idiosyncratic and that industry represents only 4.2% of total production, it is not analyzed further here.) Using this model, both *transport and communications* and *construction* exhibit significant production losses, compared with their statistically insignificant responses to annual average temperatures.

Only current SON temperature is associated with production losses, rather than future or past temperatures, further supporting the hypothesis that thermal stress during the production process is driving losses. If temperature-induced losses in agriculture were driving the losses in other industries, one might expect the losses in nonagricultural industries to lag behind temperature changes because it would take time for the "temperature signal" to propagate through the entire economy. Fig. 2*A* plots the response of *total production* to a 1 °C increase in future, current, and past

Table 2. Effect of seasonal average temperature on production (1970–2006)

	Total production, %	Wholesale, retail, restaurants and hotels, %	Other services, %	Transport and communication, %	Construction, %	Manufacturing, %	Agriculture, hunting and fishing, %	Mining and utilities, %
$Temp^{DJF}{}_t$	−0.5%	−1.4	0.1	−0.2	0.2	−2	−0.9	−3.5**
	[0.6]	[1.0]	[0.7]	[1.1]	[2.4]	[1.6]	[2.0]	[1.7]
$Temp^{MAM}{}_t$	−0.3	0.4	−0.6	0.4	2.6	1.3	0	−1.2
	[0.8]	[1.0]	[0.8]	[1.0]	[2.9]	[1.4]	[1.6]	[1.5]
$Temp^{JJA}{}_t$	0.6	−0.8	0.6	1.2	0.7	1.5	2	0.3
	[1.2]	[1.8]	[1.4]	[1.5]	[4.2]	[2.3]	[2.3]	[2.8]
$Temp^{SON}{}_t$	−2.9***	−4.6***	−2.6**	−4.3***	−5	−1.8	−3.9	1.2
	[1.0]	[1.7]	[1.0]	[1.4]	[3.1]	[2.4]	[2.4]	[2.5]
Observed	972	972	972	968	972	962	972	959

***$P < 0.01$, **$P < 0.05$, *$P < 0.1$. Units: %Δ/+1 °C.

SON temperature. Only the effect of current SON temperature is statistically different from zero. Fig. 3 plots similar results for all seven industries. In the four industries significantly impacted by SON temperature, neither future (Table S3) nor past temperatures have a significant impact on current production.

Estimating linear coefficients in Figs. 2 and 3 is a good approximation of the data. To show this, Fig. 4*A* plots nonparametric estimates of *total production*, *wholesale*, *retail*, *restaurants and hotels*, *other services*, and *transport and communications*, each against SON temperature (once the effects of other variables have been removed; see Fig. S2 for all sectors and confidence intervals). These estimated responses are also broadly robust to the statistical model used. The estimated effects of current SON temperature do not change substantially with the number of lags used, whether country-specific trends are included, whether output is measured relative to the previous year's output (rather than relative to a trend), or whether structural breaks following large cyclone events are allowed (Tables S4 and S5).

As a second test for the nonlinear economic response to surface temperature, the response to daily variations in temperature within the SON season are estimated. Even though economic data are available only annually, daily production responses can be estimated using "degree days" (*Methods*). Fig. 5*A* plots the estimated response to daily average surface temperatures during SON for the robustly temperature-sensitive industries (Table S6 provides coefficients and SEM). Except for *total production*, economic responses to temperature changes below 27 °C are not statistically different from zero. For temperature changes between 27 and 29 °C, the responses become slightly steeper for all industries and statistically different from zero for *wholesale*, *retail*, *restaurants and hotels*, and *transport and communications*. Above 29 °C, the response steepens further for all industries and becomes significant for *other services* (although it is no longer significant for *wholesale*, *retail*, *restaurants and hotels*). Taken together, these results suggest that it is the years with a large number of very hot days during the hottest season that exhibit the largest production losses.

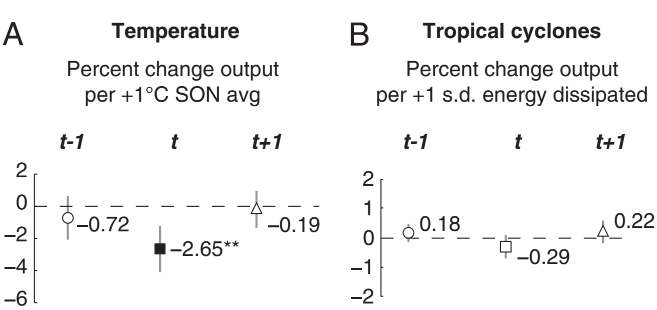

Fig. 2. The estimated impact of transient atmospheric changes in year *t* on total domestic output per capita. (*A*) Reductions in total output the year before (circle), the year of (square), and the year following (triangle) a 1° increase in September–October–November temperature. (*B*) The same, but for a 1 SD increase in cyclone energy dissipation. Whiskers are 90% confidence intervals, and a solid marker is statistically significant. Significance: ***1%, **5%, *10%.

Production's transition from weak dependence on temperature to strong dependence on temperature occurs near a daily average temperature of 27–29 °C. For normal sea-level conditions, this roughly corresponds to a "wet bulb globe temperature" (WBGT) ≥25 °C, the level of thermal stress near which human performance begins to deteriorate in laboratory experiments (21–26). Fig. 5*B* shows "average" performance losses from three metaanalyses (21, 23, 25), a literature that informed the "recommended exposure limits" of the National Institute for Occupational Safety and Health of the United States (1986) (31) (red line, Fig. 5*B*). Because humidity, radiation, and airflow affect the intensity of thermal stress experienced by workers, ergonomics research utilizes measures that capture their impact. WBGT, expressed in degrees centigrade and plotted along the abscissa in Fig. 5*B*, is one such measure. Insufficient data are available to calculate daily WBGT for this analysis; however, the WBGT equivalents of 27 and 29 °C at 80% relative humidity and 1,000 hPa ("normal" sea level conditions) are orange crosses in Fig. 4 for reference. Daily average temperatures in the region regularly exceed these threshold temperatures (black curve, bottom of Fig. 5*A*) and are associated with years in which labor-intensive industries experience the largest economic losses. This is consistent with the hypothesis that country-level production losses associated with high-temperature years reflect individual-level responses to thermal stress.

Addressing Cyclones as Confounding Phenomena

To ensure the estimated impact of surface temperature on production captures direct thermal effects, not the influence of cyclones, the influence of cyclones must be modeled simultaneously. This is important because tropical Atlantic sea surface temperatures have been correlated with basin cyclone activity during the last half century (27–30). If the responses to cyclones and surface temperature are not modeled simultaneously, the effects of the omitted variable might contaminate the estimates of the modeled response. Using a parametric kernel for the wind field of storms (Fig. 1*A*), the historical exposure of countries to cyclones is reconstructed for every year and every country (*Methods*). For this analysis, "exposure" is measured as dissipated wind energy per unit area and normalized to the observed SD (mean = 0.32, min = 0, max = 13.1).

Regression of *total production* on cyclone energy (Fig. 2*B*) suggests that the overall effect of cyclones on output is not distinguishable from zero, but this is misleading. Decomposition of this response by industry (Fig. 3) reveals that there are both large negative and positive output responses to cyclone events. Also,

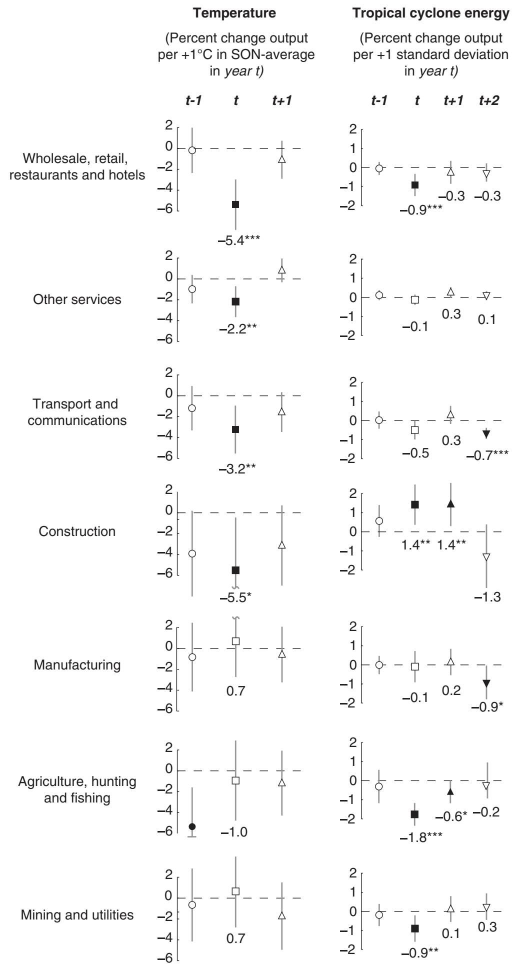

Fig. 3. Industry-level production responses to temperature and tropical cyclones. Rows are industries. The *Left* column plots responses to average September–October–November temperature, and the *Right* column plots responses to cyclone energy dissipation. Markings and units are the same as in Fig. 2.

contrasting with the impact of temperature changes, significant cyclone impacts may persist beyond the year of the initial event. *Agriculture*, *hunting and fishing* (–1.8%/+1 SD and –0.6%/+1 SD the year following), *wholesale*, *retail*, *restaurants and hotels* (–0.9%/+1 SD), and *mining and utilities* (–0.9%/+1 SD) all reduce output in response to cyclones, whereas *construction*

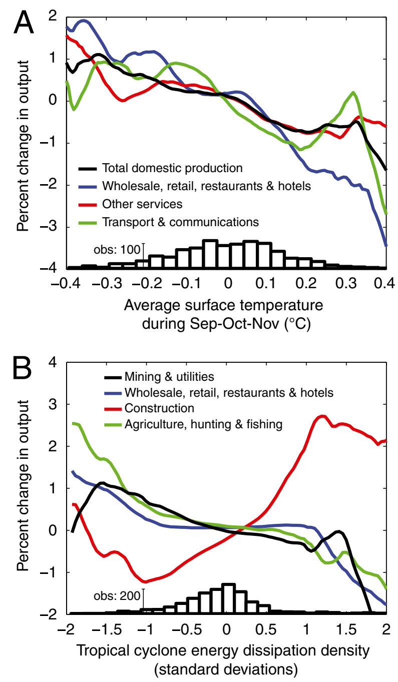

Fig. 4. Validating the appropriateness of a linear regression model. The responses to (*A*) average SON surface temperature and (*B*) tropical cyclone energy are shown. Measures are residuals following regression on all remaining regressors. Histograms plot observational densities. The response functions are most precisely estimated near zero residual values (abscissa), where observational density is high; distortion near the tails is expected from sampling noise. These relationships are well approximated by linear functions for residual values near zero. *A* also shows that the estimated responses to temperature are not driven by outliers.

(+1.4%/+1 SD and +1.4%/+1 SD the year following) expands, presumably because of its role in reconstruction. Fig. 4*B* demonstrates that a linear model of income is a good approximation for the production response to cyclones for all but the most extreme observations (see Fig. S3 for all industries and confidence intervals). These impacts are broadly robust to the statistical model used (Tables S4 and S5).

The impact of cyclones on tourism-related income is disproportionately large. Data on total income attributed to tourists, across all industries, are available for a shorter period (1995–2006) and reveal substantial losses that persist multiple years. Table 3 displays reductions in tourism income relative to a trend

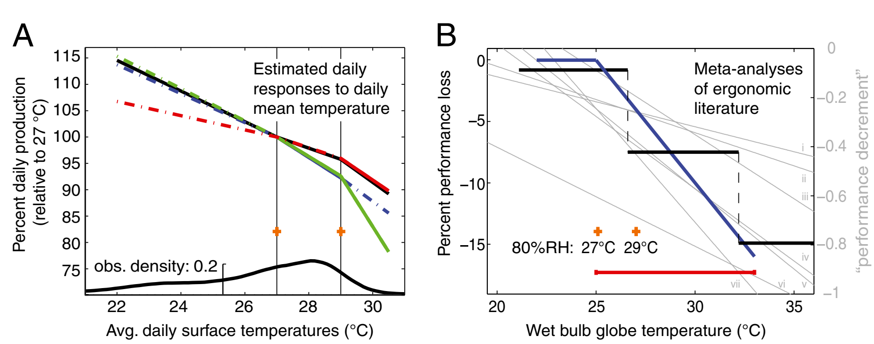

Fig. 5. Nonlinear industry responses mirror laboratory ergonomic studies. (*A*) Production responses to daily SON surface temperatures using "degree days." Production at 27 °C is normalized to 100%. Industries and colors are the same as those in Fig. 4*A*. Solid lines indicate the slope is statistically significant; otherwise lines are dashed. (*B*) Productivity surfaces from metaanalyses of ergonomic studies. Orange crosses correspond to crosses in *A* under "normal" sea level conditions. Black (23) and blue (25): "average" performance losses (left axis). Gray (21): unitless "performance decrement" following 2 h of thermal stress for tasks: *i*, mental; *ii*, mental/reaction time; *iii*, reaction time; *iv*, tracking/vigilance/complex; *v*, complex; *vi*, vigilance; *vii*, tracking. Red: range of "recommended (1 h) exposure limits" from the National Institute for Occupational Safety (31).

Table 3. Effect of cyclones on tourism (1995–2006)

Dependent variable	Deviations from a trend, %			Change from prior year, %		
	Receipts	Visitors	$ per visit	Receipts	Visitors	$ per visit
$Cyclones_t$	−1.6%	−0.9	−0.6	−1.0*	−1.5**	0.3
	[1.0]	[0.6]	[1.1]	[0.5]	[0.5]	[0.4]
$Cyclones_{t+1}$	−3.5***	−2.8**	−0.7	−1.8**	−2.0**	0.1
	[1.2]	[1.1]	[1.0]	[0.8]	[0.8]	[0.4]
$Cyclones_{t+2}$	−2.5**	−0.9	−1.4	1.1	1.4	−0.3
	[1.0]	[1.2]	[0.9]	[0.7]	[1.4]	[0.8]
$Cyclones_{t+3}$	−3.0**	−2.0*	−1.0*	—	—	—
	[1.4]	[1.2]	[0.6]			
$Cyclones_{t+4}$	−1.8*	−1.2	−0.7	—	—	—
	[1.0]	[0.9]	[0.7]			
$Cyclones_{t+5}$	−0.4	−0.3	−0.2	—	—	—
	[0.7]	[0.7]	[0.7]			
$Cyclones_{t+6}$	0.0	−0.9	0.6	—	—	—
	[0.6]	[0.7]	[0.6]			
Observed	275	273	273	252	250	250

***$P < 0.01$, **$P < 0.1$, *$P < 0.1$. Units: %Δ/+1 Units: % Δ/+1 SD cyclone energy per area.

and relative to the previous year. The response in both models is large and driven primarily by reductions in tourist visits, rather than by reductions of income per visit.

Discussion

Economies recover from shocks slowly, so the short-term impacts of temperature changes have larger long-term consequences. The estimated 2.5% reduction in output associated with a 1 °C temperature increase in year t is the direct effect of temperature on output in year t. However, it is well known that output in a given year will affect investments, thereby affecting output in the following year (4). Thus, a temperature change in a given year (t) will *indirectly* affect output in the following year ($t + 1$) by altering output in the first year (t). This indirect influence is independent of the observation that temperature in the first year (t) did not *directly* influence output the following year ($t + 1$). In this sample, total production in any year is observed to be ≈0.9 times output the year before. Therefore, a one-time reduction in output of 2.5% at time t leads to additional indirect reductions over all future years that sum to 22.5% of output (as measured at time t). [Cumulative future losses are $(\sum_{s>t}^{\infty} 0.9^{s-t} \times 2.5\%) = (1/(1-0.9)-1) \times 2.5\% = 22.5\%$. This loss is additional to the initial loss of 2.5% at time t.]

This work analyzes only transient and unexpected variations in the atmosphere around the expected climatological state. When individuals adapt to changes in climatological conditions, the response may differ (32, 33). Agriculture and tourism, industries where geographic location plays a central role in production, suffer most from tropical cyclones. This observation suggests that other industries, where relocation is a less costly adaptive strategy, may have adapted successfully to cyclones. Adaptation to thermal stress may take many forms and some strategies will be available to individuals even over short time horizons. For example, individuals may work less if high temperatures make their efforts more exhausting (34), although the costs of these strategies may themselves be considerable. For this reason, it is possible that as countries become wealthier, they are better able to cope with environmental changes (19, 13). Within this sample of countries, when the responses to temperature changes and cyclones are allowed to be functions of income (*SI Appendix S3* and Tables S7 and S8), there is suggestive evidence that this intuition is generally true.

Whereas these results are specific to the Caribbean and Central America, the mechanisms are plausibly quite general. Nonetheless, future work should evaluate the extent to which similar patterns hold in other regions, taking into account those regions' meteorological patterns and correlates of temperature.

Projected impacts from global climatic change have included capital losses from cyclones (35, 36) and the impact of temperature on agriculture and health (13–18). However, none of these integrated assessments have accounted explicitly for the impacts of thermal stress on human labor. Whereas agriculture's vulnerability to high temperature is a focus of most estimates, impacts on agriculture may be only a small fraction of our economic vulnerability to changes in local temperature. It is estimated here that output in the studied region would drop 2.5% in response to a temporary increase of 1 °C, but only 0.1% of this is attributable to reductions in agricultural output. The remaining 2.4% occurs in industries that have been omitted from existing cost estimates of global climatic change (13–18).

Methods

Annual economic data are available for 28 of 31 countries in the region (see blue boundaries in Fig. 1*B*). Their combined population in 2007 was 81 million people. Details on the data are in *SI Appendix S1* and Table S1 contains summary statistics.

Atmospheric Data. The local energy dissipated at the surface per square meter by tropical cyclone winds is estimated and denoted C. Flooding, landslides, and storm surges are not modeled explicitly. Storm locations and intensities are taken from the Best Track record (37). Storms are parametrically modeled as translating Rankine vortices (38) out to a radius of 250 km on a 10-km grid (Fig. 1*A*). Surface temperature T and rainfall R estimates are spatially averaged over each country. Surface temperatures are from National Centers for Environmental Prediction–National Center for Atmospheric Research Climate Data Assimilation System 1 reanalysis (39). Rainfall estimates are from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (40) (CMAP), with missing observations replaced with National Oceanic and Atmospheric Administration (NOAA)'s Climate Anomaly Monitoring System (CAMS) (41) estimates.

Economic Data. The production of goods and services is measured by per capita value added and its logarithm taken (denoted V) so percentage changes can be estimated linearly. National accounts are collected and maintained by the United Nations (42) (UN). Production in each country is aggregated into industries according to the International Standard Industrial Classification of All Economic Activities (ISIC): *agriculture*, *hunting*, *and fishing* (ISIC code: A + B); *mining and utilities* (C + E); *manufacturing* (D); *construction* (F); *wholesale*, *retail*, and *hotels and restaurants* (G + H); *transport and communication* (I); and *other services* (J–P). Tourism data are collected by the UN World Tourism Organization (43).

Regressions. The dependence of production on exogenous fluctuations in atmospheric states is estimated by multivariate panel regressions using ordinary least squares (*SI Appendix S2*). Such connections are identified by comparing only year-to-year variations in local conditions that do not follow the secular time trend of the country and are distinct from regional shocks. This methodology differs from cross-sectional analyses that compare levels of production between economies exposed to different average environments (14, 44, 45). If the relation of interest is approximately linear, short-run impacts can be identified by comparing idiosyncratic, year-to-year variations. To account for simultaneous variations in temperature, rainfall, and cyclone exposure, all responses are estimated simultaneously using a distristributed-lag, autoregressive (2) regression

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

for industry j in country i and year t. ρ_{1-2} represent autoregressive coefficients, γ and δ are country-specific trends for each industry, η is a region-industry by year constant, μ is an industry by country constant, and ε is a disturbance term. The variables of interest are the coefficients β, the derivatives of production with respect to fluctuations in surface temperature T, tropical cyclone energy C, and rainfall R. These coefficients are assumed to

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be the same for all 28 countries, motivating the restriction of analysis to a small group of countries with limited heterogeneity. Positive "lags" L are used to track and measure the impact of events from previous years, up to some maximum lag $\tau \leq 5$. ε characterizes variations in output not explained by temporary atmospheric changes. Eq. **1** is adjusted when estimating seasonal impacts by replacing T with T^{SON} and/or a vector of seasonal temperatures (in the case of Table 2). A second regression model that omits the lagged values of the dependent variable and the country-specific trends while replacing V_{it}^{j} with $\Delta V_{it}^{j} = V_{it}^{j} - V_{i,t-1}^{j}$ is also estimated (Tables S4 and S5) and provides similar estimates to Eq. **1**. Because this second model provides a more consistent description of cyclone responses (across lag specifications), it is the model displayed in cyclone panels of Figs. 2 and 3. Table S9 displays correlations between atmospheric variables and Table S10 displays estimation results when atmospheric variables are omitted from the statistical model (see S2 Methods for discussion).

The nonparametric curve in Fig. 4 is a Nadaraya–Watson moving average with an Epanechnikov kernel (46, 47). The bandwidth in Fig. 4*A* is 0.1 °C, and in Fig. 4*B* it is 1 SD of cyclone energy. Bootstrapped SEs for these curves are in Figs. S1 and S2. Both variables are residuals from regressions on all remaining regressors in Eq. **1** (48).

Daily Production. Daily production data are unavailable; however, analysis of "accumulated degree days" can recover the response to daily average conditions if the response to temperature is constant throughout the year (49). In Eq. **1**, the temperature term is replaced by three terms representing the accumulated degree days in three temperature bins: <27, 27–29, and >29 °C. Temperature variations within each bin are treated as separate variables, with the OLS coefficient for a bin representing the response of production to daily temperature variations only within that bin. A full derivation of this model is in *SI Appendix*.

Uncertainty. Uncertainty in the estimated values of β is calculated using generalized method of moments estimates for variance of β. Nonparametric estimation of the variance–covariance matrix for ε allows for contemporaneous spatial correlations between countries whose centroids lie within 300 km of one another (50). Following Conley (51), weights in this matrix are uniform up to that cutoff distance. In addition, nonparametric estimates of country-specific serial correlation are estimated using linear weights that decay to zero after a lag length of 5 y (52). This technique ensures that uncertainty in β is adjusted to account for heteroscedasticity, country-specific serial correlation, and cross-sectional spatial correlation. Due to computational difficulties, uncertainty for tourism-related regressions is computed with a variance–covariance matrix that allows for uniformly weighted clustering by country (53, 52), but no spatial correlation. Significance tests are two-tailed t tests. For details, see *SI Appendix*.

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