Appendices for

"Climate Shocks and Economic Growth: Evidence from the Last Half Century"

Not for publication

Appendix I: Climate Data

Our primary source for climate data is the *Terrestrial Air Temperature and Precipitation: 1900-2006 Gridded Monthly Time Series*, Version 1.01 (2007), compiled by Kenji Matsuura and Cort Willmott in conjunction with NASA. The data are available at http://climate.geog.udel.edu/~climate/html_pages/download.html. This dataset combines station data on mean air temperature and precipitation from a number of sources, with the primary source being the Global Historical Climatology Network (Peterson and Vose, 1997).

Matsuura and Willmott interpolate monthly averages of air temperature and precipitation to a 0.5 degree by 0.5 degree latitude/longitude grid. The gridded fields were estimated from monthly weather-station averages using a combination of spatial interpolation methods: digital-elevation-model (DEM) assisted interpolation (temperature only; Willmott and Matsuura, 1995); traditional interpolation (Willmott et al., 1985); and climatologically aided interpolation (CAI) (Willmott and Robeson, 1995). An average of twenty nearby stations influenced each grid-node estimate.

We calculate the average yearly temperature and precipitation within each country using geospatial software. We investigate several weighting schemes: landmass area, population, urban population, and rural population. Landmass weights weight each temperature or precipitation cell by the fraction of the country's landmass it covers. Urban (rural) population weights limit the sample to urban (rural) areas. Population and urban extents data for 1990 are at a resolution of 30 arc seconds (approximately one kilometer at the equator) and were produced by Columbia University's Center for International Earth Science Information Network (SEDAC, 2004).

Appendix II: Dynamic Regression Models

This section discusses and estimates a more general econometric model for identifying growth effects in the context of a dynamic panel growth regression, following the derivation in Bond et al. (2007). To begin, consider a general dynamic growth equation for the log-level of per-capita output:

$$y_{it} = A_{it} + \alpha_1 y_{it-1} + ... + \alpha_p y_{it-p} + \beta_0 T_{it} + \beta_1 T_{it-1} + ... + \beta_p T_{it-p} + \varepsilon_{it} \qquad \text{(A1.1)}$$

This equation generalizes equation (1) in the text by adding p lags of temperature, allowing output to depend on p lags of past output, and adding an error term.

We assume that A_{it} evolves according to a generalized version of the dynamic process specified in (2) with p lags, i.e.

$$\Delta A_{it} = g_i + \gamma_0 T_{it} + ... + \gamma_p T_{it-p} \qquad \text{(A1.2)}$$

This form allows both current and lagged temperature to affect the growth rate of A.

Substituting (A1.2) into the first differenced version of (A1.1) yields a dynamic panel estimation equation of the form:

$$\begin{aligned}\Delta y_{it} &= g_i + \alpha_1 \Delta y_{it-1} + \ldots + \alpha_p \Delta y_{it-p} \\ &\quad + \gamma_0 T_{it} + \ldots + \gamma_p T_{it-p} + \beta_0 \Delta T_{it} + \beta_1 \Delta T_{it-1} + \ldots + \beta_p \Delta T_{it-p} + \Delta \varepsilon_{it}\end{aligned} \quad \text{(A1.3)}$$

Rewriting the ΔT terms as T terms yields

$$\begin{aligned}\Delta y_{it} &= g_i + \alpha_1 \Delta y_{it-1} + \ldots + \alpha_p \Delta y_{it-p} + \\ &\quad (\gamma_o + \beta_0) T_{it} + (\gamma_1 + \beta_1 - \beta_0) T_{it-1} + \ldots + (\gamma_p + \beta_p - \beta_{p-1}) T_{it-p} - \beta_p T_{t-p-1} + \Delta \varepsilon_{it}\end{aligned} \quad \text{(A1.4)}$$

or, relabeling the coefficients on *T*,

$$\Delta y_{it} = g_i + \alpha_1 \Delta y_{it-1} + \ldots + \alpha_p \Delta y_{it-p} + \sum_{j=0}^{p+1} \rho_j T_{ij} + \Delta \varepsilon_{it} \quad \text{(A1.5)}$$

To find the growth effect, consider what happens if temperature is constant and growth is in steady-state, i.e., $\Delta y_{it-j} = \Delta y$ and $T_{ij} = T$. Solving equation (A1.5) shows that

$$\Delta y_i = \frac{g_i}{1 - \alpha_1 - \ldots - \alpha_p} + \frac{\sum_{j=0}^{p+1} \rho_j}{1 - \alpha_1 - \ldots - \alpha_p} T_i \quad \text{(A1.6)}$$

so that the growth effect of temperature is simply $\frac{\sum_{j=0}^{p+1} \rho_j}{1 - \alpha_1 - \ldots - \alpha_p}$. From (A1.4), it is also clear that this is identical to $\frac{\sum_{j=0}^{p} \gamma_j}{1 - \alpha_1 - \ldots - \alpha_p}$, since the β terms all cancel.

As noted by Bond et al. (2007), estimation of (A1.5) is complicated by the fact that the error term, $\Delta \varepsilon_{it}$, is correlated with the lagged dependent variable, Δy_{it-1}. Bond at al. suggest instrumenting for Δy_{it-1} with further lags of growth. However, since growth is only very weakly serially correlated (the correlation of growth and lagged growth is only 0.07), these instruments are very weak.

Given these issues, as well as the very low serial correlation in growth, we focus in the text on (4), which imposes $\alpha_j = 0$ for all *j*. However, for completeness, Appendix Table 1 presents estimates of the growth effect for poor countries under a variety of alternative empirical specifications that estimate α flexibly. For convenience, the first row of Appendix Table 1 replicates the equivalent results from Table 3, which imposes $\alpha_j = 0$ for all *j*. The second row of Appendix Table 1 report estimates of (A1.5) with 1 lag of growth. The reported coefficients are the implied growth effects for poor countries from equation (A1.6). The third and fourth rows of Appendix Table 1 estimate (A1.5) with *p* lags of growth, where $p = 1$ in column (1), $p = 4$ in column (2) and $p = 9$ in column (3), which means that a total of 1, 5 and 10 lags of temperature, respectively, are included in the regression. The third row presents OLS results and the fourth row presents results instrumenting for the first lag of growth with the $p+1$ lag.

Broadly speaking, these results are very similar to the main results shown in the paper. If anything, the estimated growth effects from the dynamic panel specifications tend to be slightly larger in magnitude than the results that do not include lags of growth. As expected given the low serial correlation of growth, the IV results are less precisely estimated than the OLS results, although the 10 lag IV results remain statistically significant.

Finally, as an additional check on the empirical specification, we have run Monte Carlo analyses of (4) using actual output and climate data to ensure that this econometric specification provides correct inference and unbiased estimates. Specifically, in each Monte Carlo iteration, we randomly reassigned the temperature series from one to country to another country's real output series, and then tested for temperature effects in model (4).

With random reassignment, we rejected the null of no climate effects at the 5% significance level approximately 4% of the time, suggesting that our inference is accurate against the null hypothesis of no climate effects and, if anything, is slightly conservative. In additional simulations, we again randomly reassigned the real climate series of one country to the real output series of another country, but then adjusted each output series according to assumed growth and level effects of temperature. These Monte Carlos showed that the distributed lag coefficients, and the cumulated lags, provided unbiased estimates for both level effects and growth effects of temperature. These Monte Carlo results are available from the authors upon request.

Appendix III: Projections Methodology

1. Future temperature

The CCSM v3.0 model provides gridded, monthly air temperature projections with a spatial resolution of 1.4x1.4 degrees. Annual country averages are calculated by taking arithmetic, population-weighted means for each country. This aggregation method is the same as that used for the historical climate data as described in the text. The CCSM projection data are provided by the University Corporation for Atmospheric Research (UCAR) and can be downloaded at http://www.gisclimatechange.org.

2. Future growth

The marginal growth effect in any country in any future year is calculated in two parts. First, we calculate the marginal increase in temperature in that country and year versus in the baseline of no warming. Second, we calculate the marginal effect of the temperature change on economic growth, which depends on whether the country is rich or poor in the given year. The marginal growth effect of temperature for rich and poor countries is taken from the 10-lag model presented in Column 1 of Table 4. In the historical data, the absolute level of income per-capita that separates rich and poor countries is $3170 (PPP, year 2000 dollars). Regression models based on finer gradations of income (3, 4, or 5 quantiles instead of 2) produce broadly similar results.

Whether a country is rich or poor in the future depends in part on the accumulation of marginal growth effects from climate and in part on the background growth rate for the country. To calculate the baseline growth rate, we assume that countries grow in the future at their historical rate over the 1971-2003 period (or the 1991-2003 period if the longer period is not available). This growth rate is further adjusted for "conditional convergence", by correcting for country-specific convergence rates to United States income levels. This ensures, for example, that countries like China do not continue at high growth forever but ultimately slow as they come closer to United States per-capita income. The convergence term, β_i, for country *i* is calculated such that

$$\bar{g}_i = \bar{g}_{US} + \beta_i (\ln y_{US,1971} - \ln y_{i,1971})$$

where $\bar{g}_i$ is the average growth rate in country i from 1971-2003, $\bar{g}_{US}$ is the equivalent average for the United States, and $\ln y_{US,1971}$ and $\ln y_{i,1971}$ are log per-capita income in the US and country i, respectively, in 1971.[1] The baseline growth rate for any year *t* in the future is then calculated as

$$g_{i,t}^B = \bar{g}_{US} + \beta_i (\ln y_{US,t} - \ln y_{i,t})$$

The estimated growth rate in year *t* is this baseline growth rate plus the marginal effect of temperature in that year

$$g_{i,t} = g_{i,t}^B + \gamma^P \Delta T_{i,t} I_{i,t} + \gamma^R \Delta T_{i,t} (1 - I_{i,t})$$

where $\Delta T_{i,t}$ is the change in temperature against the baseline of no warming, $I_{i,t}$ is an indicator equal to 1 if the country is poor, and γ^P and γ^R are the growth effects for poor and rich countries, respectively, as calculated from the panel model. In the projections presented in Table 9, we set $\gamma^R = 0$. Starting in the present, we use these calculated growth rates to project per-capita income forward year-by-year for each country. The results in Section 5 present economic projections under the A2 scenario compared against the case of no climate change (where $\Delta T_{i,t} = 0$ for all *i* and *t*).

[1] For countries with growth data that begins after 1971 we use 1991 instead. If a country's convergence term appears negative (i.e. it grows more slowly than the U.S. historically), then we set the convergence rate to zero and simply set the baseline growth rate to the country's historical average.

Appendix Table 1: Dynamic Panel Estimates

	Implied growth effects for poor countries		
	(1)	(2)	(3)
	1 lag	5 lag	10 lags
Model:			
No lagged growth effects	-1.275*	-1.662**	-1.946**
	(0.681)	(0.728)	(0.869)
1 lag of growth, OLS	-1.397*	-1.794**	-2.058**
	(0.726)	(0.748)	(0.894)
p lags of growth, OLS		-1.780**	-2.382***
		(0.807)	(0.877)
p lags of growth, IV	-1.745	-1.275	-2.004**
	(1.174)	(1.053)	(0.806)

Notes: Each reported coefficient is the estimated growth effect of temperature in poor countries, calculated using equation (A1.6), from a separate regression of the form in equation (A1.5). The underlying equations include country fixed effects, region × time fixed effects, poor x year FE, temperature and precipitation interacted with poor/rich dummies, and the number of lags of temperature and precipitation shown in the column. Robust standard errors are in parentheses, adjusted for clustering at the country level. Note that the estimates in the first row exactly replicate the 'sum of all temp. coefficients in poor countries' shown in columns (7), (9), and (10) of Table 3. In row 2, the equation includes 1 lag of growth as an independent variable. In row 3, the equation includes 4 lags of growth in column (2) and 9 lags of growth in column (3). In row 4, the equation includes 4 lags of growth in column (2), with the 1st lag instrumented using the 5th lag, and 9 lags of growth in column (3), with the 1st lag instrumented using the 10th lag.