GDP and Temperature: A Cross-Section Analysis with Implications for Global Warming

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The relationship between per-capita GDP and long-run average temperature in the capital city is investigated for a cross-section of 97 countries. A neoclassical growth model with Cobb-Douglas production is estimated. A simple regression of log of per-capita GDP against log of temperature shows that temperature explains more than forty-five percent of the variance in income. The effect of temperature on capital stocks and economic growth is also analyzed.

Implications for the effects of global warming are discussed. Under the interpretation with the strongest implications, we predict that a one-percent increase in temperature will lead to a decrease in per-capita GDP of between 2.0 and 3.5 percent. A 2° F increase in average temperature in the U.S. translates to a three-and-a-half percent increase in temperature, which is then predicted to lead to a 7.7 percent decrease in the U.S. GDP.

1. Introduction

It has long been noted that the economies located in temperate zones are more developed than those in tropical zones (Kamarck; Ram; Theil and Chen). This phenomenon is relatively new, perhaps just a few centuries old; as many authors have pointed out, many of the earliest civilizations were in warm, not cool locales. Yet a clear relationship between income and temperature exists in the modern world, as we show here. There are a wide variety of possible explanations, ranging from differences in labor productivity in different climates; to differences in political and social institutions that were developed, perhaps, under a certain set of climate-dependent technologies (or lack of technologies) and then passed on to subsequent generations; to differences in how quickly capital depreciates in different climates. All of the possible explanations rely, however, at least to start, on a clear and precise understanding of the relationship between income and temperature. We attempt this understanding in this paper.

Concern about global warming makes this relationship particularly relevant. If global warming is going to make Switzerland's climate more like Austria's, then the current difference between Switzerland's per-capita GDP ($14,864) and Austria's GDP ($11,131) gives a possible prediction of the economic effect of this climate change. To make this prediction reliable, it would be helpful to have as precise and broad-based a measure of the temperature-GDP relationship as possible. We use the Summers-Heston data, which, with its emphasis on comparability of income measures across countries, is particularly valuable for this task.

One recent paper that tackles this question, at least briefly, is Nordhaus. He gives primarily a qualitative assessment of the possible relationships. He states that for a temperature range of 40° F to about 65° F, there is no relationship between mean temperature and income per capita, and further notes that latitude, which is correlated with climate, explains less than one percent of the variance in income per capita. He then argues that land value or income per unit area may provide a better measure of the relevant relationship and finds that there is a modest hump-shaped relationship between income per unit area and temperature. Our paper focuses on income per capita and looks at the full range of worldwide temperatures.

We use as our measure the average temperature in the capital city (see Data section). A simple regression of log of per-capita GDP against log of temperature shows that temperature explains roughly *forty-five percent* of the variance in log-income, a figure we found astonishingly high.

We then set up and estimate a Solow-Swan growth model with both human and physical capital, based on Mankiw, Romer, and Weil, and add temperature as an input. Our results are highly consistent with this model. Our estimates conform to the model across reduced and structural form estimates for GDP; across separate estimates for physical capital, human capital, and GDP; and with a cross-section estimate of GDP growth.

We then discuss the implications of these results for the economic effects of global warming. Different explanations of the temperature-income relationship have different implications about what would happen if temperatures got warmer as a result of global warming. Under the interpretation with the strongest implications, we find that a one percent increase in temperature yields, on average, a two to three-and-a-half percent decrease in steady-state per-capita GDP. This decrease comes from a predicted three percent decrease in physical capital, a two percent decrease in human capital, plus a one percent decrease in income that is predicted to occur even if capital stocks were held constant.

When our estimates are interpreted for individual countries, we find that a two degree Fahrenheit increase in all temperatures, which is a crude approximation to current predictions about global warming, yields a 7.4 percent decrease in total GDP among the 97 countries in our data. Note that a 2° F increase is a higher percentage increase in lower-temperature countries, which have higher than average per-capita GDP. Our assessment of the cost of global warming is higher than most other published estimates, which have typically not been based on econometric analysis (see, for example, Tol).

2. Model

We adopt the model of Mankiw, Romer, and Weil (hereafter MRW), which in turn is based on Solow and Swan. Production is assumed to be a constant returns to scale function of labor, physical capital, and human capital. It is not initially clear how temperature should affect the production relationship. To tackle this problem, we treat climate as a natural resource and enter it as a multiplicative input in a Cobb-Douglas production function, just as with the other inputs. Under this view, a lower average temperature increases the marginal product of capital and labor. Also, temperature cannot produce output without the other inputs.

When production is Cobb-Douglas, output per capita, y_t, is given by:

$$(1) \qquad y_t = A_t k_t^{\alpha} h_t^{\beta} T^{-\gamma}$$

where A_t is an exogenous technology input, k_t and h_t are physical and human capital per-capita, and T is average temperature. The exponents (α, β, γ) are assumed identical across countries. Suppose there are constant savings rates for the two types of capital, s_k and s_h; constant depreciation, δ; and constant population growth, n. If a steady-state exists, then steady-state output per-capita, y*, will be given by:

$$(2) \qquad \ln y^* = \psi \ln T - (\alpha+\beta)\theta \ln(n+g+\delta) + \alpha\theta \ln(s_k) + \beta\theta \ln(s_h) + \theta \ln A_t$$

with $\psi = -\gamma\theta$ and $\theta = 1/(1-\alpha-\beta)$. Thus, ψ measures the percentage change in steady-state output caused by a one percent change in average temperature. We expect $\psi < 0$.

Alternatively, we can look at steady-state capital per-capita, denoted k* and h*. These are:

$$(3) \qquad \ln k^* = \psi \ln T - \theta \ln(n+g+\delta) + \alpha\theta \ln(s_k) + (1-\alpha)\theta \ln(s_h) + \theta \ln A_t$$

(4) $$\ln h^* = \psi \ln T - \theta \ln(n+g+\delta) + (1-\beta)\theta \ln(s_k) + \beta\theta \ln(s_h) + \theta \ln A_t$$

Equation (1) might also be used to specify growth in income when the economy is not in a steady-state. Growth is given by the equation:

(5) $$\ln y_t - \ln y_{t-k} = (1-e^{-\lambda k})\ln y^* - (1-e^{-\lambda k})\ln y_{t-k}$$

The convergence rate is $\lambda = (n+g+\delta)(1-\alpha-\beta)$. Typically, however, equation (5) is used to infer λ, which is also then assumed constant across countries.[1]

3. Econometric Specification

In the analysis below, we estimate regressions of the following form, which correspond to equations (2)-(4) with additive error terms:

(6) $$\ln y = a_2 + \psi_2 \ln T + \varepsilon$$

(7) $$\ln k = a_3 + \psi_3 \ln T + \upsilon$$

(8) $$\ln h = a_4 + \psi_4 \ln T + \nu$$

where the error terms are functions of country-specific savings rates, population growth, and technology. The coefficient on ln(T) is our estimate of the steady-state effect of a change of temperature.

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[1] Recent research has pointed out empirical problems with the MRW model. (A separate line of research has pointed out conceptual problems.) Cho and Graham note that MRW's estimates imply that, on average, countries with lower per capita incomes are above their steady-state positions and that the underlying growth model is therefore suspect. The prediction that some countries will be above their steady-state income is inevitable since forty-two of our ninety-seven (43 percent) countries experienced negative per capita growth between 1980 and 1985. A smaller but still sizeable proportion, twenty-eight of eighty-four countries (33 percent), experienced negative per capita growth between 1985 and 1990.

In contrast, the (steady-state) income model appears well-behaved. Of course, any true model must simultaneously explain both growth and income. We leave this problem for subsequent research. A

Equations (6)-(8) can be estimated singly or jointly. Joint estimation allows us to impose the restriction that the coefficient on temperature be identical in each of the regressions, which follows from equations (2) through (4). The null hypothesis is $\psi_i = \psi_j$.

GDP Growth. For the sake of comparison with growth studies, we also estimate equation (5). Estimation is complicated by the fact that y* is unobservable and must either be proxied (as in Sala-i-Martin, for example) or explicitly modeled (as in MRW or Sachs and Warner). Specification of y* will typically be incomplete. Any omitted variables will necessarily be correlated with lagged income and therefore the coefficients will typically be biased.

We use income data from 1980 and 1985. The estimated equation is:

$$\ln y_{1985} - \ln y_{1980} = b_0 + b_1 \ln T + b_2 \ln y_{1980} + \eta \tag{9}$$

The coefficients are $b_1 = (1-e^{-5\lambda})\psi$ and $b_2 = -(1-e^{-5\lambda})$. Thus $\psi = -b_1/b_2$.

It may be possible to assess the bias in estimates of b_1 and b_2. If the covariance between ln(T) and η is zero then the expectations of the coefficient estimates are:

$$E\hat{b}_1 = b_1 - \frac{1}{\Delta}\operatorname{cov}(\ln(T), \ln(y_{1980}))\operatorname{cov}(\ln(y_{1980}), \eta) \tag{10a}$$

$$E\hat{b}_2 = b_2 + \frac{1}{\Delta}\operatorname{var}(\ln(T))\operatorname{cov}(\ln(y_{1980}), \eta) \tag{10b}$$

where Δ is the determinant of $X'X$, where $X = [\ln(T), \ln(y_{1980})]$.

4. Data

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preliminary exploration of the effect of temperature on growth is in Section 6.

A data set with ninety-seven countries was compiled from various sources. The regressions require data on physical capital stock per capita, human capital stock per capita, GDP per capita, and temperature. Summary statistics are in Table 1.

Physical capital data are from King and Levine, who constructed the series using the Summers and Heston data, more commonly known as the Penn World Tables (Mark 5). King and Levine first assume a steady-state and hold capital to output ratios constant within each country. They use data on investment, capital depreciation rates, GDP, and population to estimate an initial value for physical capital stock per capita. They then employ the perpetual inventory method to construct a time-series. The regressions use the data for 1985, unless otherwise stated, and are given in 1985 U.S. dollars per person.

Human capital data are taken from Barro and Lee. Average educational attainment in each country acts as the measure of human capital; this is a different measure from MRW. Barro and Lee constructed a data set with estimates of average schooling years for each country's population aged 25 or older. The estimates are based on census information from individual governments as compiled by UNESCO and other sources. The regressions use average years of schooling for 1985.

Per-capita GDP is taken directly from Summers and Heston. The data in our cross-section regressions are for 1985 unless otherwise stated and are in 1985 $US. For some of our calculations, we use total GDP, which is also taken from Summers and Heston.

Temperature data are from the National Climatic Data Center, a national data center for the National Oceanic and Atmospheric Administration. The data were retrieved from *The Weather Almanac,* also available as the web-site *worldclimate.com.*

For each country, we used temperature data from the capital city or the nearest weather station to the capital city.[2] We then calculated an average annual temperature as the average of four average monthly maximum and minimum temperatures (July, October, January, and April.) The average monthly temperatures are based on data collected over a period of around 30 years.

Table 1. Summary statistics (N = 97)

	Physical capital per capita (1985 $US)	Schooling (years)	GDP per capita in 1980 (1985 $US)	GDP per capita in 1985 (1985 $US)	Mean temp. (°F)
Mean	$10994	4.8	$4852	$4946	67.25
Median	$5502	4.5	$3232	$3184	68.88
Maximum	$47922	11.9	$20040	$16570	84.88
Minimum	$94	0.4	$474	$442	39.88
Std. dev.	11726	2.8	4332	4478	12.3
Skewness	1.2	0.5	1.1	1.0	-0.6

5. Results

Estimates of ψ based on a Cross-Section of GDP

Results are given in Tables 2 and 3 and equations (11)-(14). In the single equation regressions (Table 2), temperature accounts for forty-five percent of the variance in income and for twenty-seven and thirty-six percent of the variance in physical and human capital. Estimates of ψ range from -2.0 to nearly -3.7.

The null hypothesis that the temperature coefficients are equal cannot be rejected in any of the four tests for the jointly estimated equations (Table 3). Such cross-equation restrictions provide an important test of the MRW model which is rarely reported. When

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[2] Five countries in our data have no weather station. When there was a weather station sufficiently close, although in another country, we used that weather station.

we estimate the full system of equations (6)-(8), we obtain $\psi = -2.29$.

Table 2. The Effect of Temperature on Income and Capital

	ln(y)	ln(k)	ln(h)
Constant	22.39 (13.83)	23.87 (9.10)	10.50 (8.41)
ln T	-3.42 (8.87)	-3.66 (5.85)	-2.18 (7.33)
R^2	0.45	0.27	0.36

t-statistics in parentheses. n = 97.

Table 3. Joint Estimation of the Effect of Temperature on Income and Capital

	(6) & (7)		(6) & (8)		(7) & (8)		(6), (7) & (8)		
	ln(y)	ln(k)	ln(y)	ln(h)	ln(k)	ln(h)	ln(y)	ln(k)	ln(h)
Constant	22.01 (19.08)	22.51 (19.80)	17.58 (10.14)	10.89 (6.26)	16.89 (13.03)	9.69 (7.39)	17.65 (18.52)	18.16 (19.62)	10.97 (11.57)
ln T	-3.33 (12.39)	-3.33	-2.28 (5.53)	-2.28	-1.99 (6.45)	-1.99	-2.29 (10.52)	-2.29	-2.29
χ^2, $\psi_i=\psi_j$	0.01		0.35		0.34		0.30		

t-statistics in parentheses. n = 97.

Structural Form Estimation. We can also use our data to calculate the effect of a temperature increase on current GDP; that is, holding both kinds of capital fixed. We estimated a structural form equation based on (1). The estimated equation is:

$$\ln y = \underset{(7.75)}{8.74} + \underset{(9.59)}{0.39}\ln k + \underset{(4.76)}{0.41}\ln h - \underset{(4.57)}{1.10}\ln T \qquad (11) \qquad R^2 = 0.87,\ n = 97$$