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

by

Conrad J. Choinière and John K. Horowitz

WP 99-09

Department of Agricultural and Resource Economics
The University of Maryland, College Park

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

by

Conrad J. Choinière and John K. Horowitz
University of Maryland

October 1999

Send correspondence to:
John K. Horowitz
Department of Agricultural and Resource Economics
2200 Symons Hall
University of Maryland
College Park MD 20742-5535
horowitz@arec.umd.edu
(301) 405-1273

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

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.

---

[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

---

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

[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:

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

Equation (11) predicts that a one percent increase in temperature would lead to a 1.10 percent decrease in GDP if physical and human capital were to remain unchanged. This figure is roughly one-third of the predicted final change (based on single-equation estimation of (6)) when physical and human capital also adjust to the higher temperature.

An estimate of the steady-state effect can be derived using equations (7) and (8) to predict the effect of temperature on capital stocks, then using (11) to predict the effects of both temperature and the capital stock changes. The calculation is:

$$(12) \qquad \frac{d\ln y}{d\ln T} = 0.39\frac{d\ln k}{d\ln T} + 0.41\frac{d\ln h}{d\ln T} - 1.10$$

From equations (7) and (8) we get dln(k)/dln(T) = -3.67 and dln(h)/dln(T) = -2.18 (last two columns of Table 2.) Together, equations (7), (8), and (12) predict a steady-state effect equal to -3.425, almost exactly the same as equation (6).

The coefficients on ln(k), ln(h), and ln(T) can provide estimates of α, β, and γ. We can therefore also use (11) to calculate the steady-state effect of a temperature change using the formula $\psi = -\gamma/(1-\alpha-\beta)$. Equation (11) gives ψ = -1.10/(1-0.39-0.41) = -5.50, with standard error = 0.21. This figure is higher than our other estimates.

Estimates of α and β. The regression in (11) provides estimates of the share of physical and human capital in GDP, numbers that have been, on their own, of interest to researchers of economic growth. Our estimates are very close to common predictions. MRW suggest that α should equal roughly one third. We find that physical capital is roughly thirty-nine percent of GDP. We cannot reject the hypothesis $\alpha = 1/3$ (t=1.44).

MRW further suggest that β should be between one third and one half. Our estimate, 0.41, falls squarely in the middle of that range. Our estimate of β is closer to

MRW's prediction than their own estimate but it is unclear whether this is due to the addition of temperature or to our using a different measure of human capital.

Estimates of ψ Based on the Growth Model

Estimates of the growth model, equation (9), are shown in equation (13).

$$\ln y_{85} - \ln y_{80} = \underset{(2.12)}{1.21} - \underset{(2.54)}{0.268} \ln T - \underset{(0.57)}{0.012} \ln y_{80} \qquad R^2 = 0.08,\ n = 97 \tag{13}$$

To estimate the steady-state effect of temperature, we correct for possible bias by applying (10). Suppose $\lambda = 0.02$, as suggested by Sala-i-Martin; this is also close to the estimates in Table VI of MRW.[3] This value gives $b_2 = -0.095$. The variance of ln(T) is proportional to 0.0112. Using $\hat{b}_2 = -0.012$, equation (10b) implies that the covariance between lagged ln(y) and η is proportional to 7.4. We plug this value into (10a). The covariance of ln(T) and lagged ln(y) is proportional to 0.00149. (The proportionality is the same for $\hat{b}_1$ and $\hat{b}_2$.) Using $\hat{b}_1 = -0.268$, we get an estimate of the true $b_1 = -0.257$.

Our estimate of ψ is based on the "true" b_1 and b_2. These calculations give $\psi = -2.82$. This estimate is remarkably consistent with the estimates of the previous section.

Alternatively, we can use (10) and $\psi = -3.42$ to solve for the convergence rate λ. This yields $\lambda = 0.0158$, which is squarely in the range estimated by MRW.

Note that the introduction of temperature in the growth regression yields "conditional convergence" in income, a long-standing prediction of the Solow growth model

[3]Islam, using a more rigorous econometric procedure, estimates faster convergence. Since our estimation is similar to MRW and Sala-i-Martin, their estimates of λ are more appropriate for our calculations of ψ. MRW estimate λ between 0.0142 and 0.0206.

(Sala-i-Martin).[4] Conditional convergence means that among countries with the same y*, poorer countries grow faster than richer countries. This is implied by a negative coefficient on lagged income.

6. Implications for the Economic Effects of Global Warming

There are a wide variety of explanations for the income-temperature relationship. They have different implications about what would happen if temperatures got warmer as a result of global warming. We identify two categories. They differ depending on whether one thinks of climate's effects as *contemporaneous*, like the weather; or *historical*, like an initial condition. In terms of the formal model, the difference is between whether T_t or T_0 belongs in equation (1). Since past climate and current climate are virtually the same for our purposes, both explanations will look the same in our data in the absence of further restrictions.

Under the contemporaneous model, the current climate affects current production through, for example, the possible effects of temperature on labor productivity, capital productivity, labor supply, or "technology productivity." The alternative, historical model assumes that at some time in the past, climate played a role in production – possibly even a random role – but that this role is no longer important. Nevertheless, climate's past role would still be observable if, because of it, cooler countries had acquired higher levels of capital; these capital stocks would then lead to higher current incomes. Since the current climate is similar to past climate in the cross-section, a relationship between current temperature and income would still appear in the data.

---

[4]Conditional convergence is not exhibited for growth between 1985 and 1990. In that regression (not shown), $\ln(y_{85})$ has a positive, although insignificant, coefficient.

According to this latter explanation, Europe, for example, is rich today because it got a head-start, for reasons that are economically important and historically captivating but probably irrelevant to the global warming debate. A change in temperature might make Europe's climate more like Latin America's, but the head-start it got is unaffected, and Europe would continue to exhibit the high incomes that it does.

Only under the contemporaneous model case can we measure the effects of global warming using cross-sectional temperatures. This is possible because under the contemporaneous model a change in current temperature translates directly into a change in the production process. Under the historical model, a change in current climate could conceivably have no effect on production.

(Global warming might still, of course, have serious economic consequences in a dynamic context but they would not be measured by this paper's estimates. Such consequences would, presumably, require an adjustment cost component in which T_t could play a role.)

The Contemporaneous Model

When model (1) reflects the effects of contemporaneous climate, estimates of ψ can be converted into estimates of GDP changes. From the system of equations (6)-(8), we predict that when temperature increases by one percent, GDP is expected to fall by roughly 2.3 percent.

A two-degree Fahrenheit increase in average temperature in the U.S. ($T = 57.5$) translates to a three-and-a-half percent increase, which is predicted to lead to a 7.7 percent decrease in GDP using $\psi = -2.2$, our lowest estimate. GDP in the U.S. is calculated by Summers and Heston to be $16,570. Therefore, the two-degree temperature increase will lead to a loss of close to $1300 in per capita income.

We can also calculate the effect on total GDP for the entire 97 countries in our data set. We assume a two degree Fahrenheit (1.1 degree Celsius) increase in all temperatures, a figure that is within the range of most global warming predictions; we have not simulated different temperature increases for different latitudes. We predict that GDP for the 97 countries will decrease by close to one trillion dollars, or 7.4 percent.

The importance of these numbers depends on the strength of evidence for the contemporaneous versus the historical model. We turn to the historical model next.

7. The Potential Historical Role of Temperature

The historical model of climate's role can be better understood by specifying explicitly how climate's past effects might have been transmitted to current incomes. If the more prominent versions of the historical model can be shown not to apply, then the contemporaneous model may be strengthened as an explanation of the temperature-income relationship. On the other hand, new pathways for the transmission of climate's past role may yield complicated implications for the consequences of global warming.

This section examines transmission through (i) capital stocks, both human and physical, or (ii) political, economic, or social institutions. The latter category refers more generally to some sort of capital that makes other inputs valuable; it might be labeled "useful technology." We describe these further below.

We first examine the hypothesis that cooler countries obtained higher capital stocks (physical or human) at some time in the past, which those countries then used to build higher incomes today. As time passes, the effect of this initial condition will become smaller. This implication provides a testable hypothesis. Under this specification, we should see the effect of temperature diminish over time as all countries accumulate capital. This explanation also implies that countries with similar savings rates, labor participation, and technology growth will have similar steady-state incomes.

We use the model in (1) and drop the $T^{-\gamma}$ term.[5] A closed-form solution for non-steady-state income exists if the initial conditions satisfy $k_0 / h_0 = s_k / s_h$. Then y_t is:

(14) $$\ln(y_t) = (\alpha + \beta)\theta \ln(\frac{s_h^{\beta} s_k}{g_0} + k_0 e^{-g_0 t(1-\alpha-\beta)}) + \beta \ln s_h - \beta\theta \ln s_k$$

where $g_0 = n + g + \delta$. As t goes to infinity, equation (14) collapses to (2) with $\gamma = 0$.

Suppose $k_0 = \ln(a_0 T_0^{-\xi})$, where ξ is a measure of the effect of temperature on initial capital and a_0 is a scale parameter. Countries with cooler temperatures are presumed to be endowed with higher levels of both physical and human capital; *i.e.*, $\xi > 0$. A linear approximation of (14) gives:

(15) $$\ln(y_t) \approx a_1 - a_2 \xi e^{-g_1 t} \ln(T_0)$$

where a_1 and $a_2 > 0$ are functions of the other parameters, and $g_1 = g_0(1\text{-}\alpha\text{-}\beta)$. This model makes clear that a change in *current* temperature will have no effect on income and that estimates of ξ are therefore irrelevant in assessing the consequences of global warming. We now drop the T_0 subscript since for all of our models, T_0 and T_t are indistinguishable.

According to (15), the coefficient on ln(T) should diminish over time. To test this

[5]It is possible that climate has played multiple roles. We do not model those possibilities here.

prediction, we used (15) to model income growth, which yields:

(16) $$\ln(y_{t+1}) - \ln(y_t) \approx a_2 \xi e^{-g_1 t}(1 - e^{-g_1})\ln(T)$$

The estimated coefficient on ln(T) should be positive. (Note that a_2 should be country-specific in this model.) The estimated equation is:

(17) $$\ln(y_{85}) - \ln(y_{80}) = \underset{(2.84)}{0.95} - \underset{(2.86)}{0.23}\ln(T) \qquad R^2 = 0.08,\ n = 97$$

The coefficient on ln(T) is negative and significantly different from zero. Thus, we reject the capital-based specification of the historical model.

We next examine the hypothesis that climate's initial role was to affect the "stock" of political, social, or economic institutions. Note that this inheritance of institutions must be handed down through the institutions themselves, not through the wealth they leave subsequent generations, otherwise the previous specification applies. Such institutional "capital" will still affect capital productivity and therefore wealth accumulation.

Let $A_t = A_0 e^{gt} T_0^{-\gamma\omega t}$. Here, γ continues to represent the effect of temperature on GDP and ω represents the growth or decline of this effect over time. These effects cannot be distinguished. Note that if $\omega > 0$ then the temperature effect is increasing over time provided $\gamma > 0$. Steady-state per-capita income is given by:

(18) $$\ln y_t^* = wt \ln T_0 - (\alpha + \beta)\theta \ln(g_0 - \gamma\varpi \ln(T_0)) + \alpha\theta \ln(s_k) + \beta\theta \ln(s_h) + \theta \ln A_0 + \theta g t$$

with $w = -\gamma\omega\theta < 0$. Under (18), the effect of temperature is changing over time. This provides an hypothesis test and an estimable equation identical to (17). Take differences across time in (18) to get $\ln(y^*_{t+1}) - \ln(y^*_t) = -w\ln(T)$. A test of the hypothesis w = 0 fails based on the estimates in (17).

A more informative though less rigorous assessment comes from estimating equation (18) directly, albeit without the $\ln(g_0-\gamma\omega\ln(T))$ term. We estimated this equation, now the same as equation (6), for 1980, 1985, and 1990 using a sample of 84 countries. The results are:

(19a) $$\ln y_{80} = \underset{(13.62)}{21.79} - \underset{(8.56)}{3.28} \ln T \qquad R^2 = 0.47,\ N = 84$$

(19b) $$\ln y_{85} = \underset{(13.42)}{22.52} - \underset{(8.59)}{3.45} \ln T \qquad R^2 = 0.47,\ N = 84$$

(19c) $$\ln y_{90} = \underset{(12.97)}{23.30} - \underset{(8.43)}{3.62} \ln T \qquad R^2 = 0.46,\ N = 84$$

These regressions show temperature's effect becoming more pronounced over time, as in (17). They predict a growth rate of roughly 0.6 percent (at T = 68° F) and a temperature-dependent penalty ranging from 0.2 to 0.6 percent for each ten degrees. That is, a country with a 48° average temperature is predicted to grow at 1.8 percent per year, while a country with a 78° average temperature is predicted to grow at 0.2 percent.[6]

It is important to note that this specification still cannot distinguish between the contemporaneous and historical models of climate's effects. The reason is that our formula for A_t and equations (18) or (19) might be specified with either T_t or T_0. In other words, it remains unclear whether the institutions that currently exist in cooler countries will stand up to a change in climate or will begin to exhibit characteristics of institutions of countries with higher T's.

[6]These are based on changes in the coefficients of (19). Equation (17) gives lower estimates of growth, primarily because of the larger temperature penalty.

A similarly interesting but so far unknown pathway exists when A_t stands for the stock of useful technology. The idea that the "knowledge" stock is what leads to differences in income or growth is consistent with a recent piece by Sachs in which he argues that "for myriad reasons, the technological gains in wealthy countries do not readily diffuse to the poorest ones... Research and development of new technologies are overwhelmingly directed at rich-country problems." This argument suggests a potentially complex role for either T_0 or T_t. We leave such question for future research.

Our estimates do, however, lead *either* to a richer model of temperature's effect on growth (in the contemporaneous model) *or* to a different explanation of the transmission of early temperature-dependent economic advantages (in the historical model) other than that cooler countries happened to get rich early. The idea that cooler countries simply accumulated higher capital stocks at some time in the past is rejected by our regressions.

8. Further Comments

8.1 Measuring Climate

Our model includes a single measure of a country's temperature. In contrast, Mendelsohn, Nordhaus, and Shaw, in their study of climate's effects on U.S. land values, used four temperature and four precipitation variables plus squared terms, for a total of sixteen climate variables. We have not been able to find any other econometric studies of temperature and income.

The temperature measure we use can be defended on two grounds. First, a single climate variable is easiest to introduce into the production model and then to conduct comparative statics on. When our interest is global warming, some measure of long-run average temperature (rather than, say, temperature variability) will be the most useful single climate variable. We use average temperature in the capital city since this is where the largest single component of economic activity typically takes place, particularly in developing countries. It is also the place where climate's effects on institutions are most likely to be felt, if that is the path by which temperature affects income. Second, our temperature measure works.

Measurement of temperature, however, is really part of the larger question about climate's effects on income or production: If a more detailed specification of climate's role were available, it would then be possible to know more precisely which measures of temperature and other climate variables should be used in the regressions. We mention this issue next.

8.2 Climate's Role in Production and Income

Our model is obviously a simplification. The ways in which climate might affect GDP are subtle, complex, and multifarious. Temperature might affect the marginal product of labor differently from capital, and different types of capital are likely to be affected differently, as are different types of labor. Population growth, savings, and technological progress might also be affected. Quiggin and Horowitz argue that the main costs of an increase in temperature are almost sure to be adjustment costs, which do not exist in the Solow-Swan model.[7] It would be useful to derive a model that included and perhaps could test for at least some of these possibilities.

[7]Quiggin and Horowitz also argue that the costs of global warming, absent adjustment costs, will likely be small, a claim that this paper's results appear to contradict.

Consistent with these claims is the need for a richer model of production, especially one that might include natural resources, especially land and water, as input.

8.3 Future Research

Our estimates might be further refined by including a richer set of explanatory variables (savings rates, labor force participation, population growth) and a richer econometric model, as in Islam, Nerlove, and others. These advances must be balanced against possible problems from introducing endogenous variables as regressors, problems which temperature is less likely to invoke. We hope that our approach is bolstered by the high degree of consistency of our estimates (in the non-econometric sense) across different cross-section estimates and between the cross-section and growth models; and to a lesser extent by the closeness of our cross-section estimates of capital shares (α and β) to what has been predicted, though perhaps not so commonly found, in the literature.

The most important task for future research, we believe, is to develop a more "micro" theory of the relationship between temperature and income. There are many reasons other than those underlying the Cobb-Douglas model why temperature and income might show a strong relationship. Alternative explanations may have greatly different implications about what will happen if climates were to get warmer as a result of global warming.

In particular, it is possible that climate has affected the institutions that have facilitated economic growth (thereby explaining the current strong relationship), but that a change in climate will not affect those institutions once they have been established. It would be helpful to have models that distinguished between possible explanations, thereby providing more accurate evidence about the possible effect of global warming on incomes and growth.

9. References

Barro, R., and J.-W. Lee, "International Comparisons of Educational Attainment," *Journal of Monetary Economics* (December 1993) 32(3): 363-394.

Cho, D., and S. Graham, "The Other Side of Conditional Convergence," *Economics Letters* (1996) 50: 258-90.

Islam, N., "Growth Empirics: A Panel Data Approach," *Quarterly Journal of Economics* (November 1995) 110(4): 1127-70.

Kamarck, A., *The Tropics and Economic Development*. Baltimore: Johns Hopkins University Press, 1976.

King, R.G., and R. Levine, "Capital Fundamentalism, Economic Development, and Economic Growth," *Carnegie-Rochester Conference Series on Public Policy* (1994) 40: 259-92.

Mankiw, G., D. Romer, and D. Weil, "A Contribution to the Empirics of Economic Growth," *Quarterly Journal of Economics* (1992) 108: 407-37.

Mendelsohn, R., W. Nordhaus, and D. Shaw, "The Impact of Global Warming on Agriculture: A Ricardian Analysis," *American Economic Review* (Sept. 1994) 84(4): 753-71.

Nerlove, M., "Growth Rate Convergence: Fact or Artifact?" in *Festschrift for Pietro Balestra*, J. Krishnakamur and E. Ronchetti, eds. Amsterdam: North-Holland, 1999.

Nordhaus, W.D., "Climate and Economic Development: Climates Past and Climate Change Future," in *Proceedings of the World Bank Annual Conference on Development Economics 1993*, The World Bank, 1994.

Quiggin, J., and J. Horowitz, "The Impact of Global Warming on Agriculture: A Ricardian Analysis: Comment," *American Economic Review* (Sept. 1999) 89(4).

Ram, R., "Tropics and Economic Development: An Empirical Investigation," *World Development* (1997) 25(9): 1443-52.

Sachs, J., "Helping the World's Poorest," *The Economist* (August 14, 1999).

Sachs, J., and A. Warner, "Fundamental Sources of Long-Run Growth," *American Economic Review* (May 1997) 87(2): 184-88.

Sala-i-Martin, X., "The Classical Approach to Convergence Analysis," *Economic Journal* (July 1996) 106: 1019-36.

Solow, R., "A Contribution to the Theory of Economic Growth," *Quarterly Journal of Economics* (1956) 70: 65-94.

Summers, R., and A. Heston, "The Penn World Table (Mark 5): An Expanded Set of International Comparisons, 1950-1988," *Quarterly Journal of Economics* (May 1991) 2:327-368.

Swan, T.W., "Economic Growth and Capital Accumulation," *Economic Record* (November 1956) 32: 343-61.

Theil, H., and D. Chen, "The Equatorial Grand Canyon," *De Economist* (1995) 143(3): 317-27.

Tol, R., "The Damage Costs of Climate Change Towards a Dynamic Representation," *Ecological Economics* (1996) 19: 67-90.

Wood, R. A. (ed.), *The Weather Almanac*, Eighth edition. New York: Gale Research, 1998.

List of Countries (n=97)

ALGERIA
ARGENTINA
AUSTRALIA
AUSTRIA
BANGLADESH
BARBADOS
BELGIUM
BOLIVIA
BOTSWANA
BRAZIL
CAMEROON
CANADA
CENTRAL AFR. REP.
CHILE
COLOMBIA
CONGO
COSTA RICA
CYPRUS
DENMARK
DOMINICAN REP.
ECUADOR
EGYPT
EL SALVADOR
FIJI
FINLAND
FRANCE
GAMBIA
GERMANY, WEST
GHANA
GREECE
GUATEMALA
GUYANA
HAITI
HONDURAS
HONG KONG
ICELAND
INDIA
INDONESIA
IRAN
IRAQ
IRELAND
ISRAEL
ITALY
JAPAN
JORDAN
KENYA
KOREA, SOUTH
KUWAIT
LESOTHO
LIBERIA
MALAWI
MALAYSIA
MALI
MALTA
MAURITIUS
MEXICO
MOZAMBIQUE
MYANMAR
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NORWAY
PAKISTAN
PANAMA
PAPUA-NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
PORTUGAL
RWANDA
SENEGAL
SIERRA LEONE
SINGAPORE
SOUTH AFRICA
SPAIN
SRI LANKA
SWAZILAND
SWEDEN
SWITZERLAND
SYRIA
TAIWAN
THAILAND
TOGO
TRINIDAD & TOBAGO
TUNISIA
TURKEY
U.K.
U.S.A.
U.S.S.R.
URUGUAY
VENEZUELA
ZAIRE
ZAMBIA
ZIMBABWE