A Production Function Approach to the GDP-Temperature Relationship*

by

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Hotter countries tend to be poorer. In this paper, we estimate the income-temperature relationship for a cross-section of 97 countries. The relationship is distinct and powerful. A simple regression of the log of per capita GDP against log of average temperature in the capital city shows that temperature explains more than forty-five percent of the variance in income. A one percent increase in temperature is associated with a decrease in per capita GDP of between 2.0 and 3.5 percent.

We investigate the income-temperature relationship using a Cobb-Douglas production function with temperature added as an input along with physical and human capital. A property of this model is that temperature lowers the marginal product of physical and human capital, which further implies that hotter countries will accumulate lower levels of these forms of capital. We discuss the evidence for these propositions.

We also discuss different explanations of the income-temperature relationship, which are shown to 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 predict that a 2 degree F increase in average temperatures will lead to a 7.7 percent decrease in U.S. GDP and a 7.4 percent decrease in total GDP among the 97 countries in our data. Our estimates provide rare econometric evidence about possible economic consequences of global warming.

1. Introduction

It has long been noted that the economies located in temperate zones are more developed than those in the tropics (Kamarck; Ram; Theil and Chen). The relationship between a country's income and its average temperature, with hotter countries being poorer, is not difficult to see; most curious people will have noted its existence and contemplated its roots. Figure 1 shows the data, which exhibit a clear downward slope between temperature and income per capita for 97 countries in 1985 (see Section 4 for a description of the data.) The statistics reveal not only a distinct pattern but a powerful one: A simple regression of log of per-capita GDP against log of average temperature in the capital city shows that temperature explains forty-five percent of the variance in log-income. The regressions show that temperature indeed has a strong association with per capita income.

In this paper, the income-temperature relationship is investigated using a Solow-Swan growth model with both human and physical capital, based on Mankiw, Romer, and Weil. Temperature is added as an input into the underlying Cobb-Douglas aggregate production function.

A property of this model is that a higher temperature lowers the marginal product of both physical and human capital, which further implies that hotter countries will accumulate lower levels of the two forms of capital. We find evidence for each of these effects. A one percent increase in temperature is associated with a decrease in per-capita GDP of between 2.0 and 3.5 percent. 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 predicted to occur even if capital stocks were held constant. These results do not “explain” why temperature apparently affects the marginal productivity of physical or human capital, but they do give structure to our understanding of the income-temperature relationship.

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 difference between Switzerland’s per-capita GDP ($14,864 in 1985) and Austria’s GDP ($11,131) gives a possible prediction of the economic effect of this climate change. Of course, there are many possible reasons for cooler countries to be richer on average than warmer ones, many of which do not yield implications about the effects of a temperature *change*. But the possibility that the income-temperature relationship contains a clue about the economic consequences of global warming makes it compelling for research. To the extent that regression analysis does help predict global warming’s effects, it provides valuable econometric evidence on a subject for which there has so far been mostly only indirect econometric work.[1]

The different explanations of the income-temperature 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 2 degree F increase in all temperatures, which is an 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 degree 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]

The purpose of this paper is to derive a joint model of temperature, income, and physical and human capital. We aim to show that a production function approach is an appropriate, useful, and rigorous framework in which to do this. This framework imposes a specific set of functional forms and focuses on cross-section rather than panel data. The findings set the stage for further research into temperature's role in the individual sectors of an economy; we start with the aggregate economy here.

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[1] We have found no other published estimates of the income-temperature relationship. The closest we found in the modern economics literature is Nordhaus (1994), who gives primarily a qualitative assessment of possible relationships. He states that for a temperature range of 40 and 65 degrees 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.

[2] The exception is Mendelsohn, Nordhaus, and Shaw, who looked at the relationship between quarterly temperatures and precipitation and land prices in agricultural counties in the U.S.

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 return to a basic concept about climate, namely that it is a "natural resource" that operates as an input in the production function. We enter it as a multiplicative input in a Cobb-Douglas production function, just as with the other inputs. Under this view, a higher average temperature decreases the marginal product of the two forms of capital.

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

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

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:

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

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*:

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

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

3. Econometric Specification

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

$$\ln y = a_2 + \psi_2 \ln T + \varepsilon \tag{5}$$

$$\ln k = a_3 + \psi_3 \ln T + \upsilon \tag{6}$$

$$\ln h = a_4 + \psi_4 \ln T + \nu \tag{7}$$

where the errors are functions of country-specific savings, population growth, and technology. The ln(T) coefficient is our estimate of the steady-state effect of temperature.[3]

Equations (5)-(7) 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 ψ_i = ψ_j.

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[3] The functional form assumption in (5) is strong but necessary to connect the estimates of income, physical capital and human capital; that is, to impose the restrictions implied by model (1).

4. Data

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.[4]

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 from Summers and Heston.

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[4] Our analysis treats OECD and non-OECD countries together, as do MRW for their main results (although they also analyze OECD countries alone.) While we do not wish to gloss over the possibility that temperature might affect OECD countries differently from non-OECD countries, we also wish to examine the extent to which the observed temperature-GDP-capital relationship (across all countries) is consistent with the Solow-Swan/MRW model. Sections 7 and 8 suggest ways by which the OECD-temperature correlation might be understood in the context of our model.

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. The use of a single city's temperature to represent a nation's climate is discussed in Section 5. We 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. (^{o}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 (8)-(9). In the single equation regressions (Table 2), temperature accounts for forty-five percent of the variance in income and twenty-seven and thirty-six percent of the variance in physical and human capital. Estimates of ψ range from -2.0 to -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 we estimate the full system of equations (5)-(7), we obtain $\psi = -2.29$.

Table 2. The Effect of Temperature on Income and Capital

	ln(y) #(5)	**ln(k)** #(6)	**ln(h)** #(7)
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

	(5) & (6)		(5) & (7)		(6) & (7)		(5), (6) & (7)		
	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:

$$\ln y = \underset{(7.75)}{8.74} + \underset{(9.59)}{0.39}\ln k + \underset{(4.76)}{0.41}\ln h - \underset{(4.57)}{1.10}\ln T \qquad R^2 = 0.87,\ n = 97 \tag{8}$$

Equation (8) 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 (5)) when physical and human capital also adjust to the higher temperature.

An estimate of the steady-state effect can be derived using equations (6) and (7) to predict the effect of temperature on capital stocks, then using (8) to predict the effects of both temperature and the capital stock changes. The calculation is:

$$\frac{d\ln y}{d\ln T} = 0.39\frac{d\ln k}{d\ln T} + 0.41\frac{d\ln h}{d\ln T} - 1.10 \tag{9}$$

From equations (6) and (7) we get dln(k)/dln(T) = -3.66 and dln(h)/dln(T) = -2.18 (last two columns of Table 2.) Together, equations (6), (7), and (9) predict a steady-state effect equal to -3.42, the same as equation (5).

The coefficients on ln(k), ln(h), and ln(T) can provide estimates of $\alpha, \beta,$ and γ. We can therefore also use (8) to calculate the steady-state effect of a temperature change using the formula $\psi = -\gamma/(1-\alpha-\beta)$. Equation (8) 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 (8) provides estimates of the share of physical and human capital in GDP, numbers that have been, on their own, of interest to economists. 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 differences in the sample or different measures of human capital.

Further Issues

Other Explanatory Variables. Regression (5) is an extremely spare reduced form that excludes many variables often used in explaining GDP. This exclusion is purposeful since many of the typical explanatory variables have some degree of endogeneity. These include savings rates, depreciation, labor force participation, and population growth; measures of natural resource endowment such as share of natural resources or agriculture in GDP; and measures of government or institutional quality. The possibility that these variables are themselves influenced by temperature is potentially informative and cannot be dismissed. Including them as explanatory variables would clearly be undesirable here. Other excluded variables that are more clearly exogenous may, however, be useful for future research; a prominent one is an estimate of oil resources. Excluding this or other exogenous variables, as we have done, could distort the observed income-temperature relationship although it is difficult to say how important this distortion might be or even in what direction. We leave this issue for a subsequent paper.

At least one form-of-government might be considered exogenous, namely being a former Soviet republic. We give a brief picture of this issue next.

Former Soviet Union. We used 1985 data in the preceding analysis because it had the most complete set of physical and human capital. This has the unfortunate consequence of treating the fifteen former Soviet countries as one data point.

To see the income-temperature relationship for the former Soviet countries, we used 1998 GDP and population data from the *World Development Report* (PPP index) to estimate (5). The result is:

$$\ln y = \underset{(6.37)}{14.77} - \underset{(5.86)}{3.49} \ln T \qquad R^2 = 0.73,\ n = 15 \tag{10}$$

The results are remarkably close to the rest of our estimates. They show that a one percent increase in temperature leads to a 3.49 percent decrease in GDP per capita, almost exactly the same as equation (5) in Table 2. They further show a strong relationship between temperature and income as captured by the R^2 of 0.73.

Aggregate Production and the Measurement of Temperature. Although it is common in the income and growth literature to use aggregate measures of inputs such as physical and human capital, less is known about the role for "representative" temperature.

Furthermore, having chosen to work with a representative temperature, we must then select the temperature to use. Alternatives to using the capital city's temperature pose the following sorts of problems. A country's temperature averaged over the entire country will include economically irrelevant areas (think of Canada). Weighting temperatures by the amount of economic activity in an area introduces endogeneity, since this is in part a manifestation of what we hope to explain. We chose the capital city for our analysis because it seemed the "most exogenous" and still likely to be representative of the conditions under which productive activity takes place in each country.[5]

To examine the income-temperature relationship under the possibility that the capital city's climate is not sufficiently representative, we dropped the seven largest countries (Canada, USSR, U.S., Brazil, India, Australia, Argentina), since these countries are most likely to have substantial spatial temperature variation. This leaves a sample in which temperatures across the country are more likely to be uniform.[6] The result is:

$$\ln y = \underset{(12.98)}{22.52} - \underset{(8.38)}{3.46} \ln T \qquad R^2 = 0.44,\ n = 90 \tag{11}$$

If there is an error-in-variables problem with the capital city's temperature, then dropping these seven countries (for which the error is likely to be largest) should increase the absolute value of the estimate of ψ. (Note that the coefficient in (10) may be providing a similar test.) We find that the estimated coefficient is slightly larger in absolute value but not substantially so. This test is crude, and clearly more research would be useful, but we conclude that there is sufficient evidence to warrant using the capital city's temperature for this paper's purposes.[7]

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[5] A country's geographic center, for example, is exogenous but not necessarily representative of the temperatures under which economic activity occurs. The largest city may be more representative but is "less exogenous" than the capital city. This line of inquiry suggests a further research question about whether countries have tended to set their capitals in places that are cooler than the rest of the country, as in Australia and India.

[6] A measure of spatial temperature variation would be difficult to construct. What is important for our purpose is that the excluded countries have spatial variation that is above average. We also tried dropping three other countries with what appeared to us to be substantial economically relevant spatial temperature variation: Colombia, Japan, and Mexico. The coefficient in the ln(y) equation was –3.43 (N = 87), again essentially the same as in Table 2.

[7] We have addressed this question solely in the context of the aggregate production function. As we have stated, further research into temperature's role in individual economic sectors remains to be conducted.

<u>Production Function Estimates without Temperature</u>. Temperature's role in production might also be demonstrated by looking at an estimate of the production function with temperature excluded. This is shown in (12).

$$\ln y = \underset{(12.23)}{3.74} + \underset{(9.28)}{0.41}\ln k + \underset{(6.37)}{0.56}\ln h \qquad R^2 = 0.84,\ n = 97 \tag{12}$$

These results show a much different picture of the role of physical and human capital in production, particularly human capital as measured by average education, and show the potential error of excluding temperature. The large change in the coefficient on ln(h) suggests that the returns to education may especially be affected by temperature.[8]

6. Relationship to Growth Literature

For the sake of comparison with growth studies, we also show the implications of the model for economic growth. Growth is given by the equation:

$$\ln y_t - \ln y_{t-k} = (1 - e^{-\lambda k})\ln y^* - (1 - e^{-\lambda k})\ln y_{t-k} \tag{13}$$

The convergence rate is $\lambda = (n + g + \delta)(1 - \alpha - \beta)$. Typically, however, equation (13) is used to infer λ, which is also then assumed constant across countries.[9]

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[8] An F-test of constant returns to scale, $\alpha + \beta = 1$, cannot be rejected (F =0.21). This test, however, must be viewed skeptically, since the estimates in (12) are biased by the exclusion of temperature.

[9] Recent research has pointed out empirical problems with the MRW growth 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 countries experienced negative per capita growth between 1980 and 1985. A smaller but still sizeable proportion, twenty-eight of eighty-four countries, 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.

Estimation is complicated by the fact that y* is unobservable and must either be proxied (as in Sala-i-Martin) 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 and use equation (5) to model y*. The estimated equation is:

$$\ln y_{1985} - \ln y_{1980} = b_0 + b_1 \ln T + b_2 \ln y_{1980} + \eta \tag{14}$$

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

$$E\hat{b}_1 = b_1 - \frac{1}{\Delta}\operatorname{cov}(\ln(T),\ln(y_{1980}))\operatorname{cov}(\ln(y_{1980}),\eta) \tag{15a}$$

$$E\hat{b}_2 = b_2 + \frac{1}{\Delta}\operatorname{var}(\ln(T))\operatorname{cov}(\ln(y_{1980}),\eta) \tag{15b}$$

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

Estimates of ψ Based on the Growth Model

Estimates of the growth model, equation (14), are shown in equation (16).

$$\ln y_{85} - \ln y_{80} = \underset{(2.12)}{1.21} - \underset{(2.54)}{0.268}\ln T - \underset{(0.57)}{0.012}\ln y_{80} \qquad R^2 = 0.08,\ n = 97 \tag{16}$$

To estimate the steady-state effect of temperature, we correct for possible bias by applying (15). Suppose $\lambda = 0.02$, as suggested by Sala-i-Martin; this is also close to the estimates in Table VI of MRW.[10] This value gives $b_2 = -0.095$. The variance of ln(T) is proportional to 0.0112. Using $\hat{b}_2 = -0.012$, equation (15b) implies that the covariance between lagged ln(y) and η is proportional to 7.4. We plug this value into (15a). 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 (14), (16), 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 (Sala-i-Martin).[11] 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.

7. Explanations for the Income-Temperature Relationship and their Implications for Global Warming

There are a wide variety of explanations for the income-temperature relationship exhibited in Figure 1. Indeed, the difficulty for researchers is not in coming up with an explanation but in trying to narrow down the vast array of candidates, both sensible and far-fetched. They range from differences in labor productivity in different climates; to

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[10] Islam 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. See Nerlove for a different view of the convergence problem.

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. An editorial in *The Straits Times* of Singapore considers whether a "rash of killer-litter incidents" – people being killed by flowerpots and other items being tossed out of windows – is due to high heat: "Does extreme afternoon heat in west-facing [apartment] blocks alter moods?" Put this in a macroeconomic model and it yields yet another explanation for the income-temperature relationship.

In this paper we do not attempt to discriminate among these explanations. For our purposes, the explanations are most important for how they might be incorporated into the production function model and for their implications about what would happen if temperatures got warmer as a result of global warming.

In general, explanations differ depending on whether one thinks of climate's effects as *contemporaneous*, like other inputs; or *historical*, like an initial condition. In terms of the formal model, the difference is between whether current temperature (T_t) or past temperature (say, T_0) belongs in equation (1); that is, whether current or past conditions are the root of the income-temperature relationship. Since past and current temperature are virtually identical, both explanations will look the same in our data in the absence of further restrictions. Yet only when current temperature is the productive input will our estimates have much to say about the effects of global warming.

Under the contemporaneous model, the current climate affects production through, for example, the possible effects of temperature on labor productivity, capital

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

productivity, labor supply, or "technology productivity." Under the alternative historical model, climate played a role in production at some time in the past – possibly even a random role – but 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.

According to this latter explanation, Europe, for example, is rich today because it got a head-start, for reasons that are economically and historically important 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 Economic Costs of Global Warming

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 (5)-(7), 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 ψ = -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.[12]

We can also calculate the effect on total GDP for the entire 97 countries in our data set. We assume a 2 degree Fahrenheit (1.1c) 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. It is not possible, unfortunately, to distinguish between these models based on the current data.

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[12] The log-log specification, while necessary for our cross-equation restrictions, may yield particularly large estimates of the costs of global warming because it imposes a constant percentage effect. This is costly since a given temperature increase becomes a higher percentage increase in cooler countries, which also happen to be richer. Several readers have pointed out that the true relationship should be hump-shaped (as Quiggin and Horowitz also argue) since both very hot and very cold climates preclude economic activity. The steady-state for this form of production fuction is difficult to derive; we leave it for future research.

It is, however, possible to examine the question: If the historical model were true, how were the initial conditions, namely temperature's effects, transmitted to current conditions? We turn to this next.

8. The Potential Historical Role of Temperature: An Observation

We first examine the hypothesis that cooler countries obtained *higher physical or human capital stocks* at some time in the past, which those countries then used to build higher incomes today.

Our key observation is that as time passes the effect of this initial condition should become smaller. This implication provides a testable hypothesis. Under this hypothesis, 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.

An informative initial assessment comes from estimating (5) for 1980, 1985, and 1990 using a sample of 84 countries. The results are:

(17a) $$\ln y_{80} = \underset{(13.62)}{21.79} - \underset{(8.56)}{3.28} \ln T \qquad R^2 = 0.47,\ N = 84$$

(17b) $$\ln y_{85} = \underset{(13.42)}{22.52} - \underset{(8.59)}{3.45} \ln T \qquad R^2 = 0.47,\ N = 84$$

(17c) $$\ln y_{90} = \underset{(12.97)}{23.30} - \underset{(8.43)}{3.62} \ln T \qquad R^2 = 0.46,\ N = 84$$

These results show temperature's effect becoming more pronounced over time, not less.

To model this case explicitly, we return to the MRW model without temperature.[13] 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:

$$(18) \qquad \ln y_t = (\alpha+\beta)\theta \ln\left(\frac{s_h^{\beta} s_k}{g_0} + k_0 e^{-g_0 t(1-\alpha-\beta)}\right) + \beta \ln s_h - \beta\theta \ln s_k$$

where $g_0 = n + g + \delta$. As t goes to infinity, equation (18) 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, T_0 is "initial temperature," 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 (18) gives $\ln(y_t) \approx a_1 - a_2 \xi e^{-g_1 t} \ln(T_0)$ where a_1 and $a_2 > 0$ are functions of the other parameters, and $g_1 = g_0(1-\alpha-\beta)$. This model makes clear that under the historical explanation, a change in current temperature would have no effect on income and that estimates of ξ would therefore be irrelevant in assessing the consequences of global warming. We now drop the time subscript since for all of our models T_0 and T_t are indistinguishable.

According to (18), the coefficient on ln(T) should diminish over time. To test this prediction, we used (18) to model income growth, which yields:

$$(19) \qquad \ln y_{t+1} - \ln y_t \approx a_2 \xi e^{-g_1 t}(1 - e^{-g_1}) \ln T$$

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

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

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

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

Technological and Institutional Capital

We return to the basic model in (1). The variable A_t is used to capture a wide variety of technological and institutional – political, economic, and social institutions – capital, of the sort that makes other inputs valuable. For simplicity, call this "TI capital." The idea that this TI 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."

Suppose that at some time in the past, cooler countries accumulated *higher stocks of TI capital*; that is, they developed institutions and technologies that increased the output achieved from their physical and human capital. As with the previous example, a change in current temperature could then conceivably have little effect on incomes, since those TI capital stocks are already in place, in which case the coefficient in (5) then merely captures the initial temperature-A_0 relationship. Unlike the physical capital example, however, the effect of this initial condition will not become smaller over time and may even increase if there is growth in TI productivity.

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.

While it seems clear from this analysis that cooler countries have better institutions or technologies, it remains unclear whether it is past or current climate that affects these. That is, 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 temperatures. The idea that cooler countries simply accumulated higher capital stocks at some time in the past, however, is so far rejected.[14]

9. Concluding Comments

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 chose our temperature specification because 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 will be the most useful single climate variable.

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

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[14] Another pertinent observation, with respect to choosing the temperature measure, is that the capital city is often likely to be the "seat" of TI capital; that is, the place where many of a country's institutions are based.

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.

Climate's Role in Production

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.[15] It would be useful to derive a model that included and perhaps could test for at least some of these possibilities.

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

Future Research

We have not attempted to identify the pathway by which temperature affects output in the production function in (1). The most important task for future research, we believe, is to develop and test more sophisticated theories about this pathway. As we have emphasized, alternative explanations may have greatly different implications about

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[15] 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.

what will happen if climates were to get warmer as a result of global warming, so distinguishing between those explanations becomes important.

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*. Johns Hopkins Univ. 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. 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.

The Straits Times (Singapore), "And still it falls (editorial)," July 16, 2000.

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.

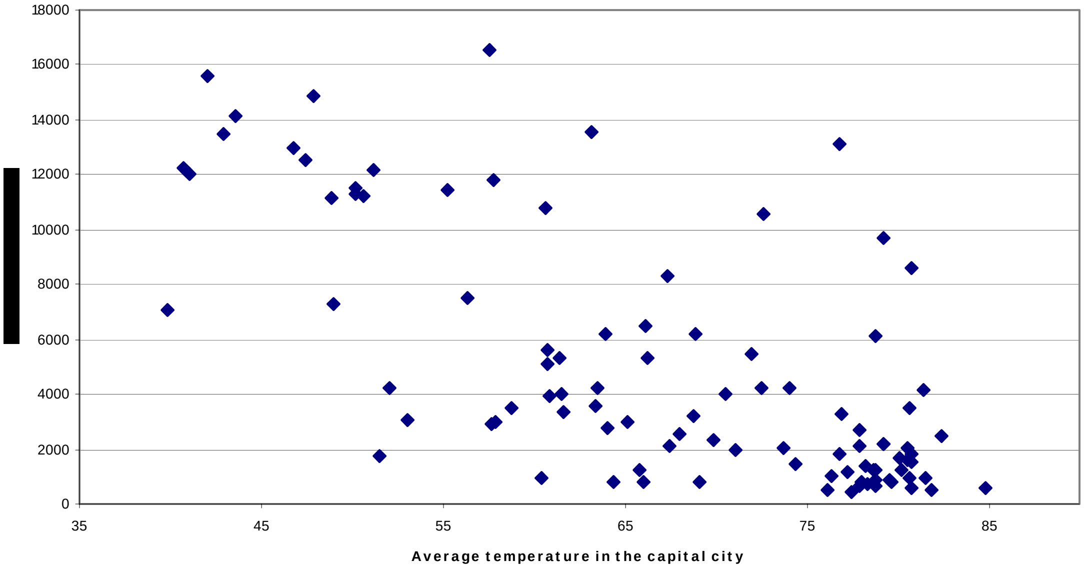
Theil, H., and D. Chen, "The Equatorial Grand Canyon," *De Economist* (1995) 143(3): 317-27.

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

World Development Report, Washington DC: The World Bank, 1998.

Wood, R. A. (ed.), *The Weather Almanac*, 8th edition. New York: Gale Research, 1998.

Figure 1. The GDP-Temperature Relationship for 97 Countries



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