

The Income–Temperature Relationship in a Cross-Section of Countries and its Implications for Predicting the Effects of Global Warming

John K. Horowitz

Accepted: 19 May 2009 / Published online: 19 June 2009
© Springer Science+Business Media B.V. 2009

Abstract Hotter countries are poorer on average. This paper attempts to separate the historical and contemporaneous components of this income–temperature relationship. Following ideas by Acemoglu et al. (Am Econ Rev 91(5):1369–1401, 2001), we use colonial mortality data to account for the historical role of temperature since colonial mortality was highly correlated with countries’ average temperatures. The remaining income–temperature gradient, after colonial mortality is accounted for, is most likely contemporaneous. This contemporaneous effect can be used to estimate the consequences of global warming. We predict that a 1°C temperature increase across all countries will cause a decrease of 3.8% in world GDP. This prediction is robust across functional forms and an alternative method for separating historical effects.

Keywords Climate change · Global warming · Gross domestic product · Settler mortality

1 Introduction

Climate change will likely have substantial effects on human material well-being. The predicted size of the effects is an important part of the discussion about the policies that governments should adopt to reduce greenhouse gas emissions. These predictions are based on qualitative assessments and quantitative modeling and, to a lesser extent, econometric analysis of the economic role of climate. Econometric analysis in this context is laden with more than the usual reservations and conditions but is valuable because economists take econometric evidence more seriously than other evidence or argument.

J. K. Horowitz (✉)
Department of Agricultural and Resource Economics, University of Maryland, College Park,
MD 20742-5535, USA
e-mail: jhorowit@umd.edu
URL: <http://faculty.arec.umd.edu/jhorowitz/>

J. K. Horowitz
Economic Research Service, U.S. Department of Agriculture, Washington, DC, USA

In undertaking econometric analysis of the economic role of climate, analysts can take two approaches. One approach is to examine climate's role in specific sectors, primarily agriculture (Dechênes and Greenstone 2007; Maddison et al. 2007; Mendelsohn et al. 1994; Schlenker et al. 2004) and health (Chima et al. 2003; see also papers cited in Bosello et al. 2006), and then to construct an overall prediction of climate change impacts by aggregating these sectors. Tol (2002) provides a particularly thorough example of this approach. A second approach is to examine climate and incomes directly. This income-based approach, while less specific than the sectoral approach, is appealing precisely because it does not require us to specify the exact pathways for climate's effects. By focusing directly on climate and income, analysts do not have to be concerned about capturing effects in each and every sector or about correctly accounting for pathways that cut across sectors.¹ As Dell et al. (2008) write, this income-climate approach "examines aggregated outcomes directly, rather than relying on a priori assumptions about what mechanisms to include and how they might operate, interact, and aggregate" (p. 2).

Econometric analysis of the income-temperature relationship appears promising because temperature has a strong and robust relationship to per capita income: Hot countries are poorer than cool countries, as we show below. The broad form of this relationship is easy to recognize and has long been remarked on (see discussions in Acemoglu et al. 2002; Easterly and Levine 2003; Kamarck 1976). The relationship has also played an important although often indirect (in the form of latitude or a dummy variable for *tropics*) role in many recent studies of development and growth.

There are, of course, many possible reasons why hotter countries are mostly poorer, such as climate's effects on disease, agriculture, capital depreciation, worker productivity, or human behavior, say in the form of culture or institutions. The number of candidate pathways is large; Nordhaus (1994) gives a particularly wide-ranging discussion of how temperature has been viewed as a factor in economic activity, particularly at the individual level, as when worker or student performance is affected by ambient temperature.

The most important distinction, however, is not among these various paths but between effects that are *contemporaneous*, that is, due to current climate, and those that are *historical*, that is, due to past climate. Historical effects are those that arose because climate played a role at some time in the past, but this role is no longer important. In other words, cool climates may have given some countries a head-start but the reason for that head-start no longer affects current economic performance. Climate's past role would still be observable if because of it cooler countries acquired higher levels of capital or better institutions, which would then lead to higher current incomes. Since current climate is similar to past climate in the cross-section, a relationship between current temperature and income would still appear in the data. Note that all of the candidate pathways—disease, agriculture, capital depreciation, worker productivity, institutions—could conceivably be contemporaneous, historical, or a combination of both.

The distinction between contemporaneous and historical effects is crucial because only when climate's effects are contemporaneous does the cross-sectional income-temperature relationship yield evidence about possible economic effects of global warming. If the income-temperature relationship is due to historical causes then global warming could still have a possibly strong effect on incomes but the cross-sectional income-temperature relationship would not yield any information about its magnitude. The widespread belief is that the income-temperature relationship is mostly historical. We generally concur.

¹ See Quiggin and Horowitz (2003) for an example of how climate effects on agriculture would show up in transportation rather than the agricultural sector.

The purpose of this paper is to separate econometrically the historical and contemporaneous effects of temperature. This task requires us first to specify the historical pathway by which temperatures affected early incomes. Acemoglu et al. (2001) (AJR) have recently made great gains in identifying a potential historical path. They argue that potential mortality rates of early colonizing settlers had a profound effect on the institutions that were set up in those colonies. These institutional differences persist to this day (because of transactions costs, collective choice problems, and irreversible investment), they argue, and have strong effects on current per capita incomes. Because colonial mortality and average temperature are highly correlated (as we show), the mortality-institution-income relationship also manifests itself as an income–temperature relationship.

Thus, the main thrust of this paper is to use the colonial mortality data reported in AJR to capture the historical effect of temperature on current incomes.² We then interpret any remaining temperature effects as contemporaneous. Historical effects of temperature are shown to account for roughly sixty percent of the cross-sectional income–temperature relationship. We attribute the residual forty percent to temperature’s contemporaneous effect and use this estimate to predict the effects of climate change on world GDP.

Our results do not require that colonial mortality be determined solely or even mostly by temperature, although a role for climate is highly plausible and we frame our discussion based on this assumption. We are claiming instead that colonial mortality wholly captures the “head start” that countries experienced to varying degrees, a position convincingly argued by AJR. This fact is sufficient for our results. A weaker but still sufficient assumption for our interpretation is that any “head start” not captured by colonial mortality is uncorrelated with temperature. We do not test this assumption directly (and have little reason to pursue it given AJR’s exhaustive analysis). It appears reasonable for the set of OECD countries, however, in which case their income–temperature relationship presents an alternative method of identifying the contemporaneous temperature effect. We show that this relationship is almost identical to the one estimated using colonial-era mortality.

Two other approaches (Dell et al. 2008; Nordhaus 2006) may provide information that allows researchers to separate contemporaneous and historical temperature effects. We discuss their contributions below.

Section 2 presents a model and describes the data. Section 3 first shows the total temperature effect which must then be apportioned between contemporaneous and historical effects; it then shows the temperature effect conditional on colonial mortality. Section 4 presents an alternative approach and discusses other estimates available in the literature. Predictions and concluding comments are in Sect. 5.

2 Data and Model

2.1 Data

We conduct cross-sectional regressions of income per-capita against long-run average temperature and other explanatory variables. A scatter plot of the data is shown in Fig. 1. A list of countries in each of our samples is in the “Appendix”.

² Diamond (1997) argues qualitatively that suitability for grain production, including the size of areas similarly suitable, also gave particular civilizations an advantage in development. This historical explanation does not lend itself as readily to statistical analysis as the colonial mortality explanation of AJR. The *Guns, Germs, and Steel* explanation may account in part for colonial mortality, in which case the colonial-mortality-based estimates would incorporate the historical effects propounded by Diamond.

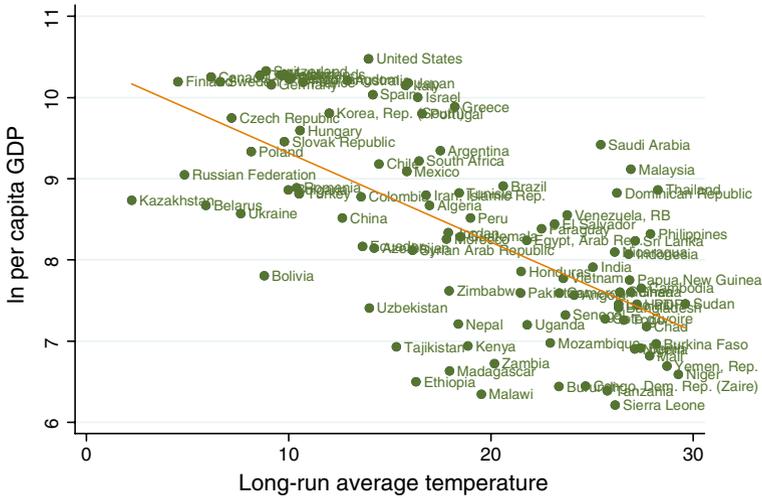


Fig. 1 The income–temperature gradient for 100 countries. This figure shows a log-linear regression with no other covariates (slope = -0.11)

2.1.1 *Dependent Variable*

As our income measure we use average GDP per capita measured using purchasing power parity in constant 2000 international dollars, published by the World Bank. Because of possible year-to-year variability, we use the average GDP per capita over the 3 year period 2002–2004. The exception is Haiti, which is missing GDP data for 2004 and whose average was therefore calculated over 2002 and 2003. Note that GDP is likely to better reflect temperature’s effects than GNP, which includes economic activity outside the country.

There are several temperature-related issues that arise in our measure of income. Heating expenditures in cold countries are considered a “plus” but the amenity value of the climate when space heat is not needed is not included. This difference has the effect of exaggerating the utility losses from higher temperatures. Put another way, the income–temperature relationship and any implied measure of the cost of higher temperatures excludes the amenity value of climate. Air-conditioning expenses cause a problem in the opposite direction but on a global scale these are less important than heating expenses.

The income measures also exclude non-market goods such as pollution and greenery. Drinking water quality and quantity are accounted for only partially, since there are many non-market aspects to these marketed goods. To the extent that these non-market and quasi-market goods are affected by temperature, the observed income–temperature relationship will differ from the true utility–temperature relationship. If pollution’s effects are exacerbated by warm temperatures or if drinking water is scarcer in warmer countries (with scarcity unreflected in the price), then the observed income–temperature will underestimate the consequences of higher temperatures.

2.1.2 *Temperature*

Many different climate measures are possible. Since our interest is in global warming, some measure of long-run average temperature will be the most useful single climate variable. It is important to note that the “best” climate measure(s) is both a question and an answer.

That is, if economists had a better understanding of how climate affects incomes then it would be clear which climate variables would be appropriate for regressions. But developing this understanding is the purpose of those regressions in the first place.

We use long-run average temperature in the capital city as reported by the UN's World Meteorological Organization. We calculated the average based on monthly average temperature data from 1960 through 2005. We averaged over all monitoring stations in the capital city. We did not attempt to identify monitoring stations that might be in or near the capital city but carry names other than the capital. To correct for missing months we averaged the monthly average temperature for each station, then constructed a weighted average of the twelve monthly average temperatures based on number of month-year observations used to construct them and the number of days per month. Data were not available for Rwanda.

There are five included countries that have multiple candidates for the capital city: Bolivia, Israel, Nigeria, Pakistan, and South Africa. We used La Paz, Jerusalem, Abuja, Islamabad, and Cape Town.

Alternatives to our using the capital city's temperature pose various sorts of issues. A country's temperature averaged over the entire country will include economically irrelevant areas (think Canada). Nordhaus (2006) used this geographic average of temperature but his unit of observation was a one-degree latitude/longitude cell rather than countries, and cells without economic data were excluded. Dell et al. (2008) used population-weighted average temperatures. The population-weighted average temperature has a slight degree of endogeneity since the location of economic activity is implicitly what we aim to explain, although the nature of this endogeneity is unknown and the implications probably minor. We chose the capital city because it seemed the "most exogenous" and still likely to be representative of the conditions under which economic activity takes place in each country, and its long-run temperature easy to calculate.³

Our use of temperature monitoring stations in cities raises the possibility that the temperature measures will reflect a "heat island" effect: Because of growth in area and infrastructure, cities will experience increases in temperature that may not reflect the temperatures of other parts of the country. The heat island effect would likely weaken the observed income–temperature relationship, however, because cities that are growing most quickly will be subject to the greatest heat island effect and also exhibit higher incomes.

2.1.3 Sample

We ranked countries based on their population averaged over 2002–2004 using the same World Bank data. In our main regression, we use the 100 most populous countries that had GDP and temperature data, with the exception of Hong Kong. These 100 countries account for 94.7% of world population and 95.4% of world GDP.⁴ For regressions using colonial mortality, we use the countries in AJR with exceptions as noted below. For regressions that used OECD countries we expanded the sample to include less populous OECD countries (to increase sample size).

³ This issue is, of course, worthy of further investigation, since there are a vast number of ways to characterize country-specific climates. Note that if alternative approaches were to find a weaker relationship than we find, it would remain incumbent on researchers to explain the apparently large capital-city-long-run-temperature/income relationship that we show.

⁴ In cross-section regressions to explain per-capita income, all countries are treated as equally informative. This assumption becomes more questionable as more low-population countries are included. Therefore, we restricted our analysis to the most populous countries.

Populous countries that are not included due to lack of GDP data are Cuba, Libya, Myanmar, North Korea, Serbia, and Montenegro. Afghanistan and Iraq further lacked World Bank population data, though other population estimates suggest that these countries would also be in the list of the most populous nations. We did not attempt to correct for sample selection arising from these countries' omission.

We removed Hong Kong since its economy is clearly different from other included countries. This exclusion clearly increases the estimated magnitude of the income–temperature gradient. We are confident that this exclusion is warranted but it raises two related sets of questions: (1) Why is Hong Kong different from other economies and, a natural follow-up, what lessons can be gleaned from this difference? Are these lessons useful for dealing with global warming? (2) Is there a continuum of countries with different historical or contemporaneous temperature roles (with Hong Kong at one extreme) and if so have we drawn an appropriate line in excluding only Hong Kong?

In regressions using settler mortality data, we further excluded Singapore, for the same reason as Hong Kong, and the Bahamas, again because its economy is clearly different from the other included countries, in this case due to its reliance on tourism. Temperature-driven tourism—as when someone from a cool country visits a hot country for its warmer weather—is an example of a role for temperature very different from the ones described in the introduction. Furthermore, the consequences of climate change for temperature-driven tourism are not easy to disentangle. (Neither Singapore nor Bahamas is among the 100 most populous countries.)

2.1.4 Mortality

We use the data reported in [Acemoglu et al. \(2001\)](#), which is based on extensive research by [Curtin \(1989, 1998\)](#) and [Gutierrez \(1986\)](#). We added France and the United Kingdom, which were in [Acemoglu et al. \(2000\)](#) but not in AJR.

These data are constructed mortality rates for European soldiers and for Catholic bishops in Latin America, mostly from the early nineteenth century. Issues that arose in AJR's compilation of these data included distinctions between mortality rates of soldiers on campaign and "in barracks," the comparability of mortality rates across time periods due to improvements over time in medical treatment, the comparability between bishops and soldiers, correction of mortality rates where needed to reflect sampling-with-replacement, and the assignment of death rates in one country to neighboring countries. The AJR data have been criticized by [Albouy \(2004, 2008\)](#) and defended by [Acemoglu et al. \(2005\)](#); the latter paper has an extensive discussion of the data. Our main regressions also include mortality data that was published in a working paper ([Acemoglu et al. 2000](#)) but that those authors chose not to include in AJR.

It is not surprising that mortality data should be viewed with skepticism. Our purpose is different from AJR, [Albouy \(2008\)](#), or [Easterly and Levine \(2003\)](#), however, since we are interested in the mortality data only to the extent that they capture the historical pathway for temperature. Any revision in those data that reduced their explanatory power (which [Albouy 2008](#) claims) would almost surely attribute a *larger* role to contemporaneous temperature. We therefore did not pursue refinements in the mortality data.

2.1.5 Other Explanatory Variables

Our investigation of temperature's role uses a sparse reduced-form. Because temperature is clearly exogenous at the country level, we use only explanatory variables with a similar degree

of exogeneity. Other common explanatory variables such as savings rates, population growth, or measures of institutional quality are themselves possibly influenced by temperature and so should not be included as regressors, or else should be uncorrelated with temperature and therefore can be excluded with no loss of accuracy in measuring temperature’s role. We therefore include only two sorts of regressors besides temperature: energy resource endowments and former Soviet bloc. In regression 10, we further include percent of population living within 100 km of a coast.

Oil, natural gas, and coal production are from the Energy Information Administration’s *International Energy Annual*, Tables F.2, F.4, and F.5. We used production averaged over 2002–2003 measured in quadrillion BTUs, divided by population, thus creating a per capita measure. Data for 2004 were unavailable at the time of the research. Countries with no entry were given a value of zero. Other possible measures, such as reserves, seemed too imprecise and the data did not have as wide a coverage.

In general, “form of government” should be considered endogenous. Yet at least one form might be considered exogenous, namely being part of the former Soviet bloc (FSB). Our FSB dummy applies to the former Soviet republics and the formerly communist European countries, including the former Yugoslavia. See “Appendix” for list.

We also used the variable *pop 100km* from Harvard’s Center for International Development (<http://www.cid.harvard.edu/ciddata/geographydata.htm>). This variable is the ratio of the population within 100 km of an ice-free coast buffer to total population, which they created in ArcView using Plate Carree equidistant projection.

2.1.6 Calculations

To gauge the size and sensitivity of the results we calculate the effect of a $\Delta T = 1^\circ\text{C}$ increase in all temperatures on the GDP of these 100 countries. This change is at the lower end of the range predicted for world temperatures to rise (IPCC). We discuss this choice further in Sect. 5.

To calculate the effects, let y_i be the multi-year average GDP per capita for country i with $\ln(y_i) = f(X; \beta) + \varepsilon_i$. We are interested in $\Delta y_i = E(y_i|X) - E(y_i|X')$ where X' includes temperature plus ΔT but all other X variables unchanged. For the log-log regressions, we construct $\Delta y_i = y_i \left[\left(\frac{\Delta T}{T} + 1 \right)^\beta - 1 \right]$ where β is the coefficient on $\ln(T)$. For the log-cubic and log-linear regressions we construct $\Delta y_i = y_i \times \left[e^{\Delta T \cdot \beta_1 + \beta_2(T'^2 - T^2) + \beta_3(T'^3 - T^3)} - 1 \right]$ where the β_j ’s are the coefficients on the temperature polynomial and $T' = T + \Delta T$.

We use 2004 population to convert predicted per capita changes into changes in total GDP. We then construct the total percentage change as $\sum_i \Delta y_i \text{POP}_{2004} / \sum_i y_i \text{POP}_{2004}$ with the summation taken over the sample countries used to estimate those β ’s.

2.2 Model

To demonstrate the distinction between historical and contemporaneous temperature effects we adapt the Solow–Swan model of Mankiw et al. (1992) to include temperature. Let output per capita, y_t , be given by the Cobb–Douglas production function:

$$y_t = a_t k_t^\alpha h_t^\beta T_t^{-\gamma} \tag{1}$$

where k_t and h_t are physical and human capital per capita. T_t represents the climate (in this case, average temperature) prevailing at t ; it is not meant to represent a yearly weather variable. a_t captures all exogenous country-specific variables, which may include historical

temperature T_0 , which we specify as $a_t = A_t T_0^{-\phi}$. The exponents α , β , γ , and ϕ are assumed identical across countries and presumed positive. The parameters γ and ϕ capture the effects of contemporaneous and historical temperature, respectively.

Again following Mankiw et al. (1992), suppose there are constant savings rates for the two types of capital, constant depreciation, and constant population growth; these need not be identical across countries. When $T_t = T_0 = T$ then steady-state output per-capita, y^* , if it exists, will be given by:

$$\ln y^* = B_t + \psi \ln T \tag{2}$$

with $\psi = -(\gamma + \phi)\theta$ and $\theta = 1/(1 - \alpha - \beta)$. B_t is a country-specific term that includes both time invariant (but country-specific) elements based on savings rates, depreciation, and population growth, and time-varying elements arising from technological change. Note that steady-state output may be increasing due to technological change. See Choinière and Horowitz (2006) for further discussion of this model.

The combined contemporaneous and historical effects of temperature are given by ψ . The effects of global warming, however, show up only through γ . An increase in temperature to $T_t + \Delta T$ yields new steady-state per-capita output:

$$\ln y^* = -\gamma\theta \ln(T_t + \Delta T) - \phi\theta \ln(T_0) + B_t \tag{3}$$

Any assessment of the effects of ΔT on y^* therefore requires identifying $\gamma\theta$ separately from $\psi\theta$. We accomplish this by using colonial mortality as a proxy for T_0 . Equation 3, with this substitution (and $\Delta T = 0$) and the addition of a random error, forms the basis of our estimates.

Equation 3 suggests that we could also estimate income growth and use observed changes in climate (T_t versus T_0) to identify $\gamma\theta$. This growth approach, however, would rely on cross-sectional differences in $\{T_t \text{ versus } T_0\}$ to identify γ ; that is, identification would rest on differences between, say, observed long-run warming in Oslo and in Rome. These differences are neither large nor precisely measured. Therefore, we stick, at least for the present paper, to our cross-sectional approach.

(We should expect the measurable long-run temperature change in Norway over the past 35 years to be roughly the same as the long-run temperature change in Italy or elsewhere, for example. In this case, a growth model could not be used to separately identify γ and ϕ . It is possible that there *are* observed cross-sectional differences in warming rates. These differences must be both sufficiently large and meaningful (for example, not due to heat island effects) for a growth model to be workable. Alternatively, the time period over which T_t is calculated could be deemed sufficiently short that one could use time-series variation in T_t to identify γ . We should also make the rather obvious point that model (1) applies only within the last 40–60 years and cannot be used to describe the effect of temperature in earlier centuries.)

3 Results

3.1 The Income–Temperature Relationship

The basic income–temperature relationship is shown in regressions 1 and 2 in Table 1. We estimate both log-log and log-cubic regressions. Figure 1 shows the data and their simple log-linear relationship.

The log-log form makes for easy comparison across regressions and is implied by model (1). Several authors have pointed out that the true relationship should be hump-shaped

Table 1 The income–temperature relationship in a cross-section of countries

	#1 100 most populous	#2 100 most populous	#3 Former Soviet Union	#4 Africa
$\ln(T)$	−1.71 (7.26)	−	−1.36 (2.63)	−1.11 (1.72)
T	−	0.41 (2.01)	−	−
T^2	−	−0.037 (2.88)	−	−
T^3	−	0.00076 (2.98)	−	−
Oil per capita	1.42 (1.16)	2.35 (2.09)	−3.68 (0.59)	4.03 (2.42)
Natural gas per capita	2.42 (0.76)	1.31 (0.45)	1.78 (0.32)	9.77 (1.36)
Coal per capita	3.12 (1.40)	2.91 (1.45)	−3.09 (0.36)	15.17 (2.53)
Former Soviet Bloc	−1.06 (3.31)	−1.06 (3.61)	−	−
Intercept	13.21 (18.70)	8.66 (8.70)	11.24 (9.22)	10.66 (5.27)
Implied GDP change over countries in sample (+1c)	−12.0%	−12.3%	−21.3%	−5.4%
F -statistic & p -value for $T = T^2 = T^3$ $= 0$	−	29.13 (0.00)	−	−
Observations	100	100	14	38
R^2	0.47	0.58	0.57	0.41

Absolute value of t -ratios in parentheses

(Masters and McMillan 2001; Mendelsohn et al. 1994; Quiggin and Horowitz 1999) since very cold climates will also hamper economic activity. The log-log form cannot capture such a relationship. Therefore, we also estimated a log-cubic relationship. These functional forms yield similar results.

To gauge the size and sensitivity of the results we calculate the effect of a 1°C increase in all temperatures on the GDP of these 100 countries. In regressions 1 and 2, this temperature increase is associated with a decrease in GDP of nearly 12%, an extremely large effect.

Table 1 also shows the income–temperature relationship for two other samples, Africa (38 countries) and former Soviet republics (14 countries) for which we have data. We include these samples because they demonstrate the pervasiveness of the income–temperature relationship. The former Soviet Union is particularly interesting because these are countries for which the colonial mortality explanation would be unlikely to apply, since pre-Soviet institutions were largely obliterated and homogeneous institutions imposed.

In each case, we report the predicted effect of temperature increase on the GDP of the sample countries. For the former Soviet Union, we find that a 1° increase implies a 21.3% reduction in their GDPs (regression 3). For Africa, we find that such an increase implies a smaller but still quite large 7% reduction in their GDPs (regression 4). Due to the small numbers of observations in these samples and our focus on historical versus contemporaneous roles of temperature, we do not explore these results further.

We must be clear that the calculations in Table 1 are not our predictions of the consequences of climate change. They are presented to demonstrate the size and pervasiveness of the income–temperature relationship. Regressions 1 and 2 show the overall temperature

Table 2 The income–temperature relationship with colonial mortality included

	#5	#6	#7	#8
Ln (T)	−1.61 (4.62)	–	−0.64 (1.94)	–
T	–	0.10 (0.20)	–	−0.0031 (0.01)
T^2	–	−0.0098 (0.35)	–	−0.0023 (0.10)
T^3	–	0.00015 (0.30)	–	4.5×10^{-5} (0.11)
Oil per capita	1.96 (0.61)	2.13 (0.67)	2.39 (0.92)	2.44 (0.92)
Natural gas per capita	2.16 (1.18)	2.54 (1.38)	1.31 (0.87)	1.43 (0.92)
Coal per capita	3.95 (1.84)	3.64 (1.66)	1.47 (0.82)	1.42 (0.76)
Former Soviet Block	–	–	–	–
Intercept	12.91 (1.08)	3.17 (0.14)	12.26 (13.84)	10.01 (0.52)
Ln (mortality)	–	–	−0.48 (5.55)	−0.47 (5.19)
Implied GDP change over countries in sample (+1c)	−10.1%	−8.1%	−4.2%	−3.8%
F -statistic & p -value for $T = T^2 = T^3$ $= 0$	–	8.41 (0.00)	–	1.30 (0.28)
Observations	63	63	63	63
R^2	0.45	0.47	0.64	0.64

Absolute value of t -ratios in parentheses

effect (roughly 12%) that is to be divided between contemporaneous and historical causes, a task we pursue in the following sections.

3.2 Regressions Including Colonial Mortality

This section looks more explicitly at the historical explanation put forth by AJR. We are interested in the extent to which the observed income–temperature relationship is due to an historical effect of colonizers' mortality, which is strongly correlated with average temperature. (The log-log correlation is 0.61 for the 63 countries in our sample.) The connections between colonial mortality and past institutions or between past and current institutions, both insights of AJR, are not the focus of our research.

We first repeat regressions 1 and 2 for the set of countries for which we have mortality data (regressions 5 and 6). We then add log mortality (regressions 7 and 8). Results are shown in Table 2. Figure 2 shows the data for this sample, the log-linear relationship including mortality (based on regression 10) and, for comparison, the simple log-linear relationship comparable to Fig. 1. Mortality flattens the income–temperature relationship, as expected, but a statistically significant and economically important role for temperature remains, as Fig. 2 and the regressions show.

We find that among these countries, a 1°C increase in average temperatures is associated with between a 3.8 and 4.2% decrease in their GDP's. These are our main estimates of the contemporaneous income–temperature relationship. These numbers are larger than researchers working with bottom-up models have found.

We also calculated the predicted percentage changes in GDPs for a range of values of ΔT (not shown). The predicted percentages were quite close to linear, at least up to $\Delta T \approx 2$.

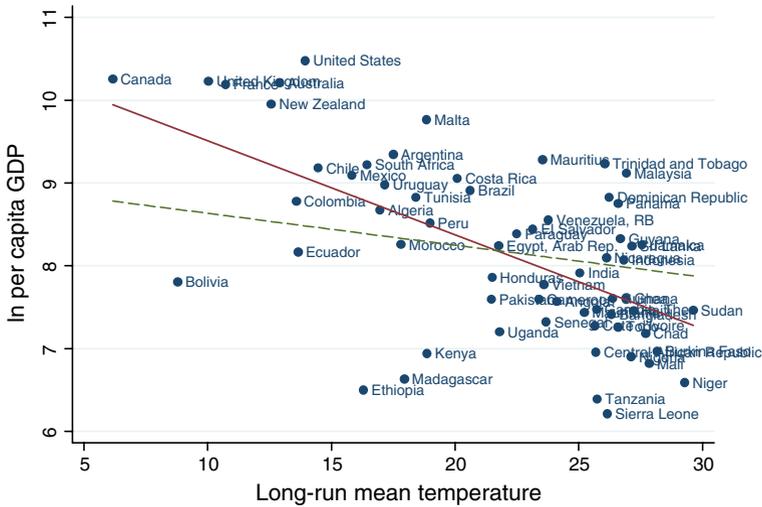


Fig. 2 The income–temperature gradient with and without colonial mortality. The solid line shows a log-linear regression with no other covariates for the set of countries used in regressions 5–8 (regression not shown; slope = -0.11). The dashed line shows the slope of the log-linear regression with log mortality and other covariates (regression 10, slope = -0.038)

Expanding the predictions beyond $\Delta T = 2$ is problematic because it is far out of sample and many countries begin to enter the upward-sloping region of the cubic.

It is somewhat difficult to gauge the representativeness of the set of countries for which mortality data are available. The countries show a less-steep income–temperature relationship than the world’s 100 most populous countries (compare 1 vs. 5 or 2 vs. 6).

3.3 Further Regressions Using Colonial Mortality

Table 3 includes three further regressions using colonial mortality. These regressions investigate the robustness of the Table 2 results.

3.3.1 Non-OECD Countries with Mortality Data

To see the extent to which OECD countries (those for which measures of colonial era mortality are available) are affecting the relationship in regression 8, we ran this regression using only non-OECD countries (regression 9). The resulting prediction, a loss of 3.5% of within-sample GDP due to a 1°C temperature increase, is just slightly lower than the full sample regression. This results show that our estimates are not unduly affected by the inclusion of the substantially wealthier OECD countries.

3.3.2 Log-Linear Specification

We next ran a regression using only a linear temperature term (regression 10). We ran this specification in part to demonstrate that the income–temperature relationship is essentially linear, a phenomenon that might be suspected based on the similarity of the log-log and log-cubic specifications and the non-significance of the temperature coefficients in regression 8. The resulting prediction, a loss of 3.8% of within-sample GDP, is identical to the log-cubic result.

Table 3 Further income–temperature regressions

	#9 Non-OECD	#10 Linear	#11 (Coastal)	#12 OECD	#13 OECD
Ln (T)	–	–	–	–0.34 (1.97)	–
T	0.18 (0.27)	–0.038 (2.01)	–0.060 (3.38)	–	0.025 (0.06)
T^2	–0.0058 (0.16)	–	–	–	–0.0060 (0.15)
T^3	3.0×10^{-5} (0.05)	–	–	–	0.00018 (0.14)
Oil per capita	2.01 (0.73)	2.40 (0.93)	2.55 (1.12)	–	–
Natural gas per capita	1.53 (0.99)	1.43 (0.96)	0.85 (0.64)	–	–
Coal per capita	3.38 (0.57)	1.46 (0.81)	1.40 (0.88)	–	–
Former Soviet Block	–	–	–	–0.60 (3.13)	–0.64 (3.02)
Intercept	8.49 (2.04)	11.09 (26.62)	10.47 (3.94)	10.87 (27.00)	10.30 (8.21)
Ln (mortality)	–0.41 (4.41)	–0.47 (5.32)	–0.33 (3.94)	–	–
Coastal popn. percentage	–	–	0.95 (4.03)	–	–
Implied GDP change over countries in sample (+1c)	–3.5%	–3.8%	–5.9%	–2.7%	–3.6%
F -statistic & p -value for $T = T^2 = T^3$ $= 0$	0.60 (0.70)	–	–	–	1.31 (0.30)
Observations	56	63	62	29	29
R^2	0.49	0.64	0.73	0.32	0.33

Absolute value of t -ratios in parentheses

Thus, although the log-cubic relationship is appealing based on the arguments described in Sect. 3.1, the data show that this is neither significantly nor economically different from a log-linear relationship. (For this reason, we do not cover the implied local maximum and minimum implied by the cubic functional forms.)

3.3.3 Coastal Population Percentage

A large number of recent papers have examined the effect on incomes of geographical variables such as climate, disease ecology, and coastal proximity (Easterly and Levine 2003; Sachs 2003). This literature is relevant here because of any possibility that temperature is capturing the effects of such variables. We are interested only in variables that may be correlated with temperature but whose role is separate from temperature, since in this case the “contemporaneous” temperature coefficient would be capturing effects that would not in fact be affected by climate change. Disease vectors, for example, would not be an appropriate candidate since they are themselves affected by climate.

We focused on the percent of population living within 100km of a coast. We chose this variable because it has been examined by previous authors, is believed to contribute to a country’s ability to trade (itself a contributor to income), and is likely correlated with temperature. If cooler countries have greater coastal access, then temperature (in regressions 7–10) could be capturing this important asset rather than wholly reflecting a true temperature effect.

Results are shown in regression 11. The resulting prediction, a loss of 5.9% of within-sample GDP, is larger, not smaller, than the prediction when this variable is not included (regression 10).⁵ This leads us to suspect that temperature is not capturing the effect of this topography variable in a way that biases upward our measures of the contemporaneous temperature effect.

3.4 Other Results

Our regressions provide several other results unrelated to the income–temperature issue. Colonial mortality is again shown, as in AJR, to be a strong predictor of current per-capita GDP. A 10% increase in colonial mortality, say from 71 (Mexico) to 78.1 (Honduras), is associated with a 4.7% decrease in GDP per capita.

Soviet bloc countries are poorer than would be expected for other countries with similar temperature and energy resources (regressions 1, 2, 12, 13). Energy resources increase per capita incomes.

We also investigated the status of OPEC countries. The data contain 6 non-OECD OPEC members (Algeria, Indonesia, Iran, Nigeria, Saudi Arabia, and Venezuela). We added a dummy variable for these countries to a log-log regression (comparable to regression 1; results not shown.) The OPEC coefficient was small and insignificant (0.07, $t = 0.18$) and the oil coefficient essentially unchanged. In other words, relatively wealthy countries like Iran or Saudi Arabia are “just like” other nations once we account for their oil resources.

4 Alternative Tests and Comparison to Other Studies

4.1 OECD Countries

To provide a different perspective on historical versus contemporaneous temperature effects we next look at the income–temperature relationship solely in OECD countries. We treat the coefficient(s) on temperature as a measure of its contemporaneous effect. This interpretation does not require the assumption that all OECD countries had the same edge in economic growth, only that this edge be uncorrelated with temperature. We do not attempt to verify this assumption here.

In the OECD regressions, we add Iceland, Ireland, New Zealand, and Norway, which are not in the 100 country sample, to increase the sample size. (We did not add Luxembourg because it is substantially smaller; see Footnote 4.) We drop the energy resource variables because (1) they are small and do not add much explanatory power to the other regressions, (2) their role would be expected to be diminished even further in developed countries, and (3) we run ex ante the risk that they are highly correlated with specific countries in the small OECD sample.

One might expect that among developed nations, temperature’s effects would be minimized by technology, health care, and the small role played by agriculture. Nordhaus (1994) claims that “from a mean temperature of about 40° to about 65°, there is no relationship

⁵ *Coastal Population Percentage* is endogenous and could be affected by temperature if the advantage of living closer to the coast (where feasible) is greater in hotter countries. In this case, the coefficient on temperature would increase when coastal percentage is included, but the contemporaneous effect of temperature would not be measured solely by the temperature variable since we must count the opportunity for people to move closer to the coast. This is the likely explanation for the result in regression 11. The coastal population percentage is correlated with colonial mortality but this is not relevant for our analysis.

between mean temperature and income per capita” (p. 362); his paper, however, is oriented to a discussion of climate’s roles and is not a detailed empirical exploration. [Masters and McMillan \(2001\)](#) write that “above the 50-degree [latitude] line, the distribution [of growth] appears to be flat.” (p. 1). While neither of these papers specifically claims that the income–temperature gradient for OECD countries will be flat, they clearly leave the impression that climate is unimportant for developed countries.

Instead, we find a substantial income–temperature gradient. A 1°C temperature increase is estimated to cause a decrease in within-sample GDP of 2.7 or 3.6% (regressions 12 and 13). These predictions are close to or slightly below those based on the mortality data. The finding of a substantial income–temperature gradient within the OECD is further striking because, since the OECD capitals are relatively cool, a lot of the worldwide temperature variation is removed.

We also estimated the OECD and non-OECD countries jointly, with separate intercepts and separate slope coefficients for temperature (results not shown). A test that the OECD dummy and OECD dummy \times log temperature are jointly zero fails. (We did not allow the error variances to differ.) In other words, non-OECD countries are not “just like” OECD countries that happen to be warmer.

4.2 Previous Literature

Previous papers that have looked at temperature-related effects on income or growth have mostly focused on the role of latitude ([Hall and Jones 1999](#); [Nordhaus 1994](#); [Ram 1997, 1999](#); [Theil and Chen 1995](#); [Theil and Finke 1983](#); [Theil and Seale 1994](#)), the percentage tropical ([Gallup et al. 1998](#)), or a simpler dichotomy between temperate and tropical countries ([Easterly and Levine 2003](#); [Masters and McMillan 2001](#)). A common result: “Affluence tends to decline when we move toward the Equator” ([Theil and Seale 1994](#), p. 403). [Masters and McMillan \(2001\)](#) used a temperature rather than latitude-based definition of the tropics. Authors differ on why distance to the equator has such a strong effect, although its correlation with temperature—with temperature then affecting disease or agriculture—is at the heart of most explanations. Only daylight pattern is more closely correlated with latitude. Daylight patterns could, of course, have a substantial effect on economic performance (see [Nordhaus \(1994\)](#) cite of Woodruff), but this pathway does not appear to have been taken very seriously.

A few studies have looked more explicitly at temperature’s role but have not looked at the effect on overall income (e.g., [Mendelsohn et al. 2007](#)). [Masters and McMillan \(2001\)](#) looked at the number of frost-free days. Frost has a direct role in reducing pests and pathogens that may be missed by a focus on average temperature. They showed that frost free days has a significant effect on population density and cultivation intensity even when average temperature is included as an explanatory variable. They did not look at joint effects of temperature and frost-free days on incomes.

The studies most relevant to our research are [Nordhaus \(2006\)](#) and [Dell et al. \(2008\)](#). [Nordhaus \(2006\)](#) constructed the “gross cell product” for cells of one-degree latitude by one-degree longitude. He conducted a cross-sectional regression of this gross cell product on temperature and other covariates, including country-specific dummies, and finds a quite small effect of temperature. A 3°C increase in temperatures is predicted to reduce world GDP by 1–2%. This result must be treated with caution. When country-specific effects are included in a cross-sectional regression, the temperature effect is identified based only on within-country temperature variation (that is, cool parts of a country versus warm parts.) Countries with greater within-country temperature variation will drive the estimated effect.

The sample of countries with substantial within-country temperature variation is small, however, and its representativeness is unknown.⁶

Dell et al. (2008) used both cross-sectional and time-series variation in temperatures to study income and growth in 136 countries. Cross-sectional time-series variation in temperatures allows the authors to include country-specify dummies in the growth equation; these dummies should capture historical temperature effects. Their dynamic framework also explicitly captures the time path by which contemporaneous temperature effects might manifest themselves.

They found a substantial effect of temperature on growth for poor countries but not for rich countries. The estimated magnitude for poor countries appears larger than ours, however; namely, that a 1°C increase in temperatures will (eventually) reduce aggregate poor country GDP by 11%. The estimated effect of a temperature increase on world GDP was negligible, however, since most of the world's GDP comes from rich countries, which are found not to be affected by temperature.

There are two other issues raised by the Dell et al. (2008) results. Their main regressions measured the effect of weather more than climate. Climate changes must, of course, manifest themselves as weather changes but it is not clear that the economic effects of weather should be the same as the economic effects of climate. Second, their long-run regressions used cross-sectional variation in temperature changes, which we previously argued were not necessarily meaningful. Further research is needed to show how our results and Dell et al. (2008) might be reconciled.

5 Concluding Comments

Previous econometric estimates of the consequences of climate change have predominately been based on bottom-up approaches in which analysts attempt to estimate climate's role in each sector of the economy. This paper has attempted an alternative top-down approach, looking directly at the effects of long-run temperature on incomes without specifying the pathways or sectors through which these effects occur. To use this income–temperature relationship to predict the consequences of global warm requires us to separate the historical and contemporaneous effects of temperature, which in turn requires us to specify a likely historical pathway. We argue that colonial-era mortality provides a powerful proxy for the temperature-correlated head start that some countries experienced, based on pioneering work by Acemoglu et al. (2001).

We predict that a 1°C increase in all temperatures will reduce world income by between 2.7 and 4.2%, with a best estimate of 3.8%. These estimates are robust across functional forms and an alternative method for separating historical from contemporaneous effects.

These predictions are subject to important caveats. They do not capture adjustment costs or nonmarket losses. They cannot be reliably extended to larger temperature changes. As Weitzman (2009) points out, uncertainty over temperature change is large and the possibility of larger changes should swamp estimates based on the mean temperature change. On the other side, our estimates do not include economic growth due to exogenous technological change.

⁶ In general we might expect that the income–temperature relationship within a given country should be informative because it holds historical effects constant and therefore measures only contemporaneous effects. Within-country factor mobility is much different from cross-country factor mobility, however, and this possible mobility (or lack thereof) is highly relevant for the worldwide effects of climate change.

Within the context of our model, the key question is whether there are historical temperature effects that our two approaches have missed. While this is possible, we note that AJR argue that once the effects of colonial mortality are accounted for, current institutions have no additional explanatory for current income, and they argue against the historical (and empirically untested) explanations of Hall and Jones (1999). Thus, it appears to us that any remaining income–temperature gradient after colonial mortality is accounted for is most likely contemporaneous.

Our procedure for measuring the costs of global warming has other sorts of limitations. Because of opportunities for international trade, the cross-sectional model may produce either an under- or overestimate of the effects of temperature change. The reason for this ambiguity is that it is the vector of worldwide temperatures that determines trading patterns and incomes. Thus, any change in temperature is “out of sample” and its effects unknown. It would be wrong, however, to presume that trade must weaken the 3.8% loss estimate; these calculations already include the effect of trade, subject to the other caveats described.

We have not specified the mechanisms through which temperature’s contemporaneous effects are felt. Many factors may contribute, including disease, agriculture, capital depreciation, worker productivity, and institutions. Untangling these is the central task for further research. The pervasiveness of the income–temperature effect suggests that multiple effects may be at work. Country-level temperature studies, while useful, will be made considerably more informative by being combined with an understanding of the underlying mechanisms by which climate affects incomes.

Acknowledgments I thank Richard Carson for extensive discussion. I also thank Allan Brunner, Matt Kotchen, Ted McConnell, Maggie McMillan, Marc Nerlove, Nancy Qian, John Quiggin, Sjak Smulders, and Jon Strand for helpful comments, and Beat Hintermann, Zhenchun Hou, and Steve Kasperski for research assistance. The views expressed represent those of the author and do not necessarily represent those of the Economic Research Service or the U.S. Department of Agriculture.

Appendix

See Table 4.

Table 4 A Country lists

<i>Regressions 1 & 2</i>	Chad	Guinea
Algeria	Chile	Haiti
Angola	China	Honduras
Argentina	Colombia	Hungary
Australia	Congo, Dem. Rep. (Zaire)	India
Austria	Cote d’Ivoire	Indonesia
Azerbaijan	Czech Republic	Iran
Bangladesh	Denmark	Israel
Belarus	Dominican Republic	Italy
Belgium	Ecuador	Japan
Benin	Egypt	Jordan
Bolivia	El Salvador	Kazakhstan
Brazil	Ethiopia	Kenya
Bulgaria	Finland	Korea, Rep. (South)
Burkina Faso	France	Lao PDR
Burundi	Germany	Madagascar
Cambodia	Ghana	Malawi
Cameroon	Greece	Malaysia
Canada	Guatemala	Mali

Table 4 continued

Mexico	Latvia	Senegal
Morocco	Lithuania	Sierra Leone
Mozambique	Macedonia, FYR	South Africa
Nepal	Moldova	Tanzania
Netherlands	Mongolia	Togo
Nicaragua	Poland	Tunisia
Niger	Romania	Uganda
Nigeria	Russian Federation	Zambia
Pakistan	Slovak Republic	Zimbabwe
Papua New Guinea	Slovenia	<i>Regressions 5–8</i>
Paraguay	Tajikistan	Algeria
Peru	Ukraine	Angola
Philippines	Uzbekistan	Argentina
Poland	<i>Regression 3</i>	Australia
Portugal	Armenia	Bangladesh
Romania	Azerbaijan	Bolivia
Russian Federation	Belarus	Brazil
Saudi Arabia	Estonia	Burkina Faso
Senegal	Georgia	Cameroon
Sierra Leone	Kazakhstan	Canada
Slovak Republic	Kyrgyz Republic	Central African Republic
South Africa	Latvia	Chad
Spain	Lithuania	Chile
Sri Lanka	Moldova	Colombia
Sudan	Russian Federation	Costa Rica
Sweden	Tajikistan	Cote d'Ivoire
Switzerland	Ukraine	Dominican Republic
Syria	Uzbekistan	Ecuador
Tajikistan	<i>Regression 4</i>	Egypt
Tanzania	Algeria	El Salvador
Thailand	Angola	Ethiopia
Togo	Benin	France
Tunisia	Botswana	Gambia
Turkey	Burkina Faso	Ghana
Uganda	Burundi	Guinea
Ukraine	Cameroon	Guyana
United Kingdom	Central African Republic	Haiti
United States	Chad	Honduras
Uzbekistan	Congo, Dem. Rep. (Zaire)	India
Venezuela	Congo, Rep.	Indonesia
Vietnam	Cote d'Ivoire	Jamaica
Yemen, Rep.	Egypt, Arab Rep.	Kenya
Zambia	Ethiopia	Madagascar
Zimbabwe	Gabon	Malaysia
<i>Former Soviet Bloc</i>	Gambia, The	Mali
Albania	Ghana	Malta
Armenia	Guinea	Mauritania
Azerbaijan	Kenya	Mauritius
Belarus	Lesotho	Mexico
Bosnia and Herzegovina	Madagascar	Morocco
Bulgaria	Malawi	New Zealand
Croatia	Mali	Nicaragua
Czech Republic	Mauritania	Niger
Estonia	Morocco	Nigeria
Georgia	Mozambique	Pakistan
Hungary	Namibia	Panama
Kazakhstan	Niger	Paraguay
Kyrgyz Republic	Nigeria	Peru

Table 4 continued

Senegal	Belgium	Poland
Sierra Leone	Canada	Portugal
South Africa	Czech Republic	Slovak Republic
Sri Lanka	Denmark	Spain
Sudan	Finland	Sweden
Tanzania	France	Switzerland
Togo	Germany	Turkey
Trinidad and Tobago	Greece	United Kingdom
Tunisia	Hungary	United States
Uganda	Iceland	
United Kingdom	Ireland	
United States	Italy	
Uruguay	Japan	
Venezuela	Korea, Rep. (South)	
Vietnam	Mexico	
<i>Regressions 12–13</i>	Netherlands	
Australia	New Zealand	
Austria	Norway	

References

- Acemoglu D, Johnson S, Robinson JA (2000) The colonial origins of comparative development: an empirical investigation. Working Paper 00-22, Department of Economics, MIT, September 2000
- Acemoglu D, Johnson S, Robinson JA (2001) The colonial origins of comparative development: an empirical investigation. *Am Econ Rev* 91(5):1369–1401
- Acemoglu D, Johnson S, Robinson JA (2002) Reversal of fortune: geography and institutions in the making of the modern world income distribution. *Q J Econ* 117(4):1231–1294
- Acemoglu D, Johnson S, Robinson JA (2005) A response to Albouy's 'A reexamination based on improved settler mortality data'. Unpublished working paper, March 2005
- Albouy D (2004) The colonial origins of comparative development: a reexamination based on improved settler mortality data. Unpublished working paper, Department of Economics, University of California, Berkeley, September 2004
- Albouy D (2008) The colonial origins of comparative development: an investigation of the settler mortality data. NBER Working Paper #14130, June 2008
- Bosello F, Roson R, Tol RSJ (2006) Economy-wide estimates of the implications of climate change: human health. *Ecol Econ* 58:579–591
- Chima RI, Goodman CA, Mills A (2003) The economic impact of malaria in Africa: a critical review of the evidence. *Health Policy* 63:17–36
- Choinière C, Horowitz JK (2006) A production function approach to the GDP-temperature relationship. Unpublished working paper
- Curtin PD (1989) *Death by migration: Europe's encounter with the tropical world in the nineteenth century*. Cambridge University Press, Cambridge
- Curtin PD (1998) *Disease and empire: the health of European troops in the conquest of Africa*. Cambridge University Press, Cambridge
- Dechènes O, Greenstone M (2007) The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. *Am Econ Rev* 97(1):354–385
- Dell M, Jones BF, Olken BA (2008) Climate change and economic growth: evidence from the last half century. NBER Working Paper #14132, June 2008
- Diamond JM (1997) *Guns, germs, and steel*. W.W. Norton, New York
- Easterly W, Levine R (2003) Tropics, germs, and crops: how endowments influence economic development. *J Monet Econ* 50:3–39
- Gallup JL, Sachs JD, Mellinger AD (1998) Geography and economic development. NBER Working Paper #6849, December 1998
- Gutierrez H (1986) La Mortalite des Eveques Latino-Americains aux XVIIe et XVII Siecles. *Ann Demogr Hist* 29–39

- Hall RE, Jones C (1999) Why do some countries produce so much more output per worker than others? *Q J Econ* 114:83–116
- Kamarck A (1976) *The tropics and economic development*. Johns Hopkins University Press, Baltimore
- Maddison D, Manley M, Kurukulasuriya P (2007) The impact of climate change on African agriculture. Policy Research Working Paper #4306, The World Bank, Development Research Group, August 2007
- Mankiw NG, Romer D, Weil D (1992) A contribution to the empirics of economic growth. *Q J Econ* 107:407–437
- Masters WA, McMillan MS (2001) Climate and scale in economic growth. *J Econ Growth* 6(3):167–186
- Mendelsohn R, Nordhaus W, Shaw D (1994) The impact of global warming on agriculture: a Ricardian analysis. *Am Econ Rev* 84(4):753–771
- Mendelsohn R, Basist A, Kurukulasuriya P, Dinar A (2007) Climate and rural income. *Clim Change* 81: 101–118
- Nordhaus W (1994) 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
- Nordhaus WD (2006) Geography and macroeconomics: new data and new findings. *PNAS* 103(10):3510–3517
- Quiggin J, Horowitz JK (1999) The impact of global warming on agriculture: a Ricardian analysis: comment. *Am Econ Rev* 89(4):1044–1045
- Quiggin J, Horowitz JK (2003) Costs of adjustment to climate change. *Aust J Agric Res Econ* 47(4):429–446
- Ram R (1997) Tropics and economic development: an empirical investigation. *World Dev* 25(9):1443–1452
- Ram R (1999) Tropics and income: a longitudinal study of the US states. *Rev Income Wealth* 45(3):1–6
- Sachs J (2003) Institutions don't rule: indirect effects of geography on per capita income. National Bureau of Economics Research Working Paper 9490 (February 2003)
- Schlenker W, Hanemann WM, Fisher AC (2004) The impact of global warming on US agriculture: an econometric analysis of optimal growing conditions. CUDARE Working Papers #1003, University of California, Berkeley
- Theil H, Chen D (1995) The equatorial grand canyon. *Economist* 143(3):317–327
- Theil H, Finke R (1983) The distance from the equator as an instrumental variable. *Econ Lett* 13:357–360
- Theil H, Seale JL (1994) The geographic distribution of world income. *Economist* 142(4):387–419
- Tol RSJ (2002) Estimates of the damage costs of climate change. *Environ Resour Econ* 21:47–73
- Weitzman M (2009) On modeling and interpreting the economics of catastrophic climate change. *Rev Econ Stat* 91(1):1–19