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

by

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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, Johnson, and Robinson, we use colonial mortality data to account for the historical role of temperature, since colonial mortality was highly correlated with countries' average temperatures. We argue that the remaining income-temperature gradient, after colonial mortality is accounted for, is most likely contemporaneous.

This contemporaneous temperature effect can be used to estimate the cost of global warming. We predict that a 2 degree Fahrenheit temperature increase across all countries will cause a decrease of roughly 4 percent in world GDP. This prediction is robust across samples, functional forms, and two methods for separating historical effects.

The Income-Temperature Relationship in a Cross-Section of Countries and its Implications for Predicting the Effects of Global Warming[1]

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.

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 (Deschênes and Greenstone; Madison, Manley, and Kurukulasuriya; Mendelssohn, Nordhaus, and Shaw; Schlenker, Hanemann, and Fisher) and health (Chima, Goodman, and Mills; see also papers cited in Bosello, Roson, and Tol), and then to construct an overall prediction of climate change impacts by aggregating these sectors. Tol 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

[1] I thank Richard Carson for extensive discussion. I also thank Matt Kotchen, Maggie McMillan, Marc

about correctly accounting for pathways that cut across sectors.[2] As Dell, Jones, and Olken 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 it has long been remarked on (see discussions in Acemoglu, Johnson, and Robinson (2002); Easterly and Levine; Kamarck). 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

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Nerlove, Nancy Qian, John Quiggin, and Sjak Smulders for helpful comments. I thank Beat Hintermann, Zhenchun Hou, and Steve Kasperski for research assistance.

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

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. Acemoglu, Johnson, and Robinson (2001) (AJR) have recently made great gains in identifying a specific historical path. They argue that 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, 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.[3] We then interpret any remaining temperature effects as contemporaneous. Historical effects of temperature are shown to account implicitly for nearly two-thirds of the cross-sectional income-temperature relationship. We attribute the residual one-third to temperature's contemporaneous effect and use this estimate to predict the effects of climate change on world GDP.

The colonial mortality pathway is compelling but limited for several reasons. In addition, two other approaches (Dell, Jones, and Olken; Nordhaus, 2006) have been used to separate contemporaneous and historical temperature effects. We discuss these issues and contributions below.

Section 2 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 covers weaknesses, alternative tests, and other approaches. Predictions and concluding comments are in Section 5.

2. 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

[3] Diamond 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. Note that the

in Figure 1. Summary statistics and lists of countries in our samples are in the Appendix.

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 three 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 much 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

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Guns, Germs, and Steel explanation may account in part for colonial mortality, so the colonial-mortality-based estimates may be incorporating the historical effects propounded by Diamond.

in warmer countries (with scarcity unreflected in the price), then the observed income-temperature will underestimate the consequences of higher temperatures.

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 U.N.'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, Jones, and Olken 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 is easy to calculate. A country's geographic center is also 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.

Our focus on temperature at a single location is the most problematic for countries with a large degree of temperature variation. An interesting question, deserving of further research, is whether countries have tended to locate their capitals in the cooler part of their countries, as Australia, China, India, Mexico, Pakistan, Turkey and others appear to have done. The U.S. is an exception, since our capital is in a warmer spot than the center of economic activity (New York). An interesting aside is that most of these countries (China, Pakistan, Turkey, and the U.S.) would be *closer* to their predicted incomes in Figure 1 if the temperature of the center of economic activity (Shanghai, Karachi, Istanbul, New York) were used instead of the capital's.

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 *weaken* the observed income-temperature relationship, however. The reason is that cities that are growing most quickly will be subject to the greatest heat island effect and also exhibit higher incomes.

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 percent of world population and 95.4 percent of world GDP. 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) but did not do so for non-OECD countries. A list of countries in each of the samples is in the Appendix.

Populous countries that are not included due to lack of GDP data are Cuba, Libya, Myanmar, North Korea, and 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. First, 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? Second, 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.)

Mortality. We use the data reported in AJR (2001), which is based on extensive research by Curtin (1989, 1998) and by Gutierrez. We added France and the United Kingdom, which were in Acemoglu, Johnson and Robinson (2000) but not in AJR.

Other explanatory variables. Our investigation of temperature's role uses a spare reduced-form. Because temperature is so clearly exogenous at the country level, we use only explanatory variables with a similar degree of exogeneity. Other commonly used explanatory variables such as savings rates, population growth, or measures of institutional quality are themselves possibly influenced by temperature and so either should not be included as regressors or else should be modeled jointly with income. We therefore include only two sorts of regressors besides temperature: energy endowments and former Soviet bloc.

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.

Calculations. To gauge the size and sensitivity of the results we calculate the effect of a $\Delta T = 2$ degree Fahrenheit increase in all temperatures on the GDP of these 100 countries. This change is in the range predicted for world temperatures to rise (IPCC).

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 regressions we construct $\Delta y_i = y_i\left[e^{\Delta T\cdot\beta_1+\beta_2(T'^2-T^2)+\beta_3(T'^3-T^3)}-1\right]$ 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 $\Sigma_i \Delta y_i POP_{2004} / \Sigma_i y_i POP_{2004}$. For all regressions, we sum over the 100 country sample to facilitate comparisons across regressions. Where the temperatures of the countries used in a regression differ substantially from the temperatures in the 100-country sample, we also summed over the sample countries used to estimate those β's.

3. Results

3.1 The Income-Temperature Relationship

The basic income-temperature relationship is shown in regressions 1 and 2 in Table 1. Theory gives little guide to the appropriate functional form. We estimate both log-log and log-cubic regressions. Figure 1 shows the data and an estimated log-log relationship.

The log-log form makes for easy comparison across regressions and is implied by a steady-state Cobb-Douglas production function with temperature as an input (Choinière and Horowitz). The log-log form may seem extreme, however, because it implies that it is the percentage change in temperature that affects the percent change in incomes. This property could make global warming seem particularly costly: A given temperature increase (a 2˚ F increase in all countries) will be a higher percentage increase in cooler countries, which also happen to be richer. These countries are then predicted to lose an even greater proportion of their income than poor/warm countries. Several authors have pointed out that the true relationship should be hump-shaped (Masters and McMillan; Mendelssohn, Nordhaus, and Shaw; 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 cubic relationship for temperature. As expected, the cubic regressions predict a slightly smaller effect for climate change, although the difference between the log-cubic and the log-log specifications is surprisingly minor.

The main cubic results indeed show a cool region over which an increase in temperature raises incomes. They also show a second region of much higher temperatures over which an increase in temperature again raises incomes, although this temperature is outside the sample in most cases. Each cubic regression shows the implied temperature at which a local maximum and minimum income occurs. Each cubic regression also shows an F-test of the joint hypothesis that all temperature coefficients are zero.

To gauge the size and sensitivity of the results we calculate the effect of a 2 degree Fahrenheit 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 14 percent, an extremely large effect. The estimate provides a dramatic demonstration of the income-temperature relationship.

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. In each case, we report the predicted effect of temperature increase on 100-country GDP and the GDP of the sample countries, with emphasis on the latter, for reasons discussed in Section 3.2.

First, consider the former Soviet Union, whose result (regression 3) implies a 14.4

percent reduction in their GDPs as a result of a 2 degree Fahrenheit rise. 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. The observed gradient is particularly striking given the presumed homogeneity of the sample: Not long ago, this regression would have been a within-country regression.

Consider next the results for Africa, which predicts a smaller but still quite large 7 percent reduction in their GDPs. In this case, distance to Europe plays no obvious role.

We must be clear that the calculations in Table 1 are not our predictions of the costs 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 effect (13-14 percent) 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.

There are several important results. First, colonial mortality is a strong predictor of current per-capita GDP. A 10 percent increase in colonial mortality, say from 71 (Mexico) to 78.1 (Honduras), is associated with a 4.7 percent decrease in GDP per capita. Second, temperature's effect is diminished by the inclusion of mortality but still large. We find that even among these countries, strongly influenced as they were by their colonial-era experience, a two degree increase in average temperatures is associated with between a 4.2 and 4.5 percent decrease in aggregate GDP. These are our main estimates of the contemporaneous income-temperature relationship. These numbers are considerably larger than researchers working with bottom-up models have found.[4]

We also calculated the predicted percentage changes in GDPs for a range of values of ΔT. The predicted percentages were quite close to linear, at least up to $\Delta T \approx 4$. (Expanding the predictions beyond ΔT=4 is problematic because it is far out of sample and countries begin to enter the upward-sloping region of the cubic.) The predicted effect of a one degree Celsius increase, which is the temperature change simulated by DJO, on within-sample GDP was 3.8 to 4.1 percent (regressions 8 and 7).

Third, only countries with temperatures below 30 degrees or above 97 degrees are predicted to benefit from global warming. This range is almost empty. It encompasses only Mongolia, with an average temperature of 27°. (Mongolia is not included in any of our calculations because its population is too low.)

The precision of the estimate of the contemporaneous temperature effect is

[4]The contemporaneous effect is 42 to 47 percent of the overall temperature effect (4.5/10.7 = 0.42; 4.2/9.0 = 0.47). It is not clear whether this percentage can be applied about of sample. If it were applied out of sample then the predicted effect of this temperature increase on 100-country GDP is a staggering 5.85 percent decline (regression 1: 0.42×13.9 = 5.85; regression 2: 0.47×13.5=5.85).

difficult to gauge. The coefficient on ln(T) is precisely estimated (regression 7) but the temperature coefficients under the presumably more reasonable cubic functional form are not precisely estimated and include zero in the joint confidence interval (regression 8). On the other hand, the implied effects are almost identical (4.5 percent vs. 4.2 percent).

It is also 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). On the other hand, the difference between the 100-country predictions and within-sample predictions is rather small.

4. Discussion

Mortality Data

The AJR data have been criticized by Albouy (2004, 2008) and defended by Acemoglu, Johnson, and Robinson (2005). Furthermore, our regressions include mortality data that was published in a working paper (Acemoglu, Johnson, and Robinson, 2000) but that those authors chose not to include in AJR. It is not surprising that mortality data should be noisy and viewed with skepticism.

Our purpose is different from AJR, Albouy (2008), or Easterly and Levine, however, since we are interested in the mortality data only to the extent that they capture the historical pathway for temperature. Any weakness in those data that reduces their explanatory power would almost surely attribute a *larger* contemporaneous component of the income-temperature relationship. Since our predicted contemporaneous temperature effect is already quite large compared to other estimates, we do not pursue refinements in the mortality data.

The more important issue is whether colonial mortality captures all of the historical effects of temperature, which is the assumption that allows us to claim that roughly forty percent of the observed income-temperature effect is contemporaneous. In the next two sections we provide one candidate check on this finding and discuss other existing estimates.

OECD and Non-OECD Countries

To provide a different perspective on historical vs. contemporaneous temperature effects we next look at the income-temperature relationship separately in OECD and non-OECD countries. This is a coarse attempt to correct for historical temperature effects. Within-group estimates will provide a good measure of the contemporaneous temperature effect to the extent that any temperature-correlated "head start" (or delay) in development is the same among all OECD or all non-OECD countries. Our interpretation does not need the condition that all OECD countries had the same edge in economic growth, only that this edge be uncorrelated with temperature within this sample. This is a strong assumption, of course, and we do not attempt to verify it here.

Temperature-related historical effects should be relatively uniform among the OECD countries, so the estimate among OECD countries should provide a relatively accurate picture of the contemporaneous effect. Temperature-related historical effects are less likely to be uniform among the non-OECD countries (hence the mortality explanation), so we expect the non-OECD sample to be less accurate in filtering out temperature's historical effects. We reiterate that this within-sample treatment is a coarse approach to our identification problem, though potentially interesting.

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.) We drop the energy resource variables because (i) they are small and do not add much explanatory power to the other regressions, (ii) their role would be expected to be diminished even further in developed countries, and (iii) we run the risk that they are highly correlated with specific countries in the small OECD sample. The non-OECD sample is unchanged except where noted.

Results are in Table 3. There is a substantial income-temperature gradient within both OECD and non-OECD countries. First, consider the OECD countries. 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 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 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 supposedly unimportant for developed countries.

Instead, we find a substantial income-temperature gradient. A 2 degree temperature increase is estimated to cause a decrease in within-sample GDP of 3.7 to 4.0 percent (regressions 9 and 10).[5] These predictions are essentially identical to those based

[5] As always, results must be treated with caution when expanded to the 100-country sample. The OECD sample includes much cooler countries than the full sample. Therefore, estimates of temperature's role are

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.

Results for the non-OECD sample are shown in regressions 11 and 12. The predicted non-OECD losses are again very close to those in the mortality regressions, 4.0 to 6.1 percent of total within-sample GDP. Note that this sample is a more diverse set of countries and it is much less likely that past temperature effects (or effects correlated with temperature) were identical among them. This reason may be why the non-OECD estimates are slightly higher than the estimated contemporaneous effects from the colonial mortality or the OECD regressions.

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 × log temperature are jointly zero fails strongly. (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.

For the sake of completeness we also included colonial mortality in the regression of non-OECD countries (regression 13). Again, this regression would yield accurate estimates of the contemporaneous income-temperature relationship if temperature-related variability in the historical status of non-OECD countries conditional on colonial mortality is especially small. We again find quite similar predictions for the effect of a 2

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out-of-sample for the hotter economies in the 100-country sample. This is particularly a problem for the cubic specifications; for example, the predicted local minimum of 67.9° is higher than the temperature of the highest-temperature OECD country, Greece. Likewise, under regression 10 countries like Sudan or Niger would be predicted to benefit tremendously from warming, an untenable result. This is the reason why we restrict attention to percentage changes in the within-sample GDP.

degree Fahrenheit temperature increase on total within-sample GDP, 3.9 percent.[6]

Other Evidence: Nordhaus and DJO

Most papers that have looked at temperature-related effects on income or growth have focused on the role of latitude (Hall and Jones; Nordhaus, 1994; Ram, 1997, 1999; Theil and Chen; Theil and Finke; Theil and Seale), the percentage tropical (Gallup, Sachs, and Mellinger), or a simpler dichotomy between temperate and tropical countries (Easterly and Levine; Masters and McMillan). A common result: "Affluence tends to decline when we move toward the Equator" (Theil and Seale, p. 403). Masters and McMillan use 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 is more closely correlated with latitude. Daylight 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., Mendelssohn *et al.*, 2007). Masters and McMillan look 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 show that frost free days has a significant effect on population density and cultivation intensity even

[6]This sample includes much warmer countries than other samples because it eliminates the generally cool former Soviet bloc (no mortality data) and OECD countries. Therefore estimates of temperature change effects are particularly far out-of-sample for the cooler economies, the opposite of the issue for regression 10. This out of sample property leads us to predict a 3.3 percent gain for 100-country GDP. This gain

when average temperature is included as an explanatory variable. They do 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, Jones, and Olken (DJO). 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 degree Celsius increase in temperatures is predicted to reduce world GDP by just 1-2 percent. 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.[7]

Dell, Jones, and Olken use 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 find a substantial effect of temperature on growth for poor countries but not

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comes from countries such as Ethiopia and Uruguay being predicted to benefit from climate change.

[7]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, which is what

for rich countries. The estimated magnitude for poor countries appears larger than ours, however; namely, that a 1 degree Celsius increase in temperatures will (eventually) reduce aggregate poor country GDP by 11 percent. The estimated effect of a temperature increase on world GDP is 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 DJO results. Their main regressions measure 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 look use cross-sectional variation in temperature changes. Although such variation may indeed be present in the data, it is not clear what it captures.[8] Further research is needed to show how our results and DJO might be reconciled.

Other Results

The Table 3 regressions provide several other results unrelated to the income-temperature issue. Soviet bloc countries are still poorer than would be expected for other countries with similar temperature and energy resources. Energy resources generally increase per capita incomes. The regressions do not, however, lend themselves to easy interpretation of the nature of this relationship.

We also investigated the status of OPEC countries. The data contain 6 OPEC members (Algeria, Indonesia, Iran, Nigeria, Saudi Arabia, and Venezuela). We added a

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is relevant for the worldwide effects of climate change.

[8]For example, economic researchers would surely be reluctant to measure climate change based on a time series of world temperature data because the nuances and difficulties in teasing out climate change are

dummy variable for these countries to a log-log regression (results not shown.) The OPEC coefficient was small and insignificant (0.07, t = 0.18) and the oil coefficient essentially unchanged. In other words, countries like Iran or Saudi Arabia are just like other less developed nations once we account for their oil resources and temperatures.

5. Concluding Comments

This paper has attempted to separate historical from contemporaneous effects of temperature on world incomes. We predict that a 2 degree Fahrenheit increase in all temperatures will reduce world income by roughly 4 percent, an estimate that is remarkably robust across samples, functional form, and a two methods for separating historical from contemporaneous effects. This figure is also higher than most other predictions.

Our procedure for measuring the costs of global warming has several important limitations. In the absence of trade (clearly an unwarranted assumption), the cross-sectional method would underestimate the effects of temperature change because it does not include the costs of adjusting to a new temperature (Quiggin and Horowitz, 2003). It assumes that countries can costlessly and immediately develop infrastructure to match a new climate, as countries currently operating at that temperature have done.

In the presence of trade (but without adjustment costs), 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

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substantial. Cross-sectional variation in these temperature changes would seem to embody an even greater set of possible causes and effects.

sample" and its effects unknown. It would be wrong to presume that trade must ameliorate the 4 percent figure; this calculation already includes 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 considerably more informative with an understanding of the underlying mechanisms by which climate affects incomes.

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)	-4.32 (8.43)	--	-4.51 (3.20)	-2.08 (1.76)
T	--	1.37 (2.73)	--	--
T^2	--	-0.024 (2.94)	--	--
T^3	--	0.00013 (2.98)	--	--
Oil per capita	1.79 (1.54)	2.35 (2.09)	-1.12 (0.20)	4.03 (2.43)
Natural gas per capita	1.67 (0.56)	1.31 (0.45)	0.48 (0.09)	9.71 (1.35)
Coal per capita	2.98 (1.42)	2.91 (1.45)	-2.11 (0.29)	15.16 (2.54)
Former Soviet Bloc	-1.09 (3.67)	-1.06 (3.61)	--	--
Intercept	26.39 (12.17)	-14.65 (1.47)	25.79 (4.65)	16.11 (3.17)
Implied 100-country GDP change (+2° F.)	-13.9%	-13.5%	-18.9%	-5.9%
Implied GDP change over countries in sample (+2° F.)	"	"	-14.4%	-6.9%
Temp. at local max and min.	--	44.2° 78.9°	--	--
F-statistic & p-value for $T = T^2 = T^3 = 0$	--	7.30 (0.00)	--	--
Observations	100	100	14	38
R^2	0.53	0.58	0.64	0.42

Absolute value of *t*-ratios in parentheses.

Table 2. The Income-Temperature Relationship Conditional on Colonial Mortality

	#5	#6	#7	#8
Ln(T)	-3.43 (4.82)	--	-1.39 (2.00)	--
T	--	0.33 (0.30)	--	0.067 (0.07)
T^2	--	-0.0055 (0.33)	--	-0.00145 (0.12)
T^3	--	2.63×10^{-5} (0.30)	--	7.68×10^{-6} (0.11)
Former Soviet Bloc	--	--	--	--
Oil per capita	1.96 (0.63)	2.13 (0.67)	2.39 (0.93)	2.44 (0.92)
Natural gas per capita	2.32 (1.28)	2.54 (1.38)	1.38 (0.92)	1.43 (0.92)
Coal per capita	3.76 (1.76)	3.64 (1.66)	1.45 (0.80)	1.42 (0.76)
Intercept	22.60 (7.44)	3.17 (0.14)	16.18 (5.85)	10.01 (0.52)
Ln(mortality)	--	--	-0.47 (5.39)	-0.47 (5.19)
Implied 100-country GDP change (+2° F.)	-11.2%	-8.3%	-4.7%	-4.2%
Implied GDP change over countries in sample (+2° F.)	-10.7%	-9.0%	-4.5%	-4.2%
Temp. at local max and min.	--	43.7° 95.7°	--	30.5° 95.4°
F-statistic & p-value for $T = T^2 = T^3 = 0$	--	0.12 (0.89)	--	0.10 (0.90)
Observations	63	63	63	63
R^2	0.46	0.47	0.64	0.64

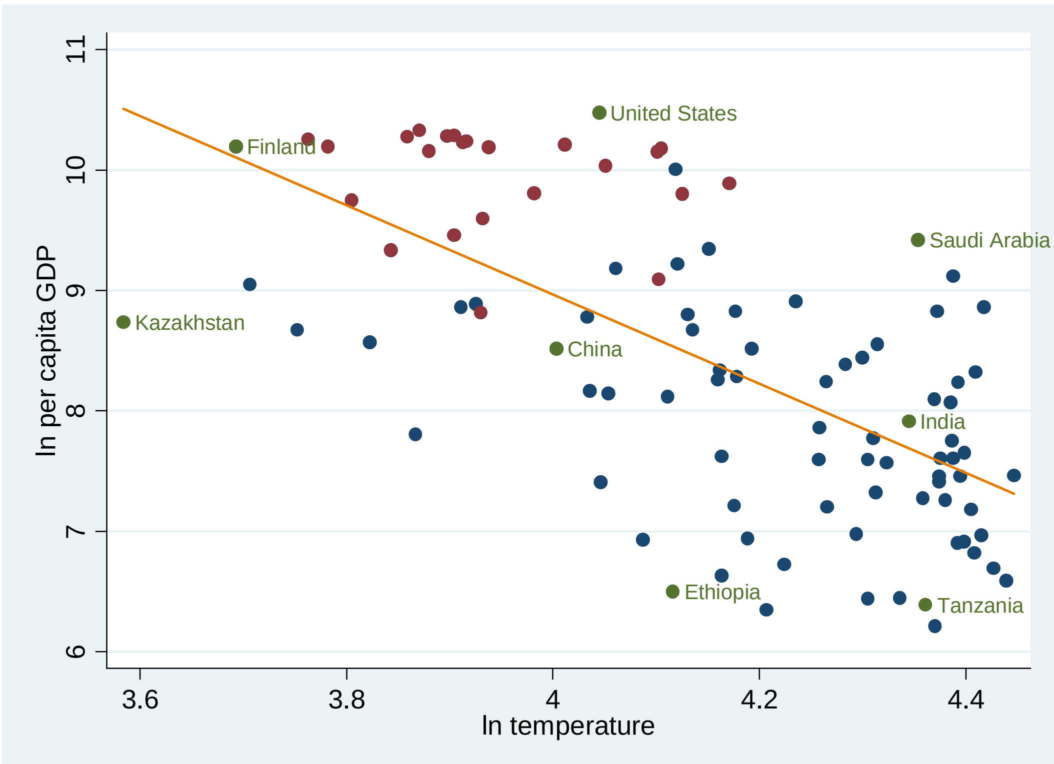
t-ratios in parentheses.

Table 3. The Income-Temperature Relationship for OECD and Non-OECD countries

	#9 OECD	#10 OECD	#11 Non-OECD	#12 Non-OECD	#13 Non-OECD w/ mortality
ln(T)	-1.04 (2.04)	--	-1.94 (2.67)	--	--
T	--	0.23 (0.13)	--	0.74 (1.31)	0.23 (0.15)
T^2	--	-0.0048 (0.14)	--	-0.012 (1.34)	-0.0022 (0.11)
T^3	--	3.05×10^{-5} (0.14)	--	6.44×10^{-5} (1.32)	5.15×10^{-6} (0.05)
Former Soviet Bloc	-0.62 (3.23)	-0.64 (3.02)	-0.55 (1.42)	-0.48 (1.13)	--
Oil per capita	--	--	1.67 (1.47)	1.85 (1.62)	2.01 (0.73)
Natural gas per capita	--	--	6.65 (1.55)	7.03 (1.64)	1.53 (0.99)
Coal per capita	--	--	7.17 (1.33)	10.23 (1.76)	3.39 (0.57)
Intercept	14.16 (7.10)	6.94 (0.24)	15.99 (5.11)	-5.60 (0.50)	3.25 (0.11)
Ln(mortality)	--	--	--	--	-0.41 (4.41)
Implied 100-country GDP change (+2° F.)	-3.5%	-1.9%	-6.5%	-5.4%	+3.3%
Implied GDP change over countries in sample (+2° F.)	-3.7%	-4.0%	-6.1%	-4.0%	-3.9%
Temp. at local max and min	--	37.0° 67.9°	--	56.9° 67.4°	69.0° 100°+
F-statistic & p-value for $T = T^2 = T^3 = 0$	--	0.04 (0.96)	--	0.93 (0.40)	0.45 (0.64)
Observations	29	29	75	75	56
R^2	0.33	0.33	0.31	0.34	0.49

t-ratios in parentheses.

Figure 1. The Income-Temperature Gradient for 100 Countries



This figure shows a log-log regression with no other covariates. Red dots represent OECD countries. Blue dots represent non-OECD countries. Green dots show a selected set of representative countries.

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Appendix

A. Country lists

100 country sample

Algeria
Angola
Argentina
Australia
Austria
Azerbaijan
Bangladesh
Belarus
Belgium
Benin
Bolivia
Brazil
Bulgaria
Burkina Faso
Burundi
Cambodia
Cameroon
Canada
Chad
Chile
China
Colombia
Congo, Dem. Rep. (Zaire)
Cote d'Ivoire
Czech Republic
Denmark
Dominican Republic
Ecuador
Egypt
El Salvador
Ethiopia
Finland
France
Germany
Ghana
Greece
Guatemala
Guinea
Haiti
Honduras
Hungary
India
Indonesia
Iran
Israel
Italy
Japan
Jordan
Kazakhstan
Kenya
Korea, Rep. (South)
Lao PDR
Madagascar
Malawi
Malaysia
Mali
Mexico
Morocco
Mozambique
Nepal
Netherlands
Nicaragua
Niger
Nigeria
Pakistan
Papua New Guinea
Paraguay
Peru
Philippines
Poland
Portugal
Romania
Russian Federation
Saudi Arabia
Senegal
Sierra Leone
Slovak Republic
South Africa
Spain
Sri Lanka
Sudan
Sweden
Switzerland
Syria
Tajikistan
Tanzania
Thailand
Togo
Tunisia
Turkey
Uganda
Ukraine
United Kingdom
United States
Uzbekistan
Venezuela
Vietnam
Yemen, Rep.
Zambia
Zimbabwe

Former Soviet Bloc

Albania
Armenia
Azerbaijan
Belarus
Bosnia and Herzegovina
Bulgaria
Croatia
Czech Republic
Estonia
Georgia
Hungary
Kazakhstan
Kyrgyz Republic
Latvia
Lithuania
Macedonia, FYR
Moldova
Mongolia
Poland
Romania
Russian Federation
Slovak Republic
Slovenia
Tajikistan
Ukraine
Uzbekistan

Former Soviet Union

Armenia
Azerbaijan
Belarus
Estonia
Georgia
Kazakhstan
Kyrgyz Republic
Latvia
Lithuania
Moldova
Russian Federation
Tajikistan
Ukraine
Uzbekistan

Africa

Algeria
Angola
Benin
Botswana
Burkina Faso
Burundi
Cameroon
Central African Republic
Chad
Congo, Dem. Rep. (Zaire)
Congo, Rep.
Cote d'Ivoire
Egypt, Arab Rep.
Ethiopia
Gabon
Gambia, The
Ghana
Guinea
Kenya
Lesotho
Madagascar
Malawi
Mali
Mauritania
Morocco
Mozambique
Namibia
Niger
Nigeria
Senegal
Sierra Leone
South Africa
Tanzania
Togo
Tunisia
Uganda
Zambia
Zimbabwe

Countries with colonial mortality data

Algeria
Angola
Argentina
Australia
Bangladesh
Bolivia
Brazil
Burkina Faso
Cameroon
Canada
Central African Republic
Chad
Chile
Colombia
Costa Rica
Cote d'Ivoire
Dominican Republic
Ecuador
Egypt
El Salvador
Ethiopia
France
Gambia
Ghana
Guinea
Guyana
Haiti
Honduras
India
Indonesia
Jamaica
Kenya
Madagascar
Malaysia
Mali
Malta
Mauritania
Mauritius
Mexico
Morocco
New Zealand
Nicaragua
Niger
Nigeria
Pakistan
Panama
Paraguay
Peru
Senegal
Sierra Leone
South Africa
Sri Lanka
Sudan
Tanzania
Togo
Trinidad and Tobago
Tunisia
Uganda
United Kingdom
United States
Uruguay
Venezuela
Vietnam

OECD

Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Japan
Korea, Rep. (South)
Mexico
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States

Non-OECD countries are those in the 100-country list minus the OECD countries.

Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
lngdppc02_04	100	8.390008	1.212483	6.214057	10.47639
lntemp_f	100	4.155959	0.212331	3.584081	4.446424
temp_f	100	65.19507	13.0686	36.02023	85.32124
Tempsq	100	4419.477	1670.113	1297.457	7279.714
tempcubic	100	309642.8	165324.3	46734.7	621114.3
Oil	100	0.027721	0.08544	0	0.772957
Drygas	100	0.015676	0.035496	0	0.212571
Coal	100	0.011913	0.043192	0	0.384177
sovietbloc	100	0.13	0.337998	0	1

Variable	Obs	Mean	Std. Dev.	Min	Max
lngdppc02_04	14	8.293605	0.821601	6.930296	9.420464
lntemp_f	14	3.868505	0.159093	3.584081	4.087507
Oil	14	0.024724	0.045417	0	0.123255
Drygas	14	0.02174	0.043568	0	0.151403
Coal	14	0.017578	0.03304	0	0.097987

Variable	Obs	Mean	Std. Dev.	Min	Max
lngdppc02_04	38	7.375251	0.82544	6.214057	9.216059
lntemp_f	38	4.290353	0.102454	4.048012	4.439211
Oil	38	0.01935	0.068178	0	0.397932
Drygas	38	0.003642	0.016399	0	0.100569
Coal	38	0.003712	0.019379	0	0.119144

Variable	Obs	Mean	Std. Dev.	Min	Max
lngdppc02_04	63	8.183175	1.072086	6.214057	10.47639
Lnmortality	63	4.643964	1.271095	2.145931	7.986165
lntemp_f	63	4.251381	0.157338	3.763293	4.446424
temp_f	63	71.01624	10.31928	43.09007	85.32124
Tempsq	63	5148.103	1388.455	1856.754	7279.714
tempcubic	63	379656.4	143212.7	80007.66	621114.3
Oil	63	0.022786	0.047638	0	0.217725
drygas	63	0.022918	0.081156	0	0.598743
Coal	63	0.011867	0.051472	0	0.384177

Variable	Obs	Mean	Std. Dev.	Min	Max
lngdppc02_04	29	10.01307	0.412956	8.814692	10.47639
lntemp_f	29	3.924024	0.13249	3.665998	4.17093
temp_f	29	51.03272	6.740463	39.09514	64.77566
tempsq	29	2648.206	698.8016	1528.43	4195.886
tempcubic	29	139680.7	55302.45	59754.18	271791.3
oil	29	0.065642	0.243482	0	1.313373
drygas	29	0.047305	0.116981	0	0.600299
coal	29	0.028433	0.072869	0	0.384177
sovietbloc	29	0.137931	0.350931	0	1

Variable	Obs	Mean	Std. Dev.	Min	Max
lngdppc02_04	75	7.863707	0.886821	6.214057	10.00227
lntemp_f	75	4.227563	0.186072	3.584081	4.446424
temp_f	75	69.6421	11.61672	36.02023	85.32124
tempsq	75	4983.171	1514.383	1297.457	7279.714
tempcubic	75	364303.2	153227	46734.7	621114.3
oil	75	0.029273	0.095543	0	0.772957
drygas	75	0.011364	0.027116	0	0.151403
coal	75	0.005562	0.018707	0	0.119144
sovietbloc	75	0.12	0.32715	0	1

Variable	Obs	Mean	Std. Dev.	Min	Max
lngdppc02_04	56	7.967652	0.912188	6.214057	10.10264
lnmortality	56	4.844855	1.165819	2.74084	7.986165
lntemp_f	56	4.289801	0.123127	3.867453	4.446424
temp_f	56	73.47142	8.438747	47.82042	85.32124
tempsq	56	5467.99	1177.889	2286.792	7279.714
tempcubic	56	411481.1	125247.6	109355.4	621114.3
oil	56	0.018233	0.045848	0	0.217725
drygas	56	0.017119	0.081285	0	0.598743
coal	56	0.003267	0.016355	0	0.119144