New Empirical Evidence on Climate Change and Economic Growth

by

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Abstract

The impact of climatic changes on economic growth is measured by using annual variation in temperature and precipitation throughout the world on the past 60 years. Two primary results are shown in this paper. First, higher temperatures have substantial negative effects on economic growth in rich countries. Second, higher temperatures reduce growth rates in rich countries, not only the level of output. Analysis of longer-run model shows that the magnitude and statistical significance of negative effects increases over time. Thus, a quick reaction to climate changes is necessary.

Contents

1. Introduction

Global climate change has become a central issue for the world economy after the publication of the influential Stern Review's Economics of Climate Change (Stern 2007). Nevertheless, assessing the economic impact of climate change faces a fundamental challenge of complexity. Environmental economics suggests that three important characteristics make the study of climate change unique. First, it is global in nature. Secondly, its impacts are of an unusually long-term character. Lastly, comprehension of both the nature of climate change and the effects of policies designed to mitigate it remain deficient (Owen and Hanley 2004). As a result, the set of mechanisms through which climate may influence economic outcomes is extremely large and difficult to understand. When studying environmental economics, one would be faced with the challenge of how various mechanisms interact to shape macroeconomic outcomes, even if the effect of climate on each relevant mechanism were known. Rather than relying on a priori assumptions about the underlying mechanisms, it might be simpler to examine the effects of climate change on a single aggregate measure: economic growth (Dell, Jones and Olken 2008). To study the relationship between climate and economy, it is necessary to examine both the microeconomic and macroeconomic foundations then apply the theory to empirical work.

The global nature of climate change arises from the fact that irrespective of where on earth greenhouse gases are emitted they are rapidly absorbed into the atmosphere and spread around the globe. The consequences of the resulting global climate change, however, are projected to be far from uniform, with some countries expected to suffer far greater adverse impacts than others. In addition, unilateral action by any one country could not alter this situation significantly. Therefore, it requires concerted remedial cooperative action at the international level to address the problem. Fankhauser and Tol (2005) draws attention to the global nature of climate change and the fact that the direct impact of climate change on the economy is not the only way in which global warming affects future welfare. They argue that "the prospect of future damages (or benefits) also affects capital accumulation and people's propensity to save, and hence the rate of economic growth". To study the basic interlinkages between climate change and economic growth, they use a standard Ramsey-Cass-Koopmans growth model and conclude that climate change will always have a negative effect on the absolute capital stock and the capital-labor ratio is also certain to decrease if agents are allowed to change their savings behavior. Numerical simulations suggest that the dynamic effects are unlikely to reverse the prospect for future long-term growth, except in the most vulnerable countries.

The long-term nature of the impacts of climate change arises from the fact that greenhouse gases comprise a stock in the atmosphere that is continually augmented by new emissions. The natural rate of breakdown of this stock varies from a few decades for short-lived gases such as methane, to hundreds of years (for carbon dioxide) (Solomon et al 2009), through to thousands of years (for longer-lived gases such as perfluorocarbons). Thus, impacts induced by these emissions, such as global average temperature increases and rises in sea level, will be progressive over long time horizons. These long time lags will also influence remedial measures, where the risks of climate change in the future have to be offset against the costs of undertaking mitigating action today.

Nordhaus and Yang (1996) presents a dynamic, multi-region, general-equilibrium model (RICE) of climate and the economy. It differs from earlier work, which focused on a globally aggregated approach, by introducing production, consumption, emissions, and damages for different regions. This approach compares three different strategies for the control of global warming: a market approach in which no climate change policies are taken, a global cooperative approach in which all countries choose climate-change policies to maximize global incomes, and a non-cooperative or nationalistic approach in which each country takes policies to maximize its own national income. The results of an integrated model of climate and the economy emphasizes the implications of the fact that while climate change is a global externality, the decision makers are national and relatively small. These inherent difficulties involved in planning over a horizon of a century or more about so uncertain and complex a phenomenon are compounded by the dispersed nature of the decisions and the strong tendency for free-riding by nonparticipants in any global agreement. Countries may therefore be triply persuaded not to undertake costly efforts today - first because the benefits are so conjectural, secondly because they occur so far in the future, and third because no individual country can have a significant impact upon the pace of global warming. The present study indicates that the third of these, the dispersed nature of the decision marking and the consequent diluted incentives to act, is a powerful hindrance to setting efficient climate-change policies.

Hassler and Krusell (2012) extended Nordhaus's pioneering RICE model. The authors develop a model that integrates the climate and the global economy - an integrated assessment model - with which different policy scenarios can be analyzed and compared. The model used is a dynamic stochastic general-equilibrium setup with a continuum of regions. Thus, it is a full stochastic general-equilibrium version of RICE. Like RICE, their model features traded fossil fuel but otherwise has no markets across regions. The extreme form of market incompleteness is not fully realistic but arguably not a bad approximation of reality. Its major advantage is that, along with a set of reasonable assumptions on preferences, technology, and nature, it allows a closed-form model solution. By using this simple and transparent model, the authors show that in absence of international transfer mechanisms, Pareto-improving policies to curb climate change may not exist.

The ultimate physical impact of climate change has yet to be determined with a realistic degree of precision. Although this is true for other pollutants, uncertainty over climate change impacts involves a huge scale and breadth of possibilities worldwide. As a consequence, there is uncertainty about the magnitude of damage costs associated with changing weather patterns, changing agricultural patterns and numerous other effects. This makes policy options difficult to determine and encourages decision makers to delay their response until stronger scientific evidence of potential damages becomes available.

Given the complexity of measuring the effect of climate change on economic growth, the traditional approach to estimating the overall economic impact is to use "Integrated Assessment Models" (IAM), which take some subset of mechanisms, specify their effects, and then add them up (Nordhaus and Boyer 2000). Implementations of the IAM approach require many assumptions about which effects to include, how each operates, and how they aggregate. This paper takes a different approach. Rather than identifying mechanisms one-by-one and summing them up, we examine the effects of temperature and precipitation fluctuations on economic growth. Specifically, I construct historical temperature and precipitation data for each country and year in the world from 1950 to 2010 and combine this data set with respective growth data. The main identification strategy uses year-to-year fluctuations in temperature and precipitation within countries to estimate the impact of temperature and precipitation on growth. This approach estimates the effect of short-run climate fluctuations using relatively few assumptions. Furthermore, I extend the main identification strategy to estimate the longer-run climate impact on economic output.

The main panel results show that substantial, negative correlation between temperature and growth, but only in rich countries. I estimate that a 1℃ rise in temperature in a given year is associated with a 0.26 points decrease in economic growth on average, all else constant. In poorer countries, changes in temperature do not seem to be correlated with growth rates. Moreover, changes in precipitation also have no discernible association with growth in either rich or poor countries. These results are consistent across a wide range of alternative specifications. There are two potential ways to interpret these effects: the level effects or the growth effects. By looking at multiple lags of climate variables, one can examine whether climate shocks have temporary or persistent impacts on economic output, and thus whether climate shocks have level or growth effects or both. My estimated results show that higher temperatures are associated with reduction on the growth rate in rich countries, not simply the level of output. Since even small growth effects have large consequences over time, if the growth effects of temperature persist in the longer run, the magnitude of temperature impacts would increase. By further examining the longer run climate shocks, we show that a 1℃ increase in temperature is related to reduction on annual growth in rich countries by 0.40 percentage points.

The remainder of the paper proceeds as follows. Section 2 introduces the data and provides descriptive statistics. Section 3 presents the empirical framework and considers the interlinkage between climate change and growth rate. Section 4 presents the main results and considers a number of robustness checks. Section 5 estimates the effects of longer-run climate shifts. Section 6 discusses and section 7 concludes.

2. Data and Descriptive Statistics

2.1. Data

The climate data is taken from the *Terrestrial Air Temperature and Precipitation: 1900-2010 Gridded Monthly Time Series, Version 3.01* (2012), compiled by Willmott and Matsuura with support from NASA. This data set provides terrestrial monthly mean temperature and precipitation data at 0.5 degree by 0.5 degree latitude/longitude grid. The gridded fields were estimated from monthly weather-station averages using a combination of spatial interpolation methods: digital-elevation-model (DEM) assisted interpolation (Willmott and Matsuura, 1995); traditional interpolation (Willmott et al., 1985); and climatologically aided interpolation (CAI) (Willmott and Robeson, 1995). Values are interpolated for each grid node from an average of 20 different weather stations, with corrections for elevation. A geospatial software package (Google Earth) is used to project the historical climate data to the country-year level. The main specifications use yearly average temperature and precipitation around the centroid of each country.

The economic data is extracted from the *World Development Indicators* (World Bank 2013). The World Development Indicators is the primary World Bank collection of development indicators, compiled from officially recognized international sources. It presents the most current and accurate global development data available, and includes national, regional and global estimates. I also use data from the *Penn World Tables Version 7.1* (Heston et al. 2012). The Penn World Table displays a set of national accounts economic time series covering 189 countries/territories for some of all of the years 1950-2010. The PWT is described as a forerunner of a new kind of international data base, both through time and across space. I focus on the panel of 167 countries with at least 20 years of GDP per capita growth data, and consider other samples as robustness checks.

2.2. Descriptive statistics

Figure 1 and Figure 2 present the global mean temperature and precipitation between 1950 and 2010. Figure 1 shows that the world has become about 1℃ warmer since the 1970s and the warming continues in a linear trend. On the other hand, the global precipitation has slightly declined about 200mm since the 1950s. Both the rise in temperature and the decline in precipitation are well-documented in previous literature which has been further established using sub-national data (Nordhaus 2006). Figure 3 indicates the global mean growth rate from 1950 to 2010. The figure shows no obvious trend or seasonality, and the world economy has roughly grown at a constant rate at the beginning and the end of the period.

Figure 4 and Figure 5 summarize mean temperature and precipitation for each country in the sample, plotted against the corresponding mean growth rate from the World Development Indicators. Figure 4 shows the tremendous temperature variation across countries: the hottest country in the sample is Chad, with a mean temperature of 29.3℃, and the coldest is Greenland, with a mean temperature of -28.0℃. Figure 4 also shows a potential inverse relationship between temperature and growth with hot countries tending to be poor and cold countries rich. This relationship has been known since the 18th century and has been further established using sub-national data (Nordhaus 2006). The only exceptions to this rule fall into two groups of states: oil states of the Middle East, which are hot and rich, and Communist or post-Communist states, which are cold and poor. Figure 5 presents the precipitation variation across countries: the wettest country is Ecuador, with an average precipitation of 43,150mm, and the driest country is Egypt, with an average precipitation of 50mm. However, there is no clear relationship between the level of precipitation and the growth rate.

Figure 1: Time trend in global mean temperature between 1950 and 2010

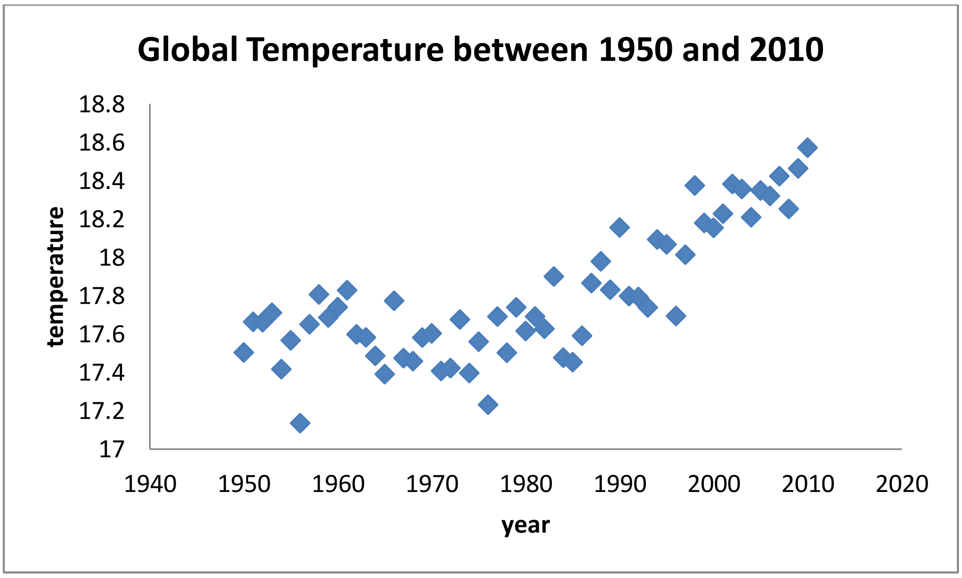


Figure 2: Time trend in global mean precipitation between 1950 and 2010

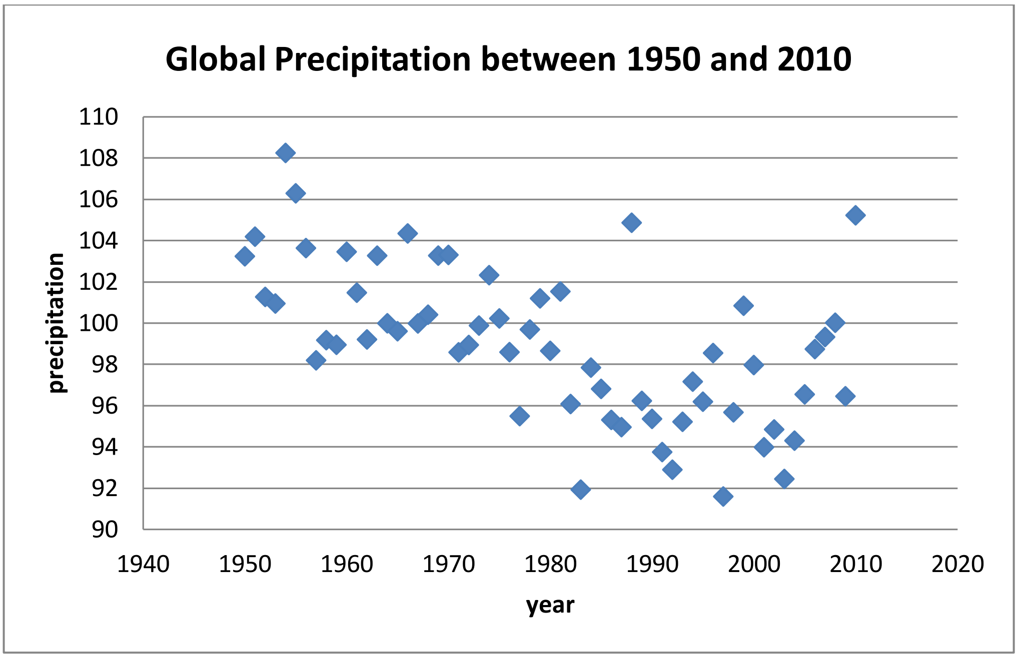


Figure 3: Time trend in global mean growth rate between 1950 and 2010

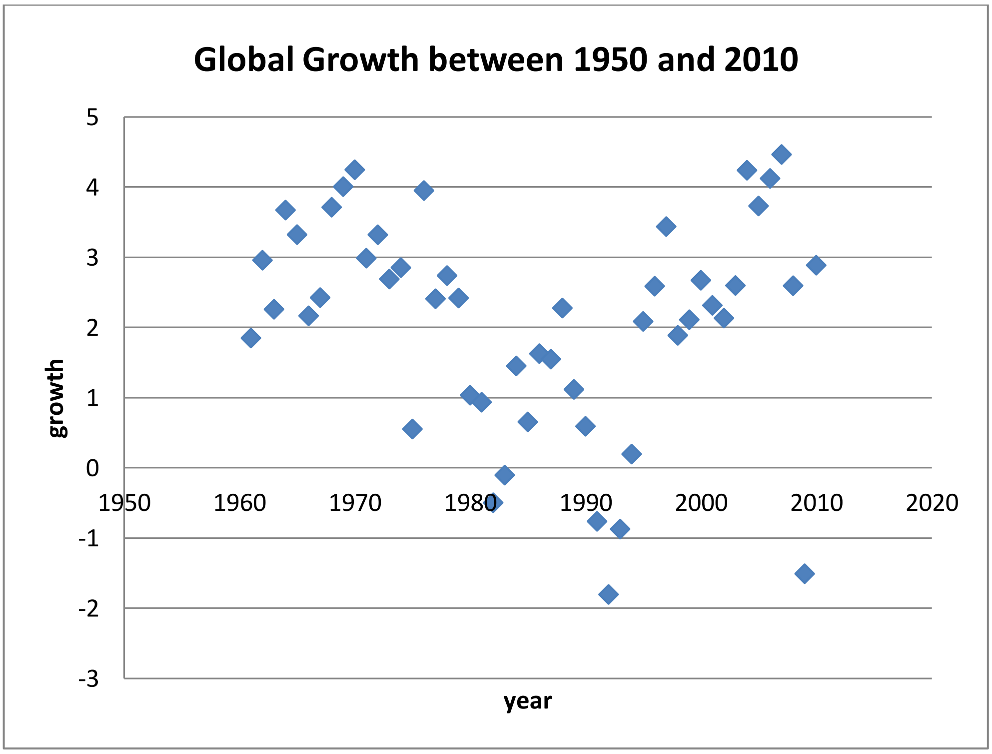


Figure 4: Temperature vs Growth

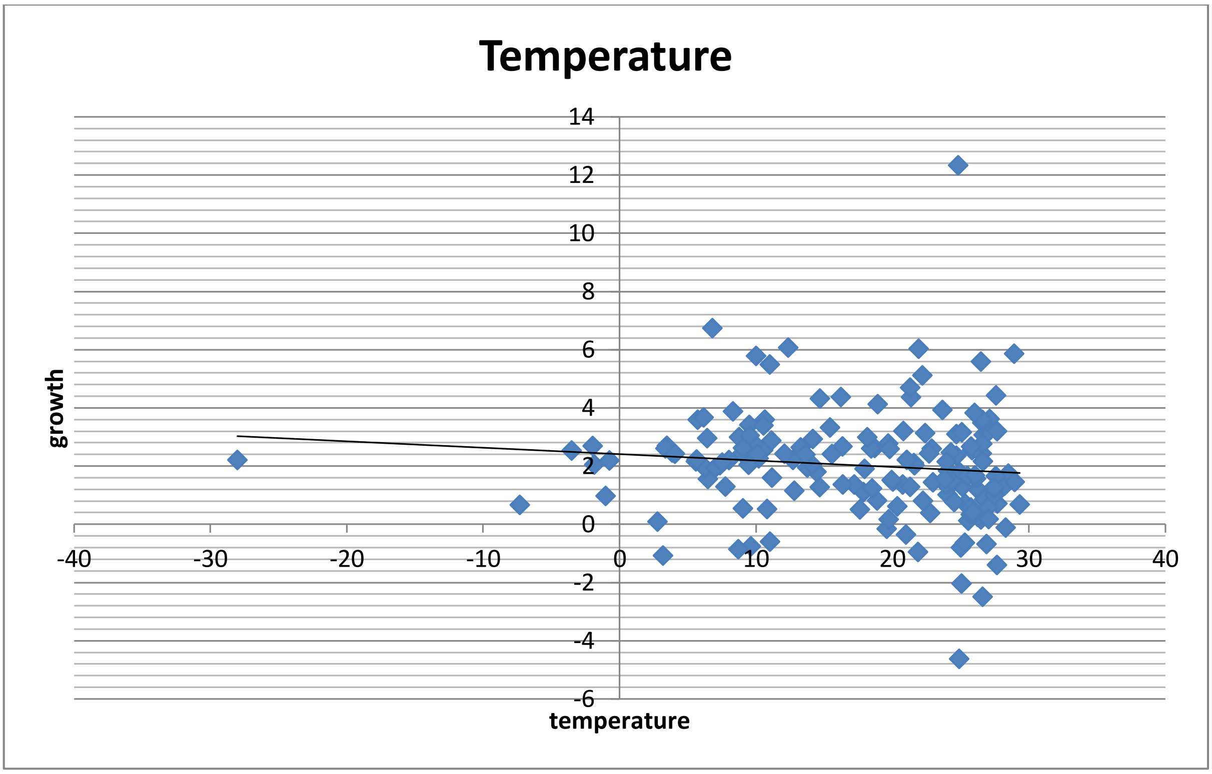
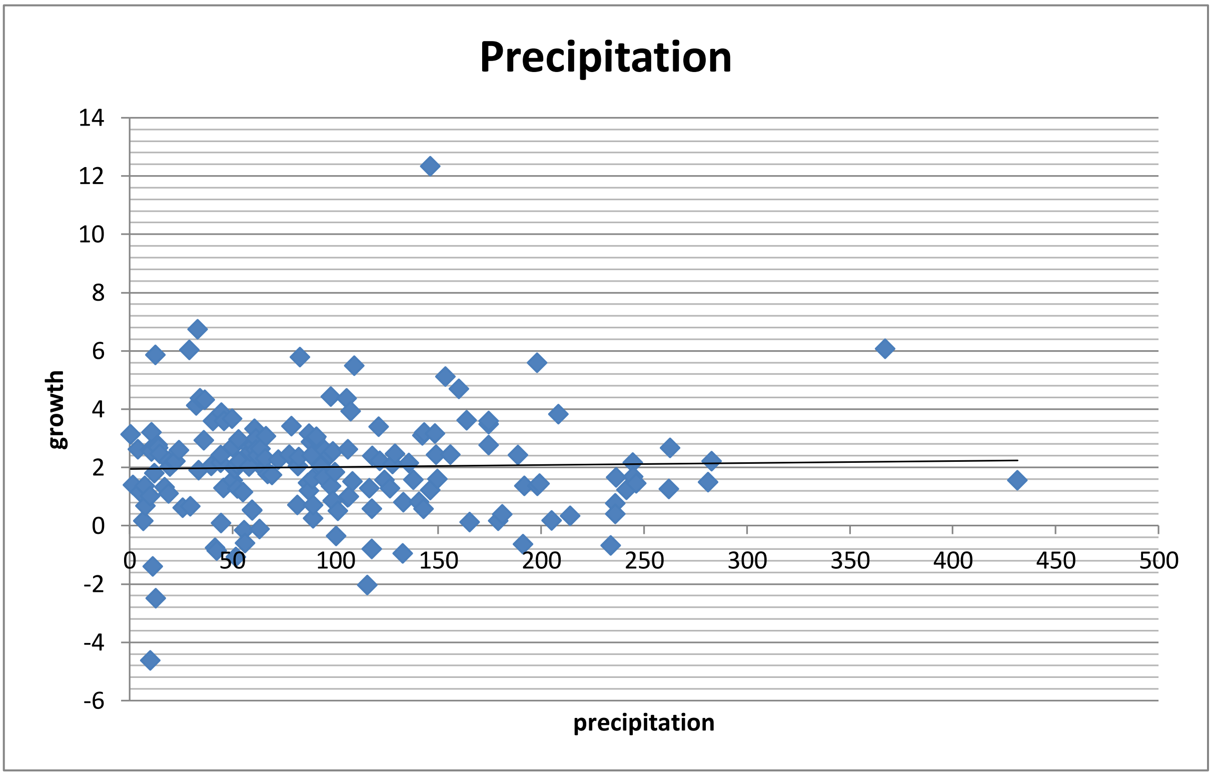


Figure 5: Precipitation vs Growth



3. Empirical Framework

Considering the empirical framework follows the derivation in Bond et al. (2007)

and assuming the simple economy is of endogenous growth:

$$Y_{it} = e^{\beta T_{it}} A_{it} L_{it} \tag{1}$$

$$\vartriangle A_{it}/A_{it} = g_i + \gamma T_{it} \tag{2}$$

where Y is aggregate output, L is population, A measures labor productivity, and T measures climate. Equation (1) captures the level effect of climate on production and equation (2) captures the growth effect.

Taking logarithms on both sides of the production function and differencing with respect to time,

$$\log Y_{it} = \beta T_{it} + \log A_{it} + \log L_{it} \tag{3}$$

$$\vartriangle Y_{it}/Y_{it} = \beta \vartriangle T_{it} + \vartriangle A_{it}/A_{it} \tag{4}$$

Substituting equation (2) into equation (4), we get the same dynamic growth equation shown in Dell, Jones and Olken:

$$g_{it} = g_i + (\beta + \gamma) T_{it} + \beta T_{it-1} \tag{5}$$

where g_{it} measures the growth rate of per-capita output, β measures the "level effects" of climate shocks on growth rate of per-capita output, and γ measures the "growth effects".

The dynamic growth equation implies that both the level effects and the growth effects influence the growth rate in the initial period of the climate shock. The difference is that the level effect will eventually reverse itself as the climate returns to its prior state but the growth effect will not be reversed. Therefore, the growth effect identified by γ in fact measures the over-time climate effects. Thus, we can extend Equation (5) to a more general lag model:

$$g_{it} = \theta_i + \theta_{rt} + \sum_{j=0}^{L} \rho_j T_{it-j} + \varepsilon_{it} \tag{6}$$

where θ_i represents country fixed effects, θ_{rt} represents time fixed effects (interacted separately with region dummies), ε_{it} is an error term clustered by country, and T_{it} is a vector of climate variables (temperature and precipitation) with up to L lags included.

Let's start by estimating models with no lags. The null hypothesis is that temperature and precipitation fluctuations are not correlated to growth:

$$H_0(L = 0): \rho_0 = 0$$

A rejection of null hypothesis implies that either the level effects or the growth effects influence the growth rates. For models with lags, we separately test the immediate effect of climate:

$$H_0(L > 0): \rho_0 = 0$$

and the cumulated effect of temperature:

$$H_0(L > 0): \sum_{j=0}^{L} \rho_j = 0$$

The summation of the lag coefficients corresponds to the parameter γ, the growth effect, in the simple model and the more general model with longer lag structures.

4. Results

4.1. Models with no lags

Table 1 presents the panel results of models with no lags (models with lags are examined in the next subsection). Column (1) and Column (2) of Table 1 examine the null hypothesis that temperature fluctuations are not associated with growth, neither through level effects nor growth effects. Column (1) shows a positive but statistically insignificant relationship between temperature fluctuations and growth. Next, I interact temperature with a dummy variable for a country being "rich", defined as having above the median of average PPP-adjusted per-capita GDP of all countries in the sample. By adding the interaction between the "rich" and temperature, both the coefficient on temperature and that on its interaction with the "rich" dummy in column (2) appear statistically significant at 1% significance level. The point estimates imply that a 1℃ rise in temperature is related to a 0.784 percentage points decrease in growth rates in all countries in the sample but a 1.047 points decrease in rich countries, all else remain constant. The negative and significant coefficient on the interaction between the "rich" dummy and temperature indicates substantial heterogeneity between rich and poor countries. As shown in the last row of the table (which reports the sum of the main effect of temperature and its interaction with the rich country dummy), the net effect of a 1℃ rise in temperature is associated with a decrease in growth rates in rich countries by 0.263 percentage points, which is statistically significant at 1% level.

The next two columns of Table 1 examine the null hypothesis that precipitation does not affect growth. Column (3) shows that precipitation and growth are not significantly related to each other. In Column (4), the interaction between the "rich" country dummy and precipitation is added. By adding this interaction term, both the coefficient on precipitation and that on its interaction with the "rich" dummy appear significant. The coefficients imply that a 100mm rise in precipitation corresponds to a 0.011 percentage points raise on growth rates in all countries and a 0.017 points reduction on growth in rich countries. However, the positive estimates of precipitation fluctuations on growth and the negative estimates of the interaction between "rich" and precipitation offset each other. As a result, the cumulative effect of precipitation fluctuations on growth rates is statistically insignificant at the conventional level. Column (5) shows that controlling for temperature and precipitation simultaneously leaves both estimates unchanged (the net effect of a 1℃ rise in temperature is related to decrease growth rates in rich countries by 0.269 percentage points whereas the net effect of a 100mm rise in precipitation is statistically insignificant at the conventional level).

As richer countries tend to be colder, it is necessary to consider whether a country being "rich" proxies for being "cold". In Column (6), I add the interaction between temperature and "cold" country dummy, defined as having below the median of average temperature in each country. By controlling the interaction between temperature and "cold", the negative effect of temperature appears through being a rich country, not through being a cold country, with the rich coefficient remaining unchanged. Using different definitions of a country being "cold", such as being above the 75th or 90th percentiles of the world average temperature distribution, yields results similar to the results presented in Column (6). This suggests that being rich characterizes the main negative temperature effects.

4.2. Models with lags

In the previous subsection, we reject the null hypothesis that temperature has no effect on growth in rich countries in the simple model with no lag structures. However, we cannot reject the null hypothesis that precipitation and growth are uncorrelated to each other. In this subsection, we are going to examine more flexible models with up to 10 lags of temperature to better understand the dynamics of these temperature effects.

Table 2 presents results from estimating equation (6) with no lags, one lag, three lags, five lags, or ten lags of the temperature and precipitation variables. In columns (1) to (5), only temperature and its lags are included into the panel regression. In columns (6) through (10), precipitation and its lags are also included. All climate variables are interacted with the rich country dummy. The last row of each columns presents the cumulated temperature effect on rich countries, which calculated by summing the respective temperature variable and its lags. In models with more than three lags, we only report the first three lags and the sum of all the lags in order to save space.

Column (1) to column (5) of Table 2 present the panel results of models with no lags, one lag, three lags, five lags, or ten lags of the temperature variables. The null hypothesis being examined is that longer-run temperature fluctuations do not affect growth. Column (1) shows that a 1℃ rise in temperature is to correlated with a 0.784 percentage points increase growth rates worldwide but a 1.047 points decrease in rich countries. The cumulative effect of a 1℃ rise in temperature is related to decrease growth rates in rich countries by 0.263 percentage points, which is statistically significant at the conventional significance level. In column (2), one lag of the temperature variables is added. After adding the lagged variables, the impact of current temperature shock on growth rate becomes insignificant. Instead, the first lag of the temperature variables appears statistically significant. The point estimates indicate that a 1℃ rise in temperature in the previous period brings a 0.985 percentage points increase in growth rates all countries but a 1.533 points decrease in growth in rich countries. The net effect of a 1℃ rise in temperature in the previous period is associated with a reduction on growth rates in rich countries by 0.571 percentage points. Column (3) adds up to three lags of the temperature variables and only the first lag appear significant. With three lags of the temperature variables added, the cumulative temperature effect lowers growth in rich countries further by 0.877 points. In columns (4) and (5), five lags and ten lags of the temperature variables are included respectively. With five lags included, the cumulative effect is associated with a reduction of 0.868 percentage points. As ten lags are added, the negative effect becomes smaller but it is still statistically significant.

The next five columns of Table 2 present the results of models with no lags, one lag, three lags, five lags, or ten lags of both temperature and precipitation variables included and examine the null hypothesis that longer-run temperature or precipitation fluctuations do not affect growth. Controlling for temperature and precipitation simultaneously yields similar temperature effects as the results presented in columns (1) to (5). Column (1) shows that a one-time 1℃ temperature increase in a rich country is related to a reduction on growth by 0.269 percentage points. With one lag included, the cumulative effect is associated with a reduction of 0.578 points. By including three, five, or ten lags, the cumulative effects remain statistically significant, with a 1℃ temperature increase producing a 0.562 to 0.876 percentage point reduction in growth. In columns (6) to (10), the coefficients on precipitation variables are suppressed to save space since none of the precipitation variables is significant.

The last row of Table 2 presents that the cumulative temperature effect in rich countries. Generally, this effect becomes more negative as more lags are included. With no lags, in columns (1) and (6), a one-time 1℃ temperature increase in a rich country is correlated with a decrease in growth by 0.263 to 0.269 percentage points. With three lags included, in columns (3) and (8), the cumulative effect of a 1℃ temperature increase is related to a reduction on growth by 0.876 to 0.877 percentage points. Including five lags, the cumulative temperature effect is associated with a reduction of 0.857 to 0.868 points. With ten lags included, the negative effect of a 1℃ temperature rise slightly drops to produce a reduction in growth by 0.562 to 0.598 percentage points. Except for ten lags, including more lags increases the magnitude of these cumulative effects. Of course, temperature effects may be mitigated beyond the 10-year horizon. However, as we have observed that including more lags increases the magnitude of the cumulative temperature effects, we believe that the temperature effects strengthen over time rather than diminish.

The individual lag coefficients show little evidence of a level effect of temperature on output. That is, the effect of above average temperature appear to persist in the medium-run, rather than being reversed. Recalling the empirical framework from Section 3, level effects are reversed when the climate shock is reversed. In the model with one lag, a level effect would appear as equal and opposite coefficients on the immediate effect and the first lag. Since the first lag appears significant in our sample, if level effects exist, the significant temperature effects in the first lag would eventually be reversed once the shock disappears. Therefore, to the extent temperature effects are level effects, the cumulated sum of the temperature effect and all its lags should be zero. As the lags in Table 2 do not sum to zero (in fact, the cumulated temperature effect becomes stronger as more lags are included), this suggests that the effects of temperature persist in the medium run.

4.3. Robustness

Tables 3 and 4 consider a variety of robustness checks. Table 3 deliberates alternative specifications using the same WDI data. Table 4 reports all the relevant results using the economic data extracted from the Penn World Tables Version 7.1. For each specification, we estimate equation (6) with no lags, one lag, three lags, five lags, or ten lags of both temperature and precipitation variables. Moreover, results from models with one and three lags are suppressed as they are qualitatively similar.

Panel A of table 3 presents the panel results of limiting the sample to the years 1971-2003, for which we have a balanced sample. The cumulative temperature effects are weakened in the balanced sample while all the other characteristics remain unchanged except for the model with no lags. With no lags included, the effect of a 1℃ temperature rise appears negative but statistically insignificant. Another potential concern is that climate data for Africa may be of poor quality. Then, we split the sample into Sub-Saharan African countries (panel B) and all other countries (panel C). In the model with no lags, the negative impacts of temperature are much stronger in non Sub-Saharan African countries, in which a 1℃ temperature increase associates with a reduction on growth by 2.363 percentage points in rich countries. However, the results of models with five and ten lags are similar (negative and statistically significant) in both samples. It is uncertain whether the difference is caused by poor quality climate data.

Table 4 reconsiders the main specifications using growth data extracted from the Penn World Tables Version 7.1. The layout of table 4 is the same as table 2. The null hypothesis being examined is that climate change does not affect growth. Columns (1) and (6) show that a one-time 1℃ temperature increase in a rich country is correlated with about 0.03 percentage points reduction in growth. With one lag included, the cumulative effect is related to a reduction of 0.222 to 0.230 points. Including three or five lags increase the statistical significance of these cumulative effects, with a 1℃ temperature increase producing a 0.175 to 0.388 percentage point reduction in growth. Using growth data from the PWT, the negative point estimates of models including zero, one, three, or five lags are smaller but significant at the conventional level. However, the ten-lag results attenuate somewhat and is statistically insignificant.

5. The longer-run

The short-run panel results indicate substantial effects of temperature shocks in rich countries, with approximately 0.3 percentage points decrease in growth rates correlated to a 1℃ rise in temperature. The negative effect persists for 10 years in the short-run panel model, i.e. there is no level effect; moreover, this effect strengthens in the first few years then attenuates over time. In this section, we consider the longer-run analogue of our panel specification, examining the relationship between climate changes and growth changes in the early and late periods in the sample. We also observed the substantial heterogeneity in temperature increases over this period, with some countries such as Tunisia, Zambia, and Botswana warming by approximately 1℃ since the mid 1980s, while others such as Laos, Kenya, and Nigeria experienced almost no warming over the same period. It is necessary to examine whether countries with sustained warming saw sustained growth changes.

Specifically, we estimate the following regression

$$\overline{g_{i2}} - \overline{g_{i1}} = \alpha + \theta_r + \gamma(\overline{T_{i2}} - \overline{T_{i1}}) + \varepsilon_i \quad (7)$$

where $\overline{g_{i1}}$ is the mean growth rate in country i in the early period (1970-1985) and $\overline{g_{i2}}$ is the mean growth rate in the late period (1986-2000). $\overline{T_{i1}}$ and $\overline{T_{i2}}$ represent the mean temperature and precipitation in the early and late period respectively. θ_r

captures country fixed effects and a dummy for being poor, and ε_i is assumed to be an independently distributed error term. This first-differenced regression is the longer-run version of equation (6). It is derived by taking averages of both sides of equation (6) then first differencing. By doing so, we difference out any fixed national characteristics that might influence growth and have one observation for each country.

Table 5 presents the results of estimating equation (7) using various specifications. The baseline specification compares the 1970-1985 period to the 1986-2000 period and shows statistically significant negative effects of warming on rich countries. The cumulative effect indicates that a 1℃ increase in temperature is associated with reducing annual growth in rich countries by 0.403 percentage points, while a 100mm rise in precipitation are not correlated to growth significantly. By including region fixed effects, the cumulative temperature effects become significantly smaller. In columns (3) to (5), we allow for different estimation period than the baseline specification. Although the results are similar, the statistical significance is sensitive to the estimation period. Column (3) presents the estimation results using slightly longer periods from 1970-1987 and 1988-2003. When excluding the period 1981-1990, the temperature effect reverses but insignificant. Comparing the 1980s to the 1990s reveals that a temperature rise of 1℃is related to a 0.447 points decrease in annual growth in rich countries by 0.447 points. In columns (6) and (7), we split the sample into Sub-Saharan African countries and all other countries. We find similar effects in both samples, though the negative temperature effect is very substantial in Sub-Saharan African countries.

Overall, the longer-run analysis continues to suggest statistically significant negative effects of warming on growth rates in rich countries. Moreover, the estimated effect in the longer-run is typically larger than in the short-run panel analysis. Thus, just as the 5 and 10 year lag results suggest that the growth effect strengthens over time, the longer-run relationship in Table 5 tends to show even larger effects. Thus, we do not observe that rich countries adapt and eliminate the negative consequences of warming over the time horizons with our empirical analysis.

6. Discussion

The estimates above replicate the analysis of Dell et al (2008) using different data and specifications. Nevertheless, similar results attain. The first similarity is that both paper find the substantial dichotomy between rich and poor countries. Also, we present estimated results that differ from the predicted results by the traditional IAM-based approaches, which show neither the large negative effects in rich countries nor the are diversion between rich and poor countries. These differences come primarily for three reasons. First, we rely on aggregate data to estimate the effects, rather than assuming a set of channels and adding them up as in IAM approaches. Estimating aggregate effects directly helps capture important channels. and interactions between channels, which are not captured by the disaggregated approach. Second, IAM approaches often build the underlying sector-specific models from evidence of behavior in rich countries. As demonstrated in this paper, the effects of climate change in rich and poor countries are different. Finally, most existing literature assumes that temperature will affect the level of output, as opposed to the growth rate of output. In our method, we consider the possibility of both level and growth effects (Dell et al 2008).

Our estimated impacts of climate change are much smaller than the results shown in Dell et al. They find that a 1℃ rise in temperature in a given year is associated with a reduction on economic growth by 1.1 percentage points in poor countries. This implies that a one-time 1℃ increase in temperature would halve the current growth rates in approximately 60 years. In section 2.2 of this paper, I summarize that all the countries in the data set has become about 1℃ warmer since the 1970s and the warming continues. However, the global mean growth rate remains nearly constant over the same period. My results, on the other hand, show that a temperature rise of 1℃ correlates to a decrease in growth by 0.26 points in rich countries. Thus, the same level of increase in temperature would reduce growth by 20 percent in 60 years, which seems more reasonable. Secondly, I find statistically significant effect of climate change on rich countries but not on poor countries. Since rich countries tend to be more industrialized, the substantial significant negative effect suggest that a rapid adaptation of the climate change problem is necessary.

For further study on the relationship between climate change and economic growth, one major drawback need be dealt with. Our main specifications use yearly average temperature and precipitation around the centroid of each country. To be more precise, one would use an accurate geospatial software to map all climate data within the border of each country then take average using different weighting scheme.

7. Conclusion

This paper presents new estimates for the effect of climatic changes on economic growth. I estimate climate effects directly by examining the empirical relationship between climate fluctuations and economic growth. This differs from the standard "Integrated Assessment Models", which assume a set of mechanisms, specify their effects, and sum them up.

By estimating the relationship between climate fluctuations and economic growth directly, we find substantial negative effects of climatic changes, but only in rich countries. In rich countries, a 1℃ rise in temperature in a given year is associated with a 0.26 percentage points decrease in economic growth on average. The estimates suggest that climate change has impact on the national economy. In poorer countries, changes in temperature have no significant effect on growth. Moreover, changes in precipitation have no discernible effects on growth in either rich or poor countries. These results are consistent across a wide range of alternative specifications. The longer-run results show that the negative effect even strengthens over time, with a cumulative effect of a 1℃ increase in temperature correlates to a reduction on annual growth in rich countries by 0.403 percentage points. Further work is needed to identify precise causal mechanisms. This paper suggests such analysis is of first-order importance, as the economic effects in rich countries appear large.

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Table 1: Panel results for models with no lags

	Dependent variable is the annual growth rate					
	(1)	(2)	(3)	(4)	(5)	(6)
Temperature	0.156 (0.149)	0.784*** (0.035)			0.840*** (0.033)	0.403*** (0.030)
Temperature interacted with…						
Rich country dummy		-1.047*** (0.086)			-1.109*** (0.083)	-1.283*** (0.042)
Cold country dummy						0.411 (0.319)
Precipitation			0.005 (0.004)	0.011*** (0.004)	0.014*** (0.004)	0.013*** (0.005)
Precipitation interacted with…						
Rich country dummy				-0.017** (0.009)	-0.021** (0.009)	-0.021** (0.009)
Cold country dummy						0.012 (0.010)
Observations	6922	6387	6922	6387	6387	6387
R-squared	0.0018	0.0067	0.0000	0.0034	0.0066	0.0049
Temperature effect in rich countries		-0.263*** (0.066)			-0.269*** (0.063)	-0.880*** (0.036)
Precipitation effect in rich countries				-0.006 (0.007)	-0.007 (0.007)	-0.008 (0.007)

Note: All specifications use WDI data and include country FE, region*year FE, and rich*year FE. Robust standard errors are presented in parentheses, adjusted for clustering at country level. Sample includes all countries with at least 20 years of growth observations. Rich dummy is defined as having above the median of world average PPP adjusted GDP per capita. Cold dummy is defined as having below the median of world average temperature. Temperature is in degrees Celsius and precipitation is in units of 100mm per year.
* significant at 10%; ** significant at 5%; *** significant at 1%

Table 2: Panel results for models with lags

	Dependent variable is the annual growth rate									
	(1) No lags	(2) 1 lag	(3) 3 lags	(4) 5 lags	(5) 10 lags	(6) No lags	(7) 1 lag	(8) 3 lags	(9) 5 lags	(10) 10 lags
Temperature	0.784*** (0.035)	0.291 (0.254)	0.312 (0.253)	0.196 (0.252)	0.068 (0.259)	0.840*** (0.033)	0.353 (0.249)	0.375 (0.247)	0.263 (0.247)	0.148 (0.253)
L1: Temperature		0.985*** (0.022)	1.031*** (0.026)	0.908*** (0.024)	0.833*** (0.023)		0.985*** (0.028)	1.035*** (0.023)	0.913*** (0.021)	0.860*** (0.028)
L2: Temperature			-0.110 (0.244)	-0.245 (0.259)	-0.369 (0.257)			-0.126 (0.247)	-0.271 (0.261)	-0.362 (0.262)
L3: Temperature			-0.018 (0.229)	-0.257 (0.215)	-0.442** (0.218)			-0.013 (0.234)	-0.271 (0.218)	-0.437** (0.219)
Temperature*Rich	-1.047*** (0.086)	-0.314 (0.286)	-0.294 (0.285)	-0.180 (0.286)	-0.094 (0.297)	-1.109*** (0.083)	-0.382 (0.281)	-0.368 (0.281)	-0.254 (0.283)	-0.182 (0.293)
L1: Temperature*Rich		-1.533*** (0.054)	-1.414*** (0.038)	-1.298*** (0.046)	-1.240*** (0.047)		-1.534*** (0.026)	-1.420*** (0.045)	-1.309*** (0.052)	-1.275*** (0.052)
L2: Temperature*Rich			-0.126 (0.278)	0.033 (0.292)	0.138 (0.291)			-0.092 (0.280)	0.072 (0.294)	0.150 (0.296)
L3: Temperature*Rich			-0.258 (0.254)	0.016 (0.245)	0.205 (0.246)			-0.267 (0.258)	0.025 (0.248)	0.192 (0.246)
Precipitation vars included	NO	NO	NO	NO	NO	YES	YES	YES	YES	YSE
Observations	6387	6387	6387	6387	6387	6387	6387	6387	6387	6387
R-squared	0.0067	0.0065	0.0063	0.0064	0.0066	0.0066	0.0065	0.0062	0.0064	0.0064
Cumulative temperature effect in rich countries	-0.263*** (0.066)	-0.571*** (0.192)	-0.877*** (0.193)	-0.868*** (0.195)	-0.598*** (0.195)	-0.269*** (0.063)	-0.578*** (0.189)	-0.876*** (0.195)	-0.857*** (0.197)	-0.562*** (0.198)

Note: All specifications use WDI data and include country FE, region*year FE, and rich*year FE. Robust standard errors are presented in parentheses, adjusted for clustering at country level. Sample includes all countries with at least 20 years of growth observations. Rich dummy is defined as having above the median of world average PPP adjusted GDP per capita. Columns (6) though (10) include Precipitation and Precipitation*Rich, with the same number of lags as the temperature variables shown in the table. Columns (4) and (9) also include the 4th and 5th lags of Temperature*Rich and Precipitation*Rich. Moreover, columns (5) and (10) also include the 4th through 10th lags of Temperature*Rich and Precipitation*Rich. Those coefficients are suppressed to save space. Sums of all temperature coefficients in rich countries shows the sum of Temperature*Rich and all of the lags of Temperature*Rich included in the regression. Temperature is in degrees Celsius and precipitation is in units of 100mm per year.

* significant at 10%; ** significant at 5%; *** significant at 1%

Table 3: Alternative specifications using WDI data

	Dependent variable is the annual growth rate								
	Panel A Balanced Sample: 1971-2003			Panel B Sub-Saharan Africa Only			Panel C Sub-Saharan Africa Excluded		
	(1) No lags	(2) 5 lags	(3) 10 lags	(4) No lags	(5) 5 lags	(6) 10 lags	(7) No lags	(8) 5 lags	(9) 10 lags
Temperature	0.632 (0.432)	0.702 (0.507)	0.936 (0.504)	1.088*** (0.398)	0.644** (0.314)	0.526 (0.323)	0.407 (0.286)	-0.548* (0.303)	-0.652** (0.295)
L1: Temperature		1.044*** (0.099)	1.301*** (0.056)		0.706*** (0.087)	0.671** (0.086)		1.324*** (0.055)	1.300*** (0.042)
L2: Temperature		-0.392 (0.316)	-0.045 (0.303)		-0.204 (0.362)	-0.297 (0.375)		-0.340 (0.350)	-0.550 (0.350)
L3: Temperature		-0.305 (0.303)	-0.220 (0.325)		-0.375 (0.314)	-0.486 (0.317)		0.090 (0.272)	-0.123 (0.283)
Temperature*Rich	-0.801* (0.457)	-0.636 (0.532)	-0.840 (0.603)	-1.283*** (0.418)	-0.544 (0.340)	-0.475 (0.353)	-2.770** (1.064)	-2.331** (1.001)	-2.337** (1.061)
L1: Temperature*Rich		-1.185*** (0.038)	-1.389*** (0.035)		-1.145*** (0.033)	-1.137*** (0.034)		-0.463 (0.044)	-0.228 (0.078)
L2: Temperature*Rich		0.362 (0.348)	0.031 (0.418)		0.022 (0.388)	0.105 (0.400)		-0.432 (0.602)	-0.231 (0.523)
L3: Temperature*Rich		-0.050 (0.336)	-0.015 (0.359)		0.081 (0.334)	0.199 (0.336)		1.768 (2.118)	2.161 (1.541)
Precipitation vars included	YES	YSE	YES	YSE	YES	YES	YES	YES	YES
Observations	4393	3872	3314	4704	4704	4704	1683	1683	1683
R-squared	0.0076	0.0066	0.0030	0.0072	0.0188	0.0281	0.0084	0.0317	0.0604
Cumulative temperature effect in rich countries	-0.263 (0.445)	-0.641** (0.296)	-0.437* (0.298)	-0.195 (0.408)	-0.851*** (0.282)	-0.574*** (0.283)	-2.363*** (0.779)	-0.109* (0.078)	-0.341*** (0.074)

Note: All specifications use WDI data and include country FE, region*year FE, and rich*year FE. Robust standard errors are presented in parentheses, adjusted for clustering at country level. Sample includes all countries with at least 20 years of growth observations. Rich dummy is defined as having above the median of world average PPP adjusted GDP per capita. Columns (1) through (3) use the balanced sample between 1971 and 2003. Columns (4) through (6) include the Sub-Saharan Africa countries only. Columns (7) through (9) include all the other countries except for Sub-Saharan Africa countries. Sums of all temperature coefficients in rich countries shows the sum of Temperature*Rich and all of the lags of Temperature*Rich included in the regression. Temperature is in degrees Celsius and precipitation is in units of 100mm per year. * significant at 10%; ** significant at 5%; *** significant at 1%

Table 4: Alternative specifications using PWT data

	Dependent variable is the annual growth rate									
	(1) No lags	(2) 1 lag	(3) 3 lags	(4) 5 lags	(5) 10 lags	(6) No lags	(7) 1 lag	(8) 3 lags	(9) 5 lags	(10) 10 lags
Temperature	0.098*** (0.030)	0.277*** (0.024)	0.478*** (0.074)	0.442*** (0.071)	0.492*** (0.066)	0.138*** (0.032)	0.321*** (0.026)	0.499*** (0.058)	0.458*** (0.054)	0.530*** (0.049)
L1: Temperature		-0.339*** (0.074)	-0.076 (0.055)	-0.094* (0.057)	-0.143** (0.068)		-0.370*** (0.077)	-0.116** (0.054)	-0.137** (0.058)	-0.193*** (0.060)
L2: Temperature			-0.375 (0.257)	-0.426 (0.260)	-0.543* (0.261)			-0.327 (0.248)	-0.355 (0.268)	-0.446 (0.273)
L3: Temperature			-0.467** (0.201)	-0.536** (0.250)	-0.621** (0.281)			-0.433** (0.203)	-0.520** (0.206)	-0.592** (0.286)
Temperature*Rich	-0.130*** (0.035)	-0.334*** (0.033)	-0.558 (0.339)	-0.523 (0.334)	-0.541 (0.327)	-0.169*** (0.037)	-0.377*** (0.037)	-0.580* (0.325)	-0.549* (0.319)	-0.593* (0.312)
L1: Temperature*Rich		0.174*** (0.037)	-0.100 (0.086)	-0.063 (0.087)	-0.073 (0.068)		0.196*** (0.038)	-0.073 (0.085)	-0.039 (0.089)	-0.046 (0.093)
L2: Temperature*Rich			0.453 (0.325)	0.537 (0.350)	0.632* (0.341)			0.413 (0.317)	0.482 (0.337)	0.553 (0.335)
L3: Temperature*Rich			0.470* (0.258)	0.643** (0.208)	0.752*** (0.232)			0.439* (0.263)	0.639** (0.317)	0.735** (0.339)
Precipitation vars included	NO	NO	NO	NO	NO	YES	YES	YES	YES	YSE
Observations	5398	5397	5318	5230	4987	5398	5397	5318	5230	4987
R-squared	0.0000	0.0005	0.0016	0.0024	0.0060	0.0003	0.0013	0.0027	0.0050	0.0118
Cumulative temperature effect in rich countries	-0.032 (0.032)	-0.222*** (0.036)	-0.175** (0.099)	-0.358*** (0.099)	-0.108** (0.098)	-0.031 (0.035)	-0.230*** (0.035)	-0.176** (0.099)	-0.388*** (0.099)	-0.007 (0.100)

Note: All specifications use PWT data and include country FE, region*year FE, and rich*year FE. Robust standard errors are presented in parentheses, adjusted for clustering at country level. Sample includes all countries with at least 20 years of growth observations. Rich dummy is defined as having above the median of world average PPP adjusted GDP per capita. Columns (6) though (10) include Precipitation and Precipitation*Rich, with the same number of lags as the temperature variables shown in the table. Columns (4) and (9) also include the 4th and 5th lags of Temperature*Rich and Precipitation*Rich. Moreover, columns (5) and (10) also include the 4th through 10th lags of Temperature*Rich and Precipitation*Rich. Those coefficients are suppressed to save space. Sums of all temperature coefficients in rich countries shows the sum of Temperature*Rich and all of the lags of Temperature*Rich included in the regression. Temperature is in degrees Celsius and precipitation is in units of 100mm per year.

* significant at 10%; ** significant at 5%; *** significant at 1%

Table 5: Longer-run relationship

	Dependent variable is the change in mean growth rate							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Baseline	Alternative comparison years				Africa Only	Excluding Africa	PWT
Change in Temperature	0.114 (0.115)	0.194 (0.102)	0.190 (0.119)	0.397 (0.311)	0.322 (0.264)	0.596* (0.322)	0.322 (0.313)	0.099* (0.058)
Change in Temperature * Rich Country	-0.517* (0.292)	-0.457* (0.242)	-0.270 (0.281)	-0.376 (0.503)	-0.769*** (0.279)	-6.969*** (0.896)	-0.560 (0.567)	-0.275*** (0.054)
Change in Precipitation	0.004 (0.024)	0.012 (0.027)	-0.002 (0.024)	0.061 (0.053)	0.054 (0.038)	0.122* (0.065)	-0.034 (0.025)	0.037 (0.028)
Change in Precipitation * Rich Country	0.026 (0.030)	0.026 (0.032)	0.024 (0.031)	-0.041 (0.058)	-0.043 (0.047)	0.328*** (0.065)	0.072** (0.031)	-0.023** (0.032)
Region FE	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Rich Country Dummy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Early Period	1970-1985	1970-1985	1970-1987	1971-1980	1981-1990	1970-1985	1970-1985	1970-1985
Late Period	1986-2000	1986-2000	1988-2003	1991-2000	1991-2000	1986-2000	1986-2000	1986-2000
Observations	144	144	149	125	155	37	107	5318
R-squared	0.0144	0.0273	0.0283	0.1294	0.0833	0.2206	0.0013	0.0027
Cumulative temperature effect in rich countries	-0.403* (0.221)	-0.263** (0.111)	-0.080 (0.232)	0.019 (0.418)	-0.447** (0.214)	-6.373*** (0.673)	-0.238 (0.460)	-0.176*** (0.056)
Cumulative precipitation effect in rich countries	0.030 (0.027)	0.038 (0.030)	0.022 (0.028)	0.020 (0.056)	0.011 (0.034)	0.450*** (0.065)	0.038* (0.022)	0.014 (0.030)

Notes: All specifications have one observation per country. Change in temperature and precipitation are computed for each country as the difference between the mean value in the late period and that in the early period (these periods are indicated in the table for each specification). The dependent variable is the change in mean growth rate between the late period and the early period. Region fixed effects and a dummy for being rich are included as indicated for each specification. Robust standard errors are presented in parentheses. Temperature is in degrees Celsius and precipitation is in units of 100mm per year.
* significant at 10%; ** significant at 5%; *** significant at 1%