Climate Shocks and Economic Growth: Evidence from the Last Half Century

Melissa Dell
MIT

Benjamin F. Jones
Northwestern University and NBER

and

Benjamin A. Olken
MIT and NBER

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ABSTRACT

This paper uses annual variation in climate to examine the impact of temperature and precipitation on national economies. We find three primary results. First, higher temperatures substantially reduce economic growth in poor countries. Second, higher temperatures appear to reduce growth rates, not just the level of output. Third, higher temperatures have wide-ranging effects, reducing agricultural and industrial output, investment, innovation, and political stability. Decade or longer increases in temperature also show substantial negative effects on poor countries' growth. These findings inform debates over climate's role in economic development and suggest substantial negative impacts of future climate change on poor countries.

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1. Introduction

Climate may – or may not – be central to understanding the world economy. In this paper, we use historical fluctuations in temperature and precipitation within countries to identify their effects on aggregate economic outcomes. We use this approach to inform old debates about the role of climate in economic development and new debates about possible impacts of future climate change.

The relationship between climate and aggregate economic activity has traditionally been quantified using two approaches. The Integrated Assessment Model (IAM) approach, utilized extensively in the climate change literature to model climate-economy interactions, typically estimates or postulates the effects of climate on a subset of sectors, and then adds up these effects (e.g. Mendelsohn et al. 2000, Nordhaus and Boyer 2000, Tol 2002). A fundamental challenge for this enumerative approach is complexity: the set of candidate mechanisms through which climate may influence economic outcomes is extremely large and, even if each mechanism could be enumerated and its operation understood, how they interact and aggregate to shape macroeconomic outcomes raises additional difficulties.

The breadth of this challenge is apparent in a brief survey of the climate-economy literature, which has investigated climate's impact on agriculture (e.g., Adams et al. 1990; Mendelsohn et al. 2001; Deschenes and Greenstone 2007; Guiteras 2007), health (e.g. Curriero et al. 2002; Deschenes and Moretti 2007; Deschenes and Greenstone 2007; Gallup and Sachs 2001; Sachs and Malaney 2002), labor productivity (Meese et al. 1982; Huntington 1915), crime (e.g. Field 1992; Jacob et al. 2007), conflict (Miguel et al. 2004), migration, storm frequency, tourism, and many other dimensions extensively discussed in the recent Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC 2007). Main users of IAM models acknowledge that the final aggregate estimates therefore rest to an important degree on modeling decisions and other assumptions (Stern 2007, p. 145).[1]

[1] The Stern report on the economics of climate change (2007) describes IAM models as follows (p. 145):

> "Making such estimates is a formidable task in many ways (discussed below). It is also a computationally demanding exercise, with the result that such models must make drastic, often heroic, simplifications along all stages of the climate-change chain. What is more, large uncertainties are associated with each element in the cycle. Nevertheless, the IAMs remain the best tool available for estimating aggregate quantitative global costs and risks of climate change."

The second approach (e.g., Sachs and Warner 1997; Gallup, Sachs, and Mellinger 1998) avoids difficulties of aggregation by examining the relationship between climate and aggregate economic variables in a cross-section of countries. Such analysis estimates a strong relationship between climate and economic performance, but many argue that this correlation is driven by spurious associations of climate with national characteristics such as institutional quality (e.g., Acemoglu, Johnson, and Robinson 2002; Rodrik, Subramanian, and Trebbi 2004).

This paper takes an alternative approach. We first construct temperature and precipitation data for each country and year in the world from 1950 to 2003 and combine this dataset with data on aggregate output. We then examine the historical relationship between changes in a country's temperature and precipitation and changes in its economic performance. Our main identification strategy uses year-to-year fluctuations in temperature and precipitation, though we find similar effects on growth when we examine decade or longer changes in average temperature and precipitation.[2] By examining aggregate outcomes directly, we avoid relying on *a priori* assumptions about what mechanisms to include and how they might operate, interact, and aggregate. By utilizing fluctuations in temperature and precipitation, we isolate their effects from other country characteristics.

Our main results show large, negative effects of higher temperatures on growth, *but only in poor countries*. In poorer countries, we estimate that a 1°C rise in temperature in a given year reduced economic growth in that year by about 1.1 percentage points. In rich countries, changes in temperature had no discernable effect on growth. Changes in precipitation had no substantial effects on growth in either poor or rich countries. We find broadly consistent results across a wide range of alternative specifications.

To interpret these effects, one can distinguish two potential ways temperature could affect economic activity: 1) influencing the *level* of output, for example by affecting agricultural yields, or 2) influencing an economy's ability to *grow*, for example by affecting investments or institutions that influence productivity growth. By looking at multiple lags of temperature, we can examine whether temperature shocks appear to have temporary or persistent impacts on

[2] The use of annual variation to estimate the impact of climate change was pioneered by Deschenes and Greenstone (2007), who use annual county-level U.S. data to estimate the impact of climate on U.S. agricultural output. Several authors have also used higher frequency data, focusing on the GDP effect of rainfall in Africa as an instrument for conflict (Miguel et al 2004) and to explain the African growth tragedy (Barrios et al forthcoming).

economic output, and thus whether temperature has level or growth effects (or both). Our results suggest that higher temperatures may reduce the growth rate in poor countries, not simply the level of output. Since even small growth effects have large consequences over time, these growth effects – if they persist in the medium run – would imply large impacts of temperature increases.

We also find evidence that temperature affects numerous dimensions of poor countries' economies. While agricultural output contractions appear to be part of the story, we likewise find adverse effects of hot years on industrial output and aggregate investment. Poor countries also produce fewer scientific publications in hot years, which suggests that higher temperatures may impede innovation. Moreover, we show that higher temperatures lead to political instability in poor countries, as evidenced by irregular changes in national leaders. Many of these effects sit outside the primarily agricultural focus of much economic research on climate change and underscore the challenge for approaches that seek to build aggregate estimates of climate impacts from a narrow set of channels. These broader relationships also help explain how temperature might affect growth rates in poor countries, not simply the level of output.

These results are identified using short-run fluctuations in temperature and precipitation, whereas the long-run effects of climate may be quite different. For example, in the long run, countries may adapt to a particular climate, mitigating the short-run economic impacts that we observe. This type of adaptation may explain why our estimates of short-run economic impacts of temperature shocks are substantially larger than what the overall cross-sectional relationship between temperature and income across the world would imply (see Section 6). Alternatively, sustained levels of a given climate may have additional long-run effects on dimensions such as water tables, soil quality, and health, producing larger impacts (e.g., Meehl et al. 2004).[3]

Although our approach (like others) cannot fully overcome these challenges, we can make further headway by examining longer-term climate shifts within countries. Mean global land temperatures have risen nearly 1°C since 1970 (Brohan et al. 2006), but countries have not warmed equally. We therefore examine whether those countries that experienced the largest climate shifts between early and late periods in our sample had the largest shifts in their growth rates. Though this approach has less statistical power than using annual variation, the estimated

[3] In the context of future global climate change, other factors such as changing sea levels, increasing frequency of natural disasters, and issues of biodiversity may create additional costs not captured here (IPCC 2007; Nicholls and Leatherman 1995)

effects of increased temperature over 10 or 15-year time horizons are very similar to (and in fact larger than) our annual panel estimates, showing substantial negative effects in poor countries.

Our findings have implications for estimating potential future impacts of climate change. To assess future climate change, any method must make assumptions about the speed of adaptation. Our historical analysis, in which we do not observe adaptation over a 10-year time horizon, suggests a means of constructing lower bounds on the future economic impacts of climate change. In particular, we assume that economies receive the negative impact of a temperature change for 10 years, consistent with our estimates, but that full adaptation occurs immediately thereafter. Coupling this historically-grounded lower-bound approach with a standard global climate model to predict climate changes through the year 2100, our estimates imply future negative effects of climate change for poor countries that are quite consistent with what the historical cross-country relationship between temperature and income would imply. These estimated effects are, however, substantially larger than those of existing integrated assessment models and suggest how future implementations of IAMs could be modified to better match the historical climate-economy evidence.

Our results also inform the older debate over climate's role in economic development. It has long been known that hot countries tend to be poor (e.g. Montesquieu 1750, Nordhaus 2006). Whether climate has a contemporary, direct effect is contentious, with some scholars arguing that the cross-sectional relationship between climate and poverty is due primarily to the historical impacts of climate on country characteristics such as institutions (Acemoglu et al. 2001, Sachs 2003). Our findings, by using exogenous changes in temperature within countries, identify a substantial contemporary causal effect of temperature on aggregate output.

The remainder of the paper is organized as follows. Section 2 introduces the data and provides descriptive statistics. Section 3 describes the estimation strategy, presents the main results, and considers a number of robustness checks. Section 4 considers channels that may link climate change to national output. Section 5 estimates the effects of longer-run climate shifts. Section 6 relates the historical panel estimates to the cross-sectional relationship between temperature and income, and offers projected lower-bound implications of climate change for poor countries using a standard climate model. Section 7 concludes.

2. Data and Descriptive Statistics

2.1. Data

The historical climate data is taken from the *Terrestrial Air Temperature and Precipitation: 1900-2006 Gridded Monthly Time Series, Version 1.01* (Matsuura and Willmott 2007). This data set provides worldwide (terrestrial) monthly mean temperature and precipitation data at 0.5 x 0.5 degree resolution (approximately 56km x 56km at the equator). Values are interpolated for each grid node from an average of 20 different weather stations, with corrections for elevation.

We use geospatial software to aggregate the climate data to the country-year level. Our main specifications use population-weighted average temperature and precipitation, where the weights are constructed from 1990 population data at 30 arc second resolution (approximately 1km at the equator) from the *Global Rural-Urban Mapping Project* (Balk et al. 2004). We also consider averaging based on geographic area, which produces broadly similar climate variables for most countries.[4] Appendix I presents additional details about the climate data (all appendices are available online).

For economic data, we primarily use the *Penn World Tables Version* 6.2 (Heston et al. 2006). We also use data from the *World Development Indicators* (World Bank 2007) to examine robustness and disaggregated value-added output from agriculture and industry. We focus on the panel of 136 countries with at least 20 years of GDP data in the Penn World Tables, and consider other samples as robustness checks.

2.2. Descriptive statistics

Figure 1 presents population-weighted global mean temperature and precipitation from 1950 to 2006. The figure shows that the world has become about 1°C warmer since the early 1970s, and that average precipitation has fallen by about 10 cm. The warming trend since the 1970s is well-documented (e.g. Brohan et al. 2006) and suggests a linear rate of change that, should it continue, would predict an additional 3°C warming by 2100, in line with many climate models. The decline in precipitation is also well-documented, though this trend stands in contrast to most climate models, which predict that global warming will come with increased

[4] Countries where the weighting scheme makes a substantial difference are those with large, sparsely populated areas with unusual climates: Russia (Siberia), Canada (the arctic and sub-arctic areas), the United States (Alaska), and Australia (central Australia).

precipitation on average.[5]

To examine variation in climate, Figure 2 summarizes temperature (left graph) and precipitation (right graph) data for each country in the sample, plotted against log per-capita PPP GDP in the year 2000. For each country, the circle symbols represent the mean levels of temperature and precipitation in the first decade of our sample (1950-1959), the plus symbols represent the mean levels in the last decade of our sample (1996-2005), and the gray lines indicate the range of annual mean levels we observe for that country.

The left panel of Figure 2 shows the tremendous temperature variation across countries: the hottest country in the world is Mauritania, with an average population-weighted temperature of 28.4 ºC, and the coldest is Mongolia, with an average population-weighted temperature of -1.77 ºC. Figure 2 also shows the strong relationship between temperature and per-capita income, with hot countries tending to be poor and cold countries rich. This relationship has been known since at least the 18th century (Montesquieu 1750) and has been further established using sub-national data (Nordhaus 2006). The exceptions to this rule fall into two main groups: oil states of the Middle East, such as Qatar and Kuwait, which are hot and wealthy, and Communist / post-Communist states, such as Mongolia and North Korea, which are cold and poor. On average, a simple cross-section regression in the year 2000 shows that a 1°C increase in average temperature predicts a fall in per-capita income by 0.085 log points (i.e. about 8 percent).

Looking at variability within countries, we see fluctuations in annual mean temperatures on the order of about 2-3ºC. Thus, the max-min variation within countries is more than twice the average increase in temperature observed over the period, and similar to the increase in global temperatures expected to occur over the next century. Figure 2 further shows that, while there tend to be larger temperature fluctuations in cooler countries, the upward trend in temperature has occurred globally with similar magnitude in both hot and cold countries.

Examining the data on precipitation in the right panel of Figure 2 shows substantial annual variability in precipitation in all but the very driest countries. However, there is no clear relationship between the level of precipitation and the level of per-capita income in 2000.

[5] Historical area-weighted data for land shows a precipitation increase of nearly 1 cm over the 20th century. However, a peak occurred in the 1950s, with precipitation falling across more recent decades (Neng et al. 2002; New et al. 2001). On average, climate projections predict a rise in precipitation equal to about half of the recent global decrease by the end of the 21st century (see IPCC 2007 Working Group 1 Chapter 10).

To examine the variability further, Table 1 documents the extent of temperature and precipitation fluctuations within countries. While the max-min difference in temperature is about 2-3ºC (Figure 2), a country's temperature deviates more than 1ºC from the country mean approximately once every fifteen years. Precipitation is more volatile, with deviations from mean rainfall of about 400-500mm appearing once every fifteen years. When common global or region-specific year fixed effects are removed, these deviations become somewhat more modest.

3. The effect of climate fluctuations on economic activity

In this section we develop the empirical framework for the analysis of climate shocks, present our main results, and consider a variety of robustness checks.

3.1. Empirical framework

Our empirical framework follows the derivation in Bond et al. (2007). To fix ideas, consider the following simple economy:[6]

$$Y_{it} = e^{\beta T_{it}} A_{it} L_{it} \qquad (1)$$

$$\Delta A_{it} / A_{it} = g_i + \gamma T_{it} \qquad (2)$$

where Y is aggregate output, L measures population, A measures labor productivity, and T measures climate. Equation (1) captures the *level effect* of climate on production; e.g. the effect of current temperature or precipitation on crop yields. Equation (2) captures the *growth effect* of climate; e.g. the effect of climate on features such as institutions that influence productivity growth.

Taking logs in the production function and differencing with respect to time, we have the dynamic growth equation

$$g_{it} = g_i + (\beta + \gamma) T_{it} - \beta T_{it-1} \qquad (3)$$

where g_{it} is the growth rate of per-capita output. The "level effects" of climate shocks on output, which come from equation (1), appear through β. The "growth effects" of climate shocks, which come from equation (2), appear through γ.[7]

[6] We focus here on this simple production model. Appendix II extends the reasoning developed here to more general dynamic panel models that incorporate richer lag structures and lagged dependent variables.

[7] Rather than first-differencing (1), one could integrate (2), producing a fully-specified equation in the log level of output. However, as Bond et al. (2007) notes, this creates non-stationarity in both output levels (on the left-hand

The growth equation in (3) allows separate identification of level effects and growth effects through the examination of transitory weather shocks. In particular, both effects influence the growth rate in the initial period of the shock. The difference is that the level effect eventually reverses itself as the climate returns to its prior state. For example, a temperature shock may reduce agricultural yields, but once temperature returns to its average value, agricultural yields bounce back. By contrast, the growth effect appears during the climate shock and is not reversed: a failure to innovate in one period leaves the country permanently further behind. The growth effect is identified in (3) as the summation of the climate effects over time.

The above reasoning extends to models where climate effects play out more slowly.[8] With more general lag structures in (1) and (2), the growth effect is still identified by summing the lagged effects of the climate shock. This standard distributed-lag result is demonstrated formally in Appendix II.

To estimate these effects, we run panel regressions of the form

$$g_{it} = \theta_i + \theta_{rt} + \sum_{j=0}^{L} \rho_j T_{it-j} + \varepsilon_{it} \qquad (4)$$

where θ_i are country fixed effects, θ_{rt} are time fixed effects (interacted separately with region dummies and a poor country dummy in our main specifications), 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. In addition, we also consider variations of (4) that include interactions between climate variables and country characteristics. We have verified using Monte Carlo analysis that the specification in (4) produces unbiased estimates of both growth and level effects and has appropriate size given the properties of our data. (See Appendix II for more details.)

We begin by estimating (4) with no lags, focusing on the null hypothesis that climate does not affect growth:

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

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side) and accumulable factors (on the right-hand side). To avoid relying on cointegration assumptions for identification, Bond et al recommend first-differencing.

[8] For example, low temperatures in the latter part of one year could affect harvests the next year – which would generate a lagged level effect. Alternatively, a permanent shock to productivity could influence subsequent capital accumulation as the capital stock adjusted to its new steady state – which would generate a lagged growth effect. The key distinction is that, as in equation (3), level effects eventually generate equal and opposite responses through further lags, whereas growth effects do not. See Appendix II.

A failure to reject this hypothesis would indicate an absence of both level and growth effects. In subsequent regressions with lags, following the conventions in the distributed-lag literature (see Greene 2000), we separately test the immediate effect of temperature:

$$H_0^1(L>0): \rho_0 = 0$$

and the cumulated effect of temperature:

$$H_0^2(L>0): \sum_{j=0}^{L} \rho_j = 0$$

The summation of the lag coefficients corresponds to the parameter γ, the growth effect, in the simple model above, as well as a more general concept of growth effects in models with longer lag structures, as demonstrated in Appendix II. Appendix II also discusses generalizations of the empirical model and tests following Bond et al. (2007) that allow for more general short-run dynamics. As discussed in the appendix, the results from the extended dynamic model are very similar to the results from the simpler model developed here.

3.2. Panel results

Table 2 examines the null hypothesis that climate does not affect growth, either through level effects or growth effects. It presents results from estimating equation (4) with no lags (i.e., imposing $\rho_j = 0$ for all $j > 0$; models with lags are examined in the next subsection). Column (1) of Table 2 shows a negative but statistically insignificant relationship between temperature fluctuations and growth. In column (2), we interact temperature with a dummy for a country being "poor", defined as having below-median PPP-adjusted per-capita GDP in the first year the country enters the dataset. The coefficient on the interaction between the "poor" dummy and temperature is negative and statistically significant, indicating substantial heterogeneity between poor and rich countries.[9] As shown in the last row of the table (which reports the sum of the main effect of temperature and its interaction with the poor dummy), the net effect of a 1°C rise in temperature is to decrease growth rates in poor countries by -1.09 percentage points.

The next columns of Table 2 examine the impact of precipitation and do not show strong effects, in rich or poor countries. Focusing on column (4), an extra 100mm of annual precipitation is associated with a 0.07 percentage point lower growth rate in rich countries and a statistically insignificant 0.05 percentage point higher growth rate in poor countries. Since global

[9] We have also considered quintiles of initial per-capita income rather than a binary distinction. We find the largest negative effects of temperature on the bottom 2 quintiles of temperature.

mean precipitation levels have fallen nearly 100mm in the last 50 years (see Figure 1), a 100mm variation in precipitation is on the same order historically as the 1° C rise in temperature. By this metric, the precipitation effects typically appear at least a factor of 10 smaller than the temperature effect in poor countries. Moreover, Table 4 below shows that the statistical significance of the precipitation effects are sensitive to specification, suggesting that they should be interpreted with caution. Column (5) shows that controlling for temperature and precipitation simultaneously leaves both estimates unchanged.

Poorer countries tend to be both hotter and more agricultural. In columns (6) and (7) we consider whether being "poor" proxies for these characteristics. Column (6) adds the interaction between temperature and "hot", defined as having above median temperature in the 1950s. The negative effect of temperature appears through being poor, not through being hot, with the poor coefficient remaining unchanged.[10] Column (7) controls for the interaction between temperature and "agricultural", defined as having an above median agricultural GDP share in 1995.[11] Once again, the negative effect of temperature appears through being poor.[12] While it is impossible to definitively separate the impacts of poverty from those of the agriculture share or mean temperature (other the many other variables that are correlated with poverty), this evidence suggests that being poor usefully characterizes a locus of substantial negative temperature effects.

3.3. Models with lags

The above results, using the simple model with no lags, reject the null hypothesis that temperature has no effect on growth in poor countries. This section considers more flexible models with up to 10 lags of temperature to better understand the dynamics of these temperature

[10] In results not reported in the table, we have also experimented with different definitions of "hot," such as being above the 75th or 90th percentiles of the world average temperature distribution, as well a linear temperature variable. The results from these alternative specifications are qualitatively similar to the results presented in the Table.

[11] We use 1995 data for agricultural share because data coverage from earlier years is sparse. Using earlier data cuts sample sizes considerably but produces broadly similar results.

[12] In results not reported in the table, regressions that control only for temperature fluctuations and their interaction with the agriculture share (i.e. not including interactions with national income) produce statistically insignificant effects for agriculture, further suggesting that poverty is the more informative characteristic. Furthermore, regressions that include linear interactions with initial income, temperature, and agriculture share (as opposed to binary dummies) continue to show that initial poverty is the relevant distinction.

effects, nesting both the level and growth effects of temperature described in Section 3.1.

Table 3 presents results from estimating equation (4) with no lags, one lag, three lags, five lags, or ten lags of the climate variables. In columns (1) – (5), temperature and its lags are the only climate variables included. Columns (6) – (10) present results where precipitation and its lags are also included. All climate variables are interacted with poor and rich country dummies. The bottom two rows of each column present, separately, the cumulated effect of temperature for poor and rich countries, calculated by summing the respective temperature variable and its lags. In models with more than three lags, given space constraints, the table reports only the first three lags and the sum of all the lags.

Table 3 shows that the cumulative effect of temperature in poor countries becomes more negative as more lags are included. With no lags, in columns (1) and (6), a one-time 1ºC temperature increase in a poor country reduces growth by 1.07 – 1.09 percentage points. With one lag included, the cumulative effect is a reduction of 1.28 – 1.30 percentage points. Including three, five, or ten lags increases the magnitude and statistical significance of these cumulative effects, with a 1ºC temperature increase producing a 1.58 – 2.01 percentage point reduction in growth.

The individual lag coefficients show little evidence of a level effect of temperature on output. That is, the effects of above average temperature appear to persist in the medium-run, rather than being reversed. Recalling the empirical framework from Section 3.1, level effects are reversed when the climate shock is reversed. In the model with one lag – i.e., columns (2) and (6) – a level effect would appear as equal and opposite coefficients on the immediate effect and the first lag. More generally, even if level effects occur with lags – i.e., if last year's temperature affects this year's harvest – level effects are eventually 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. That the lags in Table 3 do not sum to zero – and, in fact, the cumulated effect of temperature becomes stronger as more lags are added – suggests that the effects of temperature persist in the medium run; i.e., they look more like growth effects than level effects.

Of course, temperature effects may be mitigated beyond the 10-year horizon examined here. However, the increasing cumulative impact of temperature as longer lags are considered suggests that, if anything, the effects of temperature shocks strengthen over time rather than

diminish. In Section 5.1, we consider an alternative empirical approach that examines longer-run historical relationships between changes in temperature and changes in growth. That analysis finds longer-run effects consistent with these panel results.

3.4. Robustness

Table 4 considers a variety of robustness checks. For each specification, Panel A reports the results from models with no lags (i.e., equivalent to column 5 of Table 2), Panel B reports cumulative effects from models with five lags (i.e., equivalent to the cumulative effects in column 9 of Table 3), and Panel C reports cumulative effects from models with ten lags (i.e., equivalent to the cumulative effects in column 10 of Table 3). Results from models with one and three lags are qualitatively similar and are omitted to conserve space. To facilitate comparisons, the relevant results from Tables 2 and 3 are repeated in the first column of Table 4.

We find that the results are broadly consistent across a range of alternative specifications. Column (2) shows that including only country and region × year fixed effects (i.e., dropping the poor × year fixed effects) produces similar estimated temperature effects in poor countries. Similar results also emerge in column (3), which uses common global year fixed effects instead of region × year fixed effects, and column (4), which incorporates country-specific trends as well as region × year and poor × year fixed effects, though the standard errors increase in column (4) so that the five and ten lag results are no longer statistically significant. [13]

Column (5) shows that limiting the sample to 1971-2003, for which we have a balanced sample, strengthens the temperature effect in poor countries. Column (6) adds countries with less than 20 years of data, and continues to show substantial negative effects in poor countries. In this sample, the zero-lag model shows a positive effect of increased temperature in richer countries. This effect is driven by several post-Soviet states, which are grouped as rich and which enter the data in the early 1990s, and appears to be driven by extreme outliers during the post-Communist

[13] In addition, we have also considered using logs rather than levels of annual average temperature and precipitation. This specification strengthens the results. We have also estimated a first differenced version of (4), i.e. $\Delta g_{it} = \Delta\theta_{rt} + \sum_{j=0}^{L} \rho_j \Delta T_{it-j} + \Delta\varepsilon_{it}$. This produces very similar results for the 0 lag model, while the estimates become substantially more negative and more imprecise as we add additional lags.

transition.[14]

Column (7) re-considers the main specification using growth data from the World Development Indicators rather than the Penn World Tables. The zero-lag and five-lag results are very similar using WDI data. The ten-lag result attenuates somewhat and is statistically insignificant. Column (8) uses climate data aggregated using area-weighting rather than population-weighting and shows similar effects.[15] Finally, we split the sample into Sub-Saharan African countries (column 9) and all other countries (column 10). In the model with zero lags, the negative impacts of temperature are especially pronounced in Sub-Saharan Africa and much weaker elsewhere. However, when we examine either the five or ten lag models, the negative point estimates are similar and large (though statistically insignificant) in both samples.[16]

In our analysis, temperature enters linearly, whereas one might suspect that temperature has non-linear effects. [17] To investigate this possibility, we examined more flexible aggregations of the sub-national temperature data. Using daily climate data available on a 1.0 x 1.0 degree grid (NCC, 2005), we calculated the number of 'people-days' spent at each temperature and precipitation level throughout the year for each country. We then repeated the panel analysis above (e.g., equation (4) with no lags) allowing the climate effects to vary arbitrarily at different temperature and precipitation ranges. Unfortunately, we did not have sufficient power to tease out detailed effects of the distribution of days within different climate ranges. While the results are imprecise, the point estimates suggest that the impact of temperature on GDP is roughly linear, supporting the focus on annual averages (results available

[14] Estimating the effect of temperature on growth for the sub-sample of post-Soviet / Eastern European countries shows that each 1°C is associated with 3.9 percentage points higher growth. However, when excluding the transition years 1992, 1993, and 1994, each 1°C rise becomes associated with 0.62 percentage points *lower* growth.

[15] Weighting by rural population or urban population yields similar results to using total population weights.

[16] Another potential concern is that climate data quality may be lower for Africa. We have repeated our analysis of Africa with a number of (independently collected) alternative datasets – the Global Precipitation Climatology Project, the National Center for Environment Prediction, and the UN Food and Agricultural Organization Climatic Data. Results are very similar in all samples. Our results do differ from Barrios et al (forthcoming), who in their investigation of rainfall in Sub-Saharan Africa include temperature as a control in one specification, finding no effects. Our specification differs from theirs on many dimensions; Barrios et al examine fewer countries and fewer years of data, use a different temperature variable, and use a somewhat different empirical specification.

[17] For example, Deschenes and Greenstone (2007a, 2007b) find non-linear temperature effects for agriculture and mortality.

on request).[18]

4. Channels

The large and persistent effects of climate shocks on aggregate output in poor countries that we estimate suggest further investigation of the climate-economy relationship. Many macroeconomic studies of climate's effects have emphasized a narrow set of channels, especially agriculture, whereas the micro-economic literature has considered a larger set of dimensions through which climate could affect the economy. At the same time, the evidence in the micro literature often comes from local or laboratory environments, which may or may not extend to national settings (Hancock and Vasmatzidis, 2003; Ramsey and Kwon, 1992; Seppanen et al., 2003). In this section, we apply our panel methodology to explore whether the effects of temperature are primarily limited to agriculture, or whether temperature affects other important economy-wide dimensions.

It is important to note that these analyses are reduced-form, and therefore do not identify the possibly complex structural relationships between climate, growth, and other outcomes. For example, higher temperature could lead directly to political instability by making a population more prone to riot (United States Riot Commission, 1968; Carlsmith and Anderson, 1979**)**. Conversely higher temperatures could lower agriculture yields, with the resulting GDP reduction leading to political instability. Teasing out structural relationships between these many variables would require a number of ad hoc identifying assumptions. We focus instead on net climate effects, to shed light on the breadth and type of potential channels through which climate may affect aggregate output. The results, which show that temperature not only impacts agriculture, but also affects industrial output, investment, scientific research, and political stability, emphasize climate's broad influences, and help inform our findings of growth effects.

4.1. Agriculture, Industry, and Investment

Table 5 examines the impact of temperature and precipitation on several components of

[18] We have also conducted several exercises to look for nonlinear effects of the average temperature variable and found little evidence for non-linearities at that level as well. First, we verified that both hot and cold deviations from the national temperature mean have effects of similar absolute magnitude on growth. Second, we used median regressions to verify that the results are not driven by outliers. Third, we found that temperature shocks do not affect poor countries differentially depending on whether the country is typically hot or cold, though the tiny number of cold poor countries prevents a definitive conclusion on this dimension (results available on request).

GDP. Panel A begins with zero-lag models to test the null hypotheses of no effects of temperature and precipitation. Column (1) examines growth in agricultural value-added, and column (2) investigates growth in industrial value-added.[19] These variables are taken from the World Development Indicators. (Note that the WDI sample is more limited than the PWT sample.) Column (3) examines growth in investment, using data from the Penn World Tables.

The results in Panel A show substantial, negative effects of temperature in poor countries on all three of these components of GDP. Column (1) shows that a 1°C higher temperature in poor countries is associated with 2.37 percentage points lower growth in agricultural output. For wealthier countries, the point estimate is substantially smaller and not statistically significant, showing 0.34 percentage points lower growth in agricultural output for each additional 1°C of temperature. As might be expected, precipitation positively impacts agriculture – each additional 100mm of annual rainfall is associated with 0.24 percentage points higher growth in agricultural output in poor countries and 0.14 percentage points higher growth in agricultural output in richer countries.

Column (2) of Panel A shows negative temperature impacts on the growth of industrial value-added in poor countries. Specifically, a 1°C higher temperature in poor countries is associated with 2.44 percentage points lower growth in industrial output. This effect may reflect labor productivity losses, consistent with a long literature documenting the impact of temperature on output in factory settings.[20] Alternatively, this effect could represent a demand-side spillover from the negative effect of temperature on agricultural output.

The results on investment in column (3) also show substantial negative impacts of temperature in poor countries. Specifically, a 1°C higher temperature in poor countries reduces the growth rate of investment by 3 percentage points. We find no temperature effects in rich

[19] The residual category, services, is typically computed as the difference between total value-added and the sum of agricultural and industrial value added. As such, it is likely more noisily measured and, consistent with increased measurement error we find no statistically significant results when we examine services (results available on request).

[20] Building on classic ideas in economic development that link productivity to temperature (Montesquieu 1750; Marshall 1890), Huntington (1915) documented that high temperature reduces the productivity of piece-rate Connecticut factory workers and Florida cigar-makers. More recently, Link and Pepler (1970), Wyon (1976), Meese et al. (1982), and others have found substantial negative impacts of higher temperatures on the productivity of factory workers.

countries.[21]

Panel B examines the lag structure of these effects. For each dependent variable (growth in agriculture, growth in industry, and growth in investment), we present results with 1, 5, and 10 lags. For all three dependent variables, the impact effect – i.e., the coefficient on contemporaneous temperature – is negative, large, and statistically significant. For agriculture and investment, the point estimates of the cumulative effects, while imprecise, are somewhat smaller than the immediate effects, suggesting the presence of some combination of growth and level effects for these variables. By contrast, for industrial value added, the point estimates of the cumulative effects are virtually identical to the immediate effect.[22]

4.2. Scientific research

Our findings that temperature affects growth, rather than just the level of output, suggests examining innovative activity as one potential source of changes in TFP. To do so, we examine one type of innovative activity that is precisely measured and available annually for all countries: scientific publications.

Specifically, we examine 12.9 million Science and Engineering journal articles indexed by the Web of Science from 1980-2003.[23] Using this database, we determined for each country and each year (i) total publications in that year (illustrating the *quantity* of innovative output), (ii) mean subsequent citations received per paper published in that year (illustrating the *quality* of innovative output), and (iii) total citations for papers published in that year, as the product of these measures.[24] We then re-estimate equations (4), where the dependent variable is the growth

[21] Note, however, that there is a significant precipitation effect in rich countries. Using daily data on precipitation (NCC 2005), we find that having a larger number of days with very high precipitation has a significant negative effect on aggregate output in rich countries (results available upon request). One conjecture is that construction responds negatively to rain, providing the investment effect.

[22] There also is some evidence of cumulative effects of precipitation on agricultural output, particularly in rich countries. One potential explanation involves the effects of drought on soil erosion, which may have longer-run consequences. For example, Hornbeck (2007) documents that soil erosion during the Dust Bowl years in the United States had substantially negative and lasting consequences on agricultural output.

[23] This data set includes all Science and Engineering papers where all authors are from the same country.

[24] See Wuchty et al. (2007) for a description of the Web of Science database. Note that authors in the hard sciences typically produce many papers per year and with rapid journal review processes, so that substantial research effort occurs in the year of publication. For example, in biomedical journals the average duration between submission and print publication is less than 140 days (Dong et al. 2006).

rate of each of these measures of scientific research, examining specifications with no lags, one lag, five lags, or ten lags of the climate variables.

While these measures can only illustrate one dimension of innovative activity, the results are striking. In Panel A of Table 6, we see that a 1°C rise in temperature is associated with 8.8% lower growth in publication volume in poor countries (column 1). The effect on citations per paper is also negative, but not statistically significant (column 2). In Panel B of Table 6, we see that – in contrast to the results on overall economic growth – the impact of temperature on scientific publications appears to be a level effect. The immediate effect of warming is sharply negative and statistically significant for the quantity and quantity x quality measures, but these effects are already largely reversed after 1 year (Panel B columns 1, 4, and 7), as can be seen in the cumulative effects. Interestingly, to the extent that innovative levels imply productivity growth rates, as in standard endogenous growth models, this finding of a *level* effect of temperature on innovation is consistent with our findings of growth effects on per-capita income (see equation 2).

Overall, the findings in Tables 5 and 6 demonstrate broad negative effects of increased temperature. We find effects not only on agriculture, but also on industrial output, investment, and innovation. These wide-ranging effects may help explain both the magnitude of the overall effect of temperature on output as well as its persistence.

4.3. Political economy

Temperature may also impact growth if increased temperature leads to political instability, which in turn impedes investment and productivity growth. The possibility that riots and protests are more likely in warmer weather has found substantial empirical support (e.g., United States Riot Commission 1968; Carlsmith and Anderson 1979; Boyanowsky 1999).[25] If warm weather causes riots, in some fraction of cases these riots could spill over into political change and instability. Alternatively, economic shocks from climate might provoke dissatisfied citizens to seek institutional change.

We examine the impact of temperature on several measures of political instability. First, the *Polity IV* dataset (Marshall and Jaggers 2004) rates the political system in each country

[25] Medical studies have documented that levels of platelet paroxitine – a chemical that blocks impulsivity and aggression – fall when temperatures increase and have linked low levels of platelet paroxitine to higher rates of aggression (Tihonen et al. 1997). Violent crime also increases with temperature (Jacob et al. 2007).

annually from -10 (fully autocratic) to +10 (fully democratic). This POLITY variable further designates "interregnum periods", which are years when the political system is in flux and no clear political regime has emerged. We consider two dummy variables: one for any change in the POLITY variable, indicating a political change, and one for a POLITY interregnum period, indicating a period of political turmoil.

The second set of measures comes from the *Archigos* dataset on political leaders (Goemans et al. 2006). This dataset classifies the primary national political leader for each country and year and codes all leader transitions into two categories: "regular" transitions, which take place according to the prevailing institutional rules of the country, and "irregular" transitions (such as coups), which do not follow the prevailing institutional rules. We consider a dummy variable for years with leadership transitions, as well as separate dummy variables for regular and irregular transitions.

The results are presented in Table 7. Looking first at POLITY, an additional 1°C in poor countries is associated with a (statistically insignificant) 2.3 percentage point increase in the probability of any change in POLITY. Column (2) shows that a 1°C increase in temperature leads to a 2.3 percentage point increase in the probability of a POLITY interregnum period, which suggests that all of the changes in POLITY induced by temperature occur through increases in political instability. Though these effects are statistically insignificant (p-values of 0.16 and 0.20 respectively), the estimated magnitudes are substantial, given that the baseline probability of a POLITY change in poor countries is 13.1 percent and the baseline probability of an interregnum period in poor countries is only 5.7 percent. The results on precipitation are somewhat weaker, but suggest that political change in poor countries is more likely in years with lower rainfall.

The Archigos results show a similar pattern and are stronger statistically. A one degree rise of temperature raises the probability of leader transitions by 3.7 percentage points in poor countries (column 3). Moreover, this effect comes not from regular leadership transitions (column 4) but from irregular leader transitions – i.e. coups (column 5). This effect of 3.9 percentage points is large, as the baseline probability of an irregular leader transition is only 4.5 percent per year in poor countries. By contrast, we see no effects on leader transitions in rich countries.

Combined, the POLITY and Archigos data tell a consistent story: higher temperatures are

associated with political instability in poor countries. Whether temperature has direct effects on political instability, which in turn affects economic growth, or whether temperature has direct effects on economic growth, which in turn affects political instability – or both – is difficult to distinguish, since poor economic performance and political instability are likely mutually reinforcing. Nevertheless, the impact of temperature on political instability in poor countries is suggestive of an institutional mechanism through which temperature might affect productivity growth, rather than just the level of income.

The final columns of Table 7 consider the impact of temperature and precipitation on conflict. We use the PRIO conflict data (PRIO 2006), which indicates for every country-year whether the country was involved in a high-intensity conflict (defined as ≥ 1,000 conflict deaths / year) or a low-intensity conflict (defined as 25 to 1000 conflict deaths / year). Column (6) examines the start of conflicts (i.e., the probability a conflict begins given no conflict in the previous period), and column (7) examines the end of conflicts (i.e., the probability a conflict ends given conflict in the previous period).[26] We find no significant effect of temperature or precipitation on either the start or conclusion of conflicts.[27] The political impacts of temperature and precipitation thus appear more concentrated in political instability rather than outright civil or interstate wars.

5. Medium-run estimates

In this section, we re-examine the historical data to investigate climate changes over the medium run. The above short-run panel estimates indicate substantial effects of temperature shocks in poor countries, with per-capita income growth falling approximately 1 percentage point for a 1°C rise in temperature. Although this effect persists for 10 years in the panel model, the effect of sustained temperature increases might attenuate over time if economies adapt. On the other hand, sustained higher temperatures may reinforce growth-related problems by placing continued pressure on political systems or other relevant factors.

We therefore consider the longer-run analogue of our panel specification, examining the

[26] Given how rare conflicts are, we use year fixed effects rather than region-by-year fixed effects in these specifications.

[27] These results differ from Miguel et al. (2004), who find - also using the PRIO dataset - that greater precipitation is associated with a lower probability of conflict. Miguel et al. examine only Sub-Saharan African countries from 1981-1999, and use a somewhat different empirical specification from the one in Table 7.

relationship between climatic changes and growth changes in the early and late periods in our dataset. There is substantial heterogeneity in temperature increases over this period, with countries such as Tunisia, Zambia, and Botswana warming by approximately 1°C since the mid 1980s, while others such as Laos, Kenya, and Nigeria experienced almost no warming over the same period. We exploit this variation to ask whether countries with sustained warming saw sustained changes in growth.

Specifically, we estimate the following regression

$$\bar{g}_{i2} - \bar{g}_{i1} = \alpha + \theta_r + \gamma(\bar{T}_{i2} - \bar{T}_{i1}) + \varepsilon_i$$

where $\bar{g}_{i1}$ is the mean growth rate in country *i* in the early period (1970-1985 in our main specification), and $\bar{g}_{i2}$ is the mean growth rate in the late period (1986-2000).[28] Mean temperature and precipitation in these periods are $\bar{T}_{i1}$ and $\bar{T}_{i2}$, while θ_r captures region fixed effects and a dummy for being poor, and ε_i is an independently distributed error term. This first-differenced regression is the longer-run version of the fixed effects panel model in equation (4). To see this, start with equation (4) with no lags, take averages of the left- and right-hand sides for a given period, and then first-difference. We have one observation per country, having differenced out any initial conditions or other fixed national characteristics that might influence growth.[29]

Table 8 presents the results. The baseline specification compares the 1970-1985 period to the 1986-2000 period and shows substantial, statistically significant negative effects of warming on poor countries. In column (1), a temperature rise of 1° C reduces annual growth in poor countries by 3.2 percentage points. The inclusion of region fixed effects does not substantially change this effect, as shown in column (2). When we split the sample into Sub-Saharan African countries (column 7) and all other countries (column 8), we find similar effects in both samples,

[28] We begin in the 1970s, rather than an earlier decade such as the 1960s, because we lose most of the poor countries in our sample when we extend the sample back to the 1960s. We present results for a variety of alternative time periods below.

[29] Note also that, in cross-section, average growth is substantially lower in warmer countries over this period. While interesting, this is less well identified than the first differenced results, which net out unobserved fixed country characteristics.

though the estimates are not statistically significant.[30] Using WDI data instead of PWT data finds 1° C reduces annual growth in poor countries by 2.3 percentage points (column 9).[31]

The statistical significance of the results is more sensitive to the estimation period used, although the point estimates remain large and negative in all specifications. When using the time series up to the final year of the data, comparing slightly longer periods from 1970-1987 and 1988-2003, we find very similar results (column 3). When comparing shorter periods over various intervals, such as the 1990s to the 1960s (column 4), the 1990s to the 1970s (column 5), and the 1990s to the 1980s (column 6), we find similar point estimates of the effect of temperature on poor countries, but less statistical significance.

Overall, this analysis continues to suggest substantial negative effects of warming on growth in poor countries. Moreover, the estimated effect in the longer-run analysis is typically larger than in the short-run panel analysis. Thus, just as the 5 and 10 year lag results (Tables 3 and 4) suggest that the growth effect strengthens the longer the time interval considered, the longer-run relationship in Table 8 tends to show even larger point estimates. Put another way, we find little evidence that poor countries adapt and eliminate the negative consequences of warming over the time horizons considered here.

6. Discussion

The results above have documented large negative effects of temperature on poor countries. Using annual variation in temperature, we find that an extra 1°C reduces poor countries' growth rates by about 1.1 percentage points. Using 10 or 15 year changes in average temperatures, we find that an extra 1°C reduces poor countries' annual growth rate by at least that much. These estimates inform debates over the role of geography in economic development as well as attempts to predict the impacts of future climate change.

6.1. Climate and economic development

The negative cross-sectional association between temperature and per-capita income (see

[30] The Africa sample shows similarly large effects in poor countries as other specifications, but the standard errors have increased with the substantially smaller sample size, so the result is not quite statistically significant.

[31] With so few observations, one might be concerned that a few outliers drive the results. However, we find very similar results using median regressions, which give much less weight to outliers. For example, using median regressions, the estimated impact on poor countries in column (1) is -2.30 ($p = 0.075$), as opposed to a coefficient of -2.34 ($p = 0.020$) using OLS (results available on request).

Figure 2) has long been known (e.g., Huntington 1915). Yet there has been a vigorous debate over whether this correlation is due to a direct impact of climate on economic activity (e.g., Sachs 2003), or whether some third variable (e.g., a country's institutions) drives prosperity in contemporary times, leaving little or no room for geography (e.g., Acemoglu, Johnson and Robinson 2002; Rodrik, Subramanian and Trebbi 2004). This debate has primarily proceeded by treating climate variables as fixed for a given country, which makes testing these alternative hypotheses challenging.

By using climate changes within countries, we can better identify climate's effects. Our results show that temperature *per se* has an important impact on national economic performance. The evidence thus rejects the hypothesis that climate does not influence national production. Moreover, the estimated impacts persist for at least a decade and are large in magnitude – in fact, more than large enough to explain the cross-sectional climate-income relationship between rich and poor countries.[32] Our results do not rule out many other forces that may play important roles in economic development; rather, our contribution in this paper is to reject views that climate does not matter, show that climate's effects are substantial, and identify a group of countries where climate appears to have large effects.

6.2. Future climate change

Our estimates have implications for estimating impacts of future climate change. Of course, a key difference between our estimates and long-run climate change is that countries may adapt to permanent changes in climate but may not adapt to the sort of annual or decade-long climate shocks that we examine empirically. Although there is extensive discussion of adaptation in the literature on climate change (see for example IPCC 2007) – there is little rigorous evidence on the extent to which entire economies are likely to adapt. Thus, modeling adaptation necessarily requires making some assumptions about the speed with which it occurs.

[32] To see this, recall that the cross-sectional relationship shows a decline in per-capita income of 8.5 log points for a 1°C increase in temperature (see Figure 2). Our panel estimates show that a 1°C temperature increase reduces poor country growth rates by 1.1 percentage points. In a world with no adaptation, our panel estimates imply that cross-country temperature differences would need to be sustained for only 8 years to generate the cross-sectional correlation between temperature and per-capita income seen in Figure 2. In practice, adaptation may mitigate these effects substantially in the long run – a point we return to below – but our panel estimates of the effect of increased temperature are large enough to generate the overall world cross-section even allowing for substantial adaptation.

Our empirical results suggest a reasonable starting point. In particular, the estimates in Section 5 show that the negative growth effects estimated from annual data are still present (and if anything, are larger in magnitude) when examining average temperature changes over a 10-year period. We therefore construct plausible lower bound estimates of the impact of climate change by assuming no adaptation over the first 10 years and full adaptation thereafter. That is, we assume that a given permanent increase in temperature has negative effects for the first 10 years and no effects thereafter.

Using this approach, we calculate the projected impact of climate change by integrating our estimated marginal effects of temperature with standard climate change projections over the 21st century.[33] Note that the marginal growth effect is contingent upon whether the country is rich or poor at the time, which depends partly on the country's background growth rate. We project the background growth rate using the country's historical growth rate, allowing for country-specific convergence rates to U.S. income levels. This methodology is detailed in Appendix III.

Table 9 illustrates the effects of climate change assuming full adaptation occurs after 10 years, as well as under alternative scenarios where adaptation occurs more slowly. The results show that – even using the 10-year adaptation horizon – the cumulative growth effect in poor countries could be quite large. With a 10-year adaptation horizon, the median growth rate among poor countries appears 0.6 percentage points lower through 2099 compared to the case of no warming. Extrapolated over 100 years, this implies that the median poor country's income will be about 50% lower than it would be had there been no climate change. Moreover, because the effects are large for poor countries – and we estimate no impact on rich countries – the estimates in Table 9 suggest that climate change could substantially widen world income inequality. Assuming a longer time lag before adaptation occurs increases these estimates further.

While the magnitudes we estimate are large, when allowing for reasonably rapid adaptation they suggest effects on the same order of magnitude as the overall temperature-output

[33] Climate projections depend on the greenhouse gas emissions scenario and the climate model. We use climate predictions from a standard model, the *Community Climate System Model* (CCSM) v3.0 (UCAR 2007), and present results from the A2 (high) emission scenario. More details can be found in IPCC (2007). The marginal effects of temperature on growth are taken from the 10-year panel model in column (1) of Table 4. The general patterns are similar when employing alternative estimates.

relationship we observe in the world today. A simple cross-section regression in the year 2000 shows that a 1°C increase in average temperature predicts a fall in per-capita income by 0.085 log points (i.e. about 8 percent). By comparison, assuming a 10-year adaptation horizon and a 1.1 percentage point loss in growth for each 1°C warming (i.e., the estimated panel effect in Table 2), a permanent increase in temperature of 1°C would reduce income permanently by 0.11 log points (-0.011 * 10), which is close to what the world cross-section predicts.

Despite these large, negative effects for poor countries, we find very little impact of long-run climate change on world GDP. This result follows from (a) the absence of estimated temperature effects in rich countries and (b) the fact that rich countries make up the bulk of world GDP. Moreover, if rich countries continue to grow at historical rates, their share of world GDP becomes more pronounced by 2099, so even a total collapse of output in poor countries has a relatively small impact on total world output.[34]

Our estimated effects differ from those predicted by existing IAM implementations, which typically show neither the large effects we find in poor countries nor the large dichotomy 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. 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, so extrapolating analyses of rich-countries is likely to understate the effects in poorer regions. 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. Because growth effects compound over time, even modest growth effects can accumulate into large income effects. Our results suggest ways in which future implementations of IAMs could be modified to better match the historical climate-economy relationship.

7. Conclusion

This paper examines the historical relationship between climate fluctuations and

[34] Note that the rapid growth of India and China suggest that they will quickly cross the 'rich country' threshold, and therefore in the projections they are not assigned significant negative consequences of climate change.

economic growth. We find substantial effects of climate shocks, but only in poor countries. In poor countries, a 1°C rise in temperature in a given year reduces economic growth by 1.1 percentage points on average. The estimates suggest that climate change may affect the rate of economic growth, rather than just the level of output. Moreover, estimates using the overall change in climate from 1970 to 2000 rather than annual variation produce even larger estimates, suggesting that adaptation may not undo these effects in the medium term.

By focusing on fluctuations in temperature and precipitation, we seek to inform old debates over climate's role in economic development and new debates over future impacts of climate change. Our findings of large effects of climate shocks on poor countries act to reject claims that climate does not influence national production. Our results also suggest that future climate change may substantially widen income gaps between rich and poor countries. While higher temperatures reduce agricultural output in poor countries, we also find that they lead to reductions in industrial output, aggregate investment, scientific research, and political stability. These results underscore the breadth of mechanisms underlying the climate-economy relationship and emphasize many channels not usually considered in the aggregate climate literature. Further work is needed to identify precise causal mechanisms surrounding each of these channels. While teasing out the mechanisms is challenging, this paper suggests such analysis is of first-order importance, as the economic effects in poor countries appear large.

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Table 1: Observed climate variation, 1950-2003

	Proportion of country-years with temperature […] degrees above/below country mean:					
	0.25	0.50	0.75	1.00	1.25	1.50
Raw data	0.570	0.294	0.144	0.065	0.029	0.011
After removing worldwide year fixed effects	0.508	0.213	0.085	0.034	0.013	0.005
After removing region × year and poor × year fixed effects	0.451	0.158	0.054	0.020	0.008	0.003
	Proportion of country-years with precipitation […] 100 mm units above/below country mean:					
	1	2	3	4	5	6
Raw data	0.480	0.229	0.123	0.072	0.044	0.029
After removing worldwide year fixed effects	0.495	0.222	0.113	0.063	0.039	0.025
After removing region × year and poor × year fixed effects	0.461	0.213	0.106	0.060	0.034	0.022

Table 2: Main panel results

	Dependent variable is the annual growth rate						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Temperature	-0.197	0.219			0.208	0.130	0.177
	(0.216)	(0.210)			(0.212)	(0.203)	(0.232)
Temperature interacted with…							
Poor country dummy		-1.305***			-1.282***	-1.303***	-1.400***
		(0.479)			(0.482)	(0.477)	(0.526)
Hot country dummy						0.262	
						(0.411)	
Agricultural country dummy							-0.120
							(0.390)
Precipitation			-0.019	-0.071*	-0.072*	-0.125**	-0.088*
			(0.040)	(0.040)	(0.042)	(0.053)	(0.050)
Precipitation interacted with…				0.118	0.102	0.096	0.142
Poor country dummy				(0.075)	(0.076)	(0.076)	(0.093)
						0.081	
Hot country dummy						(0.070)	
							0.006
Agricultural country dummy							(0.077)
Observations	6014	6014	6014	6014	6014	6014	5432
R-squared	0.14	0.14	0.14	0.14	0.15	0.15	0.15
Temperature effect in poor countries		-1.087**			-1.074**	-1.173***	-1.223**
		(0.442)			(0.446)	(0.404)	(0.525)
Precipitation effect in poor countries				0.047	0.030	-0.029	0.054
				(0.065)	(0.065)	(0.072)	(0.098)

Notes: All specifications use PWT data and include country FE, region × year FE, and poor x year FE. Robust standard errors in parentheses, adjusted for clustering at parent-country level. Sample includes all countries with at least 20 years of growth observations. Poor is defined as a dummy for a country having below median PPP gdp per capita in its first year in the data. Hot is defined as a dummy for a country having above median average temperature in the 1950s. Agricultural is defined as a dummy for a country having above median share of GDP in agriculture in 1995. 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: Models with lags

	(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 × Poor	-1.087**	-0.954*	-0.932*	-0.933*	-1.112*	-1.074**	-0.945*	-0.925*	-0.925	-1.071*
	(0.442)	(0.559)	(0.560)	(0.562)	(0.586)	(0.446)	(0.558)	(0.557)	(0.559)	(0.585)
L1: Temperature × Poor		-0.351	-0.247	-0.328	-0.216		-0.330	-0.213	-0.333	-0.217
		(0.854)	(0.919)	(0.909)	(0.958)		(0.852)	(0.921)	(0.909)	(0.954)
L2: Temperature × Poor			-0.210	-0.183	-0.120			-0.249	-0.226	-0.140
			(0.441)	(0.459)	(0.485)			(0.443)	(0.458)	(0.484)
L3: Temperature × Poor			-0.216	-0.096	-0.231			-0.189	-0.075	-0.262
			(0.519)	(0.559)	(0.606)			(0.511)	(0.549)	(0.594)
Temperature × Rich	0.219	0.202	0.243	0.293	0.392	0.208	0.197	0.237	0.272	0.383
	(0.210)	(0.232)	(0.241)	(0.238)	(0.255)	(0.212)	(0.234)	(0.243)	(0.240)	(0.260)
L1: Temperature × Rich		0.047	0.074	0.094	0.093		0.038	0.067	0.083	0.056
		(0.268)	(0.251)	(0.252)	(0.268)		(0.269)	(0.250)	(0.252)	(0.266)
L2: Temperature × Rich			0.062	0.115	0.043			0.064	0.143	0.098
			(0.190)	(0.195)	(0.209)			(0.190)	(0.194)	(0.209)
L3: Temperature × Rich			-0.019	0.120	0.203			-0.045	0.097	0.211
			(0.197)	(0.186)	(0.198)			(0.197)	(0.185)	(0.197)
Includes precipitation vars.	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES
Observations	6014	6014	5905	5785	5449	6014	6014	5905	5785	5449
R-squared	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Sum of all temp. coeff. in poor countries	-1.087**	-1.304*	-1.605**	-1.718**	-2.006**	-1.074**	-1.275*	-1.576**	-1.662**	-1.946**
	(0.442)	(0.677)	(0.641)	(0.720)	(0.866)	(0.446)	(0.689)	(0.651)	(0.737)	(0.881)
Sum of all temp. coeff. in rich countries	-0.102	0.219	0.249	0.361	0.184	0.208	0.235	0.324	0.155	-0.147
	(0.647)	(0.210)	(0.268)	(0.331)	(0.455)	(0.212)	(0.271)	(0.332)	(0.460)	(0.654)

Notes: All specifications use PWT data and include country FE, region × year FE, and poor x year FE. Robust standard errors in parentheses, adjusted for clustering at parent-country level. Sample includes all countries with at least 20 years of growth observations. Columns (6) – (10) also include Precipitation × Poor and Precipitation × Rich, with the same number of lags as the temperature variables shown in the table. Columns (4) and (9) also include the 4^{th} and 5^{th} lags of Temperature × Poor, Temperature × Rich, Precipitation × Poor and Precipitation × Rich. Similarly columns (5) and (10) also include the 4^{th} through 10^{th} lags of Temperature × Poor, Temperature × Rich, Precipitation × Poor and Precipitation × Rich; those coefficients are suppressed in the table to save space. Sum of all temperature coefficients in poor countries shows the sum (and calculated standard error) of Temperature × Poor and all of the lags of Temperature × Poor included in the regression; sum of all temperature coefficients in rich countries is calculated analogously.* significant at 10%; ** significant at 5%; *** significant at 1%

Table 4: Alternative specifications of panel results

	(1) Baseline	(2) Country FE and Region×Yr FE only	(3) Country FE and Year FE only	(4) All FE and country specific trends	(5) Balanced sample: 1971 - 2003	(6) Add countries with < 20 years of data	(7) GDP data from World Devel. Indicators	(8) Area-weighted climate data	(9) Sub-Saharan Africa Only	(10) Sub-Saharan Africa Excluded
Panel A: Models with no lags										
Temp. immediate effect – Poor	-1.074**	-0.753**	-0.986***	-1.009**	-1.423**	-0.892**	-1.535***	-0.927*	-1.774**	-0.404
	(0.446)	(0.354)	(0.295)	(0.438)	(0.560)	(0.381)	(0.397)	(0.501)	(0.826)	(0.402)
Temp. immediate effect – Rich	0.208	-0.026	-0.120	0.417*	0.473**	0.611**	0.306	0.333	-0.310	0.264
	(0.212)	(0.203)	(0.169)	(0.238)	(0.228)	(0.271)	(0.250)	(0.225)	(1.792)	(0.202)
Precip. immediate effect – Poor	0.030	0.008	0.007	0.032	0.013	-0.015	0.110**	0.047	0.185	-0.057
	(0.065)	(0.065)	(0.061)	(0.067)	(0.065)	(0.053)	(0.050)	(0.071)	(0.113)	(0.074)
Precip. immediate effect – Rich	-0.072*	-0.060	-0.028	-0.093**	-0.095**	-0.039	-0.089**	-0.074	0.210	-0.080**
	(0.042)	(0.041)	(0.039)	(0.045)	(0.047)	(0.051)	(0.039)	(0.047)	(0.209)	(0.039)
Observations	6014	6014	6014	6014	4290	6347	4927	6014	1809	4205
Panel B: Models with 5 lags										
Temp. cumulative effect – Poor	-1.662**	-1.087*	-1.002	-1.362	-2.257**	-1.300**	-1.375**	-1.592**	-1.767	-1.231
	(0.737)	(0.643)	(0.615)	(1.088)	(0.985)	(0.575)	(0.541)	(0.721)	(1.057)	(1.316)
Temp. cumulative effect – Rich	0.155	-0.284	-0.481	0.445	0.257	0.336	0.118	0.256	1.636	0.031
	(0.460)	(0.441)	(0.422)	(0.704)	(0.593)	(0.541)	(0.381)	(0.459)	(2.748)	(0.453)
Precip. cumulative effect – Poor	0.128	0.061	0.039	0.184	0.131	-0.034	0.339*	0.141	0.683	-0.083
	(0.146)	(0.142)	(0.138)	(0.175)	(0.172)	(0.106)	(0.197)	(0.146)	(0.412)	(0.123)
Precip. cumulative effect – Rich	-0.127	-0.097	-0.057	-0.237**	-0.191**	0.022	-0.143*	-0.128	0.694	-0.124*
	(0.085)	(0.091)	(0.079)	(0.117)	(0.078)	(0.143)	(0.078)	(0.086)	(0.646)	(0.073)
Observations	5785	5785	5785	5785	4290	6029	4919	5785	1785	4000
Panel C: Models with 10 lags										
Temp. cumulative effect – Poor	-1.946**	-1.553*	-1.486**	-1.655	-2.830**	-1.633**	-0.927	-1.811**	-1.897	-1.444
	(0.881)	(0.811)	(0.739)	(1.460)	(1.111)	(0.697)	(0.712)	(0.872)	(1.277)	(1.397)
Temp. cumulative effect – Rich	-0.147	-0.299	-0.816	0.033	-0.109	0.051	0.180	-0.043	3.669	-0.343
	(0.654)	(0.667)	(0.635)	(1.454)	(0.824)	(0.842)	(0.490)	(0.653)	(4.034)	(0.639)
Precip. cumulative effect – Poor	0.107	0.029	-0.011	0.222	0.119	-0.071	0.576**	0.122	0.516	-0.028
	(0.171)	(0.170)	(0.167)	(0.213)	(0.204)	(0.137)	(0.225)	(0.168)	(0.463)	(0.178)
Precip. cumulative effect – Rich	-0.112	-0.060	-0.033	-0.355**	-0.213**	0.061	-0.117	-0.115	0.472	-0.040
	(0.109)	(0.115)	(0.107)	(0.176)	(0.107)	(0.220)	(0.107)	(0.111)	(0.841)	(0.096)
Observations	5449	5449	5449	5449	4290	5563	4909	5449	1737	3712

Notes: All specifications use PWT data and include country FE, region × year FE, and poor x year FE unless otherwise noted. Robust standard errors in parentheses, adjusted for clustering at parent-country level. Except where noted in the text, panel A follows the same specification as column (5) of Table 2, panel B follows the same specification as column (9) of Table 3, and panel C follows the same specification as column (10) of Table 3. * significant at 10%; ** significant at 5%; *** significant at 1%

Table 5: Components of Output Growth

Panel A: Models with no lags

	Dependent variable is:		
	(1) Growth in Agriculture Value Added	(2) Growth in Industrial Value Added	(3) Growth in Investment
Temperature	No lags	No lags	No lags
Immediate effect – Poor	-2.367***	-2.443**	-2.991**
	(0.816)	(0.958)	(1.189)
Immediate effect – Rich	-0.340	0.410	-0.103
	(0.512)	(0.376)	(0.470)
Precipitation			
Immediate effect – Poor	0.242**	0.295**	0.040
	(0.117)	(0.133)	(0.170)
Immediate effect – Rich	0.138*	-0.050	-0.425***
	(0.077)	(0.071)	(0.109)
Observations	3812	3812	6014

Panel B: Models with lags

	Dependent variable is:								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Growth in Agriculture Value Added			Growth in Industrial Value Added			Growth in Investment		
Temperature	1 Lag	5 Lags	10 Lags	1 Lag	5 Lags	10 Lags	1 Lag	5 Lags	10 Lags
Cumulative effect – Poor	-1.078	-1.440	-1.800*	-2.842**	-2.076	-2.410	-2.078	-2.071	-2.118
	(0.777)	(0.880)	(1.044)	(1.235)	(1.672)	(2.129)	(1.325)	(2.070)	(2.896)
Cumulative effect – Rich	0.419	0.346	0.662	0.517	0.473	0.852	-0.401	-1.194	-1.312
	(0.538)	(0.588)	(0.717)	(0.455)	(0.565)	(0.762)	(0.534)	(0.817)	(1.112)
Immediate effect – Poor	-3.081***	-2.947***	-3.044***	-2.182**	-2.350**	-2.532**	-3.512**	-3.943***	-3.930***
	(1.056)	(1.008)	(1.019)	(0.930)	(0.999)	(1.000)	(1.417)	(1.338)	(1.386)
Immediate effect – Rich	-0.791	-0.731	-0.861	0.369	0.323	0.292	0.091	0.316	0.303
	(0.640)	(0.625)	(0.641)	(0.372)	(0.381)	(0.389)	(0.600)	(0.638)	(0.719)
Precipitation									
Cumulative effect – Poor	0.153	0.118	0.087	0.416***	0.407**	0.390	0.196	-0.076	-0.030
	(0.105)	(0.129)	(0.169)	(0.132)	(0.166)	(0.301)	(0.192)	(0.269)	(0.305)
Cumulative effect – Rich	0.174**	0.392***	0.495**	-0.118	-0.259	-0.147	-0.456***	-0.236	-0.512*
	(0.078)	(0.095)	(0.197)	(0.108)	(0.197)	(0.252)	(0.128)	(0.211)	(0.297)
Immediate effect – Poor	0.270**	0.309**	0.331**	0.238	0.138	0.098	-0.037	0.032	0.000
	(0.127)	(0.130)	(0.132)	(0.145)	(0.125)	(0.117)	(0.209)	(0.209)	(0.209)
Immediate effect – Rich	0.136	0.137	0.149	-0.030	-0.038	-0.027	-0.405***	-0.454***	-0.445***
	(0.091)	(0.093)	(0.093)	(0.068)	(0.071)	(0.072)	(0.123)	(0.135)	(0.146)
Observations	3812	3804	3794	3812	3804	3794	6014	5785	5449

Notes: Growth in agriculture value-added and industrial value-added are from the World Development Indicators; growth in investment is from the Penn World Tables. All specifications include country FE, region × year FE, and poor x year FE. Robust standard errors in parentheses, adjusted for clustering at parent-country level. Sample includes all countries with at least 20 years of PWT growth observations (i.e., the same set of countries considered in the previous tables.)

Table 6: Innovation and Climate

Panel A: Models with no lags

	Dependent variable is:		
	(1) Quantity	(2) Quality	(3) Quantity x Quality
Temperature	No lags	No lags	No lags
Immediate effect – Poor	-0.088**	-0.094	-0.171
	(0.044)	(0.078)	(0.105)
Immediate effect – Rich	-0.016	-0.013	-0.035
	(0.018)	(0.020)	(0.028)
Precipitation			
Immediate effect – Poor	-0.002	-0.003	-0.005
	(0.005)	(0.008)	(0.008)
Immediate effect – Rich	0.006	-0.014*	-0.008
	(0.005)	(0.008)	(0.008)
Observations	2417	2325	2325

Panel B: Models with lags

	Dependent variable is:								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
		Quantity			Quality			Quantity x Quality	
Temperature	1 Lag	5 Lags	10 Lags	1 Lag	5 Lags	10 Lags	1 Lag	5 Lags	10 Lags
Cumulative effect – Poor	-0.048	-0.050	-0.078	-0.036	-0.006	-0.084	-0.063	-0.082	-0.181
	(0.050)	(0.055)	(0.088)	(0.099)	(0.104)	(0.093)	(0.132)	(0.138)	(0.148)
Cumulative effect – Rich	-0.033	-0.000	0.013	0.021	0.046	0.028	-0.016	0.048	0.048
	(0.024)	(0.032)	(0.041)	(0.028)	(0.034)	(0.048)	(0.037)	(0.048)	(0.071)
Immediate effect – Poor	-0.100**	-0.101**	-0.107**	-0.109	-0.113	-0.122	-0.199*	-0.198*	-0.211*
	(0.050)	(0.050)	(0.052)	(0.079)	(0.086)	(0.085)	(0.106)	(0.111)	(0.112)
Immediate effect – Rich	-0.009	-0.013	-0.010	-0.029	-0.021	-0.017	-0.045	-0.040	-0.033
	(0.020)	(0.022)	(0.021)	(0.022)	(0.024)	(0.024)	(0.029)	(0.031)	(0.032)
Precipitation									
Cumulative effect – Poor	0.003	0.007	0.011	-0.007	-0.019**	-0.008	-0.005	-0.012	0.000
	(0.006)	(0.010)	(0.008)	(0.007)	(0.008)	(0.012)	(0.009)	(0.010)	(0.014)
Cumulative effect – Rich	0.011*	0.007	-0.015	-0.004	0.008	0.000	0.006	0.011	-0.016
	(0.006)	(0.007)	(0.012)	(0.008)	(0.011)	(0.022)	(0.010)	(0.012)	(0.023)
Immediate effect – Poor	-0.006	-0.005	-0.004	-0.002	-0.004	-0.005	-0.007	-0.008	-0.008
	(0.008)	(0.008)	(0.008)	(0.010)	(0.011)	(0.011)	(0.010)	(0.010)	(0.010)
Immediate effect – Rich	0.005	0.005	0.004	-0.016*	-0.015*	-0.015*	-0.011	-0.011	-0.012
	(0.005)	(0.004)	(0.004)	(0.008)	(0.008)	(0.008)	(0.009)	(0.008)	(0.009)
Observations	2417	2417	2417	2325	2325	2325	2325	2325	2325

Notes: See notes to Table 5. "Quantity" is the country's annual growth in total Science and Engineering publications, "Quality" is annual growth in the mean future citations received by the published papers, and "Quantity x Quality" is growth in the total citations of the published papers

Table 7: Political economy effects

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
			Political Stability			Conflict	
	Any change in POLITY score	POLITY interregnum period	Leader transition	Regular leader transition	Irregular leader transition	Start of new conflicts (conditional on conflict = 0 in t-1)	End of conflicts (conditional on conflict > 0 in t-1)
Temperature	-0.008	-0.015**	-0.003	-0.002	-0.001	-0.005	0.019
	(0.009)	(0.007)	(0.013)	(0.013)	(0.005)	(0.005)	(0.051)
Temperature X Poor	0.031*	0.037**	0.040*	(0.001)	0.041***	0.014	(0.017)
	(0.018)	(0.018)	(0.022)	(0.017)	(0.013)	(0.012)	(0.056)
Precipitation	0.000	0.001	0.002	0.002	0.000	0.001	0.009
	(0.003)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)	(0.015)
Precipitation X Poor	-0.010**	(0.005)	-0.006*	-0.006*	0.000	-0.003	-0.015
	(0.004)	(0.003)	(0.004)	(0.003)	(0.002)	(0.002)	(0.016)
Obs.	5804	5804	7143	7143	7143	6087	966
R-squared	0.14	0.21	0.18	0.2	0.11	0.09	0.43
Temperature effect in poor	0.023	0.023	0.037**	-0.002	0.039***	0.009	0.002
Countries	(0.016)	(0.018)	(0.018)	(0.010)	(0.012)	(0.011)	(0.032)
Precipitation effect in poor	-0.010***	-0.005	-0.004	-0.004	0.000	-0.001	-0.006
Countries	(0.004)	(0.003)	(0.003)	(0.002)	(0.001)	(0.001)	(0.006)

Notes: Columns (1) and (2) use data from the POLITY IV dataset; columns (3), (4), and (5) use data from the Archigos dataset; and columns (6) and (7) use data from the PRIO dataset. Columns (1) – (5) include country FE, region × year FE, and poor x year FE; columns (6) and (7) include country FE and year FE. Robust standard errors in parentheses, adjusted for clustering at parent-country level. Sample includes all countries with at least 20 years of PWT growth observations (i.e., the same set of countries considered in the previous tables.)

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

Table 8: Changes in growth and climate in the medium-run

	Dependent variable: change in mean growth rate								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Baseline Sample	Alternative comparison years					Africa Only	Excluding Africa	WDI data
Change in Temperature	1.499	1.900*	1.014	-0.544	1.677*	0.854	-3.022	2.084*	1.403
	(0.978)	(1.023)	(0.732)	(0.778)	(0.974)	(1.050)	(1.811)	(1.064)	(0.891)
Change in Temperature	-4.700***	-5.145***	-4.377***	-1.744	-4.194**	-2.168	0.081	-4.686**	-3.696**
X Poor Country	(1.584)	(1.619)	(1.542)	(1.710)	(1.780)	(2.164)	(2.751)	(2.229)	(1.463)
Change in Precipitation	0.097	0.130	0.051	-0.014	0.016	-0.010	0.654	0.145	-0.066
	(0.127)	(0.148)	(0.117)	(0.256)	(0.121)	(0.168)	(1.463)	(0.159)	(0.108)
Change in Precipitation	-0.157	-0.268	-0.164	0.121	0.046	0.114	-0.155	-0.428	0.100
X Poor Country	(0.255)	(0.252)	(0.235)	(0.499)	(0.244)	(0.265)	(1.586)	(0.270)	(0.203)
Region FE	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Poor Country Dummy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Early Period	1970-1985	1970-1985	1970-1987	1961-1970	1971-1980	1981-1990	1970-1985	1970-1985	1970-1985
Late Period	1986-2000	1986-2000	1988-2003	1991-2000	1991-2000	1991-2000	1986-2000	1986-2000	1986-2000
Observations	134	134	134	93	134	134	41	93	121
R-squared	0.07	0.16	0.13	0.12	0.10	0.13	0.09	0.23	0.13
Temperature effect on poor	-3.201**	-3.245**	-3.363**	-2.289	-2.518	-1.314	-2.942	-2.602	-2.294*
Countries	(1.245)	(1.348)	(1.426)	(1.523)	(1.592)	(2.037)	(2.071)	(2.108)	(1.188)
Precipitation effect on poor	-0.059	-0.137	-0.114	0.107	0.062	0.105	0.499	-0.284	0.035
Countries	(0.221)	(0.207)	(0.203)	(0.418)	(0.219)	(0.212)	(0.614)	(0.215)	(0.168)

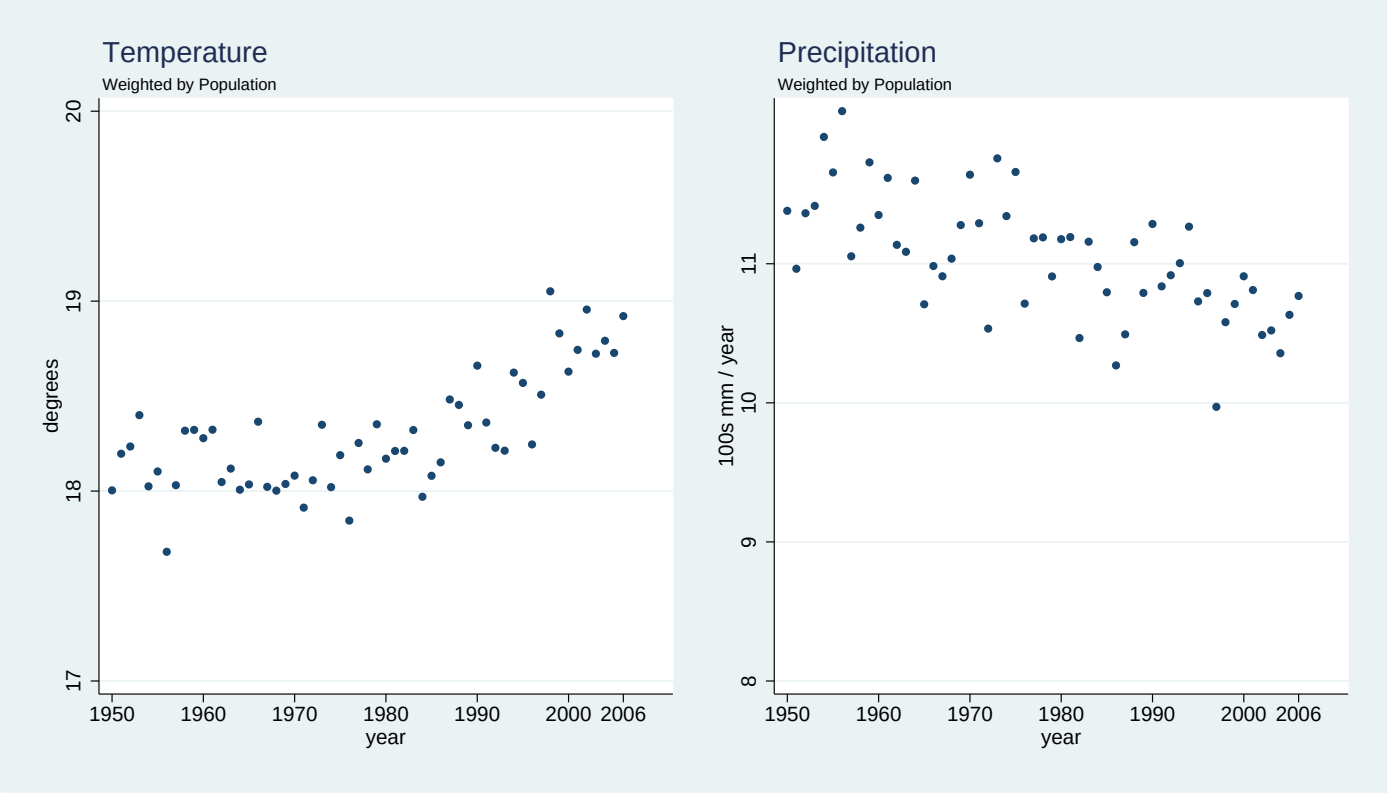
Notes: All specifications have one observation per country. Change in temperature and precipitation are computed for each country as the difference between the mean value in the Late Period and the mean value in the Early Period (these periods are indicated in the table for each specification). The dependent variable is the change in mean growth rate comparing the indicated Late and Early Periods. Region fixed effects and a dummy for being an initially poor country are included as indicated for each specification. Robust standard errors in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%

Table 9: Illustrated Growth Impacts of Temperature Change through 2099, Compared to Baseline of No Temperature Change

	Time Horizon for Adjustment			
	10 years	25 years	50 years	No adaptation
Poor countries				
Median growth rate effect	-0.6%	-1.4%	-2.3%	-2.9%
World Economy				
World GDP loss	-0.2%	-0.3%	-0.3%	-0.3%
World 75/25 Inequality	+88%	+340%	+1100%	+2100%

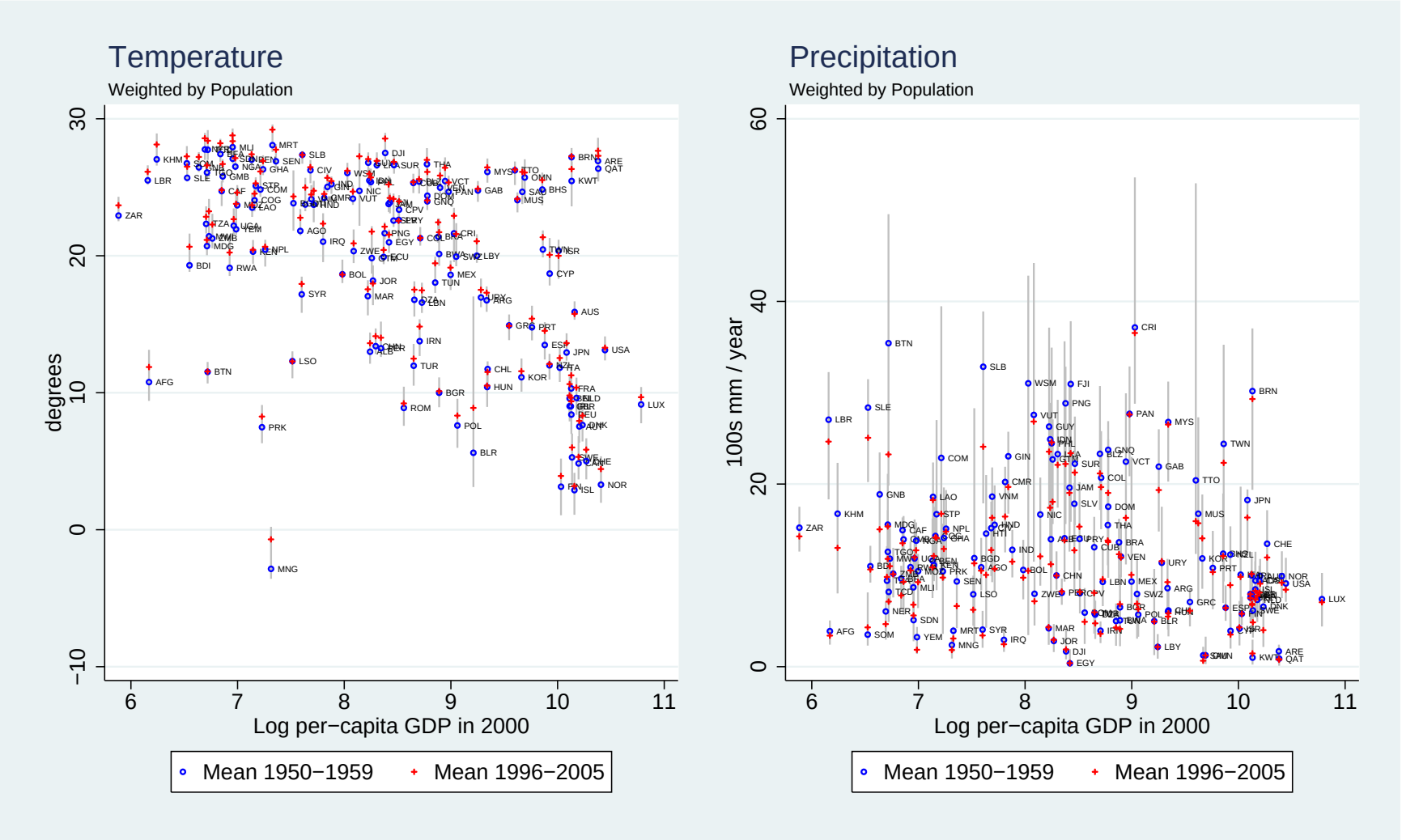
Notes: Projections are made for 122 countries under the A2 emissions scenario. The 10-lag model of column (1) in Table 4 is used for the estimated growth effect in poor countries. Zero effect is assumed for rich countries, given the statistical insignificance of the historical estimates in rich countries. The lower bound income is taken as the 1st percentile of income witnessed historically in the Penn World Tables. See further discussion in text.

Figure 1: Time trends in world average temperature and precipitation



Notes: Calculations are done using 1990 population weights.

Figure 2: Changes and variability in climate



Notes: These graphs present data on each country's temperature (left graph) and precipitation (right graph), potted against per-capita PPP GDP from the Penn World Tables in the year 2000. For each country, the circle symbols represent the mean level of temperature / precipitation in the first decade of our sample (1950-1959), the plus symbols represent the mean level of temperature / precipitation in the last decade of our sample (1996-2005), and the gray lines indicate the range of annual temperature / precipitation levels we observe for that country during our sample period. Country averages are calculated using population weights, as discussed in the text.