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Is temperature adversely related to economic growth?

Evidence on the short-run and the long-run links from sub-national data

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Is temperature adversely related to economic growth? Evidence on the short-run and the long-run links from sub-national data[*]

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Abstract

We investigate the effect of rising temperatures on economic development, using sub-national data for approximately 1,500 sub-national regions in 81 countries from the 1950s to the 2010s. Accounting for region- and time-fixed factors by means of a two-way fixed effects panel approach, we find no evidence that rising temperatures are adversely related to regional growth measured as changes in regional per capita gross domestic product (GDP). In addition to a panel setting, we also consider the long-run analogue of the panel model, exploring the relationship between regional temperature and growth over longer time periods. Applying this long-difference approach, we find evidence of a statistically significant negative association between temperature and regional economic activity. This suggests that intensification effects matter, meaning that the adverse relationship between temperature increases and growth may compound and materialize only in the longer run. What is more, we find that these adverse long-run effects of regional warming matter only to regions located in countries with relatively unfavorable economic and institutional conditions, that is, in countries with high levels of poverty, a lack of democracy, and a weak rule of law. This strongly points to the role of sound (country-specific) economic and institutional conditions in reducing vulnerability to higher temperatures. In line with this interpretation, we find no evidence for an adverse long-run relationship between temperature and growth for regions located in richer and democratic countries or those with an established rule of law.

Keywords: regional temperature; regional economic growth; sub-national data; long-difference approach
JEL Classification: Q54; Q56; R11

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I. INTRODUCTION

From 1820 to 2016, gross domestic product (GDP) per capita in most of the Western world grew by about 25 times, and in the non-Western world it grew by 13.5 times (Deaton, 2013). Economic growth has been associated with improvements in different indicators of human well-being, such as higher life expectancy, lower child mortality, and lower malnutrition (Deaton, 2013; Weil 2013). Promoting and maintaining future economic growth is thus, most likely, in humanity's vital interest. In terms of the future, a survey of experts by Christensen et al. (2018) predicted a global annual median 2010–2100 per capita GDP growth rate of 2.1%, suggesting that incomes will increase more than fivefold over the remainder of the century. However, there is substantial uncertainty in these estimates. Currently, a relevant factor of uncertainty regarding (future) economic growth is global warming.[1] According to the latest report of the Intergovernmental Panel on Climate Change (IPCC), the United Nations (UN) body for assessing the science related to climate change, global surface temperature was (on average) 1.09°C higher during 2011–2020 compared with the 1850–1900 period (IPCC, 2021: SPM-5). What is more, the IPCC forecasts that average surface temperatures will be from 1.2°C to 3.0°C higher in the 2041–2060 period compared with the 1850–1900 period, with further increases being likely for the remainder of the twenty-first century (IPCC, 2021: SPM-18). Global warming, in turn, is expected to negatively affect human lives, for example, by jeopardizing food security or water availability, contributing to the spread of diseases, and fostering political instability, especially in the more vulnerable parts of the world (IPCC, 2014). Consequently, global warming is also expected to adversely affect global growth pathways: in its most recent synthesis report, the IPCC (2014: 16) projects that "[a]ggregate economic losses

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[1] Global warming refers to the observed warming of the Earth's land and ocean surfaces. It is mainly due to anthropogenic greenhouse gas emissions such as carbon dioxide, methane, and nitrous oxide (e.g., IPCC, 2014).

accelerate with increasing temperature . . . [and] climate change impacts are projected to slow down economic growth . . .”

We contribute to the exploration of adverse effects of higher temperatures on economic growth by employing regional, that is, sub-national, data. The existing research on the nexus between temperature increases and economic development at the sub-national level remains limited and inconclusive regarding statistical significance (Nordhaus, 2006; Dell et al., 2009; Zhao et al., 2018; Kalkuhl and Wenz, 2020; Greßer et al., 2021). Using panel data for approximately 1,500 regions within 81 countries from 1950 to 2014, we add to the empirical exploration of this nexus in three ways.

First, with our dataset, we improve on those used in previous empirical studies. Rather than using auxiliary estimates of regional economic activity, we measure regional economic activity by *regional per capita GDP* using data from Gennaioli et al. (2014), such that we can directly compare our results with the larger literature exploring the economic consequences of climate change in cross-country settings (e.g., Dell et al., 2012). Moreover, we are able to exploit a panel structure. This means that we can account for region-fixed effects as well as country-time-fixed effects that may correlate with warming and regional economic growth (e.g., regional geographical conditions or national policy changes). After accounting for these fixed effects, we find no evidence of a general and statistically relevant association between regional temperature and regional per capita GDP growth. Rather, the correlation between the two variables is close to zero.

Second, we evaluate the *long-run effect* of rising temperatures on regional economic growth. We are able to do so because our dataset provides regional temperature and per capita GDP data over several decades. A long-run perspective on the temperature–growth relationship is warranted because climate change is commonly regarded as a cumulative and persistent phenomenon that can induce *adaptation* or *intensification effects* (e.g., Dell et al., 2014). For instance, adaptation effects imply that warming may induce adaptive behavior (e.g., farmers may change to crops that are better adapted to potential effects of climate change), while intensification effects imply that economically damaging effects of climate change only materialize after longer time periods (e.g., farmland may gradually desertify). Consequently, if adaptation effects prevail, we are likely to overestimate the link between warming and regional economic growth when only considering the short run, while the prevalence of intensification effects means that we are likely to underestimate the link when disregarding the long run. Indeed, using the *long-difference approach* of Dell et al. (2012, 2014) and Burke and Emerick (2016), which allows us to consider the long-run effects of climatic change on regional economic activity, we find evidence for intensification effects. A 1°C increase in regional temperature is associated with a 9.3% lower regional per capita GDP. Both in terms of size and statistical significance, this association is much more pronounced than the one emerging from a fixed effects panel approach that only considers the short-run perspective.

Third, we study *heterogeneity* in the temperature–growth relationship at the regional level. Previous cross-country research (e.g., Dell et al., 2012; Burke et al., 2015a) emphasizes that richer countries are less vulnerable to the adverse consequences of rising temperatures, as they potentially have the means (e.g., agricultural and health technology) available to adequately counter them. We add to this research by (1) considering the role of economic and political institutions as potential moderators in the temperature–growth relationship and (2) studying heterogeneity in the regional temperature–growth relationship in both the short and long run. For example, acknowledging that sound institutions ought to encourage innovation and investment (which, in turn, are expected to mitigate the adverse effects of increasing temperatures), we test whether countries with sound political and economic institutions (i.e., democratic countries with a strong rule of law) are less vulnerable to the potential ill effects of warming in both a panel and long-difference setting. We find no evidence for any statistically relevant heterogenous links between temperature and regional GDP in our panel setting that is attuned to detecting short-run linkages between temperature and regional economic activity.

However, by means of additional long-difference regressions, we find support for the notion that temperatures are related to regional growth in the long run when regions are located in countries that are comparatively "poor," "non-democratic," and with a "weak" rule of law. By contrast, there is no evidence for any statistically relevant long-run link between regional temperature and growth in countries that are "rich," "democratic," and with a "strong" rule of law. Indeed, these latter findings point to the important role that country-specific moderators play in addressing the potentially ill economic effects of rising temperatures.

The remainder of this paper is organized as follows: Section II discusses the related literature. Section III describes our regional data. Section IV examines the relationship between temperature and regional income using a panel approach. Section V presents our findings from a long-difference approach. The heterogeneity in the short- and long-run temperature–growth relationship is explored in Section VI. Section VII offers concluding remarks.

II. RELATED LITERATURE

The literature suggests that higher temperatures could *depress* economic growth through four major pathways. First, higher temperatures may adversely affect *agriculture*, for example, by contributing to water stress or the spread of plant pests (e.g., Deschênes and Greenstone, 2007; Schlenker and Lobell, 2010; Burke and Emerick, 2016; Carter et al., 2018). This may, in turn, adversely affect incomes, especially in less developed economies with larger agricultural sectors. Second, rising temperatures may directly affect *labor productivity*, for example, due to increased heat stress (e.g., Burke et al., 2015a). Such adverse effects on labor productivity may depress industrial and services output, meaning that economic growth may also suffer due to increasing temperatures when economies rely on industrial production and the service industries (e.g., Dell et al., 2014). Third, temperature increases may adversely affect *human health*, for example, by contributing to the spread of disease vectors (e.g., mosquitos that carry malaria or dengue fever) and cardiovascular disease (e.g., Gallup et al., 1999; Barreca, 2012;

Deschênes, 2014; Meierrieks, 2021). Reduced human health, in turn, is expected to curtail economic growth by constraining human capital accumulation.[2] Fourth, there are further *knock-on effects* that may reinforce the adverse effects of rising temperatures. For instance, by aggravating resource scarcity (e.g., as agricultural land becomes rarer), temperature increases could promote political instability (e.g., Miguel et al., 2004; Burke et al., 2015b). Political instability, in turn, is expected to depress economic activity. As another potential knock-on effect, by inducing economic and political instability, increasing temperatures may incentivize mass migration (e.g., Beine and Parsons, 2015; Cattaneo and Peri, 2016; Berlemann and Steinhardt, 2017; Helbling and Meierrieks, 2021). Out-migration, as a result, may deprive economies of human capital, again depressing economic growth.

Given these potential pathways from temperature increases to economic activity, a negative association between higher temperatures and economic growth seems the prevailing prior.[3] Indeed, recent empirical studies on the temperature–growth relationship usually suggest that warming may hurt economic activity. This pertains to empirical studies on the cross-country level (e.g., Hsiang, 2010; Dell et al., 2012; Lanzafame, 2014; Burke et al., 2015a, 2018) as well as to studies that examine the temperature–growth relationship within sufficiently large countries such as China (e.g., Li et al., 2019) or the United States (e.g., by Deryugina and Hsiang, 2014; Colacito et al., 2019).

There is some evidence that temperature and income may be non-linearly related in an inverted U-shaped fashion, where the economic effects of temperature increases tend to be benign in temperate environments, while temperature increases tend to create adverse effects (e.g., concerning human health, agricultural production, or labor productivity) in already hot environments, for example, due to the limited capability of the human body to regulate its

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[2] Furthermore, by adversely affecting human health, temperature increases may also discourage education, for example, by contributing to school absenteeism or permanent mental or physical disability.

[3] A noteworthy recent exception is Zhao et al. (2021) who analyze mortality and ambient temperatures from 750 locations at a grid size of 0.5° x 0.5° across the globe and find that temperatures which minimize mortality are usually well above the median temperature, that is, higher median temperatures might decrease mortality.

temperature when outside temperatures approach body temperature (e.g., Nordhaus, 2006; Deryugina and Hsiang, 2014; Burke et al., 2015a, 2018; Li et al., 2019).

More closely related to our study, a relatively small body of empirical research furthermore investigated the impact of *within*-country variation in temperature on sub-national economic outcomes with a broader (global) scope. Related studies include Nordhaus (2006), Dell et al. (2009), Zhao et al. (2018), Kalkuhl and Wenz (2020), and Greßer et al. (2021). The evidence concerning the temperature–growth relationship in these studies is inconclusive. Using cross-sectional data for over 25,000 grid cells (on a 1° x 1° latitude longitude scale), Nordhaus (2006) found that temperature increases reduce economic activity at the grid level. Zhao et al. (2018) analyzed approximately 10,500 grid cells using updated data from Nordhaus (2006) in a panel setting. While they found a negative association between temperature and economic activity, this relationship was statistically significant only in some specifications. Similarly, Dell et al. (2009) studied a cross-section of approximately 7,500 municipalities in 12 countries in the Americas, showing that while temperature increases were linked to a decline in labor income at the municipal level, this relationship was substantially weaker than any cross-country correlation between temperature and income. Kalkuhl and Wenz (2020) explored sub-national level data from 1900 to 2014 and did not find evidence for temperature effects on permanent growth rates except on the productivity level. Their regional average annual per capita growth rate is 7.0% and, thus, remarkably high in comparison with the average growth rate when looking at the country level during that period (e.g., Maddison, 2006; Bolt et al., 2018). Greßer et al. (2021) studied the relationship between average temperatures and per capita income for a sample of repeated cross-sections of regions but found no evidence that both variables are related in a statistically meaningful way.

III. DATA

Regional Economic Development and Regional Temperature

To examine the relationship between temperature and regional economic growth, we employ data for a maximum of 1,487 regions in 81 countries. Thus, on average, there are approximately 18 regions per country. Here, "region" refers to the "most disaggregated administrative division available (typically states or provinces), or, when such data does not exist . . . the most disaggregated statistical division level" (Gennaioli et al., 2014: 266). For instance, the constituent states of federations such as the United States or Russia are examples of such "regions." Our sample size is dictated by the regional economic data provided by Gennaioli et al. (2014). While it covers more than 90% of the world's GDP (including a large number of countries and regions in Asia, Oceania, the Americas, and Europe), African countries and regions tend to be underrepresented in the dataset. A list of countries is provided in the Appendix (Table A1).

Our dataset covers the 1950-2014 period. As most of the economic data are not observed annually, we average all data series, creating a series of five-year periods (1950-54, 1955-59, etc.). This allows us to consider a maximum of 13 consecutive five-year observations per region. There are between-country differences concerning temporal coverage (see Gennaioli et al., 2014: 268-270 for an overview). For instance, a number of countries only entered the sample in later years, for example, because these countries were not independent before the 1970s, 1980s, or 1990s. Thus, on average, we observe approximately six five-year periods per region.

Our main dependent variable reflecting regional economic activity is *regional per capita* GDP, collected by Gennaioli et al. (2014). The GDP data is drawn from national or regional statistical offices. To make the data comparable between regions and countries, Gennaioli et al. (2014) provide GDP data in per capita terms and in constant 2005 purchasing power parity dollars.[4]

Data on our main independent variable, regional temperature, is from a recent update of the University of Delaware Air Temperature & Precipitation Dataset of Willmott and Matsuura (2001). This dataset provides data on monthly mean surface air temperatures (available since 1900) at a 0.5° x 0.5° grid resolution (approximately 56 km^2 at the equator).[5] These temperature values are interpolated for each grid node using data from a set of local weather stations. To make the temperature data comparable to our economic data, we (1) use the shape file of Gennaioli et al. (2014) to aggregate the temperature data to the corresponding regional level and (2) create five-year averages in temperature for each region. Thus, we have one temperature data point per five-year-region observation, allowing us to relate the climate data at the regional level to regional per capita GDP.

The summary statistics of our main variables and other regional controls employed in our subsequent empirical analyses are reported in Table 1.

Table 1. Summary Statistics

Variable	N*T	Mean	SD	Min	Max
Log Regional per capita GDP	9,036	8.849	1.141	5.242	12.020
Temperature (in °C)	9,036	14.391	7.953	-12.442	29.6
Precipitation	9,036	1,068.674	673.455	3.02	5,323.599
Years of Education	7,201	7.244	3.238	0.388	13.757
Log Population	9,036	3.994	1.738	-4.646	10.055
Per capita GDP (country-level)	9,036	15,754.32	11,411.42	675.6	89,885.77
Democracy (country-level)	9,036	1.909	0.9	0	3
Rule of Law (country-level)	9,036	0.666	0.275	0.055	0.997

Notes: N = Number of regions, T = Number of years, SD = Standard deviation. “Regional Per capita GDP” and “Population” enter models in logged form. Variables “Per capita GDP,” “Democracy,” and “Rule of Law” are measured at the country-level.

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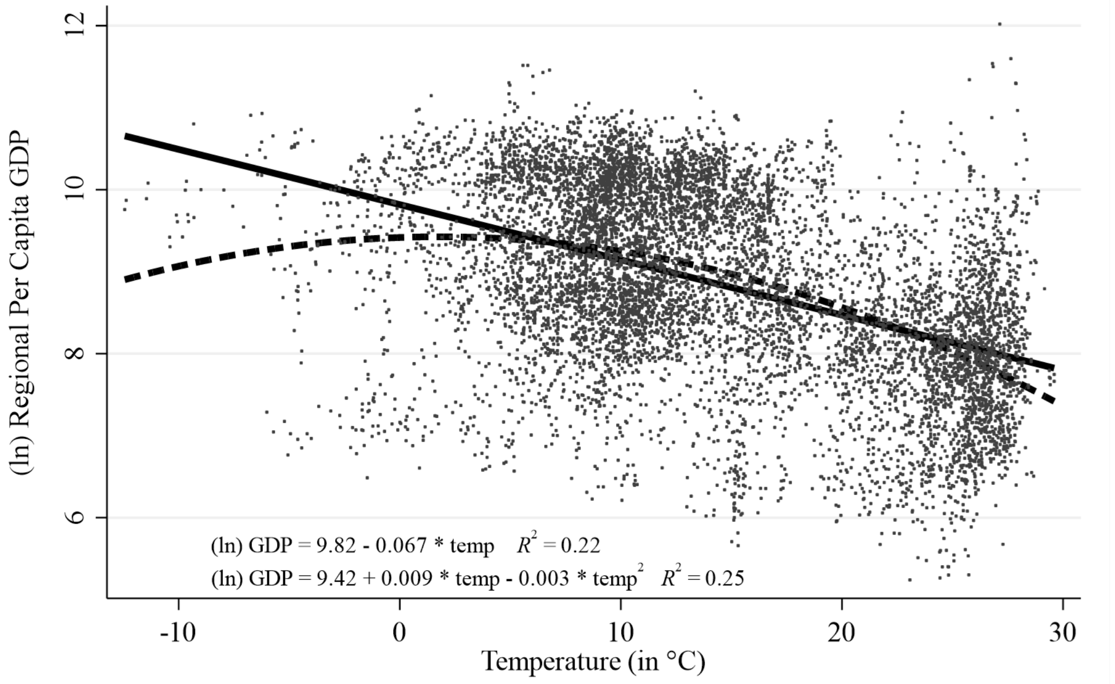
[4] For further information on the methods employed, we refer to Gennaioli et al. (2014) and the online appendix to Gennaioli et al. (2014).

[5] An overview of this dataset can also be found here: https://climatedataguide.ucar.edu/climate-data/global-land-precipitation-and-temperature-willmott-matsuura-university-delaware.

The Temperature–Growth Relationship at the Regional Level

In Figure 1, we plot regional per capita GDP against regional temperatures. As expected and indicated by the standard deviation reported in Table 1, there is huge variation in regional per capita GDP levels, reflecting large levels of economic inequality in the world. Variation in regional temperatures is substantial, too; here, the standard deviation associated with regional temperature (7.95°C) is larger than past global temperature increases (1.09°C on average) and expected future temperature increases from 2041 to 2060 (1.2°C to 3.0°C on average), according to a recent IPCC report (IPCC, 2021).



Number of Observations = 9,036

Figure 1. The Relationship between Regional Temperatures and Per Capita GDP

As shown in Figure 1, in the linear setting, there is a negative relationship between regional temperatures and regional per capita GDP, suggesting that warmer regions are poorer. In the quadratic setting (to allow for non-linearities), we find that both very cold and hot regions tend to be poorer than their more temperate counterparts. The fit of the quadratic model is, however, only marginally better than its linear counterpart, which leads to the question of whether a quadratic relationship between both variables is really supported by the data.

More importantly, though, Figure 1 only reports a simple association. For instance, we do not account for the time dimension of the data, nor do we account for the role of region- and country-fixed characteristics that may influence the regional temperature–growth nexus. We shall do so in subsequent sections.

IV. PANEL APPROACH

Estimation Strategy Employing Regional Panel Data

We analyze the relationship between temperature and per capita GDP at the regional level by considering the following two-way fixed effects model:

$$GDPpc_{jit} = \beta_1 T_{jit} + \theta_j + \varphi_{it} + \gamma X'_{jit} + \epsilon_{jit}. \tag{1}$$

Here, *GDPpc* refers to the (logged) per capita income of region *j* in country *i* in period (i.e., five-year interval) *t*. We are most interested in the coefficient β_1 reflecting the link between temperature (*T*) and regional per capita GDP. Additionally, we control for region-fixed effects (θ_j) to account for the role of time-invariant regional characteristics that may correlate with economic growth and temperatures.[6] Furthermore, we control for time-fixed effects that are also interacted with country-fixed effects (φ_{it}). The inclusion of these additional country-time-fixed effects allows us to control for time-specific effects such as global economic up- and downturns as well as country-specific time trends.[7] Finally, in some specifications, we also include a vector of control variables (*X*). Concerning these controls, Auffhammer et al. (2013: 188) argue that due to the strong correlation between temperature and *precipitation*, it may be advisable to account for both variables at the same time.[8] Moreover, *education* (in years of

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[6] For instance, Jetter et al. (2019) show that access to the sea (by affecting transportation costs) is conducive to regional economic development; at the same time, such geographical features are also expected to influence regional temperature (e.g., as rivers and the sea have cooling effects).

[7] Note that the country-fixed effects alone do not enter our model as they are perfectly collinear with the region-fixed effects.

[8] For our sample, the correlation between regional temperature and precipitation is $r = 0.48$ ($p < 0.01$).

education) and (logged) *population* are expected to correlate with regional economic development. Education may promote productivity and innovation, which allow for adaptation, while larger populations can reduce economic development, for example, by contributing to capital dilution (e.g., Weil, 2013). To make statistical inferences, we always compute standard errors that are simultaneously clustered at the region- and country-period level (e.g., Cameron et al., 2011).

An impact from regional GDP on regional temperatures can be plausibly excluded, as temperatures are affected by global anthropogenic and global/regional non-anthropogenic factors. Therefore, it is reasonable to suppose β_1 in Eq. (1) is not affected by reverse causality. Moreover, regional temperature can plausibly be assumed as being *external* to the regional economy. However, this does not imply that temperature is necessarily *exogenous* in an econometric sense (Deaton, 2010). While our fixed effects strategy captures *all regional time-invariant* influences (e.g., geography) through θ_j and it captures *all country-time variant* influences (e.g., national trade patterns over time, national policies over time, etc.) through φ_{it}, there are omitted time-variant variables at the regional level (e.g., the changing health status of the regional population over time) for which we cannot control due to missing data. This may lead to β_1 being biased. As it has become apparent from our previous literature discussion, there is a prior that temperatures negatively affect many aspects of human life such as agriculture, health, and political stability (see also, e.g., Dell et al., 2014; IPCC, 2014). If this prior is correct, omitting such time-variant regional controls would induce a *downward* bias in β_1, that is, we would overstate any potential negative impact of higher temperature on regional per capita GDP. For example, if regional temperature is adversely related to human health (e.g., Gallup et al., 1999; Barreca, 2012; Deschênes, 2014; Meierrieks, 2021) and if it is negatively related political stability (e.g., Burke et al., 2015b), then not accounting for time-variant *regional* health indicators or time-variant *regional* instability would lead to a downward bias of β_1. In this sense, we give regional temperatures a comparatively good chance to emerge as a statistically relevant and negative correlate of regional economic growth.

Empirical Results: No Relationship between Temperature and Growth in Panel Setting

We report the results of our panel approach in Table 2. We find that higher temperatures are associated with lower levels of regional per capita GDP in a setting where no fixed effects are considered (Specification 1, Table 2). Indeed, the estimated association of a one-unit (1°C) increase in temperature corresponds to the correlation (-0.067) shown in Figure 1. However, once we include our set of fixed effects (Specification 2, Table 2), the relationship between temperature and regional income becomes statistically insignificant, with effect sizes becoming substantially smaller. We also observe a substantial increase in the goodness of fit for the model when accounting for region- and country-time-fixed effects.

Table 2. Panel Estimates of the Link between Temperature and Regional Income

	(1)	(2)	(3)	(4)	(5)
Temperature	**-0.067*****	**-0.005**	**-0.037**	**0.012**	**-0.008**
	(0.011)	**(0.021)**	**(0.040)**	**(0.024)**	**(0.025)**
Temperature Squared			**0.001**		
			(0.001)		
Precipitation				-0.000	-0.000
				(0.000)	(0.000)
Years of Education				0.072*	0.096**
				(0.040)	(0.044)
Population				-0.081*	-0.100**
				(0.041)	(0.046)
Region-Fixed Effects	No	Yes	Yes	Yes	Yes
Country*Time-Fixed Effects	No	Yes	Yes	Yes	Yes
Adjusted R^2	0.220	0.982	0.982	0.985	0.986
Observations	9,036	9,036	9,036	7,136	5,619
No. of Regions	1,487	1,487	1,487	1,405	896
No. of Countries	81	81	81	77	47

Notes: Standard errors clustered at region- and country-period level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Moreover, we test for non-linear effects between temperature and regional economic development via the inclusion of a squared temperature term (Specification 3, Table 2). This allows for a potential inverted U-shaped relationship between temperature and income, where the economic effects of temperature increases tend to be benign in temperate environments, while temperature increases tend to create strong adverse effects, as previously suggested by, for example, Deryugina and Hsiang (2014), Burke et al. (2015a, 2018), and Li et al. (2019). However, we find no evidence in favor of a non-linear relationship between both variables.[9]

Finally, we examine whether our results are robust to the inclusion of further controls (Specification 4, Table 2). Indeed, we again find that rising temperatures do not have an association with regional economic growth and, if anything, the coefficient estimate is positive. There is also no relationship between precipitation and regional per capita GDP, reinforcing the notion that regional climatic factors are not associated with regional economic growth. By contrast, we can show that regional differences in education and population matter: consistent with the literature (e.g., Weil, 2013), increases in education are positively associated with growth (e.g., due to the increase of the human capital stock), while increases in population reduce growth (e.g., due to the impact of capital dilution).

As a first robustness check, we consider whether a different relationship between regional temperatures and per capita GDP emerges for a smaller sample (Specification 5, Table 2). This smaller sample only considers countries and regions that are suitable for the long-difference approach we employ below; that is, this sample covers countries and regions for which observations are available over many decades. Reassuringly, we find that regional temperature does not correlate with regional economic growth for this smaller subsample in a panel setting, suggesting that our results are not due to specific sample choices.

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[9] One may argue that a quadratic specification is not appropriate to capture non-linearities. Indeed, a number of contributions instead suggest the existence of temperature thresholds only beyond which temperature increases become truly economically disruptive (e.g., Nordhaus, 2006; Deryugina and Hsiang, 2014; Burke et al., 2015a, 2018; Zhao et al., 2018; Li et al., 2019). As a robustness check, we therefore consider the role of such temperature thresholds. As shown in the Appendix (Section A1), this approach, however, yields results that are very similar to those reported in the main text. That is, there is no evidence of such threshold effects, consistent with our finding that there is no non-linear relationship between regional temperature and economic activity.

In sum, our panel approach provides little, if any, evidence that rising temperatures are systematically related to regional living standards measured by regional per capita GDP. That is, climate does not necessarily appear to determine (economic) destiny. Instead, our results indicate that non-climatic factors, such as education and demographics as well as further time-invariant factors that likely correlate with the region-fixed effects (e.g., geographical characteristics) or country-time-variant factors (such as national economic policies), more prominently affect regional economic growth. This suggests that regional growth pathways are largely unrelated to regional climate, at least in a panel setting that focuses on the short-run (5-year average) relationship between growth and temperature.

Clearly, the absence of evidence does not mean evidence of absence, that is, climatic conditions may still be linked to regional economic growth. However, such links would have to come through single extreme weather conditions or through the increased variation in seasonal temperatures, among others, rather than from deviations from region-specific temperature and precipitation means. Nevertheless, disregarding zero effects of (average) temperature on economic growth can be critical, as such information may lead to an update of existing priors (Abadie, 2020), especially in an opinion climate where priors regarding the effects of global warming on indicators of human well-being tend to be predominantly negative. Thus, our panel results challenge existing priors.

V. LONG-DIFFERENCE APPROACH

Global warming refers to a gradual but non-mean-reverting change in temperatures, meaning that warming becomes more pronounced when longer time horizons are considered (IPCC, 2014, 2021). The cumulative and persistent nature of global warming is, in turn, expected to induce cumulative and persistent effects on nature and human behavior and, thus, economic outcomes. As noted by Dell et al. (2014), the latter effects may materialize as *adaptation* or *intensification effects*.

Concerning adaptation effects, the idea is that economic agents do not instantaneously adapt to changing climate conditions. Rather, we would expect adaptive behavior to occur under persistence, that is, after some time has passed; otherwise, adaptive behavior would not be cost-efficient. For example, incentives for farmers to switch to different crops or invest in additional agricultural technology to counter losses in agricultural production are less likely to be economically sound after a short-run but mean-reverting weather shock (e.g., a short period of particularly hot years) compared with the situation where temperatures do not revert to a stable long-run mean. Concerning intensification effects, the idea is that the full adverse effects of rising temperatures do not materialize instantaneously. Rather, effects compound over time. For example, as a consequence of persistent warming, in the long run, arable land may permanently vanish due to desertification, salinization, or rising sea levels; however, in the shorter run, such effects may remain largely unnoticed.

Theoretically, the presence of adaptation and intensification effects implies that there may be differences between the shorter- and longer-run estimates of regional temperatures on regional economic growth. For instance, if intensification effects matter in the long run, the long-term effects of regional warming on regional economic growth may be more pronounced than its short-run impacts. This, in turn, might explain the statistically insignificant relationship between temperature and regional economic growth for a shorter-run time horizon reported in Table 2.

Empirical Strategy Focusing on Long-Differences

To explore long-run links between rising temperatures and regional per capita GDP, we resort to the *long-difference approach* applied by Dell et al. (2012, 2014) and Burke and Emerick (2016). This approach involves contrasting the difference in temperature between the 1960s–1980s and the 1990s–2010s to evaluate their impact on differences in regional economic growth over the same time periods.

We estimate the following model:

$$\overline{GDP}_{ji2} - \overline{GDP}_{ji1} = \alpha + \beta_1\left[\overline{T}_{ji2} - \overline{T}_{ji1}\right] + \gamma[\overline{X'}_{ji2} - \overline{X'}_{ji1}] + \varphi_i + \epsilon_i. \qquad (2)$$

Here, we first construct region-specific averages in per capita income, temperature, and the controls between the 1960s and 1980s (subscript 1) and between the 1990s and 2010s (subscript 2). Then, we subtract these averages from each other, meaning that we take the difference of all variables of interest over long time horizons.[10] Importantly, our use of regional data still allows us to include a set of country-fixed effects (φ_i), thereby again systematically improving on the cross-country literature. In particular, these fixed effects account for initial country-wide temperature levels, that is, for the fact that regions are either located in a generally warm or cold country. The constant (α) accounts for trending in the dependent variable between the *early* and the *late* period. As the long-difference approach requires data for both the late and early period, we run this analysis for a subsample of approximately 900 regions in 47 countries (see Appendix Table A1 for the country list). We compute heteroskedasticity-robust standard errors to make statistical inferences.

The long-difference approach has several advantages, which are summarized by Dell et al. (2014) and Burke and Emerick (2016). First, in contrast to the panel approach, we estimate the economic effects of regional warming from long-term changes in average climate conditions rather than short-run (5-year) variation. This means the long-difference approach is less susceptible to extreme (but mean-reverting) temperature events and more likely to capture the true impact of (non-mean-reverting) climate change. Therefore, the literature suggests that the long-difference approach is closer to identifying long-run impacts that account for any adaptation and intensification effects that only materialize over longer time horizons (e.g., Dell et al., 2014: 778). Second, due to this change of temporal perspective, the long-difference approach more closely resembles an idealized climate change "impact experiment," where we

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[10] Note that we disregard data for the 1950s to create two long-run averages for time horizons of approximately equal size.

would compare regions with different climate change trends and levels of regional economic activity (Burke and Emerick, 2016: 115). Third, we can directly compare how regional economic growth is linked to short-run (panel approach) and long-run temperature variation (long-difference approach). Thus, we can quantify whether long-run adjustment to rising temperatures (in terms of regional per capita GDP) is smaller (e.g., consistent with adaptation) or larger (e.g., consistent with intensification) than short-run adjustment (Dell et al., 2012, 2014; Burke and Emerick, 2016).

Empirical Results: Negative Associations in the Long Run

Figure 2 illustrates that most regions experienced some warming from the 1960s–1980s to 1990s–2010s, where the average regional level of warming was 0.35°C, which is broadly consistent with recent IPCC reports (IPCC, 2014, 2021). There were some regions experiencing moderate cooling (e.g., Peru and Bolivia) as well as much more severe warming (e.g., Thailand and Canada).

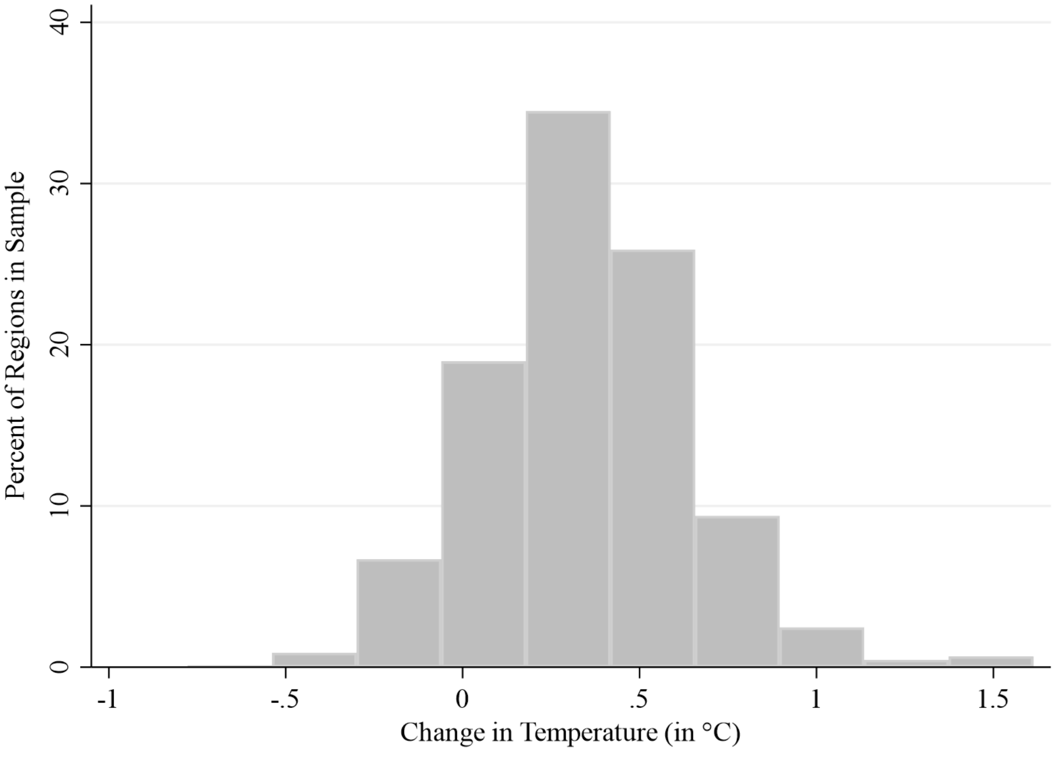

Figure 2. Histogram of Change in Temperature (1960s–1980s versus 1990s–2010s)

Estimates of Eq. (2) for the long-difference approach are reported in Table 3. We do not find that temperature increases between the 1960–1980 versus 1990–2010 periods are associated at statistically significant levels with regional economic growth for a parsimonious model (Specification 1, Table 3) without country-fixed effects. The coefficient for changes in temperature is, if anything, positive.

Table 3. Long-Difference Estimates for the Link between Temperature and Regional Incomes

	(1)	(2)	(3)	(4)	(5)
Δ Temperature	**0.060**	**-0.092****	**-0.109**	**-0.093****	**-0.055*****
	(0.058)	**(0.045)**	**(0.069)**	**(0.042)**	**(0.015)**
Δ Temperature Squared			**0.022**		
			(0.068)		
Δ Precipitation			-0.000	-0.000	0.000
			(0.000)	(0.000)	(0.000)
Δ Years of Education				0.122***	0.140***
				(0.036)	(0.016)
Δ Population				-0.176***	-0.143***
				(0.051)	(0.033)
Country-Fixed Effects	No	Yes	Yes	Yes	Yes
Adjusted *R*2	0.002	0.650	0.650	0.667	0.501
Observations	896	896	872	872	872
No. of Countries	47	47	46	46	46

Notes: Δ=First-difference operator (refers to difference between “early” and “late” period). Dependent variable=Δ Regional per capita GDP. Model (5) reports results from a median regression and the pseudo-R^2 instead of the adjusted R^2. Constant not reported. Heteroskedasticity-robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Once we add country-fixed effects (Specification 2, Table 3), temperature increases over time are negatively associated with regional growth. Allowing for a non-linear relationship between temperature and regional per capita GDP (Specification 3, Table 3), we find no evidence that both variables are non-linearly related. When we include additional controls, we continue to observe a statistically significant and negative coefficient for changes in temperature, suggesting a negative relationship with economic growth over time (Specification 4, Table 3). Here, the point estimates between the parsimonious model and the model with the controls are almost identical (cf., Specifications 2 and 4, Table 3). Considering these controls, we can confirm our earlier panel results that increases in education encourage regional economic growth in the long run, while population growth depresses it. We still find no evidence that long-run changes in precipitation affect regional per capita GDP. Finally, we ran a median regression to reduce the influence of outliers (Specification 5, Table 3). As before, we find that higher temperatures are related to lower levels of per capita income.

In sum, the most important difference between the panel approach (Section IV) and the long-difference approach is that temperature increases are associated with lower regional economic growth only in the latter approach. Indeed, our findings suggest that a one-unit (1°C) increase in temperature is associated with about a 9.3% *decrease* in regional per capita GDP (*90% CI* [-16.2, -2.4]) in the long-difference approach (cf., Specification 4, Table 3). By contrast, the comparable specification from the panel approach (cf., Specification 4, Table 2) suggests that a one-unit (1°C) increase in temperature is associated with a statistically insignificant 1.2% *increase* in per capita GDP (*90% CI* [-2.7, +5.1]).

As argued by Dell et al. (2012, 2014), the long-difference approach can be interpreted as capturing the influence of adaptation or intensification effects. According to this interpretation, our findings suggest that, in the longer run, intensification effects adversely affect regional economic growth. However, as discussed in reference to our previous panel approach, long-run changes in temperature may be negatively linked to numerous unobservables that matter for economic growth. Thus, if higher temperatures indeed negatively affect other unobserved factors (e.g., political stability, human health) which, in turn, affect regional growth, our estimated baseline loss of 9.3% in regional per capita GDP most likely presents an upper bound of the negative long-run impact per degree Celsius.

VI. HETEROGENEITY IN THE REGIONAL TEMPERATURE–GROWTH RELATIONSHIP

The literature suggests that certain *country-specific conditions* may moderate the temperature–growth relationship. Such conditions may affect a region's vulnerability to climate change.

We focus on two sets of conditions. First, country-specific levels of *economic development* may matter. That is, poorer countries may be more vulnerable to the adverse consequences of global warming (e.g., Dell et al., 2012; Burke et al., 2015a). This is because these countries tend to lack the resources to invest in technology (e.g., agricultural machinery) and public goods (e.g., levees) to counter potential unfavorable warming effects. Second, we explore the role of *sound institutions* in the temperature–growth relationship. Here, the idea is that sound institutions encourage private (long-run) investment and innovation because they promote private contracting and provide checks against government expropriation and other forms of predation (e.g., North, 1981; Acemoglu and Johnson, 2005). Investment and innovation are key to reducing vulnerability to rising temperatures. For instance, private businesses are more likely to invest in measures that reduce their vulnerability to rising temperatures (e.g., air conditioning, flood walls, and supply line security) when the risk of expropriation and predation (and thus loss of investment) is low.

Importantly, we explore the moderating role of country-specific differences in economic and institutional development not only in the short but also in the long run. That is, we consider a regional short- and long-term perspective on heterogeneity with respect to the temperature–growth nexus.

Empirical Strategy to Explore Heterogeneity

To explore the potential role of economic and institutional moderators in the temperature–growth relationship, we first consider a panel model of the following form:

$$GDP_{jit} = \beta_1 T_{jit} + \beta_2 T_{jit} * Mod_i + \theta_j + \varphi_{it} + \gamma X'_{jit} + \epsilon_{jit.} \qquad (3)$$

Here, Eq. (3) extends our previous two-way fixed-effects panel model (Eq. [1]) with an interaction term, where temperature is interacted with a country-level moderator variable (*Mod*).[11] In detail, we consider the following three moderators:

(1) ***Income***. Income is measured as per capita GDP at the country level, with the data coming from the V-Dem Dataset of Coppedge et al. (2021). Using this data, we create a binary moderator variable that is equal to unity when a country is "poor," that is, when its level of per capita income (measured at the country level) is below the sample median; this median is US$12,089 for our sample. Countries above the median are considered to be "rich," so that *Mod*=0 for regions in these countries. We hypothesize that regions in poorer countries are especially exposed to economic threats due to rising temperatures, for example, because they cannot afford technology or public goods to adequately counter the ill effects of regional warming.

(2) ***Democracy***. Data on democratic institutions are also from the V-Dem Dataset, where countries are considered democratic because of high competitiveness for access to power (e.g., due to free and fair elections) as well as a strong adherence to principles of freedom (e.g., due to sufficient respect for personal liberties). As with income, we use the democracy variable to create a moderator variable that is equal to unity when a country is "non-democratic" (i.e., when the level of democracy is below the sample median of 1.87 with a potential maximum of 3) and equal to zero otherwise (meaning that such countries are instead "democratic"). We hypothesize that regions within non-democratic countries are more vulnerable to the impact of rising temperatures. For instance, governments of non-democratic countries may be less likely to respond to climate change by adjusting public policy and spending, as they do not depend on electoral consent for political survival.

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[11] Note that the moderator-specific fixed effects and time trends do not enter our model as they are perfectly collinear with the region-fixed effects and country time trends.

(3) ***Rule of Law***. Finally, to indicate the soundness of economic institutions, we utilize a rule of law index from the V-Dem Dataset. Here, the strength of the rule of law depends on, inter alia, the quality of law enforcement, access to justice, and the extent of corruption. We use this index to create a moderator variable that is equal to unity when a country's rule of law is "weak" (i.e., when the level of the rule of law index is below the sample median of 0.68 with a potential maximum of 1), while it is equal to zero when the rule of law is "strong" (coinciding with above-median values of the rule of law index). We hypothesize that weak institutions at the country level make regions more vulnerable to the adverse economic impact of rising temperatures. For instance, weak institutions may disincentive private investment in climate change mitigation due to the risk of expropriation or may lead to public resources designated to aid adaptation to climate change dissipating due to corruption.

The relationship between temperatures and growth in "rich" and "democratic" countries with a "strong" rule of law is given by β_1 in Eq. (3) because, for these countries, *Mod* and thus the associated interaction term are equal to zero. By contrast, the relationship of rising temperatures in "poor" and "non-democratic" countries with a "weak" rule of law is given by ($\beta_1 + \beta_2$). Contrasting both estimates (i.e., β_1 as well as [$\beta_1 + \beta_2$]) determines whether there are differences in the economic response to rising temperatures in regions characterized by country-specific conditions.

Similarly, we also amend our long-difference approach (Eq. [2]) with interaction terms between temperature and the previously introduced moderators to consider the role of these moderators in the long-run relationship between regional temperature and per capita GDP. Also, including a set of country-fixed effects (φ_i) and moderator dummy variables (Mod_i), this model has the following form:

$$\begin{aligned}\overline{GDP}_{ji2} - \overline{GDP}_{ji1} = \ & \alpha + \beta_1\left[\overline{T}_{ji2} - \overline{T}_{ji1}\right] + \ \beta_2\left[\overline{T}_{ji2} - \overline{T}_{ji1}\right] * Mod_i + \beta_3 Mod_i \\ & +\gamma\left[\overline{X'}_{ji2} - \overline{X'}_{ji1}\right] + \varphi_i + \theta_m + \epsilon_i. \end{aligned} \tag{4}$$

As before, we only apply the long-difference approach to a smaller sample of regions and countries for which data is available from the 1960s onwards.

Empirical Results: Moderation in the Short and Long Run

We report our panel estimates concerning heterogeneity in the temperature–growth relationship in Table 4.

Table 4. Heterogeneity in the Regional Temperature–Growth Relationship (Panel Approach)

	(1)	(2)	(3)	(4)	(5)	(6)
Moderator →	Mod = Poor		Mod = Democracy		Mod = Rule of Law	
Temperature (β_1)	**0.000**	**0.009**	**-0.000**	**0.012**	**-0.011**	**0.006**
	(0.019)	**(0.017)**	**(0.024)**	**(0.023)**	**(0.021)**	**(0.020)**
Temperature* Moderator (β_2)	**-0.009**	**0.006**	**-0.007**	**-0.001**	**0.010**	**0.010**
	(0.040)	**(0.045)**	**(0.039)**	**(0.042)**	**(0.038)**	**(0.042)**
($\beta_1 + \beta_2$)	*-0.009*	*0.014*	*-0.008*	*0.012*	*-0.001*	*0.016*
	(0.034)	*(0.041)*	*(0.031)*	*(0.035)*	*(0.032)*	*(0.037)*
Precipitation		-0.000		-0.000		-0.000
		(0.000)		(0.000)		(0.000)
Years of Education		0.072*		0.072*		0.072*
		(0.040)		(0.040)		(0.040)
Population		-0.081*		-0.081*		-0.081*
		(0.041)		(0.041)		(0.041)
Region-Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Country*Time-Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.982	0.985	0.982	0.985	0.982	0.985
Observations	9,036	7,136	9,036	7,136	9,036	7,136
No. of Regions	1,487	1,405	1,487	1,405	1,487	1,405
No. of Countries	81	77	81	77	81	77

Notes: Poor=Country is below the median-level of economic development measured at the country-level. Demo=Country is below the median-level of democracy. Law=Country is below the median-level of rule of law index. β_1 and β_2 refer to the regression coefficients in Eq. (3). ($\beta_1 + \beta_2$) gives the total effect of temperature on regional income when the moderator is equal to unity (i.e., in countries characterized by relative poverty, lack of democracy and of rule of law). Standard errors clustered at region- and country-period level in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Using our panel approach, we find no evidence for any heterogeneity in the temperature–growth relationship. All coefficients are close to zero and statistically insignificant. This finding does not allow us to stipulate that temperature increases have different associations with regional economic growth in countries with different levels of economic, political, or institutional development. We can, however, confirm our earlier panel estimates (Table 2) regarding the beneficial role of education and the unfavorable role of population increases for economic growth.

Next, we consider heterogeneity in the temperature–growth relationship in the long run. Our findings are reported in Table 5.

Table 5. Heterogeneity in the Regional Temperature–Growth Relationship (Long-Difference Approach)

	(1)	(2)	(3)	(4)	(5)	(6)
Moderator →	Mod = Poor		Mod = Democracy		Mod = Rule of Law	
Δ Temperature (β_1)	**-0.009**	**-0.033**	**-0.000**	**-0.031**	**-0.030**	**-0.062**
	(0.040)	**(0.040)**	**(0.038)**	**(0.038)**	**(0.038)**	**(0.039)**
Δ Temperature*Moderator (β_2)	**-0.144***	**-0.105**	**-0.156****	**-0.104**	**-0.111**	**-0.054**
	(0.080)	**(0.082)**	**(0.079)**	**(0.077)**	**(0.081)**	**(0.080)**
($\beta_1 + \beta_2$)	*-0.153***	*-0.139***	*-0.157***	*-0.135***	*-0.141**	*-0.117**
	(0.070)	*(0.069)*	*(0.069)*	*(0.066)*	*(0.072)*	*(0.069)*
Δ Precipitation		-0.000		-0.000		-0.000
		(0.000)		(0.000)		(0.000)
Δ Years of Education		0.120***		0.121***		0.121***
		(0.036)		(0.036)		(0.036)
Δ Population		-0.171***		-0.171***		-0.173***
		(0.050)		(0.050)		(0.050)
Country-Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Moderator Dummy	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.651	0.667	0.651	0.667	0.650	0.667
Observations	896	872	896	872	896	872
No. of Countries	47	46	47	46	47	46

Notes: Δ=First-difference operator (refers to difference between "early" and "late" period). Dependent variable=Δ Regional per capita GDP. Poor=Country is below the median-level of economic development measured at the country-level. Demo=Country is below the median-level of democracy. Law=Country is below the median-level of rule of law index. β_1 and β_2 refer to the regression coefficients in Eq. (4). (β_1 + β_2) gives the total effect of temperature on regional income when the moderator is equal to unity (i.e., in countries characterized by relative poverty, lack of democracy and of rule of law). Heteroskedasticity-robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

There are two main results. First, we find no evidence that changes in regional temperature increases are adversely related to regional economic growth in countries that are characterized as "rich," "democratic," and having a "strong" rule of law. Second, there is evidence that regional temperature increases are negatively associated with regional economic growth when regions are located in countries that are comparatively "poor," "non-democratic," and have a “weak” rule of law. Here, we find that a one-unit (1°C) increase in temperature may reduce regional per capita GDP by about 13.9% in “poor” countries (*90% CI* [-25.3, -2.5]), by about 13.5% in “non-democratic” countries (*90% CI* [-24.4, -2.6]) and by about 11.7% in countries with a “weak” rule of law [*CI 90%*: -23.1; -3.5].

One potential challenge of our analysis concerning heterogeneity in the regional temperature–growth relationship is that the country-specific moderators may be endogenous to climate change. For instance, Brücker and Ciccone (2011) show that adverse economic shocks triggered by changing weather conditions may foster democratic governance by lowering the opportunity cost of contesting autocratic power. As a robustness check, we therefore also consider *initial* economic and politico-institutional conditions (i.e., values in the 1960s) as moderators rather than economic and politico-institutional conditions that are averaged over the full period of observation. As reported in the Appendix (Section A2), this approach, however, yields results that are very similar to those reported in the main text.

In sum, the panel and long-difference approaches displayed in Tables 4 and 5 yield two main empirical conclusions. First, we can confirm our earlier finding that a link between temperature and regional growth only emerges in the long run, consistent with the notion of unfavorable intensification effects. Second, we show that the long-run relationship between regional temperature and economic activity is heterogeneous, only emerging prominently and in an unfavorable fashion in regions located in countries with comparatively low levels of economic and politico-institutional development.

VII. CONCLUSION

Motivated by growing concerns about the adverse effects of rising temperatures on human well-being and economic prosperity, we study the relationship between temperature and per capita GDP using sub-national data for 81 countries and almost 1,500 regions from the 1950s to the 2010s.

Our main results can be summarized as follows. First, using a panel approach, we find no statistically significant evidence that rising regional temperatures are negatively related to regional economic growth. There is also no evidence for a curvilinear (inverse-U) relationship between both variables. We do not find that regions located in specific countries (characterized by high poverty and weak political and economic institutions) are especially vulnerable. Instead of temperature, our panel estimates stress the role of education, demographics, and variables correlated with region-fixed effects (e.g., geography) or country-time-fixed effects as substantial covariates that are linked to regional economic outcomes.

Second, compared to a panel approach, a long-difference approach is more attuned to exploring the long-run relationship between rising temperatures and regional economic activity. Applying a long-difference approach to our data, a statistically significant negative relationship between rising temperatures and regional economic growth emerges. This finding is consistent with the prevalence of intensification effects, implying that the adverse economic consequences of temperature may compound and become more noticeable over time. On closer inspection, regional warming is only negatively related to growth in regions that are located in countries with relatively unfavorable economic and institutional conditions, that is, high (initial) poverty, lack of democracy, and a weak rule of law. Thus, country-specific conditions may crucially moderate regional economic vulnerability to climate change, for example, by affecting mitigation and adaptation strategies.

In sum, our findings point to a more nuanced relationship between regional temperature increases and regional economic activity. This may lead to an update of existing priors concerning the economic consequences of climate change (Abadie, 2020), while also inviting future research that could more compellingly account for the short- and long-run as well as moderating effects of temperature on economic outcomes. At the same time, we acknowledge the limitations of our analysis. First, our economic data remain rather coarse, leading to uncertainty, especially concerning the long-run link between temperature increases and regional economic development. Second, our data lack information on many African countries. These countries, however, are poised for extensive economic fallout due to climate change, especially given unfavorable country-specific economic and institutional conditions. We hope that future research can resolve these data issues to more precisely explore the linkages between regional temperature increases and regional economic activity.

Global warming and climate change are projected to continue for the coming decades (IPCC, 2014, 2021). Our empirical results suggest that potential adverse effects of warming on sub-national economic growth could take decades to materialize; these adverse effects may become more pronounced if future climate change is more rapid and impactful, for example, when tipping points in the climate system are crossed. Our study also suggests that rising temperatures are – for the moment – especially relevant to regions located in countries that are already poor and exhibit weak political and economic institutions. Thus, the vulnerability to higher temperatures is not constant. This matters for economic models of climate change (see also Tol 2021). As regions in poorer countries are more vulnerable, the impacts of global warming could be reduced with economic growth. Climate does not necessarily determine (economic) destiny. For instance, efforts to improve institutional performance and democracy at the country-level can help to reduce economic vulnerability to potential negative effects of global warming. Importantly, such efforts can be pursued independently of and in addition to global efforts to reduce greenhouse gas emissions to curtail global warming.

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APPENDIX

Table A1. List of Countries

Albania
Argentina*
Australia*
Austria*
Bangladesh*
Belgium*
Benin
Bolivia*
Brazil*
Bulgaria
Canada*
Chile*
China*
Colombia*
Croatia
Czech Republic
Denmark*
Ecuador
Egypt
El Salvador
Estonia
Finland*
France*
Germany*
Greece*
Guatemala
Honduras
Hungary*
India*
Indonesia*
Iran
Ireland*
Italy*
Japan*
Jordan
Kazakhstan
Kenya*
Korea (South)*
Kyrgyz Republic
Latvia
Lesotho*
Lithuania
Macedonia
Malaysia*
Mexico*
Mongolia
Morocco
Mozambique
Nepal
Netherlands*
Nicaragua*
Nigeria
Norway*
Pakistan*
Panama
Paraguay
Peru*
Philippines*
Poland
Portugal*
Romania
Russia
Serbia (Yugoslavia)*
Slovak Republic
Slovenia
South Africa*
Spain*
Sri Lanka
Sweden*
Switzerland*
Tanzania*
Thailand*
Turkey*
Ukraine
United Arab Emirates*
United Kingdom*
United States*
Uruguay*
Uzbekistan
Venezuela*
Vietnam

* Country is included in smaller dataset when long-difference approach is applied.

A1. Examination of Non-Linearities in the Temperature–Growth Relationship

In Table 2, Specification 3, we tested for the presence of a non-linear relationship between regional temperature and income by the inclusion of a squared temperature term. We found no evidence in favor of an inverted U-shaped relationship between the two variables. As a robustness check, we explored potential non-linearities by considering various temperature thresholds. The idea of a non-linear relationship is that temperature increases may have a relatively benign effect on economic growth when temperature levels are moderate, but that the same temperature increases can be strongly disruptive in hot environments (e.g., Burke et al., 2015a). Thus, we can hypothesize that regions below a specific temperature threshold are less vulnerable to rising temperatures (in terms of regional per capita GDP losses) than their counterparts above this threshold. In Table A, we follow the literature (e.g., Nordhaus, 2006; Deryugina and Hsiang, 2014; Burke et al., 2015a, 2018; Zhao et al., 2018; Li et al., 2019) and consider temperature thresholds at 9, 13, 17, 21, and 24°C, respectively.

We report our estimates in Table A2, where we always use the largest available sample of approximately 1,500 regions in 81 countries to be able to fully exploit inter-regional variation in temperatures. We find that higher temperatures are associated with reduced economic activity below and above the various temperature thresholds. The respective coefficient estimates are never statistically significant. When comparing the size of the temperature effects below and above the threshold, we never find that these effect sizes are distinct from each other in statistically meaningful ways. Thus, our analysis and data do not allow us to assert that temperature is linked to regional economic growth. There is no evidence for non-linear links (threshold effects) between increasing temperatures and per capita income at the regional level. This speaks to earlier findings reported by Dell et al. (2009, 2012) and Lanzafame (2014), who also find no convincing evidence that the relationship between income and temperature is non-linear.

Table A2. Non-Linear Relationship between Temperature and Regional Growth

	(1)	(2)	(3)	(4)	(5)
Temperature Threshold →	9°C	13°C	17°C	21°C	24°C
Temperature Effect	-0.006	-0.004	-0.005	-0.001	-0.004
below Threshold	(0.022)	(0.022)	(0.020)	(0.022)	(0.021)
Temperature Effect	-0.005	-0.005	-0.005	-0.006	-0.005
above Threshold	(0.021)	(0.021)	(0.021)	(0.022)	(0.021)
[Equality of Coefficients F-Stat.]	[0.73]	[0.79]	[0.02]	[2.44]	[0.28]
[p-value]	[0.39]	[0.37]	[0.89]	[0.12]	[0.60]
Region-Fixed Effects	Yes	Yes	Yes	Yes	Yes
Country*Time-Fixed Effects	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.982	0.982	0.982	0.982	0.982
Observations	9,036	9,036	9,036	9,036	9,036
No. of Regions	1,487	1,487	1,487	1,487	1,487
No. of Countries	81	81	81	81	81

Notes: Standard errors clustered at region- and country-period level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

A2. Robustness of the Heterogeneity in the Temperature–Growth Relationship

One problem of the previous analysis concerning heterogeneity in the regional temperature–growth relationship is that the country-specific moderators we consider may be endogenous to climate change. For instance, Brücker and Ciccone (2011) show that adverse economic shocks triggered by changing weather conditions may lead to improvements in democratic governance by lowering the opportunity cost of contesting autocratic power.

To address such concerns, we proceed as follows. First, we drop data for the 1950s as country-level data are not available for most countries during this time period. Second, we calculate the average of all three country-level variables (per capita income, democracy, and rule of law) over the 1960-1970 period. Note, however, that this still reduces our sample size to some extent, as for some countries data are also not available for the 1960s. Third, we use these averages to create a set of binary moderator variables analogous to the way described in the paper, which now refer to *initial* levels of per capita income, democracy, and the rule of law at the country level. Finally, we use these new moderators to estimate the models specified in Eq. (3) and (4). By only considering initial country-level conditions, this robustness check ought to reduce concerns about endogeneity in the moderators.

As shown in Tables A3 and A4, this robustness check indeed supports our main findings. That is, there is little evidence that initial economic, political, and institutional conditions affect the role of regional warming in regional economic growth in the panel setting (Table A3). By contrast, we again find that rising temperatures are negatively related to regional economic growth over the long run, that is, in a long-difference approach (Table A4). What is more, we show that temperature increases tend to depress regional economic development only when initial conditions are unfavorable, such as when they are characterized by initially low levels of economic and politico-institutional development.

Tale A3. Heterogeneity in the Regional Temperature–Growth Relationship (Panel Approach)

	(1)	(2)	(3)	(4)	(5)	(6)
Moderator →	Mod = Poor		Mod = Democracy		Mod = Rule of Law	
Temperature (β_1)	**0.012**	**0.007**	**-0.030**	**-0.026**	**-0.012**	**-0.012**
	(0.018)	**(0.017)**	**(0.025)**	**(0.029)**	**(0.014)**	**(0.014)**
Temperature* Moderator (β_2)	**-0.013**	**0.012**	**0.052**	**0.076***	**0.011**	**0.034**
	(0.038)	**(0.044)**	**(0.040)**	**(0.042)**	**(0.036)**	**(0.042)**
($\beta_1 + \beta_2$)	*-0.001*	*0.019*	*0.021*	*0.049**	*-0.001*	*0.022*
	(0.033)	*(0.040)*	*(0.032)*	*(0.029)*	*(0.034)*	*(0.040)*
Precipitation		-0.000		-0.000		-0.000
		(0.000)		(0.000)		(0.000)
Years of Education		0.075**		0.086**		0.087**
		(0.038)		(0.039)		(0.039)
Population		-0.077*		-0.084*		-0.084*
		(0.045)		(0.046)		(0.046)
Region-Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Period*Country-Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.983	0.985	0.984	0.986	0.984	0.986
Observations	8,643	7,066	7,956	6,668	7,956	6,668
No. of Regions	1,487	1,405	1,301	1,257	1,301	1,257
No. of Countries	81	77	68	66	68	66

Notes: Decades considered=1960s-2010s. Poor=Country is below the median-level of economic development measured at the country-level over 1960-1970 period. Demo=Country is below the median-level of democracy over 1960-1970 period. Law=Country is below the median-level of rule of law index over 1960-1970 period. β_1 and β_2 refer to the regression coefficients in Eq. (3). ($\beta_1 + \beta_2$) gives the total effect of temperature on regional income when the moderator is equal to unity (i.e., in countries characterized by relative initial poverty, initial lack of democracy and of initial rule of law). Standard errors clustered at region- and country-period level in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table A4: Heterogeneity in the Regional Temperature–Growth Relationship (Long-Difference Approach)

	(1)	(2)	(3)	(4)	(5)	(6)
	Mod = Poor		Mod = Democracy		Mod = Rule of Law	
Δ Temperature (β_1)	**-0.018**	**-0.049**	**-0.039**	**-0.072***	**-0.035**	**-0.068**
	(0.041)	**(0.042)**	**(0.042)**	**(0.042)**	**(0.041)**	**(0.042)**
Δ Temperature*Moderator (β_2)	**-0.132**	**-0.078**	**-0.094**	**-0.037**	**-0.106**	**-0.046**
	(0.081)	**(0.080)**	**(0.081)**	**(0.079)**	**(0.082)**	**(0.081)**
($\beta_1 + \beta_2$)	*-0.150***	*-0.127**	*-0.133**	*-0.110**	*-0.141***	*-0.114**
	(0.069)	*(0.066)*	*(0.069)*	*(0.066)*	*(0.071)*	*(0.067)*
Δ Precipitation		-0.000		-0.000		-0.000
		(0.000)		(0.000)		(0.000)
Δ Years of Education		0.121***		0.121***		0.121***
		(0.039)		(0.039)		(0.039)
Δ Population		-0.162***		-0.163***		-0.163***
		(0.049)		(0.049)		(0.049)
Country-Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Moderator Dummy	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.650	0.665	0.649	0.665	0.649	0.665
Observations	869	845	869	845	869	845
No. of Countries	45	44	45	44	45	44

Notes: Δ=First-difference operator (refers to difference between “early” and “late” period). Dependent variable=Δ Regional per capita GDP. Decades considered=1960s-2010s. Poor=Country is below the median-level of economic development measured at the country-level over 1960-1970 period. Demo=Country is below the median-level of democracy over 1960-1970 period. Law=Country is below the median-level of rule of law index over 1960-1970 period. β_1 and β_2 refer to the regression coefficients in Eq. (4). ($\beta_1 + \beta_2$) gives the total effect of temperature on regional income when the moderator is equal to unity (i.e., in countries characterized by relative initial poverty, initial lack of democracy and of initial rule of law). Heteroskedasticity-robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.