Institute for Research in Economic and Fiscal issues

IREF Working Paper Series

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Evidence on the Short-Run and the Long-Run Links From Sub-National Data

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IREF Working Paper No. 202208

September 2022

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

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September 2022

Abstract

We investigate the effect of rising temperatures on regional economic development, using annual sub-national data for over 1,500 regions in 155 countries between 1990 and 2017. In a panel setting with region- and country-time-fixed effects, we find no evidence of a homogeneous or heterogeneous effect of rising temperatures on economic development as measured by regional per capita income. We also employ a long-difference approach that is attuned to exploring the long-run relationship between rising temperatures and regional income. We find that for a minority of regions located within countries with weak economic-legal and political institutions, rising temperatures are negatively associated with regional per capita income in the long run. For those vulnerable regions, we also show that rising temperatures curtail long-run regional population and human capital development. Exploring alternative regional per capita GDP data from 1950 onwards yields identical empirical conclusions. In sum, our results suggest that the adverse economic consequences of temperature compound over time, only becoming noticeable in the long run for regions in already disadvantaged countries. Thus, country-specific conditions crucially moderate regional economic vulnerability to future temperature increases due to global warming.

Keywords: regional temperature; regional per capita income; sub-national data; long-difference approach; threshold models; global warming

JEL Classification: O44; O47; Q54; R11

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[*] Acknowledgements: Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2052/1 – 390713894.

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I. Introduction

From 1820 to 2016, per capita gross domestic product in most of the Western world grew by approximately 25 times, while in the non-Western world it grew by 13.5 times. This economic development, in turn, was associated with broader improvements in human living standards and well-being, for example, in the form of higher life expectancy, reduced child mortality and lower malnutrition (Deaton, 2013; Weil 2013). Promoting and maintaining future economic development is thus in humanity's vital interest. Indeed, a survey of experts by Christensen et al. (2018) predicts a global annual median 2010-2100 per capita income growth rate of 2.1%, suggesting that per capita incomes will increase more than fivefold over the remainder of the century.

However, there is substantial uncertainty associated with such estimates. A factor contributing to this uncertainty is *global warming*.[1] According to the latest report of the *Intergovernmental Panel on Climate Change* (*IPCC*), the United Nations body for assessing the science related to climate change, during the 2011-2020 period average global surface temperatures were 1.09°C higher compared to 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 to the 1850-1900 period, with further increases being possible for the remainder of the twenty-first century (IPCC, 2021: SPM-18). Global warming, in turn, is expected to negatively affect human life. For example, it might curtail water availability and plant growth, thus jeopardizing food security, adversely affect health by contributing to the spread of diseases as well as foster resource scarcity and subsequent political instability, especially in already more vulnerable parts of the world (IPCC, 2014). Consequently, global warming is also expected to adversely affect global economic pathways. For instance, in a recent synthesis report, the IPCC (2014: 16) projects that "[a]ggregate economic losses accelerate with increasing temperature […] [and that] climate change impacts are projected to slow down economic growth […]".

We contribute to the exploration of the adverse economic effects of global warming by studying the relationship between rising temperatures and per capita levels of economic development with regional (i.e., sub-national) data for over 1,500 regions in 155 countries

[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).

between 1990 and 2017. The existing research on the nexus between temperature increases and economic outcomes 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; Kahn et al. 2021; Greßer et al., 2021). We add to the empirical exploration of this nexus in three ways.

First, we use annual economic data from the *Global Data Lab Dataset* (Smits, 2016; Smits and Permanyer, 2019; Permanyer and Smits, 2020) which is available for many regions worldwide, especially within emerging and developing economies. As we measure regional economic activity by *regional per capita gross national income*, we can compare our results with the larger literature exploring the economic consequences of climate change in cross-country settings (e.g., Dell et al., 2012). In comparison to earlier contributions on the regional temperature–income nexus (e.g., Greßer et al., 2021), we can fully exploit the panel structure of the data. This means that we can account for region-fixed effects as well as country-year-fixed effects that may correlate with warming and regional economic development (e.g., regional geographical conditions or national economic policy changes).

Second, we evaluate the *long-run relationship* between rising temperatures and regional economic development. A long-run perspective on the temperature–income relationship is warranted because climate change is commonly regarded as a cumulative and persistent phenomenon that may induce *adaptation* or *intensification effects* (e.g., Dell et al., 2014). Here, adaptation effects imply that warming may induce adaptive behavior (e.g., farmers may change to crops that are better adapted to changing climatic conditions), while intensification effects imply that economically damaging effects of climate change only materialize after longer time periods (e.g., as farmland may gradually desertify). Consequently, if adaptation effects prevail, we are likely to overestimate the link between regional warming and income when only considering the short run, while the prevalence of intensification effects means that we are likely to underestimate the same link when disregarding the long run. To uncover adaptation or intensification effects, we employ the *long-difference approach* of Dell et al. (2012, 2014) and Burke and Emerick (2016).

Third, we investigate potential *heterogeneities* in the temperature–income relationship at the regional level by means of threshold-models. 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 various economic and political institutions as potential moderators in the temperature–income relationship at the regional level, (2) examining the influence of moderators that have previously received no attention in the literature (e.g., differences between rural and urban areas), (3) studying heterogeneity in the regional temperature–income relationship in both the short and long run and (4) using a threshold-approach following Hansen (1999) to empirically determine (rather than justifying in an ad-hoc manner) economic and political conditions under which the role of rising temperatures in regional economic development could become especially pronounced.

Our main findings can be summarized as follows. First, accounting for various fixed effects, we find no evidence of a general and statistically relevant association between regional temperature and regional per capita income in a panel setting. Second, there is also no statistically significant relationship between rising temperatures and changing income levels in the long-difference setting that captures long-run links. These results do not speak to the prevalence of adaptation or intensification effects that matter to *all* regions in our sample. Third, allowing for heterogeneity in the temperature–income nexus by means of a threshold-approach, we find no evidence of such threshold effects in the short-run (fixed-effects panel approach) but can detect them in the long run (long-difference approach). In the long run, we find support for the notion that temperature increases are negatively related to regional economic development within countries with weak economic-legal and political conditions. For instance, rising temperatures are only negatively associated with regional income within countries that do not facilitate equal access to legal institutions and public goods. For one, this points to intensification effects, reducing long-run regional economic development within countries that lack sound economic-legal and political institutions. For another, it also points to the important role that country-specific moderators play in addressing the potentially ill economic effects of rising temperatures. Fourth, we systematically assess the robustness of our main finding by using alternative data on regional economic development between 1950 and 2014 (Gennaioli et al., 2014). Finally, we explore how increasing temperatures might undermine regional income especially in the long run. We find evidence that rising temperatures adversely may affect long-run regional population and education levels within countries that exhibit relatively weak economic-legal and political institutions.

The remainder of this paper is organized as follows. Section II discusses the related literature. Section III describes our regional economic and climate 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. Short- and long-run heterogeneity in the temperature–income relationship is explored in Section VI. In Section VII we show that all our interpretations also hold when investigating regional data from 1950 onwards. Furthermore, we explore some of the potential transmission channels in the long-run temperature–income relationship in Section VIII. Section IX offers concluding remarks.

II. Theory and Literature Review

The Temperature–Income Nexus: Theoretical Mechanisms

The literature suggests that higher temperatures could *depress* economic activity 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 economies with large agricultural sectors.

Second, rising temperatures may directly affect *labor productivity* (e.g., Burke et al., 2015a; Kahn et al. 2019), for example, due to increased heat stress. Such adverse effects on labor productivity may depress industrial and services output, meaning that the adverse economic effects of increasing temperatures would not be restricted to agriculture-dependent economies but also matter to economies that rely more strongly on industrial production and the service industries (e.g., Dell et al., 2014; Carleton and Hsiang 2016; Nath 2020).

Third, temperature increases may adversely affect *human capital*. For one, such 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) or cardiovascular disease (e.g., Gallup et al., 1999; Barreca, 2012; Deschênes, 2014; Meierrieks, 2021). For another, higher temperatures may also discourage *education*, for example, by contributing to school absenteeism (e.g., Zivin and Shrader, 2016; Zivin et al, 2018; Park, 2022). Consequently, economic activity is expected to suffer when increasing temperatures constrain human capital accumulation.

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 scarcer), temperature increases might 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 migration (e.g., Beine and Parsons, 2015; Cattaneo and Peri, 2016; Berlemann and Steinhardt, 2017; Helbling and Meierrieks, 2021). Out-migration may deprive economies of human capital, again depressing economic development.

Empirical Evidence on the Temperature–income Nexus

Given these theoretical mechanisms, a negative association between higher temperatures and aggregate economic activity is the prevailing prior (e.g., Carleton and Hsiang 2016).[2] Indeed, this prior is consistent with recent empirical studies that suggest that warming may hurt economic performance. 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 relationship between temperature and *economic growth* within sufficiently large countries such as China (e.g., Li et al., 2019) or the United States (e.g., Deryugina and Hsiang, 2014; Colacito et al., 2019). Newell et al. (2021) report considerable uncertainty in cross-country econometric models which is greatest when investigating the link between temperature and GDP growth (leading to impacts in terms of GDP levels in 2021 between -84% and +359%), while models that explore the relationship between temperature and GDP per capita levels yield much narrower distributions.

There is some evidence that climatic and economic conditions may be non-linearly related in an inverted U-shaped fashion, where the aggregate 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 (e.g., Nordhaus, 2006; Deryugina and Hsiang, 2014; Burke et al., 2015a, 2018; Li et al., 2019). There is also evidence that the effect of temperature on economic activity tends to be more pronounced in poorer countries due to their limited capabilities to adapt to the adverse consequences of global warming (e.g., Dell et al., 2012, 2014).

More closely related to our study, a small body of empirical research furthermore investigated the impact of *within*-country variation in temperature on sub-national economic outcomes (especially economic growth) with a broader (global) scope. Related studies include Nordhaus (2006), Dell et al. (2009), Zhao et al. (2018), Kahn et al. (2019), Kalkuhl and Wenz (2020),

[2] 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.

and Greßer et al. (2021). The evidence concerning the temperature–economy 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) finds that temperature increases reduce economic activity at the grid level. Zhao et al. (2018) analyze approximately 10,500 grid cells using updated data from Nordhaus (2006) in a panel setting. While they find a negative association between temperature and economic activity, this relationship is statistically significant only in some specifications. Similarly, Dell et al. (2009) study 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 is substantially weaker than any cross-country correlation between temperature and income. Kahn et al. (2019) analyze the case of 48 U.S. states from 1963 to 2016. Half of their specifications show a statistically significant link between their climate indicator and state-level output growth. Analyzing the period from 1976 the results are more robust and negative. Further evidence suggests that adaptation has limited potential negative impacts of rising temperatures in the United States. Kalkuhl and Wenz (2020) explore sub-national level data from 1900 to 2014 and do 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 the same period (e.g., Maddison, 2006; Bolt et al., 2018). Finally, Greßer et al. (2021) study the relationship between average temperatures and per capita income for a sample of repeated cross-sections of regions, finding no evidence that both variables are related in a statistically meaningful way.

III. DATA

Regional Economic Development and Regional Temperature

To empirically investigate the relationship between regional temperature and regional economic development, we draw economic data from the *Global Data Lab* (Smits, 2016; Smits and Permanyer, 2019; Permanyer and Smits, 2020) as a primary source. This dataset uses data from national statistical offices and various household surveys (e.g., the *Demographic and Health Surveys*; the *UNICEF Multiple Indicator Cluster Surveys*; *Afrobarometer*; or the *Integrated Public Use Microdata Series*) to provide harmonized sub-national economic data that is comparable across time and space (for a further discussion see Smits, 2016; Smits and

Permanyer, 2019; Permanyer and Smits, 2020).[3] Our main indicator of regional economic development is the *per capita gross national income* (*GNI*) in thousands of 2011 PPP-adjusted US$. For the *Global Data Lab Dataset*, "regions" are usually based on official administrative subdivisions used in the countries of interest such as states (e.g., federal states in the United States or Germany), prefectures or districts (Smits, 2016).

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).[4] These temperature values are interpolated for each grid node using data from a set of local weather stations. We use the shape file provided by the *Global Data Lab Dataset* to aggregate the temperature data to the corresponding regional level for which economic data is available. Thus, we have one temperature data-point per year-region observation, allowing us to relate the climate data to the economic data at the regional level.

We can use data for up to 1,549 regions in 155 countries. Thus, on average, there are approximately 10 regions per country. A country list is provided in the Appendix. We have available annual data for regional economic development and temperature between 1990 and 2017, where the start and end year of our observation period is dictated by the availability of the economic data. As part of our robustness checks, below we also consider alternative measures of regional economic development and climate conditions. In recent years, some presumably standard results have been overturned by using marginally different specifications or data sources (e.g., Johnson et al. 2013 with respect to the use of GDP data). Thus, next to our primary data source, as part of our robustness checks, we also employ alternative data for regional GDP per capita between 1950 and 2014 for 1,446 regions in 81 countries from Gennaioli et al. (2014). We match regional temperatures to this alternative dataset.

The summary statistics of our main variables and other explanatory variables employed in our subsequent empirical analyses are reported in Table 1. Focusing on the main dependent variable of interest, there is a large variation in regional per capita income levels. Variation in regional temperatures is substantial, too. Here, the standard deviation associated with regional

[3] The dataset and information on the methodology can be found at https://globaldatalab.org/ (accessed August 28, 2022).

[4] A description of this dataset can be found at https://climatedataguide.ucar.edu/climate-data/global-land-precipitation-and-temperature-willmott-matsuura-university-delaware (accessed August 28, 2022).

temperature (7.5°C) is substantially 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).

Table 1: Summary Statistics

Variable	N*T	Mean	SD	Min	Max
Regional per Capita Income	36,887	13,570	15,196	360	103,777
Regional per Capita Income (log)	36,887	8.871	1.207	5.887	11.55
Regional HDI	36,887	0.629	0.176	0.168	0.973
Economic Growth	36,887	0.036	0.083	-1.494	2.737
Temperature	38,807	18.956	7.558	0.011	31.725
Temperature (log)	38,807	2.822	0.572	-4.499	3.457
Maximum Temperature	38,807	27.336	5.187	7.1	42.1
Temperature Variation	38,807	4.896	3.095	0.198	16.965
Precipitation	38,807	95.4	67.167	0	491.02

Notes: HDI=Human Development Index. N=Number of regions, T=Number of years. SD=Standard deviation. Summary statistics reported for baseline sample from our primary dataset which excludes regions with temperatures below zero. Economic and climate variables usually enter models in logged form. Summary statistics for our alternative dataset from 1950 onwards are available on request.

The Temperature–Income Relationship at the Regional Level

In Figure 1, we plot regional per capita income (in logs) against regional temperatures for all regions and years in our dataset. The figure illustrates the high variation of the data. There is a negative relationship between regional temperatures and regional per capita income, suggesting that warmer regions are poorer. A fit of a quadratic model (illustrated as a dashed line) performs similarly to the linear counterpart (solid line) in terms of the coefficient of determination. Figure 1 only reports a simple association between regional temperature and temperature. 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–income nexus. We shall do so in subsequent sections.

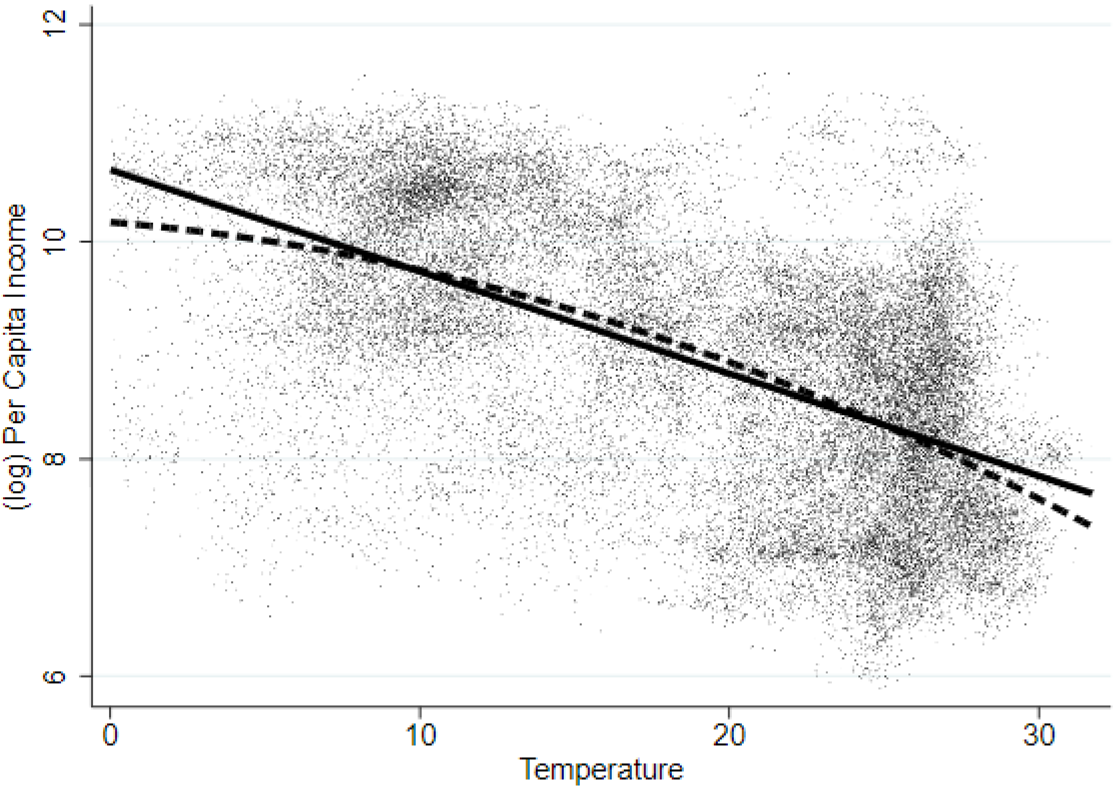

Figure 1: The Relationship between Regional Temperatures (in °C) and (log) Regional per Capita Income

IV. Panel Approach

Empirical Strategy Employing Regional Panel Data

We analyze the relationship between temperature and per capita income at the regional level by considering the following fixed effects model:

$$Income_{jit} = \beta_1 T_{jit-1} + \theta_j + \varphi_{it} + \epsilon_{jit} \quad (1)$$

Here, *Income* refers to the (logged) per capita income of region *j* in country *i* in year *t*. We are most interested in the coefficient β_1 reflecting the link between (logged) temperature (*T*) and (logged) regional per capita income.[5] Temperature is lagged by one period. We control for

[5] As we use the log of temperature as our explanatory variable, we drop all regions with a negative temperature; this concerns 20 regions (or about 1% of regions in the *Global Data Lab Dataset*) such as Alaska, Russian Siberia as well as parts of Northern Canada and Scandinavia. We do so because our main dependent (economic) variable is also logged. Especially in the long-run, this transformation will help us understand how *growth* in temperature affects *growth* in regional per capita income. As a robustness check, below we also use a non-logged temperature variable, showing that our interpretations are not affected by this transformation.

region-fixed effects (θ_j) to account for the role of time-invariant regional characteristics that may correlate with regional income and temperatures.[6] Furthermore, we control for time-fixed effects that are interacted with country-fixed effects (φ_{it}). The inclusion of these additional country-time-fixed effects allows us to control for year-specific effects such as global economic up- and downturns as well as country-specific time trends. Country-fixed effects alone do not enter our model as they are perfectly collinear with the region-fixed effects. To make statistical inferences, we always compute standard errors that are simultaneously clustered at the region- and parent-country level (Cameron et al., 2011).

Regarding endogeneity, an effect of regional income on regional temperatures can be plausibly excluded, as temperatures are affected by global anthropogenic and non-anthropogenic factors (e.g., volcanic eruptions). Therefore, it is reasonable to suppose β_1 in Eq. (1) is not affected by reverse causality. Moreover, regional temperature can plausibly be assumed to be *external* to the regional economy, that is, temperature at the regional level is reasonably regarded as given by economic and political actors. However, this does not imply that temperature is *exogenous* in an econometric sense (e.g., Deaton, 2010). While our fixed effects strategy captures *all regional time-invariant* influences (e.g., regional geographic conditions) through θ_j and *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 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 prevailing prior that temperature increases negatively affect many aspects of human life such as agriculture, health or political stability (e.g., 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 direct impact of higher temperature on regional per capita income. For example, if regional temperature is adversely related to political stability (e.g., Burke et al., 2015b), then not accounting for time-variant *regional* instability indicators 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 development.

[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).

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

We report our panel estimates in Table 2. In a setting where no fixed effects are considered (specification 1), we find that higher temperatures are negatively associated regional per capita income at statistically significant levels ($p<0.01$). Once we include the fixed effects (all other specifications), the relationship between temperature and regional income becomes statistically insignificant, with coefficient sizes becoming substantially smaller and approaching zero. Interpreting the coefficient for temperature in specification (2), a 10% increase in regional temperature (approximately 1.9 °C for the sample average), would be associated with a statistically insignificant increase in income per capita of about 0.05%, $CI_{95\%}$ = [-0.12%; 0.22%], holding all regional time-invariant and country-year specific conditions constant.

We observe a substantial increase in the goodness of fit (adjusted R^2) for the model when accounting for region- and country-time-fixed effects. This is the likely consequence of the inclusion of various fixed effects in our models. Still, a high R^2 could also indicate that our results are spurious, for example, because both the economic and climate data series are trending in similar ways. To assess this possibility, we always inspect the regression residuals for unit root presence; in case of spurious regression, the residuals would be non-stationary. Using the Fisher-type panel unit root test of Choi (2001), we reassuringly find that the regression residuals are always stationary, dispelling concerns about spurious regression.[7]

Numerous additional model specifications do not affect our conclusion that higher temperatures are *not* associated at statistically significant levels with lower regional income levels. The coefficient sizes remain close to zero. In detail and motivated by the literature, we present here nine alternative specifications.

[7] We use the test of Choi (2001) because it works for the kind of unbalanced panel data we use in this study. Other panel unit root tests require a balanced dataset. We therefore also run our analysis for a fully balanced panel (which covers 1,304 regions in 125 countries). We continue to find that higher temperatures are not associated with lower income levels in statistically significant ways. At the same time, we can now also inspect the associated regression residuals for non-stationary using more advanced panel unit root tests (which need balanced data) that are robust to heteroskedasticity and cross-sectional dependence. Reassuringly, the panel unit root tests of Herwartz and Siedenburg (2008) as well as Demetrescu and Hanck (2012) also tell us that the associated regression residuals are stationary.

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

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Model →	No Fixed Effects	Baseline Model	Rainfall as Control	Alternative Operationalization of Warming				Non-Linear Links	HDI as DV	Growth as DV	SSA Only
Temperature $_{t-1}$	-1.078***	0.005	0.004						0.019	-0.013	-0.218
	(0.141)	(0.009)	(0.009)						(0.089)	(0.011)	(0.255)
Precipitation $_{t-1}$			-0.003								
			(0.003)								
Temperature $_{t-0}$				0.009							
				(0.008)							
Maximum Temperature $_{t-1}$					-0.001						
					(0.002)						
Temperature Variation $_{t-1}$						-0.004					
						(0.004)					
Temperature (No Log) $_{t-1}$							-0.008				
							(0.005)				
Temperature (<17°C) $_{t-1}$								0.008			
								(0.007)			
Temperature (>17°C) $_{t-1}$								-0.201			
								(0.146)			
Region-Fixed Effects	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country*Year-Fixed Effects	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Panel Unit Root Test (p-value)	(0.00)***	(0.00)***	(0.00)***	(0.00)***	(0.00)***	(0.00)***	(0.00)***	(0.00)***	(0.00)***	(0.00)***	(0.00)***
Adjusted R^2	0.261	0.997	0.997	0.977	0.997	0.997	0.997	0.997	0.997	0.740	0.991
No. of Observations	38,807	38,807	38,807	38,807	38,807	38,807	38,807	38,807	38,807	38,417	10,007
No. of Regions	1,549	1,544	1,544	1544	1,544	1,544	1,539	1,544	1,544	1,536	431
No. of Countries	155	152	152	152	152	152	152	152	152	151	42

Notes: Dependent variable (DV) is (logged) regional per capita income, except in Models (10) and (11). H_0 of the Fisher-type panel unit root test: all panels contain unit roots. Standard errors clustered at the regional and country-year level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

First, Auffhammer et al. (2013: 188) argue that due to the correlation between temperature and *precipitation*, it may be advisable to account for both variables at the same time. Controlling for (logged) precipitation (drawing data from the *University of Delaware Air Temperature & Precipitation Dataset*), there is still no statistically significant relationship between regional temperature and income. The coefficient size of temperature is close to zero. Precipitation itself is also not a statistically relevant predictor.

Next, we consider alternative operationalization of warming, employing contemporaneous (rather than lagged) temperature (column 4); the maximum temperature per region-year observation to study whether changes in temperature extremes rather than average temperature matter (column 5); temperature variation indicated by the annual standard deviation of temperature calculated from monthly temperature data to explore the association of regional climate variability and income per capita (column 6); and temperature in absolute rather than logged form to evaluate whether data transformation matters (column 7). Regardless of which alternative measure we employ, we continue to find no statistically significant association between any of the measures and regional income. Coefficient sizes are always close to zero. In the Appendix (Section A1), we also study whether the use of alternative lag structures (e.g., by allowing for deeper lags of temperature) matters to our empirical conclusions. We do not find that temperature adversely affects regional income using a variety of lag structures.

We test for a non-linear link between temperature and income via the inclusion of an interacting threshold dummy variable that is equal to unity when mean regional temperatures are larger than 17°C.[10] Here, the idea is that temperature increases might be benign in moderate environments, while similar increases may create adverse effects (e.g., by curtailing plant growth) in environments with non-moderate temperatures (e.g., Deryugina and Hsiang 2014, Burke et al. 2015a, 2018; Li et al. 2019). We find no evidence in favor of a non-linear relationship between regional temperature and income.[11]

We use alternative measures of economic development, namely the regional *Human Development Index* (HDI) in column 9 the regional growth rate of income in column 10. Both variables are from the *Global Data Lab*. The sub-national HDI is a translation of the UNDP's

[10] Note that the threshold dummy itself is collinear with the fixed effects and will therefore not be reported.

[11] While we used a temperature threshold of 17°C, the empirical literature also suggests other temperature thresholds (e.g., Nordhaus, 2006; Deryugina and Hsiang, 2014; Burke et al., 2015a, 2018; Zhao et al., 2018; Li et al., 2019). We therefore consider various alternative thresholds in the Appendix (Section A2). The results are consistent with the notion that there is no statistically significant non-linear relationship between regional temperature and economic development.

official HDI to the regional level, accounting for education (years of schooling), health (life expectancy at birth) and income (see Permanyer and Smits, 2020 for a further discussion). We find no statistically robust evidence that temperature is related to any of these alternative economic outcomes.

Finally, estimate a model where we only focus on regions in Sub-Saharan African in column 11. These regions may be especially vulnerable to rising temperatures, for example, by nature of being located in already hot environments or due to the lack of resources to address potential challenges related to rising temperature. Again, however, the results show now statistically significant relationship between regional temperature and regional income, though the coefficient is negative and higher in absolute terms than for the full sample. Investigating a sample without regions from Sub-Saharan Africa would yield a statistically insignificant, positive coefficient for the association between temperature and income.

Discussion

Our panel approach provides no evidence that temperature is systematically and statistically significantly related to regional economic activity. That is, climate does not necessarily appear to determine (economic) destiny. Instead, our results indicate that time-invariant factors that likely correlate with the region-fixed effects (e.g., geographical characteristics) and country-time-variant factors (such as national economic policies) appear to affect regional economic development more prominently. This suggests that pathways of regional economic development are largely unrelated to regional temperature, at least in a panel setting that focuses on the short-run (annual) relationship between both variables.

Clearly, the absence of evidence does not mean evidence of absence of any link between regional temperature and per capita income. That is, climatic conditions may still be linked to regional economic activity. For instance, rather than through deviations from region-specific temperature means or increases in maximum temperatures and temperature variability, adverse economic effects may emerge through extreme weather conditions (e.g., weather-related disasters) which our empirical approach does not fully capture. Nevertheless, disregarding zero effects of (average) temperature, maximum temperature and temperature variability on regional economic development can be critical. Such information on absence of evidence may lead to an update of existing priors (Abadie, 2020), especially given a climate of opinion where priors regarding the effects of climate change on indicators of human well-being are predominantly negative. Our panel results challenge these 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 may, in turn, be expected to induce cumulative effects on nature and human behavior and, thus, economic outcomes. Such effects may materialize as *adaptation* or *intensification effects* (Dell et al., 2014).

Concerning adaptation effects, economic agents may not instantaneously adapt to changing climate conditions. One may also 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., after one particularly hot year) compared with the situation where temperatures do not revert to a stable long-run mean.

Concerning intensification effects, the full adverse effects of rising temperatures may not materialize instantaneously. Rather, effects compound over time. For example, because 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.

The presence of adaptation and intensification effects would imply that there may be differences between the short- and long-run estimates of regional temperatures on regional per capita income. For instance, if intensification effects matter in the long run, the long-term effects of regional warming on regional economic development may be more pronounced than its short-run effects. This, in turn, might explain the statistically insignificant relationship between temperature and regional income 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 income, we resort to the *long-difference approach* applied by Dell et al. (2012, 2014) and Burke and Emerick (2016).[12] This approach involves estimating the following model:

[12] For other approaches to differentiating short and long-run links between temperature and income, see for example, Deryugina and Hsiang (2017) or Lemoine (2021).

$$\overline{Income}_{ji2} - \overline{Income}_{ji1} = \alpha + \beta_1[\overline{T}_{ji2} - \overline{T}_{ji1}] + \varphi_i + \epsilon_{ji}. \tag{2}$$

Here, we first construct region-specific (logged) averages in per capita income and temperature between 1990 and 1993 (subscript 1) and between 2014 and 2017 (subscript 2). Then, we take the long-difference associated with these variables: that is, we subtract these averages from each other. This allows us to gauge the extent of regional economic development and warming between the early 1990s and mid-2010s.

Figure 2 illustrates that most regions indeed experienced some warming between the 1990-1993 and 2014-2017 periods, where the average regional level of warming was 0.78°C, which is consistent with recent IPCC reports (IPCC, 2014, 2021). Variation in temperature changes is, at the same time, substantial.

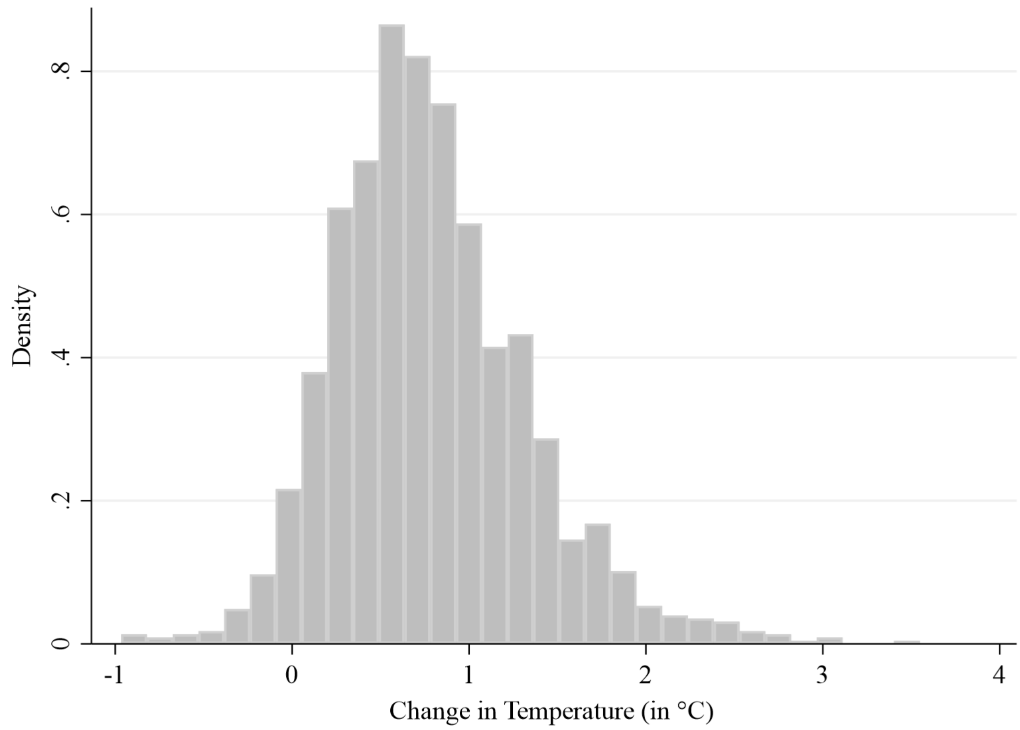

Figure 2: Histogram of Change in Temperature (1990-93 versus 2014-2017)

In general, estimating Eq. (2) allows us to evaluate how differences in temperature between 1990-1993 and 2014-2017 (which are indicative of non-mean-reverting warming) are related to differences in regional economic development over the same time periods. Importantly, our use of regional data still allows us to include a set of country-fixed effects (φ_i), thereby again improving on the cross-country literature. For instance, country-fixed effects account for initial country-wide temperature levels, that is, they account 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* (subscript 1) and the *late* (subscript 2) period. As the long-difference approach requires data for both the late and early period, we run this analysis for a subsample of approximately 1,300 regions in 125 countries. We compute heteroskedasticity-robust standard errors to make statistical inferences.

The long-difference approach complements our previous panel analysis, as also previously summarized by Dell et al. (2014) and Burke and Emerick (2016). For one, given that we estimate the economic effects of regional warming from long-run changes in average climate conditions rather than short-run annual variation (as we did in the panel approach), the long-difference approach is less susceptible to extreme (but mean-reverting) temperature events and more likely to capture a potential impact of (non-mean-reverting) climate change. Therefore, the long-difference approach is closer to identifying long-run relationships between temperature and income accounting for adaptation or intensification effects that only materialize over longer time horizons (e.g., Dell et al., 2014: 778). At the same time, we can directly compare how regional economic development is linked to short-run (panel approach) and long-run temperature variation (long-difference approach).[13] Thus, we can quantify whether long-run adjustment to rising temperatures (in terms of regional per capita GDP) is smaller (consistent with adaptation) or larger (consistent with intensification) than short-run adjustment (Dell et al., 2012, 2014; Burke and Emerick, 2016).

Empirical Results: No Relationship between Temperature and Income in Long-Run

Our long-difference estimates of Eq. (2) are reported in Table 3. Briefly summarized, the findings do not suggest that temperature increases between the 1990–1993 versus 2014–2017 periods are robustly associated with lower levels of regional income at conventional levels of statistical significance. Coefficient sizes for the change in regional temperate tend to be close to zero.

[13] This is because the long-difference approach in Eq. (2) is equivalent to the panel approach of Eq. (1), with the only difference between both approaches being that Eq. (1) is not expressed in years but in demi-decades. This correspondence between long-difference and panel approach allows us to compare the estimated link between temperature and income is also demonstrated in Dell et al. (2014: 778).

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

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Model →	Baseline Model	Rainfall as Control	Alternative Temperature Data			Non-Linear Links	Δ HDI as DV	SSA Only
Δ Temperature	0.014	0.014					-0.238	-1.259
	(0.109)	(0.110)					(1.013)	(0.833)
Δ Precipitation		-0.007						
		(0.039)						
Δ Maximum Temperature			-0.016*					
			(0.009)					
Δ Temperature Variation				-0.046				
				(0.030)				
Δ Temperature (No Log)					-0.023*			
					(0.013)			
Δ Temperature (<17°C)						0.019		
						(0.108)		
Δ Temperature (>17°C)						-0.013		
Country Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Period Dummy (Intercept)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.989
No. of Observations	1,288	1,288	1,288	1,288	1,304	1,288	1,288	227
No. of Regions	1,288	1,288	1,288	1,288	1,304	1,288	1,288	277
No. of Countries	125	125	125	125	125	125	125	31

Notes: Dependent variable (DV) is difference of the (logged) regional per capita income the early and late period (1990-1993 vs. 2014-2017), except in Model (7). Δ always refers to the difference between the early and late period (1990-1993 vs. 2014-2017). Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

When we control for rainfall (column 2), a change in regional temperature is positively but statistically insignificantly related with changes in regional incomes. When we use alternative temperature measures (columns 3-5), the positive temperature coefficient of columns (1) and (2) turns negative and statistically significant at the 10% level for the association between long-run increases in maximum temperatures and a non-logged temperature variable, respectively. For the change in temperature variation (column 4) no statistically significant relationship with changes in regional per capita income emerges. Similarly, there is no evidence for a non-linear relationship (column 6), and the regional HDI shows no robust relationship with long-differences in temperature (column 7). Finally, when focusing only on regions in Sub-Saharan Africa, we do not find evidence for a statistically robust negative relationship when employing the long-difference approach. Thus, the long-difference estimates speak to our panel estimates of Table 2 in that we find no robust evidence of a relationship of temperature shocks or increases in temperature, respectively, on regional economic outcomes.

VI. Heterogeneity in the Regional Temperature–Income relationship

Empirical Strategy to Explore Heterogeneity

The cross-country literature suggests that certain *country-specific conditions* may moderate the temperature–income relationship. Such conditions might also affect a region's vulnerability to rising temperatures. Most prominently, existing research suggests that a country's income level matters, where very poor countries may lack the adaptative capability to counter the adverse effects of weather shocks or warming and are thus expected to suffer more adverse economic effects (e.g., Dell et al., 2012, 2014; Burke et al., 2015a).

Below, we consider the role of country-specific economic, legal and political conditions in the short and long run to investigate potential heterogeneities in the temperature–income relationship. Here, we first consider a panel threshold-model of the following form:

$$Income_{jit} = \beta_1 T_{jit-1}(q_{it} < \gamma) + \beta_2 T_{jit-1}(q_{it} \geq \gamma) + \theta_j + \varphi_{it} + \epsilon_{jit} \quad (3)$$

In the long-difference setting, this model has the following form:

$$\overline{Income}_{ji2} - \overline{Income}_{ji1} = \beta_1\left[\overline{T}_{ji2} - \overline{T}_{ji1}\right](q_{it} < \gamma) + \beta_2\left[\overline{T}_{ji2} - \overline{T}_{ji1}\right](q_{it} \geq \gamma)$$
$$+\alpha + \varphi_i + \epsilon_{ji} \quad (4)$$

In both the short- and long-run case, the threshold model follows Hansen (1999). Here, the threshold parameter γ divides the respective equation into two regimes that describe the effect of temperature on income below and above the threshold. The threshold describes a structural break in the relationship between temperature and income; for instance, in poor countries (below a certain country-level income threshold) a potential link between rising temperatures and regional economic development might be more pronounced than in comparatively rich countries (above the income threshold). The exact value of γ is determined empirically following Hansen (1999). Testing for a threshold effect is the same as testing for the equality of coefficients between both regimes (i.e., to test whether $\beta_1=\beta_2$ for both equations). Rejecting the null hypothesis of equal coefficients would imply that the threshold approach is more informative than the non-threshold models estimated in Table 2 and 3.

Threshold Variables

We explore potential threshold country-specific variables that may account for differential associations between rising regional temperatures and regional per capita income in both the short- and long-run. These country-specific economic-legal and political variables may, in turn, be affected by rising temperatures and thus potentially be endogenous. For instance, Brückner and Ciccone (2011) find that changing weather conditions may foster democratic governance by lowering the opportunity cost of contesting autocratic power. To address such endogeneity concerns, we consider *initial* economic-legal and politico-institutional conditions (as averages over the 1980-1989 period) as threshold variables. In detail, we consider the following six variables:

1. ***Per capita GDP***: *Per capita GDP* at the country-level is drawn from the *World Development Indicators* (World Bank, 2021). Here, we speak to the idea that poorer countries and their regions may be more vulnerable to adverse consequences of global warming (e.g., Dell et al., 2012; Burke et al., 2015a). For instance, they may lack the resources to invest in technology (e.g., agricultural machinery) and public goods (e.g., levees) to counter potential unfavorable warming effects on their economies.
2. ***Democracy***: Democratic development is indicated by an index of *electoral democracy* from the *V-Dem Dataset* of Coppedge et al. (2021). Regions within non-democratic countries may be 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.

3. ***Civil Liberties***: An index of *equality before the law and individual liberty* from the *V-Dem Dataset* accounts for a broad range of political and legal-economic civil liberties (e.g., property rights protection, access to the justice system and freedom of movement). By accounting for legal and economic liberties, this variable is distinct from the democracy variable, reflecting the broader institutional framework that would allow economic agents to adequately respond to warming to mitigate its economic effects. For instance, sound legal and political institutions may encourage private (long-run) investment and innovation because they promote private contracting and provide checks against expropriation and other forms of predation (e.g., North, 1981; Acemoglu and Johnson, 2005). Investment and innovation, in turn, are potentially relevant 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.
4. ***Equality***: An index of *egalitarianism* from that the *V-Dem Dataset* considers the extent of equality of access to rights, freedoms, public goods and political power between different societal groups. Potentially, higher levels of equity reduce vulnerability to the adverse economic effects of rising temperatures by providing vulnerable segments of society (e.g., the poor) with resources (e.g., access to public health) to counter them.
5. ***Rural Exclusion***: Potential adverse economic consequences of warming could be more strongly felt in countries in which rural parts of the country are penalized. For example, when climate change threatens agricultural production, but a national politics prioritizes urban over rural areas, this may exacerbate related economic losses. We use an index of *rural exclusion* (accounting for, e.g., differences in political power and access to public goods between cities and rural areas) from the *V-Dem Dataset* to account for this idea.
6. ***Composite Measure***: Comparatively rich countries tend to be more democratic, while democratic countries, in turn, tend to promote equality and civil liberties. Thus, we also construct a *composite measure of sound economic and institutional starting conditions* by means of *principal component analysis*. Principal component analysis is used to reduce the dimensionality of a dataset with many interrelated variables, while retaining as much

information and variation as possible (e.g., Jolliffe, 2002). We extract the first principal component as our composite measure.[14]

In line with our discussion above and prevailing priors, we expect countries with relatively sound economic and institutional starting conditions to be less vulnerable to the adverse economic consequences of rising temperatures.

Empirical Results: Heterogeneity in the Short and Long Run

We report our panel threshold estimates in Table 4 and our long-difference threshold estimates in Table 5. For each threshold variable, we identify a likely threshold value following Hansen (1999). For instance, for the panel approach (Table 4) countries with a 1980-1989 per capita income below 994 US$ would be considered as relatively poor; this concerns 33 countries, mainly located in Sub-Saharan Africa and parts of Asia.

Estimating the panel threshold model, we do not find any heterogeneous link between temperature and regional per capita income (column 1, Table 4). For regions in poor countries the coefficient between temperature and income is positive, while it is negative for regions in rich countries. Both coefficients are close two zero and statistically not different from zero at conventional significance levels. They are also not statistically different from each other (row "Equality of Coefficients Test p-value").

All other panel threshold models (columns 2-6) yield similar interpretations: The estimated coefficients are not statistically significant and rather close to zero, suggesting no heterogeneity in the link between temperature and regional per capita income. Testing for the equality of coefficients below and above the various estimated thresholds, we also do not find threshold effects to matter. Thus, we find no evidence that regional temperatures affect regional economic development in the panel threshold approach, regardless of which threshold variable we consider. This provides indirect support for our more parsimonious panel models reported in Table 2.

[14] The factor loadings for the first principal component are 0.43 (per capita income), 0.46 (democracy), 0.45 (civil liberties), 0.43 (equality) and -0.46 (rural exclusion), implying that higher values of the composite measure correspond to higher income levels, stronger democratic development and civil liberties, more equal institutions and lower levels of rural exclusion. The Kaiser-Meyer-Olkin measure of sampling adequacy associated with the principal component analysis is 0.82, indicating that the results of the analysis are meritorious (e.g., Jolliffe, 2002).

Table 4: Panel Threshold Estimates

	(1)	(2)	(3)	(4)	(5)	(6)
Moderator →	Per Capita Income	Electoral Democracy	Civil Liberties	Equality	Rural Exclusion	Composite Measure
Interpretation when Moderator=1	Rich	Democratic	Relatively Free	Relatively Equal	Strong Rural Exclusion	Sound Starting Conditions
Temperature (Moderator=0) $_{t-1}$	0.042	0.029	0.012	-0.142	0.004	0.023
	(0.044)	(0.050)	(0.039)	(0.109)	(0.015)	(0.047)
Temperature (Moderator=1) $_{t-1}$	-0.052	-0.039	-0.050	0.019	-0.034	-0.038
	(0.036)	(0.029)	(0.036)	(0.026)	(0.049)	(0.033)
[Equality of Coefficients Test p-value]	[0.10]	[0.25]	[0.24]	[0.16]	[0.45]	[0.30]
Threshold Estimate	994$	0.15	0.38	0.41	0.19	-1.39
Region-Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Country*Year-Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.996	0.996	0.996	0.997	0.996	0.996
No. of Observations	29,943	32,535	32,535	32,535	31,995	29,079
No. of Regions	1,109	1,205	1,205	1,205	1,185	1,077
No. of Countries	102	112	112	112	111	98

Notes: Dependent variable is (logged) per capita income. Threshold estimates for Models (2) to (5) refer to values of respective index. Standard errors clustered at the regional and country-year level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 5: Long-Difference Threshold Estimates

	(1)	(2)	(3)	(4)	(5)	(6)
Moderator (=Threshold Variable) →	Per Capita Income	Electoral Democracy	Civil Liberties	Equality	Rural Exclusion	Composite Measure
Interpretation when Moderator=1	Rich	Democratic	Relatively Free	Relatively Equal	Strong Rural Exclusion	Sound Starting Conditions
Δ Temperature (Moderator=0)	-0.462	-0.161	-0.190*	-1.144***	0.097	-1.088**
	(0.371)	(0.101)	(0.106)	(0.412)	(0.092)	(0.488)
Δ Temperature (Moderator=1)	-0.070	0.153	0.154	0.122	-1.196**	-0.060
	(0.104)	(0.098)	(0.095)	(0.086)	(0.581)	(0.114)
[Equality of Coefficients Test p-value]	[0.31]	[0.02]**	[0.01]**	[0.00]***	[0.02]**	[0.04]**
Threshold Estimate	1,663$	0.25	0.32	0.40	0.66	-1.57
Country Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Period Dummy (Intercept)	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.995	0.996	0.996	0.996	0.996	0.995
No. of Observations	1,118	1,216	1,216	1,216	1,196	1,084
No. of Regions	1,118	1,216	1,216	1,216	1,196	1,084
No. of Countries	104	113	113	113	112	99

Notes: Dependent variable (DV) is difference of the (logged) per capita income between the early and late period (1990-1993 vs. 2014-2017). Δ refers to the difference between the early and late period (1990-1993 vs. 2014-2017). Threshold estimates for Models (2) to (5) refer to values of respective index. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

In Table 5, we consider heterogeneity in the temperature–income relationship in the long run. We do not find any statistically significant heterogeneity in the long-run link between regional temperature and income for regions in poor vs. rich countries (column 1) and democratic vs. not democratic countries (column 2). Still, some heterogenous relationships emerge: We find evidence that temperature is associated with long-run regional economic development in countries with relatively poor (initial) economic-legal and political conditions, characterized by relatively weak civil liberties (column 3), low levels of equality (column 4), strong rural exclusion (column 5) as well as less sound starting conditions in general (column 6). By contrast, for regions in countries that have strong (initial) civil liberties, high levels of equality, weak rural exclusion and sound starting conditions no statistically significant relationship between temperature and per capita income emerges in the long run. Our long-difference threshold estimates suggest that the adverse effects of temperature increases concern 350 regions in 17 countries such as Haiti, Laos, Nepal and the Democratic Republic of the Congo. For regions in these countries, we find that a 10% increase in temperature is associated with a decrease in per capita income by approximately 10.9%, $CI_{95\%}$ = [-1.3%; -20.5%] for the time period considered according to column (6). For the remainder of the sample of regions in 82 countries, temperature is not found to sway regional economic development in the long run in statistically meaningful ways.

As argued by Dell et al. (2012, 2014), the long-difference estimated can be interpreted as capturing the influence of adaptation or intensification effects. According to this interpretation, our findings suggest that for most regions, neither adaptation nor intensification are identifiable. However, for regions within especially vulnerable countries, intensification effects (where the long-difference estimates are more pronounced than their panel counterparts) appear to matter. For instance, this may point to the role of rising temperatures in hurting agricultural development in the long run when weak institutions do not sufficiently incentivize investment, innovation and other forms of adaptation.[15] At the same time, it is important to note that long-run changes in temperature may be linked to a variety of unobservables that could be relevant to regional economic development. That is, if higher temperatures negatively affect other unobserved factors (e.g., political stability) which, in turn, affect regional income, our estimates for regions in countries with initially unfavorable economic and institutional conditions may

[15] We further study the role of agriculture in the temperature-income relationship by considering agricultural and industrial development as potential threshold variables (see Appendix, Section A3). We find weak support that higher temperatures especially hurt regions in weakly industrialized countries. There is no evidence of heterogeneity using a panel approach.

presents an upper bound of the negative long-run impact of warming in regions in vulnerable countries.

VII. Use of Alternative Economic Data from 1950 to 2014

We use an alternative dataset on regional economic development by Gennaioli et al. (2014) to cross-validate our main empirical findings. Drawing from national and regional statistical offices, Gennaioli et al. (2014) report regional economic activity as *regional per capita GDP*.[16] For their dataset, "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."

The dataset of Gennaioli et al. (2014) allows us to consider 1,446 regions in 81 countries between 1950 and 2014. Thus, we extend the time dimension of the data, while the number of countries is reduced. The economic data are not observed annually. We therefore 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, potentially making it more likely to uncover – given the longer time horizon – unfavorable long-run effects of rising temperatures. On average, we observe approximately six five-year periods per region (see also Gennaioli et al., 2014: 268-270). While the data of Gennaioli et al. (2014) covers more than 90% of the world's GDP (including many countries in Asia, Oceania, the Americas and Europe), African countries are underrepresented in the dataset. The list of countries in the appendix reports the exact country coverage.

For our empirical analysis, we proceed as follows: First, we study the relationship between temperatures and regional per capita GDP in an unbalanced panel setting.

[16] To make the data comparable between regions and countries, Gennaioli et al. (2014) provide per capita GDP data in constant 2005 purchasing power parity dollars. For further information on their methods, we refer to Gennaioli et al. (2014) and the online appendix to Gennaioli et al. (2014).

Table 6: Use of Alternative Economic Data from 1950 to 2014:
Temperatures and Regional per Capita GDP in the short and long-run

	(1)	(2)	(3)	(4)	(5)	(6)
	Panel Approach			Long-Difference Approach		
Model and Data →	Regional per Capita GDP			Δ Regional per Capita GDP		
Temperature	-0.028		-0.033			
	(0.030)		(0.047)			
Temperature (Moderator=0)		-0.038				
		(0.055)				
Temperature (Moderator=1)		-0.013				
		(0.034)				
Δ Temperature				-0.097		-0.078
				(0.062)		(0.082)
Δ Temperature (Moderator=0)					-0.185***	
					(0.049)	
Δ Temperature (Moderator=1)					0.125	
					(0.138)	
[Equality of Coefficients Test p-value]		[0.70]			[0.03]**	
Region-Fixed Effects	Yes	Yes	Yes			
Country*Period-Fixed Effects	Yes	Yes	Yes			
Country Dummies				Yes	Yes	Yes
Period Dummy (Intercept)				Yes	Yes	Yes
Adjusted R^2	0.982	0.984	0.984	0.981	0.988	0.988
No. of Observations	8,793	7,537	7,537	675	560	560
No. of Regions	1,446	1,133	1,133	675	560	560
No. of Countries	81	61	61	81	67	67

Notes: Dependent variable (DV) is (logged) regional per capita GDP. Δ always refers to the difference between the early and late period (1960-1980 vs. 1990-2010). “Moderator” refers to composite measure measuring economic and institutional conditions for the 1980-1989 period as described in the main text, where “Moderator=1” refers to sound conditions. Standard errors clustered at the regional and country-year level in parentheses for Models (1) to (3). Robust standard errors in parentheses for Models (4) to (6). *** p<0.01, ** p<0.05, * p<0.1.

Second, we allow for heterogeneous effects by amending our panel model with a moderator variable that is equal to unity when economic and institutional conditions are sound and zero otherwise. Practically, we use the composite measure (from a PCA analysis) of the soundness of country-specific economic and institutional circumstances (with respect to per capita income, democracy, equality etc.) that we constructed above as the moderator variable. Given that the country-specific data is not available for all countries, when studying heterogeneous effects, the sample shrinks. We therefore also report the homogenous panel estimates for a reduced sample to make sure that our results are not driven by sampling effects. Third, we test for the presence of both homogenous and heterogeneous effects of temperature changes on regional GDP per capita changes in a long-difference setting. To maximize coverage, in the long-difference setting the early period is the 1960-1980 period, which is compared (by means of taking the long-difference) to the late period of 1990-2010.

We report our results in Table 6. We find that higher temperatures are not associated with lower per capita GDP levels both in the homogenous and heterogeneous panel setting (columns 1, 2 and 3). In the long-difference approach, temperature increases are not associated to changes in regional per capita GDP (columns 4 and 6). However, we observe a negative and statistically significant association between temperature and per capita GDP in the long run for regions within in countries with comparatively weak economic and institutional country-specific conditions. Thus, all empirical conclusions based on the Gennaioli et al. (2014) data match our previously shown findings employing the *Global Data Lab Dataset*.

VIII. EXPLORING LONG-RUN TRANSMISSION CHANNELS

Finally, we explore potential mechanisms through which higher temperatures may hurt regional economic development in the long run. We focus on three potential mechanisms: (1) regional population size, (2) regional levels of education (in years of schooling) and (3) regional health (measured as life expectancy at birth). All three variables come from the *Global Data Lab Dataset*.

Table 7: Exploration of Transmission Channels

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable →	Δ Population		Δ Mean Years of Schooling		Δ Life Expectancy at Birth	
Δ Temperature	0.006		-0.203		0.364	
	(0.129)		(0.195)		(1.155)	
Δ Temperature (Moderator=0)		-1.232**		-4.506***		1.351
		(0.610)		(1.405)		(7.110)
Δ Temperature (Moderator=1)		0.108		-0.067		1.682
		(0.160)		(0.349)		(1.941)
[Equality of Coefficients Test p-value]		[0.03]**		[0.00]***		[0.96]
Country Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Period Dummy (Intercept)	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.993	0.993	0.994	0.994	0.989	0.988
No. of Observations	1,282	1,084	1,288	1,084	1,288	1,084
No. of Regions	1,282	1,084	1,288	1,084	1,288	1,084
No. of Countries	124	99	125	99	125	99

Notes: Δ always refers to the difference between the early and late period (1990-1993 vs. 2014-2017). "Moderator" refers to composite measure measuring economic and institutional conditions for the 1980-1989 period as described in the main text, where "Moderator=1" refers to sound conditions. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

For one, higher temperatures may adversely affect regional population growth, e.g., by influencing fertility decisions or inducing out-migration (e.g., Lam and Miron, 1996; Beine and Parsons, 2015; Berlemann and Steinhardt, 2017; Barreca et al., 2018; Sellers and Gray, 2019; Meierrieks and Helbling, 2021). For another, higher temperatures may depress human capital (education and health) by contributing to the spread of diseases or malnutrition (e.g., Barreca, 2012; Deschênes, 2014; Zivin and Shrader, 2016; Zivin et al, 2018; Meierrieks, 2021; Park, 2022). The reduction in the availability of (skilled and healthy) human labor due to rising temperatures may, in turn, reduce regional economic development (e.g., Weil, 2013; Gennaioli et al., 2013, 2014).

There are two caveats to this exploration of transmission channels. First, we use specific indicators of population and human capital development as provided by the *Global Data Lab*. Other variables measuring, e.g., urbanization, tertiary education or child mortality may exhibit a different relationship with rising temperatures, while also sharing additional links with regional economic development. Second, our exploration of potential transmission channels does not – again, due to data constraints – account for further potential transmission channels from rising temperatures to reduced regional economic activity. For instance, this includes regional measures of political instability, resource scarcity, labor productivity or agricultural production. Indeed, there is ample evidence that these variables also matter as transmission variables to the temperature–income nexus (e.g., Schlenker and Lobell, 2010; Dell et al., 2012, 2014; Burke et al., 2015b; Carter et al., 2018).

Bearing these caveats in mind, the results in Table 7 show that higher temperatures do not have a uniform and statistically significant association with the three potential transmission channels in the long run (columns 1, 3, 5). However, higher temperatures are negatively associated with population size and education in those regions within countries characterized by poor initial economic-legal and political conditions (columns 2 and 4); there are no comparable associations for human health measured by life expectancy (column 6). Again, these findings are in line with earlier results in that we find that higher temperatures are only associated with potential drivers of economic development precisely in those regions for which we also find higher temperatures being negatively associated regional economic development in the long run.

IX. 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 income using annual sub-national data for over 1,500 regions in 155 countries between 1990 and 2017.

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 per capita income. Various sensitivity checks (e.g., concerning the measurement of regional climatic and economic conditions) support this finding. There is also no evidence for a curvilinear (inverse-U) relationship between regional temperature and per capita income. Second, we employ a long-difference approach that is more attuned to exploring the long-run relationship between rising temperatures and regional economic activity. Relying on this approach, we also find no robust evidence that rising temperatures correlate with lower per capita income levels in the long run. Third, we use short- and long-run threshold-approaches to detect heterogeneous effects with respect to the temperature–income relationship. We show that for a minority of regions located within countries with weak economic-legal and political institutions (characterized by weak property rights, insufficient access to legal institutions and public goods, weak civil liberties etc.), rising temperatures are negatively associated with regional per capita income in the long run. All our findings hold when using an alternative dataset starting that covers the 1950-2010 period and reports alternative regional income data.

Our results can be interpreted as being consistent with the prevalence of intensification effects, implying that the adverse economic consequences of temperature may compound and become more noticeable over time especially in vulnerable economies. Thus, country-specific conditions may crucially moderate regional economic vulnerability to climate change, for example, by affecting mitigation and adaptation strategies. Within vulnerable countries rising temperatures may curtail long-run regional population and human capital development as potentially important transmission channels from rising temperatures to lower per capita income levels.

In sum, our findings point to a nuanced relationship between regional temperature increases and regional economic development. This may lead to an update of existing priors concerning the economic consequences of climate change (Abadie, 2020), while also inviting future research that accounts for the short- and long-run as well as moderating effects of temperature on other economic outcomes. For one, our main dataset starts in 1990. It may be fruitful to move to regional economic data from the 1960s, 1970s and 1980s once such data becomes available, as this may make it more likely to capture the full association of long-run climate change and regional economic development. Our use of data by Gennaioli et al. (2014) starting in 1950 already explore this direction, but this dataset does not cover many regions in Africa for which the economic effects of warming could be more pronounced. Furthermore, future research may investigate the role of other economic and politico-institutional factors in moderating the temperature–income relationship at the regional level. For instance, this research may account for the roles of trade and other forms of international exchange or of differences in the division of political power between regional and central governments. Finally, when we investigate heterogeneous effects in the temperature–income nexus, we employ variables measuring initial economic, legal and political conditions in the 1980s to ameliorate endogeneity concerns regarding the potential role of climatic conditions in institutional development. Still, one may argue that this does not fully solve the underlying simultaneous equation issue, which consequently invites the use of more elaborate empirical methods in the future such as instrumental-variable threshold models (e.g., Caner and Hansen, 2004).

Global warming and climate change are projected to continue for the coming decades (IPCC, 2014, 2021). Our study suggests that rising temperatures have been – for the moment – particularly relevant to regions located in countries that may be considered especially vulnerable, that is, countries that exhibit weak political and economic institutions. This finding matters for economic models of climate change (see also Tol 2021). At the same time, it suggests that the vulnerability to higher temperatures is not constant, which has relevant public policy consequences. For instance, efforts to improve institutional performance at the country-level can help to reduce economic vulnerability to potential negative regional economic effects of warming. Importantly, such efforts can be pursued independently of and in addition to global efforts to reduce greenhouse gas emissions. At the same time, our study is by no means meant as encouragement for “climate change skepticism”. That is, we want to emphasize that potential adverse effects of higher temperatures on sub-national per capita income could take further decades to fully materialize; furthermore, adverse economic effects could become more pronounced if future climate change is more rapid and impactful.

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APPENDIX

List of Countries

Afghanistan	Dominican Republic	Lesotho*	Serbia*
Albania*	Ecuador*	Liberia	Sierra Leone
Algeria	Egypt*	Libya	Slovakia*
Angola	El Salvador*	Lithuania*	Slovenia*
Argentina*	Equatorial Guinea	Madagascar	Somalia
Armenia	Eritrea	Malawi	South Africa*
Australia*	Estonia*	Malaysia*	South Korea*
Austria*	Eswatini	Mali	South Sudan
Azerbaijan	Ethiopia	Mauritania	Spain*
Bangladesh*	Finland*	Mauritius	Sudan
Belarus	France*	Mexico*	Suriname
Belgium*	Gabon	Moldova	Sweden*
Belize	Gambia	Mongolia*	Switzerland*
Benin*	Georgia	Montenegro	Syria
Bhutan	Germany*	Morocco*	Tajikistan
Bolivia*	Ghana	Mozambique*	Tanzania*
Bosnia & Herzegovina	Greece*	Myanmar	Thailand*
Botswana	Guatemala*	Namibia	Timor Leste
Brazil*	Guinea	Nepal*	Togo
Bulgaria*	Guinea Bissau	Netherlands*	Trinidad & Tobago
Burkina Faso	Guyana	New Zealand	Tunisia
Burundi	Haiti	Nicaragua*	Turkey*
Cambodia	Honduras*	Niger	Turkmenistan
Cameroon	Hungary*	Nigeria*	Uganda
Canada*	India*	North Macedonia*	Ukraine*
Central African Republic	Indonesia*	Norway*	United Kingdom*
Chad	Iran*	Pakistan*	United States*
Chile*	Iraq	Palestine	Uruguay*
China*	Ireland*	Panama*	Uzbekistan*
Colombia*	Italy*	Papua New Guinea	Vanuatu
Comoros	Jamaica	Paraguay*	Venezuela*
Congo (Brazzaville)	Japan*	Peru*	Vietnam*
Congo (DR)	Jordan*	Philippines*	Yemen
Costa Rica	Kazakhstan*	Poland*	Zambia
Cote d'Ivoire	Kenya*	Portugal*	Zimbabwe
Croatia*	Kuwait	Romania*	
Cuba	Kyrgyzstan*	Russian Federation*	
Czech Republic*	Lao	Rwanda	
Denmark*	Latvia*	Saudi Arabia	
Djibouti	Lebanon	Senegal	

Note: (*) indicates that this country is also included in the dataset of Gennaioli et al. (2014). This dataset also includes the countries of Sri Lanka and the United Arab Emirates that are not included in the *Global Data Lab Dataset*.

A1. Alternative and More Complex Lag Structures

In Table 2, we predict regional per capita income by regional temperature in the previous year (i.e., at *t-1*). In Table 2, column (4) we look at contemporaneous temperature. Inspired by Dell et al. (2012), we consider whether alternative and more complex lag structures yield different results in Table A2. For instance, such lag structures may allow us to consider whether potential adverse economic effects of rising temperatures materialize only after some years or whether these unfavorable effects cumulate over time.

We proceed as follows. First, we run models where regional per capita income is explained separately by contemporaneous regional temperature or by regional temperature at *t-2*, *t-3*, *t-4* and *t-5*, respectively. Second, we allow for cumulative effects, e.g., by predicting regional per capita income by regional temperature at *t-0* to *t-5*.

As reported in Table A2, all coefficient estimates are never statistically significant both individually and jointly. Thus, line with our main results reported in Table 2, our analysis provides no evidence that increasing temperatures at the regional level are associated with higher or lower per capita income, regardless of which lag structure we employ.

Table A1: Panel Estimates of the Link between Temperature and Regional Income: Alternative Lag Structures

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Temperature $_{t-0}$	0.004					-0.003	-0.001	-0.006	-0.012	-0.010
	(0.009)					(0.009)	(0.011)	(0.010)	(0.012)	(0.011)
Temperature $_{t-1}$						-0.000	-0.005	-0.002	-0.003	-0.009
						(0.010)	(0.007)	(0.008)	(0.009)	(0.011)
Temperature $_{t-2}$		0.000					-0.004	-0.011	-0.007	-0.006
		(0.010)					(0.014)	(0.011)	(0.012)	(0.012)
Temperature $_{t-3}$			-0.003					-0.007	-0.012	-0.008
			(0.010)					(0.015)	(0.012)	(0.012)
Temperature $_{t-4}$				-0.006					-0.013	-0.014
				(0.010)					(0.018)	(0.015)
Temperature $_{t-5}$					-0.013					-0.028
					(0.010)					(0.018)
[Cumulative Effect]						[-0.003]	[-0.010]	[-0.027]	[-0.045]	[-0.076]
[Standard Error]						[0.018]	[0.029]	[0.039]	[0.052]	[0.065]
Region-Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country*Year-Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997
No. of Observations	40,108	37,507	36,204	34,907	33,609	38,741	37,411	36,086	34,774	33,466
No. of Regions	1,544	1,544	1,543	1,543	1,543	1,539	1,538	1,535	1,534	1,532
No. of Countries	152	152	152	152	152	152	152	152	152	151

Notes: Dependent variable (DV) is (logged) regional per capita income as described in the text. Standard errors clustered at the regional and country-year level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

A2. Further Examination of Non-Linearities in the Temperature–income Relationship

In Table 2, specification 8, we tested for the presence of a non-linear relationship between regional temperature and income by considering a 17°C threshold. We found no evidence in favor of a non-linear relationship between the two variables. As a robustness check, we explore potential non-linearities by considering various further temperature thresholds. Here, we follow other results from the empirical 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, 21 and 24°C, respectively.

Table A2: The Link between Temperature and Regional Income: Alternative Temperature Thresholds

	(1)	(2)	(3)	(7)
Temperature Threshold →	9°C	13°C	21°C	24°C
Temperature (<Threshold) $_{t-1}$	0.008	0.007	0.005	0.007
	(0.007)	(0.008)	(0.008)	(0.008)
Temperature (>Threshold) $_{t-1}$	-0.083	-0.124	-0.053	-0.325
	(0.050)	(0.092)	(0.202)	(0.219)
Region-Fixed Effects	Yes	Yes	Yes	Yes
Country*Year-Fixed Effects	Yes	Yes	Yes	Yes
Adjusted R^2	0.997	0.997	0.997	0.997
No. of Observations	38,807	38,807	38,807	38,807
No. of Regions	1,544	1,544	1,544	1,544
No. of Countries	152	152	152	152

Notes: Dependent variable (DV) is (logged) regional per capita income as described in the text. Standard errors clustered at the regional and country-year level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

As reported in Table A2, higher temperatures are not associated with economic activity below and above the various temperature thresholds in statistically significant ways. That is, in line with our main results reported in Table 2, there is no evidence for non-linear links between increasing temperatures and per capita income at the regional level.

A3. Role of Agriculture and Manufacturing

For our baseline approach, we consider a variety of economic, legal and politico-institutional variables as potential threshold variables, that is, moderators accounting for potential heterogeneity in the temperature–income relationship in the short and long run. As an extension, we also investigate whether a country's economic and industrial structure matter. For instance, higher temperatures might depress economic output by hurting agricultural production. This would imply that a stronger dependence on agriculture (a lower dependence on manufacturing) could increase a country's economic vulnerability to rising temperatures.

Table A3: Role of Agriculture and Manufacturing

	(1)	(2)	(3)	(4)
	Panel Approach		Long-difference approach	
Moderator →	Agriculture	Manufacturing	Agriculture	Manufacturing
Temperature (Moderator=0) $_{t-1}$	-0.117	-0.017		
	(0.090)	(0.033)		
Temperature (Moderator=1) $_{t-1}$	0.012	-0.132		
	(0.044)	(0.097)		
Δ Temperature (Moderator=0)			-0.083	-1.249*
			(0.122)	(0.657)
Δ Temperature (Moderator=1)			-0.629	-0.136
			(0.395)	(0.134)
[Equality of Coefficients Test p-value]	[0.20]	[0.26]	[0.19]	[0.09]*
Threshold Estimate	10.02	15.81	20.56	7.76
Region-Fixed Effects	Yes	Yes		
Country*Period-Fixed Effects	Yes	Yes		
Country Dummies			Yes	Yes
Period Dummy (Intercept)			Yes	Yes
Adjusted R^2	0.994	0.995	0.993	0.994
No. of Observations	23,328	21,060	873	787
No. of Regions	864	780	873	787
No. of Countries	80	72	82	73

Notes: Dependent variable (DV) is (logged) per capita income in Models (1) and (2) and Δ (logged) per capita income in Models (3) and (4). Δ always refers to the difference between the early and late period (1990-1993 vs. 2014-2017). "Agriculture" is the value added (as a share of GDP) from agriculture, forestry and fishing, while "Manufacturing" is the value added (as a share of GDP) from manufacturing. The threshold estimates refer to these shares. For both variables, "Moderator=1" refers to a relatively large agricultural or manufacturing sector in the country of interest, respectively. Standard errors clustered at the regional and country-year level in parentheses for Models (1) and (2). Robust standard errors in parentheses for Models (3) and (4). *** p<0.01, ** p<0.05, * p<0.1.

Using our usual short- and long-run threshold approaches, we consider the role of a country's agriculture (measured as the value added by agriculture as a share of GDP) and manufacturing (indicated by the value added by manufacturing as a share of GDP) in the regional temperature–income nexus. Data on country-specific agricultural and industrial development comes from the *World Development Indicators*. Note that due to data availability we can only consider between 70 and 80 countries rather than the 100 to 110 in our baseline threshold analyses.

As shown in Table A3, the link between temperature and regional economic activity does not differ between low and high country-specific levels of agricultural or industrial development in the panel setting. In the long-difference setting, there is some (statistically rather weak) evidence that higher temperatures reduce regional economic development when manufacturing plays no strong role in the country of interest. These findings thus tend to speak to our results that temperature increases may only matter to regional income in the long run and to regions in more vulnerable countries.