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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

Daniel Meierrieks [a], David Stadelmann [b,*]

[a] WZB Berlin Social Science Center, Reichpietschufer 50, 10785 Berlin, Germany
[b] University of Bayreuth, Universitätsstraße 30, 95447 Bayreuth, Germany

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A B S T R A C T

We examine the effect of rising temperatures on regional economic development, using annual sub-national data for over 1500 regions in 152 countries between 1990 and 2017. In a panel setting with region- and country-year 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. Additionally, we find no non-linear relationship between temperature and economic development. We also employ a long-difference approach that is attuned to exploring the long-run relationship between rising temperatures and regional income. Results indicate that rising temperatures have a negative long-run impact on regional per capita income for a minority of regions located in countries with weak economic, legal and political institutions. Furthermore, these vulnerable regions experience a decline in long-term population and human capital development. The use of alternative regional per capita GDP data from 1950 onwards yields similar empirical results. Our findings suggest that negative economic effects of temperature increase with time, only becoming apparent in the long run for regions in already disadvantaged countries. Thus, country-specific conditions may moderate regional economic vulnerability to future temperature increases due to global climate change.

## 1. Introduction

Over the past 200 years, per capita gross domestic product in most of the Western world has increased more than twenty-fivefold, while in much of the non-Western world it has grown more than tenfold (e.g., Deaton, 2013; Bolt and van Zanden, 2024). This economic development, in turn, was associated with improvements in human living standards and well-being, for example, in the form of higher life expectancy, reduced child mortality and lower malnutrition (e.g., 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, on average, 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 a recent 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 fuel resource scarcity and subsequent political instability, especially in already more vulnerable parts of the world (IPCC, 2014). Consequently, global climate change is also expected to adversely affect global economic pathways. For instance, in a 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 […]".

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* Corresponding author.

*E-mail addresses:* daniel.meierrieks@wzb.eu (D. Meierrieks), david.stadelmann@uni-bayreuth.de (D. Stadelmann).

[1] Global climate change 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).

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We contribute to the exploration of the adverse economic effects of global temperature rises by studying the relationship between rising temperatures and per capita levels of economic development with regional (i.e., sub-national) data for over 1500 regions in 152 countries between 1990 and 2017 and with an alternative economic dataset form 1950 onwards for robustness tests. The existing research on the nexus between temperature increases and economic outcomes at the sub-national level remains limited and inconclusive regarding statistical significance (e.g., Nordhaus, 2006; Dell et al., 2009; Zhao et al., 2018; Kalkuhl and Wenz, 2020; Greßer et al., 2021; Kahn et al., 2021; Kotz et al., 2024). 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 some 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). 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 key findings are as follows. First, after controlling for various fixed effects, we do not find a consistent and statistically significant relationship between regional temperature and regional per capita income in our panel analysis. Second, in the long-difference analysis, which captures long-term linkages, there is no statistically significant relationship between rising temperatures and changing income levels when analyzing the whole sample of countries. Third, we do not observe a non-linear relationship between temperature and economic development in the short or long run. All these results do not speak to the prevalence of adaptation or intensification effects that matter to *all* regions in our sample. Fourth, in a threshold approach that considers heterogeneity in the temperature-income relationship, we find no evidence of threshold effects in the short run (fixed-effects panel approach) but do detect them in the long run (long-difference approach). The long-run results support the idea that temperature increases are negatively related to regional economic development only within countries with weak economic-legal and political institutions, leading to intensification effects that reduce long-term regional economic development. Fifth, our findings are robust to alternative operationalizations of regional economic development and warming. Moreover, they also hold when using an alternative economic dataset starting in 1950. Finally, we provide evidence that rising temperatures may be negatively related long-term regional population and education levels within countries with weak economic-legal and political institutions.

Previous research on the determinants of differences in regional economic performance has emphasized the role of within-country differences in, inter alia, geography, human capital (health and education), urban development, entrepreneurial inputs and investment (e.g., Gennaioli et al., 2013, 2014; Cuaresma et al., 2014; Mitton, 2016; Jetter et al., 2019). Given our main empirical findings, we show that regional economic disparities can also emerge from the (long-term) local impacts of global warming especially when accounting for heterogeneity due to country-level differences in economic and institutional vulnerability. This vulnerability emerges as a crucial moderating factor regarding the long-term temperature-income relationship according to our results.

This paper is organized as follows. Section 2 discusses the related literature, while Section 3 describes our regional economic and climate data. Section 4 analyzes the temperature-income relationship using a panel approach. In Section 5 we present findings from a long-difference approach. Section 6 explores short- and long-run heterogeneity in the temperature-income relationship, while Section 7 provides additional robustness checks and empirical extensions. Section 8 explores potential long-run transmission channels. Section 9 concludes.

## 2. Theory and literature overview

### 2.1. The temperature-income nexus: Theoretical mechanisms

The literature suggests that higher temperatures could *depress* economic activity through several 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; Letta and Tol, 2019), for example, due to increased heat stress especially if cooling technology such as air conditioning cannot be employed. 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 as increasing temperatures constrain human capital accumulation.

Finally, 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.

### *2.2. Empirical evidence on the temperature-income nexus*

Given these theoretical mechanisms, a negative association between higher temperatures and aggregate economic outcomes is the prevailing prior (e.g., Tol, 2009; Carleton and Hsiang, 2016).[2] Indeed, this prior is mostly consistent with recent empirical studies that suggest that warming may hurt economic performance and is expected to continue to do so as climate change intensifies, especially in already poor and already relatively hot countries. For one, this pertains to empirical studies conducted at the cross-country level (e.g., Tol, 2009; Hsiang, 2010a, 2010b; Dell et al., 2012; Lanzafame, 2014; Burke et al., 2015a, 2018; Letta and Tol, 2019; Kahn et al., 2021). For instance, using a panel of countries from 1960 to 2006, Letta and Tol (2019) show that annual increases in temperature may reduce total factor productivity growth in poor countries, while having no effect in rich countries. For another, studies that examine the relationship between temperature and *economic growth* within sufficiently large countries tend to come to similar conclusions, e.g., in the cases of China (e.g., Li et al., 2019) or the United States (e.g., Deryugina and Hsiang, 2014; Colacito et al., 2019; Mohaddes et al., 2023). For instance, Mohaddes et al. (2023) analyze the case of 48 U.S. states from 1963 to 2016. They find that climate change has an adverse effect on economic outcomes (e.g., productivity and output) in various U.S. states and economic sectors.

More closely related to our study, a smaller body of empirical research investigates 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), Kalkuhl and Wenz (2020), Greßer et al. (2021) and Kotz et al. (2024). The evidence concerning the temperature–income 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 7500 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. 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. Similarly, 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 significant way. By contrast Kotz et al. (2024) use data for over 1600 regions over 40 years, projecting that the world economy will experience a 19% reduction in income until 2050 independent of future emission choices relative to a world without a temperature increase.

## 3. Data

### *3.1. 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 $\text{km}^2$ 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 1544 regions in 152 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.

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 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).

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[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 can, up to a point, *decrease* mortality.

[3] The dataset and information on the methodology can be found at https://globaldatalab.org/ (accessed May 1, 2024).

[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 May 1, 2024).

**Table 1**
Summary Statistics.

| Variable | N*T | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| Regional per Capita Income (logged) | 40,108 | 8.88 | 1.206 | 5.887 | 11.55 |
| Regional HDI | 40,108 | 63.169 | 17.589 | 16.8 | 97.4 |
| Economic Growth | 38,420 | 0.035 | 0.082 | −1.494 | 2.737 |
| Temperature | 40,108 | 18.96 | 7.558 | 0.011 | 31.725 |
| Maximum Temperature | 40,108 | 27.346 | 5.197 | 7.1 | 42.6 |
| Temperature Variation | 40,108 | 4.901 | 3.1 | 0.198 | 16.965 |
| Precipitation (in 10 ml) | 40,108 | 95.54 | 67.323 | 0 | 491.017 |
| Temperature Deviation from 20-Year Mean | 38,296 | 0.518 | 1.067 | −5.209 | 10.577 |

*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. Temperature variable usually enters models in logged form.

### 3.2. *The temperature–income relationship at the regional level*

In Fig. 1, we plot regional per capita income (in logs) against regional temperatures for all regions and years in our primary dataset. The figure illustrates the high variation of the data: Rich regions may experience extreme temperatures, both very hot and cold, like poor regions. This variation suggests that climate alone does not predetermine a region's economic development trajectory, thus challenging notions of climate determinism. However, there is a negative relationship between regional temperatures and regional per capita income, suggesting that warmer regions are poorer when not controlling for other factors that may drive economic development. A fit of a quadratic model (illustrated by the dashed line) performs similarly to the linear counterpart (solid line) in terms of the coefficient of determination. Fig. 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.

## 4. Panel approach

### 4.1. *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:

$$Income_{it} = \beta_1 T_{it} + \theta_j + \varphi_{it} + \epsilon_{jit} \tag{1}$$

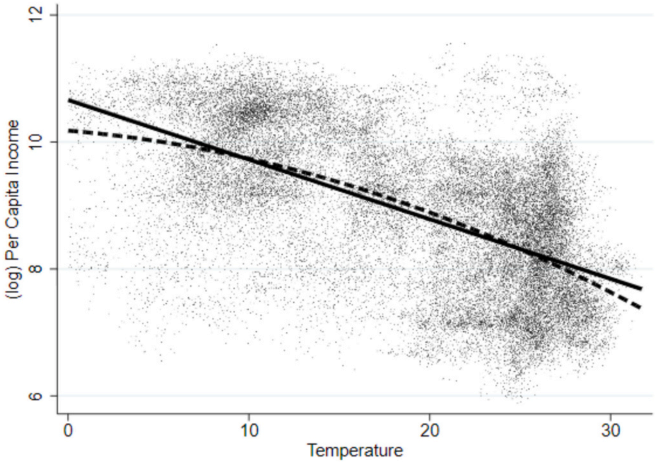

**Fig. 1.** Relationship between Regional Temperature and Per Capita Income.

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 $\beta_1$, which reflects the link between (logged) temperature (*T*) and (logged) regional per capita income.[5] To make statistical inferences, we always compute standard errors that are simultaneously clustered at the region- and parent-country level (Cameroon et al., 2011).

We control for region-fixed effects ($\theta_j$) 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 ($\varphi_{it}$). 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. By accounting for various fixed effects, our baseline specification (1) allows us to investigate changes in GDP per capita between regions, comparing regions that experience higher temperature increases with regions in the same country with lower temperature increases. Country-time-fixed effects allow us to better understand the role of local climate conditions in explaining regional economic disparities because economic effects of climate change that could materialize at the country level are absorbed by the country-year-fixed effects. This, of course, has the important analytical ramification that our empirical results reported below, where our findings are relevant to understanding *regional* economic responses to weather and climate shocks rather than *national* socio-economic aggregates such as national economic growth or public health outcomes.

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 $\beta_1$ 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 $\theta_j$ and *all country-time variant* influences (e.g., national trade patterns over time, national policies over time, etc.) through $\varphi_{it}$, there are omitted time-variant variables at the regional level for which we cannot control due to missing data. This may lead to $\beta_1$ 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, by omitting such time-variant regional controls we would overstate any potential negative impact of higher temperatures on regional per capita income. In this sense, we give regional temperatures a comparatively good chance to emerge as a statistically relevant and negative correlate of regional economic development.

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[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, we also use an inverse hyperbolic sine transformation of temperature. Using this alternative transformation does not yield different empirical findings. Finally, below we also use a non-logged temperature variable, showing that our interpretations are not affected by this transformation (see Hsiang, 2010a, 2010b).

[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).

### 4.2. Empirical results

We report our first set of 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 ($p < 0.01$). Conditional on separate country- and year-fixed effects (specification 2), however, there is only a marginally significant and negative association between temperature and income at the regional level. Once, we account for region-fixed effects (specification 3), the relationship between temperature and regional income becomes statistically insignificant, with coefficient becoming positive but coefficient sizes approaching zero. The same is true for our baseline specification (specification 4), where we control for regional- and country-year-fixed effects. Interpreting the coefficient for temperature associated with our baseline specification, 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 0.04%, $CI_{95\%} = [-0.14\%; 0.22\%]$, holding all regional time-invariant and country-year specific conditions constant.

We observe a substantial increase in the goodness of fit (adjusted $R^2$) when accounting for the various fixed effects. 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]

As a first robustness check, in specifications 5 and 6 we examine the relationship between temperature and the regional *Human Development Index* (HDI) and the regional growth rate of income, respectively.[8] We find no statistically robust evidence that temperature is related to any of these alternative economic outcomes.

Finally, we estimate a model where we only focus on regions in Sub-Saharan Africa (specification 7). These regions may be especially vulnerable to rising temperatures, for example, by nature of being in already hot environments or due to the lack of resources to address potential challenges related to rising temperature. Though the coefficient for temperature is negative and larger in absolute terms than for the full sample, it is not statistically significant. Still, the magnitude of the coefficient and its negative sign suggest that regions in countries/continents that are comparatively poor and potentially vulnerable might potentially experience negative effects of rising temperatures.

To further add to the robustness of our main empirical finding—that temperature increases are on average not associated with changes in regional income—in Table 3 we focus on alternative operationalizations of weather and temperature.

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.[9] 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.

Second, we operationalize warming as the maximum temperature per region-year observation to study whether changes in temperature extremes rather than average temperature matter (specification 2); 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 (specification 3); and temperature in absolute rather than logged form to evaluate whether data transformation matters (specification 5). 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.

Third, 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. Thereby, we follow empirical contributions that allow temperature increases to take more time to potentially affect GDP per capita or growth (e.g., Kotz et al., 2024).[10] Analyzing different lag structures, we do not find that temperature adversely affects regional income using a variety of lag structures and all coefficients are close to zero.

Finally, there is a discussion in the literature 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). Consequently, 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 in specification (5).[11] We find no evidence for a non-linear relationship between regional temperature and income. 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). Our results are consistent with the notion that there is no statistically significant non-linear relationship between regional temperature and economic development.

### 4.3. Discussion

Our panel approach provides no evidence that temperature is systematically and statistically significantly related to regional economic activity after accounting for region-fixed and county-year-fixed effects, meaning that identification of the coefficient for temperature relies on inter-annual fluctuations that are not common across regions of a given

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[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 1275 regions in 123 countries). We continue to find that temperature is not associated regional income in statistically significant ways. At the same time, we can 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.

[8] The sub-national HDI is a translation of the UNDP's 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).

[9] Relatedly, Kotz et al. (2022) show that economic growth rates are affected by precipitation, in particular by extreme daily precipitation, but not by daily mean temperatures.

[10] However, in contrast to some of that literature, we do not interact the lags with annual mean temperature over time for our units of observation. Introducing such interactions would also require accounting for interactions with many other regional variables to reduce omitted variable bias potentially affecting the interaction term.

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

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

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| Temperature | −1.073***<br>(0.142) | −0.063*<br>(0.035) | 0.033<br>(0.022) | 0.004<br>(0.009) | −0.004<br>(0.091) | −0.005<br>(0.003) | −0.162<br>(0.246) |
| Country-Fixed Effects | No | Yes | No | No | No | No | No |
| Year-Fixed Effects | No | Yes | Yes | Yes | Yes | Yes | Yes |
| Region-Fixed Effects | No | No | Yes | Yes | Yes | Yes | Yes |
| Country*Year-Fixed Effects | No | No | No | Yes | Yes | Yes | Yes |
| Panel Unit Root Test (p-value) | (0.00)*** | (0.00)*** | (0.00)*** | (0.00)*** | (0.00)*** | (0.00)*** | (0.00)*** |
| Adjusted $R^2$ | 0.260 | 0.925 | 0.975 | 0.997 | 0.997 | 0.740 | 0.991 |
| No. of Observations | 40,108 | 40,108 | 40,108 | 40,108 | 40,108 | 38,420 | 10,284 |
| No. of Regions | 1544 | 1544 | 1544 | 1544 | 1544 | 1536 | 431 |
| No. of Countries | 152 | 152 | 152 | 152 | 152 | 151 | 42 |

*Notes:* Dependent variable (DV) is (logged) regional per capita income, except in Models (5) and (6), where it is the regional HDI and regional economic growth rate, respectively. $H_0$ of the Fisher-type panel unit root test: all panels contain a unit root (i.e., are non-stationary) against the alternative that at least one panel is stationary. Standard errors clustered at the regional and country-year level in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

**Table 3**
Alternative Operationalizations of Temperature.

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Temperature | 0.004<br>(0.009) | | | | |
| Precipitation | −0.005<br>(0.004) | | | | |
| Maximum Temperature | | −0.002<br>(0.002) | | | |
| Temperature Variation | | | −0.004<br>(0.003) | | |
| Temperature (*not* logged) | | | | −0.007<br>(0.004) | |
| Temperature ($<17$ °C) | | | | | 0.007<br>(0.008) |
| Temperature ($>17$ °C) | | | | | −0.183<br>(0.137) |
| Region-Fixed Effects | Yes | Yes | Yes | Yes | Yes |
| Country*Year-Fixed Effects | Yes | Yes | Yes | Yes | Yes |
| Panel Unit Root Test (p-value) | (0.00)*** | (0.00)*** | (0.00)*** | (0.00)*** | (0.00)*** |
| Adjusted $R^2$ | 0.997 | 0.997 | 0.997 | 0.997 | 0.997 |
| No. of Observations | 40,107 | 40,108 | 40,108 | 40,108 | 40,108 |
| No. of Regions | 1544 | 1544 | 1544 | 1544 | 1544 |
| No. of Countries | 152 | 152 | 152 | 152 | 152 |

*Notes:* Dependent variable (DV) is (logged) regional per capita income. $H_0$ of the Fisher-type panel unit root test: all panels contain a unit root (i.e., are non-stationary) against the alternative that at least one panel is stationary. Standard errors clustered at the regional and country-year level in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

country. In other words, our findings imply that higher temperatures due to climate change do not necessarily determine economic destiny and development pathways, i.e., there is no evidence for climate determinism. Rather, the results from our panel approach suggest 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 might emerge through extreme weather conditions (e.g., weather-related disasters) which our empirical approach does not fully capture. Nevertheless, it is important to not disregard zero effects of (average) temperature, maximum temperature and temperature variability on regional economic development. Such information on absence of evidence may lead to an update of existing priors (Abadie, 2020), especially given an opinion climate where priors regarding the effects of climate change on indicators of human well-being are predominantly negative. Our panel results challenge these existing priors to some extent.

## 5. Long-difference approach

Global climate change 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 climate change 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 are 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 and quasi-zero relationship between temperature and regional income for a shorter-run time horizon reported in Tables 2 and 3 when accounting for a set of fixed effects.

### 5.1. *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 for region *j* in country *i*:

$$\overline{Income}_{ji,2} - \overline{Income}_{ji,1} = \alpha + \beta_1 \left[ \overline{T}_{ji,2} - \overline{T}_{ji,1} \right] + \varphi_i + \epsilon_{ji}. \tag{2}$$

Here, we first construct region-specific (logged) averages in per capita income and temperature between 1990 and 1993 (subscript 1 in *ji,1*) and between 2014 and 2017 (subscript in *ji,2*). Then, we take the so-called 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. The two periods are chosen for two reasons. First, in this manner we can maximize the temporal differences between both data points, making it more likely that we can indeed capture the adverse economic effects of climate change that are expected to emerge especially over longer time horizons. Second, by taking averages over multiple years we can reduce the influence of short-run temperature and business cycle fluctuations.

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

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 ($\varphi_i$), 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 ($\alpha$) 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 1300 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 potential 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).

### 5.2. Empirical results

Our long-difference estimates of Eq. (2) are reported in Table 4. Briefly summarized, the findings do not indicate that temperature increases between the 1990–1993 versus 2014–2017 periods are robustly associated with lower levels of regional economic development at conventional levels of statistical significance. Coefficients are positive or negative depending on the specification but their sizes for the change in regional temperate tend to be close to zero. Thus, the long-difference estimates speak to our panel results of Tables 2 and 3 in that we find little robust evidence of an unfavorable effect of temperature increases on regional economic outcomes.

In detail, in both a parsimonious model (specification 1) and a model controlling for rainfall (specification 2), a change in regional temperature is positively but statistically insignificantly related with changes in regional incomes. When we use alternative temperature measures (specifications 3–5), the positive temperature coefficient turns negative and statistically significant at the 10% level for the association between long-run increases in maximum temperatures and changes in regional income, while the association between income and non-logged temperature and temperature variation, respectively, is not statistically significant. There is also no evidence for a non-linear relationship (specification 6). While long-differences in temperature share no robust relationship with changes in the regional HDI (specification 7), they are negatively associated with changes in regional economic growth (specification 8) at the 10% significance level. Finally, when focusing only on regions in Sub-Saharan Africa (specification 9), we do not find evidence for a statistically robust negative relationship when employing the long-difference approach, though, the coefficient size increases in absolute terms.

## 6. Heterogeneity in the regional temperature-income relationship

### 6.1. Empirical strategy to explore heterogeneity

So far, both our panel and long-difference analyses suggest that regional economic development is not (adversely) affected by regional temperature shocks. In other words, comparing regions that experience higher temperature increases with regions in the same country with lower temperature increases (and controlling for a variety of fixed effects), the former regions do not exhibit stronger adverse economic effects due to warming. This, in turn, suggest that there is no uniform effect of warming on regional economic disparities within countries. One theoretical argument to explain this finding is that any regional disparities due to warming are offset at the national level, e.g., by government activity or adaptive behavior of economic agents. At the same time, however, this argument would also suggest that there could be *heterogeneity* in the temperature-income relationship, with regions being economically exposed to temperature increases when they are in countries that lack the capability to offset regional disparities. Thus, below we explore various country-specific conditions that may make it more or less likely for a link between temperature and income to emerge.

Indeed, the cross-country literature suggests that certain *country-specific conditions* may moderate the temperature-income relationship. Most prominently, existing research suggests that a country's income level matters. Here, it is argued that 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).

Similarly, such conditions might also affect a region's vulnerability to rising temperatures. 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

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

[13] This is because the long-difference approach in Eq. (2) is equivalent to the panel approach of Eq. (1), with the difference between both approaches being that Eq. (2) is not expressed in years but in decades (see also Dell et al., 2014: 778).

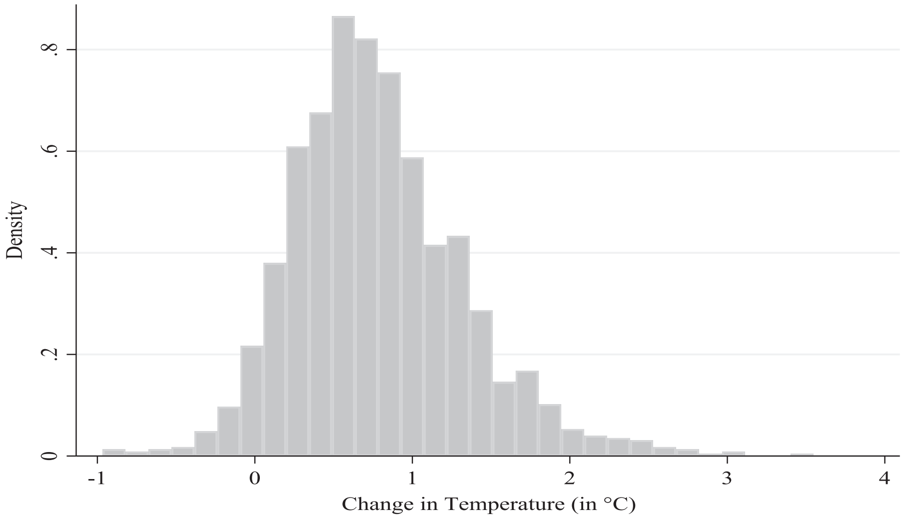

**Fig. 2.** Histogram of Change in Temperature (1990–93 versus 2014–2017).

**Table 4**
Long-Difference Estimates for the Link between Temperature and Regional Incomes.

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| Δ Temperature | 0.014<br>(0.109) | 0.014<br>(0.110) | | | | | −0.002<br>(0.010) | −0.048*<br>(0.026) | −1.259<br>(0.833) |
| Δ Precipitation | | −0.007<br>(0.039) | | | | | | | |
| Δ Maximum Temperature | | | −0.016*<br>(0.009) | | | | | | |
| Δ Temperature Variation | | | | −0.046<br>(0.030) | | | | | |
| Δ Temperature (No Log) | | | | | −0.026*<br>(0.013) | | | | |
| Δ Temperature (<17 °C) | | | | | | 0.019<br>(0.108) | | | |
| Δ Temperature (>17 °C) | | | | | | −0.013<br>(0.108) | | | |
| Country Dummies | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Period Dummy (Intercept) | Yes | 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 | 0.927 | 0.989 |
| No. of Observations | 1288 | 1288 | 1288 | 1288 | 1304 | 1288 | 1288 | 1288 | 227 |
| No. of Regions | 1288 | 1288 | 1288 | 1288 | 1304 | 1288 | 1288 | 1288 | 277 |
| No. of Countries | 125 | 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 Models (7) and (8), where it is the regional HDI and regional economic growth rate, respectively. Δ always refers to the difference between the early and late period (1990–1993 vs. 2014–2017). Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

following form:

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

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

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

$$+ \alpha + \varphi_i + \epsilon_{ji} \qquad (4)$$

In both the short- and long-run case, the threshold model follows Hansen (1999). Here, the threshold parameter $\gamma$ 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 $\gamma$ 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 before. Moreover, in such a case specific country-wide conditions can explain the emergence of a link between temperature and income.

### 6.2. *Threshold variables*

We explore potential country-specific threshold 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 focus on *initial* economic-legal and politico-institutional conditions (as averages over the 1980–1989 period). 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). Employing this variable as a moderator speaks to the idea that poorer countries may be more vulnerable to adverse consequences of global climate change (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 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, non-democratic governments may be less likely to respond to climate change by adjusting public policy because 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 (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 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 equality 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 that disfavor their rural parts. 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.

### 6.3. Empirical results: Heterogeneity in the short and long run

We report our panel threshold estimates in Table 5 and our long-difference threshold estimates in Table 6. For each threshold variable, we identify a likely threshold value following Hansen (1999). For instance, for the panel approach (Table 5) 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 (specification 1). 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 to zero and statistically not different from zero at conventional significance levels. All other panel threshold models (specifications 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 in the short run. Testing for the equality of coefficients below and above the various estimated thresholds, we also find little evidence 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 above suggesting no general link and no heterogenous link between temperature and income in the short run.

In Table 6, 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 (specification 1) and democratic vs. not democratic countries (specification 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 (specification 3), low levels of equality (specification 4), strong rural exclusion (specification 5) as well as less sound starting conditions as measured by our composite measure (specification 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.

Focusing on our composite measure, our long-difference threshold estimates imply that the adverse effect of temperature increases concern 350 regions in 17 countries that have unsound starting conditions 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 substantial decrease in per capita income by

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[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 5**
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) | 0.033 | 0.006 | 0.014 | −0.122 | 0.004 | 0.009 |
| | (0.022) | (0.035) | (0.029) | (0.110) | (0.023) | (0.032) |
| Temperature (Moderator = 1) | −0.040 | −0.023 | −0.044 | 0.018 | −0.049 | −0.022 |
| | (0.035) | (0.029) | (0.033) | (0.020) | (0.060) | (0.031) |
| [Equality of Coefficients Test p-value] | [0.08]* | [0.51] | [0.19] | [0.21] | [0.41] | [0.49] |
| Threshold Estimate | 994$ | 0.16 | 0.47 | 0.41 | 0.54 | −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 | 31,052 | 33,740 | 33,740 | 33,740 | 33,180 | 30,156 |
| No. of Regions | 1109 | 1205 | 1205 | 1205 | 1185 | 1077 |
| 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 6**
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 |
| $\Delta$ 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) |
| $\Delta$ 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 | 1663$ | 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 | 1118 | 1216 | 1216 | 1216 | 1196 | 1084 |
| No. of Regions | 1118 | 1216 | 1216 | 1216 | 1196 | 1084 |
| 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). $\Delta$ 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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

approximately 10.9%, $CI_{95\%} = [-1.3\%; -20.5\%]$. For the remainder of the sample of regions in all other countries, temperature is not found to sway regional economic development in the long run in statistically robust ways.

As argued by Dell et al. (2012, 2014), the long-difference estimates can be interpreted as capturing adaptation or intensification effects. According to this interpretation, 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 regional economic development in the long run when weak institutions do not sufficiently incentivize investment, innovation and other forms of adaptation. 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, too. That is, if higher temperatures negatively affect other unobserved factors which, in turn, affect regional income, our estimates may constitute an upper bound of the long-run economic impact of warming in regions within especially vulnerable countries. For instance, if political instability is such an unobserved factor, improving political stability (e.g., by fostering conflict prevention) may contribute to lowering the adverse effects of climate change in regions within particularly vulnerable countries.

## 7. Further robustness checks and empirical extensions

### 7.1. Use of alternative economic data

The use of alternative data sources may matter to empirical analyses (see, e.g., Johnson et al., 2013 with respect to the use of GDP data). Thus, as part of our robustness checks, we employ alternative data for regional GDP per capita from Gennaioli et al. (2014) to cross-validate our main empirical findings (see also Greßer et al., 2021). Drawing from national and regional statistical offices, Gennaioli et al. (2014) report regional economic activity as *regional* per capita *GDP*.[15] 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).

The dataset of Gennaioli et al. (2014) allows us to consider 1446 regions in 81 countries between 1950 and 2014. Thus, we can extend the temporal coverage of the data, while the number of countries is reduced. The country list in the appendix details the country coverage. The economic data are not observed annually and Gennaioli et al. (2014) do not

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

provide external data (e.g., on different growth determinants) that could be used to reliably interpolate the missing data. Following Gennaioli et al. (2014: 266) and, more generally the past growth literature, we thus analyze a series of five-year period averages (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, meaning that the panel dataset is unbalanced (see also Gennaioli et al., 2014: 268–270).

We estimate the relationship between the alternative regional economic development variable and temperature in both a panel and 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. In both settings, we also allow for heterogeneous effects by amending our models with a variable that is equal to unity when economic and institutional conditions are sound and zero otherwise, using 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 already constructed above as the moderator variable.

We report our results in Table 7. We find that higher temperatures are not associated with lower per capita GDP levels both in the homogenous and heterogeneous panel setting. In the long-difference approach, temperature increases are not associated to changes in regional per capita GDP. However, we observe a negative and statistically significant association between temperature and per capita GDP in the long run for regions in countries with comparatively weak economic and institutional country-specific conditions.[16] Thus, when using the data of Gennaioli et al. (2014) we arrive at empirical findings that mirror those reported above where we employed the economic data from the *Global Data Lab Dataset* such that our overall interpretations do not change: There is no evidence of a homogeneous or heterogeneous effect of rising temperatures on regional economic development in the short run when accounting for different fixed effects. For regions in countries with a weak economic, legal and political institutions, the association between higher temperatures and regional income is negative in the long run.

**Table 7**
Use of Alternative Economic Data.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Empirical Approach ➔ | Panel Approach | | Long-Difference Approach | |
| Dependent Variable ➔ | Regional per Capita GDP | | Regional per Capita GDP | |
| Temperature | −0.028 | | | |
| | (0.030) | | | |
| Temperature (Moderator = 0) | | −0.038 | | |
| | | (0.055) | | |
| Temperature (Moderator = 1) | | −0.013 | | |
| | | (0.034) | | |
| Δ Temperature | | | −0.097 | |
| | | | (0.062) | |
| Δ Temperature (Moderator = 0) | | | | −0.185*** |
| | | | | (0.049) |
| Δ Temperature (Moderator = 1) | | | | 0.125 |
| | | | | (0.138) |
| Region-Fixed Effects | Yes | Yes | | |
| Country*Period-Fixed Effects | Yes | Yes | | |
| Country Dummies | | | Yes | Yes |
| Period Dummy (Intercept) | | | Yes | Yes |
| Adjusted $R^2$ | 0.982 | 0.984 | 0.981 | 0.988 |
| No. of Observations | 8793 | 7537 | 675 | 560 |
| No. of Regions | 1446 | 1133 | 675 | 560 |
| No. of Countries | 81 | 61 | 81 | 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). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

### 7.2. *Warming as deviations from long-run temperature means*

As another robustness check, we consider an alternative way to investigate potential effects of increasing temperatures, by analyzing the annual deviation of temperature from average temperatures observed in the 20 years prior. We calculate these temperature deviations as described in Kahn et al. (2021: 4). Kahn et al. (2021) argue that operationalizing warming in this manner may avoid introducing a linear trend in temperature (as it follows from global warming) and thus also avoid a spurious regression problem. A similar approach to measuring warming is also used by Mohaddes et al. (2023).

We consider the relationship between regional economic development and warming—measured as deviations from long-term temperature means—in both a panel and long-difference setting with our primary economic dataset. Our findings are reported in Table 8. We find no evidence that year-to-year temperature deviations matter to regional per capita income (panel approach). In the long run, temperature deviations reduce economic activity only in regions within countries with poor starting conditions, i.e., within countries that are especially vulnerable. Thus, the findings in Table 8 are fully consistent with our main empirical findings—where we consider (logged) temperature as our baseline climate measure—reported above.

### 7.3. *Capturing long-run linkages through a moving-difference approach*

To further explore potential long-run linkages between temperature and income, we perform a robustness test by employing a moving-difference approach.[17] We start by calculating the five-year difference between the economic and temperature variables, respectively. For instance, this means we calculate the difference in regional per capita income between 1990 and 1995, 1991 and 1996, 1992 and 1997 and so on. We then estimate how five-year differences in temperature are associated with five-year differences in per capita income at the regional level. The advantage of this approach over the long-difference approach employed above is that we can still exploit the time-series dimension of the data to some extent, allowing us to employ a larger number of observations and increasing variation in the data. At the same time, it comes at the potential expense of short-run temperature and business cycle fluctuations becoming more influential, which are averaged out in the long-difference approach employed above. When applying the moving-difference approach, we also consider longer time horizons by means of constructing ten-year and fifteen-year moving averages, respectively, to account for the (theoretical) argument that the economic effects of higher temperature might only be felt after some time

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[16] Given that the country-specific data is not available for all countries, when studying heterogeneous effects, our sample shrinks. We therefore also estimate the homogenous panel and long-difference estimates for a reduced sample. We do not find that our results are driven by sample choices.

[17] We thank an anonymous reviewer for pointing out this empirical approach.

**Table 8**
Warming as Deviations from Long-Run Means.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Empirical Approach ➔ | Panel Approach | | Long-Difference Approach | |
| Dependent Variable ➔ | Regional per Capita GDP | | Δ Regional per Capita GDP | |
| Temperature Deviation | −0.001<br>(0.002) | | | |
| Temperature Deviation (Moderator = 0) | | 0.001<br>(0.003) | | |
| Temperature Deviation (Moderator = 1) | | −0.003<br>(0.003) | | |
| Δ Temperature Deviation | | | −0.007<br>(0.007) | |
| Δ Temperature Deviation (Moderator = 0) | | | | −0.046**<br>(0.019) |
| Δ Temperature Deviation (Moderator = 1) | | | | −0.003<br>(0.008) |
| Region-Fixed Effects | Yes | Yes | | |
| Country*Period-Fixed Effects | Yes | Yes | | |
| Country Dummies | | | Yes | Yes |
| Period Dummy (Intercept) | | | Yes | Yes |
| Adjusted $R^2$ | 0.996 | 0.996 | 0.995 | 0.995 |
| No. of Observations | 38,761 | 29,176 | 1252 | 1042 |
| No. of Regions | 1480 | 1042 | 1252 | 1042 |
| No. of Countries | 151 | 99 | 125 | 99 |

Notes: Dependent variable (DV) is (logged) regional per capita GDP. Δ 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. 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). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

has passed.

We report our moving-differences findings in Table 9. We find that rising temperatures are not statistically significantly associated with changes in regional income when we consider five-year moving averages (positive coefficient estimates of temperature but close to zero) or ten-year moving differences (negative coefficient estimates of temperature but close to zero) in both a homogeneous and heterogeneous setting. However, a statistically significant and negative relationship emerges when we consider fifteen-year moving averages, where we find—on closer inspection—that this relationship is especially felt in regions within countries with poor starting conditions.[18] That is, we find the usual evidence for heterogeneity in the economic response to rising temperatures. Finding that this relationship is most precisely estimated when considering fifteen-year moving averages suggests that any potential adverse economic effects of warming are more likely to emerge (and thus be empirically detected) in the longer run, where they are limited to regions in particularly vulnerable countries.

### 7.4. *Further sources of country-level heterogeneity*

When studying heterogeneity in the temperature-income relationship, above we focused especially on the role of country-specific institutional conditions. Clearly, however, there are many other conditions or variables that may also moderate the relationship between regional temperature and income. Thus, as an empirical extension, in this sub-section we explore four additional sources of heterogeneity: a country's dependence on agricultural and industrial production, respectively, its country-level exposure to temperature changes as well as its response to the economic shocks of warming at the country level. In the Appendix (Section A3) we discuss on more detail the theoretical rationale behind each moderator and how we operationalize each moderator.

We report our empirical results in Table A3 in the Appendix. In short, we find that local temperature increases do not matter to regional income in the short run but only in the long run in those regions that are especially vulnerable to rising temperatures as operationalized by the country-specific dependence on manufacturing and the country-specific (i.e., national average) experience of warming. These findings are, of course, in line with our main results reported above. In detail, we find weak evidence that higher temperatures reduce regional economic development in the long run especially when a country's manufacturing sector is small. Furthermore, we show that regional temperature increases are negatively associated with regional economic activity in the long run when the region of interest is in a country that—as a whole—has not experienced high levels of warming. This finding may imply that such a region receives fewer resources from the central government to adapt to higher temperatures because the central government sees less necessity or has fewer incentives to foster adaption. This interpretation of the heterogenous link in the long run would again speak to our idea and the evidence presented before that institutional arrangements at the country level matter to the regional temperature-income nexus. At the same time, however, future research is necessary to examine the country-specific roots of heterogeneity in this nexus in more detail.

## 8. Exploring long-run transmission channels

Finally, we explore potential mechanisms through which higher temperatures may hurt regional long-run economic development in vulnerable countries. 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*.

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; Helbling and Meierrieks, 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).

Table 10 shows that higher temperatures do not have a uniform and statistically significant association with the three potential transmission channels in the long run (specifications 1, 3 and 5). However, in the long run higher temperatures are negatively associated with population size and education in those regions within countries characterized by poor initial economic-legal and political conditions (specifications 2 and 4); there are no comparable associations for human health measured by life expectancy (specification 6). That is, higher temperatures are only adversely associated with potential determinants of economic development precisely in those regions for which we also find higher temperatures being negatively associated regional economic development in the long run.

There are two caveats to this exploration of transmission channels. First, we only have available data for some specific indicators of population and human capital development as provided by the *Global Data*

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[18] As sample size is reduced when we consider longer moving differences, we also test whether our findings are due to changes in sample size by estimating specifications (1) and (3) with the same observation as specification (5) and estimating specifications (2) and (4) with the same observations as specification (6). Results for five- and ten-year moving averages remain statistically insignificant.

**Table 9**
Capturing Long-Run Linkages: Moving-Difference Approach.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Moving-Differences Time Horizon ➔ | 5 Years | | 10 Years | | 15 Years | |
| Temperature | 0.009 | | −0.003 | | −0.009* | |
| | (0.006) | | (0.008) | | (0.005) | |
| Temperature (Moderator = 0) | | 0.006 | | −0.017 | | −0.024** |
| | | (0.032) | | (0.027) | | (0.011) |
| Temperature (Moderator = 1) | | 0.009 | | 0.023 | | 0.008 |
| | | (0.045) | | (0.046) | | (0.018) |
| Region-Fixed Effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Country*Year-Fixed Effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Adjusted $R^2$ | 0.895 | 0.859 | 0.935 | 0.918 | 0.975 | 0.970 |
| No. of Observations | 32,370 | 24,771 | 24,740 | 19,386 | 17,254 | 14,001 |
| No. of Regions | 1539 | 1077 | 1523 | 1077 | 1428 | 1077 |
| No. of Countries | 152 | 98 | 150 | 98 | 139 | 98 |

*Notes:* Dependent variable (DV) is (logged) regional per capita income. “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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

**Table 10**
Exploration of Long-Run 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 | 1282 | 1084 | 1288 | 1084 | 1288 | 1084 |
| No. of Regions | 1282 | 1084 | 1288 | 1084 | 1288 | 1084 |
| 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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

*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, due to data constraints, our exploration of potential transmission channels cannot 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 to the temperature–income nexus as relevant transmission variables (e.g., Schlenker and Lobell, 2010; Dell et al., 2012, 2014; Burke et al., 2015b; Carter et al., 2018).

## 9. 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 1500 regions in 152 countries between 1990 and 2017. In so doing, we add to the currently still small body of literature on the economic consequences of climate change at the sub-national level as well as to the broader empirical literature on the determinants of sub-national economic disparities.

Using a panel approach, conditional on region- and country-year-fixed effects, we find no statistically significant evidence that rising regional temperatures are negatively related to regional per capita income. Various robustness checks (e.g., concerning the measurement of regional climatic and economic conditions) support this finding. When we employ a long-difference approach that is more attuned to exploring the long-run relationship between rising temperatures and changes in regional economic activity, we also find no statistically robust evidence that rising temperatures correlate with lower per capita income levels in the long run. To account for potential heterogeneous effects with respect to the temperature–income relationship, we use short- and long-run threshold approaches. We find that country-specific conditions appear to be a key moderator regarding the relationship between temperature and income in the long run. For 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; for regions in countries with strong economic-legal and political institutions, there is no statistically significant association between regional temperature and income. This finding may also speak to the prevalence of intensification effects, implying that the adverse economic impacts of higher temperature may be compounded and become more pronounced over time. We also provide tentative evidence that within vulnerable countries, rising temperatures may constrain long-term regional population and human capital development as potentially important transmission channels from rising temperatures to lower per capita income levels.

Our findings point to a nuanced relationship between regional temperature increases and regional economic development. This may lead to a relevant update of existing priors (Abadie, 2020) concerning the economic consequences of higher temperature which are expected due climate change, while also inviting future research that accounts for the short- and long-run as well as moderating effects of temperature on economic outcomes. 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 explores this direction, but this dataset does not cover many regions in Africa for which the economic effects of warming could be more pronounced due to weak economic-legal and political institutions that may make adaptation more difficult. Furthermore, as already discussed above, future research may investigate the role of further 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 or 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 such as instrumental-variable threshold models (e.g., Caner and Hansen, 2004).

Global temperature rises linked to climate change are projected to continue for the coming decades (IPCC, 2014, 2021). Our study suggests that rising temperatures are—for the time being—particularly relevant for regions in countries with weak political and economic institutions. On average—and for already richer economies with stronger political and economic institutions—we could detect no direct relationship between temperature and income. For one, this central finding matters for economic models of climate change (see also Tol, 2021). For another, 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 vulnerability to potential negative regional economic effects of warming. Such efforts can be pursued independent of and in addition to global efforts to reduce greenhouse gas emissions. At the same time, our results are by no means meant to encourage so-called "climate change denial". Global temperatures have increased, and our empirical results point to (heterogeneous) economic losses due to rising temperatures. Finally, we want to emphasize that potential adverse effects of higher temperatures on sub-national per capita income could take longer time horizons to fully materialize and could become more pronounced if future climate change accelerates or leads to very volatile conditions.

## CRediT authorship contribution statement

**Daniel Meierrieks:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **David Stadelmann:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization.

## Declaration of competing interest

None.

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## Appendix A. List of countries

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

(*continued on next page*)

(*continued*)

| | | |
|---|---|---|
| Cote d’Ivoire | Kuwait | Russia* |
| Croatia* | Kyrgyzstan* | Rwanda |
| Cuba | Lao | Saudi Arabia |
| Czech Republic* | Latvia* | Senegal |
| Denmark* | Lebanon | Serbia* |
| Dominican Republic | Lesotho* | Sierra Leone |
| Ecuador* | Liberia | Slovakia* |

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.

### *A.1. Alternative and more complex lag structures*

In Table 2, we predict regional per capita income by contemporaneous regional temperature in the previous year (i.e., at *t*). Inspired by Dell et al. (2012), we consider whether alternative and more complex lag structures yield different results in Table A1. 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-1*, *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 A1, all coefficient estimates are never statistically significant both individually and jointly. Thus, in line with our main results reported in the main text, 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**
Alternative Lag Structures.

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | 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 $_{t-1}$ | | 0.005 | | | | | −0.000 | −0.005 | −0.002 | −0.003 | −0.009 |
| | | (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 | Yes |
| Country*Year-Fixed Effects | Yes | 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 | 0.997 |
| No. of Observations | 40,108 | 38,807 | 37,507 | 36,204 | 34,907 | 33,609 | 38,741 | 37,411 | 36,086 | 34,774 | 33,466 |
| No. of Regions | 1544 | 1544 | 1543 | 1543 | 1543 | 1539 | 1538 | 1535 | 1534 | 1534 | 1532 |
| No. of Countries | 152 | 152 | 152 | 152 | 152 | 152 | 152 | 152 | 152 | 152 | 151 |

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

### *A.2. Further examination of non-linearities in the temperature–income relationship*

In Table 3, 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.

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

**Table A2**
Alternative Temperature Thresholds.

| | (1) | (2) | (3) | (7) |
|---|---|---|---|---|
| Temperature Threshold ➔ | 9 °C | 13 °C | 21 °C | 24 °C |
| Temperature (<Threshold) | 0.007 | 0.006 | 0.004 | 0.005 |
| | (0.008) | (0.008) | (0.009) | (0.009) |
| Temperature (>Threshold) | −0.083* | −0.105 | −0.008 | −0.248 |
| | (0.047) | (0.086) | (0.194) | (0.212) |

(*continued on next page*)

**Table A2** (*continued*)

| | (1) | (2) | (3) | (7) |
|---|---|---|---|---|
| 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 | 40,108 | 40,108 | 40,108 | 40,108 |
| No. of Regions | 1544 | 1544 | 1544 | 1544 |
| 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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

### *A.3. Further sources of country-level heterogeneity*

For our baseline approach, we consider a variety of economic, legal and politico-institutional variables as potential threshold variables, i.e., as moderators accounting for potential heterogeneity in the temperature-income relationship in the short as well as long run. Clearly, there are many additional variables that may likewise moderate the relationship between regional temperature and income. As an empirical extension, we focus on four additional sources of heterogeneity: a country's dependence on agricultural and industrial production, respectively, the country-level exposure to temperature changes as well as the economic response to the shocks of warming at the country level.

First, to study the role of a country's agricultural sector, we collect the country-specific *value added by agriculture as a share of GDP* as a moderator from the *World Development Indicators*. For instance, higher temperatures might depress economic output by hurting agricultural production. This could imply that a stronger dependence on agriculture might disproportionately increase regional economic vulnerability to rising temperatures.

Second, to explore the role of a country's level of industrial development in the regional temperature-income nexus, from the *World Development Indicators* we draw the *value added by manufacturing as a share of GDP*. For example, a larger industrial sector ought to imply a smaller agricultural sector, potentially meaning that more industrialized countries are less vulnerable to climate shocks. Alternatively, the adverse relationship between rising temperatures and labor productivity may make regions in industrialized countries (which rely on high levels of labor productivity) also vulnerable to some extent, e.g., when cooling technologies are not employed.

Third, it is also possible that the local impact of warming on regional economic activity is different depending on how strongly countries (as a whole) are subject to warming. For instance, when a country as a whole does not experience strong warming, policy measures to foster adaption would be less likely to be at the top of the central government's political agenda. This, in turn, could imply that regions within such countries that do experience warming may receive fewer resources from the central government and thus be more susceptible to the ill local economic effects of warming. Below, we operationalize a country's susceptibly to warming (as a moderator variable) as the *country-level change in temperature between 1990–1993 and 2014–2017*. In other words, we use the distribution of temperature change between 1990 and 2017 to create a moderator variable to distinguish between countries with different levels of warming.

Finally, regional economic activity may respond differently to local warming depending on whether a region is located within a country that has a high or low aggregate (i.e., country-specific) economic response to temperature shocks. For example, if there were economic losses due to warming at the country level, this may mean that there are fewer resources available to counter the adverse effects of warming at the local level. To study the role of aggregate economic effects of higher temperatures on the regional economy, we proceed as follows. First, we estimate the relationship between income and temperature at the country level separately for each country in the sample. Second, we estimate how temperature affects income for each country regions, using the *associated point estimates for each country* (i.e., the aggregate economy) as a moderator variable to split the dataset into countries with low and high responses (in terms of the size of the point estimates) to temperature increases.

We report our findings in Table A3. Keeping in mind that sample sizes differ to data availability and using our usual short- and long-run threshold approaches, we find that in the panel setting, the link between temperature and regional economic activity does not differ for regions located in countries with low versus high levels of agricultural or industrial development. They also do not differ for regions located in countries that experience low versus high aggregate temperature increases or that have a low versus high correlation between temperature and income at the country level (aggregate economy). Furthermore, we find that in the long-difference setting, there is some (statistically rather weak) evidence that higher temperatures are negatively associated with regional economic development when manufacturing (but not agriculture) plays no strong role in the country of interest. Finally, in the long-difference setting, we also find that country-level differences in the extent of temperature changes matter, while weaker or stronger associations between temperature and the aggregate economy play no statistically significant role for the link between regional temperature and income. For the extent of temperature changes, we find that regions that experience higher temperature increases but that are located in countries that have been warming less than others (where, i.e., the associated Moderator = 0), show a stronger negative association between the temperature increase and regional income than regions in countries have been warming more strongly. This may indicate that regions in countries experiencing lower temperature increases receive fewer resources from the central government to adapt to rising temperature because the central government feels less political pressure or has fewer incentives to foster adaption. Furthermore, economic agents may relocate (e.g., via internal migration or business relocation) in such situations to other parts of a country when specific regions are strongly affected by higher temperature as warming is more moderate in other parts of the country. As such, these heterogeneous relationships in the long run point to potential future research directions when exploring potential effects of higher temperature. Here, adaptation possibilities need not only be moderated by (poor) legal and economic institutions but potentially also by existing experience with recent increases in temperature.

In general, the findings reported in Table A3 are in line with our main findings in that (1) temperature increases may only matter to regional income in the long run and (2) in a heterogeneous manner, where the adverse effects of warming are especially felt in regions that are plausibly more vulnerable or have less experience with potential adaptation possibilities.

**Table A3**
Role of Further Country-Level Moderators.

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|---|---|---|---|---|---|---|---|---|
| Empirical Approach ➔ | Panel Approach | | | | Long-Difference Approach | | | |
| Moderator ➔ | Agriculture | Manufacturing | Temperature Change | Aggregate Economy | Agriculture | Manufacturing | Temperature Change | Aggregate Economy |
| Temperature (Moderator = 0) | −0.099 | −0.002 | −0.135 | −0.013 | | | | |
| | (0.087) | (0.033) | (0.108) | (0.029) | | | | |
| Temperature (Moderator = 1) | 0.016 | −0.010 | 0.009 | −0.030 | | | | |
| | (0.031) | (0.093) | (0.019) | (0.033) | | | | |
| Δ Temperature (Moderator = 0) | | | | | −0.083 | −1.249* | −1.369*** | −0.517 |
| | | | | | (0.122) | (0.657) | (0.385) | (0.352) |
| Δ Temperature (Moderator = 1) | | | | | −0.629 | −0.136 | 0.088 | 0.063 |
| | | | | | (0.395) | (0.133) | (0.093) | (0.099) |
| [Equality of Coefficients Test *p*-value] | [0.21] | [0.33] | [1.75] | [0.16] | [0.19] | [0.09]* | [13.50]*** | [0.11] |
| Threshold Estimate | 10.02 | 15.81 | 0.04 °C | 0.03 | 20.56 | 7.76 | 0.04 °C | −0.50 |
| Region-Fixed Effects | Yes | Yes | Yes | Yes | | | | |
| Country*Period-Fixed Effects | Yes | Yes | Yes | Yes | | | | |
| Country Dummies | | | | | Yes | Yes | Yes | Yes |
| Period Dummy (Intercept) | | | | | Yes | Yes | Yes | Yes |
| Adjusted $R^2$ | 0.994 | 0.995 | 0.996 | 0.996 | 0.993 | 0.994 | 0.996 | 0.996 |
| No. of Observations | 24,192 | 21,840 | 35,700 | 35,700 | 873 | 787 | 1289 | 1289 |
| No. of Regions | 864 | 780 | 1275 | 1275 | 873 | 787 | 1289 | 1289 |
| No. of Countries | 80 | 72 | 123 | 123 | 82 | 73 | 125 | 125 |

*Notes:* Dependent variable (DV) is (logged) per capita income in Models (1) to (4) and Δ (logged) per capita income in Models (5) to (8). 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. "Manufacturing" is the value added (as a share of GDP) from manufacturing. "Temperature Change" is the change in temperature between 1990 and 1993 and 2014–2017 at the country level. "Aggregate Economy" is the point estimate associated with the individual country-level effect of temperature on country-level per capita income. The threshold estimates refer to the specific moderator variable shares. For the moderator variable, "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) to (4). Robust standard errors in parentheses for Models (5) to (8). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

## Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2024.107758.

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