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Persistent Temperature, Capital Structure, and the Long-Run Level of Output

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ABSTRACT: This paper shows that separating persistent (permanent) temperature changes from transitory weather fluctuations can reshape our understanding of the macroeconomic costs of warming. Using a Kalman filter state-space decomposition, it separates temperature into a permanent component and transitory weather fluctuations, and links the permanent component to trend output using a panel cointegration and error-correction framework. A one-degree Celsius higher permanent temperature is associated with a significant decline in the long-run level of output, with full adjustment unfolding over multiple decades to a century. Decomposing aggregate output into population and output per capita reveals that the long-run output losses operate primarily through demographic adjustment in the full sample, while in advanced economies, both long-run output per capita and population decline as the climate warms. Economies with higher capital intensity and more durable capital stocks experience larger long-run per capita output losses. These findings suggest that long-run economic vulnerability to persistent warming is more broadly distributed across rich and poor countries than the short-run weather literature implies, reflecting differences in capital structure. They complement rather than contradict the well-established finding that developing countries are more exposed to short-run weather shocks.

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Persistent Temperature, Capital Structure, and the Long-Run Level of Output

Ha M. Nguyen*

May 20, 2026

Abstract

This paper shows that separating persistent (permanent) temperature changes from transitory weather fluctuations can reshape our understanding of the macroeconomic costs of warming. Using a Kalman filter state-space decomposition, it separates temperature into a permanent component and transitory weather fluctuations, and links the permanent component to trend output using a panel cointegration and error-correction framework. A one-degree Celsius higher permanent temperature is associated with a significant decline in the long-run level of output, with full adjustment unfolding over multiple decades to a century. Decomposing aggregate output into population and output per capita reveals that the long-run output losses operate primarily through demographic adjustment in the full sample, while in advanced economies, both long-run output per capita and population decline as the climate warms. Economies with higher capital intensity and more durable capital stocks experience larger long-run per capita output losses. These findings suggest that *long-run* economic vulnerability to persistent warming is more broadly distributed across rich and poor countries than the short-run weather literature implies, reflecting differences in capital structure. They complement rather than contradict the well-established finding that developing countries are more exposed to *short-run* weather shocks.

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1 Introduction

While there is now broad consensus that higher temperatures depress short-run output growth, far less is known about how persistent changes in temperature affects economic activity over longer horizons. Most of the empirical literature uses realized temperature (or transformations thereof) as the explanatory variable, implicitly conflating persistent climate dynamics with transitory weather fluctuations (see for example, Dell et al. (2012); Burke et al. (2015); Colacito et al. (2019); Kahn et al. (2021); Nguyen (2024)). As a result, existing estimates capture a mixture of short-run weather responses and long-run climate effects. However, unlike transitory weather shocks, climate change unfolds gradually and may alter economic outcomes through slow-moving adjustment processes such as capital accumulation and structural transformation. Understanding these long-run mechanisms is essential for evaluating the macroeconomic costs and the channels through which economies adapt to evolving climatic conditions.

This paper develops a new empirical framework to separate climate change from weather shocks and to quantify their distinct macroeconomic effects. The central idea is that observed global temperature evolves as the sum of a permanent climate component, characterized by a gradually adjusting warming rate, and transitory weather fluctuations. In this paper, I use the term climate to refer to this permanent component of temperature, while weather denotes short-run fluctuations around it. A climate shock is defined as an innovation that permanently shifts the trajectory of the warming rate, thereby altering long-run climate dynamics, while a weather shock reflects short-term deviations that eventually dissipate. By disentangling these components, the paper isolates climate change as a structural force and traces its impact on real GDP.

The paper makes three contributions. First, conceptually, it shifts the focus from short-run responses to weather shocks toward the long-run effects of persistent climate change on economic activity. Second, methodologically, it models the global temperature trend as a stochastic process with shocks to the warming rate itself. This formulation allows climate change to operate through persistent changes in the warming rate rather than through one-time level shifts in temperature. This decomposition is implemented by Kalman filter in the spirit of standard unobserved-components models. Building on this structure, the paper develops a Kalman filter that decomposes country-level temperature into exposure to a common global climate trend, a country-specific climate deviation, and transitory local weather shocks. Third, with a panel cointegration framework[1], it links these decomposed

[1]Panel cointegration provides a natural framework for studying the macroeconomic effects of climate change because both temperature and output are highly persistent and evolve primarily at low frequencies. In contrast to standard growth regressions that emphasize short-run weather responses, a cointegrated system

climate and weather components to output, itself modeled with permanent and transitory components, enabling direct estimation of how global and local climate forces anchor long-run output levels while weather shocks generate cyclical fluctuations. In doing so, the paper connects three previously separate literatures: the macroeconomic effects of weather shocks identified from short-run temperature variation, the recent global-versus-local temperature literature emphasizing common climate forces, and new unobserved-components approaches that distinguish persistent climate dynamics from transitory fluctuations.

This work has conceptual implications concerning adaptation. Climate change is, by construction, persistent: trend shocks shift the baseline warming rate. Weather shocks, however, are transitory, fluctuating around the climate component, moving in both directions, and eventually dissipating. This difference matters for policy. Adaptation to weather shocks involves short-term measures to smooth fluctuations, whereas adaptation to climate change requires structural adjustments to reposition the economy on a new long-run path. Misclassifying climate change as weather shocks risks misdirecting adaptation resources toward transient variability rather than the persistent changes that shape long-run growth. By separating these components, this framework clarifies where scarce adaptation resources should be concentrated.

This paper contributes to two emerging strands of research on the macroeconomic effects of temperature. The first strand emphasizes the global nature of climate risk. Bilal and Känzig (2026) show that global temperature shocks have substantially larger macroeconomic effects than local temperature shocks and derive a global damage function. Their identification strategy exploits global temperature variation, highlighting the importance of common climatic forces. However, their analysis is conducted using aggregate temperature realizations and does not distinguish between persistent climate change and transitory weather fluctuations.

The second strand explicitly separates persistent climate dynamics from short-run weather variation. In an early paper, Bloomfield (1992) extracts stochastic trends in global temperature. Rebei (2025) applies an unobserved-components model to national temperature and GDP series, decomposing both into permanent and transitory components and moving beyond reduced-form regressions on raw temperature realizations. In Rebei (2025), the model is estimated country by country and does not distinguish between global and local climate forces. The permanent climate component is specified as a local-level process, that is, a random walk in levels with i.i.d. innovations. While this framework captures

models long-run equilibrium relationships in levels while allowing for gradual adjustment through error-correction dynamics. To my knowledge, this paper is the first to apply a panel cointegration and error-correction framework to quantify the long-run macroeconomic effects of climate change.

persistence in temperature, it implies a zero expected rate of warming, so periods of accelerating or decelerating warming are interpreted as sequences of level innovations rather than as changes in the underlying warming trajectory. Closely related, Gospodinov et al. (2025) use frequency-domain methods to separate low-frequency temperature variation from high-frequency weather shocks and show that low-frequency temperature movements are associated with economically meaningful effects on output growth over medium horizons, while high-frequency weather shocks primarily affect short-run fluctuations.

This paper contributes to this literature in several dimensions. It models climate change as a stochastic trend with shocks to the warming rate itself. This specification nests the local-level model as a special case and allows the data to determine whether persistence operates through levels or through the warming rate. In addition, it explicitly decomposes country-level temperature into exposure to a common global climate trend and country-specific local climate deviations, helping to distinguish the long-run effects of global climate change from those of local climate. These climate components are then linked to output within a panel cointegration framework. Rather than estimating country-by-country relationships, this paper estimates the long-run climate-output relationship using panel cointegration with country and year fixed effects.

Applying this framework to a global panel of 192 countries yields five main findings. First, persistent climate change has large and highly gradual effects on the long-run level of output. A permanent increase in the climate component leads economies to converge slowly to a lower output path. A one-degree Celsius increase in the permanent climate component is associated with, over the long run of multiple decades, roughly a 22 percent lower level of trend real GDP within countries.[2,3] Note that this is a not a short-run impact or forecast as the adjustment unfolds extremely slowly: roughly half of the long-run loss materializes only after several decades, and close to a century is required for most of the adjustment to occur. Climate change therefore acts primarily as a slow-moving constraint on long-run productive capacity rather than as a sharp short-run growth shock.

Second, decomposing aggregate output into population and output per capita reveals

[2]My estimated long-run output losses are of similar magnitude to those reported by Bilal and Känzig (2026), with differences in empirical objects and identification. While Bilal and Känzig (2026) infer the effect of a permanent temperature increase from the ratio of cumulative impulse responses to identified global temperature shocks, my estimates are based on a direct decomposition of output and temperature into permanent and transitory components. Relatedly, Kahn et al. (2021) estimate long-run growth effects of persistent temperature deviations from historical climate norms; by contrast, my paper directly identifies the climate component and links it with long-run output.

[3]In the data, the standard deviation of annual changes in the estimated global climate component is approximately 0.04°C. Scaling the estimates by this variation implies that a one-standard-deviation increase in annual global climate change is associated with about a 1 percent reduction in the long-run level of output once adjustment is complete.

that long-run climate damages operate through multiple structural margins. In the full sample, a substantial portion of the aggregate output loss reflects demographic adjustment rather than declines in output per person. However, this pattern is not uniform across country groups. In advanced economies, persistent warming is associated with reductions in both permanent population and permanent GDP per capita, while in emerging market and developing economies, on average, neither channel exhibits a statistically significant long-run relationship with climate. These findings highlight the importance of structural heterogeneity in shaping long-run climate responses.

Third, examining the components of GDP per capita indicates that the per-capita channel operates primarily through capital accumulation rather than through total factor productivity. Persistent climate change is associated with declines in the long-run level of the capital stock and capital per worker, particularly in advanced economies, while the relationship with long-run TFP is small and statistically insignificant. These results point to capital deepening and capital adjustment as central mechanisms through which climate change affects long-run productive capacity.

Fourth, long-run climate damages are highly heterogeneous across countries and appear closely related to structural characteristics of the capital stock. Economies with more capital-intensive production structures and more durable capital stocks tend to experience larger long-run output losses from persistent warming. These economies rely on extensive networks of long-lived capital and infrastructure accumulated under historically colder climatic conditions. As the climate warms persistently, this legacy capital may become less well matched to prevailing temperature regimes, generating gradual but sustained reductions in effective productive capacity. This pattern contrasts with the conventional narrative in the climate-macro literature, which emphasizes larger damages in hot and developing countries based on responses to short-run weather shocks.

Finally, results indicate that long-run climate damages are driven primarily by exposure to the global climate trend rather than by persistent country-specific local climate deviations. Decomposing temperature into global and local components shows that the global climate trend anchors long-run output dynamics, while local climate deviations play a limited role. By contrast, short-run output fluctuations are driven mainly by transitory global weather shocks, with local weather shocks having comparatively small effects.[4]

My decomposition of temperature into permanent and transitory components follows a large and well-established literature in macroeconometrics that uses state-space models and Kalman filtering to separate stochastic trends from cyclical fluctuations. These methods have

[4]Realized temperature, and hence natural disasters, which are closely linked to global temperature (Bilal and Känzig, 2026), reflect both climate and weather components.

long been applied to output and productivity, beginning with early unobserved-components models of GDP (Clark, 1987) and formalized in the structural time-series framework of Harvey (1989). Closely related approaches have been used to model drifting trends and time-varying volatilities in inflation and other macroeconomic aggregates (Cogley and Sargent, 2005). Similar state-space techniques have also been applied to other topics, including to environmental and climate data, where Bloomfield (1992) extracts stochastic trends in global temperature, and to commodity markets, where permanent and transitory shocks are identified in oil prices using Kalman filtering (Rebei and Sbia, 2021). In this sense, my approach applies standard signal-extraction tools to temperature data rather than introducing an ad hoc decomposition. Nevertheless, the core results remain remarkably robust to alternative low-frequency representations of temperature, including Hodrick-Prescott filtering and long-difference specifications.

The remainder of the paper is organized as follows. Section 2 introduces the state-space framework used to decompose global and country-level temperature into persistent climate components and transitory weather shocks, and to extract trend and cyclical components of real GDP. Section 3 presents the estimated temperature and output decompositions and documents the key properties of global climate dynamics, country-specific climate exposure, and short-run weather fluctuations. Section 4 estimates the long-run relationship between persistent climate change and trend output using a panel cointegration and error-correction framework, and characterizes the slow adjustment dynamics toward the climate-consistent output path. Section 4 also provides robustness checks to the baseline results. Section 5 disentangles the roles of global and local climate forces, showing that long-run output losses are driven primarily by exposure to the global climate trend. Section 6 decomposes output losses into population and per-capita output components across income groups. Section 7 examines capital structure, specifically, capital intensity and capital durability, as a potential mechanism underlying the results. Section 8 analyzes short-run macroeconomic responses to global and local weather shocks around the climate-anchored output path. Section 9 concludes.

2 Methodology

2.1 Global temperature

The observed global temperature at time t, denoted T_t^G, is decomposed into a smooth climate trend component μ_t^G and a short-run weather component w_t^G:

$$T_t^G = \mu_t^G + w_t^G \tag{1}$$

The global climate trend follows a damped local linear trend with a mean-reverting slope:

$$\mu_t^G = \mu_{t-1}^G + \beta_t^G, \tag{2}$$

$$\beta_t^G = c^G + \psi^G \beta_{t-1}^G + e_t^G, \qquad e_t^G \sim \mathcal{N}(0, \sigma_{e,G}^2),\ |\psi^G| < 1. \tag{3}$$

Here, β_t^G is the global warming rate, c^G is the slope drift, and ψ^G governs the persistence of deviations from the long-run warming rate $\beta_G^* = c^G/(1-\psi^G)$. Because the level of temperature evolves as the accumulation of the warming rate, innovations to β_t^G permanently affect the path of μ_t^G, implying that shocks to the warming rate have lasting effects on the global climate trend. The shocks e_t^G therefore represent innovations to the global warming rate.[5]

The global weather component follows an AR(1) process[6]:

$$w_t^G = \phi^G w_{t-1}^G + \varepsilon_t^G, \qquad \varepsilon_t^G \sim \mathcal{N}(0, \sigma_{\varepsilon,G}^2) \tag{4}$$

2.2 Country-level temperature model

For each country c, the observed temperature $T_{c,t}$ is modeled as a combination of the global climate signal, a country-specific (filtered) climate deviation, and short-run local weather:

$$T_{c,t} = \alpha_c + \lambda_c \mu_t^G + \mu_{c,t}^{\text{loc}} + w_{c,t} \tag{5}$$

Here, α_c is a country fixed effect and λ_c is the loading of the country on the global climate level μ_t^G. Note that the global climate level μ_t^G is estimated separately using global-average temperature data (see above) and is treated as an observed common state in the country-level

[5] In a special case where $c^G = 0$ and $\psi^G = 0$, the global temperature setup would be equivalent to Rebei (2025).

[6] Long-lived climate oscillations such as the El Nino-Southern Oscillation (ENSO) generate persistent but mean-reverting temperature fluctuations at interannual and decadal frequencies (e.g., Cashin et al., 2017). Because the climate component in our framework is modeled as a non-stationary persistent process, ENSO-related variation should be primarily captured by the transitory temperature.

Kalman filter. For each country c, the filter conditions on μ_t^G and estimates the country-specific parameters (α_c, λ_c) as well as the state variables. In other words, the country-level system projects each country's temperature series onto the common global climate signal through the loading parameter λ_c, while allowing for persistent local climate deviations and transitory weather fluctuations. The filtered component $\mu_{c,t}^{\text{loc}}$ captures persistent local deviations from the global baseline, evolving as:

$$\mu_{c,t}^{\text{loc}} = \mu_{c,t-1}^{\text{loc}} + \beta_{c,t}^{\text{loc}}, \tag{6}$$

$$\beta_{c,t}^{\text{loc}} = \psi_c^{\text{loc}}\, \beta_{c,t-1}^{\text{loc}} + e_{c,t}^{\text{loc}}, \qquad e_{c,t}^{\text{loc}} \sim \mathcal{N}(0, \sigma_{e,c}^2),\ |\psi_c^{\text{loc}}| < 1. \tag{7}$$

The local warming rate $\beta_{c,t}^{\text{loc}}$ follows a stationary AR(1) around zero, and $e_{c,t}^{\text{loc}}$ are local slope innovations. Local weather is represented as

$$w_{c,t} = \phi_c w_{c,t-1} + \varepsilon_{c,t}, \qquad \varepsilon_{c,t} \sim \mathcal{N}(0, \sigma_{\varepsilon,c}^2) \tag{8}$$

2.3 Country GDP decomposition

For each country c, observed real GDP (in logs), $y_{c,t}$, is decomposed into a long-term trend component $\mu_{c,t}^y$ and a short-run transitory component $w_{c,t}^y$:

$$y_{c,t} = \mu_{c,t}^y + w_{c,t}^y \tag{9}$$

The GDP trend $\mu_{c,t}^y$ evolves as a damped local–linear trend:

$$\mu_{c,t}^y = \mu_{c,t-1}^y + \beta_{c,t}^y \tag{10}$$

$$\beta_{c,t}^y = c_c^y + \psi_c^y \beta_{c,t-1}^y + e_{c,t}^y, \qquad e_{c,t}^y \sim \mathcal{N}(0, \sigma_{e,y,c}^2),\ |\psi_c^y| < 1 \tag{11}$$

where $\mu_{c,t}^y$ is the filtered GDP trend (log level); $\beta_{c,t}^y$ is the filtered GDP growth rate (trend slope); c_c^y determines the long-run mean growth rate; $\beta_c^{*y} = c_c^y/(1-\psi_c^y)$; $e_{c,t}^y$ are structural growth shocks.

The short-run transitory component $w_{c,t}^y$ captures cyclical fluctuations around the trend and is modeled as an AR(1) process:

$$w_{c,t}^y = \phi_c^y w_{c,t-1}^y + \varepsilon_{c,t}^y, \qquad \varepsilon_{c,t}^y \sim \mathcal{N}(0, \sigma_{\varepsilon,y,c}^2),\ |\phi_c^y| < 1 \tag{12}$$

This structure provides filtered estimates of the GDP trend ($\mu_{c,t}^y$), trend growth rate ($\beta_{c,t}^y$), and cyclical component ($w_{c,t}^y$). Using superscripts for GDP variables ensures full distinction from the temperature trends μ_t^G and $\mu_{c,t}^{\text{loc}}$ defined earlier.

3 Empirical Decomposition

3.1 Data

The analysis combines long-span temperature and macroeconomic data designed to distinguish persistent climate dynamics from transitory weather fluctuations. Global temperature data (land and ocean surface) are obtained from the National Oceanic and Atmospheric Administration (NOAA) and span the period 1960 - 2022. Country-level temperature series are constructed from the ERA5 reanalysis dataset and aggregated to the national level using 2015 population weights. This approach ensures that measured temperature variation reflects conditions experienced by economic agents rather than sparsely populated regions, which is particularly important when linking climate dynamics to aggregate economic outcomes. The sample begins in 1960, corresponding to the onset of sustained global warming and the availability of reliable, internationally comparable national accounts data. Earlier decades exhibit weaker low-frequency temperature movements, providing limited identifying variation for persistent climate dynamics, while pre-1960 GDP data are much less consistent across countries.

Macroeconomic outcomes are measured using annual real GDP series from the Global Macroeconomic Database (GMD), which provides harmonized national accounts with broad postwar coverage. Population data are also from the GMD. The combined dataset covers 192 countries over the period 1960-2022. Appendix Table A1 lists countries by income group, while Appendix Table A2 summarizes data coverage across countries.

Capital, employment, and total factor productivity are from the Penn World Table (PWT) version 11.0. The capital stock is measured using the variable $rnna$, which reports the real capital stock constructed using the perpetual inventory method and expressed at constant 2021 prices. Employment is measured using emp, the number of persons engaged, and total factor productivity is proxied by $rtfpna$, the level of TFP at constant national prices. Capital intensity is defined as the logarithm of capital per worker, $\log(K/L)$, where K denotes the capital stock and L denotes employment. These variables allow the analysis to decompose output per capita into capital accumulation, labor inputs, and productivity. In addition, the depreciation rate reported in PWT is used to construct a measure of capital durability, defined as the inverse of the depreciation rate. The depreciation rate reflects the weighted average depreciation across different capital asset types, including structures, equipment, and other capital goods.

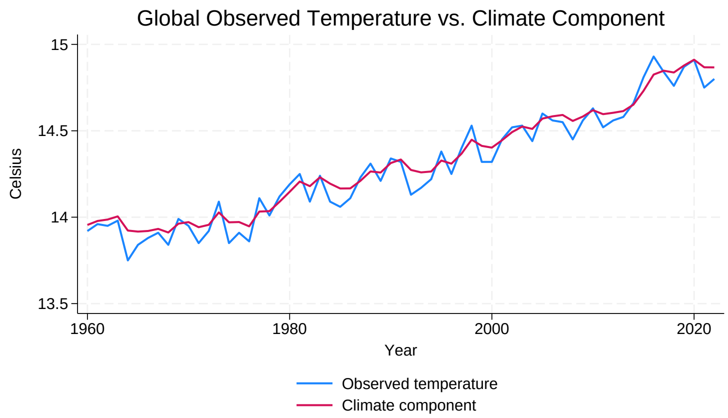
Observed temperatures and GDP are used only as inputs into the state-space model; all climate, weather, trend GDP, and cyclical GDP variables used in the regressions are filtered outputs from the estimated system rather than transformed versions of the raw series. No smoothing, demeaning, or detrending is applied to either temperature or GDP prior to estimation. All trend-cycle decompositions are generated internally by the state-space model, allowing the data to determine the degree of persistence and volatility in both climate and economic variables.

The regression analysis begins in 1970 to mitigate sensitivity to initial conditions in the Kalman filter. Although the panel is unbalanced due to unavailable GDP data, coverage is extensive: more than the 90 percent of countries have the full 53 annual observations from 1970-2022, and results are robust to restricting the sample to countries with near-complete coverage. When real GDP growth is used, it is winsorized at the 1st and 99th percentiles to reduce the influence of extreme observations that are unlikely to reflect weather- or climate-related fluctuations. Appendix Table A3 reports summary statistics for the 1970-2022 sample.

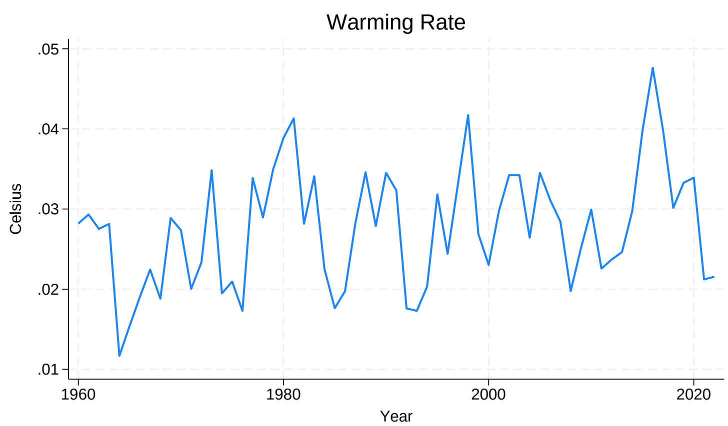
3.2 Global temperature

Figure 1 presents the decomposition of global observed temperature into its underlying climate component, the estimated warming rate, and the warming shocks. Panel (a) shows that the observed global temperature has closely tracked the estimated climate component since the 1960s, with both series trending upward by about 1°C over the sample period. Panel (b) presents the estimated warming rate, which exhibits considerable variability but generally trended upward from the 1970s through the 1990s before stabilizing at roughly 0.02 to 0.03°C per year in the 2000s and 2010s. This pattern highlights that the pace of warming has not been constant, instead alternating between acceleration phases and periods of stabilization. ψ^G is estimated equal 0.716298, implying that global climate change operates through gradual shifts in the trajectory of temperature rather than through one-time level jumps. Panel (c) displays the estimated warming shocks, which fluctuate around zero with no apparent persistence, consistent with the econometric assumption that innovations to the warming rate follow a white-noise process.

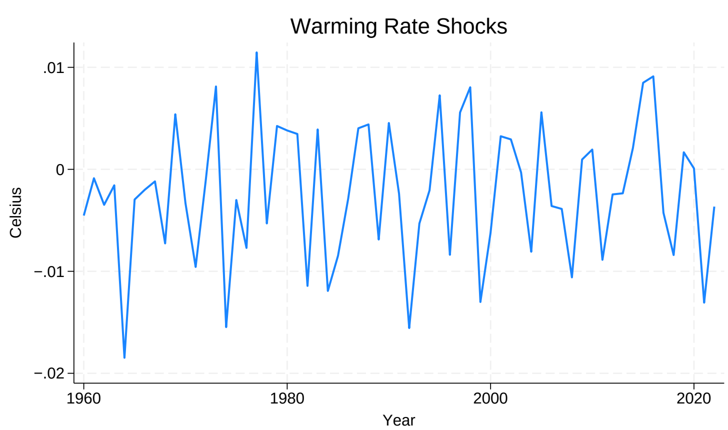
Figure 2 shows the estimated global weather component w_t^G (blue) together with its associated shocks ε_t (red). The shocks represent unpredictable innovations that directly drive the short-term fluctuations in global temperature. As expected from an AR(1) process, ε_t and w_t^G move closely together: shocks generate contemporaneous jumps in the weather series, which then decay gradually according to the estimated autoregressive parameter.



(a) Observed global temperature (T_t^G) and estimated climate component μ_t^G



(b) Estimated warming rate (β_t^G)



(c) Estimated warming shock (e_t^G)

Figure 1: Global Climate Trend

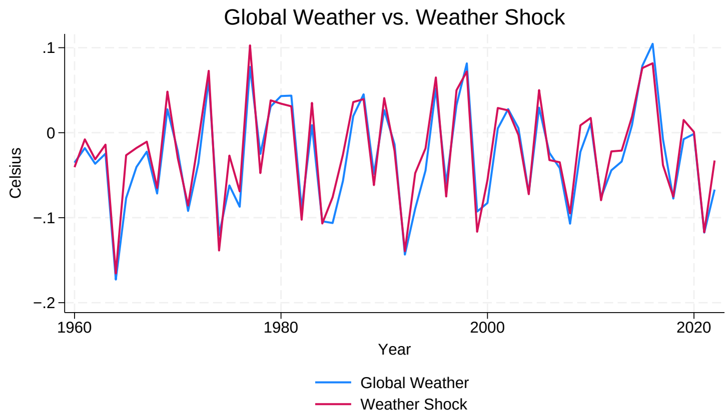


Figure 2: Global weather (w_t^G) and weather shocks (ε_t^G)

3.3 Country temperature decomposition

Figure 3 presents temperature decomposition observed across nine selected countries representing different climate (named country 1 to 9) over the period from 1965 to 2022. The first five years of the estimation window (1960-1965) are dropped because the filtered components are less stable at the beginning of the sample. Each depicts two key metrics: the observed temperature, represented by a fluctuating blue line, and a climate component produced by the model, illustrated by a smoother red line. The climate model includes both global and local climate components. Most countries exhibit a noticeable upward trajectory in both observed temperatures and the climate component, suggesting a general warming trend over the seven-decade span, and some countries have sharper rises in temperature. For instance, country 2 shows increases from 6°C to approximately 9°C.

Figure 4 illustrates the estimated weather component $w_{c,t}$ for the same set of representative countries. For each country, the blue line represents the weather component $w_{c,t}$ and the red line represents the weather shocks. The blue line highlights the short-run fluctuations in annual temperature (i.e. the weather). It reflects the difference between the two lines in Figure 3. The magnitude of these shocks varies substantially across countries. Overall, the weather component captures the noisy, transitory shocks that can temporarily obscure longer-run climate signals in the observed temperature record. The magnitude of the year-to-year weather fluctuations is large compared to the slow change in climate.

Figure 5 displays the estimated country loadings on the global climate trend (λ_c). These loadings quantify how strongly each country's temperature responds to changes in the global warming trend. The spatial pattern reveals clear heterogeneity: polar and high-latitude regions often exhibit values well above one, consistent with polar amplification, while many coastal or maritime countries load less heavily on the global trend, reflecting oceanic buffer-

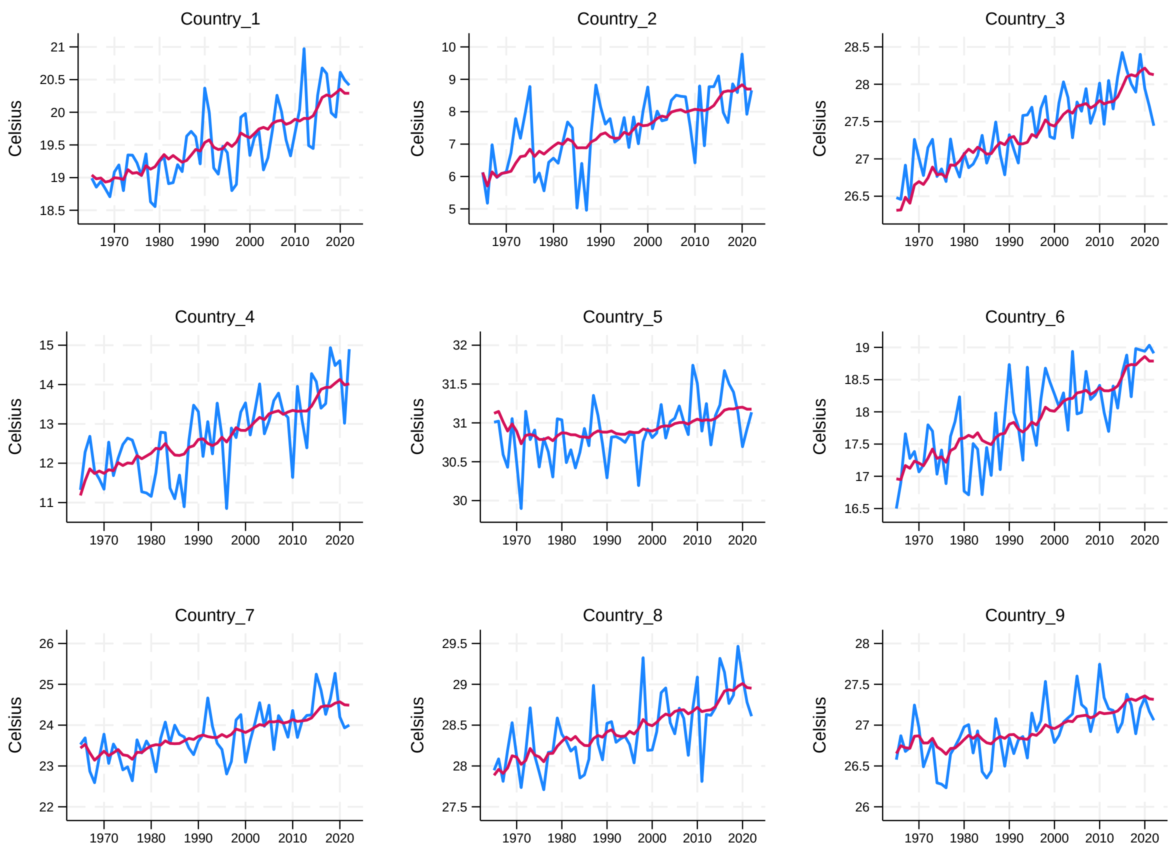


Figure 3: Country temperature ($T_{c,t}$) and country climate ($\alpha_c + \lambda_c \mu_t^G + \mu_{c,t}^{\text{loc}}$)

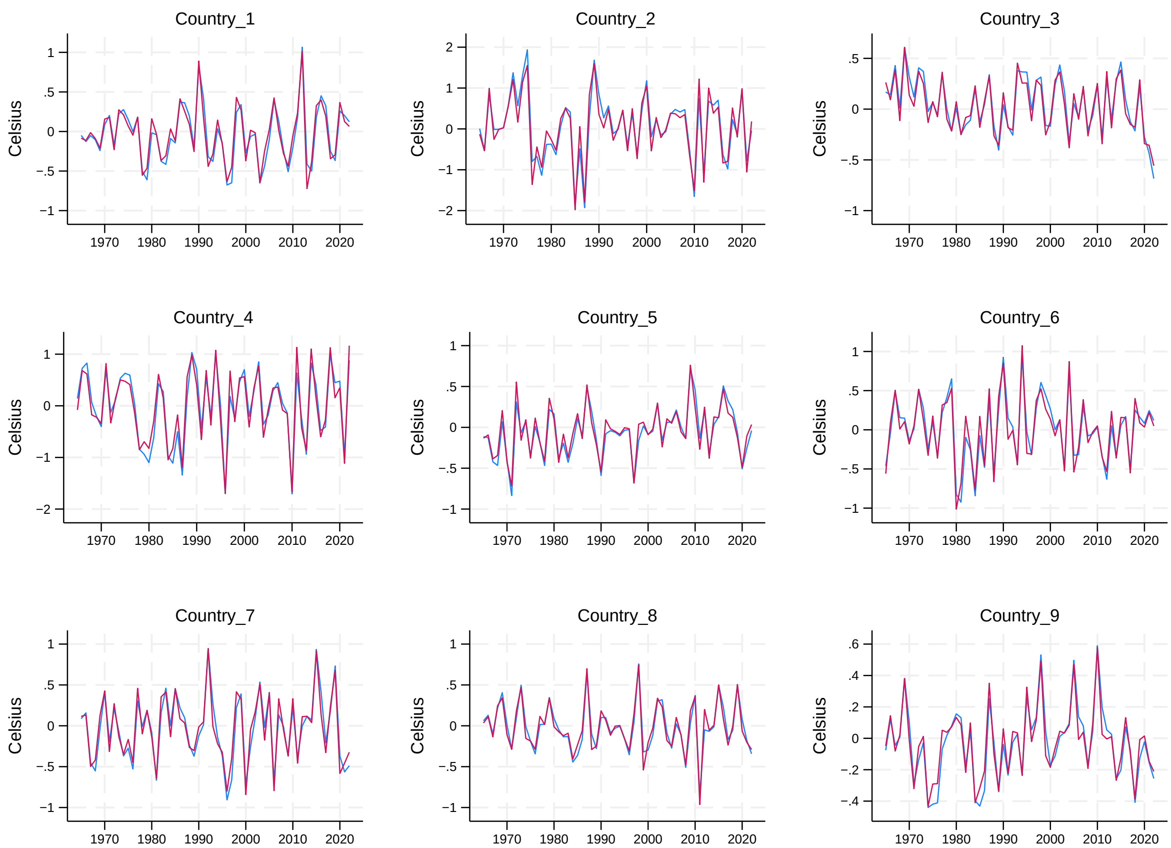


Figure 4: Country weather ($w_{c,t}$, in blue) and weather shocks ($\varepsilon_{c,t}$, in red)

ing. These differences are not surprising: climate science has long emphasized polar amplification and maritime moderation. Their magnitude highlights the importance of allowing country-specific responses rather than imposing a one-size-fits-all global temperature measure. This heterogeneity strengthens identification in the panel regressions and underscores that the global warming signal translates unevenly across geographies.

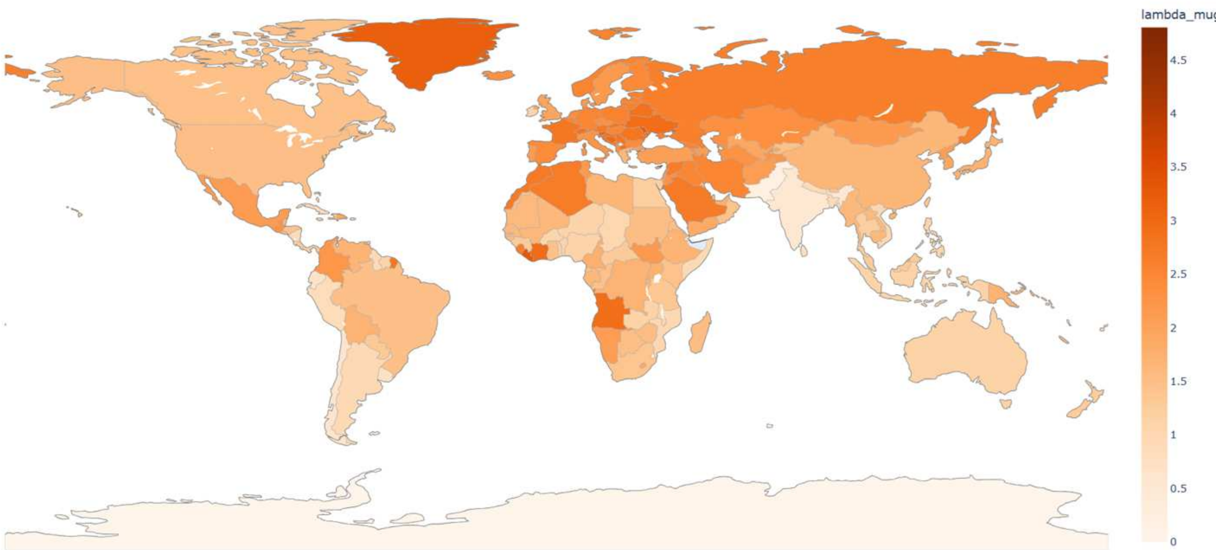


Figure 5: Country loading of global temperature (λ_c)

Figure 6 illustrates country climate decomposition from 1965 to 2022 across the nine countries: global climate loading (blue), country fixed effects (green), and country varying local climate (red). Across all countries, the blue line shows a clear upward trend, indicating that global climate forces are the primary driver of rising temperatures. In contrast, both the green and red lines remain flat, suggesting that country aggregate climate conditions are generally connected to global warming

3.4 GDP composition

Figures 7 and 8 present the decomposition of real GDP into permanent (trend) and transitory components for the same representative set of countries. For most cases, observed log real GDP almost visibly overlaps with the estimated trend component throughout the sample period, indicating that output is driven primarily by persistent shifts in the underlying growth path rather than by short-lived fluctuations. In a smaller number of cases, most notably countries 4 and 6, deviations between observed GDP and its trend are more visible, reflecting larger cyclical episodes or prolonged periods of adjustment. The close alignment

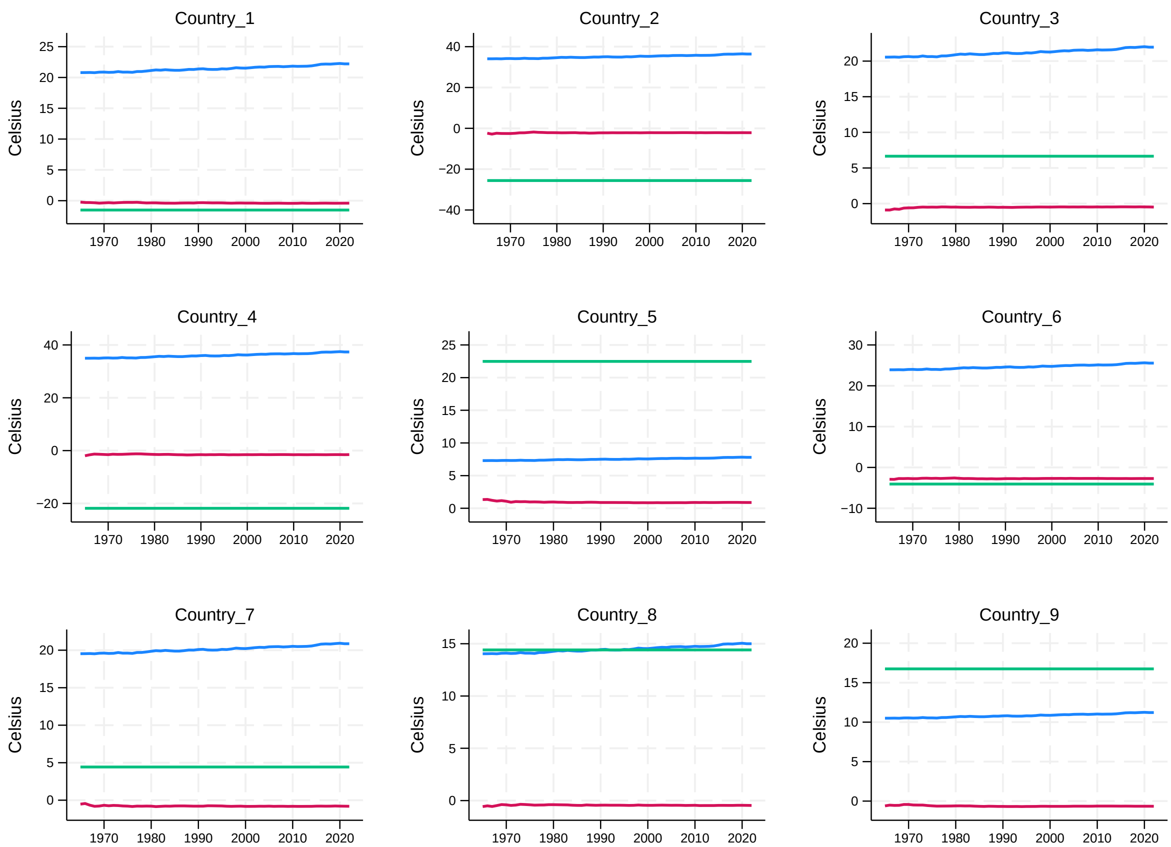


Figure 6: Global loading (blue, $\lambda_c \mu_t^G$), country fixed effects (green, α_c) and country local climate (red, $\mu_{c,t}^{\text{loc}}$)

between observed and trend GDP in most countries reflects the dominance of low-frequency output movements, as evidenced by the presence of meaningful but mean-reverting transitory components in countries with larger cyclical fluctuations (see Figure 8)

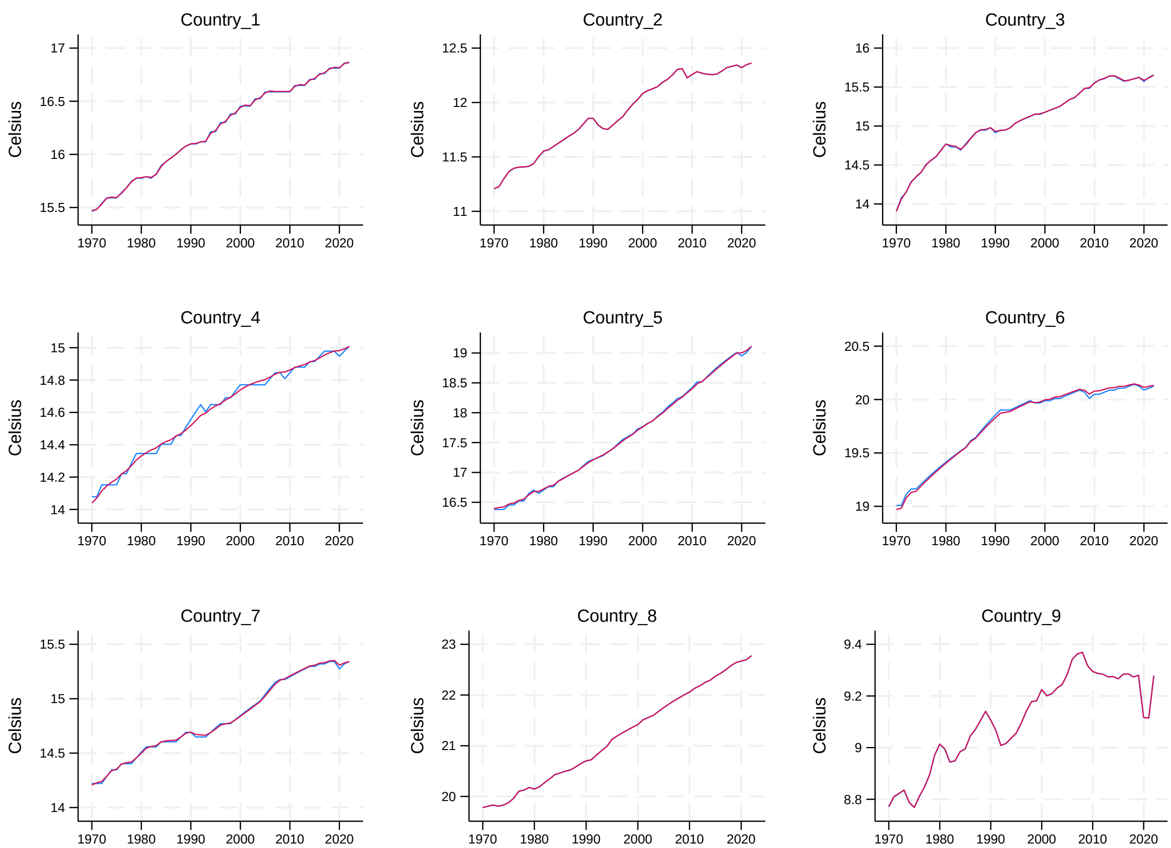


Figure 7: Log of Real GDP ($y_{c,t}$) in blue and Log of Real Trend GDP ($\mu^y_{c,t}$) in red

4 Long-run Impacts of Climate: a Panel Cointegration Approach

To estimate the long-run impacts of climate change on economic activity, this section estimates the long-run relationship between the permanent (climate) component of temperature and the long-run (trend) component of real GDP, and then characterizes the adjustment dynamics toward that long-run relationship. The key motivation is that both climate and potential output are slow-moving objects that exhibit strong persistence and are unlikely

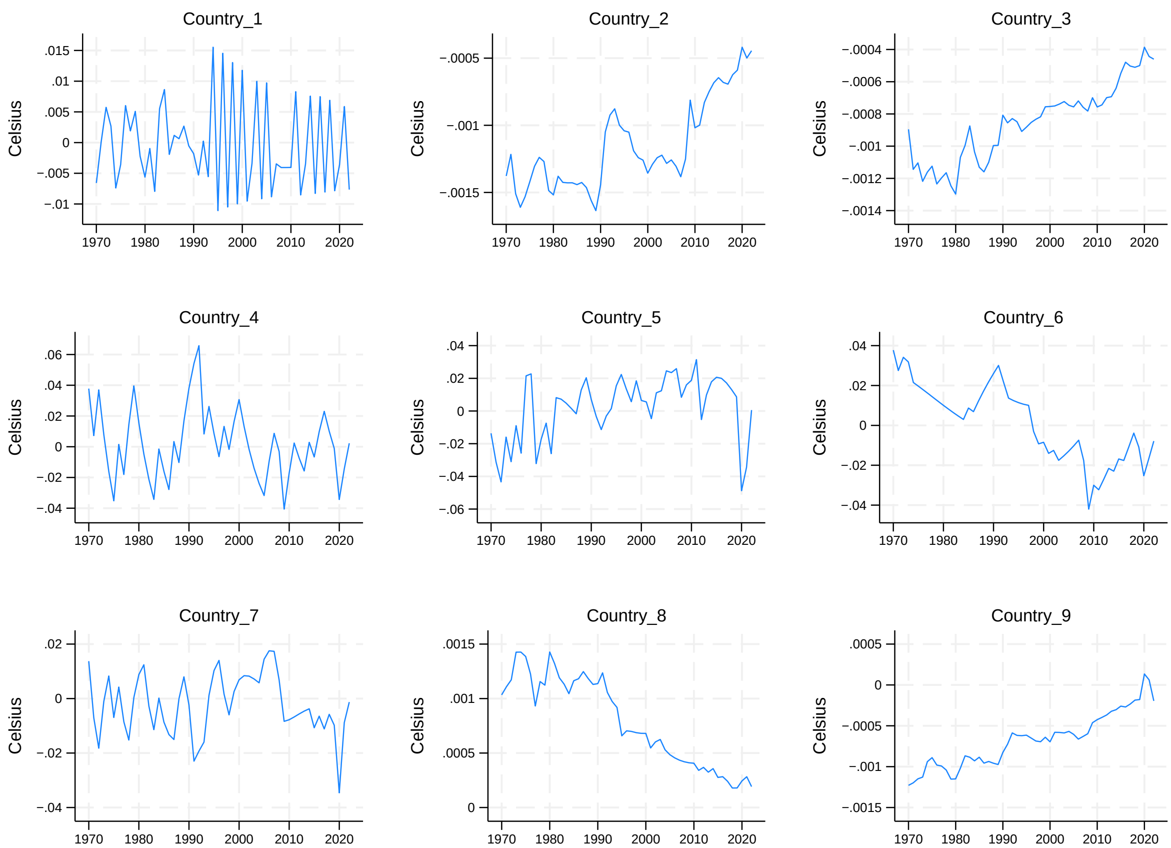


Figure 8: Log of Real Transitory GDP ($w_{c,t}^{y}$)

to be stationary in levels. Regressions that treat these processes as stationary shocks may have low power at annual frequencies and can yield unstable short-run estimates. An error-correction model (ECM) provides a disciplined way to combine (i) a long-run equilibrium relationship in levels with (ii) short-run dynamics in growth rates, while allowing temporary deviations from the long-run relationship to be gradually corrected over time.

4.1 Constructing the permanent climate component

Let μ_t^G denote the estimated global climate trend from Section 2.1 and $\mu_{c,t}^{loc}$ the country-specific climate deviation from Section 2.2. Country c loads on the global climate trend with loading λ_c. Define the permanent climate component for country c as

$$\mu_{c,t}^T \equiv \alpha_c + \lambda_c \mu_t^G + \mu_{c,t}^{loc}, \tag{13}$$

which captures the slow-moving, non-stationary component of local temperature that arises from (i) global warming transmitted differentially across countries and (ii) persistent local deviations from the global baseline.

I measure the long-run component of output using the filtered GDP trend $\mu_{c,t}^y$ (log level) from the GDP decomposition in Section 2.3. The empirical analysis focuses on the post-1970 sample to ensure broad country coverage and stable measurement.

4.2 Step 1: The long-run (cointegrating) relationship in levels

I first estimate the long-run equilibrium relationship between trend log real GDP and the permanent climate component using a two-way fixed-effects panel specification:

$$\mu_{c,t}^y = \alpha_c + \tau_t + \beta\, \mu_{c,t}^T + u_{c,t}, \tag{14}$$

where α_c are country fixed effects and τ_t are year fixed effects. Country fixed effects absorb time-invariant differences in levels of output and climate across countries, while year fixed effects absorb global macroeconomic shocks common to all countries. Importantly, identification of the long-run relationship does not rely on common global variation alone. Because countries differ systematically in their exposure to global climate change and has their own local climate, permanent temperature retains substantial low-frequency within-country variation even after demeaning by year fixed effects. As a result, equation (14) captures a long-run relationship between permanent output and temperature driven by differential exposure to global climate, and own local climate.

Estimated long-run semi-elasticity. Table 1 reports the estimated β from (14). The coefficient is negative and statistically significant. Since $\mu^y_{c,t}$ is in logs and $\mu^T_{c,t}$ is measured in degrees Celsius, β can be interpreted as a semi-elasticity: a one-degree (permanent) increase in the climate component is associated with an approximately $100 \times \beta$ percent lower level of trend GDP in the long run, within country (for small β).

Table 1: Long-run relationship between trend GDP and the permanent climate component

Dependent variable	$\mu^y_{c,t}$ (trend log real GDP)
$\mu^T_{c,t}$ (permanent climate component, °C)	-0.2542^{***}
	(0.0713)
Country fixed effects	Yes
Year fixed effects	Yes
Observations	9,943
Countries	192
Within R^2	0.707

Notes: The table reports estimates of the long-run relationship between trend log real GDP and the permanent climate component. The sample includes only countries classified as advanced economies or emerging market and developing economies (EMDEs) according to the IMF World Economic Outlook (WEO). Robust standard errors clustered by country are reported in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1 percent levels, respectively.

Box 1: How to Read the Estimated Coefficient -0.2542 in Table 1

- The point estimate implies that a one-degree Celsius increase in the permanent climate component is associated with approximately a 22 percent lower level of trend GDP in the long run, within country ($exp(-0.254) = 0.776$).
- This is not an immediate impact. The estimate describes where output eventually settles after a one-degree Celsius permanent increase in the underlying climate trend – an endpoint that takes *many decades* to approach. GDP does not drop by 22 percent overnight or even within a generation.
- The adjustment is exceptionally slow. Section 4.3 will show that roughly half of the long-run loss materializes only after about 30 years, and it takes close to a century to close 90 percent of the gap. In the near term, the annual drag on trend growth is a few tenths of a percentage point – easily obscured by ordinary business-cycle fluctuations.
- The 22 percent is not a prediction about the future. The estimate is based on historical patterns across 192 countries from 1970 to 2022. It describes what has been associated with warmer underlying temperatures in the past –not what will happen under any

particular future scenario. Different levels of adaptation, technology, or policy could lead to very different outcomes going forward.

The estimated coefficient on the permanent climate component is negative and statistically significant. The high within-country R-squared indicates that the permanent climate component and common time effects jointly explain a substantial share of within-country variation in trend GDP. At the same time, the near-zero between-country R-squared (not shown) reflects the fact that cross-country level differences are absorbed by fixed effects, reinforcing that the estimate relies on time-series rather than cross-sectional variation. The point estimate implies that a one-degree Celsius increase in the permanent climate component is associated with approximately a 22 percent lower level of trend GDP in the long run, within country ($exp(-0.254) = 0.776$). Here, permanent refers to the underlying persistent temperature trend in the model, not to a one-time or irreversible increase in temperature. This estimate reflects a long-run level association after full adjustment over many decades, rather than a short-run impact or a forecast. To assess whether the estimated long-run effect is driven by outliers, Appendix Figure A1 presents the partial regression plot corresponding to the specification in Table 1. The negative relationship between trend output and the permanent climate component is visible across the distribution of the data after removing country and year fixed effects, indicating that the estimated effect is not likely driven by outliers.[7]

This estimate reflects the cumulative impact of persistent climate change. The magnitude of the estimated coefficient should be interpreted as the long-run anchoring effect of climate on economic activity. A permanent increase in climate temperature does not imply an immediate collapse in output; instead, it lowers the level around which the economy operates in the long run. This distinction is crucial. The estimate does not imply that GDP falls by about 22 percent in the year of warming. Rather, it indicates that, once adjustment is complete, the economy converges to a persistently lower output path consistent with climate-constrained productive capacity. Climate change affects output primarily through slow-moving channels such as capital depreciation, infrastructure durability, labor productivity, health, and sectoral reallocation. As a result, the long-run level effect of climate change can be economically large even when short-run growth responses are modest or difficult to detect at annual frequency. In addition, these estimates reflect the historical relationship between

[7] My approach is closely related to recent work that infers the long-run impact of climate change from short-run temperature shocks using local projections or VARs, following the logic of Sims (1986), including Kahn et al. (2021) and Bilal and Känzig (2026). While these studies recover the permanent effect as the ratio of cumulative impulse responses of output and temperature, I estimate the same long-run object directly by linking trend output to the permanent component of temperature in a state-space framework. My contribution is to estimate the permanent climate–output relationship transparently and directly, without relying on the extrapolation of short-run dynamics.

persistent temperature and output over the sample period and should not be extrapolated mechanically to future warming scenarios or adaptation responses.

Equivalent growth interpretation. Although equation (14) is written as a levels relationship between the permanent components of output and temperature, it has an equivalent representation in terms of growth. Taking first differences of equation (14) yields

$$\Delta\mu^{Y}_{c,t} = (\tau_t - \tau_{t-1}) + \beta\Delta\mu^{T}_{c,t} + \Delta u_{c,t}, \tag{15}$$

which implies that the same coefficient β links changes in permanent output to changes in permanent temperature. In this representation, the model states that countries experiencing faster increases in the permanent climate component tend to exhibit slower growth in permanent GDP. In practice, however, annual changes in the permanent temperature component are very small because climate evolves gradually over time. As a result, estimating this relationship directly in annual first differences is statistically underpowered. For this reason, the levels specification provides a more informative estimate of the long-run semi-elasticity of permanent output with respect to permanent temperature, while the differenced equation provides a useful interpretation of the underlying mechanism.

4.3 Step 2: Error-correction dynamics

The regression in (14) provides an estimate of the long-run relationship, but it does not by itself establish that the relationship is an equilibrium anchor to which the economy returns after shocks. To test for equilibrium adjustment, I construct the error-correction term (ECT) as the residual from the long-run relationship:

$$\widehat{ECT}_{c,t} \equiv \mu^{y}_{c,t} - \widehat{\alpha}_c - \widehat{\tau}_t - \widehat{\beta}\,\mu^{T}_{c,t}. \tag{16}$$

If trend output and climate are linked by a stable long-run relationship, then deviations from that relationship should predict subsequent adjustments in trend GDP growth.

I estimate the ECM in (trend) growth rates:

$$\Delta\mu^{y}_{c,t} = \phi\,\widehat{ECT}_{c,t-1} + \gamma\,\Delta\mu^{T}_{c,t} + \sum_{j=1}^{2}\rho_j\Delta\mu^{y}_{c,t-j} + \theta_0\Delta w_{c,t} + \theta_1\Delta w_{c,t-1} + \gamma_c + \tau_t + \eta_{c,t}, \tag{17}$$

where $\Delta\mu^{y}_{c,t}$ is trend GDP growth, $\Delta\mu^{T}_{c,t}$ is the change in the permanent climate component and $\Delta w_{c,t}$ is the change in the country-specific weather component. γ_c and τ_t are country and year fixed effects. Standard errors are clustered by country.

The coefficient ϕ governs error correction. A negative and statistically significant ϕ implies that when trend GDP is above the level implied by climate (a positive $\widehat{ECT}_{c,t-1}$), subsequent trend GDP growth is lower, bringing output back toward the long-run path. The term γ captures whether changes in the permanent climate component have an immediate effect on trend growth. In a climate context, a natural benchmark is that permanent climate change shifts the long-run level of output, while short-run growth fluctuations are dominated by transitory weather and global cyclical forces. In that case, ϕ is expected to be negative, while γ may be small at annual frequencies.

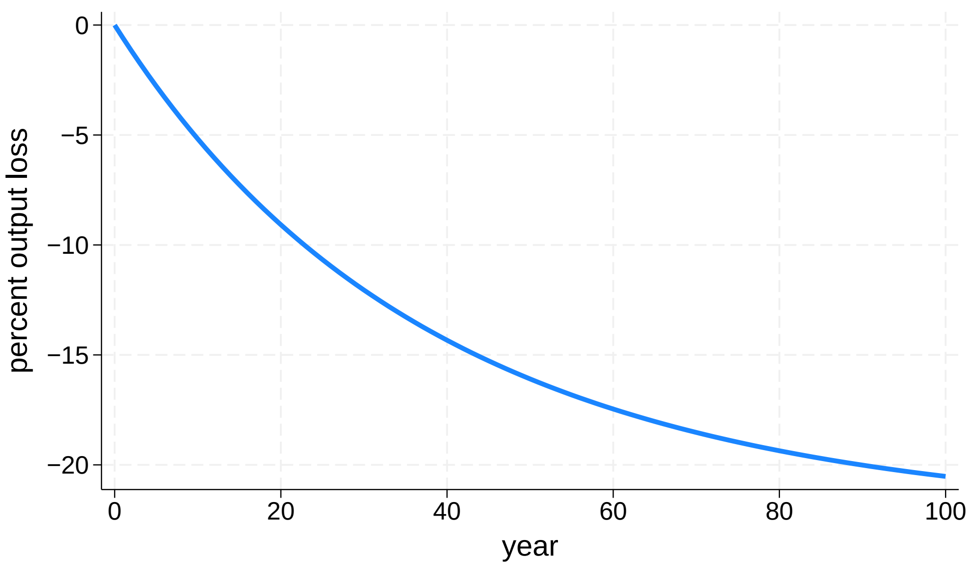
Table 2: Error-correction model for trend GDP growth

Dependent variable	$\Delta\mu^y_{c,t}$ (trend GDP growth)
$\widehat{ECT}_{c,t-1}$ (error-correction term)	-0.0232^{***}
	(0.0028)
$\Delta\mu^T_{c,t}$ (permanent climate change)	-0.0036
	(0.0120)
$\Delta\mu^y_{c,t-1}$	0.4423^{***}
	(0.0291)
$\Delta\mu^y_{c,t-2}$	0.0598^{***}
	(0.0169)
$\Delta w_{c,t}$ (local weather)	-0.0006
	(0.0013)
$\Delta w_{c,t-1}$ (local weather)	-0.0012
	(0.0009)
Country fixed effects	Yes
Year fixed effects	Yes
Observations	9,367
Countries	192
Within R^2	0.294

Notes: The table reports estimates of an error-correction model for trend GDP growth. The error-correction term $\widehat{ECT}_{c,t-1}$ is constructed as the lagged residual from the long-run relationship between trend GDP and the permanent climate component reported in Table 1. The sample includes only countries classified as advanced economies or emerging market and developing economies (EMDEs) according to the IMF World Economic Outlook (WEO). Robust standard errors clustered by country are reported in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1 percent levels, respectively.

The ECM in Table 2 provides direct evidence of error correction. The estimated coefficient on the lagged error-correction term is $\widehat{\phi} \approx -0.0232$, indicating that deviations of trend GDP from the climate-consistent long-run path are gradually corrected over time. The statistically significant error-correction term is consistent with gradual adjustment toward a stable long-run relationship between $\mu^y_{c,t}$ and $\mu^T_{c,t}$. The magnitude implies very slow adjustment: roughly 2.3 percent of the remaining deviation is eliminated each year. In practical terms, following a one-degree permanent increase in temperature, it takes approximately 30 years to close half of the resulting output gap and close to a century (around 95–100 years) to eliminate 90 percent of the gap toward the lower climate-consistent path. This adjustment initially manifests as a modest but persistent drag on trend growth, on the order of about 0.6 percentage points in the first few years (given by $0.0232 \times 0.254 \approx 0.006$), and then declines mechanically over time as the gap narrows. Figure 9 illustrates the very slow adjustment of output implied by the ECM estimates after a permanent 1°C climate shock. The estimated standard error of the error-correction coefficient suggests the implied adjustment horizons are subject to uncertainty, with an approximate 95 percent confidence interval of 24-39 years for the half-life and 79-129 years for the time required to close 90 percent of the gap, which in any case still indicates highly gradual adjustment.

Figure 9: Simulated output adjustment following a permanent 1°C climate shock.



Note: The figure shows the transition path implied by the estimated error-correction model. Output converges very slowly toward its lower long-run equilibrium, reflecting the slow speed of adjustment estimated in the ECM.

In the climate context, these dynamics reflect the gradual erosion of productive capacity through channels such as capital depreciation, rising maintenance costs, reduced labor productivity, and slow sectoral reallocation. Because these forces operate through long-lived stocks, adjustment unfolds over decades rather than through abrupt contractions. Moreover, the average climate shock is only 0.03°C per year, implying that in practice, the output adjustments are very small and very gradual.

In contrast, contemporaneous changes in the permanent climate component $\Delta\mu^T_{c,t}$ have a limited short-run association with trend growth at annual frequency. This is consistent with the view that climate change does not operate as a conventional macroeconomic shock, but rather as a slow-moving structural force whose effects accumulate over time. At annual horizons, incremental changes in the climate trend are small relative to weather shocks and cyclical fluctuations, so their economic consequences emerge primarily through gradual adjustment in levels rather than through immediate changes in growth rates.

Local weather shocks have no statistically significant effect on trend GDP growth once long-run climate conditions and error-correction dynamics are controlled for, indicating that idiosyncratic weather fluctuations mainly influence short-run economic volatility rather than the long-run path of output.

Panel cointegration diagnostics: Because permanent output and temperature components are highly persistent, I complement the error-correction analysis with formal panel cointegration diagnostics. I employ the error-correction-based tests of Westerlund (2007), which assess whether deviations from a candidate long-run relationship are corrected over time. This approach allows for heterogeneous adjustment dynamics across countries and accounts for cross-sectional dependence through bootstrap inference.

Appendix Table A4 reports the results. In the full sample of 192 countries, the panel statistic (Pt) rejects the null hypothesis of no cointegration at the 10% level using dependence-robust bootstrap p-values, while group-mean statistics provide weaker evidence (Panel A). This pattern is consistent with heterogeneous long-run adjustment and the presence of global shocks, which are known to reduce the power of cointegration tests in finite samples.

As a robustness check, I re-estimate the tests excluding countries that experience prolonged episodes of exceptional growth, which are likely to reflect idiosyncratic structural breaks unrelated to climate. In this restricted sample of 179 countries, the panel statistic rejects the null of no cointegration at the 5% level (Panel B). The strengthening of the diagnostics is consistent with structural breaks weakening cointegration tests in the full sample. In this restricted sample, the estimated long-run coefficient on permanent temperature is slightly larger in magnitude and more precisely estimated, with an estimate of -0.265.

Overall, I interpret these results as suggestive evidence of long-run adjustment between permanent temperature and output components. Given the presence of global shocks, heterogeneous climate exposure, and generated permanent states, I view cointegration tests as complementary diagnostics that support the error-correction dynamics discussed above.

4.4 Robustness checks

This subsection assesses the robustness of the long-run climate-output relationship using several complementary approaches. I examine specifications based on annual first differences and long differences, alternative measures of trend output including HP-filtered GDP and unfiltered GDP levels, alternative constructions of the climate variable such as HP-filtered country temperature and a 30-year moving average of temperature, and discuss potential concerns related to reverse causation from economic activity to temperature.

First differences: First, I estimate a panel regression of annual real GDP growth on annual changes in the permanent climate component, including country and year fixed effects. Consistent with the slow-moving nature of climate change, the estimated coefficient shown in Appendix Table A5 is imprecise and statistically insignificant at annual frequency. This lack of power is expected: incremental changes in the climate trend are small from year to year, while output growth is dominated by short-run cyclical variation, making it difficult to detect level effects using first differences alone.

Long differences: Second, I estimate long-difference regressions that relate changes in output between 1970 and 2022 to the corresponding change in the permanent climate component over the same period. In contrast to the annual first-difference specification, the long-difference estimates (in the same Table) are large, negative, and highly statistically significant, whether output is measured using filtered trend GDP or observed GDP levels. These long-difference results closely mirror the magnitude of the long-run coefficient obtained from the cointegration specification, indicating that the estimated climate damages are not an artifact of the state-space filtering or the ECM structure. These benchmarks reinforce the interpretation that climate change primarily operates through gradual level effects that accumulate over decades, rather than through detectable contemporaneous effects on annual growth rates. The ECM framework is therefore well suited to the data: it reconciles weak short-run growth responses with strong long-run anchoring of output to persistent climate dynamics.

Hodrick-Prescott (HP)-filtered GDP: As a further robustness check, I assess whether the long-run climate-output relationship depends on the specific trend extraction method used for output. In the baseline analysis, trend output is obtained from a state-space decomposition that allows for stochastic trend growth. To provide a more well-known benchmark, I replace this measure with alternative low-frequency representations of output based on the HP filter applied to log real GDP, using annual smoothing parameters of $\lambda = 100$ and $\lambda = 6.25$, and also consider specifications using log GDP levels without statistical filtering (see Appendix Table A6). Re-estimating the long-run fixed-effects regression with these alternative measures yields remarkably similar results: the estimated coefficient on the permanent climate component remains negative, highly statistically significant, and quantitatively close to the baseline estimates across all specifications. This stability indicates that the main findings are not an artifact of the state-space trend specification or of a particular filtering choice, but instead reflect a robust low-frequency relationship between persistent climate change and the level of output.

HP-filtered country temperature: Finally, I assess robustness to the construction of the climate variable itself by replacing the state-space permanent climate component with a purely statistical low-frequency temperature trend. Specifically, I apply the HP filter to observed country-level temperature, extracting a smooth temperature trend separately for each country using annual smoothing parameters of $\lambda = 100$ and $\lambda = 6.25$. Appendix Table A7 reports the corresponding long-run fixed-effects regressions of trend output on these HP-filtered temperature measures. Across both specifications, the estimated coefficients remain negative and statistically significant, confirming that the long-run climate-output relationship does not hinge on the state-space decomposition of temperature. The magnitudes are modestly attenuated relative to the baseline estimates, which is expected given that HP filtering is a coarse statistical procedure that mixes medium-frequency variation with persistent climate dynamics. Nevertheless, the stability of the sign and statistical significance provides strong evidence that the main results reflect a robust low-frequency relationship between warming and output levels rather than an artifact of the particular climate filtering approach.

30-year moving average temperature: As an additional robustness check, we construct a simple measure of climate based on a 30-year moving average of annual temperature, consistent with the standard climatological definition of climate used by the World Meteorological Organization. The moving average is computed using a backward-looking window covering the previous thirty years for each country. Appendix Table A8 reports the results. The estimated coefficient remains negative and statistically significant, indicating that higher long-run temperatures are associated with lower levels of output. The magnitude of the coefficient (-0.29) is close to the baseline estimates obtained using the statistical climate decomposition. This similarity suggests that the results are not driven by the specific filtering approach used to isolate the climate component. Instead, the negative long-run relationship between temperature and output emerges even when climate is measured using a simple climatological moving average.

Correlation between warming and long-run growth: A potential concern is that the negative association between the permanent climate component and trend output partly reflects differences in long-run growth paths across countries rather than the effect of climate itself. In particular, countries located in colder regions may have experienced faster warming over the sample period while also exhibiting lower long-run growth because they started at higher levels of development. To address this concern, I augment the baseline specification by interacting year fixed effects with initial GDP per capita from the Penn World Table. This allows countries with different initial development levels to follow flexible time paths in output, thereby absorbing convergence and divergence dynamics unrelated to climate. Formally, the specification becomes

$$\mu^Y_{c,t} = \alpha_c + \tau_t + \beta\mu^T_{c,t} + \theta_t \log(y_{0,c}) \times D_t + u_{c,t}, \tag{18}$$

where $y_{0,c}$ denotes initial GDP per capita, and D_t indicates year t dummy and θ_t allows the effect of initial income to vary flexibly over time. Appendix Table A9 reports the results using initial GDP per capita measured in 1990 and, alternatively, in 1970 (with fewer countries). In both cases, the estimated coefficient on the permanent climate component remains negative and statistically significant. The magnitude is also broadly comparable to the baseline estimates, indicating that the long-run relationship between permanent temperature and trend output is not driven by differential growth paths associated with initial levels of development.

For ease of interpretation, the specification can be rewritten in first differences as

$$\Delta\mu^Y_{c,t} = \lambda_t + \beta\Delta\mu^T_{c,t} + \gamma_t \log(y_{0,c}) + \varepsilon_{c,t}, \tag{19}$$

where $\lambda_t = \tau_t - \tau_{t-1}$ and $\gamma_t = \theta_t - \theta_{t-1}$. In this representation, the model relates growth in the permanent component of output to changes in the permanent climate component, while allowing countries with different initial income levels to follow distinct growth paths over time. The negative estimate of β therefore implies that, conditional on initial development levels, countries experiencing faster increases in the permanent climate component tend to exhibit slower growth in permanent GDP.

Potential reverse causations: An important concern is reverse causation from economic activity to temperature, whereby higher output raises greenhouse gas emissions and could affect local temperature. Climate science, however, indicates that changes in surface temperature are driven by the accumulation of global emissions rather than contemporaneous national emissions. As a result, fluctuations in a country's output and emissions are unlikely to generate meaningful variation in its local temperature trend. Another related concern is that reductions in aerosol emissions, which exert a cooling effect, may raise temperature while coinciding with economic transitions that affect GDP. Such aerosol clean-up has been more pronounced in advanced economies, reflecting earlier environmental regulation and structural change. However, the estimated climate effects are identified from within-country variation over time and remain strong when the analysis is restricted to advanced economies (see Section 6). To the extent that advanced economies experienced broadly similar air-quality improvements, these common trends are absorbed by year fixed effects. For aerosol clean-up to explain the results, it would need to vary across advanced economies in a way that is systematically correlated with the permanent climate component, $\mu^T_{c,t}$. Empirically, this channel does not appear to drive the results: when controlling for SO_2 emissions, a key aerosol gas, the estimated long-run impact of climate change on advanced economies' output remains strong (results not shown).[8]

4.5 Comparison with conventional raw temperature regressions

For comparison, this section reports conventional panel regressions that relate output directly to raw observed temperature, following the dominant approach in the climate–macro literature. In contrast to my baseline framework, these specifications do not distinguish between persistent climate change and transitory weather fluctuations. The purpose of this exercise is not to provide alternative estimates of long-run climate damages, but rather to illustrate how standard temperature regressions behave when applied to output levels and growth.

Appendix Table A10 reports fixed-effects regressions of output on observed temperature, controlling for country and year fixed effects and clustering standard errors at the country level. Columns (1) and (2) use trend output and log real GDP, respectively, as dependent variables. In both cases, the estimated temperature coefficient is negative, statistically significant, and is much smaller in magnitude compared to my baseline result. However, the economic interpretation of these coefficients is unclear as the raw temperature combines persistent climate change with high-frequency weather variation.

Column (3) of Table A10 reports a regression of output growth (winsorized at p1 and p99 levels) on observed temperature, which is the specification most commonly used in the existing literature. Consistent with prior findings, the estimated effect is smaller and less significant, reflecting short-run weather responses rather than persistent climate change. These benchmark results highlight the limitations of conventional temperature regressions for assessing long-run macroeconomic impacts of climate change and motivate my decomposition-based approach, which isolates the persistent climate component and links it explicitly to trend output in a panel cointegration framework.

[8] SO_2 emissions are included solely as a robustness check and should not be interpreted as a preferred control. SO_2 emissions are closely correlated with economic activity and industrial structure. Conditioning on them may absorb part of the endogenous output responses.

5 Global or Local Climate as a Main Driver?

A new literature emphasizes that climate change should be understood as a global phenomenon rather than as a collection of independent local shocks. Bilal and Känzig (2026) show that global temperature fluctuations have substantially larger and more persistent macroeconomic effects than country-level temperature variation. They argue that this difference arises because global temperature captures the evolution of the climate system itself and is closely linked to the incidence of extreme climatic events such as heatwaves, droughts, and storms. By contrast, local temperature variation used in conventional panel regressions is weakly correlated with these extremes and therefore understates the macroeconomic costs of climate change.

Motivated by this global–local distinction, this section examines whether a similar asymmetry emerges when climate dynamics are decomposed directly at the country level. Rather than contrasting global temperature with local temperature measures, as in the existing literature, I decompose country-level climate into exposure to a common global climate factor and a residual local climate component. This approach allows us to isolate the macroeconomic effects of globally-driven climate change from those of country-specific climate deviations within a unified panel framework, and to assess whether global climate forces embedded in local temperature dynamics serve as the primary long-run anchor for output.

Formally, I estimate the following specification:

$$\mu^T_{c,t} \; = \; \alpha_c + \tau_t \; + \; \beta_1 \left(\lambda_c \mu^G_t\right) \; + \; \beta_2 \, \mu^{\text{loc}}_{c,t} \; + \; u_{c,t}, \tag{20}$$

where $\mu^T_{c,t}$ denotes the climate-driven component of temperature for country c at time t. The term μ^G_t represents the common global climate factor, capturing the evolution of the global climate system over time. The country-specific loading λ_c measures each country's exposure to this global factor, allowing the impact of global climate change to vary across countries.[9] It is useful to emphasize that λ_c is estimated entirely from temperature dynamics. The component $\mu^{\text{loc}}_{c,t}$ captures local climate deviations that are orthogonal to the global factor. The specification includes country fixed effects α_c and year fixed effects τ_t, so identification comes from differential exposure to the global climate factor across countries and from within-country variation in local climate deviations over time.

To assess the relative importance of global and local climate forces, I decompose the within-country variance of the permanent climate component, $\mu^T_{c,t} = \lambda_c \mu^G_t + \mu^{\text{loc}}_{c,t}$, into the

[9] Countries differ systematically in their exposure λ_c (see Figure 5), reflecting geographic and physical climate characteristics. This heterogeneity implies that a common global warming trajectory maps into distinct country-specific permanent climate paths $\mu^T_{c,t}$ over time.

contributions of each component. The decomposition shows that low-frequency climate variation within countries is overwhelmingly driven by exposure to the global climate factor. The global-exposure term $\lambda_c \mu_t^G$ accounts for essentially most (about 117%) of the within-country variance of $\mu_{c,t}^T$, while the local component $\mu_{c,t}^{\text{loc}}$ accounts for about 10%. The shares sum to 100% once the negative covariance term is included, with $2\,\text{Cov}(\lambda_c \mu_t^G, \mu_{c,t}^{\text{loc}})$ contributing about -27%. This negative covariance indicates that local climate deviations tend to partially offset globally-driven climate movements.

Table 3: Global versus Local Climate Components

	(1) $\mu_{c,t}^Y$	(2) $\mu_{c,t}^Y$
$\lambda_c \mu_t^G$	-0.3236^{***}	-0.1927^{**}
	(0.0786)	(0.0912)
$\mu_{c,t}^{\text{loc}}$	-0.0114	
	(0.1274)	
Country fixed effects	Yes	Yes
Year fixed effects	Yes	No
Climate-zone × year FE	No	Yes
Observations	9,943	9,943
Countries	192	192
Within R^2	0.712	0.725

Notes: This table reports fixed-effects estimates of equation (20). The term $\lambda_c \mu_t^G$ captures each country's exposure to the common global climate factor, where μ_t^G denotes the global climate component and λ_c measures country-specific exposure. The variable $\mu_{c,t}^{\text{loc}}$ captures country-specific local climate deviations from the global component. Column (1) includes country and year fixed effects. Column (2) replaces global year fixed effects with climate-zone-by-year fixed effects, absorbing any global shocks or secular trends common to countries within the same climate regime. The local climate component is excluded in column (2) to isolate identification from within-zone heterogeneity in exposure to the global climate trend. Standard errors are clustered at the country level and reported in parentheses. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

Table 3 reports the corresponding fixed-effects estimates with trend (permanent) output $\mu_{c,t}^Y$ as the dependent variable. Column (1) shows a sharp contrast between global and local climate components. Exposure to the global climate factor, $\lambda_c \mu_t^G$, is associated with a large, negative, and statistically significant effect on output, while the coefficient on the local climate component $\mu_{c,t}^{\text{loc}}$ is small and statistically indistinguishable from zero. In other words, long-run climate damage to trend output is driven primarily by exposure to the global warming trend rather than by persistent country-specific local climate drift. Countries that are more exposed to global climate change experience systematically larger output losses, even after controlling for common global shocks through year fixed effects and for time-invariant country characteristics through country fixed effects. This finding indicates that global climate change operates as a binding long-run force on aggregate economic performance.

The insignificance of the local climate component is economically intuitive and informative. Local climate deviations net of global warming are comparatively small and more likely to be partially offset through adaptation, migration, or changes in production patterns. As a result, local climate variation does not appear to anchor the long-run level of aggregate output once exposure to the global climate factor is accounted for.

A potential concern with this specification is that countries with higher exposure to the global climate trend, λ_c, are disproportionately located in colder regions, so that $\lambda_c \mu_t^G$ could partly correlate with other time-varying forces that differentially affect cold-climate economies. To address this concern, Column (2) replaces global year fixed effects with climate-zone-by-year fixed effects, which absorb any global shocks or secular trends common to countries within the same climate regime. Identification in this specification therefore comes exclusively from within-zone heterogeneity in exposure to global warming. The estimated effect of $\lambda_c \mu_t^G$ remains negative and statistically significant, indicating that long-run output losses are not driven by generic cold-region trends but by differential exposure to the global climate factor itself.

6 Structural Decomposition of Long-Run Climate Damages

While the previous section examined whether global or local climate forces drive the temperature variation relevant for economic outcomes, the analysis so far has focused on aggregate output. The next step is to examine through which economic margins this decline in output occurs.

The baseline results establish that persistent climate change is associated with a large and highly gradual reduction in the long-run level of aggregate output. However, aggregate real GDP can adjust along multiple structural margins. In particular, a decline in total output may reflect lower productive capacity per person, changes in the size of the population through fertility, mortality, and migration, or both. This distinction is first-order for interpretation. If long-run climate damages operate primarily through GDP per capita, they point to productivity and factor-accumulation mechanisms (e.g., capital deepening, misallocation, and TFP). If, instead, damages are amplified by population responses, especially in advanced economies, then demographic adjustment is an important margin through which climate change affects aggregate output. This section therefore decomposes permanent GDP into its two structural components: permanent GDP per capita and permanent population, and documents how these margins respond to persistent climate change across country groups.

6.1 Accounting identity and empirical objects

Let $Y_{c,t}$ denote real GDP and $N_{c,t}$ denote population in country c at time t. The log identity

$$\log Y_{c,t} \; = \; \log\left(\frac{Y_{c,t}}{N_{c,t}}\right) \; + \; \log N_{c,t} \tag{21}$$

implies that long-run movements in aggregate output can be decomposed into movements in output per capita and population. To align this decomposition with my climate framework, I apply the same trend–cycle methodology used in Sections 2 and 3 to each series and focus on their permanent components. Let $\mu^{Y}_{c,t}$ denote the permanent (trend) component of log real GDP, let $\mu^{N}_{c,t}$ denote the permanent component of log population, and let $\mu^{Y/N}_{c,t}$ denote the permanent component of log real GDP per capita. The permanent components satisfy the same identity:

$$\mu^{Y}_{c,t} \; = \; \mu^{Y/N}_{c,t} \; + \; \mu^{N}_{c,t}, \qquad \text{where} \quad \mu^{Y/N}_{c,t} \equiv \mu^{Y}_{c,t} - \mu^{N}_{c,t}. \tag{22}$$

This decomposition provides a transparent mapping from the estimated long-run climate–output relationship to underlying structural margins. Specifically, I estimate long-run relationships between the permanent climate component, $\mu^{T}_{c,t}$, and (i) permanent GDP per capita, $\mu^{Y/N}_{c,t}$, and (ii) permanent population, $\mu^{N}_{c,t}$, using the same fixed-effects cointegration specification as in Section 4. I then examine heterogeneity across country groups and, for advanced economies, relate permanent GDP per capita losses to baseline measures of capital intensity and capital durability.

Table 4 decomposes the long-run climate-output relationship into demographic and per capita components. Column (1) shows that the permanent component of temperature is negatively and statistically significantly associated with log population. The estimated coefficient implies that persistent warming is linked to a sizable reduction in the permanent level of population. In contrast, Column (2) indicates that the relationship between permanent temperature and permanent GDP per capita is small in magnitude and statistically insignificant in the full sample. These results suggest that a substantial portion of the long-run aggregate output losses documented earlier operates through demographic adjustment rather than through declines in output per person. Since aggregate output can be written as the product of population and output per capita, the identity $\mu^{Y}_{ct} = \mu^{Y/N}_{ct} + \mu^{N}_{ct}$ implies that long-run GDP losses may reflect either productivity effects or population responses. The

Table 4: Decomposition of Long-Run Climate Effects: Population and GDP per Capita

Dependent variable	$\mu^N_{c,t}$ (trend log population)	$\mu^{Y/N}_{c,t}$ (trend log real GDP per capita)
$\mu^T_{c,t}$ (°C)	-0.2052^{***}	-0.0490
	(0.0575)	(0.0704)
Country fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	9,943	9,943
Countries	192	192
Within R^2	0.668	0.363

Notes: The table reports estimates of the long-run relationship between permanent temperature and structural components of output. Column (1) uses the permanent component of log population ($\mu^N_{c,t}$). Column (2) uses the permanent component of log real GDP per capita ($\mu^{Y/N}_{c,t}$). The sample includes only countries classified as advanced economies or emerging market and developing economies (EMDEs) according to the IMF World Economic Outlook (WEO). Robust standard errors clustered by country are reported in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1 percent levels, respectively.

estimates indicate that, at the global level, population dynamics account for a large share of the aggregate effect.

This finding has important implications for interpretation. First, it helps reconcile the magnitude of aggregate GDP effects with more modest per capita responses. Second, it points to demographic channels, such as migration, fertility, and mortality, as potential adjustment margins in the long run. In particular, if persistent climate change induces outward migration or reduces population growth in affected regions, aggregate output may decline even in the absence of large per capita productivity losses.

At the same time, the population relationship should be interpreted with caution. Long-run demographic trends in many economies might also reflect structural forces unrelated to climate, including population aging and declining fertility. To the extent that these trends are correlated with gradual warming over the sample period, part of the estimated association between permanent temperature and permanent population may reflect these underlying demographic dynamics rather than a direct causal effect of climate on population. For this reason, the results in this section should primarily be viewed as a decomposition of the aggregate climate-output relationship rather than as definitive evidence of a structural demographic response to climate change.

The decomposition nonetheless motivates the heterogeneity analysis that follows. While the full-sample results suggest that demographic responses are quantitatively important, the relative importance of population versus per capita channels may differ across country groups. In the next subsection, I examine whether advanced and emerging economies display distinct adjustment patterns and whether capital intensity and durability shape the per capita response to persistent climate change.

6.2 Decomposition by country groups

Table 5 reports the decomposition of long-run climate effects within advanced economies. In contrast to the full-sample results, both demographic and per capita channels are economically and statistically meaningful in this subsample. The permanent climate component is negatively associated with the trend level of population, with an estimated coefficient of -0.23, statistically significant at the 1 percent level. This suggests that persistent warming is correlated to sizeable long-run demographic adjustment in advanced economies, although the correlation may or may not be causal. The permanent climate component is also negatively associated with trend GDP per capita. The estimated coefficient of approximately -0.28 is statistically significant at the 10 percent level. Thus, unlike the global sample, where aggregate output losses largely reflect population dynamics, advanced economies exhibit both demographic responses and meaningful declines in output per person.

These findings imply that long-run aggregate output losses in advanced economies operate through multiple structural margins. Persistent climate change is associated with declines in both population and per capita productive capacity; the latter is consistent with mechanisms involving capital adjustment. At the same time, changes in population in advanced economies may also reflect broader demographic forces that are not directly related to climate. The next section investigates these economic mechanisms more directly by examining capital deepening and total factor productivity.

Table 6 presents the same decomposition for emerging market and developing economies (EMDEs). In contrast to advanced economies, neither the demographic nor the per capita channel is statistically significant in this subsample. The estimated coefficient on the permanent climate component is negative in both specifications, but the magnitudes are smaller and imprecisely estimated. These results indicate that, on average within EMDEs, persistent climate change does not exhibit a clear long-run association with either permanent population or permanent GDP per capita. This stands in contrast to the advanced-economy subsample, where both demographic and per capita channels were economically meaningful.

Table 5: Advanced Economies: Decomposition of Long-Run Climate Effects

Dependent variable	$\mu^N_{c,t}$ (trend log population)	$\mu^{Y/N}_{c,t}$ (trend log real GDP per capita)
$\mu^T_{c,t}$ (°C)	-0.2287^{***}	-0.2811^{*}
	(0.0786)	(0.1532)
Country fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	1,923	1,923
Countries	37	37
Within R^2	0.627	0.775

Notes: The table reports estimates of the long-run relationship between the permanent climate component and structural components of output for advanced economies (AEs). Column (1) uses the permanent component of log population ($\mu^N_{c,t}$). Column (2) uses the permanent component of log real GDP per capita ($\mu^{Y/N}_{c,t}$). All specifications include country and year fixed effects. Robust standard errors clustered by country are reported in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1 percent levels, respectively.

Table 6: Emerging Market and Developing Economies: Decomposition of Long-Run Climate Effects

Dependent variable	$\mu^N_{c,t}$ (trend log population)	$\mu^{y/n}_{c,t}$ (trend log real GDP per capita)
$\mu^T_{c,t}$ (°C)	-0.0751	-0.1154
	(0.0770)	(0.0898)
Country fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	8,020	8,020
Countries	155	155
Within R^2	0.713	0.306

Notes: The table reports estimates of the long-run relationship between the permanent climate component and structural components of output for emerging market and developing economies (EMDEs). Column (1) uses the permanent component of log population ($\mu^N_{c,t}$). Column (2) uses the permanent component of log real GDP per capita ($\mu^{y/n}_{c,t}$). All specifications include country and year fixed effects. Robust standard errors clustered by country are reported in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1 percent levels, respectively.

7 Capital Structure and Long-Run Climate Vulnerability

The results in the previous sections show that persistent climate change has important long-run macroeconomic effects. In advanced economies, the population decomposition indicates that these losses arise from declines in both population and GDP per capita, suggesting that climate change affects not only demographic dynamics but also per-capita productive capacity. This raises a natural question: through which structural mechanisms might persistent climate change reduce per-capita productivity?

One potential mechanism involves the interaction between persistent climate change and the structure of the capital stock. Climate change evolves slowly over time, while capital stocks adjust only gradually. When production relies heavily on installed capital, or when capital goods are long-lived and depreciate slowly, the productive structure may adapt only slowly to evolving climatic conditions. In such settings, persistent warming may generate larger efficiency losses because existing capital vintages become less well suited to the new climate environment. By contrast, economies characterized by lower capital intensity or faster capital turnover may adjust more rapidly as older capital depreciates and is replaced.

These considerations suggest that two structural features of the capital stock may be particularly relevant for understanding climate vulnerability: the overall intensity of capital in production and the durability of capital goods. Economies with higher capital intensity rely more heavily on installed capital, while economies with more durable capital experience slower capital turnover due to lower depreciation rates. Both characteristics may reduce the speed at which the capital stock can adapt to persistent changes in climatic conditions. The empirical analysis below examines whether countries with higher capital intensity or more durable capital stocks exhibit stronger long-run output responses to climate change.

7.1 Capital Accumulation Channel

Before examining how capital structure shapes climate vulnerability across countries, I first investigate whether persistent climate change affects capital accumulation directly. Using data from the Penn World Table, I estimate fixed-effects regressions relating the permanent climate component to the permanent components of the capital stock (μ^K), capital per worker ($\mu^{K/L}$), and total factor productivity (μ^A). These outcomes correspond to the key components of long-run GDP per capita in a standard growth accounting framework.

Table 7 reveals a clear pattern across country groups. In advanced economies, persistent warming is associated with a statistically significant decline in the capital stock and in capital per worker. The estimated coefficients indicate that higher permanent temperatures are linked to lower levels of installed capital and reduced capital deepening over the long run. By contrast, there is no statistically significant relationship between persistent temperature and total factor productivity. One interpretation is that climate change may depress the effective productivity of capital, but technological progress and adaptation partly offset these effects in measured TFP. As a result, the net effect on TFP appears limited, while adjustment operates primarily through capital accumulation. In this framework, adaptation is not modeled explicitly but is embedded in the observed equilibrium adjustment.

In EMDEs, the estimated relationships are considerably weaker. Persistent warming is not significantly associated with changes in the capital stock, capital per worker, or total factor productivity. These results are consistent with the idea that economies with lower capital intensity and faster capital turnover face smaller adjustment costs when climatic conditions shift persistently. The stronger role of the capital channel in advanced economies should not be interpreted as weaker adaptation. Rather, because these economies are more capital intensive, adaptation operates primarily through adjustments in capital accumulation. The observed decline in capital in advanced economies thus reflects an equilibrium response to persistent climate conditions, rather than a failure to adapt. Lastly, these findings should not be interpreted as indicating lower overall climate vulnerability in EMDEs, but rather as only reflecting differences in the channels captured by this framework.

Table 7: Persistent Climate Change and Capital Accumulation

	Advanced Economies			EMDEs		
	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	μ^K	$\mu^{K/L}$	μ^A	μ^K	$\mu^{K/L}$	μ^A
$\mu_{c,t}^T$	-0.662^{***}	-0.330^{**}	-0.009	-0.141	-0.003	-0.080
	(0.203)	(0.153)	(0.100)	(0.105)	(0.124)	(0.092)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,735	1,735	1,711	6,848	6,421	4,027
Countries	35	35	35	136	136	83
Within R^2	0.846	0.760	0.362	0.779	0.394	0.126

Notes: The table reports fixed-effects regressions relating the permanent climate component ($\mu_{c,t}^T$) to the permanent components of the capital stock (μ^K), capital per worker ($\mu^{K/L}$), and total factor productivity (μ^A). All regressions include country and year fixed effects. Robust standard errors clustered at the country level are reported in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels, respectively. The sample of countries is smaller than in the baseline due to data availability in the PWT.

7.2 Continuous Evidence

To examine how structural characteristics of the capital stock shape climate vulnerability across countries, I relate the long-run response of GDP per capita to persistent climate change to cross-country variation in capital intensity and capital durability. Using data from the Penn World Table (PWT), capital intensity is measured as the ratio of the capital stock to employment, while capital durability is proxied by the inverse depreciation rate ($1/\delta$) [10].To mitigate concerns about reverse causality, both variables are constructed using country averages over the period 1970–1990, well before the bulk of the warming observed in later decades. These pre-determined structural characteristics are then interacted with the permanent climate component, $\mu_{c,t}^{T}$, in the fixed-effects specification.

The first three columns of Table 8 report the results for advanced economies. Column (1) allows the climate response to vary with capital intensity. The interaction between the permanent climate component and log capital intensity is negative and statistically significant, indicating that economies with more capital-intensive production structures experience larger long-run declines in trend GDP per capita in response to persistent warming. Column (2) instead interacts the climate component with capital durability. The estimated coefficient is again negative, suggesting that economies characterized by more durable capital stockswhere depreciation rates are lower and capital remains in place for longer periodstend to experience larger adverse effects from persistent climate change. Column (3) includes both interaction terms simultaneously. The interaction with capital intensity remains strongly negative and statistically significant, while the durability interaction also remains negative, indicating that both dimensions of capital structure contribute to amplifying the long-run impact of warming.

The last three columns present the corresponding estimates for emerging market and developing economies (EMDEs). Earlier, without the interactions, Section 6 shows that the average relationship between persistent climate change and trend GDP per capita is relatively modest, but substantial heterogeneity emerges once differences in capital structure are taken into account. The interaction terms for both capital intensity and capital durability are negative and statistically significant, indicating that the long-run economic consequences of persistent warming are also larger in EMDEs with more capital-intensive production and more durable capital stocks.

[10]The Penn World Table constructs aggregate depreciation rates as weighted averages of asset-specific depreciation rates based on the composition of the capital stock. These rates vary widely across assets: for example, about 1.1 percent for residential structures and 3.1 percent for non-residential structures, compared with around 31.5 percent for computers and software and about 11 to 19 percent for machinery and transport equipment (PWT 9.0 User Guide). Since the economic lifetime of capital is approximately the inverse of the depreciation rate, $1/\delta$ provides a natural proxy for capital durability.

Table 8: Capital Intensity, Durability, and Climate Damages (Continuous Measures)

	Advanced Economies (AEs)			EMDEs		
	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	$\mu^{y/n}_{c,t}$	$\mu^{y/n}_{c,t}$	$\mu^{y/n}_{c,t}$	$\mu^{y/n}_{c,t}$	$\mu^{y/n}_{c,t}$	$\mu^{y/n}_{c,t}$
$\mu^T_{c,t}$	4.459***	0.637	5.175***	1.200***	1.407***	2.288***
	(1.241)	(0.677)	(1.333)	(0.431)	(0.529)	(0.542)
$\mu^T_{c,t} \times \log(K/E)$	−0.369***		−0.359***	−0.117***		−0.104***
	(0.095)		(0.091)	(0.035)		(0.037)
$\mu^T_{c,t} \times \log(\text{Durability})$		−0.300	−0.246*		−0.492***	−0.388**
		(0.196)	(0.145)		(0.161)	(0.171)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,817	1,817	1,817	6,932	7,091	6,932
Countries	35	35	35	133	136	133
Within R^2	0.840	0.795	0.846	0.384	0.376	0.398

Notes: The table reports fixed-effects estimates for advanced economies (AEs) and emerging market and developing economies (EMDEs). Capital intensity is measured as the log of the capital-to-employment ratio averaged over 1970–1990 using data from the Penn World Table (PWT). Capital durability is measured as the log of the inverse depreciation rate ($1/\delta$), also averaged over 1970–1990. These predetermined measures are interacted with the permanent climate component ($\mu^T_{c,t}$). Robust standard errors clustered by country are reported in parentheses. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

A potential concern is that capital intensity and durability may proxy for initial development level, since richer economies tend to be more capital-intensive with longer-lived infrastructure. To address this, I augment the specifications with an interaction between the permanent climate component and initial GDP per capita (measured in 1990, from the PWT). The results remain robust. In both subsamples, the initial GDP per capita interaction is small and statistically insignificant, while the capital structure interactions retain their sign and significance, particularly for durability, which strengthens in the EMDE sample. This indicates that capital structure, and durability in particular, represents a distinct structural channel through which persistent climate change affects long-run productive capacity, rather than a reflection of development-level heterogeneity.

7.3 Bucket Evidence

To further illustrate these patterns, Table 9 presents an alternative specification in which countries are grouped into discrete categories based on combinations of capital intensity and capital durability. The bucket classification is constructed separately within each country group so that the thresholds reflect the distribution of capital structure among advanced economies and EMDEs, respectively. In both samples, the baseline group consists of economies characterized by relatively low capital intensity and lower capital durability.

The estimates reveal a clear and consistent pattern across the two country groups. Relative to the baseline category, the interaction coefficients become increasingly negative as either capital intensity or capital durability increases. In advanced economies, countries with higher capital intensity or more durable capital exhibit larger declines in trend GDP per capita in response to persistent warming. Although the coefficients are estimated with somewhat less precision in the smaller AE sample, the pattern of increasingly negative effects across capital structures is evident.

A similar relationship emerges in the EMDE sample. Countries characterized by higher capital intensity experience substantially larger negative responses of trend GDP per capita to the permanent climate component, and the most negative coefficients occur in economies that combine both high capital intensity and high capital durability. The results across both advanced economies and EMDEs indicate that economies with more capital-intensive production structures and slower capital turnover tend to experience larger long-run economic losses from persistent climate change.

The evidence across advanced economies and EMDEs suggests that the structure of the capital stock may play a central role in shaping the long-run macroeconomic consequences of climate change. Economies characterized by more capital-intensive production structures

Table 9: Capital Intensity and Durability (Bucket Specification)

Dependent variable	Advanced Economies $\mu^{y/n}_{c,t}$	EMDEs $\mu^{y/n}_{c,t}$
$\mu^{T}_{c,t}$ (Low capital intensity – Low durability)	0.1128	0.0837
	(0.2725)	(0.1035)
$\mu^{T}_{c,t}\times$ (Low capital intensity – High durability)	-0.2974	-0.3090^{*}
	(0.1854)	(0.1684)
$\mu^{T}_{c,t}\times$ (High capital intensity – Low durability)	-0.3457^{*}	-0.3694^{***}
	(0.1820)	(0.0955)
$\mu^{T}_{c,t}\times$ (High capital intensity – High durability)	-0.3508^{*}	-0.4220^{***}
	(0.1831)	(0.1144)
Country fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	1,817	6,932
Countries	35	133
Within R^2	0.813	0.3897

Notes: The table reports fixed-effects estimates for advanced economies and emerging market and developing economies (EMDEs). Countries are grouped according to capital intensity and capital durability using pre-determined measures constructed from the Penn World Table (PWT). Capital intensity is defined as the capital-to-employment ratio averaged over 1970–1990. Capital durability is measured as the inverse depreciation rate ($1/\delta$), also averaged over 1970–1990. The baseline group consists of countries with both low capital intensity and low capital durability. Robust standard errors clustered by country are reported in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1 percent levels, respectively.

and slower capital turnover appear to face larger adjustment costs when climatic conditions shift persistently. By contrast, countries with lower capital intensity and faster capital depreciation exhibit smaller responses. These patterns are consistent with a capital-adjustment mechanism in which persistent climate change interacts with existing capital vintages, generating larger efficiency losses when the installed capital stock is both abundant and slow to adapt to changing climatic conditions.

8 Short-Run Dynamics of Global and Local Weather Shocks

8.1 Conceptual distinction between climate and weather

Previous sections focus on the long-run relationship between climate and aggregate output, emphasizing how exposure to global climate change anchors the level of economic activity over time. Much of the existing empirical literature, however, studies a different object, namely short-run macroeconomic responses to weather fluctuations. These studies typically exploit high-frequency variation in temperature, precipitation, or extreme events at the local or global level and document economically meaningful effects on output growth, productivity, and sectoral activity over horizons ranging from one to several years.

The distinction between climate and weather is primarily one of persistence. Climate reflects slow-moving shifts in the underlying state of the climate system, while weather captures transitory deviations around that state. As a result, climate change is associated with long-run level effects on output, whereas weather shocks are more likely to generate short-run fluctuations and adjustment dynamics. Importantly, these two dimensions are complements rather than substitutes. Short-run weather shocks occur around a climate-dependent baseline, and their economic effects may depend on prevailing climate conditions.

A similar distinction applies to the global versus local dimension. Global weather phenomena, such as El Nino events or synchronized heat anomalies, generate correlated shocks across countries and can affect global economic activity in the short to medium run. Local weather shocks, by contrast, are more idiosyncratic and primarily influence domestic economic outcomes. While both types of weather variation matter for short-run dynamics, neither necessarily determines the long-run level of output once persistent global climate exposure is taken into account.

This section complements the long-run framework developed earlier by examining short-run dynamics around the climate-driven output path. I show how short-run responses to global and local weather shocks can coexist with the finding that long-run output levels are primarily anchored by exposure to global climate change.

8.2 Econometric specification for short-run weather dynamics

I use weather shocks extracted from the state-space decomposition of temperature discussed in Sections 2 and 3. Global weather shocks are defined as innovations to the global weather component,

$$w_t^G = T_t^G - \mu_t^G,$$

where ε_t^G denotes the corresponding innovation to the AR(1) process governing w_t^G. Local weather shocks are defined analogously as innovations to the country-specific weather component,

$$w_{c,t} = T_{c,t} - (\alpha_c + \lambda_c \mu_t^G + \mu_{c,t}^{\text{loc}}),$$

with $\varepsilon_{c,t}^\ell$ denoting the innovation to local weather in country c at time t. By construction, both shocks are orthogonal to persistent climate dynamics and capture unpredictable, transitory fluctuations in temperature.

To estimate short-run responses, I follow the global temperature literature and employ panel local projections. For each horizon $h = 0, 1, \ldots, H$, I estimate the following local projection, following Jordà (2005):

$$\Delta y_{c,t+h} = \alpha_c^{(h)} + \theta_h^G \, \varepsilon_t^G + \theta_h^\ell \, \varepsilon_{c,t}^\ell + \sum_{j=1}^{2} \rho_j^{(h)} \Delta y_{c,t-j} + u_{c,t+h}^{(h)}, \tag{23}$$

where $\Delta y_{c,t}$ is year-on-year change in log real GDP (and not trend GDP), ε_t^G is the global weather shock, $\varepsilon_{c,t}^\ell$ is the local weather shock, $\alpha_c^{(h)}$ are horizon-specific country fixed effects, and $u_{c,t+h}^{(h)}$ is the horizon-specific error term. The coefficients θ_h^G, θ_h^l trace the impulse responses of output growth to global and local weather shocks.

I do not include year fixed effects in equation (23). The reason is that the global weather shock ε_t^G is identical across countries by construction, so time fixed effects would mechanically absorb it. This choice follows directly from the logic in Bilal and Känzig (2026), who emphasize that global weather shocks must be identified from common time-series variation rather than cross-sectional differences. Identification of local weather effects, by contrast, relies on cross-country heterogeneity in $\varepsilon_{c,t}^\ell$.

8.3 Short-run responses to global and local weather shocks

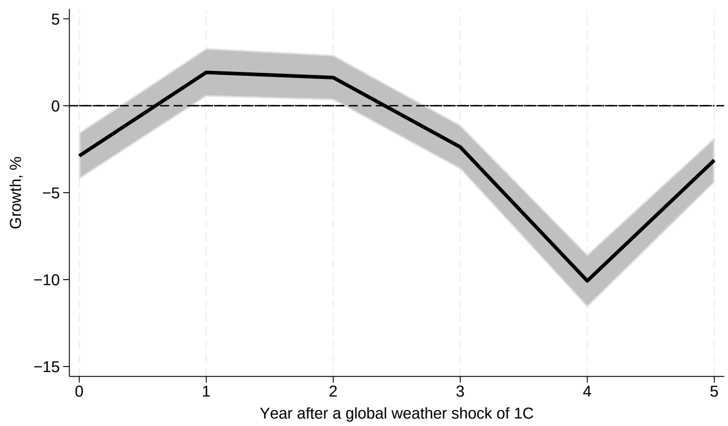
Panel A of Figure 10 reports the impulse response of output growth to a one degree Celsius global weather shock, defined as an innovation to the transitory global weather component orthogonal to the global climate trend. The response is economically large and transitory. Output growth declines on impact, turns positive in the first two years following the shock, and then reverses sharply several years later before gradually converging back toward zero. The non monotonic profile indicates delayed propagation (such as natural disasters or reconstruction). These dynamics relate closely to the mechanism emphasized by Bilal and Känzig (2026). In their framework, global temperature shocks generate large macroeconomic effects because they are associated with extreme climate events such as natural disasters. Although disasters materialize as discrete local events, their economic impact reflects exposure to common global climatic forces that simultaneously strain adjustment capacity across countries. My results complement this insight by showing that innovations to global weather around the climate path induce substantial short-run macroeconomic fluctuations.

Panel B of Figure 10 presents the corresponding impulse response to a local weather shock. In contrast, the response is small, statistically weak, and short lived. The wide confidence bands indicate substantial heterogeneity across countries, consistent with local weather shocks being absorbed through short-run adaptation, spatial reallocation, and sectoral adjustment.

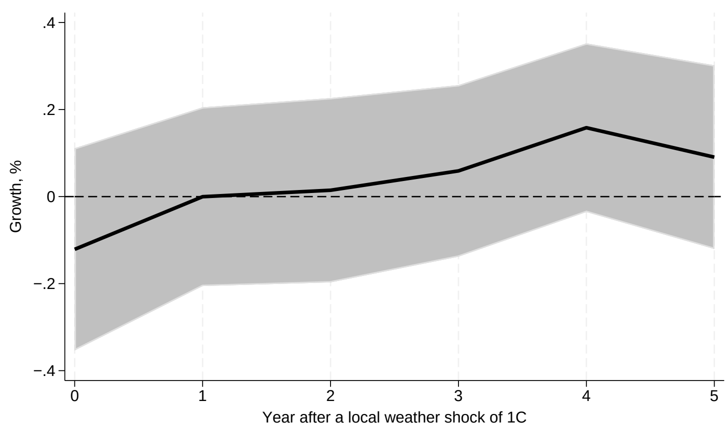
The contrast between global and local weather responses reinforces the distinction highlighted by Bilal and Känzig (2026). Shocks that are driven by global climatic forces, whether observed through disaster realizations or through synchronized weather anomalies, generate larger and more systematic macroeconomic effects than shocks that are purely local in nature. Local weather variation, while relevant for short-run volatility, does not give rise to sustained aggregate responses once global climate exposure is accounted for.

In summary, the impulse responses reconcile short-run weather-based evidence with the long-run climate results in this paper. Persistent global climate change anchors long-run output levels, as shown in Section 6. Global weather shocks, which are larger in magnitude, generate sizable short-run dynamics around that path. Local weather shocks primarily affect transitory volatility without shaping aggregate growth trajectories.

Again, it is useful to clarify how this framework differs from Bilal and Känzig (2026), who study the macroeconomic effects of temperature shocks without explicitly separating persistent climate dynamics from transitory weather fluctuations. In this paradigm, global temperature realizations are a combination of both climate and weather components. Global



(a) Global weather shock



(b) Local weather shock

Figure 10: Impulse responses of output growth to global and local weather shocks

temperature shocks can materialize through extreme events such as natural disasters.[11] Natural disasters can be interpreted as manifestations of global temperature shocks, which include both global climate and weather. My approach adopts a different but complementary paradigm. I decompose temperature into a persistent climate component and a transitory weather component using a state-space framework. As a result, the shocks analyzed in this Section are explicitly weather shocks, defined as innovations orthogonal to the underlying climate path. This allows me to study short-run macroeconomic dynamics around a climate-dependent baseline, while keeping long-run climate anchoring, the focus of this study, analytically separate.

9 Conclusions

This paper shows that distinguishing persistent climate change from transitory weather fluctuations is essential for understanding the macroeconomic consequences of warming. By isolating the permanent component of temperature and linking it to the permanent component of output within a panel cointegration framework, the analysis uncovers large and economically meaningful long-run level effects of climate change. Throughout the paper, "permanent" refers to the persistent underlying temperature trend in the model, rather than an irreversible temperature change. An increase in the permanent component of temperature leads economies to converge gradually to a lower output path, with an estimated decline in the long-run level of real GDP of roughly 22 percent following a one-degree Celsius increase in this component. However, this adjustment unfolds very slowly, taking many decades to materialize, and does not represent a short-run impact or a forecast.

Decomposing aggregate output reveals that long-run climate damages operate through multiple structural margins. In the full sample, a substantial portion of the aggregate output loss reflects demographic adjustment, while in advanced economies persistent warming is associated with declines in both population and GDP per capita. Further decompositions indicate that the per-capita channel operates primarily through capital accumulation rather than through total factor productivity, highlighting the role of capital deepening and capital adjustment in shaping long-run climate outcomes.

The results also reveal substantial heterogeneity across countries. Economies with higher capital intensity and more durable capital stocks experience significantly larger long-run output losses. These economies rely on extensive networks of long-lived capital and infrastructure accumulated under historically colder climatic conditions. As the climate warms

[11] There is a large literature on the short-run macroeconomic impacts of natural disasters, see Noy (2009), Loayza et al. (2012), Felbermayr and Gröschl (2014), Nguyen et al. (2025)...

persistently, this legacy capital may become less well matched to prevailing temperature regimes, generating gradual but sustained reductions in effective productive capacity. These findings suggest that structural characteristics of the capital stock are an important determinant of long-run climate vulnerability.

The results highlight that long-run climate damages are larger in economies with more capital-intensive production and more durable capital stocks. While the existing climate-macro literature emphasizes larger damages in hot and developing economies based on short-run weather shocks, the evidence here shows that long-run damages vary with capital structure within both advanced economies and EMDEs. In particular, countries at all income levels with higher capital intensity and slower capital turnover tend to experience larger long-run output losses from persistent climate change. This suggests that long-run economic risks from climate change may be more broadly distributed across countries than implied by short-run evidence alone. Note that these findings do not necessarily imply lower overall climate vulnerability in EMDEs, but rather reflect differences in the capital structural channels captured by this framework.

The analysis in this paper points to important directions for future research. First, the estimates are based on historical data and reflect past patterns of adaptation, technology, and economic structure; the magnitude of future climate damages may differ as economies adjust, innovate, or implement new climate policies. Because the empirical literature on climate change (as distinct from weather shocks) is still developing, future research should aim to uncover the mechanisms and vulnerabilities underlying long-run climate damages. In particular, the finding that long-run losses are concentrated in capital-intensive countries raises important questions about the role of capital vintage, infrastructure design, and sectoral specialization, which warrant deeper investigation using micro-level data and structural approaches.

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A Appendix

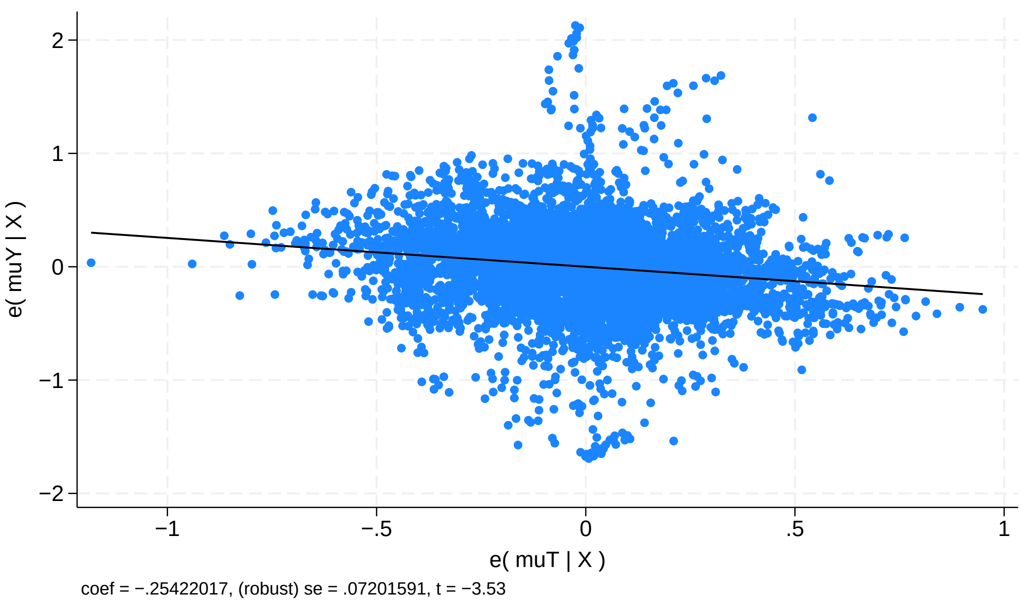

Figure A1: Partial scatterplot

Note: This figure presents the partial regression plot corresponding to the long-run specification in Table 1. Both trend real GDP $\mu^y_{c,t}$ and the permanent climate component $\mu^T_{c,t}$ are residuals after removing country and year fixed effects. The fitted line corresponds to the estimated coefficient in Table 1 ($\beta = -0.252$). The negative relationship is supported across the distribution of the data and is not driven by a small number of extreme observations. The upper outliers are driven by episodes of exceptionally rapid, largely resource-based growth in Equatorial Guinea, Liberia, and Nauru.

	Countries
Advanced Economies (AEs)	Australia, Austria, Belgium, Canada, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Netherlands, New Zealand, Norway, Poland, Portugal, Puerto Rico, Singapore, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Taiwan Province of China, United Kingdom, United States
Emerging Market and Developing Economies (EMDEs)	Afghanistan, Albania, Algeria, Andorra, Angola, Antigua and Barbuda, Argentina, Armenia, Aruba, Azerbaijan, Bahrain, Bangladesh, Barbados, Belarus, Belize, Benin, Bhutan, Bolivia, Bosnia and Herzegovina, Brazil, Brunei Darussalam, Bulgaria, Burkina Faso, Burundi, Cambodia, Cameroon, Cabo Verde, Central African Republic, Chad, Chile, China, Colombia, Comoros, Congo, Costa Rica, Cote d'Ivoire, Croatia, Cuba, Democratic Republic of the Congo, Djibouti, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Fiji, Gabon, Gambia, Georgia, Ghana, Grenada, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Hungary, India, Indonesia, Iran, Iraq, Jamaica, Jordan, Kazakhstan, Kenya, Kuwait, Kyrgyz Republic, Laos, Lebanon, Lesotho, Liberia, Libya, Madagascar, Malawi, Malaysia, Maldives, Mali, Mauritania, Mauritius, Mexico, Moldova, Mongolia, Montenegro, Morocco, Mozambique, Myanmar, Namibia, Nepal, Nicaragua, Niger, Nigeria, North Korea, North Macedonia, Oman, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Qatar, Romania, Russian Federation, Rwanda, Sao Tome and Principe, Saudi Arabia, Senegal, Serbia, Seychelles, Sierra Leone, Solomon Islands, Somalia, South Africa, South Sudan, Sri Lanka, St. Lucia, St. Vincent and the Grenadines, Sudan, Suriname, Syria, Tajikistan, Tanzania, Thailand, Timor-Leste, Togo, Tonga, Tunisia, Turkiye, Uganda, Ukraine, United Arab Emirates, Uruguay, Uzbekistan, Vanuatu, Venezuela, Vietnam, Yemen, Zambia, Zimbabwe

Table A1: Country groups by income classification.

Note: The sample includes 192 countries. Countries are classified as Advanced Economies (AEs) or Emerging Market and Developing Economies (EMDEs) following the IMF World Economic Outlook classification.

	Number of temperature observations	Number of GDP observations
Number of countries	192	192
Mean	51.79	51.79
Minimum	15	15
1st percentile	33	33
10th percentile	53	53
25th percentile	53	53
Median	53	53
75th percentile	53	53
90th percentile	53	53
99th percentile	53	53
Maximum	53	53

Table A2: Country-level data coverage for temperature and GDP

Note: The table reports the distribution of the number of annual observations per country in the regression sample (1970-2022). Temperature and GDP coverage are identical by construction. South Sudan has the least coverage, only from 2008 to 2022

Variable	N	Mean	Min	p1	p10	p25	p50	p75	p90	p99	Max
Observed temperature (C)	9,943	23.62	2.74	6.40	12.38	18.01	26.27	28.62	31.14	35.02	36.33
Log real GDP	9,943	12.68	1.16	3.71	7.81	10.20	12.95	15.20	17.15	22.00	23.43
GDP growth (%)	9,943	3.54	−15.98	−15.98	−2.65	0.00	3.76	6.52	9.52	22.85	22.85

Table A3: Summary statistics

Note: The table reports summary statistics for annual country-level observations used in the regression sample. Observed temperature is measured in degrees Celsius, log real GDP is in natural logarithms, and GDP growth is expressed in percent. Real GDP growth is winsorized at p1 and p99

Table A4: Panel cointegration tests: Westerlund (2007)

Statistic	Value	Z-statistic	p-value	Robust p-value
Panel A: Full sample (192 countries)				
Gt	-1.292	-4.201	0.000	0.090
Ga	-3.066	2.242	0.988	0.180
Pt	-16.417	-8.005	0.000	0.055
Pa	-1.934	-4.342	0.000	0.120
Panel B: Excluding growth-spurt countries (179 countries)				
Gt	-1.294	-4.092	0.000	0.070
Ga	-3.128	1.983	0.976	0.130
Pt	-16.417	-8.213	0.000	0.040
Pa	-2.145	-5.170	0.000	0.070

Notes: The table reports error-correction-based panel cointegration tests following Westerlund (2007). Robust p-values are obtained using dependence-robust bootstrap procedures. The null hypothesis is no cointegration. In Panel B, the sample excludes countries that experience prolonged episodes of exceptional growth, defined as at least five consecutive years of real GDP growth above 10 percent. The excluded countries are Armenia (ARM), Bosnia and Herzegovina (BIH), Botswana (BWA), China (CHN), Cabo Verde (CPV), Djibouti (DJI), Ethiopia (ETH), Equatorial Guinea (GNQ), Liberia (LBR), Maldives (MDV), Myanmar (MMR), Oman (OMN), and Qatar (QAT). These episodes largely reflect idiosyncratic structural changes such as post-conflict recoveries, commodity booms, large-scale investment surges, or economic transitions, rather than gradual climate dynamics. Excluding these countries improves the power of cointegration diagnostics without materially affecting the estimated long-run climate relationship.

Table A5: Robustness: First-Difference and Long-Difference Benchmarks

	(1) First diff. GDP growth	(2) Long diff. Trend GDP	(3) Long diff. GDP level
Change in permanent climate ($\Delta\mu^T$)	-0.290	-0.222^{***}	-0.222^{***}
	(1.283)	(0.067)	(0.067)
Country fixed effects	Yes	No	No
Year fixed effects	Yes	No	No
Observations	9,751	175	175
Countries	192	175	175
R^2	0.090	0.034	0.033

Notes: Column (1) reports a first-difference panel regression of annual real GDP growth on annual changes in the permanent climate component, including country and year fixed effects. Columns (2) and (3) report long-difference regressions relating changes in output between 1970 and 2022 to changes in the permanent climate component over the same period, using trend output and observed output, respectively. Long-difference specifications are estimated in the cross section with heteroskedasticity-robust standard errors. First-difference regressions are expected to be underpowered at annual frequency because persistent climate change evolves gradually and affects output primarily through slow-moving adjustment in levels rather than short-run growth.

Table A6: Robustness to Alternative Trend Extraction: HP-Filtered GDP

	(1) HP trend $\lambda = 100$	(2) HP trend $\lambda = 6.25$	(3) Log GDP (levels)
Permanent climate component (μ^T)	-0.254^{***}	-0.252^{***}	-0.251^{***}
	(0.071)	(0.072)	(0.071)
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	9,943	9,943	9,943
Countries	192	192	192
Within R^2	0.716	0.706	0.700

Notes: This table reports long-run fixed-effects regressions of output on the permanent climate component using alternative measures of low-frequency output. Columns (1) and (2) use Hodrick-Prescott filtered trends of log real GDP with annual smoothing parameters $\lambda = 100$ and $\lambda = 6.25$, respectively. Column (3) uses log real GDP levels without statistical filtering. All specifications include country and year fixed effects and are estimated on the post-1970 sample. Standard errors are clustered at the country level. Across all specifications, the estimated coefficient on the permanent climate component remains negative, highly statistically significant, and quantitatively similar to the baseline results, indicating that the long-run climate-output relationship is not sensitive to the choice of trend extraction method.

Table A7: Robustness to Temperature Trend Extraction: HP-Filtered Country Temperature

	(1) HP temp trend $\lambda = 100$	(2) HP temp trend $\lambda = 6.25$
HP-filtered temperature trend ($\widehat{T}^{HP}$, °C)	-0.207^{***}	-0.151^{***}
	(0.058)	(0.043)
Country fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	9,943	9,943
Countries	192	192
Within R^2	0.706	0.704

Notes: This table reports long-run fixed-effects regressions of trend log output on a purely statistical low-frequency component of country-level temperature. The regressor is the Hodrick–Prescott filtered trend of annual country temperature (in degrees Celsius), constructed from observed temperature and filtered separately within each country. Column (1) uses an annual smoothing parameter $\lambda = 100$ and column (2) uses $\lambda = 6.25$. Both specifications include country and year fixed effects and are estimated on the post-1970 sample. Standard errors are clustered at the country level and reported in parentheses. The negative and statistically significant coefficients indicate that the main long-run relationship is robust to replacing the state-space permanent climate component with a transparent HP-based temperature trend.

Table A8: Robustness: 30-Year Moving Average Temperature

	(1)
Dependent variable	$\mu^Y_{c,t}$
30-year moving average temperature	-0.2901^{***}
	(0.0836)
Country fixed effects	Yes
Year fixed effects	Yes
Observations	9,943
Countries	192
Within R^2	0.704

Notes: The table reports fixed-effects estimates relating the permanent component of output ($\mu^Y_{c,t}$) to a 30-year moving average of annual temperature. The moving average is constructed using a backward-looking window covering the previous 30 years. Country and year fixed effects are included in all specifications. Robust standard errors clustered at the country level are reported in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A9: Robustness to Convergence Dynamics

	Dependent variable: $\mu^Y_{c,t}$ (trend log real GDP)	
	(1)	(2)
$\mu^T_{c,t}$ (permanent climate component)	-0.2940^{***}	-0.1543^{**}
	(0.0740)	(0.0741)
Country fixed effects	Yes	Yes
GDP per capita (1990) × year	Yes	
GDP per capita (1970) × year		Yes
Observations	9,014	7,897
Countries	173	149
Within R^2	0.0898	0.0937

Notes: The table reports robustness checks of the baseline relationship between trend output and the permanent climate component. The baseline specification is augmented with interactions between year fixed effects and initial GDP per capita, allowing countries with different initial development levels to follow different output paths over time. Column (1) uses GDP per capita in 1990 from the Penn World Table, while Column (2) uses GDP per capita in 1970. Robust standard errors clustered at the country level are reported in parentheses. *, **, and *** denote statistical significance at the 10, 5, and 1 percent levels, respectively.

Table A10: Benchmark Regressions Using Raw Temperature

	(1) Trend Output μ_{it}^{Y}	(2) Log Output $\log Y_{it}$	(3) Output Growth ΔY_{it} (%)
Observed temperature	-0.052^{***}	-0.051^{***}	-0.163
	(0.015)	(0.015)	(0.139)
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	9,943	9,943	9,943
Countries	192	192	192
Within R^2	0.700	0.694	0.092

Notes: This table reports conventional panel regressions relating output to raw observed temperature, following the standard approach in the climate–macro literature. Column (1) uses trend log output, Column (2) uses log real GDP, and Column (3) uses output growth in percent. All specifications include country and year fixed effects, and standard errors clustered at the country level are reported in parentheses.

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