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Research Article

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Economic Output Under a Warming Climate: Non-Linear Damage Effects and Adaptive Capacity in OECD Countries

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Abstract: This study examines the long-run effects of temperature anomalies on economic output in OECD countries, with a focus on non-linear damage patterns and the mitigating role of adaptive capacity. Using annual data for 38 OECD economies over 1995–2024, the analysis estimates panel models with Driscoll–Kraay standard errors within a reduced-form damage-function framework and corroborates long-run robustness using panel FMOLS. The results indicate a non-linear temperature–output relationship: moderate temperature deviations are associated with higher output, but the marginal effect weakens as anomalies intensify, consistent with rising damages at larger deviations from historical norms. Heterogeneity analyses reveal that the temperature–output response is substantially stronger and more non-linear in warm-climate OECD countries, with additional geographic heterogeneity between European and non-European OECD economies. The results further show that higher public investment and stronger health-system capacity are associated with reduced output sensitivity to temperature shocks, with this moderating role being especially pronounced in warmer climates. Taken together, these findings highlight infrastructure and health capacity as measurable, policy-relevant adaptation channels that strengthen macroeconomic resilience to climate variability in advanced economies.

Keywords: temperature anomalies; climate change; economic output; nonlinear damage function; adaptive capacity

1 Introduction

Climate change is placing increasing pressure on long-term economic performance and social welfare. A substantial body of research over the past two decades has shown that rising temperatures affect economic output in a non-linear manner, with productivity declining sharply once temperature anomalies exceed critical thresholds (Burke et al. 2015; Dell et al. 2012). Economic activity tends to be most efficient under moderate temperatures, whereas further warming induces losses through reduced labor productivity, higher energy costs, and declining agricultural yields. Consequently, the temperature-anomaly relationship represents not only an environmental concern but also a fundamental macroeconomic determinant that shapes long-term growth trajectories.

Temperature shocks influence the economy through multiple transmission channels. These include declines in labor productivity (Letta and Tol 2018), reduced agricultural yields (Chen and Yang 2019), health and mortality impacts (Carleton and Hsiang 2016), shifts in energy demand (Chen et al. 2024), and delayed investment responses (Wan and Wang 2024). Importantly, such effects are not confined to developing economies. Recent studies show that even in temperate and high-income countries, such as the United Kingdom, temperature deviations significantly affect productivity and output (Emediegwu et al. 2025). This underscores that temperature anomalies are economically relevant across diverse country contexts, including advanced economies. Accordingly, we focus on OECD countries to study long-run climate–output sensitivities in relatively high-capacity settings and to identify measurable adaptation channels (public investment and health-system capacity) within advanced economies. Beyond real-side mechanisms, a growing literature highlights financial and behavioral transmission channels of climate risk. Physical climate exposure has been shown to influence credit allocation and mortgage market outcomes, indicating that climate risk is increasingly priced into financial decisions – for example, through reduced mortgage credit

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access in regions exposed to sea-level rise (Fu et al. 2025). Related studies document that climate risk interacts with political uncertainty and global asset pricing, amplifying volatility and generating heterogeneous climate risk premia across markets (Gong et al. 2022, 2023). Complementing these macro-financial perspectives, behavioral responses and mitigation awareness also play a role in shaping economic outcomes under climate change (Yilmaz and Habip 2025). These findings suggest that adaptation capacity may operate not only via productivity and health channels but also by stabilizing expectations and economic decision-making.

Ongoing debates center on whether temperature shocks have transitory or persistent effects on growth. Some studies find that low-frequency temperature changes can permanently alter long-term growth paths (Bastien-Olvera et al. 2021), whereas others suggest that advanced economies can recover through adaptation mechanisms, thereby mitigating long-run damage (Kalkuhl and Wenz 2020; Letta and Tol 2018). Recent evidence shows that physical climate risks increasingly shape financial conditions and economic behavior.

Adaptation capacity emerges as a crucial factor mediating climate-related shocks. National income levels, infrastructure investment, institutional quality, health-system capacity, and human capital jointly determine how temperature shocks translate into economic outcomes (Moore and Diaz 2015; Adom and Amoani 2021). Yet much of the literature continues to conceptualize adaptation capacity through broad proxies – such as per capita income or development indices – offering limited insight into specific, policy-relevant mechanisms such as public infrastructure and health-system strength. Evidence on how these mechanisms function under non-linear temperature effects remains scarce, particularly for OECD economies.

This study aims to address this gap. It examines the effect of temperature anomalies on long-term economic output within a reduced-form damage function framework and empirically investigates how public capital investment and health-system capacity shape non-linear temperature effects. By doing so, the study moves beyond traditional adaptation analyses based solely on broad macro indicators and provides concrete evidence on how two measurable and policy-relevant mechanisms – infrastructure investment and health capacity – alter the climate-economy relationship.

The empirical analysis employs a panel dataset of OECD countries covering the 1995–2024 period. A two-way fixed-effects model with Driscoll–Kraay standard errors is used to account for cross-sectional dependence and to ensure inference robust to heteroskedasticity and serial correlation. To examine how the temperature–output relationship varies across different climatic and geographic contexts, we conduct subsample analyses based on climate zones and regions. We also apply the panel FMOLS estimator as a complementary robustness check for the long-run coefficients. Together, this methodological strategy allows for reliable identification of long-run effects while providing a detailed assessment of the non-linear structure inherent in temperature shocks. This sample choice facilitates comparability in institutional and data environments, but it also implies that the results primarily speak to OECD/advanced-economy settings.

This study makes three principal contributions. First, it develops a non-linear theoretical framework that explains how temperature anomalies affect economic output and clarifies the main transmission channels through which these effects occur. Second, it conducts a comprehensive empirical examination of the temperature–output relationship for OECD countries over the long run, using methods that account for cross-sectional dependence and allowing for heterogeneous responses through subsample analyses and interaction models. Third, it demonstrates that public infrastructure and healthcare capacity can meaningfully alter the economic consequences of temperature anomalies, thereby identifying two adaptation mechanisms that are both measurable and directly relevant for policymaking. Given the OECD focus, these contributions are intended to inform adaptation and resilience mechanisms in advanced-economy contexts; external validity to developing economies should be treated with caution.

2 Literature Review

The relationship between temperature anomalies and economic performance has become a central question in climate economics, as global warming accelerates and its macroeconomic footprint widens across regions. A large and expanding body of evidence indicates that temperature deviations from historical norms influence economic output through multiple channels that operate simultaneously – productivity losses, agricultural disruptions, energy demand shifts, health burdens, and delayed investment decisions. The magnitude and persistence of these effects vary substantially across countries, sectors, and levels of adaptive capacity.

Early cross-country research established the foundation for understanding the macroeconomic consequences of temperature changes. Dell et al. (2012) demonstrated that higher temperatures systematically reduce output growth, particularly in lower-income countries with limited adaptation capacity. Carleton and Hsiang (2016) synthesized global evidence showing that temperature affects productivity, mortality, labor supply, and agricultural yields, underscoring that climate shocks operate through multiple, interconnected pathways rather than a single mechanism. Subsequent studies such as Burke et al. (2015) confirmed that this relationship is non-linear: economic productivity peaks at moderate temperatures but declines sharply as temperatures rise. These findings are further corroborated by Zhao et al. (2018), Song et al. (2023), and Kalkuhl and Wenz (2020), who report that productivity and output losses intensify once critical temperature thresholds are exceeded.

A growing strand of literature emphasizes that the economic impacts of temperature anomalies differ across regions and sectors. Agricultural output is particularly vulnerable, as shown by Chen and Yang (2019) and Henseler and Schumacher (2019), who find that heat exposure reduces crop yields and labor productivity, especially in developing economies. In contrast, studies such as Hernández and Madeira (2022) and Arellano-González and Juárez-Torres (2025) demonstrate that even within middle-income and industrializing countries, temperature shocks disrupt both industrial and service activities through rising energy costs and reduced labor efficiency. Recent research extends these insights to advanced economies. Emediegwu et al. (2025) provide evidence that seasonal temperature variations significantly affect productivity in the United Kingdom, highlighting that climatic risks are economically relevant even in high-income settings. Furthermore, Callahan and Mankin (2022) show that extreme heat exerts globally unequal effects on economic growth, disproportionately burdening poorer and warmer regions while richer economies exhibit partial resilience due to higher adaptive capacity. This pattern underscores that temperature-related damages are not only sectorally but also geographically asymmetric, reflecting the unequal distribution of climate vulnerability across the World.

Another critical dimension of this literature concerns the persistence of temperature effects. Several studies, such as Bastien-Olvera et al. (2021) and Gospodinov et al. (2025), suggest that temperature shocks may have persistent but mixed long-term impacts on economic growth, with some evidence of compounding effects through lower capital accumulation and productivity, though results vary across regions and methodologies. In contrast, other research, including Kalkuhl and Wenz (2020) and Casey et al. (2023), finds that these effects are largely contemporaneous and that adaptive responses in advanced economies can mitigate permanent damage. Complementing these findings, Linsenmeier (2023) provides evidence that temperature variability can have persistent and structural effects on long-run economic development, although the evidence remains moderate and may vary across regions and methodological approaches. The divergence in these findings often reflects differences in empirical design, such as whether studies use national or subnational data, and in how they model nonlinearities and persistence.

The role of adaptation capacity has become increasingly central in explaining the heterogeneity of climate–growth outcomes. Moore and Diaz (2015) and Adom and Amoani (2021) emphasize that countries' income levels, institutional quality, infrastructure investment, and health-system capacity jointly determine the extent of economic losses from temperature anomalies. Kahn et al. (2019) further show that while wealthier regions experience smaller short-term effects due to better infrastructure and access to cooling technologies, these advantages have limits: extreme temperatures can overwhelm adaptive systems even in high-income settings. Despite this, much of the empirical literature continues to measure adaptation capacity using broad proxies – such as GDP per capita or general development indicators – offering limited insight into specific, policy-relevant mechanisms that enhance economic resilience.

The non-linear and asymmetric nature of climate damages is another recurring theme. Bastien-Olvera et al. (2021) and Newell et al. (2021) document that the GDP–temperature relationship is convex, meaning that each additional degree of warming produces disproportionately larger economic losses. These results reinforce earlier findings by Burke et al. (2015) and confirm that temperature shocks have marginal effects that intensify at higher thresholds. In addition to long-term warming, Kotz et al. (2021) provide compelling evidence that day-to-day temperature variability itself reduces economic growth, emphasizing that not only mean temperature increases but also short-term fluctuations generate significant output losses. At the same time, compound climate events – such as heatwaves combined with droughts or storms – create damage profiles that far exceed the sum of individual impacts (Mithal et al. 2024; Zscheischler et al. 2018).

Recent regional studies bring further nuance to this debate. Kaushik et al. (2024) find that a 1 °C increase in temperature can reduce output by up to 0.385 % in Asian economies, while Duan et al. (2022) show that temperature increases in China suppress growth through reduced industrial productivity and higher energy demand. Similarly, consistent with evidence from Africa (Abel and Jeke 2025), findings from Mexico (Arellano-González and Juárez-Torres 2025) also indicate that temperature anomalies adversely influence economic activity, especially in agriculture-based regions. However, even in temperate or wealthier countries, such as those in the OECD, temperature deviations have measurable and persistent effects on output, though their magnitude may be moderated by adaptive capacity and institutional strength.

Taken together, the literature provides compelling evidence that temperature anomalies exert non-linear, regionally heterogeneous, and persistently negative effects on economic growth. While the magnitude of these effects is greatest in hotter and poorer regions, they remain economically meaningful even in advanced economies. The overall consensus suggests that the global economy's exposure to temperature shocks depends not only on the extent of warming but also on the strength of adaptation mechanisms – particularly infrastructure investment, institutional quality, and public health capacity. Yet empirical studies directly linking these mechanisms to macroeconomic resilience remain scarce, underscoring the need for research that moves beyond abstract adaptation proxies and quantifies the concrete pathways through which policy interventions can mitigate climate-related economic losses.

3 Theoretical Model

This section develops a reduced-form theoretical framework to explain how climate change affects economic output. The core idea of the model is that climate-induced damages reduce undamaged output through a direct multiplicative loss. In this way, rather than examining pollution-stock dynamics or abatement processes, the analysis highlights the immediate effect of temperature deviations on production. This modelling choice allows the framework to remain analytically tractable and empirically testable. The damage specification follows the nonlinear functional forms commonly used in environmental economics, and the modelling strategy draws conceptually on Hritonenko and Yatsenko (2013). Within this structure, the long-run impact of temperature anomalies on output is examined from a welfare-maximization perspective.

The economy produces a single final good, and labor is normalized. Undamaged gross output follows a Cobb–Douglas form:

$$Y_G(t) = AK(t)^{\alpha}, \qquad A > 0, \qquad \alpha \in (0,1). \tag{1}$$

In Equation (1), $Y_G(t)$ represents damage-free (gross) output, $K(t)$ denotes the physical capital stock, A is total factor productivity (the level of technology), and α is the output elasticity of capital. This equation defines the economy's production capacity without accounting for climate effects.

Climate damage deducts a specific share from production. Therefore, net output is expressed as in Equation (2).

$$Y_N(t) = [1 - \Delta(T(t))]Y_G(t) \quad 0 \leq \Delta T < 1. \tag{2}$$

In Equation (2), $Y_N(t)$ represents the net output realized after climate damages, and ΔT denotes the damage share dependent on the temperature deviation. This equation demonstrates that climate change exerts a direct, reducing effect on production.

The damage function is defined in a non-linear form:

$$\Delta(T) = \vartheta_0 T + \vartheta_1 T^{\phi}, \qquad \vartheta_0, \vartheta_1 \geq 0, \qquad \phi > 1. \tag{3}$$

In Equation (3), the parameters ϑ_0 and ϑ_1 represent the coefficients of the temperature deviation on damage, while ϕ determines the convexity. This function describes approximately linear damages at low temperatures and accelerating damages at high temperatures.

The total resource constraint is written as follows:

$$Y_N = C(t) + I(t). \tag{4}$$

In Equation (4), net output (Y_N), is allocated between consumption $C(t)$ and investment $I(t)$. This constraint represents the allocation of the net output produced in the economy to its different uses.

The capital dynamics are defined in the standard form

$$\dot{K}(t) = I(t) - \delta K(t), \qquad \delta \in (0,1) \tag{5}$$

In Equation (5), $\dot{K}(t)$ represents the change in the capital stock over time, $I(t)$ denotes investment, and δ is the depreciation rate of capital. This equation indicates that the capital stock can only increase if sufficient investment is made; otherwise, it decreases over time.

Society derives utility solely from consumption. The welfare function is defined as follows:

$$\max_{\{C(t)\}_{t\geq 0}} \int_0^{\infty} e^{-\rho t} \ln C(t)\mathrm{d}t, \qquad \rho > 0. \tag{6}$$

In Equation (6), the social welfare of the society is defined as the discounted sum of the logarithmic utility derived from future consumption. Here, ρt is the time preference rate (discount rate), which determines the present value of future utilities. This equation shows how the social planner will choose consumption over time.

The analysis proceeds by deriving a reduced-form representation of output that captures the direct effect of temperature-induced damages under standard regularity assumptions, without explicitly solving the dynamic optimization problem in the main text.

The empirical reduced form is obtained by combining the definition of net output with a logarithmic approximation for small to moderate damage levels:

$$\ln Y_{\mathrm{it}} = \ln Y_{G,\mathrm{it}} + \ln(1 - \Delta(T_{\mathrm{it}})) \approx \ln A_i + \alpha \ln K_{\mathrm{it}} - \Delta(T_{\mathrm{it}}). \tag{7}$$

In Equation (7), the approximation $\ln(1 - \Delta) \approx -\Delta$ (for small/medium damages) is used. Thus, the damage share of temperature $\Delta(T)$ enters the output equation directly with a negative sign.

Substituting the damage function (3) yields the testable form for the country-year panel:

$$\ln Y_{\text{it}} = \beta_0 + \alpha \ln K_{\text{it}} - \beta_1 T_{\text{it}} - \beta_2 T_{\text{it}}^{\theta} + X_{\text{it}}'\gamma + \mu_i + \tau_t + \varepsilon_{\text{it}}. \quad (8)$$

In Equation (8), Y_{it} represents economic output, K_{it} is the proxy for capital, T_{it} is the temperature deviation, X_{it} is a vector of control variables (e.g., energy intensity, trade openness, etc.), μ_i denotes country fixed effects, and τ_t denotes year fixed effects. Since $\Delta(T)$ reduces output, $\beta_1, \beta_2 > 0$ is expected. This specification is the directly testable form of the reduced-form panel data model in Equation (7).

To more flexibly capture common shocks and slow-moving local climate trends that may confound the temperature–output relationship, the following specification is adopted:

$$\begin{aligned}\ln Y_{\text{it}} = \beta_0 + \alpha \ln K_{\text{it}} - \beta_1 T_{\text{it}} - \beta_2 T_{\text{it}}^{\theta} + X_{\text{it}}'\gamma + \mu_i + \tau_t \\ + \pi_i(t) + \varepsilon_{\text{it}}. \quad (9)\end{aligned}$$

In Equation (9), $\pi_i(t)$ represents a country-specific time trend, which controls for slow-moving local trends that may confound the relationship between temperature and output. This term helps reduce finite-sample bias.

This article aims to examine, in a parsimonious and testable manner, how temperature deviations reduce production and welfare through the damage share $\Delta(T)$. The model adopts a focused approach by abstracting from pollution stock dynamics and explicit mitigation or adaptation decisions; these effects are implicitly captured within the reduced-form damage function $\Delta(T)$. In the empirical application, heterogeneity is controlled for using country and year fixed effects, along with country-specific climate trends. Relevant proxy variables are included in robustness checks. This reduced-form structure enables direct empirical testing of temperature–output elasticities. The underlying dynamic optimization framework, including the Hamiltonian formulation and steady-state derivations, is presented in Appendix A. We emphasize that the theoretical block is intentionally reduced-form. It provides a structural interpretation of how temperature-related damages operate through an output-loss share and capital accumulation, while keeping the main text empirically testable. Accordingly, our estimates are best viewed as long-run reduced-form damage elasticities identified from historical variation, rather than a fully structural climate–economy model designed to forecast regime shifts or unprecedented tipping points. Capturing such nonlinear thresholds would require explicit state dynamics, richer climate dimensions, and scenario-based climate pathways, which are beyond the scope of the present framework but constitute an important direction for future research.

4 Methodology

This study examines the long-run effects of annual temperature anomalies on economic output in OECD countries through a panel-data framework. The empirical strategy follows directly from the reduced-form model developed in the theoretical section and is designed to estimate the sensitivity of economic output to temperature deviations. In line with this objective, the structural characteristics of the dataset were first reviewed, and several diagnostic tests were conducted to assess the underlying panel-data assumptions. We use annual mean temperature anomalies to align the climate indicator with our long-run output framework and to capture persistent deviations from historical norms. This choice does not aim to measure within-year extreme events (e.g., heatwaves) that may generate sizable short-run disruptions. Accordingly, our estimates should be interpreted as long-run reduced-form responses to sustained temperature deviations rather than event-study effects of short-lived extremes.

In the initial step, the time-series properties of the variables were evaluated through the Pesaran (2007) CIPS test and the Karavias and Tzavalis (2014) panel stationarity test. Cross-sectional dependence was then assessed using the procedures proposed by Pesaran (2015, 2021), Juodis and Reese (2022), and Pesaran and Xie (2021). The homogeneity of slope coefficients was examined through the Swamy (1970) and Pesaran and Yamagata (2008) tests. Following these steps, the presence of a long-run relationship among the variables was evaluated using the Westerlund (2007) ECM panel cointegration test.

To determine the appropriate model structure, LR and F tests were applied to assess the relevance of panel effects, while LM and Hausman tests were used to evaluate model specification. The results indicate that both country-specific and time-specific effects are statistically significant and that a fixed-effects specification is preferable.

In the estimation stage, a two-way fixed-effects model with Driscoll and Kraay (1998) standard errors was adopted to obtain inference robust to heteroskedasticity, serial correlation, and cross-sectional dependence. While the baseline specification imposes slope homogeneity for the full sample, we explicitly address potential slope heterogeneity through two complementary strategies: (i) subsample analyses based on climate zones and geographic regions, and (ii) interaction terms that allow the temperature–output relationship to vary with public investment and health capacity. These approaches allow us to examine how the average effects vary across groups and institutional contexts, even if the baseline panel estimates reflect a weighted average of heterogeneous responses. In addition, panel FMOLS estimations were carried out to evaluate the robustness of the long-run coefficients. Taken together, this set of methods provides reliable inference for long-run relationships while allowing for structured heterogeneity in temperature–output responses across countries and institutional contexts.

4.1 Data and Variables

This section outlines the structural features of the dataset used in the empirical analysis and describes its main components. Before introducing the estimation strategy, it is useful to summarise the broad patterns in temperature dynamics and the cross-country differences that characterise the OECD sample. Figure 1 therefore provides an initial descriptive overview that helps situate the empirical model within its climatic context and offers a visual background for understanding the long-run behaviour of temperature anomalies.

Figure 1 presents how annual temperature anomalies evolve across OECD countries throughout the 1995–2024 period. In Panel (A), the increasing density of observations over time, together with the fitted trend line, reveals a marked upward movement in temperature deviations, and this pattern suggests that the average level of temperature anomalies is rising, with greater dispersion in observed deviations over time. Panel (B) adds a geographical dimension, since the comparison between the values recorded at the beginning and end of the period allows each country's long-term change in temperature to be observed. High-latitude members experience substantially stronger warming, while countries in the Americas and the Asia–Pacific region follow distinct warming trajectories. Taken together, the two panels jointly reveal both pronounced long-run warming and notable cross-sectional divergence.

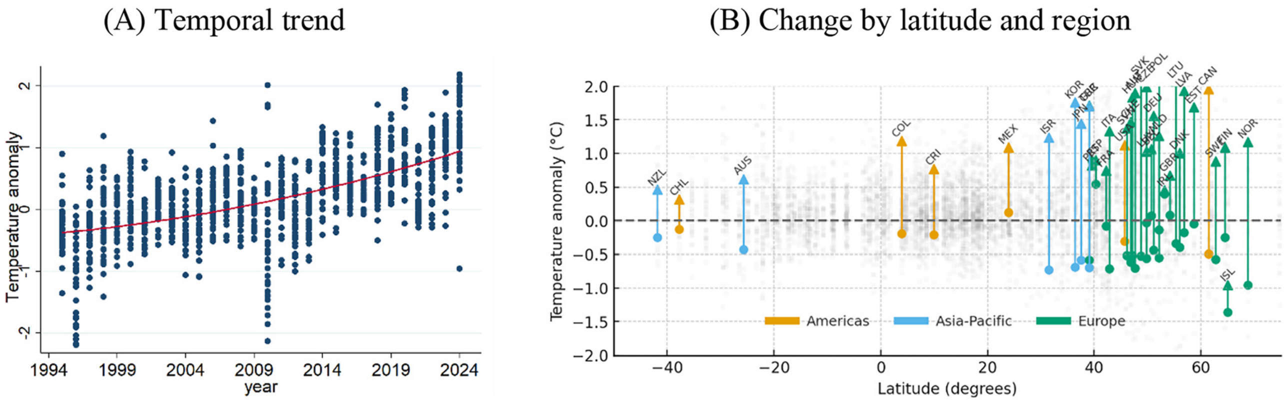
After this descriptive overview, Table 1 provides the definitions and measurement procedures for all variables included in the analysis.

The variable set is structured around output, temperature, physical capital, and structural control indicators so that the theoretical framework can be translated into the empirical model. The dependent variable is real GDP per capita, which is selected to represent both economic welfare

Table 1: Variables.

Symbol	Variables	Source
GDP	GDP per capita (constant 2015 US$)	WB
TA	Annual temperature anomalies	OWID
GFC	Gross fixed capital formation per capita (constant 2015 US$)	WB
AG	Agriculture, forestry, and fishing, value added (% of GDP)	WB
IN	Industry (including construction), value added (% of GDP)	WB
SE	Services, value added (% of GDP)	WB
TO	International trade, constant 2015 US price (% of GDP)	WB
EP	Electric power consumption (kWh per capita)	WB
PIN	Gross fixed capital formation, general government, (% of GDP)	IMF
HE1	Medical doctors per 10,000 population	WHO
HE2	Hospital beds per 10,000 population	WHO
HE3	Health expenditure per capita (PPP)	WHO
HEp	Health capacity index	WHO

HEp denotes the health capacity index constructed using principal component analysis (PCA) based on HE1–HE3. Data sources: World Bank (WB), Our World in Data (OWID), International Monetary Fund (IMF), and World Health Organization (WHO).


(A) Temporal trend

(B) Change by latitude and region

Figure 1: Evolution and cross-sectional variation of annual temperature anomalies. (A) Temporal trend. (B) Change by latitude and region. Source: Author's calculations based on data from the Copernicus Climate Change Service (via Our World in Data).

and long-run growth performance. The main explanatory variable – annual temperature anomaly (TA) – captures deviations from the historical temperature norm and thus serves as the empirical counterpart of the climate-related damage mechanism in the reduced-form framework. TA is defined as an annual mean anomaly and therefore does not directly measure intra-annual extreme-temperature exposure (e.g., heatwaves). Accordingly, the estimates should be interpreted as long-run reduced-form responses to sustained temperature deviations rather than event-level effects of short-lived extremes. We focus on temperature anomalies as a parsimonious and widely used macro-climate indicator in long-run damage-function settings; however, we acknowledge that a more complete characterization of climate exposure would also incorporate precipitation, humidity, and other climate dimensions. Physical capital is proxied by per-capita gross fixed capital formation (GFC).

In addition, the shares of agriculture (AG), industry (IN), and services (SE) in total output reflect the structural composition of the economy. Indicators for trade openness (TO), energy consumption (EP), and public gross fixed capital formation (PIN) are included to evaluate the roles of external integration, energy intensity, and public investment capacity in shaping output dynamics. The health-capacity variable (HEp) is incorporated as well, since it represents an institutional and infrastructural dimension that may influence how countries absorb the economic consequences of climate shocks. In this context, the variable set is designed to enable an empirical assessment of both the damage function and the long-run mechanism outlined in the theoretical model.

Following the definition of variables, Table 2 reports the basic descriptive statistics for all series included in the analysis.

Table 2 summarizes the mean levels, distributions, and observed value ranges of the variables for the OECD countries in the sample. Real GDP per capita displays substantial dispersion, reflecting pronounced cross-country differences in income levels. Annual temperature anomalies exhibit a predominantly positive mean, while also indicating that both cooling and warming deviations occurred over the sample period. Sectoral shares show that services dominate economic activity across the OECD, whereas the relative importance of agriculture and industry varies considerably across countries. Variation in energy consumption and capital indicators highlights meaningful heterogeneity in economic structures and factor endowments across the sample.

Table 2: Descriptive statistics.

Variable	Mean	Std. dev.	Min	Max
GDP	33,395.028	22,052.141	3,967.113	112,417.88
TA	0.17	0.66	−2.193	2.188
GFC	7,342.323	4,998.219	469.634	38,834.582
AG	2.87	2.265	0.173	16.855
IN	25.151	5.401	9.01	49.129
SE	62.259	6.542	41.823	81.872
TO	0.877	0.564	0.158	4.075
EP	8,198.911	7,437.56	839.452	55,085.168
PIN	3.46	1.055	0.455	7.153
HEp	0.000	1.1719	−3.1524	4.3555

Following these descriptive statistics, Table 3 presents the pairwise correlation coefficients to provide an initial view of the basic linear relationships among the variables.

The pairwise correlation coefficients in Table 3 reveal patterns that are broadly consistent with theoretical expectations. Real GDP per capita is positively correlated with physical capital, energy use, and trade openness, while the agricultural sector's share exhibits a strong negative association with income, reflecting structural transformation across OECD economies. The correlations involving temperature anomalies are relatively modest, suggesting that simple linear associations provide only limited insight into the economic effects of climate variability. Although some variables display high pairwise correlations, these patterns are typical in macroeconomic panel data and do not, by themselves, preclude joint inclusion in the regression framework. Formal inference therefore relies on the multivariate panel estimations reported in subsequent sections.

4.2 Model Specification

In this study, the inverse hyperbolic sine transformation (ihsTA) is applied to the temperature anomaly variable to accommodate both positive and negative values while preserving a log-like scaling for large deviations. Importantly, the ihs transformation is a scaling device and does not impose non-linearity or a 'turning point' mechanically. Any non-linear response is introduced and tested empirically through the inclusion of the squared term (ihsTA^2), which allows the marginal effect of temperature anomalies to vary with the magnitude of deviations. Interaction terms ($\text{ihsTA} \times \text{lnPIN}$) and ($\text{ihsTA} \times \text{HEp}$) are constructed to examine whether public investment capacity and health-system capacity condition the temperature–output relationship.

The empirical modeling process begins by operationalizing the reduced-form damage function presented in the theoretical section for empirical testing with OECD country data. Within this framework, the core model was first estimated to reveal the direct and non-linear effects of climate shocks on economic output.

Table 3: Pairwise correlations.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) lnGDP	1.000								
(2) ihsTA	0.133	1.000							
(3) ihsTA^2	0.043	0.251	1.000						
(4) lnGFC	0.971	0.142	0.047	1.000					
(5) lnAG	−0.736	−0.151	−0.058	−0.708	1.000				
(6) lnIN	−0.355	−0.141	−0.045	−0.236	0.322	1.000			
(7) lnSE	0.567	0.167	−0.002	0.485	−0.601	−0.793	1.000		
(8) lnTO	0.190	0.211	0.190	0.196	−0.346	−0.175	0.016	1.000	
(9) lnEP	0.814	0.051	0.069	0.810	−0.471	−0.181	0.301	0.135	1.000

Model (1) – Baseline model:

$$\ln \mathrm{GDP}_{\mathrm{it}} = \beta_0 + \beta_1 \ln \mathrm{GFC}_{\mathrm{it}} + \beta_2\,(\mathrm{ihsTA})_{\mathrm{it}} + \beta_3\,(\mathrm{ihsTA})^2_{\mathrm{it}} + X'_{\mathrm{it}}\gamma + \mu_i + \tau_t + \pi_i\,(t) + \varepsilon_{\mathrm{it}}. \tag{10}$$

$$X'_{\mathrm{it}} = \gamma_1 \ln \mathrm{AG}_{\mathrm{it}} + \gamma_2 \ln \mathrm{IN}_{\mathrm{it}} + \gamma_3 \ln \mathrm{SE}_{\mathrm{it}} + \gamma_4 \ln \mathrm{TO}_{\mathrm{it}} + \gamma_5 \ln \mathrm{EP}_{\mathrm{it}}.$$

In Model 1, the logarithm of real GDP per capita (lnGDP) is used as the dependent variable, while the main explanatory variable is the temperature anomaly (TA), which is transformed using the inverse hyperbolic sine function (ihsTA). To allow for potential non-linearities in the temperature–output relationship, the square of ihsTA is included in the model. This allows the non-linear structure of the damage function to be tested empirically. This specification tests for curvature in the data; it should not be interpreted as identifying a physical environmental threshold. The control variables are selected to encompass the fundamental determinants of output dynamics, including physical capital accumulation, sectoral composition, trade openness, and energy consumption. This structure enables the effect of climate shocks to be evaluated separately from other macroeconomic factors.

The model specification is subsequently expanded in Model 2 to test whether the climate-output relationship varies depending on the level of public capital investment. For this purpose, the public fixed capital formation indicator (lnPIN) is added to the model, and an interaction term with the temperature anomaly (ihsTA × lnPIN) is created. This allows for an empirical assessment of whether public investment capacity plays a mitigating role in the impact of temperature shocks on output.

Model (2) – Model with public investment interaction:

$$\ln \mathrm{GDP}_{\mathrm{it}} = \beta_0 + \beta_1 \ln \mathrm{GFC}_{\mathrm{it}} + \beta_2\,(\mathrm{ihsTA})_{\mathrm{it}} + \beta_3\,(\mathrm{ihsTA})^2_{\mathrm{it}} + \delta \ln \mathrm{PIN}_{\mathrm{it}} + \eta\,(\mathrm{ihsTA}_{\mathrm{it}} \times \ln \mathrm{PIN}_{\mathrm{it}}) + X'_{\mathrm{it}}\gamma + \mu_i + \tau_t + \pi_i\,(t) + \varepsilon_{\mathrm{it}}. \tag{11}$$

$$X'_{\mathrm{it}} = \gamma_1 \ln \mathrm{AG}_{\mathrm{it}} + \gamma_2 \ln \mathrm{IN}_{\mathrm{it}} + \gamma_3 \ln \mathrm{SE}_{\mathrm{it}} + \gamma_4 \ln \mathrm{TO}_{\mathrm{it}} + \gamma_5 \ln \mathrm{EP}_{\mathrm{it}}.$$

In the final stage, the model is extended once more in Model 3 to examine whether health system capacity moderates the adverse effects of climate change. For this purpose, the health capacity indicator (HEp) and its interaction term with the temperature anomaly (ihsTA × HEp) are incorporated into the model. This approach tests whether a stronger health infrastructure can function as a buffering mechanism that mitigates climate-induced damages.

Model (3) – Model with health capacity interaction:

$$\ln \mathrm{GDP}_{\mathrm{it}} = \beta_0 + \beta_1 \ln \mathrm{GFC}_{\mathrm{it}} + \beta_2\,(\mathrm{ihsTA})_{\mathrm{it}} + \beta_3\,(\mathrm{ihsTA})^2_{\mathrm{it}} + \varphi \mathrm{HEp}_{\mathrm{it}} + \omega\,(\mathrm{ihsTA}_{\mathrm{it}} \times \mathrm{HEp}_{\mathrm{it}}) + \mu_i + \tau_t + \pi_i\,(t) + \varepsilon_{\mathrm{it}}. \tag{12}$$

$$X'_{\mathrm{it}} = \gamma_1 \ln \mathrm{AG}_{\mathrm{it}} + \gamma_2 \ln \mathrm{IN}_{\mathrm{it}} + \gamma_3 \ln \mathrm{SE}_{\mathrm{it}} + \gamma_4 \ln \mathrm{TO}_{\mathrm{it}} + \gamma_5 \ln \mathrm{EP}_{\mathrm{it}}.$$

This triple-model framework allows for the initial identification of the fundamental effect of temperature anomalies on output in the first stage. In subsequent stages, it enables a comparative assessment of how this effect is modified – either strengthened or weakened – by structural factors such as public investment capacity and health infrastructure.

5 Empirical Analysis

5.1 Estimation Results

The panel diagnostic tests and model selection results support the use of Driscoll-Kraay standard errors within a two-way fixed effects model. Accordingly, the baseline and extended model estimations are reported in Table 4.

Table 4 reports the baseline and extended estimates obtained from the two-way fixed-effects model with Driscoll–Kraay standard errors. Across all specifications, temperature anomalies exhibit a statistically significant and non-linear association with real GDP per capita. The positive coefficient on the inverse hyperbolic sine of temperature anomalies (ihsTA), together with the significant squared term (ihsTA^2), indicates that the marginal effect of temperature deviations is not constant and varies with the magnitude of the anomaly. Accordingly, any implied curvature should be read as an empirical feature within the observed anomaly range rather than a statement about real-world tipping points.

In the baseline specification (Model 1), both ihsTA and ihsTA^2 are significant, confirming the presence of non-linearity in the temperature–output relationship. This pattern implies that moderate deviations from historical temperature norms are associated with limited or weakly positive output responses, while the marginal effect varies with the magnitude of temperature anomalies, as illustrated more directly by the marginal-effect analysis in Figure 2.

The estimated coefficients on the control variables are stable across specifications and align with standard macroeconomic expectations. Physical capital accumulation (lnGFC) is strongly and positively associated with income levels, while the agricultural share (lnAG) enters with a negative sign, reflecting structural transformation effects. Industry (lnIN) and services (lnSE) shares, trade openness (lnTO), and energy consumption (lnEP) all display positive and statistically significant coefficients, indicating their close association with long-run output in OECD economies.

Table 4: Two-way fixed effects with Driscoll–Kraay standard errors.

Variables	Model (1)	Model (2)	Model (3)
ihsTA	0.0148** (0.0055)	0.0364*** (0.0056)	0.0280*** (0.0068)
ihsTA^2	0.0128** (0.0053)	0.0147** (0.0069)	0.0152** (0.0065)
lnGFC	0.388*** (0.0239)	0.356*** (0.0103)	0.358*** (0.0201)
lnAG	−0.0314** (0.0137)	−0.0827*** (0.0164)	−0.0801*** (0.0220)
lnIN	0.110** (0.0473)	0.417*** (0.0597)	0.465*** (0.0880)
lnSE	0.600*** (0.103)	0.907*** (0.145)	0.820*** (0.210)
lnTO	0.266*** (0.0248)	0.396*** (0.0208)	0.408*** (0.0400)
lnEP	0.236*** (0.0320)	0.401*** (0.0237)	0.372*** (0.0360)
lnPIN		0.122*** (0.0118)	0.121*** (0.0115)
ihsTA × lnPIN		0.0445*** (0.0150)	0.0440*** (0.0148)
HEp			0.145*** (0.0350)
ihsTA × HEp			0.042*** (0.0120)
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
DK SE	Yes	Yes	Yes
Observations	1,140	1,140	1,140
Countries	38	38	38

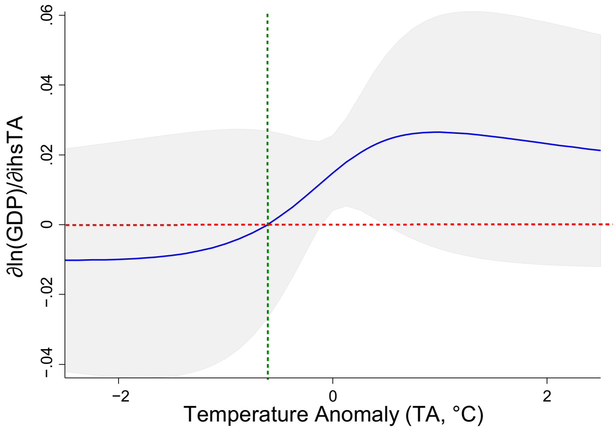
*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$. Standard errors in parentheses.

Models 2 and 3 extend the baseline specification by allowing the temperature–output relationship to vary with adaptive capacity. In Model 2, the coefficient on public fixed capital formation (lnPIN) is positive and highly significant, and the interaction term (ihsTA × lnPIN) is statistically significant. This suggests that public investment is a relevant correlate of long-run income levels and that it systematically conditions the temperature–output association within the observed anomaly range. Given that interaction estimates can be sensitive to long-run estimators and specifications, we interpret this evidence as indicating a moderating role of public investment, while placing emphasis on the robustness checks reported in Appendix D (Table D1) and the corroborating long-run results.

Model 3 introduces health-system capacity as an additional moderating factor. The health capacity indicator (HEp) is positively associated with long-run income levels, and its interaction with temperature anomalies (ihsTA × HEp) is also positive and statistically significant. This finding suggests that stronger health systems are associated with a more favorable marginal output response to temperature anomalies, consistent with a resilience mechanism that operates through health-related institutional capacity.

Given the substantial heterogeneity in baseline climatic conditions across OECD countries, average panel estimates may mask important cross-country differences. To address this issue, subsequent analyses stratify the sample by climate zones and geographic regions. These results show that the non-linear temperature–output relationship is considerably stronger in warmer-climate OECD countries, while cooler-climate economies display flatter marginal effects. Together, the results indicate that both baseline climate and adaptive capacity play a central role in shaping the economic consequences of temperature anomalies.

Because OECD countries differ markedly in their underlying climatic environments, the economic consequences of temperature anomalies are unlikely to be spatially uniform. In particular, countries located at higher latitudes are exposed to systematically different warming dynamics than those situated in warmer climatic zones. To explore this dimension of heterogeneity, we partition the OECD sample into cold-climate and warm-climate groups based on latitude and re-estimate the baseline specifications (Models 1–3) separately for each subsample. This approach allows us to assess whether the output response to temperature anomalies varies with initial climatic conditions. The corresponding results are reported in Table 5.



lnGDP	Implied extremum (within-sample)
Coef.	−0.61
Std. Err.	0.364
z	−1.67
P>z	0.094
%95 CIs	[−1.323, 0.104]

Marginal effects with respect to $ihs(TA)$ are $\beta_1 + 2\beta_2 \text{asinh}(TA)$. The derivative with respect to TA is obtained by the chain rule as $(\beta_1 + 2\beta_2 \text{asinh}(TA))/\sqrt{1 + TA^2}$.

Figure 2: Marginal effect of temperature anomalies on output. Note: Marginal effects are ∂ln(GDP)/∂ihsTA but shown against TA for interpretability.

Table 5 reveals two main findings. First, temperature anomalies exert a positive and statistically significant effect on output per capita in both climatic groups; however, the magnitude of this effect is clearly larger in warm-climate OECD countries. While the coefficient on temperature anomalies (ihsTA) ranges between 0.008 and 0.025 across specifications for cold-climate countries, it increases to 0.016–0.040 in the warm-climate group. This pattern suggests that deviations from historical temperature norms translate into stronger output responses in economies characterized by warmer baseline climates.

Second, evidence of nonlinearity is more pronounced in warm-climate countries. The squared temperature anomaly term (ihsTA^2) is generally statistically insignificant in cold-climate OECD economies, whereas it is positive and significant in the warm-climate subsample. This finding indicates that, in warmer environments, the marginal economic response to temperature deviations follows a more pronounced nonlinear trajectory.

The role of adaptive capacity further reinforces this heterogeneity. Public investment capacity (lnPIN) enters positively and significantly in both subsamples, and its interaction with temperature anomalies is consistently positive. Notably, the interaction effect is stronger in warm-climate countries, indicating a larger upward shift in the marginal temperature–output response associated with higher public investment capacity. A similar pattern emerges for health-system capacity (HEp). Both the direct

Table 5: Heterogeneity by baseline climate.

	Cold OECD (lat)			**Warm OECD (lat)**		
Variables	**(M1)**	**(M2)**	**(M3)**	**(M1)**	**(M2)**	**(M3)**
ihsTA	0.008*	0.025**	0.020**	0.016**	0.040***	0.033***
	(0.004)	(0.010)	(0.008)	(0.007)	(0.008)	(0.009)
ihsTA^2	0.004	0.007	0.008	0.015**	0.018**	0.020**
	(0.003)	(0.005)	(0.005)	(0.006)	(0.008)	(0.008)
lnPIN		0.098***	0.095***		0.145***	0.142***
		(0.019)	(0.018)		(0.026)	(0.025)
ihsTA × lnPIN		0.032**	0.030**		0.056***	0.053***
		(0.013)	(0.012)		(0.020)	(0.019)
HEp			0.125***			0.165***
			(0.028)			(0.042)
ihsTA × HEp			0.028**			0.042***
			(0.011)			(0.014)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
FE, DK SE	Yes	Yes	Yes	Yes	Yes	Yes
Obs	570	570	570	570	570	570

Standard errors in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$. All specifications include country and year fixed effects. Control variables: lnGFC, gross fixed capital formation; lnAG, agriculture value added; lnIN, industry value added; lnSE, services value added; lnTO, trade openness; lnEP, energy production.

effect and the interaction with temperature anomalies are positive and statistically significant, with larger coefficients observed in the warm-climate group. Taken together, these results indicate that while temperature anomalies affect all OECD economies, the intensity and curvature of these effects depend critically on baseline climate conditions and on the strength of investment- and health-related adaptive capacities.

Building on the climate-based heterogeneity analysis, we next examine geographic heterogeneity in the temperature–output relationship within the OECD. To this end, the sample is divided into European and non-European OECD countries, and the baseline specifications are re-estimated for each subgroup. The corresponding results are presented in Table 6.

Table 6 examines geographic heterogeneity in the temperature–output relationship by comparing OECD-Europe and OECD-Non-Europe subsamples. Across specifications, temperature anomalies are positive and statistically significant in both groups, while the magnitude of the estimated effects is consistently larger in OECD-Non-Europe economies. This pattern indicates that the economic response to temperature deviations varies systematically across regions within the OECD, even among advanced economies.

Evidence of non-linearity is present in both regional subsamples, as reflected by the positive and statistically significant squared temperature term. Notably, the estimated coefficients on the squared temperature anomaly are larger for OECD-Non-Europe countries, suggesting a more pronounced curvature in the temperature–output relationship. This pattern is consistent with stronger non-linear dynamics as temperature deviations increase outside Europe.

Adaptive capacity variables play a systematic conditioning role across regions. Public investment and health-system capacity enter positively in both subsamples, and their interaction terms with temperature anomalies are statistically significant. The larger interaction effects observed in OECD-Non-Europe economies indicate a stronger upward shift in the marginal temperature–output response associated with infrastructure investment and health capacity in regions where temperature responses are larger and more non-linear.

Taken together, these results suggest that geographic location within the OECD – rather than income differences per se – shapes both the magnitude and the structure of climate-related output responses. Regional climatic exposure and institutional context therefore play a central role in conditioning how temperature anomalies translate into macroeconomic outcomes.

To further illustrate the non-linear structure implied by these estimates, Figure 2 plots the marginal effect of temperature anomalies on economic output across the observed range of temperature deviations. This visualization clarifies how the impact of temperature changes evolves with the magnitude of anomalies and complements the regression-based evidence of non-linearity.

Figure 2 illustrates the marginal effect of temperature anomalies on real GDP per capita implied by the non-linear specification in Table 4. The marginal effects are plotted over the observed range of temperature anomalies, expressed in degrees Celsius for ease of interpretation, while the shaded

Table 6: Heterogeneity by geographic region.

	OECD-Europe			**OECD-non-Europe**		
Variables	**(M1)**	**(M2)**	**(M3)**	**(M1)**	**(M2)**	**(M3)**
ihsTA	0.012*	0.030***	0.025**	0.020**	0.045***	0.038***
	(0.006)	(0.007)	(0.010)	(0.008)	(0.009)	(0.011)
ihsTA^2	0.010*	0.012*	0.013*	0.018**	0.020**	0.021**
	(0.005)	(0.006)	(0.007)	(0.007)	(0.009)	(0.009)
lnPIN		0.115***	0.112***		0.128***	0.125***
		(0.022)	(0.021)		(0.027)	(0.026)
ihsTA × lnPIN		0.038**	0.036**		0.052***	0.049***
		(0.015)	(0.014)		(0.019)	(0.018)
HEp			0.135***			0.155***
			(0.032)			(0.038)
ihsTA × HEp			0.032**			0.038***
			(0.013)			(0.015)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
FE, DK SE	Yes	Yes	Yes	Yes	Yes	Yes
Obs	780	780	780	360	360	360

Standard errors in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$. All specifications include country and year fixed effects, and control variables.

area represents the 95 % confidence interval. The figure highlights a clearly non-linear temperature–output relationship. At relatively low levels of temperature deviation, the marginal effect is positive, indicating that modest anomalies are associated with small output gains in OECD economies. As temperature anomalies increase, however, the marginal effect gradually weakens, consistent with diminishing gains and an increasing marginal drag at larger deviations from historical norms. In this regards, the figure provides a transparent visualization of the non-linear structure identified in the regression results and underscores that the economic impact of temperature anomalies depends on the magnitude of the deviation rather than being constant across the temperature distribution.

5.2 Robustness Check

To evaluate the consistency of the results obtained from the baseline model, the long-run relationship between the variables is re-estimated using the panel FMOLS method, and the results are presented in Table 7.

The panel FMOLS estimates in Table 7 broadly confirm the long-run patterns obtained from the baseline two-way fixed effects model with Driscoll–Kraay standard errors, reinforcing the robustness of the climate–output relationship. In all three specifications, the coefficients on ihsTA and ihsTA^2 remain positive and statistically significant, indicating that the long-run association between temperature anomalies and output is non-linear rather than proportional or constant across the anomaly distribution.

The extended specifications further suggest that the long-run temperature–output relationship is conditional on adaptive-capacity proxies. In Model 2, lnPIN enters positively, while the interaction term (ihsTA × lnPIN) is negative and statistically significant. Under the FMOLS specification, this indicates that the long-run temperature–output association varies systematically with public investment capacity. At the same time, the interaction itself should be interpreted cautiously – its sign can differ across long-run estimators, suggesting some sensitivity to specification, and we therefore treat it as reduced-form evidence rather than a structural estimate. In Model 3, HEp is positive and significant, and the interaction term (ihsTA × HEp) is also positive and significant, suggesting that health-system capacity is an additional factor that conditions long-run temperature sensitivity. Taken together, the FMOLS evidence supports the broader interpretation that observable adaptation-related capacities are relevant correlates of macroeconomic resilience. Accordingly, we do not overinterpret the FMOLS interaction coefficients and place interpretive emphasis on the baseline FE-DK results and the supporting checks reported in Appendix D (Table D1).

Finally, the control variables behave as expected across specifications: physical capital (lnGFC) is positive and significant, the agriculture share (lnAG) is negative, while industry and services shares (lnIN, lnSE) are positive; trade openness (lnTO) and energy use (lnEP) also remain positive and highly significant. Table 7 indicates that the main findings are not an artifact of a single estimator, and the long-run climate–output relationship remains stable when re-estimated using panel FMOLS.

5.3 Panel Data Diagnostics and Model Specification

We begin by testing for cross-sectional dependence using the Pesaran CD test and its enhanced versions (CDw, CDw+, CD*). The results, reported in Table B1 (Appendix B), reject

Table 7: Panel FMOLS long-run estimates (Robustness).

	Model 1		**Model 2**		**Model 3**	
lnGDP	**Coef.**	**Std. err.**	**Coef.**	**Std. err.**	**Coef.**	**Std. err.**
ihsTA	0.011***	0.00087	0.034***	0.00177	0.012***	0.00057
ihsTA^2	0.010***	0.00352	0.012*	0.00732	0.001***	0.00006
lnGFC	0.290***	0.00178	0.304***	0.01656	0.290***	0.00182
lnAG	−0.011***	0.00219	−0.050***	0.00274	−0.012***	0.00145
lnIN	0.043***	0.00521	0.281***	0.01456	0.040***	0.00284
lnSE	0.345***	0.01660	0.732***	0.04327	0.281***	0.01052
lnTO	0.201***	0.00211	0.311***	0.00345	0.173***	0.00233
lnEP	0.331***	0.00369	0.490***	0.00507	0.321***	0.00341
lnPIN			0.001***	0.00008		
ihsTA × lnPIN			−0.010***	0.00091		
HEp					0.181***	0.00440
ihsTA × HEp					0.001***	0.00004

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

the null of cross-sectional independence for the vast majority of variables, indicating strong common shocks across OECD countries. Unit-root tests (Pesaran CIPS and Karavias–Tzavalis, Table B2) show that the series are a mixture of I(0) and I(1) processes. The Westerlund (2007) cointegration test (Table B3) confirms a long-run equilibrium relationship among the variables. Tests for slope homogeneity (Swamy and Pesaran–Yamagata, Table B4) reject the null of homogeneous slopes, supporting our later subsample analyses.

Specification tests (Table C1, Appendix C) favor a two-way fixed-effects model over pooled or random-effects alternatives (LR, F, and Hausman tests, all $*p < 0.01$). Residual diagnostics (Table C2) reveal groupwise heteroskedasticity, while serial correlation does not pose a material concern, and multicollinearity is not a concern (mean VIF < 5). Taken together, these diagnostics justify the use of Driscoll–Kraay standard errors and motivate the stratified (subsample) approaches that follow.

5.4 Discussion

This study documents a non-linear long-run relationship between temperature anomalies and economic output in OECD countries and shows that the magnitude of this relationship depends critically on both baseline climatic conditions and adaptive capacity. The results indicate that moderate temperature deviations are associated with limited or weakly positive output responses, while the marginal effect weakens as anomalies intensify. This pattern is consistent with damage-function frameworks in which climate-related benefits at low deviations are eventually outweighed by rising productivity and efficiency losses as temperature shocks become more severe.

A key contribution of the analysis lies in documenting meaningful cross-country heterogeneity in the temperature–output relationship based on baseline climate conditions. The stratified results indicate that the non-linear effects are considerably stronger in warmer-climate OECD economies, while cooler-climate countries exhibit flatter marginal responses. This finding underscores the importance of baseline climate in shaping economic vulnerability to temperature shocks and suggests that policy responses cannot be uniform across regions. In this sense, the results help reconcile mixed findings in the literature regarding whether advanced economies are largely insulated from climate damages: even within the OECD, exposure and sensitivity vary systematically with climatic conditions.

Beyond baseline climate differences, the results also reveal meaningful geographic heterogeneity within the OECD. The regional estimates indicate that the temperature–output relationship is systematically stronger and more non-linear in non-European OECD economies compared to their European counterparts. This pattern likely reflects differences in regional climatic exposure, economic structure, and institutional configurations, even among advanced economies operating at broadly similar income levels. Importantly, these findings suggest that geographic context – rather than income differences per se – conditions how temperature anomalies translate into macroeconomic outcomes.

The analysis further highlights the role of adaptive capacity in moderating climate-related economic impacts. Both public investment and health-system capacity significantly attenuate the marginal effects of temperature anomalies on output. These results point to concrete mechanisms through which adaptation operates. Public investment likely enhances resilience by improving infrastructure quality, reducing climate-related disruptions, and facilitating post-shock recovery, while stronger health systems mitigate productivity losses associated with heat stress, illness, and mortality. Importantly, these channels go beyond broad income-based proxies of adaptation and provide policy-relevant evidence on how specific institutional and infrastructural factors shape climate–economy linkages.

From an external-validity perspective, the estimated non-linear relationship should be interpreted in light of the observed range of temperature anomalies in the OECD sample. While historical warming has already reached levels at which marginal effects begin to weaken, projected future temperature increases may push some countries further into the damage-dominated segment of the relationship. This suggests that the buffering role of adaptation capacity identified in this study is likely to become increasingly important over time, particularly for warmer OECD economies that are closer to critical thresholds.

While the aggregate GDP framework employed in this study does not permit a direct sectoral decomposition, the observed non-linear temperature–output relationship is consistent with several well-established transmission mechanisms emphasized in the climate–economy literature. In particular, stronger effects in warmer OECD economies suggest that climate exposure may operate through channels such as reduced agricultural productivity, increased cooling-related energy demand, and heat-induced declines in labor efficiency, especially in outdoor, service-intensive, and climate-sensitive activities. These mechanisms provide a plausible explanation for why marginal output responses weaken as temperature anomalies intensify, even in advanced economies, and highlight the importance of adaptation policies that target sectoral exposure and productivity-related vulnerabilities. A detailed empirical analysis of these channels at the sectoral or factor level is left for future research.

6 Conclusions

This study has examined how temperature anomalies affect long-run economic output in OECD countries over the period 1995–2024, with particular attention to non-linear effects and the role of adaptive capacity. Using a reduced-form panel framework that accounts for cross-sectional dependence and structural heterogeneity, the analysis provides consistent evidence that the economic consequences of temperature deviations are neither uniform nor linear across countries and over time, reflecting differences in baseline climatic conditions and geographic context across OECD economies.

The empirical findings indicate that moderate temperature anomalies are not necessarily associated with immediate economic losses in advanced economies. Instead, the output response depends on the magnitude of the deviation and on countries' underlying economic and institutional conditions. While modest deviations may coincide with temporary gains in certain contexts, the marginal contribution of additional warming weakens as anomalies increase. This pattern suggests that climate-related economic risks emerge gradually and intensify once temperature deviations move sufficiently away from historical norms.

A central contribution of the study lies in identifying concrete adaptation channels that shape this relationship. The results demonstrate that public investment capacity and health-system strength significantly influence how economies respond to temperature shocks. Higher levels of public infrastructure investment are associated not only with stronger long-run output but also with greater resilience to climate-induced disruptions. Similarly, stronger health capacity shapes the productivity response to temperature stress by preserving labor supply and reducing human-capital losses. These findings highlight that adaptation is not an abstract concept but a measurable and policy-relevant margin through which climate risks can be managed. While these patterns are consistent with an adaptation-capacity interpretation, we acknowledge that public investment is likely endogenous to income levels and institutional capacity. Accordingly, the interaction estimates should be interpreted as long-run reduced-form associations rather than definitive causal effects. To mitigate simultaneity concerns and align with delayed adaptation dynamics, we re-estimate the interaction model using lagged public investment and also provide a split-sample analysis (Advanced vs. Emerging OECD). The key buffering interaction remains positive under these checks (Appendix D, Table D1).

Importantly, the results imply that the aggregate output effects documented in this study reflect underlying economic transmission channels – such as productivity, energy demand, and sectoral exposure – that vary systematically with baseline climate and adaptive capacity.

Taken together, the evidence underscores that the macroeconomic impact of climate change cannot be assessed solely by projected temperature increases. Instead, it depends critically on countries' baseline climatic conditions, geographic context, institutional characteristics, and investment in adaptive capacity. For OECD economies, this implies that strengthening infrastructure networks and health systems can play a decisive role in limiting long-run economic vulnerability to climate variability.

Despite its contributions, the study is subject to several limitations. The focus on OECD countries restricts the generalizability of the results beyond advanced economies and to settings characterized by different institutional capacities and climatic environments. In addition, the analysis concentrates on temperature anomalies and does not explicitly incorporate other climate dimensions such as precipitation variability, humidity, or extreme weather events. Future research could extend the framework to a broader set of countries, explore sector-specific responses, or employ spatial and subnational data to capture localized climate–economy interactions more precisely. Relatedly, because our identification relies on historical temperature variation, the results should not be interpreted as predicting out-of-sample climate regime shifts or future tipping points.

These findings suggest that climate resilience is not solely an environmental challenge but also an economic and institutional one. Policies aimed at enhancing public investment and health-system capacity may therefore serve a dual purpose: supporting long-run growth while simultaneously reducing exposure to climate-related economic risks.

7 Limitations and Future Research Directions

Several limitations of this study should be acknowledged, which also point to directions for future research. First, the analysis relies on annual temperature anomalies, which capture long-run climatic deviations but do not explicitly account for short-lived extreme events such as heatwaves or cold spells. While this choice is consistent with the study's focus on long-run output relationships, future research could complement this approach by incorporating high-frequency indicators of extreme temperature exposure to assess short-term economic disruptions.

Second, while the empirical strategy addresses cross-sectional dependence and allows for heterogeneous responses through interaction terms and subsample analyses, the baseline panel estimates still represent average effects across countries. Estimators explicitly designed to allow for richer forms of slope heterogeneity may provide additional insights, particularly for country-specific policy evaluation.

Third, adaptation capacity is proxied through public investment and health-system indicators, which capture key but not exhaustive dimensions of resilience. Other mechanisms – such as technological adaptation, firm-level adjustments, labor-market flexibility, or sector-specific responses – are not explicitly modeled. Future work could integrate micro-level data or sectoral outcomes to further disentangle these channels and provide a more granular understanding of how adaptation operates. Moreover, these proxies may partly reflect broader development and institutional conditions, so policy endogeneity and omitted-variable bias cannot be fully ruled out in the OECD setting. We therefore frame the public-investment interaction as reduced-form evidence and report lagged and split-sample checks as supportive (Appendix D, Table D1).

Fourth, climate exposure is multidimensional, whereas our baseline specification focuses on temperature anomalies due to data consistency and parsimony in a long-run macro framework. Omitting precipitation and humidity may leave out channels through which climate affects output (e.g., agriculture, labor productivity, and health), so future work should extend the damage function using broader climate indicators where comparable panel data are available.

Finally, the external validity of the estimated non-linear relationship depends on the range of temperature variation observed in the historical sample. As climate change accelerates, future temperature realizations may exceed past experience, potentially altering damage profiles and non-linear response patterns. Extending the analysis to longer horizons, alternative climate scenarios, or non-OECD economies would help assess the robustness of the findings under more extreme warming conditions.

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Conflict of interest: The authors declare that there is no conflict of interest regarding the publication of this manuscript.

Data availability statement: All data used in this study originate from publicly accessible databases (WDI, OWID, IMF, WHO, CIHI). Processed data and replication materials are available from the corresponding author upon reasonable request.

Appendix

A. Dynamic Optimization Framework Model Derivations

This appendix presents the dynamic optimization framework underlying the reduced-form climate–output relationship discussed in the main text. The representative social planner's problem is formulated, and the corresponding Hamiltonian, first-order conditions, and steady-state solutions are derived to illustrate how temperature-induced damages affect capital accumulation and long-run consumption.

This objective function is optimized subject to the resource constraints given in Equations (4) and (5) in the main text. The corresponding Hamiltonian is defined as:

$$H = \ln C + \lambda\left[(1 - \Delta(T))AK^{\alpha} - C - \delta K\right]. \tag{1}$$

In Equation (1), H represents the Hamiltonian function and λ denotes the shadow value of capital. The first term signifies the utility derived from consumption, while the second term represents the economy's dynamics via the shadow value of the resource constraint.

The first-order condition of the Hamiltonian with respect to consumption is:

$$H = \frac{\partial H}{\partial C} = 0 \quad \Rightarrow \quad \lambda(t) = \frac{1}{C(t)}. \tag{2}$$

The result obtained in Equation (2) shows that the shadow value $\lambda(t)$ is equated to the marginal utility of consumption, $\frac{1}{C(t)}$. This means that each unit of consumption is directly linked to the marginal utility of welfare.

The condition derived from the derivative of the Hamiltonian with respect to capital is:

$$\dot{\lambda}(t) = \rho\lambda(t) - \frac{\partial H}{\partial C} = \lambda(t)\left[\rho + \delta - \alpha(1 - \Delta(T))AK^{\alpha-1}\right]. \tag{3}$$

In Equation (3), $\dot{\lambda}(t)$ represents the change in the shadow value over time. The expression in parentheses shows that the marginal product of capital ($\alpha K^{\alpha-1}$) is reduced by climate damage $(1 - \Delta(T))$, while the effects of capital depreciation δ and discounting ρ lower welfare. This equation reflects how capital accumulation affects social welfare in the face of climate damages.

The optimal path of consumption over time is derived by using Equations (2) and (3) together:

$$\frac{\dot{C}(t)}{C(t)} = \alpha(1 - \Delta(T(t)))AK(t)^{\alpha-1} - \delta - \rho. \tag{4}$$

In Equation (4), $\frac{\dot{C}(t)}{C(t)}$ represents the consumption growth rate. The term $\alpha K^{\alpha-1}$ on the right-hand side denotes the marginal product of capital, which is reduced by the climate damage factor $(1 - \Delta(T))$. In contrast, the capital depreciation rate δ and the time preference rate ρ are factors that depress the consumption growth rate. Consequently, this equation directly demonstrates the growth-retarding effect of rising temperatures.

To examine the long-run equilibrium, the capital stock is assumed to be constant in the steady state. In this case:

$$I^* = \delta K^*. \tag{5}$$

In Equation (5), the steady-state investment I^* is set exactly equal to δK^* to offset the depreciation of capital. This means there is no net capital accumulation in the economy; investment is only undertaken to maintain the existing capital stock.

In the steady state, consumption is expressed as:

$$C^* = [1 - \Delta(T^*)]A(K^*)^{\alpha} - \delta K^*. \tag{6}$$

In Equation (6), the consumption level C^* is obtained by subtracting the investment allocation δK^* from the production achieved after accounting for the climate damage effect. Here, as the temperature level $T^*\star$ increases, the damage share $\Delta(T^*)$ grows, and net consumption decreases.

The equilibrium condition derived from the Euler equation is:

$$\alpha(1 - \Delta(T^*))A(K^*)^{\alpha-1} = \delta + \rho. \tag{7}$$

In Equation (7), the marginal product of capital $(\alpha K^{\alpha-1})$ is shown in its reduced form due to climate damage $(1 - \Delta(T^*))$. Equilibrium is achieved when this value equals the sum of the capital depreciation rate δ and the time preference rate ρ. Therefore, climate damage is one of the fundamental factors that reduces the long-run capital stock.

Using Equation (7) in the steady state, the closed-form solution for capital is obtained:

$$K^* = \frac{\alpha[1 - \Delta(T^*)]A}{\delta + \rho}. \tag{8}$$

In Equation (8), K^* represents the long-run capital stock. The denominator $(\delta + \rho)$ represents the effective "cost of capital" (depreciation + time preference), while the term αA in the numerator indicates the level of production technology and the marginal contribution of capital. The term $[1 - \Delta(T^*)]$ captures the direct reduction effect of climate damage on damage-free output; as this term decreases, K^* declines. The exponent $\frac{1}{1-\alpha}$ determines the sensitivity of the equilibrium capital stock to production parameters due to the Cobb-Douglas elasticity.

The effect of climate damage on the equilibrium capital stock is demonstrated by taking the derivative with respect to T^*:

$$\frac{\partial K^*}{\partial T^*} = -\frac{\partial K^*}{(1-\alpha)} \cdot \frac{\Delta'(T^*)}{1 - \Delta(T^*)}, \Delta(T^*) = \vartheta_0 + \vartheta_1 \phi (T^*)^{\phi-1}. \tag{9}$$

In Equation (9), $\frac{\partial K^*}{\partial T^*}$ represents the marginal effect of an increase in the climate (temperature) level on the equilibrium capital stock. The sign of the right-hand side is negative, since under the assumptions $\Delta'(T^*) > 0$ and $1 - \Delta(T^*) > 0$, an increase in temperature raises the damage share and reduces the equilibrium capital stock. The term $1/(1 - \alpha)$ in the fraction indicates that the production technology (capital elasticity α) amplifies this sensitivity; as αα increases, $(1 - \alpha)$ decreases, and vulnerability to temperature rises. The explicit form of $\Delta'(T^*)$, comprising the linear term ϑ_0 and the convex term $\left(\vartheta_1 \phi (T^*)^{\phi-1}\right)$, shows that together they accelerate marginal damage at high temperatures.

In the steady state, consumption is reduced to closed form by using Equations (6) and (7) together:

$$C^* = \frac{\rho + \delta(1-\alpha)}{\alpha} K^*. \tag{10}$$

In Equation (10), C^* represents the long-run consumption level and K^* the long-run capital stock. The coefficient $(\rho + \delta(1 - \alpha))/\alpha$ is obtained by using the Euler equilibrium (Equation (7)) to eliminate the $(1 - \Delta)A(K^*)^{\alpha}$ term. This result shows that equilibrium consumption is directly proportional to the equilibrium capital stock.

The effect of climate damage on equilibrium consumption is derived by using Equations (10) and (9) together:

$$\begin{aligned}\frac{\partial C^*}{\partial T^*} &= \frac{\rho + \delta(1-\alpha)}{\alpha} \frac{\partial K^*}{\partial T^*} \\ &= -\frac{\rho + \delta(1-\alpha)}{\alpha} \frac{K^*}{(1-\alpha)} \cdot \frac{\Delta'(T^*)}{1 - \Delta(T^*)}.\end{aligned} \tag{11}$$

In Equation (11), $\frac{\partial C^*}{\partial T^*}$ is derived. Under the assumptions $\Delta'(T^*) > 0$ and $1 - \Delta(T^*) > 0$, an increase in temperature raises the damage share, thereby reducing the equilibrium capital stock and the corresponding consumption. The multiplier (1/(1 − α)) demonstrates how the production technology (capital elasticity) amplifies vulnerability to climate effects.

B. Panel Data Diagnostics

Table B1: CD tests.

	CD	CDw	CDw+	CD*
lnGDP	126.380 (0.000)	−3.740 (0.000)	3,345.320 (0.000)	−3.100 (0.002)
IhsTA	75.410 (0.000)	−2.950 (0.003)	1,996.970 (0.000)	1.920 (0.055)
ihsTA^2	61.200 (0.000)	−1.020 (0.306)	1,630.070 (0.000)	−0.060 (0.950)
lnGFC	81.800 (0.000)	−0.630 (0.525)	2,517.100 (0.000)	−1.150 (0.249)
lnAG	91.370 (0.000)	−2.090 (0.036)	2,487.970 (0.000)	−2.750 (0.006)
lnIN	66.920 (0.000)	−2.440 (0.015)	1,991.190 (0.000)	1.600 (0.109)
lnSE	85.040 (0.000)	−2.560 (0.010)	2,321.400 (0.000)	−1.930 (0.053)
lnTO	122.890 (0.000)	−3.530 (0.000)	3,254.710 (0.000)	−0.310 (0.754)
lnEP	48.010 (0.000)	−3.510 (0.000)	2,140.260 (0.000)	1.160 (0.245)

p-Values in parentheses. CD: Pesaran (2015, 2021); CDw: Juodis and Reese (2022); CDw+: CDw with power enhancement from Fan et al. (2015); CD*: Pesaran and Xie (2021) with 4 PCs.

Table B2: Unit-root test.

	Pesaran (CIPS stat.)		Karavias and Tzavalis (minZ-stat.)	
Variables	**Level**	**1st diff.**	**Level**	**1st diff.**
lnGDP	−1.262	−3.470***	0.0337***	
IhsTA	−4.454 ***		−5.149***	
IhsTA^2	−4.154***		−23.95	−33.86***
lnGFC	−1.562	−3.628***	0.034***	
lnAG	−2.875***		−0.216***	
lnIN	−1.537	−4.512***	−0.738***	
lnSE	−1.932	−4.808***	−0.002***	
lnTO	−1.859	−4.339***	0.021***	
lnEP	−1.741	−4.792***	−7.540***	
PIN	−2.074*	−4.703***	−3.712***	
HEp	−1.081	−4.237***	−12.247	1.630***
ihsTA × lnPIN	−3.983***		−6.649***	
ihsTA × HEp	−2.550***		−5.3324***	

Significance: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. First-difference results are reported only when the level series is non-stationary. Critical values for the Pesaran (2007) CIPS unit root test are −2.04 (10 %), −2.11 (5 %), and −2.23 (1 %). The Karavias and Tzavalis (2014) unit root test is implemented with one structural break and bootstrap critical values based on 100 replications.

Table B3: Westerlund panel cointegration tests.

Statistic	Value	*Z*-value	*p*-Value
Gt	−2.288	−1.696	0.045
Ga	−7.705	1.396	0.919
Pt	−13.673	−3.014	0.001
Pa	−6.115	−0.275	0.392

Table B4: Cross-section independence and slope homogeneity rests.

CD tests				Slope homogeneity	
CD	**CDw**	**CDw+**	**CD***	**Adj. delta**	**Swamy's (χ^2)**
7.37 (0.000)	1.12 (0.264)	1,325.40 (0.000)	2.36 (0.018)	26.311 (0.000)	56,079.75 (0.000)

C. Model Choice & Specification Validity

Table C1: Panel effects and model selection tests.

Panel effect tests	Individual effect	Time effect	Joint effect
LR	χ^2 = 1,921.69 (0.000)	χ^2 = 60.69 (0.0003)	χ^2 = 2,048.64 (0.000)
F	F = 5,252.06 (0.000)	F = 125.51 (0.0000)	F = 5,609.56 (0.0000)
Model specification tests			
LM	χ^2 = 3,595.48 (0.000)		
Hausman test	χ^2 = 224.32 (0.0000)		

p-values in parentheses.

Table C2: Model validity tests.

Modified Wald (H_0: groupwise heteroskedasticity)	χ^2 = 12,579.91 (0.000)
Jochmans portmanteau test (H_0: no autocorrelation of any order)	χ^2 = 38.00 (0.6472)
Mean VIF	3.23 < 5

p-Values in parentheses.

D. Additional Robustness Checks for Endogeneity and Heterogeneity

Table D1: Public investment and climate resilience (lagged PIN and split-sample evidence).

Variables	**(1) Baseline (all OECD)**	**(2) Lagged PIN**	**(3) Advanced OECD**	**(4) Emerging OECD**
ihsTA	0.0364***	0.0351***	0.0322***	0.0398***
	(0.0056)	(0.0058)	(0.0061)	(0.0085)
ihsTA^2	0.0147**	0.0142**	0.0123*	0.0181**
	(0.0069)	(0.0070)	(0.0072)	(0.0089)
lnPIN	0.122***	–	0.095***	0.175***
	(0.0118)		(0.0125)	(0.0280)
lnPIN(-1)	–	0.105***	–	–
		(0.0120)		
ihsTA × lnPIN	0.0445***	–	0.030*	0.065***
	(0.0150)		(0.0162)	(0.0220)
ihsTA × lnPIN(-1)	–	0.038***	–	–
		(0.0148)		
Controls	Yes	Yes	Yes	Yes
Country & Year FE	Yes	Yes	Yes	Yes
Driscoll–Kraay SE	Yes	Yes	Yes	Yes
Observations	1,140	1,102	990	150
Number of countries	38	38	33	5

Standard errors in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01. All specifications include the full set of controls (lnGFC, lnAG, lnIN, lnSE, lnTO, lnEP), country and year fixed effects. Driscoll–Kraay standard errors are robust to heteroskedasticity, serial correlation, and cross-sectional dependence. Advanced OECD refers to the remaining OECD members in our sample (33 countries). Emerging OECD includes: Chile, Colombia, Costa Rica, Mexico, Türkiye. This grouping follows common OECD classifications and serves as a pragmatic proxy for development/institutional capacity differences within the OECD. Given the limited size of the Emerging OECD subsample, we keep the split-sample specifications parsimonious; the lagged-PIN specification is reported for the full OECD sample where statistical power is adequate.

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