



TEMPERATURE AND ECONOMIC GROWTH IN G20 COUNTRIES: A CS-ARDL APPROACH

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ABSTRACT

This study examines the relationship between temperature and economic growth in the G20 countries over the period 1999–2024 using the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model, which is designed to account for cross-sectional dependence. In addition to temperature, the analysis includes per capita greenhouse gas emissions, the share of renewable energy, and macroeconomic control variables (total investment, trade openness, and population growth). To explore whether the temperature–growth relationship differs across climatic conditions, the sample is divided into three climate groups: cold, temperate, and hot. The results provide no statistically significant evidence of a long-run association between temperature and economic growth, either in the full sample or in any climate group, although the estimates are imprecise given the limited time dimension and group sizes. The quadratic temperature term is also statistically insignificant, providing no evidence of a nonlinear relationship, and a linear specification leads to the same conclusion. The error-correction term is significantly negative but describes the adjustment of the whole model, not a temperature coefficient. Greenhouse gas emissions, renewable energy, total investment, and trade openness show no statistically significant associations in the full sample, while population growth displays a significant long-run coefficient that is not retained in the linear specification. Residual cross-sectional dependence warrants cautious interpretation.

1 INTRODUCTION

Temperature has increasingly been recognized as one of the important structural determinants explaining aggregate economic performance, given its far-reaching effects on productivity, investment, trade, and the dynamics of long-term

economic growth. Accordingly, climatic factors are no longer viewed in the economic literature as merely exogenous environmental conditions, but rather as significant determinants of economic performance and growth trajectories.

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Within this context, studying the relationship between temperature and economic growth is gaining increasing importance in the G20 countries, as they account for the largest share of global economic output while also contributing significantly to global carbon emissions. At the same time, considerable differences exist among G20 countries in terms of climate, levels of development, production structures, and environmental policies, making the G20 an appropriate framework for examining how the temperature-growth relationship varies across a heterogeneous, multicountry context of global significance.

Despite growing research interest in the relationship between temperature and economic growth, the empirical literature continues to provide inconsistent findings regarding the nature of this effect, particularly with respect to the possibility of nonlinear relationships and the existence of a critical temperature threshold at which the impact of temperature on economic performance changes. Furthermore, most cross-country studies estimate a single average effect across climatically diverse economies, offering limited insight into whether this relationship differs systematically between cold, temperate, and hot climates. In addition, much of the existing panel literature does not adequately account for cross-sectional dependence, a limitation that is particularly relevant for a group of highly interconnected economies such as the G20.

Against the backdrop of these research limitations, there is a need for a more comprehensive analysis of the temperature-growth relationship that accounts for cross-sectional dependence and allows for climatic heterogeneity across countries. In this context, the main research problem of this study revolves around the following question:

RQ: *What is the relationship between temperature and economic growth in the G20 countries over the period 1999–2024, and does this relationship vary systematically across cold, temperate, and hot climatic groups?*

To address this research problem, the study adopts a second-generation econometric approach based on the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL/DCCE) model, estimated in its error-

correction form, which is designed to account for cross-sectional dependence among G20 economies.

This framework allows for testing the nature of both linear and nonlinear relationships among the variables under investigation, through the following hypotheses:

Main Hypothesis:

H0: Temperature has no statistically significant relationship with economic growth in the G20 countries over the period (1999–2024).

H1: Temperature has a statistically significant relationship with economic growth in the G20 countries over the period (1999–2024), and this relationship varies across climatically heterogeneous country groups.

Sub-Hypotheses:

H1a: The annual average temperature is theoretically expected to be negatively associated with economic growth in the G20 countries, particularly in the long run.

H1b: The relationship between temperature and economic growth may be nonlinear in the long run, reflecting the possibility of a critical temperature level beyond which the nature of the association changes.

H1c: Per capita greenhouse gas emissions are theoretically expected to be negatively associated with economic growth, particularly in the long run.

H1d: The share of renewable energy in total consumption is theoretically expected to be positively associated with economic growth, particularly in the long run.

H1e: Total investment is theoretically expected to be positively associated with economic growth, particularly in the short run.

H1f: Trade openness is theoretically expected to be positively associated with economic growth, particularly in the short run, as trade effects tend to transmit relatively quickly through import and export channels.

H1g: Population growth is theoretically expected to be negatively associated with economic growth, particularly in the long run, consistent with standard growth theory.

2 LITERATURE REVIEW AND PREVIOUS STUDIES

Research on the relationship between temperature and economic growth has undergone a fundamental reorientation over the past decade, moving from treating temperature as a marginal exogenous disturbance toward recognizing it as a structural determinant of long-term growth trajectories. This reorientation finds its clearest empirical foundation in Dell et al. (2014), whose analysis of historical global panel data demonstrates that temperature fluctuations affect not merely the level of output but its growth rate — a distinction with profound implications, since growth-rate effects compound over time while level effects do not. This finding, consistent with Exogenous Shock Theory, whereby unanticipated temperature increases disrupt production functions and displace economies from their equilibrium path, established the empirical and theoretical foundation for a subsequent generation of dynamic panel studies capable of capturing the temporal and cross-country transmission of climatic shocks (Dell et al., 2014, pp. 740–741, 754).

Building directly on this foundation, Burke et al. (2015) advanced the field by challenging its implicit linearity. Using data for 166 countries over 1960–2010 within a Fixed Effects framework, they show that economic productivity follows a concave relationship with temperature, rising to a peak near 13.6°C before declining thereafter — a pattern they demonstrate holds consistently across both rich and poor economies and across agricultural and non-agricultural sectors alike (Burke, Hsiang, & Miguel, 2015, p. 2). However, both studies draw on globally diverse samples spanning highly heterogeneous climatic zones, yet analyze them within a single pooled specification rather than disaggregating countries by climatic context. As a result, neither study tests whether the estimated relationship — including the threshold Burke et al. (2015) identify — holds uniformly across climate types or masks offsetting patterns within climatically distinct subgroups. Nor do these studies address cross-sectional dependence, a limitation that is particularly consequential for tightly interconnected economies such as the G20.

Beyond the direct relationship between temperature and economic growth, a growing body of literature has examined other environmental and energy-related factors that influence economic growth through different economic mechanisms. Greenhouse gas emissions are generally viewed as an environmental indicator reflecting the environmental consequences of production and energy use, whereas renewable energy represents the structure of the energy system rather than temperature itself. Sharif et al. (2019), analysing 74 countries using heterogeneous panel estimation techniques, provide partial long-run support for the Environmental Kuznets Curve hypothesis, showing that the relationship between emissions and economic growth depends on environmental policies and technological innovation. Focusing on the G20, Ozparlak and Wang (2026) report that most member countries support the growth hypothesis, whereby restricting energy consumption adversely affects economic growth, while continued dependence on non-renewable energy increases carbon emissions and generates long-term environmental costs (Ozparlak & Wang, 2026, pp. 1, 5–7). In the present study, these variables are not interpreted as alternative measures of temperature or as components of a single causal pathway. Rather, temperature is specified as the principal climatic variable, greenhouse gas emissions are incorporated as an environmental indicator, renewable energy represents the energy structure, whereas investment, trade openness, and population growth are included as conventional macroeconomic control variables.

This pattern extends to the macroeconomic literature more broadly. Total investment strengthens productive capacity and climatic resilience, consistent with Endogenous Growth Theory's emphasis on capital accumulation (Mu, 2026, pp. 2–5); trade openness carries a dual character, facilitating clean-technology diffusion while, absent stringent environmental regulation, enabling pollution leakage toward less regulated economies (Soti et al., 2025, p. 6); and population growth indirectly amplifies environmental pressure by intensifying demand for energy and resources, reinforcing carbon-intensive production patterns (Afolabi, 2026, p. 3). Although these macroeconomic determinants are well established

in the economic growth literature, relatively few studies have analysed them jointly with temperature within a unified empirical framework. Consequently, existing evidence provides only a partial understanding of how temperature-related, environmental, and macroeconomic factors jointly influence long-run economic growth.

Taken together, the existing literature suggests that the relationship between temperature and economic growth cannot be fully understood in isolation but should instead be examined alongside environmental and macroeconomic conditions. Nevertheless, these dimensions have generally been investigated separately rather than within a single integrated empirical framework. The present study's contribution can be stated precisely against this backdrop, along five dimensions.

First, in terms of sample, the study focuses specifically on the G20, in contrast to the global samples used by Burke et al. (2015) and Dell et al. (2014). This choice is motivated not by climatic considerations but by the group's exceptional degree of economic and financial interconnectedness, which makes cross-sectional dependence a first-order empirical concern rather than a secondary statistical nuisance. Second, in terms of methodology, it addresses this cross-sectional dependence directly through a cross-sectionally augmented dynamic panel framework (CS-ARDL/DCCE), which neither prior study employs. Third, regarding nonlinearity, it formally re-tests whether the concave temperature-growth relationship identified by Burke et al. (2015) holds specifically within the G20, rather than assuming it transfers from the global sample. Fourth, and most centrally, it interrogates an assumption implicit in prior work: that the temperature-growth relationship is uniform across countries regardless of climatic context. A one-degree increase in mean temperature is unlikely to carry the same economic consequences for a cold economy operating well below any thermal optimum as for a hot economy already near or beyond it. The present study tests this proposition directly by disaggregating the G20 sample into cold, temperate, and hot climate groups and estimating the temperature-growth relationship separately within each, a dimension of climatic heterogeneity left unexplored in all studies reviewed above. Fifth, in terms of variable combination, it integrates

temperature with emissions, renewable energy, and macroeconomic controls (investment, trade openness, population growth) within a single unified framework, rather than examining climatic and macroeconomic determinants of growth in isolation, as in Sharif et al. (2019), Ozparlak and Wang (2026), and Mu (2026).

3 METHODOLOGY

3.1 Data Description

This study relies on panel data covering 19 G20 countries over the period 1999–2024. The European Union is excluded from the sample to avoid potential statistical double counting, as its aggregate indicators already incorporate the economic and environmental information of its member states. This exclusion ensures greater consistency in cross-country comparisons and enhances the reliability of the econometric estimates.

The selected period (1999–2024) is determined by the availability of consistent and comparable annual data for all countries included in the sample. The dataset is obtained primarily from the World Bank's World Development Indicators (WDI) database and complementary World Bank climate-related datasets. This period represents an important phase characterized by significant variations in global temperature patterns, increasing attention toward energy transition policies, and growing interest in understanding how temperature conditions and economic factors interact with long-term growth dynamics.

The study considers real GDP growth as the dependent variable and incorporates explanatory variables representing distinct economic mechanisms rather than grouping all variables under the same environmental concept. The variables employed in this study reflect four conceptually distinct roles. Temperature is introduced as the main variable of interest, capturing the direct relationship between temperature variations and economic activity. Greenhouse gas emissions per capita are treated as an environmental and production-related variable, measuring the amount of greenhouse gases emitted per person and reflecting the environmental consequences associated with economic activities and energy use. It is important

to note that this indicator captures total greenhouse gas emissions, including methane, nitrous oxide, and other gases converted to CO₂ equivalent, but excluding emissions and removals from land-use, land-use change, and forestry (LULUCF), and should therefore not be equated with CO₂ emissions alone, as is common in related studies.

Renewable energy share is considered an energy-structure variable, capturing the composition of the energy system and the transition toward cleaner production patterns. Investment, trade openness, and population growth serve as conventional macroeconomic control variables, included based on their established importance in standard economic growth models and their role

as independent determinants of economic performance.

These three macroeconomic controls were selected because they are consistently available for all G20 countries throughout the 1999–2024 period and represent widely recognized determinants of economic growth in empirical growth literature. Other frequently employed growth determinants, including foreign direct investment, energy intensity, and institutional quality indicators, were not incorporated due to limitations in data availability, measurement consistency, and cross-country comparability over the entire sample period. The detailed definitions, measurement units, and data sources for all variables are presented in Table 1.

Table 1. *Variables Description and Data Sources*

Type	Variable	Stata Name	Definition	Unit	Source
Dependent	GDP growth	<i>gdp_growth</i>	Annual real GDP growth rate	Fraction (0.01 = 1%)	World Bank, World Development Indicators (WDI), Indicator: NY.GDP.MKTP.KD.ZG
Temperature	Temperature	<i>temp</i>	Annual average surface temperature measured across the country	°C	World Bank Group, Climate Change Knowledge Portal (CCKP), Historical Climate Data – Annual Mean Surface Temperature
Temperature	Temperature squared	<i>temp²</i>	Square of annual mean temperature	(°C) ²	Calculated by the authors from the annual mean temperature (World Bank Climate Change Knowledge Portal)
Environmental	GHG per capita	<i>ghg_pc</i>	Total greenhouse gas emissions excluding LULUCF per capita	t CO ₂ e/capita	World Bank, WDI, Indicator: EN.GHG.ALL.PC.CE.AR5
Energy-structure	Renewable energy	<i>renew_energy</i>	Renewable energy consumption as a share of total final energy consumption	Proportion (0.01 = 1 percentage point)	World Bank, WDI, Indicator: EG.FEC.RNEW.ZS
Control	Investment	<i>inv_total</i>	Gross capital formation as a share of GDP	Fraction of GDP (0.01 = 1% of GDP)	World Bank, WDI, Indicator: NE.GDI.TOTL.ZS
Control	Trade openness	<i>trade_open</i>	Exports and imports of goods and services as a share of GDP	Fraction of GDP (0.01 = 1% of GDP)	World Bank, WDI, Indicator: NE.TRD.GNFS.ZS
Control	Population growth	<i>pop_growth</i>	Annual population growth rate	Fraction (0.01 = 1%)	World Bank, WDI, Indicator: SP.POP.GROW

3.2 Model Specification

To examine the relationship between temperature and economic growth in the presence of interdependence and common shocks among the G20 countries, this study moves beyond traditional first-generation estimators, such as Fixed Effects (FE), Random Effects (RE), and the standard Pooled Mean Group (PMG) estimator, which assume cross-sectional independence and may lead to biased estimates. Instead, the study relies on the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model, based on the Dynamic Common Correlated Effects (DCCE) estimator.

This methodology is designed to account for the effects of unobserved common shocks by augmenting the model with cross-sectional averages of the variables. The structural equation of the CS-ARDL model takes the following general form:

$$\begin{aligned} \Delta gdp_growth_{it} = & \alpha_i + \\ & \phi_i(gdp_growth_{it-1} - \beta'_i X_{it-1}) + \\ & \sum_{j=1}^{p-1} \lambda_{ij} \Delta gdp_growth_{it-j} + \\ & \sum_{j=0}^{q-1} \delta'_{ij} \Delta X_{it-j} + \sum_{j=0}^f \gamma'_{ij} \bar{Z}_{t-j} + \varepsilon_{it} \end{aligned}$$

Where:

gdp_growth_{it} : represents the real GDP growth rate of country i at time t .

X_{it} : denotes the vector of explanatory and control variables, comprising the average temperature ($temp$), the squared average temperature ($temp2$), per capita greenhouse gas emissions (ghg_pc), the share of renewable energy consumption ($renew_energy$), gross capital formation (inv_total), trade openness ($trade_open$), and the population growth rate (pop_growth).

ϕ_i : denotes the error-correction coefficient and the speed of adjustment toward the long-run equilibrium.

β'_i denotes the long-run coefficients.

λ_{ij} and δ'_{ij} denote the short-run dynamic coefficients.

$\bar{z}_t = (\overline{gdp_growth_t}, \overline{temp_t}, \overline{temp2_t})'$ denotes the vector of cross-sectional averages used to

address the problem of cross-sectional dependence.

ε_{it} denotes the random error term.

In the empirical implementation, cross-sectional averages are restricted to the dependent variable and the temperature variables (gdp_growth , $temp$, $temp2$), entering contemporaneously and with one lag, rather than the full vector of explanatory variables in X_{it} , in order to preserve degrees of freedom given the panel's dimensions ($N = 19$, $T = 26$; 24 usable observations per country after differencing and lagging). The lag order for both the dependent variable and the explanatory variables is set to one, so the model corresponds to an ARDL(1,1) structure estimated in its error-correction form, in which the lagged-difference terms of the general equation drop out. Cross-sectional averages enter the model in levels rather than first differences.

The model is estimated in Stata using the `xtdcce2` command (Ditzen, 2018, 2021), specified as follows:

```
xtdcce2 d.gdp_growth d.temp d.temp2 d.ghg_pc
        d.renew_energy d.inv_total d.trade_open
        d.pop_growth, lr(L.gdp_growth temp temp2
        ghg_pc renew_energy inv_total trade_open
        pop_growth) cr(gdp_growth temp temp2)
        cr_lags(1)
```

The specification follows a Mean Group approach, with heterogeneous country-specific intercepts partialled out and no deterministic trend included. The coefficient on the lagged dependent variable ($L.gdp_growth$), which is specified as the cointegration variable, is the error-correction term (ECT, ϕ). It measures the speed at which economic growth adjusts toward its long-run relationship with the regressors and is a parameter of the whole equation, not a coefficient on temperature; values between -2 and -1 imply damped oscillatory rather than monotonic convergence. The long-run association between temperature and growth is measured separately by the long-run coefficients on $temp$ and $temp2$, which are derived from the estimated level coefficients and the ECT and averaged across countries (Ditzen, 2021), while standard errors follow the standard Mean Group formula based on the cross-country dispersion of individual coefficients. Since GDP growth is stationary at

level (see Section 4.2.2), a significantly negative ECT is expected and is not, by itself, evidence of a cointegrating relationship between temperature and growth. With 24 observations per country, each country-level regression retains only two degrees of freedom in the baseline model (six in the linear specification reported in Section 4.6), so the estimates are imprecise and are interpreted with caution.

The error-correction specification involves three distinct elements that should not be conflated. First, the error-correction term (ECT, ϕ) is the coefficient on lagged growth and measures how quickly growth returns to its long-run relationship with the regressors after a deviation; it describes adjustment dynamics, not the effect of any particular regressor. Second, the long-run coefficients, derived from the estimated level coefficients and the ECT and averaged across countries, describe the long-run association between each regressor, including temperature, and growth; they are the quantities relevant to the temperature–growth question. Third, evidence of a long-run equilibrium (cointegrating) relationship among the variables requires more than a significant ECT, since it presupposes that the variables share stochastic trends. Because *gdp_growth* is stationary at level (see Section 4.2.2), and *temp* and *temp2* are also stationary at level, a significantly negative ECT is expected by construction and is not interpreted as evidence of cointegration. The CS-ARDL estimator in error-correction form is nevertheless appropriate here, since it accommodates a mixture of $I(0)$ and $I(1)$ regressors provided that no variable is integrated of order two, and inference on the temperature–growth association is therefore based on the long-run coefficients and their standard errors rather than on the significance of the ECT. For this reason, the study refers to long-run associations and does not claim to have established a long-run equilibrium relationship.

3.3 Nonlinearity Specification and Temperature Threshold

To investigate whether the relationship between temperature and economic growth is nonlinear, the model incorporates the temperature variable in both its linear (*temp*) and quadratic (*temp2*) forms. This specification makes it possible to test the hypothesis of a curved temperature–growth

relationship. If the long-run coefficient on the quadratic term is found to be statistically significant, the temperature level at which the estimated relationship changes direction (T^*) can be derived by differentiating the long-run relationship with respect to temperature and setting the resulting expression equal to zero, as follows:

$$T^* = -\frac{\beta_{temp}}{2 \cdot \beta_{temp2}}$$

Where,

T^* : represents the temperature at which the estimated relationship between temperature and economic growth changes direction, computed from the long-run coefficients on *temp* and *temp2*. Consistent with this conditional framing, a numerical threshold is reported and interpreted in the Results section only where the long-run coefficient on the quadratic term is statistically significant and the implied T^* lies within the observed range of temperatures (see Section 4.1).

3.4 Econometric Strategy and Model Selection

The study follows a second-generation estimation strategy suited to the characteristics of large panel datasets, according to the following stages:

1. Cross-Sectional Dependence Test (CD Test):

The CD test is applied as a preliminary step to examine the presence of cross-sectional dependence among the G20 countries, which may arise from common shocks as well as trade and financial linkages. Given the panel dimensions of this study, the CD^* statistic (Pesaran & Xie, 2021), which corrects for the influence of common factors, is treated as the primary decision criterion, while the CD, CDw, and CDw+ statistics are reported as complementary diagnostics. The outcome of this test determines the transition from first-generation to second-generation models.

2. Second-Generation Stationarity Tests (CIPS Test):

To avoid the bias associated with conventional unit root tests in the presence of cross-sectional dependence, the Cross-sectionally Augmented IPS (CIPS) test is applied, with a constant included as the deterministic component and the lag order selected via a general-to-specific procedure, to

examine whether the time series contain variables integrated of order two, $I(2)$, a condition relevant for the valid estimation of ARDL models.

3. Estimation of the CS-ARDL (DCCE) Model:

Based on the preliminary results, the CS-ARDL estimator, implemented in its error-correction form, is employed to distinguish between short-run and long-run dynamics. Following the Mean Group approach, country-specific coefficients are estimated and then averaged, allowing both the short-run and the long-run coefficients to vary across countries. Because the dependent variable is stationary at level, the error-correction term is interpreted as an adjustment parameter and not as evidence of cointegration, and inference on temperature relies on the long-run coefficients (see Section 3.2).

4. Analysis of Structural Heterogeneity (Sample Splitting):

Given that aggregating the G20 countries into a single group may mask heterogeneity due to pronounced climatic differences across countries (e.g., cold Canada versus hot Saudi Arabia), the full sample is divided into three climate groups: cold, temperate, and hot. The classification is based on each country's mean annual temperature over 1999–2024, computed from the temperature series used in the estimation (World Bank Climate Change Knowledge Portal and the Climatic Research Unit), using the following cut-offs: countries with a mean annual temperature below 11°C are classified as cold, those between 11°C and 20°C as temperate, and those above 20°C as hot. These cut-offs are a simple and transparent partition of national mean temperature; they are not taken from the Köppen–Geiger system, and they are not claimed to be uniquely correct. Table A1 reports the mean temperature of each country so that the classification can be assessed, and the countries closest to the cut-offs are identified there.

It should be noted that several countries included in this classification are geographically vast and encompass multiple internal climate zones under the Köppen–Geiger system (Beck et al., 2018), ranging from arid and continental to tropical and temperate conditions within their own borders. The classification adopted here reflects each country's baseline national-level mean annual

temperature rather than its full internal climatic diversity, and this represents an acknowledged simplification of the underlying geographical heterogeneity. The model is then re-estimated for each group to examine whether the estimated coefficients differ across groups. This comparison is descriptive rather than based on a formal statistical test of coefficient equality across groups, a limitation acknowledged below.

5. Robustness and Diagnostic Checks:

The residuals of the estimated model are tested for remaining cross-sectional dependence using the same CD test applied to the raw data, and the underlying panel structure is tested for first-order autocorrelation using the Wooldridge test, in order to assess the extent to which the model accounts for cross-sectional dependence and residual autocorrelation. As an additional robustness check, the model is re-estimated in a linear specification, without the quadratic temperature term and with cross-sectional averages of `gdp_growth` and `temp` only, which leaves more degrees of freedom per country, to assess whether the estimated temperature–growth relationship is sensitive to the specification.

3.5 Methodological Limitations

Despite the study's reliance on a second-generation econometric framework for panel data, namely the CS-ARDL model, which is designed to address cross-sectional dependence and unobserved heterogeneity across countries, its findings remain subject to several methodological limitations that should be taken into consideration when interpreting the results, as follows:

- The study relies on international secondary data that may be affected by systematic differences in measurement and reporting across countries;
- The analysis relies on annual mean temperature as the primary climatic variable and does not incorporate other climate-related dimensions, such as heatwaves, droughts, floods, or precipitation patterns, which may independently affect economic growth;
- National-level temperature averages, particularly for geographically large and climatically diverse countries, may mask meaningful sub-national climatic variation; the classification of such countries into a single

- climate group, based on simple cut-offs of national mean temperature, should therefore be interpreted with appropriate caution;
- With 24 usable observations per country, the baseline model leaves only two degrees of freedom per country (six in the linear specification), so the estimates are imprecise, and the statistically insignificant results may reflect limited statistical power rather than the absence of an association;
- Dividing the sample into climatic subgroups reduces the number of countries within each group to between six and seven, which further limits the statistical power and the stability of the estimates;
- The model does not include direct indicators measuring countries' capacity for climate adaptation or the quality of environmental and institutional policies;
- Residual cross-sectional dependence remains in the full-sample model and in the cold group, warranting caution when interpreting the standard errors and significance levels of these estimates;
- The estimates describe statistical associations and do not identify causal effects; potential simultaneity between growth and some regressors, such as investment and emissions, is not addressed by the identification strategy;
- The comparison of coefficients across climate groups is descriptive rather than based on a formal statistical test of coefficient equality, which is noted as a direction for future research.

4 RESULTS

4.1 Descriptive Statistics

To understand the behavior of the economic and climatic variables examined across time and across the countries in the sample, the basic descriptive statistics were calculated. These statistics provide preliminary indicators of economic performance levels, the degree of environmental and climatic heterogeneity, as well as trade openness and demographic structure across the G20 countries. The main findings obtained from the statistical characterization are presented in Table 2:

Table 2. Descriptive Statistics of the Study Variables

Variable	obs	Mean	Std. dev.	Min	Max
<i>gdp_growth</i>	494	0.0295597	0.0361401	-0.1089448	0.1414999
<i>temp</i>	494	14.21223	8.457614	-4.85	27.22
<i>temp2</i>	494	273.3738	227.4627	1.5376	740.9284
<i>ghg_pc</i>	494	11.39671	7.026268	1.720297	28.97903
<i>renew_energy</i>	494	0.1424251	0.1253989	0	0.5
<i>inv_total</i>	494	0.24474	0.0671043	0.1085391	0.462703
<i>trade_open</i>	494	0.5184318	0.1688873	0.195596	1.016806
<i>pop_growth</i>	494	0.008802	0.0097579	-0.0255377	0.0541149

Source: (STATA/SE 17.0 statistical software output)

Table 2 presents the descriptive statistics for the study variables for the G20 countries over the period from 1999 to 2024, based on a total of 494 observations. The mean real economic growth rate (*gdp_growth*) was approximately 2.96%, with a standard deviation of 3.61%, indicating substantial variation in economic performance across the countries in the sample over time. The minimum value reflected a sharp contraction of -10.89%, which may be associated with episodes of global crisis such as the 2008 financial crisis

and the COVID-19 pandemic, while the maximum growth rate reached approximately 14.15%.

Regarding the climatic variable, the mean temperature (*temp*) across the G20 countries was 14.21°C, with a relatively high standard deviation of 8.46°C, reflecting the substantial geographical variation among the member countries. Annual average temperatures ranged from -4.85°C to 27.22°C. This variation motivates the inclusion of the squared temperature variable (*temp2*) to test for a nonlinear relationship. It is also noteworthy

that per capita greenhouse gas emissions (*ghg_pc*) averaged 11.40 metric tons, with a considerably high maximum of 28.98 metric tons, which may reflect the high emission intensity of some major industrial economies within the group. Renewable energy accounted for approximately 14.24% of total energy consumption on average (*renew_energy*), ranging from 0% in certain observations to 50% in others.

Finally, the macroeconomic control variables also displayed considerable variation across observations. Total investment (*inv_total*) averaged approximately 24.47% of GDP, ranging from 10.85% to 46.27%, while trade openness (*trade_open*) averaged approximately 51.84%, ranging from 19.56% to 101.68%. Population growth (*pop_growth*) was low on average, at 0.88%, ranging from -2.55% to 5.41%.

4.2 Preliminary Tests

The preliminary testing stage constitutes a fundamental step in ensuring the validity of the econometric estimation and the reliability of the economic findings. Before proceeding with the

estimation of the dynamic relationship among the variables, it is necessary to examine the statistical properties of the panel data, specifically by assessing the extent of cross-sectional dependence among the countries in the sample (Cross-Sectional Dependence) and testing the stationarity of the time series (Unit Root Test).

These tests aim to avoid biased estimates and the problem of spurious regression, while ensuring the selection of the methodology most appropriate to the characteristics of the data under investigation. The results of these tests are presented below:

4.2.1 Cross-Sectional Dependence Test (Inter-Country Dependence) (CD Test)

The Cross-Sectional Dependence (CD) test is one of the most widely used tests for detecting dependence among cross-sectional units in panel data. Accordingly, it was applied to the study variables using four versions of the statistic (CD, CDw, CDw+, and CD*), whose null hypothesis (H0) is weak cross-sectional dependence, against the alternative hypothesis (H1) of strong cross-sectional dependence (see Table 3).

Table 3. Results of the Cross-Sectional Dependence (CD) Test

	CD	CDw	CDw+	CD*
<i>gdp_growth</i>	35.89 (0.000)	-2.23 (0.026)	466.23 (0.000)	-2.00 (0.045)
<i>temp</i>	32.30 (0.000)	-0.36 (0.718)	420.20 (0.000)	-1.54 (0.124)
<i>temp2</i>	22.28 (0.000)	1.14 (0.256)	422.97 (0.000)	-1.21 (0.226)
<i>ghg_pc</i>	2.11 (0.035)	1.40 (0.161)	620.63 (0.000)	-3.12 (0.002)
<i>renew_energy</i>	9.67 (0.000)	-0.39 (0.696)	500.88 (0.000)	-2.71 (0.007)
<i>inv_total</i>	8.18 (0.000)	0.92 (0.356)	301.99 (0.000)	-0.43 (0.671)
<i>trade_open</i>	8.11 (0.000)	5.96 (0.000)	435.20 (0.000)	-0.28 (0.779)
<i>pop_growth</i>	13.56 (0.000)	-0.89 (0.374)	374.79 (0.000)	-0.75 (0.453)

Source: (STATA/SE 17.0 statistical software output)

The results are not uniform across the four statistics. The CD statistic and the power-enhanced CDw+ statistic reject the null hypothesis for all eight variables at the 5% level, whereas the CDw statistic rejects it only for *gdp_growth* and *trade_open*. The bias-corrected CD* statistic rejects the null for *gdp_growth* ($p = 0.045$), *ghg_pc*

($p = 0.002$), and *renew_energy* ($p = 0.007$), but not for *temp*, *temp2*, *inv_total*, *trade_open*, or *pop_growth*.

Given the panel's cross-sectional and time dimensions ($N = 19$, $T = 26$), the CD* statistic, which corrects for the influence of common factors, is treated as the primary basis for

inference, while the CD, CDw, and CDw+ statistics are reported as complementary diagnostics. On this basis, the evidence of cross-sectional dependence is mixed rather than uniform: it is clear for economic growth, greenhouse gas emissions, and renewable energy, but not for the temperature variables or the remaining macroeconomic variables. Since the CD and CDw+ statistics nonetheless indicate dependence for all variables, and since the G20 economies are highly interconnected, the study adopts an estimator that augments the model with cross-sectional averages as a cautious choice, recognizing that this choice reduces the degrees of freedom available for each country (see Methodological Limitations).

The evidence of dependence is consistent with shared economic and environmental linkages among the G20 economies, which may reflect exposure to global factors and common shocks, such as international economic fluctuations, the integration of trade and financial markets, shared exposure to global temperature trends, and energy and environmental policies. Such interdependence is plausible given the pivotal position of the G20 countries in the global economy and their high degree of integration into international trade and investment networks. These tests, however, do not identify the source of the dependence.

Ignoring cross-sectional dependence, where it is present, may bias statistical inference and undermine the reliability of the econometric results. It is therefore important to account for it in the subsequent stages of the analysis and to select methodological tools able to accommodate interdependence among the countries in the sample. Overall, the results provide evidence of cross-sectional dependence among the G20 economies, although its strength differs across test statistics, and they support examining the relationship between temperature and economic growth within a dynamic panel framework that takes these interdependencies into account.

4.2.2 Cross-Sectionally Augmented Im-Pesaran-Shin Test (CIPS Test)

Given the evidence of cross-sectional dependence from the CD test, the second-generation unit root test known as the CIPS test was employed. The CIPS test is more appropriate

than first-generation unit-root tests in the presence of cross-sectional dependence and common shocks. The test includes a constant as the deterministic component, with the lag order selected via a general-to-specific procedure (maximum lag = 1). Table 4 presents the results of this test at the level and at the first difference.

Table 4. CIPS Unit Root Test Results

Variable	At Level I(0)	At 1 st Difference I(1)	Integrati on Order
<i>gdp_growth</i>	-3.669***	—	I(0)
<i>temp</i>	-4.873***	—	I(0)
<i>temp2</i>	-4.718***	—	I(0)
<i>ghg_pc</i>	-0.640	-4.204***	I(1)
<i>renew_energy</i>	-1.541	-4.182***	I(1)
<i>y</i>			
<i>inv_total</i>	-2.189*	—	I(0)
<i>trade_open</i>	-1.557	-3.999***	I(1)
<i>pop_growth</i>	-1.975	-4.044***	I(1)

Note: The values in parentheses (or the asterisks) represent the levels of statistical significance: (***), (**), and (*) indicate rejection of the null hypothesis at the 1%, 5%, and 10% levels, respectively. The critical values are based on Pesaran (2007) for the CIPS test. *H*₀: The series has a unit root. Critical values at the 10%, 5%, and 1% levels are -2.11, -2.20, and -2.38, respectively.

Source: (STATA/SE 17.0 statistical software output)

The results presented in Table 4 indicate that the dependent variable (*gdp_growth*), along with temperature (*temp*) and squared temperature (*temp2*), is stationary at level, I(0): the test statistics are below the 1% critical value, so the null hypothesis of a unit root is rejected. Total investment (*inv_total*) is stationary at level only at the 10% level (-2.189, against a 10% critical value of -2.11 and a 5% critical value of -2.20), so its classification as I(0) is borderline and is treated with caution.

In contrast, per capita greenhouse gas emissions (*ghg_pc*), the share of renewable energy (*renew_energy*), trade openness (*trade_open*), and population growth (*pop_growth*) are non-stationary at level. However, upon taking the first differences, all these series become stationary at the 1% level, I(1).

From a methodological perspective, this combination of variables that are stationary at

level, $I(0)$, and at first difference, $I(1)$, together with the absence of any variable integrated of order two, $I(2)$, is compatible with applying the CS-ARDL model, which can accommodate a mixture of $I(0)$ and $I(1)$ regressors provided that no variable is $I(2)$. It should be noted that, because gdp_growth is stationary at level, a significantly negative error-correction term is expected in the estimated models and is not, by itself, interpreted as evidence of cointegration between temperature and growth.

The stationarity of gdp_growth and temp at level indicates that these series do not require differencing prior to estimation. This finding is methodological in nature and does not, by itself, imply that the underlying temperature or economic trajectories are immune to permanent structural change.

4.3 Baseline Model Results

This study relies on the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) framework for panel data, estimated in its error-correction form within the Dynamic Common Correlated Effects (DCCE) approach, with the aim of analyzing the dynamic relationship between temperature and economic growth in the G20 countries over the period 1999–2024. This framework is appropriate in the presence of cross-sectional dependence among countries, as suggested by the CD test results for several of the variables (Table 3), which indicate that economic and temperature-related shocks may be transmitted across countries. Table 5 reports the baseline estimation results.

The estimation results indicate that the model does not fully eliminate cross-sectional dependence in the full sample: the residual CD statistic was 3.56 ($p = 0.0004$), which indicates remaining evidence of cross-sectional dependence in the model residuals (see Table 5). Standard errors and significance levels are therefore interpreted with caution.

Regarding the model's dynamic adjustment, the error-correction term (ECT), which is the coefficient on the lagged dependent variable ($L.\text{gdp_growth}$), was negative and statistically significant at the 1% level (coefficient = -1.3074 , $p < 0.001$). It indicates that economic growth adjusts toward its long-run relationship with the

regressors; since its value lies between -2 and -1 , the adjustment is oscillatory and damped rather than monotonic. The ECT is a parameter of the whole equation and not a coefficient on temperature, so it carries no information about the direction or magnitude of the temperature–growth association. Moreover, since gdp_growth is stationary at level (Table 4), a significantly negative ECT is expected and is not, by itself, interpreted as evidence of a cointegrating relationship between temperature and growth.

The long-run coefficient on temperature was statistically insignificant (coefficient = 1.6827 , $p = 0.358$), as was the coefficient on squared temperature (-0.0365 , $p = 0.292$). The data therefore provide no statistically significant evidence of a long-run association between temperature and economic growth, nor of a nonlinear relationship over the estimation period. This should be read as insufficient statistical evidence in the estimated model, rather than as evidence that no such association exists. The individual coefficients on temp and temp^2 are large and of offsetting sign, which is expected for two closely related terms estimated with only two residual degrees of freedom per country, and they should not be interpreted individually in terms of magnitude; accordingly, no temperature threshold is computed.

Among the remaining variables, only population growth displayed a statistically significant long-run coefficient (3.8581 , $p = 0.029$). Its sign is positive, contrary to the theoretical expectation in H1g, and it is not retained in the linear specification (see Section 4.6); it is therefore not treated as a robust finding. Per capita greenhouse gas emissions, the share of renewable energy, total investment, and trade openness exhibited not statistically significant long-run coefficients (p -values between 0.318 and 0.775). This should be read as an absence of sufficient statistical evidence for a long-run relationship for these variables in the estimated model, rather than as evidence that no such relationship exists.

With regard to the short-run dynamics, none of the coefficients reached conventional levels of statistical significance, including those on temperature (Δtemp , $p = 0.121$), squared temperature (Δtemp^2 , $p = 0.157$), and total investment ($\Delta\text{inv_total}$, coefficient = -0.0265 ,

$p = 0.939$). The overall model is jointly significant, $F(418, 38) = 2.93$, $p = 0.00$, based on 456 observations across the 19 G20 countries. However, the baseline model leaves only two

degrees of freedom per country, and the mean-group R^2 is high (0.92), which suggests that the model is close to saturation; the joint significance is therefore interpreted with caution.

Table 5. Baseline CS-ARDL Estimation Results (Full Sample, G20)

Component	Variable	Coefficient	Std. Error	z-statistic	P-value
Error correction	ECT (L.gdp_growth)	-1.3074***	0.1618	-8.08	0.000
Long-Run Effects	Temperature (<i>temp</i>)	1.6827	1.8317	0.92	0.358
	Temperature squared (<i>temp</i> ²)	-0.0365	0.0346	-1.05	0.292
	GHG emissions per capita (<i>ghg_pc</i>)	-0.0071	0.0250	-0.29	0.775
	Renewable energy consumption (<i>renew_energy</i>)	-33.6320	33.6810	-1.00	0.318
	Total investment (<i>inv_total</i>)	-0.2811	0.6973	-0.40	0.687
	Trade openness (<i>trade_open</i>)	-0.0628	0.1320	-0.48	0.634
	Population growth (<i>pop_growth</i>)	3.8581**	1.7700	2.18	0.029
Short-Run Effects	Temperature ($\Delta temp$)	0.8185	0.5278	1.55	0.121
	Temperature squared ($\Delta temp^2$)	-0.0159	0.0112	-1.42	0.157
	GHG emissions per capita (Δghg_pc)	0.0011	0.0215	0.05	0.959
	Renewable energy consumption ($\Delta renew_energy$)	4.2445	5.1812	0.82	0.413
	Total investment (Δinv_total)	-0.0265	0.3451	-0.08	0.939
	Trade openness ($\Delta trade_open$)	0.0309	0.1190	0.26	0.795
	Population growth (Δpop_growth)	1.5447	2.4796	0.62	0.533
Panel Diagnostic Tests					
Test		Statistic	P-value	Interpretation	
Pesaran Cross-Sectional Dependence (CD)		3.56	0.0004	Residual cross-sectional dependence detected	
Coefficient of Determination (R^2)		0.03	—	Overall model fit	
Mean Group R^2		0.92	—	Average within-country fit (close to saturation)	
F(418, 38)		2.93	0.00	Overall model significance	
Residual degrees of freedom per country		2	—	—	
Observations		456	—	—	
Number of Countries		19	—	—	

Note: (***) and (**) denote statistical significance at the 1% and 5% levels, respectively. The ECT is the coefficient on the lagged dependent variable (L.gdp_growth); it captures the speed of adjustment of growth toward its long-run relationship with the regressors and is a parameter of the whole equation, not a coefficient on temperature. Long-run coefficients refer to the levels of the regressors.

Source: (STATA/SE 17.0 statistical software output)

Two features of the estimation limit the strength of the inference drawn from Table 5 and should be kept in view throughout the interpretation. First, with 24 observations per country, each country-level regression retains only two residual degrees of freedom, so the mean-group estimates and their standard errors are imprecise and potentially unstable; non-significant coefficients may therefore reflect low statistical power rather than the absence of an association, and the very large coefficients on some variables (for example,

renewable energy) should not be interpreted in terms of magnitude. Second, residual cross-sectional dependence remains in the full-sample model (Table 6), which may lead to understated standard errors and overstated significance; the few statistically significant coefficients, such as that on population growth, should accordingly be regarded as indicative rather than conclusive. The results are therefore best read as cautious evidence on statistical associations, not as precise estimates or causal effects.

Table 6. Diagnostic Tests for Model Residuals

Diagnostic Test	Statistic	P-value	Interpretation
Pesaran (2015) CD	3.70	0.000	Reject H0 at the 1% level: evidence of remaining strong cross-sectional dependence in the residuals
Juodis & Reese (2022) CDw	1.47	0.142	Fail to reject H0: no evidence of strong cross-sectional dependence
CDw+ (power-enhanced, Fan et al., 2015)	216.33	0.000	Reject H0 at the 1% level: evidence of remaining strong cross-sectional dependence
Pesaran & Xie (2021) CD* (bias-corrected; principal criterion)	-2.43	0.015	Reject H0 at the 5% level: evidence of remaining strong cross-sectional dependence
Wooldridge Test for Autocorrelation (on raw data)	$F(1, 18) = 14.512$	0.0013	Reject H0: first-order serial correlation is present in the raw time series

Note: For all four cross-sectional dependence statistics, H0: residuals exhibit at most weak cross-sectional dependence (consistent with adequate filtering by the CS-ARDL specification); H1: residuals exhibit strong, persistent cross-sectional dependence (Pesaran, 2015, 2021). The residual series cover 24 years per country, and xtcd2 applied its unbalanced-panel adjustment; CD* is computed with 4 principal components. For the Wooldridge test, H0: no first-order autocorrelation.

Source: (STATA/SE 17.0 statistical software output)

4.4 Climate Heterogeneity Analysis

Building on the methodological framework adopted in this study, and to avoid the cancelling-out effect resulting from combining economies with highly divergent climatic and geographical profiles within a single panel matrix (such as high-latitude arctic/subpolar economies versus arid and equatorial tropical regions), this section proceeds by disaggregating the full G20 sample into climate-based subgroups. The climatic classification is grounded in each country's mean annual temperature over 1999–2024, an average computed from the temperature series used in the estimation process (derived from the World Bank Climate Change Knowledge Portal (World Bank Group, 2024) and the Climatic Research Unit (CRU)), with the standardized Köppen-Geiger

climate classification (Beck et al., 2018) serving as a climatological reference for describing the climate regimes of the resulting groups. The country-level mean temperatures are reported in Appendix A (Table A1). Using quantitative thermal thresholds (11°C and 20°C), the 19 G20 economies were categorized into three distinct subgroups:

- **Group 1 (Cold Countries, N = 6):** Canada, China, Germany, Russia, the United Kingdom, and the United States. This cluster comprises economies with mean annual temperatures below 11°C (group mean 5.05°C), predominantly characterized by subpolar, boreal, and cool continental climate conditions;
- **Group 2 (Temperate Countries, N = 7):** Argentina, France, Italy, Japan, South Korea,

South Africa, and Türkiye. This cluster comprises economies with mean annual temperatures between 11°C and 20°C (group mean 13.61°C), characterized by maritime, Mediterranean, and temperate continental conditions;

- **Group 3 (Hot Countries, N = 6):** Australia, Brazil, India, Indonesia, Mexico, and Saudi Arabia. This cluster comprises economies with mean annual temperatures above 20°C (group mean 24.08°C), situated predominantly within tropical, equatorial, and hyper-arid climate regimes.

As noted in Section 3.4, several countries included in this classification, most notably China, the

United States, Australia, and Brazil, encompass multiple internal climate zones. The classification adopted here reflects each country's national-level mean annual temperature rather than its full internal climatic diversity, and this represents an acknowledged simplification of the underlying geographical heterogeneity.

The present procedure re-estimates the CS-ARDL specification separately for each climate-based subgroup to examine whether the estimated coefficients differ across climatic groups, and whether the nonlinear temperature hypothesis shows variation according to the climatic baseline of the countries.

Table 7. CS-ARDL Estimation Results by Climate Sub-Groups (Sub-sample Analysis)

Component	Variable	Full Sample (G20)	Group 1: Cold Countries	Group 2: Temperate Countries	Group 3: Hot Countries
Error correction	ECT (<i>L.gdp_growth</i>)	-1.3074*** (0.1618)	-1.2976*** (0.2749)	-1.2125*** (0.4515)	-1.2926*** (0.2775)
Long-Run Effects	Temperature (<i>temp</i>)	1.6827 (1.8317)	-0.0097 (0.1277)	-0.0910 (0.5486)	-24.3994 (24.3493)
	Temperature squared (<i>temp</i> ²)	-0.0365 (0.0346)	-0.0011 (0.0071)	0.0056 (0.0195)	0.4499 (0.4536)
	GHG emissions per capita (<i>ghg_pc</i>)	-0.0071 (0.0250)	-0.0086 (0.0110)	0.0367 (0.0254)	-0.0254 (0.0515)
	Renewable energy consumption (<i>renew_energy</i>)	-33.6320 (33.6810)	-0.1990 (0.5144)	0.1476 (0.6055)	-42.8008 (43.6652)
	Total investment (<i>inv_total</i>)	-0.2811 (0.6973)	0.8663** (0.3538)	-0.4780 (0.3954)	0.8882 (0.5738)
	Trade openness (<i>trade_open</i>)	-0.0628 (0.1320)	0.1838 (0.2080)	0.4170 (0.3088)	-0.1178 (0.1082)
	Population growth (<i>pop_growth</i>)	3.8581** (1.7700)	2.4279** (1.0478)	0.2327 (1.6072)	-2.0192 (3.9398)
Short-Run Effects	Temperature ($\Delta temp$)	0.8185 (0.5278)	-0.3187 (0.3122)	0.0787 (0.3117)	1.4271 (2.6211)
	Temperature squared ($\Delta temp$ ²)	-0.0159 (0.0112)	0.0227 (0.0205)	-0.0042 (0.0113)	-0.0222 (0.0509)
	GHG emissions per capita (Δghg_pc)	0.0011 (0.0215)	0.0219 (0.0195)	0.0006 (0.0298)	-0.0775 (0.0479)
	Renewable energy consumption ($\Delta renew_energy$)	4.2445 (5.1812)	1.2501*** (0.3962)	0.2253 (1.1737)	76.6663 (77.1631)
	Total investment (Δinv_total)	-0.0265 (0.3451)	-0.1868 (0.5172)	0.8030 (0.5117)	-0.0867 (0.4433)
	Trade openness ($\Delta trade_open$)	0.0309 (0.1190)	-0.1687 (0.2075)	0.3052 (0.4657)	-0.1000 (0.2154)
	Population growth (Δpop_growth)	1.5447 (2.4796)	-4.5586 (9.5282)	-2.5485 (3.8232)	-0.2195 (13.2065)
Diagnostic Tests					

Pesaran CD statistic (p-value)	3.56 (0.0004)	-2.22 (0.0262)	-0.07 (0.9481)	-1.13 (0.2573)
F-statistic (p-value)	F(418, 38) = 2.93 (0.00)	F(132, 12) = 3.83 (0.01)	F(154, 14) = 2.70 (0.02)	F(132, 12) = 2.57 (0.03)
Mean Group R ²	0.92	0.96	0.92	0.91
Observations	456	144	168	144
Number of Countries	19	6	7	6

Note: (***), (**), and (*) denote statistical significance at the 1%, 5%, and 10% levels, respectively. Standard errors are in parentheses. The ECT is the coefficient on the lagged dependent variable (*L.gdp_growth*); it captures the speed of adjustment of growth toward its long-run relationship with the regressors and is a parameter of the whole equation, not a coefficient on temperature. Long-run coefficients refer to the levels of the regressors.

Source: (STATA/SE 17.0 statistical software output)

As reported in Table 7, the CS-ARDL estimation results across the three climatic groups (cold, temperate, and hot) show that the error-correction term (ECT) is negative and statistically significant in all three groups (-1.2976 , $p < 0.001$ in the cold group; -1.2125 , $p = 0.007$ in the temperate group; and -1.2926 , $p < 0.001$ in the hot group), in line with the full-sample estimate (-1.3074). As discussed in Section 4.3, the ECT is a parameter of the whole equation and its significance reflects the stationarity of economic growth and the speed of adjustment of the model; it is not a coefficient on temperature and should not be read as evidence about differences in temperature sensitivity across groups.

The long-run coefficient on temperature is statistically insignificant in each group: -0.0097 ($p = 0.940$) in the cold group, -0.0910 ($p = 0.868$) in the temperate group, and -24.3994 ($p = 0.316$) in the hot group. The coefficient on squared temperature is likewise insignificant in all groups ($p = 0.880$, 0.773 , and 0.321 , respectively), providing no statistical evidence of a nonlinear relationship within any subsample. The hot-group coefficients are extremely imprecise (standard error of 24.35 for temperature), reflecting six countries and only two residual degrees of freedom per country, and are not informative about the size or direction of any association. Since no temperature coefficient is statistically distinguishable from zero in any group, and no formal test of coefficient equality across groups is conducted, the results do not support conclusions about whether the temperature–growth association differs across climatic zones.

A few other coefficients reach conventional significance levels, all in the cold group: total investment (0.8663 , $p = 0.014$) and population growth (2.4279 , $p = 0.020$) in the long run, and the change in renewable energy (1.2501 , $p = 0.002$) in the short run. The population growth coefficient has a positive sign, contrary to the theoretical expectation in H1g. Given that these results arise in a group of only six countries, that residual cross-sectional dependence remains in this group, and that many coefficients are tested across the models, they are treated as tentative and are not presented as robust or generalizable findings. No other long-run or short-run coefficient was statistically significant in any of the subgroups, including total investment in the short run, which is not significant in the full sample or in any group.

All four models are jointly significant at conventional levels (F-test p-values of 0.00 for the full sample, 0.01 for the cold group, 0.02 for the temperate group, and 0.03 for the hot group). However, the denominator degrees of freedom are only 12 to 38, and the mean-group R² is high in every model (0.91 to 0.96), which suggests that the models are close to saturation; the joint significance is therefore interpreted with caution and does not validate the individual coefficients.

Finally, the residual cross-sectional dependence (CD) results vary across the groups. Statistically significant residual cross-sectional dependence remains in the full sample (CD = 3.56, $p = 0.0004$) and in the cold group (CD = -2.22 , $p = 0.0262$), whereas no evidence of residual dependence is found in the temperate group ($p = 0.9481$) or the hot group ($p = 0.2573$). This suggests that the cross-sectional averages did not fully account for common shocks in the full sample and the cold

group, and standard errors and significance levels for these two models, including the results reported above for the cold group, should be interpreted with caution.

4.5 Diagnostic Tests

To ensure the validity of econometric inference and to assess the risk of bias or spurious statistical results, this section reports diagnostic tests on the residuals of the full-sample CS-ARDL model. The residuals were extracted directly and tested with the standalone `xtcd2` command, separately from the internal CD statistic reported by `xtdcce2` in Table 5. The test results are reported in Table 6 (Section 4.3). This step is particularly important in second-generation panel-data models, as it assesses the extent to which the CS-ARDL model, augmented with cross-sectional averages, accounts for common factors in the residuals. The diagnostic assessment focuses on two dimensions:

- i) residual cross-sectional dependence, evaluated through four complementary versions of the Pesaran-type test (CD, CDw, CDw+, and CD*), each reflecting a different correction procedure;
- ii) first-order serial correlation in the raw panel data, evaluated through the Wooldridge test, prior to the estimation of the dynamic specification.

Given the panel's dimensions ($N = 19$, $T = 26$), the bias-corrected CD* statistic (Pesaran & Xie, 2021) is adopted as the principal criterion for inference regarding residual cross-sectional dependence, consistent with Section 3.4, while the remaining three statistics (CD, CDw, and CDw+) are reported as complementary diagnostics.

The diagnostic results indicate that residual cross-sectional dependence is not eliminated in the full-sample model. Based on the bias-corrected CD* statistic, adopted as the principal criterion, the null hypothesis of weak cross-sectional dependence is rejected at the 5% level (-2.43 , $p = 0.015$). The standard CD statistic (3.70 , $p < 0.001$) and the power-enhanced CDw+ statistic (216.33 , $p < 0.001$) lead to the same conclusion, whereas the CDw statistic does not reject the null (1.47 , $p = 0.142$). This divergence across test variants is reported for transparency. The `xtcd2` CD statistic

is also close to the one reported internally by `xtdcce2` in Table 5 (3.56), indicating that the two procedures are consistent.

Accordingly, the cross-sectional averages included in the specification (`gdp_growth`, `temp`, and `temp2`) do not fully absorb the common factors affecting the full-sample residuals. The standard errors and p-values of the full-sample estimates, in particular the statistically significant long-run coefficient on population growth, should therefore be interpreted with caution, since remaining cross-sectional dependence may lead to understated standard errors. Residual dependence is also statistically significant in the cold group but not in the temperate and hot groups (Table 7).

With regard to serial correlation, the Wooldridge test, applied to the raw panel data, rejects the null hypothesis of no first-order autocorrelation ($F(1, 18) = 14.512$, $p = 0.0013$), which supports the use of a dynamic specification that includes lagged terms. This test is computed prior to estimation and does not establish that the chosen lag structure fully removes serial correlation in the model residuals.

4.6 Robustness Check: Linear Specification

The baseline model leaves only two degrees of freedom per country (Table 5), which limits the precision of the estimates and complicates the interpretation of the individual `temp` and `temp2` coefficients. To assess whether the baseline findings are sensitive to this feature of the specification, the model is re-estimated in a linear specification, which drops the quadratic temperature term and restricts the cross-sectional averages to `gdp_growth` and `temp`. This raises the residual degrees of freedom to six per country, while retaining all 19 G20 countries and the same 456 observations. Excluding the year 2020 was not pursued in the corrected specification: the cross-sectional averages already absorb globally synchronized shocks such as the COVID-19 pandemic, and removing a year from a model with differences and lags left no usable degrees of freedom. Table 8 compares the long-run coefficients of the baseline and linear specifications.

Table 8. Robustness Check: Baseline vs. Linear Specification (Long-Run Coefficients)

Variable	Baseline (with temp ²)	Linear Specification
ECT (<i>L.gdp_growth</i>)	−1.3074*** (0.1618)	−1.2714*** (0.0868)
Temperature (<i>temp</i>)	1.6827 (1.8317)	−0.0032 (0.0098)
Temperature squared (<i>temp</i> ²)	−0.0365 (0.0346)	–
GHG emissions per capita (<i>ghg_pc</i>)	−0.0071 (0.0250)	0.0020 (0.0077)
Renewable energy consumption (<i>renew_energy</i>)	−33.6320 (33.6810)	1.5721 (1.6676)
Total investment (<i>inv_total</i>)	−0.2811 (0.6973)	0.0244 (0.2222)
Trade openness (<i>trade_open</i>)	−0.0628 (0.1320)	0.0419 (0.0793)
Population growth (<i>pop_growth</i>)	3.8581** (1.7700)	0.9109 (0.8841)
Pesaran CD statistic (<i>p-value</i>)	3.56 (0.0004)	−0.12 (0.9060)
F-statistic	F(418, 38) = 2.93	F(342, 114) = 2.72
Mean Group R ²	0.92	0.89
Residual degrees of freedom per country	2	6
Cross-sectional averages	<i>gdp_growth, temp, temp</i> ²	<i>gdp_growth, temp</i>
Observations / Countries	456 / 19	456 / 19

Note: (***) and (**) denote statistical significance at the 1% and 5% levels, respectively. Standard errors in parentheses. In the baseline model, *temp* and *temp*² enter jointly, so their individual coefficients are not separately interpretable. Short-run coefficients are omitted for brevity and are available upon request.

Source: (STATA/SE 17.0 statistical software output)

In the linear specification, the long-run coefficient on temperature is −0.0032 (standard error is 0.0098, and $p = 0.748$), which is statistically insignificant, with a 95% confidence interval from −0.0224 to 0.0161. Since *gdp_growth* is measured as a fraction ($0.01 = 1$ percentage point) and temperature in degrees Celsius, this corresponds to an estimated change of −0.32 percentage points in growth per additional degree Celsius, within an interval from −2.2 to +1.6 percentage points. The ECT remains negative and statistically significant (−1.2714, $p < 0.001$), and none of the long-run coefficients is statistically significant, including population growth ($p = 0.303$), whose significance in the baseline model is therefore not retained. The CD statistic reported by *xtccce2* for

this specification is −0.12 ($p = 0.906$), suggesting less residual cross-sectional dependence than in the baseline model.

The qualitative conclusion of the baseline model, that there is no statistically significant long-run association between temperature and economic growth, is therefore unchanged. However, the wide confidence interval implies that economically sizeable associations of either sign cannot be ruled out, so the result should be read as insufficient statistical evidence rather than as evidence of no association. The linear specification also tests only a linear relationship and does not address the possibility of nonlinearity.

5 DISCUSSION

The results provide no statistically significant evidence of a long-run association between temperature and economic growth in the G20 countries, either in the full sample or within the three climate groups. The main null hypothesis (H_0) is therefore not rejected, and the part of H_1 asserting that the relationship varies across climatic groups is not supported. Regarding the sub-hypotheses, H_{1a} is not supported: the long-run coefficient on temperature was statistically insignificant in the baseline model (1.6827, $p = 0.358$) and in the linear specification (-0.0032 , $p = 0.748$), and no short-run association was observed. H_{1b} is likewise not supported, given the statistical insignificance of the squared temperature coefficient (*temp2*) in the full sample and in all climate groups; this should be read as an absence of statistical evidence for curvature in the estimated model, rather than as proof that no such threshold exists. Hypotheses H_{1c} and H_{1d} , concerning greenhouse gas emissions per capita (*ghg_pc*) and the share of renewable energy (*renew_energy*), found no statistical support. H_{1e} , concerning total investment (*inv_total*) in the short run, was not supported at the full-sample level (-0.0265 , $p = 0.939$), and H_{1f} , concerning trade openness (*trade_open*) in the short run, found no support (0.0309 , $p = 0.795$). H_{1g} was not supported either: population growth (*pop_growth*) displayed a statistically significant long-run coefficient in the full sample (3.8581 , $p = 0.029$), but with a positive sign, contrary to the expectation in H_{1g} , and this result is not retained in the linear specification. These null results are interpreted as insufficient statistical evidence for these associations within the present specification, not as evidence that no such relationships exist.

The error-correction term (ECT) was negative and statistically significant in the full sample and in each climate group, indicating that economic growth adjusts toward its long-run relationship with the regressors. However, the ECT is a parameter of the whole equation, and since (*gdp_growth*) is stationary at level, a significantly negative ECT is expected; it therefore carries no information about whether, or in which direction, temperature is associated with growth. The statistical insignificance of the squared temperature coefficient (*temp2*) indicates an absence of evidence, within this sample, for a

nonlinear relationship or an identifiable temperature threshold. This differs, at first glance, from Burke et al. (2015), who reported a concave relationship between temperature and output with an optimum at an annual average temperature of around 13.6°C . This divergence does not necessarily indicate a contradiction between the two studies: those estimates rest on a much larger global sample with greater temperature variation, whereas the present estimates rely on 19 economies, 24 usable years per country, and only two residual degrees of freedom per country in the baseline model, which limits statistical power. The strong correlation between *temp* and *temp2* is a further plausible reason for the individual insignificance of the two terms.

Regarding the magnitude of the association, the baseline model does not allow a meaningful interpretation, since the individual *temp* and *temp2* coefficients are large and of offsetting sign, which is expected for two closely related terms estimated with limited degrees of freedom. The linear specification, which leaves six residual degrees of freedom per country, provides a more interpretable estimate: the long-run coefficient on temperature is -0.0032 ($p = 0.748$), corresponding to an estimated change of -0.32 percentage points in growth per additional degree Celsius, with a 95% confidence interval from -2.2 to $+1.6$ percentage points. The estimate is statistically indistinguishable from zero, but the width of the interval means that economically sizeable associations of either sign cannot be ruled out. These estimates describe statistical associations and should not be read as causal effects.

To assess the sensitivity of the baseline findings, the model was re-estimated in a linear specification with more degrees of freedom (Table 8). The conclusion of no statistically significant long-run association between temperature and growth is unchanged; the ECT remains negative and significant (-1.2714 , $p < 0.001$), and the significance of population growth in the baseline model is not retained ($p = 0.303$). Excluding the year 2020 was not feasible in the corrected specification, as it left no usable degrees of freedom; moreover, the cross-sectional averages already absorb globally synchronized shocks such as the pandemic. The consistency between the two specifications indicates that the null result for temperature is not an artifact of the quadratic term,

although both specifications rely on the same data and the same estimator.

Regarding the climatic groups, the ECT is negative and statistically significant in all three (−1.2976 in the cold group, −1.2125 in the temperate group, and −1.2926 in the hot group), which reflects the model's adjustment dynamics rather than temperature sensitivity. The long-run coefficient on temperature is statistically insignificant in each group (cold: −0.0097, $p = 0.940$; temperate: −0.0910, $p = 0.868$; hot: −24.3994, $p = 0.316$), as is the squared temperature coefficient. The hot-group estimates are particularly imprecise (standard error of 24.35), reflecting six countries and two residual degrees of freedom per country. In the absence of a formal test of coefficient equality across groups, and with no temperature coefficient distinguishable from zero in any group, the results do not provide a basis for concluding that the temperature–growth association differs across climatic zones. All four models are jointly significant (p -values between 0.00 and 0.03), but with only 12 to 38 denominator degrees of freedom and mean-group R^2 between 0.91 and 0.96, the joint significance is interpreted with caution.

A few other coefficients reached conventional significance levels, all in the cold group: total investment (0.8663, $p = 0.014$) and population growth (2.4279, $p = 0.020$) in the long run, and the change in renewable energy (1.2501, $p = 0.002$) in the short run. Given that these arise in a group of only six countries, that residual cross-sectional dependence remains in this group, and that many coefficients are tested, they are presented as tentative, sub-sample-specific associations rather than as robust or generalizable findings and would benefit from investigation in future research with larger samples.

Since the temperature coefficients are statistically insignificant in all three groups, the present results do not allow conclusions about differences in sensitivity to temperature across climatic contexts, nor about adaptation. It remains a plausible hypothesis, consistent with the literature on adaptation economics, that economies with greater historical exposure to high temperatures have developed institutional, technological, or behavioral adaptation mechanisms, such as

cooling infrastructure, adjusted working hours, or agricultural adaptation. However, no adaptation-related variable is observed or estimated here, and this is therefore presented only as a candidate hypothesis for dedicated empirical investigation, not as a finding of this study.

With respect to the remaining variables, neither greenhouse gas emissions per capita (*ghg_pc*) nor the share of renewable energy (*renew_energy*) exhibited a statistically significant long-run or short-run association with economic growth in the full sample; the one exception, the short-run coefficient on renewable energy in the cold group, is discussed above as tentative. One possible interpretation draws on the Environmental Kuznets Curve (EKC) hypothesis: as G20 economies may occupy different positions along this curve, heterogeneous country-level associations could offset one another when pooled within a single model. It is also possible that emissions represent a cumulative, slow-moving process whose associations with growth unfold over a horizon longer than the 26 years covered by this sample. These remain plausible interpretations rather than mechanisms directly tested here.

This pattern is partially consistent with Sharif et al. (2019), who found that the emissions–growth relationship is neither mechanical nor uniform across countries, but shaped by institutional quality, environmental policy, and technological innovation. It differs, in part, from Ozparlak and Wang (2026), who reported a dynamic association between energy and economic growth in the G20 countries; this difference may reflect the present study's focus on the share of renewable energy in total consumption, as distinct from the broader measures of total energy consumption examined previously, as well as differences in econometric methodology.

Total investment (*inv_total*) did not display a statistically significant short-run association with economic growth in the full sample (−0.0265, $p = 0.939$) or in any climate group, so the emphasis that endogenous growth theory places on capital accumulation is not reflected in the short-run estimates of this model. A positive long-run coefficient emerged only in the cold group (0.8663, $p = 0.014$), which, given the six countries underlying the estimate and the fact that H1e

concerns the short run, is not interpreted as support for H1e. Substantial cross-country variation in investment efficiency, together with the imprecision of the estimates, may attenuate any association once countries are pooled.

Some of these findings warrant particular caution in interpretation. The residual cross-sectional dependence diagnostics reported in Table 6 indicate that dependence is not eliminated in the full sample: the bias-corrected CD* statistic (-2.43 , $p = 0.015$), the CD statistic (3.70 , $p < 0.001$), and the power-enhanced CDw+ statistic all reject the null of weak cross-sectional dependence, while CDw does not ($p = 0.142$), suggesting that cross-sectional averaging did not fully absorb all common shocks. At the sub-group level, significant residual dependence remains in the cold group ($p = 0.0262$) but not in the temperate group ($p = 0.9481$) or the hot group ($p = 0.2573$). The CD statistic reported for the linear specification is -0.12 ($p = 0.906$), suggesting less residual dependence in the more parsimonious model. Standard errors and significance levels for the full-sample and cold-group estimates should accordingly be interpreted with caution, since remaining dependence may lead to understated standard errors.

The principal contribution of this study lies in examining the relationship between temperature and economic growth in the G20 countries within a framework that accounts for cross-sectional dependence and allows for climatic heterogeneity through cold, temperate, and hot country groupings, defined by quantitative thresholds of

mean annual temperature computed from externally sourced temperature series. The results indicate that, in this sample and specification, there is no statistically significant evidence of a long-run association between annual mean temperature and economic growth, either overall or within the climate groups.

This conclusion must be read in light of two limitations of statistical inference. First, with 24 observations per country, the baseline model leaves only two residual degrees of freedom per country (six in the linear specification), so the estimates are imprecise, and the absence of statistical significance may reflect limited power rather than the absence of an association; the confidence interval of the linear specification (from -2.2 to $+1.6$ percentage points per degree Celsius) does not exclude economically sizeable associations. Second, residual cross-sectional dependence remains in the full-sample model and in the cold group, so standard errors may be understated and the few statistically significant coefficients, notably that on population growth, should be treated as tentative. The findings therefore provide cautious, descriptive evidence on associations, not precise or causal estimates. Future research using larger panels, richer climate indicators such as temperature anomalies and extremes, and direct measures of adaptation could usefully examine whether the temperature–growth association depends on the broader climatic and adaptive context in which economies operate.

APPENDIX

Table A1. Mean Annual Temperature and Climate Group of the 19 G20 Countries

Country	Mean annual temperature 1999–2024 (°C)	Climate group
Canada	−3.38	Cold
Russian Federation	−3.14	Cold
China	7.44	Cold
United Kingdom	9.68	Cold
Germany	9.78	Cold
United States	9.92	Cold
France	11.75	Temperate
Turkey	12.11	Temperate
Japan	12.31	Temperate
South Korea	12.76	Temperate

Country	Mean annual temperature 1999–2024 (°C)	Climate group
Italy	13.43	Temperate
Argentina	14.86	Temperate
South Africa	18.04	Temperate
Mexico	21.04	Hot
Australia	22.21	Hot
India	24.35	Hot
Brazil	25.12	Hot
Indonesia	25.32	Hot
Saudi Arabia	26.43	Hot
Group means		
Cold group (mean of country means)	5.05	Cold
Temperate group (mean of country means)	13.61	Temperate
Hot group (mean of country means)	24.08	Hot

Note: Mean of the annual temperature series (temp) used in the estimation over 1999–2024. Cold: below 11°C; temperate: 11–20°C; hot: above 20°C.

Source: World Bank Group. (2024); authors' calculations.

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