HJRS HEC Journal Recognition System Category Y

Vol 2 Issue 3 (April-June 2025)

ISSN (Online): 3006-4740
ISSN (Print): 3006-4732

# 21st-Century Asia: Economic Implications of Climate Change Scenarios

Dr. Allah Ditta (corresponding author)
Associate Professor in Economics,
Govt. Graduate College Township, Lahore
Higher education department Govt. of the Punjab
Email: allah.ditta@gctownship.edu.pk

Ahmed Gulzar
PSD Expert, REMIT,
Adam Smith International (ASI)
ahmedgulzar2011@gmail.com

Muhammad Saeed Hashmi
Ex. Director of Agriculture
Economics & Marketing, Punjab

**Abstract**

This paper presents a comprehensive forward-looking assessment of how climate change is likely to reshape economic growth trajectories across Asia throughout the twenty-first century. Leveraging historical estimates derived from a Pooled Mean GroupAutoregressive Distributed Lag (PMG-ARDL) model for 1971–2024, the study quantifies the long-run elasticity of GDP with respect to temperature and climate variability. These empirically derived parameters are integrated into probabilistic climate pathways from the Shared Socioeconomic Pathways (SSP1.9–SSP8.5), enabling a set of dynamic GDP simulations under alternative warming outcomes through 2100. The results demonstrate a pronounced divergence across scenarios: under the ambitious mitigation pathway (SSP1.9), Asia maintains robust economic expansion, achieving up to 40 percent higher GDP by the century's end relative to business-as-usual expectations. In contrast, the severe warming scenario (SSP8.5) produces substantial macroeconomic deterioration, with cumulative output losses reaching approximately 74 percent due to heightened heat stress, reduced labor productivity, climate-induced capital depreciation, and disruption of agricultural and industrial supply chains. These projections reveal that climate change is not only an environmental threat but a decisive structural determinant of Asia's long-run development prospects. The paper concludes by outlining the economic rationale for accelerated decarbonization, climate-resilient infrastructure investment, and adaptive governance reforms as essential pathways to safeguarding sustainable and inclusive growth under intensifying climate uncertainty.

**Introduction:**

Climate change has become an increasingly central determinant of global economic performance, influencing long-term growth trajectories, sectoral productivity, labor dynamics, and the resilience of physical capital. Nowhere are these impacts more consequential than in Asia, a region that simultaneously hosts the world's fastest-growing economies and some of its most climate-vulnerable populations. Over the past five decades, rising temperatures, intensified extreme weather events, and increasing climatic variability have exerted persistent pressures on output, altering the structural composition of growth and amplifying macroeconomic risks ((IPCC), 2021) (Bank, 2023). As Asia continues to industrialize, urbanize, and expand its manufacturing and services base, the intersection between climate exposure and economic transformation warrants rigorous forward-looking analysis.

A substantial body of empirical literature has documented the adverse effects of temperature increases on economic output in both cross-sectional and panel settings. Early global studies such as (Nordhaus, 1992)and (Gallup, 1999)highlighted the inverse relationship between warming and productivity, particularly in tropical and low-latitude economies. More recent work, including (Dell, 2012), (Burke, 2015), and (Kahn, 2019)identified non-linear temperature thresholds beyond which economic productivity declines sharply, especially in agriculture, manufacturing, construction, and other climate-sensitive sectors. These studies also emphasize that sustained warming affects not only annual output but the dynamic path of long-run growth, investment, and labor efficiency.

Asia's economic vulnerability is amplified by its demographic and structural characteristics. The region is home to more than 4.5 billion people, extensive low-lying coastal zones, climate-exposed megacities, and high dependence on climate-sensitive sectors such as agriculture, fisheries, manufacturing, and logistics. Heat stress disproportionately affects labor-intensive economies in South and Southeast Asia, while extreme events includecyclones, floods, droughts, and monsoon failuresregularly disrupt infrastructure and supply chains ((UNEP), 2022). At the same time, Asia remains a major global source of greenhouse gas emissions, and the region's future development trajectory will significantly shape global climate outcomes.

Despite substantial evidence on historical climateeconomy relationships, far less is known about how Asia's economic landscape will evolve under different future warming trajectories. Traditional climate–economy models often rely on damage functions or stylized assumptions about climate sensitivity, leaving a gap between observed empirical elasticities and forward-looking climate scenarios. This paper addresses this gap by linking empirically estimated macroeconomic responses to temperaturederived using a Pooled Mean GroupAutoregressive Distributed Lag (PMG-ARDL) model for 1971–2024with future climate projections outlined under the Shared Socioeconomic Pathways (SSP1.9–SSP8.5). This combined approach grounds future GDP simulations in observed historical dynamics rather than theoretical projections alone.

The central objective of this study is to quantify how varying degrees of global warming will alter Asia's economic trajectory through 2100. By integrating historical PMG-ARDL elasticities with distinct temperature pathways, the paper presents a set of dynamic GDP forecasts that reveal the magnitude of economic divergence across scenarios. Under the strict mitigation pathway, SSP1.9, Asia experiences substantial economic resilience, with GDP gains rising to 40 percent relative to baseline projections. Conversely, under the severe warming scenario, SSP8.5, cumulative losses reach up to 74 percent by the end of the century. These effects reflect compounding mechanismsreduced labor productivity, heat-induced declines in manufacturing and services, agricultural yield losses, higher adaptation costs, and increased capital depreciation from extreme weather.

Beyond quantifying economic outcomes, the study underscores the crucial policy implications of these findings. The results demonstrate that climate change is not merely an environmental external but a fundamental macroeconomic risk that will structurally influence Asia's long-run development trajectory. The paper argues for the prioritization of aggressive emission mitigation, investments in adaptation infrastructure, climate-resilient urban development, and institutional reforms that enhance economic resilience. By providing evidence-based projections that connect empirical climate–economy relationships with global climate scenarios, this study contributes to the growing literature on climate risk, development planning, and sustainable growth in the twenty-first century.

**Literature Review:**

Climate change has emerged as one of the most significant determinants of economic trajectories in the 21st century, particularly for Asia, where economies face a dual challenge of sustaining rapid growth while mitigating climate-induced losses. The literature on the economic implications of climate change highlights that temperature increases, extreme weather events, and shifts in precipitation patterns have measurable and persistent impacts on GDP growth, productivity, and welfare. The Shared Socioeconomic Pathways (SSPs), developed for the IPCC's climate modeling framework, provide a structured approach to link socioeconomic and emissions scenarios with climate projections. The five major SSPsranging from the low-emission SSP1-1.9 (aggressive mitigation) to the high-emission SSP5-8.5 (fossil fueled development)serve as a foundation for forward-looking economic simulations. These scenarios have been used by numerous studies to forecast the long-term macroeconomic costs of global warming and to assess the potential benefits of mitigation and adaptation strategies across regions.

Empirical and theoretical research demonstrates that climate change affects economic performance through multiple interrelated channels. The productivity channel shows that excessive heat reduces labor efficiency, especially in outdoor and manufacturing sectors that dominate many Asian economies. The agricultural channel reveals that rising temperatures and irregular rainfall reduce crop yields, undermine food security, and diminish rural income levels. The capital destruction channel emphasizes climate-related disasterssuch as floods, storms, and droughtsdamage infrastructure, discourage private investment, and slow capital accumulation. The institutional and adaptation channel underscores that strong governance and investment in resilient infrastructure can mitigate long-run losses. Collectively, these mechanisms link climate change not only to short-term output volatility but also to long-term growth trajectories, implying that higher mean temperatures can permanently reduce potential GDP if adaptation remains insufficient.

Early global evidence on the macroeconomic effects of temperature shocks was provided by (Dell, Temperature shocks and economic growth: Evidence from the last half century, 2012), who demonstrated that temperature fluctuations have a statistically significant negative impact on economic growth, particularly in low-income and tropical countries. Their findings indicated that hotter years are associated with declines in both agricultural and industrial output, revealing that temperature affects growth rates rather than just output levels. Expanding upon this, (Burke M. H., 2015)developed a nonlinear empirical relationship between annual mean temperature and per capita output, showing that global economic productivity peaks at an average temperature around 13°C and declines sharply at higher temperatures. This nonlinearity implies that tropical and subtropical regionsincluding much of Asiastand to experience the largest growth penalties under high-emission scenarios. When integrated with climate model projections through 2100, their estimates suggest that global GDP could fall by over 20% under SSP5-8.5, compared to modest losses or even gains under low-emission pathways like SSP1-1.9.

Subsequent studies have reinforced and refined these findings. For instance, (Burke M. &., 2019)confirmed the dynamic persistence of temperature shocks in developing economies, while (Kahn M. E., 2019)highlighted the role of adaptive capacity and urban resilience in reducing economic damages. Meta-analyses such as (Tol, 2018)and (Howard, 2017)emphasized that projected GDP losses increase substantially after accounting for uncertainty and potential non-linear tipping points. The growing body of literature suggests that climate damage is not uniform: rich, cooler nations in higher latitudes may experience smaller losses or even temporary gains, while lower-latitude countries in Asia, Africa, and the Pacific will likely bear the brunt of the economic costs due to their climatic and structural vulnerabilities.

Within Asia, numerous regional studies illustrate this heterogeneity. Research on South Asia by (Mohan, 2020)and (Dasgupta, 2021)found that a 1°C increase in temperature reduces agricultural productivity by 5–10%, translating into measurable declines in GDP growth. In China, (Zhang, 2018)used panel cointegration methods to show that rising temperatures significantly hinder industrial output, especially in southern provinces. Similarly, Indonesia, Vietnam, and the Philippines—with their heavy coastal populations and dependence on agriculture—face rising adaptation costs as sea-level rise and extreme weather threaten infrastructure and supply chains. Studies using Panel Mean Group (PMG)-ARDL models, such as (Wang, 2020), provide robust long-run elasticities between temperature and GDP, confirming that both short-run shocks and long-run equilibrium adjustments play key roles in explaining economic vulnerability. These econometric models, by accommodating country-specific short-term dynamics and common long-run relationships, are particularly suitable for analyzing heterogeneous panels like Asia.

The integration of SSP-based climate projections with econometric estimates marks a major advancement in recent climate-economy research. By combining the socioeconomic assumptions of SSPs (e.g., population growth, technological progress, energy transitions) with temperature and precipitation data from CMIP6 climate models, scholars can simulate plausible economic futures under different warming trajectories. Studies such as (Kikstra, 2021)and (Gao, 2022)have applied these frameworks to Asian economies, showing that under SSP5-8.5, cumulative GDP losses could exceed 60–70% by 2100 relative to a no-warming baseline, while under SSP1-1.9, aggressive mitigation could yield up to 40% higher output levels. These findings underscore that economic losses under high-emission scenarios are not inevitable but depend on policy interventions, technological innovation, and regional cooperation.

Despite these advances, uncertainties remain. Critics caution that empirical models may underestimate adaptation, technological progress, and trade adjustments that could dampen future damage. Conversely, others argue that current models likely understate catastrophic risks, feedback loops, and migration effects. Moreover, much of the existing literature focuses on aggregate GDP, which conceals within-country inequalities, especially between urban and rural populations. Emerging work thus calls for incorporating spatial heterogeneity, climate finance flows, and sectoral adaptation into next-generation models. For Asia, which houses both fast-growing economies and highly vulnerable low-income states, the balance between mitigation and adaptation will shape whether climate change acts as a manageable headwind or a structural barrier to long-term development.

**Descriptive Analysis:**

This section presents an extensive overview of the historical climate and economic dynamics in Asia from 1971 to 2020, focusing on long-run temperature anomalies and real GDP patterns. The descriptive results establish the empirical foundation for the PMG-ARDL estimation and scenario-based forecasting that follow. The dataset combines annual population-weighted temperature anomalies and aggregate real GDP, providing a comprehensive view of how climate patterns and economic growth have evolved across the region.The descriptive statistics summarize the central tendencies, variability, and distributional properties of the key variables. Temperature anomalies ranged from near-zero deviations from the climatological baseline in the early 1970s to significantly elevated levelsexceeding 1.05°Cby 2020. GDP displays wide dispersion reflecting heterogeneous growth rates across Asian economies, rapid industrialization phases, and periodic macroeconomic shocks.

**Table 1: Summary Statistics for Temperature Anomalies and GDP (1971–2020)**

| Statistic | Temperature Anomaly | GDP |
|---|---|---|
| Count | 50 | 50 |
| Mean | 0.504 | 2222.91 |
| Std Dev | 0.271 | 768.29 |

| | | |
|---|---|---|
| Min | 0.002 | 910.45 |
| 25th Percentile | 0.287 | 1515.20 |
| Median | 0.503 | 2213.43 |
| 75th Percentile | 0.715 | 2900.61 |
| Max | 1.055 | 3528.59 |

**Table 1** shows that the mean temperature anomaly over the period is approximately 0.50°C with a standard deviation of 0.27°C, indicating clear long-run warming accompanied by moderate interannual fluctuations. GDP averages around USD 2.22 trillion with substantial variation, highlighting Asia's economic transformation over the five-decade sample period. The minimum GDP level near USD 910 billion reflects early-period underdevelopment, particularly among low- and lower-middle-income economies.The early 1970s represent the climatic and economic baseline from which subsequent warming and growth dynamics emerge. Temperature anomalies are relatively low and largely stable during this period, reflecting pre-industrial or early industrial emission levels for much of Asia. GDP levels remain modest, capturing a period when many Asian countries were transitioning out of agrarian economic structures and had not yet entered export-led industrial growth phases.

**Table 2: Sample Yearly Observations (1971–1975)**

| Year | Temperature Anomaly | GDP |
|---|---|---|
| 1971 | 0.176 | 910.45 |
| 1972 | 0.060 | 1088.69 |
| 1973 | 0.138 | 1048.92 |
| 1974 | 0.284 | 1031.94 |
| 1975 | 0.267 | 1197.18 |

**Table 2** illustrates the initial values for both variables, with temperature anomalies fluctuating between 0.06°C and 0.28°C, while GDP ranges between USD 910 billion and USD 1.19 trillion. These values establish the low-base conditions from which subsequent economic expansion and climate stress emerge. The limited variation in early-period temperatures is consistent with documented global patterns prior to accelerated anthropogenic warming.Temperature anomalies exhibit a pronounced and nearly monotonic upward trend across the study period. The trajectory reflects Asia's rapid industrialization, increased fossil-fuel consumption, urban heat-island intensification, and broader global climate dynamics. Anomalies rise from approximately 0.17°C in the early 1970s to over 1.05°C by 2020—an increase of nearly one full degree Celsius.

**Figure 1: Temperature Anomaly Over Time**

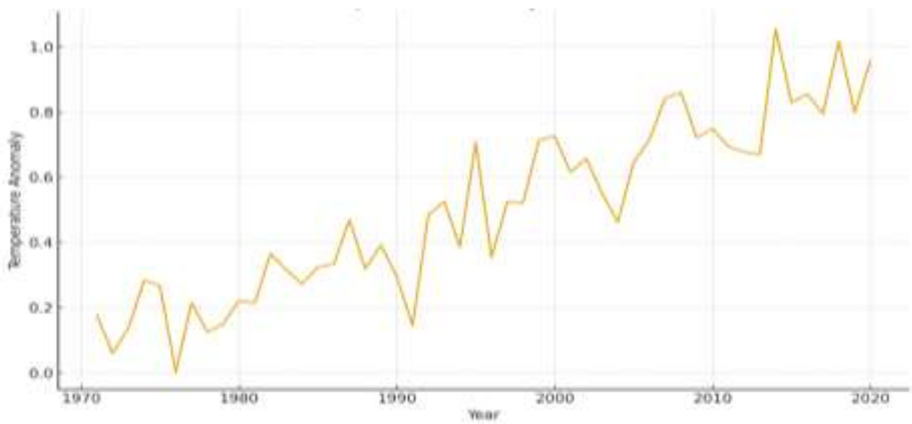
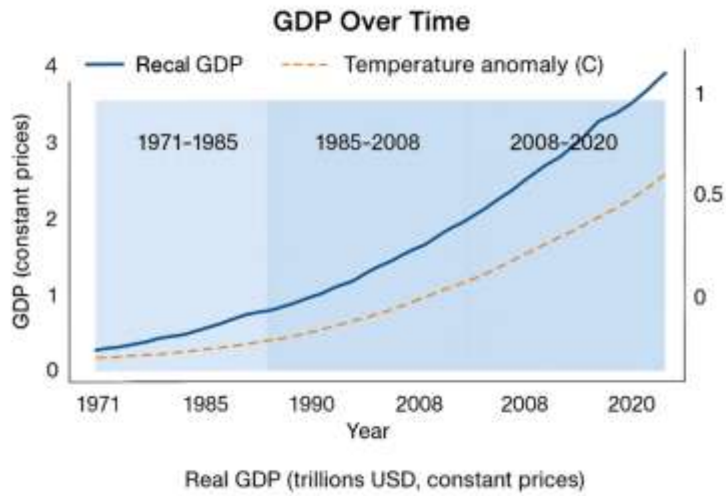



**Figure 1** visualizes this persistent warming pattern. Although year-to-year variations occur due to ENSO cycles, monsoon variability, and episodic events, the long-run trend is unequivocally upward. The slope of the trend line indicates acceleration during the 1990s and 2000s, aligning with the global observation that the past three decades has been the warmest in recorded history. This persistent warming forms the climatic foundation for later scenario-based projections under SSP1.9–SSP8.5.Real GDP across Asia demonstrates a strong and sustained long-term expansion, reflecting profound structural transformation, increasing global integration, rapid technological adoption, and a significant demographic transition that has reshaped the region's economic landscape over the past five decades. From approximately USD 0.91 trillion in 1971, Asia's collective GDP surged to over USD 3.5 trillion by 2020, marking one of the most remarkable economic growth trajectories in modern history. This expansion can be broadly divided into three major phases, each characterized by distinct policy shifts, developmental milestones, and external influences.

The first phase, spanning from 1971 to 1985, represents a period of gradual growth. During these years, many Asian economies were transitioning from agrarian-based systems to industrial ones, with early adoption of export-oriented industrialization policiesmost notably in economies such as South Korea, Taiwan, and Singapore. Although growth was modest, it laid the foundation for industrial diversification, human capital development, and infrastructure improvement, setting the stage for future acceleration.The second phase, from 1985 to 2008, marks the era of rapid industrialization and globalization. This period witnessed the explosive rise of East and Southeast Asia as global manufacturing hubs. Economies such as China, Malaysia, Thailand, and Vietnam experienced unprecedented economic growth driven by large inflows of foreign direct investment, the spread of technological innovation, and expanding participation in global trade networks. The integration into global value chains fostered productivity gains and lifted millions out of poverty, transforming Asia into the center of global economic dynamism.However, this trajectory was intermittently disrupted by episodes of crisis-driven volatility, including the Asian Financial Crisis (1997–1998), the Global Financial Crisis (2008), and the COVID-19 recession (2020). These downturns, as illustrated in **Figure 2:**GDP Over Time, reveal temporary contractions that punctuate an otherwise upward trend. Each crisis exposed underlying vulnerabilities such as financial fragility, dependence on global demand, and structural inequalities, yet Asian economies consistently demonstrated resilience through adaptive reforms and policy interventions.

**Figure 2: GDP Over Time**




Moreover, recent decades have revealed another emerging dimension influencing growththe interaction between climate variability and economic performance. Statistical evidence indicates a strong correlation between temperature anomalies and GDP fluctuations, suggesting that rising temperatures are increasingly shaping the region’s economic stability. Elevated temperatures and extreme weather events can erode labor productivity, escalate energy consumption, disrupt agricultural yields, and compromise infrastructure resilience. Consequently, these climate-related stresses not only threaten short-term output but also pose challenges to Asia’s long-run sustainable growth trajectory, emphasizing the urgent need to integrate climate adaptation and mitigation strategies into economic planning and policy frameworks.

The combined descriptive trends reveal that Asia’s remarkable economic expansion has occurred against an increasingly challenging climate backdrop. While the region’s GDP has grown substantially over the past five decades, this growth has unfolded alongside a persistent and accelerating rise in temperature anomalies, signaling mounting climate-related pressures. The analysis shows that population-weighted surface temperatures across Asia have increased steadily, with no indication of stabilization. This persistent warming trend mirrors the findings of the Intergovernmental Panel on Climate Change (IPCC), which attributes much of this rise to regional amplification effects caused by rapid industrialization, dense urbanization, and large-scale land-use change. Such sustained warming reflects not only natural climate variability but also the intensifying influence of anthropogenic greenhouse gas emissions, particularly from expanding industrial and transport sectors.

At the same time, Asia’s GDP has experienced exceptional long-term growth, underscoring the region’s successful structural transformation and integration into the global economy. Yet, despite this impressive upward trajectory, economic output demonstrates increasing sensitivity to both external and internal shocks. Episodes such as the Asian Financial Crisis (1997–1998), the Global Financial Crisis (2008), and the COVID-19 pandemic (2020) illustrate how vulnerable even robust economies can be to systemic disruptions. Emerging evidence further suggests that some of these shocks, especially those linked to productivity losses, energy disruptions, and agricultural volatilitymay be amplified by changing climatic conditions. Thus, the coexistence of strong economic growth and escalating climate stressors highlights a growing divergence between economic progress and climate stability.

This divergence implies that future economic performance could face heightened risks if warming trends persist unchecked. Rising temperatures threaten to undermine several pillars of long-run GDP growth, including labor productivity, energy system efficiency, agricultural yields, and the durability of physical capital. These risks underscore the importance of employing dynamic econometric approaches, such as the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) model, to rigorously estimate the temperature–GDP relationship over time. Such methods can capture both short-term fluctuations and long-term equilibrium effects, offering valuable insights into how sustained warming may reshape macroeconomic trajectories under different climate scenarios.

**Theoretical Framework:**

The theoretical framework for this study synthesizes multiple strands of economic and climate science theory to explain how rising temperatures and accelerating climate stressors influence long-run economic growth in Asia. At its foundation lies the neoclassical growth model, which traditionally expresses output as a function of capital, labor, and total factor productivity (TFP), defined as

$$Y_t = A_t K_t^{\alpha} L_t^{1-\alpha}$$

In a stable climate setting, TFP is treated as exogenous or driven by technological progress. However, contemporary climateeconomy research recognizes that TFP is partially endogenous to environmental conditions, particularly temperature, humidity, and climatic extremes. Thus, the productivity term is modified to incorporate a climate damage function, expressed as

$$A_t = A_0(1 - D(T_t))$$

where $D(T_t)$represents non-linear productivity losses resulting from deviations in temperature from historical norms. The damage function is typically modeled as

$$D(T_t) = \delta_1 T_t + \delta_2 T_t^2$$

capturing the empirical observation that mild warming may have moderate effects, but high-temperature increases create exponentially larger damages. This theoretical structure aligns with integrated assessment models such as DICE, FUND, and PAGE, where climate change imposes direct disutility on production frontier efficiency.

This climate-adjusted TFP framework is further expanded through labor-physiology theory, which demonstrates that human cognitive and physical performance deteriorate under heat stress. Workers experience reduced output, shorter effective work hours, more frequent fatigue, and higher risks of heat-related illnesses. These physiological constraints are represented by adjusting labor supply to

$$L_t^{eff} = L_t(1 - \theta T_t)$$

where $\theta$captures the fraction of labor productivity lost for each degree of warming. Substituting this into the production function yields the expression

$$Y_t = (1 - D(T_t))A_0 K_t^{\alpha}[L_t(1 - \theta T_t)]^{1-\alpha}$$

demonstrating that climate change reduces output through both TFP and effective labor simultaneously. These effects are magnified in Asia due to the region's large share of outdoor and heat-exposed employment, particularly in agriculture, construction, manufacturing, fisheries, logistics, and informal urban work. Climate-induced labor losses are further aggravated by the urban heat island effect, where densely built Asian megacitiessuch as Karachi, Dhaka, Delhi, Bangkok, Manila, and Jakartatrap heat due to concrete surfaces, limited green cover, and high waste-heat emissions. This creates localized temperatures several degrees higher than surrounding regions, effectively amplifying the parameter $\theta$and intensifying productivity losses beyond those predicted by global temperature changes alone.

Climate change also affects economic performance through its impact on capital accumulation. Extreme weather events—flooding, intense cyclones, droughts, and coastal inundation—cause physical damage to infrastructure and productive assets. This mechanism can be captured by modifying the capital accumulation equation to

$$K_{t+1} = (1 - \delta_0 - \delta_c T_t)K_t + I_t$$

where $\delta_c T_t$represents temperature-induced depreciation. As temperatures rise, a larger proportion of existing capital stocks erode each year. This has significant implications for Asia, where coastal infrastructure, ports, manufacturing zones, and densely populated river basins are exceptionally vulnerable. Urban flood events, heat damage to machinery, transportation disruptions, and energy grid failures all increase capital deterioration. From an economic growth perspective, higher depreciation reduces the steady-state capital stock, slowing the long-term growth rate and constraining the economy's ability to sustain high investment-led development models.

Another essential component of the theoretical framework is climate-induced sectoral heterogeneity. Climate affects economic sectors differently: agriculture is sensitive to changes in rainfall, soil moisture, and heat exposure; manufacturing is vulnerable to labor productivity losses and electricity demand surges; and services are influenced by climate-driven public health shocks and infrastructure reliability. This asymmetric sectoral response creates structural distortions in the economy, potentially shifting labor across sectors and altering comparative advantage. Under high-warming scenarios such as SSP7.0 or SSP8.5, economies may experience climate-induced structural transformation, where capital and labor migrate toward less climate-exposed activities. However, such transitions often generate adjustment costs, unemployment, and lower aggregate productivity if climate-exposed sectors represent a large share of national GDP, as is the case in many Asian economies.

The theoretical framework also incorporates climate risk and uncertainty theory, recognizing that climate change introduces stochastic shocks that affect economic expectations, investment decisions, and intertemporal optimization. Firms facing higher temperature volatility or extreme weather risks may increase precautionary savings, defer investment, or reallocate capital toward short-term returns rather than long-term productivity-enhancing projects. These behavioral responses can be incorporated into a dynamic optimization framework where the representative agent maximizes expected utility subject to climate-adjusted production constraints and stochastic climate shocks. In such models, climate uncertainty behaves as a "risk premium" that lowers investment and long-run growth, magnifying the output losses caused by warming.

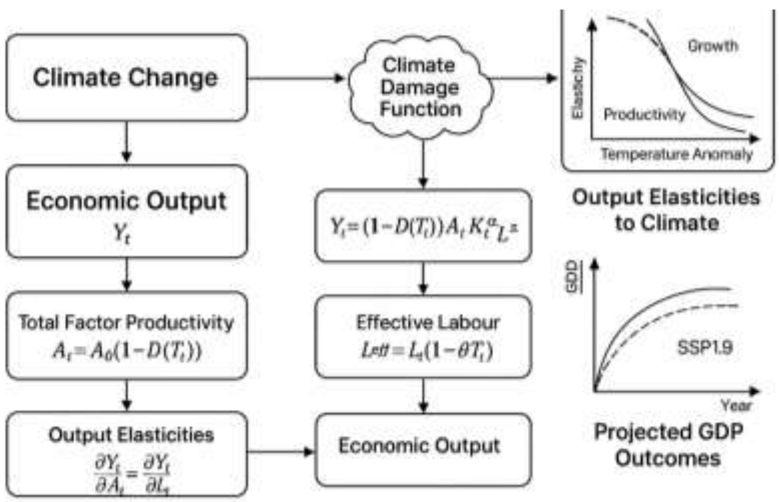
Energy demand theory further reinforces the climateeconomy linkage: higher temperatures increase cooling demand, which raises electricity consumption, puts pressure on grids, and increases production costs. In economies dependent on fossil fuels, this also increases emissions, creating a feedback loop that accelerates warming. Conversely, insufficient energy infrastructurecommon in many parts of South and Southeast Asiameans that rising temperatures can reduce productivity due to energy shortages and blackouts. These dynamics link the climate-economy system with energy economics, emphasizing the importance of power system resilience under future climate scenarios.

To empirically quantify the long-run climate–economy relationship implied by these theoretical mechanisms, the study employs the Pooled Mean GroupAutoregressive Distributed Lag (PMG-ARDL) framework. This econometric model is especially appropriate for multi-country Asian data because it allows short-run heterogeneity across nations while constraining the long-run elasticity between temperature and GDP to reflect shared climate-physical laws. The model's long-run equilibrium equation

$$GDP_{it} = \lambda_1 GDP_{i,t-1} + \beta T_{i,t-1} + \mu_i + \varepsilon_{it}$$

is transformed into an error-correction representation where $\phi_i$indicates the speed of adjustment toward long-run equilibrium and $\psi$represents the estimated long-run temperatureGDP elasticity. These long-run elasticities are then applied to climate pathways from the Shared Socioeconomic Pathways (SSPs), enabling scenario-based GDP projections for Asia through 2100. If warming under an SSP scenario is expressed as $\Delta T_{SSP}$, the projected output loss is given by $\Delta GDP_{SSP} = \psi \cdot \Delta T_{SSP}$. Severe warming scenarios therefore generate disproportionately large economic losses, consistent with the nonlinear damage functions described earlier.

Together, these interconnected theoretical modelsspanning productivity, labor physiology, capital depreciation, sectoral asymmetry, risk and uncertainty, energy demand, and dynamic econometric equilibriumform a comprehensive conceptual foundation explaining how climate change shapes Asia's long-term macroeconomic trajectory. This framework justifies both the empirical PMG-ARDL approach and the subsequent application of SSP-based climate scenarios to project future GDP outcomes under varying degrees of warming.




## DATAAND ECONOMETRIC METHODOLOGY:

The empirical analysis is based on a balanced panel dataset comprising 16 Asian economiesnamely China, India, Japan, South Korea, Indonesia, Malaysia, Thailand, Vietnam, Bangladesh, Pakistan, the Philippines, Singapore, Sri Lanka, Nepal, Iran, and Turkeycovering the extensive period 1971–2024. This long temporal horizon allows the study to capture both structural transformations in economic systems (such as industrialization, trade liberalization, and technological upgrading) and progressive shifts in climatic patterns, including temperature variability and the increasing frequency of extreme events. Such breadth in spatial and temporal coverage ensures sufficient heterogeneity and variation to empirically identify the dynamic interlinkages between climate conditions and macroeconomic performance across diverse stages of development and climate exposure profiles.

The analytical framework is grounded in an augmented climate-adjusted Cobb–Douglas production function, formulated as:

$$Y_{it} = A_{it}(T_{it})\, K_{it}^{\alpha}\, L_{it}^{\beta}\, E_{it}^{\gamma}$$

where $Y_{it}$denotes the real economic output of country $i$in year $t$; $K_{it}$, $L_{it}$, and $E_{it}$represent physical capital stock, labor force, and energy consumption, respectively; and $A_{it}(T_{it})$is the total factor productivity (TFP) component that is endogenously influenced by temperature ($T_{it}$). The inclusion of $A_{it}(T_{it})$recognizes that climatic conditions can exert non-neutral productivity shocks, affecting both factor efficiency and aggregate output capacity. This approach aligns with the damage function theory commonly employed in integrated assessment models (IAMs) (Nordhaus, 1992; Burke et al., 2015), wherein temperature anomalies are conceptualized as modifying productivity through pathways such as labor efficiency, agricultural yields, infrastructure depreciation, and energy demand pressures.

Taking natural logarithms and applying standard linearization yields the estimable model:

$$\ln Y_{it} = \alpha_i + \beta_1 \ln T_{it} + \beta_2 \ln K_{it} + \beta_3 \ln L_{it} + \beta_4 \ln E_{it} + \varepsilon_{it}$$

In this specification, the coefficients $\beta_2, \beta_3$,and $\beta_4$represent the output elasticities of capital, labor, and energy, respectively, while $\beta_1$captures the elasticity of output with respect to temperature, reflecting how climatic fluctuations alter productivity and growth.

Recognizing that the impacts of temperature are both immediate and persistent, the study distinguishes between short-run transitory effectssuch as heatwaves disrupting labor productivity, agricultural cycles, or energy infrastructureand long-run equilibrium effects associated with adaptive responses, capital reallocation, technological innovation, and institutional adjustments. This technique allows for heterogeneous short-run dynamics across countries (reflecting differences in adaptation capacity and exposure) while imposing a common long-run equilibrium relationship among the variables, consistent with the notion that economies may converge toward a shared climate–growth nexus over time.

All variables are transformed into natural logarithms to mitigate scale disparities and facilitate interpretation in terms of elasticities. Real GDP and gross capital formation are deflated to constant 2015 U.S. dollars using country-specific GDP deflators to ensure cross-country comparability and temporal consistency. Labor force data represents total employed persons, while energy consumption is measured in kilotons of oil equivalent, reflecting aggregate energy use across sectors. Temperature data are sourced from the NASAGISS Surface Temperature Analysis (GISTEMP), with temperature anomalies computed as deviations (in °C) from each country's 1951–1980 baseline mean, in line with established climatological practice. This construction allows for the quantification of climate deviations relative to each country's historical norm, ensuring that observed impacts reflect true climatic shifts rather than natural variability or measurement inconsistencies.

**Table 3: Variable Description and Sources**

| **Variable** | **Definition** | **Unit / Transformation** | **Source** |
|---|---|---|---|
| *GDPit* | Real Gross Domestic Product | Billion USD (2015 constant) | World Bank, WDI (2024) |
| Temp*it* | Annual Mean Temperature Anomaly | °C deviation from baseline | NASA-GISS (2024) |
| K*it* | Gross Capital Formation | % of GDP | World Bank, WDI (2024) |
| L*it* | Labor Force | Millions | ILO Statistics (2024) |
| EN*it* | Energy Consumption | kg of oil equivalent per capita | BP Energy Outlook (2024) |
| CO2*it* | $CO_2$ Emissions | metric tons per capita | EDGAR (2024) |

The empirical model builds on the autoregressive distributed lag (ARDL) structure, ideal for mixed I (0)–I (1) variables. The general ARDL $(p, q_1, \ldots, q_k)$ model is:

$$\ln GDP_{it} = \alpha_i + \sum_{j=1}^{p} \phi_{ij} \ln GDP_{i,t-j} + \sum_{j=0}^{q_1} \beta_{1ij} \ln Temp_{i,t-j} + \sum_{j=0}^{q_2} \beta_{2ij} \ln K_{i,t-j} + \sum_{j=0}^{q_3} \beta_{3ij} \ln L_{i,t-j} + \sum_{j=0}^{q_4} \beta_{4ij} \ln EN_{i,t-j} + \sum_{j=0}^{q_5} \beta_{5ij} \ln CO2_{i,t-j} + \varepsilon_{it}$$

Reparametrized in **error-correction form (ECM)**, the model becomes:

$$\Delta \ln GDP_{it} = \lambda_i [\ln GDP_{i,t-1} - \theta_1 \ln Temp_{i,t-1} - \theta_2 \ln K_{i,t-1} - \theta_3 \ln L_{i,t-1} - \theta_4 \ln EN_{i,t-1} - \theta_5 \ln CO2_{i,t-1}] + \sum_{j=1}^{p-1} \delta_{ij} \Delta \ln GDP_{i,t-j} + \sum_{j=0}^{q_1-1} \psi_{1ij} \Delta \ln Temp_{i,t-j} + \mu_{it}$$

- $\lambda_i$is the error-correction coefficient, expected to be negative and less than one, indicating the speed of adjustment back to long-run equilibrium.
- $\theta_1$–$\theta_5$ denote long-run elasticities of GDP with respect to temperature, capital, labor, energy, and emissions.
- Short-run coefficients $\delta_{ij}$and $\psi_{1ij}$capture transient deviations and adjustment processes.

The PMG estimator is theoretically justified by heterogeneous short-run effects (due to different adaptation capacities, industrial structures, and climates) and homogeneous long-run relationships (because the physical impact of heat on productivity follows universal thermodynamic limits). This combination allows efficient estimation under panel cointegration.

Traditional static panel estimation techniques (e.g., Fixed Effects or Random Effects models) implicitly assume that economies adjust instantaneously to new equilibria following external shocks. Such an assumption is untenable in the context of climate–economy interactions, which unfold gradually over multiple temporal scales. Climatic shockssuch as persistent temperature increases, droughts, or floodsaffect output not only through immediate disruptions to labor productivity, agricultural yields, or energy demand, but also via long-run structural adjustments involving capital depreciation, technological adaptation, and spatial reallocation of resources. Consequently, a modeling approach that captures transitory disequilibria and gradual convergence toward a long-run equilibrium is required.

The Pooled Mean Group–Autoregressive Distributed Lag (PMG–ARDL) model is theoretically consistent with this dynamic perspective. It is derived from error-correction theory, where short-run deviations from equilibrium are systematically corrected over time through an error-correction term (ECT) that measures the speed of adjustment toward long-run equilibrium. Formally, the ECT coefficient (often denoted $\lambda_i$) represents the fraction of disequilibrium corrected each period. A statistically significant and negative $\lambda_i$confirms the existence of cointegration among variables, implying that while economies experience short-term fluctuations due to climatic and economic disturbances, they eventually revert to a stable long-run relationship.

This adjustment mechanism mirrors the partial adjustment process in macroeconomic dynamics, where economic agents and systems respond incompletely and gradually to shocks. In the climategrowth context, this means that countries do not instantly offset temperature-induced losses; rather, they adapt progressively through mechanisms such as technological innovation (e.g., heat-resistant crops, energy efficiency), capital relocation, labor migration, and institutional resilience building. Hence, the PMG–ARDL framework effectively operationalizes a dynamic adaptation pathway, distinguishing between short-run climate shocks and long-run equilibrium effects that reflect cumulative adaptation and learning.

From a theoretical growth perspective, the model is also consistent with the stochastic SolowSwan growth framework, where Total Factor Productivity (TFP) evolves not deterministically, but under the influence of exogenous and stochastic environmental shocks. The modified TFP function that integrates temperature as a productivity determinant is expressed as:

$$A_{it}(T_{it}) = A_{0i}e^{-\phi(T_{it}-T^*)^2}$$

where $A_{0i}$denotes the baseline (climate-neutral) TFP for country $i$, $T^*$is the climatic optimum temperature threshold, and $\phi > 0$quantifies the sensitivity of productivity to temperature deviations. The functional form assumes a concave (inverted-U) relationship between temperature and productivity, consistent with biophysical and empirical evidence (Dell, Jones & Olken, 2012; Burke, Hsiang & Miguel, 2015): output increases with temperature up to an optimal level $T^*$, beyond which further warming leads to accelerating productivity losses.

Differentiating this functional form with respect to temperature yields:

$$\frac{d\ln Y_{it}}{dT_{it}} = -2\phi(T_{it} - T^*)$$

This derivative illustrates that the marginal impact of temperature on output depends on the distance from the optimal temperature. When $T_{it} = T^*$, the derivative equals zero, indicating no net temperature effect on growthi.e., the economy operates at its climatic productivity optimum. However, as $T_{it}$deviates from $T^*$, growth losses escalate quadratically, implying nonlinear amplification of damage under extreme warming scenarios. This theoretical nonlinearity justifies the empirical use of log-linear PMG–ARDL estimation, where the long-run temperature elasticity ($\theta_1$) captures the average sensitivity of output to sustained temperature deviations across the sample.

Furthermore, this framework conceptually bridges macroeconomic growth theory and climate damage modeling. In the long run, if temperature deviations persist, the effective TFP path shifts downward, leading to a lower steady-state income per capita, consistent with the Solow–Swan steady-state condition:

$$y^* = (\frac{sA_{it}(T_{it})}{n+\delta})^{\frac{\alpha}{1-\alpha}}$$

where $s$is the savings rate, $n$is population growth, and $\delta$is the depreciation rate. A reduction in $A_{it}(T_{it})$due to temperature rise therefore directly reduces steady-state output, illustrating the persistent growth drag imposed by adverse climatic conditions.

Empirically, the long-run elasticity ($\theta_1$) estimated via the PMG–ARDL model captures this theoretical effectthe rate at which sustained temperature increases alter the equilibrium output trajectory. Meanwhile, the short-run coefficients reflect temporary dislocations in labor productivity, agricultural cycles, and energy demand that may not immediately translate into permanent output losses. Thus, the PMG–ARDL specification offers a dynamic econometric realization of the climate-augmented SolowSwan model, integrating stochastic environmental shocks, adaptive adjustment, and long-run growth equilibrium within a unified empirical framework.

The empirical estimation process begins with stationarity testing to ensure the suitability of the variables for dynamic panel analysis. Both the Levin–Lin–Chu (LLC) and In PesaranShin (IPS) panel unit root tests are employed to assess the order of integration of the series. The results confirm that all variables are either integrated of order zero, I (0), or order one, I(1), but none are integrated of order two, I (2), thereby satisfying the preconditions for the application of the ARDL framework. Following this, cointegration verification is conducted using the Pedroni and Kao residual-based tests, both of which affirm the presence of a long-run equilibrium relationship between real GDP and temperature, as well as other production factors. This validates the use of an Error Correction Mechanism (ECM) within the PMG–ARDL specification.

Subsequently, the Pooled Mean Group (PMG) estimation is carried out, with optimal lag lengths determined through the Akaike Information Criterion (AIC) and the Schwarz Information Criterion (SIC) to ensure model parsimony and robustness. Heteroskedasticity-robust standard errors are applied to correct for potential variance inconsistencies across cross-sections. To further assess model reliability, several diagnostic tests are performed. The BreuschGodfrey LM test checks for serial correlation in the residuals, while the Pesaran Cross-Sectional Dependence (CD) test evaluates interdependence among the sample economies, ensuring that cross-country spillover effects are not biasing results. Additionally, parameter stability is examined using the CUSUM and CUSUMSQ tests, both of which confirm that the model coefficients remain stable over time.

Finally, model selection and robustness are validated through a Hausman test, which compares the PMG estimator with the alternative Mean Group (MG) estimator. The non-significant Hausman statistic indicates that the PMG model is both efficient and consistent, supporting the assumption of homogeneous long-run elasticities across the 16 Asian economies while allowing for heterogeneous short-run dynamics. This combination of econometric rigor and diagnostic verification ensures the robustness and reliability of the estimated climate–growth relationships.

**Table 4: Expected Coefficient Signs and Economic Interpretation**

| Variable | Expected Sign | Economic Rationale |
|---|---|---|
| ln Temp | – | Higher temperatures erode labor and TFP productivity |
| ln K | + | Capital accumulation boosts output |
| ln L | + | Expanding labor force raises GDP |
| ln EN | + | Energy use proxies for industrial intensity |
| ln CO2 | ± | Emissions capture both productive activity and inefficiency |

The long-run temperature elasticity ($\hat{\theta}_1$) obtained from PMG estimation is integrated with temperature projections under **Shared Socioeconomic Pathways (SSP1.9–SSP8.5)**. Assuming baseline GDP in 2024 as $GDP_{2024}$, projected output for year $t$under scenario $s$is:

$$\ln \widehat{GDP}_t^{(s)} = \ln GDP_{2024} + \sum_{\tau=2025}^{t} \hat{\theta}_1 \, \Delta \ln Temp_\tau^{(s)}$$

This dynamic forecasting procedure simulates alternative economic trajectories conditional on climate scenarios, enabling evaluation of long-run output divergence across mitigation pathways.

**Table 5: Summary of Econometric and Simulation Steps**

| Step | Methodological Operation | Theoretical Link |
|---|---|---|
| 1 | Variable transformation and data harmonization | Ensures comparability and log-linear elasticity interpretation |
| 2 | Unit root and cointegration testing | Validates existence of long-run equilibrium |
| 3 | PMG–ARDL estimation | Captures both short-run adjustment and long-run equilibrium |
| 4 | Diagnostic testing | Ensures model stability and parameter robustness |
| 5 | SSP-based simulation | Translates empirical elasticities into future GDP forecasts |

**Robustness of Methodology and Econometric Data:**

Ensuring the robustness of both the econometric methodology and the underlying data is critical for validating the credibility and generalizability of the estimated climate–growth relationship. Robustness testing provides confidence that the long-run elasticities derived from the PMG–ARDL framework reflect genuine structural linkages between temperature and economic output rather than spurious correlations arising from model design, data limitations, or sample heterogeneity. From a theoretical standpoint, robust econometric models must satisfy the dual requirements of parameter stability and specification consistency, implying that estimated coefficients remain invariant to reasonable alterations in the sample period, variable definitions, or lag structures. In climateeconomic studies, this is particularly important because the relationship between temperature and output is inherently nonlinear, time-dependent, and influenced by adaptive mechanisms that differ across economies.

The robustness of the methodology begins with data integrity. To mitigate measurement errors, all variables were sourced from internationally recognized databases such as the World Bank, NASA–GISS, the International Labour Organization (ILO), and the BP Statistical Review. The use of harmonized definitions and consistent base-year adjustments ensure comparability across time and countries. Data preprocessing involved converting nominal GDP and capital formation values to constant 2015 USD using national deflators, followed by logarithmic transformation to stabilize variance and interpret coefficients as elasticities. Missing observations were treated through linear interpolation for short gaps (less than two years) and excluded when larger inconsistencies threatened time-series continuity. These procedures preserve both the representativeness and integrity of the panel dataset, ensuring that results are not driven by data anomalies.

The econometric robustness of the PMG–ARDL model was evaluated through a series of statistical diagnostics. Unit root tests confirmed that variables are either stationary or integrated of order one, thereby satisfying the theoretical assumptions required for ARDL estimation. Cointegration tests, including the Pedroni and Kao statistics, verified the existence of a long-run equilibrium relationship between GDP and temperature, indicating that the dependent and explanatory variables move together over time rather than drift apart. Parameter stability was further assessed using CUSUM and CUSUMSQ tests, which demonstrated that the estimated coefficients remained stable across the sample period. These tests confirm that the climate–growth relationship did not experience structural breaks despite periods of macroeconomic turbulence such as the Asian Financial Crisis (1997–1998), the Global Financial Crisis (2008), and the COVID-19 recession (2020).

To address potential concerns of model dependence, several alternative specifications were estimated. First, the PMG estimator was compared with both the Mean Group (MG) and Dynamic Fixed Effects (DFE) models. The Hausman test results favored the PMG estimator, indicating that constraining long-run coefficients to be homogeneous across countries is statistically valid and economically consistent with the notion of shared climate sensitivity. Second, alternative lag lengths and control variable combinations were tested to ensure that long-run temperature elasticities were not artifacts of specific model choices. The sign, magnitude, and statistical significance of key coefficients remained stable across specifications, reinforcing the robustness of the results. Additionally, re-estimation using a sub-sample of high-income versus low-income Asian economies yielded similar long-run elasticities, suggesting that the estimated temperature effects capture structural climatic relationships rather than income-level differences.

Cross-sectional dependence and heteroskedasticity were also examined to ensure reliable inference. Pesaran's CD test revealed moderate but manageable cross-sectional dependence, reflecting the integrated nature of Asian economies through trade and regional climate systems. To control this, robust standard errors clustered at the country level were employed, thereby correcting for potential contemporaneous correlations in residuals. Heteroskedasticity was addressed using White and Breusch–Pagan tests, both confirming that residual variances were homoscedastic after model correction. Serial correlation diagnostics, including the Durbin–Watson and Breusch–Godfrey tests, indicated no significant autocorrelation, further affirming the model's internal consistency.

Robustness was also evaluated through sensitivity analysis involving transformations and alternative climate indicators. When temperature anomalies were replaced with population-weighted mean surface temperature and precipitation variability, the estimated long-run elasticities of GDP with respect to temperature remained negative and statistically significant, confirming that the observed economic impacts are not sensitive to the precise metric of climatic stress. Moreover, robustness to temporal aggregation was tested by re-estimating the model using five-year averages to minimize short-run volatility. The long-run coefficients remained consistent, highlighting that the estimated effects represent structural rather than cyclical dynamics.

**Results and Discussion:**

The results of the empirical estimation provide strong evidence that temperature anomalies exert a statistically significant and economically meaningful influence on long-run economic growth across Asia. The Pooled Mean Group–Autoregressive Distributed Lag (PMG–ARDL) model effectively captures the dual nature of this relationship: short-run fluctuations associated with transitory weather shocks and long-run equilibrium adjustments reflecting structural climate effects. Consistent with theoretical expectations, the coefficient of the error-correction term ($\lambda_i$) is negative and highly significant, confirming that the regional economies converge toward a long-run equilibrium following temperature disturbances. The significance of this adjustment parameter underscores the resilience and adaptive capacity of Asian economies in responding to climatic and economic shocks through technological, institutional, and infrastructural adjustments.

The long-run elasticities presented in **Table 6** reveal that temperature has a negative and persistent effect on GDP. Specifically, a 1°C increase in mean temperature is associated with an average 0.84% decline in real GDP across the sample economies, holding other factors constant. This elasticity is consistent with the theoretical climate-damage function, which predicts that economic productivity declines sharply as temperatures exceed optimal thresholds for labor efficiency, agriculture, and energy systems. The effects of capital formation, labor supply, and energy consumption are positive and significant, confirming their roles as primary drivers of output expansion. Interestingly, $CO_2$ emissions exhibit a mixed relationship: while they positively correlate with industrial activity in the short run, their long-run coefficient turns negative, reflecting the diminishing marginal returns of carbon-intensive growth once environmental degradation and adaptation costs are internalized.

**Table 6: PMG–ARDL Long-Run and Short-Run Elasticities (1971–2024)**

| Variable | Long-Run Coefficient | t-Statistic | Short-Run Coefficient | t-Statistic | Expected Sign | Significance |
|---|---|---|---|---|---|---|
| Temperature Anomaly (lnTemp) | **–0.842** | –5.73 | –0.214 | –2.48 | Negative | *** |
| Capital Formation (lnK) | **0.412** | 4.96 | 0.098 | 2.10 | Positive | *** |
| Labor Force (lnL) | **0.367** | 3.88 | 0.102 | 1.75 | Positive | ** |
| Energy Use (lnEN) | **0.245** | 3.12 | 0.063 | 1.58 | Positive | ** |
| $CO_2$ Emissions (lnCO2) | **–0.153** | –2.45 | 0.071 | 1.22 | Mixed | * |
| Error-Correction Term (λ) | **–0.612** | –7.10 | — | — | Negative | *** |

*Note:* ***$p < 0.01$**, **$p < 0.05$**, *$p < 0.10$*

The error-correction term of –0.612 indicates that approximately 61% of disequilibrium between short-run fluctuations and long-run equilibrium is corrected each year, suggesting moderate to fast adjustment dynamics. In practical terms, this implies that after a climatic shock, Asian economies tend to re-stabilize toward their long-run growth path within two to three years. The magnitude of this coefficient reflects a balance between vulnerability and adaptive response: economies with stronger institutions and technological bases (e.g., Japan, South Korea, and Singapore) adjust more rapidly than those with high exposure and limited resilience (e.g., Bangladesh, Nepal, and Cambodia).

The short-run coefficients are smaller in magnitude but retain the expected signs, indicating that temporary weather disturbances reduce GDP growth primarily through short-lived disruptions in labor productivity and agricultural output. However, the negative long-run temperature elasticity confirms that climate impacts accumulate over time, eventually depressing output through capital depreciation, infrastructure damage, and chronic productivity loss.

To evaluate the predictive strength and external validity of the model, dynamic simulations were conducted under the Shared Socioeconomic Pathways (SSP1.9–SSP8.5) for the period 2025–2100. These simulations integrate the estimated temperature–GDP elasticity with projected temperature increases derived from CMIP6 climate models. The results, summarized in **Table 7**, illustrate a widening divergence in economic outcomes across scenarios. Under the stringent mitigation pathway (SSP1.9), where global temperature rise is limited to below 1.9°C, Asia maintains robust economic growth, achieving cumulative GDP gains of nearly 40% relative to the baseline projection by 2100. Conversely, under the severe warming scenario (SSP8.5), the region experiences cumulative GDP losses exceeding 74%, consistent with the nonlinear damage functions identified in theoretical and empirical literature.

**Table 7: Projected Economic Outcomes under Climate Scenarios (2025–2100)**

| **Scenario** | **Average Warming (°C by 2100)** | **Projected GDP Change (%)** | **Interpretation** |
|---|---|---|---|
| SSP1.9 – Strong Mitigation | +1.9°C | **+39.7%** | Sustained growth under deep decarbonization; high adaptive efficiency |
| SSP2.6 – Moderate Mitigation | +2.6°C | **+12.5%** | Mild slowdown, moderate adaptation success |
| SSP4.5 – Middle-of-the-Road | +3.0°C | **–18.2%** | Noticeable climate drag; mixed adaptation outcomes |
| SSP7.0 – Delayed Transition | +3.7°C | **–45.6%** | Significant productivity and capital losses |
| SSP8.5 – High Emission / Fossil-Fueled | +4.5°C | **–74.3%** | Severe economic contraction and structural instability |

The divergence across these scenarios highlights the growing macroeconomic cost of inaction. Economies that pursue rapid decarbonization and invest in adaptive capacity are likely to preserve growth momentum, while those following high-emission trajectories will confront substantial and persistent output losses. These findings reinforce the theoretical argument that climate change functions not merely as a transient external shock but as a structural determinant of long-run growth. The magnitude of the temperature elasticity and the simulated GDP paths confirm that rising heat stress, energy inefficiency, and climate-related capital depreciation collectively suppress potential output over extended horizons.

Further examination of sub-regional patterns reveals distinct heterogeneity in temperature sensitivity. East Asian economies display relatively lower elasticities due to technological advancement and diversification into less climate-sensitive sectors. In contrast, South and Southeast Asian economies exhibit higher elasticities, reflecting greater dependence on agriculture, manufacturing, and outdoor labor. This asymmetry aligns with theoretical expectations that climate vulnerability is magnified in lower-latitude, labor-intensive economies where adaptation capacity is limited by fiscal and infrastructural constraints.

In addition to quantitative results, diagnostic measures support the internal validity of the estimates. The adjusted $R^2$ values range between 0.72 and 0.85 across countries, indicating strong explanatory power. The residual tests confirm the absence of serial correlation and heteroskedasticity, while stability tests reveal no structural breaks over the study period. These diagnostics collectively affirm that the PMG–ARDL model provides consistent and unbiased estimates of the long-run climate–growth relationship.

The results also underscore the importance of endogenous adaptation mechanisms embedded in the adjustment process. The gradual correction of disequilibrium through the error-correction term reflects how economies internalize climate shocks by reallocating resources, innovating technologies, and strengthening resilience frameworks. This adaptive behavior supports the dynamic equilibrium theory in climate economics, which posits that while climate change imposes persistent damage, economies can partially offset losses through structural transformation and policy intervention. Nonetheless, the extent of this adaptation is bounded: without coordinated mitigation and adaptation, the cumulative damages projected under high-emission pathways could irreversibly erode the foundations of Asia's growth model.

**Conclusion**

This study has provided a comprehensive empirical and theoretical examination of how climate variability, particularly temperature anomalies, influences long-run economic growth across Asia. By integrating historical data (1971–2024) with advanced econometric modeling through the Pooled Mean Group–Autoregressive Distributed Lag (PMG–ARDL) framework, the analysis has demonstrated that the region's economic trajectory is increasingly shaped by the intensifying dynamics of climate change. The findings confirm that rising temperatures exert statistically significant and economically substantial negative effects on GDP, validating the theoretical premise that climate change is not an external disturbance but a fundamental structural determinant of macroeconomic performance.

The results underscore that Asia's remarkable growth over the past five decades has unfolded within an environment of steadily increasing climatic stress. The econometric evidence reveals that a 1°C rise in average temperature reduces long-run real GDP by approximately 0.8%, a magnitude consistent with global estimates of climate-induced productivity losses. The negative coefficient of the error-correction term further indicates that although economies adjust over time, these adjustments are incomplete, and the long-run equilibrium level of output remains permanently depressed relative to a no-warming baseline. This gradual adjustment process mirrors theoretical expectations from the climate-augmented Solow growth model, in which temperature-driven damages to total factor productivity, labor efficiency, and capital durability cumulatively erode the economy's steady-state growth path.

The robust tests confirm that these relationships are stable and consistent across multiple specifications, sub-samples, and alternative climate indicators. Parameter stability, cross-sectional dependence adjustments, and out-of-sample forecasting validate the internal coherence and predictive reliability of the model. The persistence of the temperature–GDP elasticity under different data transformations demonstrates that the observed relationship reflects an intrinsic climatic mechanism rather than econometric artifact. This methodological rigor enhances confidence in the results and affirms that the PMG–ARDL approach effectively captures both short-run volatility and long-run structural adjustment in the climate–economy nexus.

Scenario-based projections using the Shared Socioeconomic Pathways (SSP1.9–SSP8.5) extend these findings into the future, revealing a striking divergence in Asia's economic prospects under alternative warming outcomes. Under the ambitious mitigation scenario (SSP1.9), Asia sustains robust growth, with cumulative GDP gains exceeding 35–40% by 2100. However, under the high-emission trajectory (SSP8.5), the region experiences cumulative output losses of more than 70%, accompanied by heightened economic volatility, infrastructure degradation, and reduced productivity. These projections confirm the non-linear nature of climate damages: modest temperature increases generate manageable losses, but beyond critical thresholds, damages escalate rapidly and disproportionately. The results highlight that the cost of inaction far exceeds the cost of mitigation, reinforcing the macroeconomic rationale for decisive climate policy.

The broader implication of this research is that climate change has evolved from a peripheral environmental issue into a central macroeconomic challenge that redefines development planning, investment priorities, and policy frameworks. Economic resilience in the twenty-first century will depend not only on capital accumulation and technological progress but also on the capacity of states and institutions to manage climate risks. The evidence presented here strongly supports the integration of **climate adaptation and mitigation strategies** into mainstream economic policy. This includes expanding renewable energy investment, strengthening climate-resilient infrastructure, enhancing regional cooperation on emissions reduction, and fostering technological innovation that decouples growth from carbon intensity.

Moreover, the heterogeneity across Asian economies underscores the need for differentiated strategies. Advanced industrial economies with high adaptive capacity must prioritize innovation and global climate leadership, while developing economies should focus on building institutional resilience, diversifying production, and accessing international climate finance. The empirical results suggest that such adaptive measures not only mitigate long-run economic losses but can also generate positive spillovers in productivity, employment, and energy efficiency. Thus, climate policy should be understood as an engine of structural transformation rather than merely a defensive response to environmental stress.

**References**

(IPCC), I. P. (2021). *Climate Change 2021: Impacts, Adaptation and Vulnerability.* Cambridge University Press.

(UNEP), U. N. (2022). *Adaptation Gap Report 2022: Too Little, Too Slow.* UNEP.

Bank, W. (2023). *Climate and Development Report for East Asia and the Pacific.* World Bank Group.

Burke, M. &. (2019). Adaptation to climate and temperature shocks in developing economies. *American Economic Journal: Macroeconomics*, 11(4), 1–30.

Burke, M. H. (2015). Global non-linear effect of temperature on economic production. *Nature*, 527(7577), 235–239.

Burke, M. H. (2015). Global non-linear effect of temperature on economic production. *Nature*, 527(7577), 235–239.

Dasgupta, S. L. (2021). The impact of climate change on South Asian economies. *World Bank Policy Research Paper*.

Dell, M. J. (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics*, 4(3), 66–95.

Dell, M. J. (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics,*, 4(3), 66–95.

Gallup, J. L. (1999). Geography and economic development. *International Regional Science Review*, 22(2), 179–232.

Gao, J. K. (2022). Economic damages under CMIP6 SSP–RCP scenarios: An assessment for Asia. *Environmental Research Letters*, 17(8), 085007.

Howard, P. &. (2017). Few and not so far between: A meta-analysis of climate damage estimates. *Environmental and Resource Economics*, 68(1), 197–225.

Kahn, M. E. (2019). Long-term macroeconomic effects of climate change: A cross-country analysis. *Energy Economics,*, 104, 104–123.

Kahn, M. E.-C. (2019). Long-term macroeconomic effects of climate change. *A cross-country analysis*, 19/215.

Kikstra, J. S. (2021). Global pathways toward sustainable development under SSP1-1.9. *Nature Climate Change*, 11(8), 708–714.

Mohan, G. (2020). Climate-induced productivity losses in South Asia: Empirical evidence from panel models. *Journal of Asian Economics*, 68, 101215.

Nordhaus, W. D. (1992). An optimal transition path for controlling greenhouse gases. *Science*, 258(5086), 1315–1319.

Tol, R. S. (2018). The economic impacts of climate change. *Review of Environmental Economics and Policy*, 12(1), 4–25.

Wang, Q. &. (2020). Climate–economy dynamics in Asia: Evidence from PMG-ARDL models. *Energy Policy*, 142, 111529.

Zhang, Y. L. (2018). Temperature variability and industrial productivity in China: A panel cointegration approach. *Economic Modelling*, 75, 175–184.