CLIMATE VARIABILITY AND ECONOMIC PERFORMANCE IN EGYPT USING ARDL APPROACH

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ABSTRACT

The research issue is to gauge the effect of climate change on the economic performance of Egypt and which environmental factors have the greatest restrictive effect on growth. This paper examines how climate change will affect economic growth in Egypt between 1990 and 2024, through the Autoregressive Distributed Lag (ARDL) model. The primary measure of economic performance is the GDP per capita, which is analyzed in connection with some major climate variables carbon dioxide emissions, precipitation, and average temperature and other economic variables that include investment, arable land, and natural resource rents. The ARDL model is especially the right tool to use in this analysis because it allows variables that used to be integrated into a time series of differing order, which is prevalent in climatic and economic time series. The findings demonstrate that there are evident differences in short-run and long-run effects. The effect of increasing temperatures in the short run is a decline in the economic output indicating a productivity loss associated with heat in agriculture and labor intensive sectors. The role of precipitation in economic growth in both long and short is always positive because it underlines that the availability of water is a key limiting factor on the development of Egypt. The relationship between carbon dioxide outputs and long-run economic growth is positive and significant, which demonstrates the fact that Egypt remains relying on energy-intensive production. Growth is also supported by arable land, but recent trends have indicated that there is slowdown in land expansion. The error correction process implies quite rapid adaptation to long-run equilibrium, and the diagnostic tests prove the stability of the model estimated. The results show that there is increasing conflict between economic development in the short term and the climate threat in the long term. The shrinking water supply and the mounting climatic stress imply that the growth will be necessary to be sustained with the help of immediate policy actions, especially in the area of water management, energy conversion, and climate adjustments.

Keywords: Climate change, Economic growth, Water scarcity, ARDL model, CO_2 emissions, Egypt

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INTRODUCTION

Climate change has ceased to be a far off menace but a reality that is redefining economic opportunities in the developing world. This is the case with Egypt, as although the country has only the smallest share of global greenhouse gas emissions at 0.6%, the country faces disproportionate climate risks that can jeopardize its development process and social stability (Eliw *et al.*, 2019).

The state of Egypt is vulnerable to climate because of the geographic and hydrologic peculiarities. The average rainfall is a meager 50 millimeters per annum with most of the rainfall falling in the Mediterranean coastal areas and the large interior region being hyper-arid. The Nile River that supplies more than 90% of the freshwater in the country is a river that is completely located outside Egyptian boundaries, which makes water security conditional and dependent on upstream projects and trans boundary treaties. The past decades have been marked by worrying tendencies: the average temperature has increased by about 2.5 °C since the 1990s, and even relatively small precipitation demonstrates a steady decrease (Abdelazez *et al.,* 2024). Most concerning, perhaps, is the fact that per capita renewable water resources have dropped down to less than 574 cubic meters in 2024, down as compared to the 1,020 cubic meters of 1990, which is way below the international water poverty line of 1,000 cubic meters (Ashour *et al.,* 2024). These environmental pressures directly pressurize the performance of the economy in a variety of ways. Water shortage and heat stress pose an imminent risk to agriculture, which employs about a quarter of the labor force and covers almost all arable land due to the intensive irrigation practice (Ashour *et al.,* 2024). Tourism income, which is very crucial in the foreign exchange earnings, is susceptible to the excessive weather conditions and the coastal erosion due to the rise in sea level. The trouble is that energy production is dependent on natural gas and petroleum, and it builds a carbon-intensive model of growth, which is increasingly being questioned by the climate commitments in the world. In the meantime, the city infrastructure is overloaded with the need to adapt to climate changes and serve a growing population (Elgohary, 2025).

Climate change has been the subject of increased scholarly interest with the literature reflecting adverse impacts on growth in developing economies (Zhu and Xie, 2023). Nonetheless, the majority of current studies are based on cross-country panel designs, which, although statistically effective, can obscure country-specific dynamics due to country-specific institutional, geographic or structural factors. Egypt is a country deserving of specific attention due to its overwhelming reliance on water, an agricultural economy based on the river Nile, and being a country with acute exposure to climate change. There has been recent effort towards discussing the climate problems of Egypt at sectoral levels (Ashour *et al.,* 2024) project declining water resources in Upper Egypt, while (Elgohary, 2025) evaluates conservation policies but has not been fully evaluated in terms of macroeconomics.

There is a severe development dilemma in Egypt: the country has to maintain economic growth in order to secure jobs and reduce poverty, but it also has to face the increasing climate pressure, which endangers the major productive spheres. The research issue is to gauge the effect of climate change on the economic performance of Egypt and which environmental factors have the greatest restrictive effect on growth. Available international literature provides minimal suggestions because of specific circumstances in Egypt, and the local research is more focused on the impacts of the sector, but not on the overall macroeconomic associations. This is a limitation to effective, evidence-based policymaking when water, energy and agricultural adaptation decisions have long-term economic stability implications (Nassr *et al.,* 2021).

The purpose of the study is to measure the short and long-run impacts of temperature, precipitation, and CO_2 emission on the economic growth that is expressed in terms of GDP per capita, and then to adjust these impacts with other important structural variables including investment, arable land, and rents of natural resources. It also aims at determining the strongest environmental limits to growth and how fast the economy is adapting to climate-related shocks thus providing insight on the adaptive capacity of Egypt. By so doing, the study offers methodological value in the use of ARDL framework in climate economy analysis with limited data.

MATERIALS AND METHODS

In this section, the data sources, the variables and analytical framework used in investigating the relationship between climate change and economic growth are described. The methodology will be used to attract both short-term variability and long-term equilibrium relationships giving a complete picture of the impact of environmental factors on the economic performance of Egypt.

Dependent Variable

GDP per capita (GDPPC): This variable is the most important indicator of economic growth and development that defines the average economic output per individual in Egypt.

Independent Climate Variables: The climate-related variables that have a direct measurement of the environmental change in Egypt include the following:

Carbon dioxide emissions (CO_2): Measures the level of energy consumption and industrialization, which is a proxy of carbon footprint of economic production.

Precipitation: The level of rainfall annually which is one of the main determinants of agricultural production and availability of water resources in the mainly dry climate in Egypt.

Annual mean temperature (Tasmean): Mean annual temperature, which influences workforce output, energy consumption, and the crop production.

Control Variables: In order to capture the individual effects of the climate variables, a few control variables are added to capture the other economic and structural variables:

Gross domestic investment (% of GDP) (GDI): Quantifies capital formation and its contribution to the economic growth.

Total natural resource rents (% of GDP) (Rent): Represents the economic value of the natural resources such as oil, gas, and minerals.

Arable land (% of land area) (Land): Indicative of the presence of arable land, which is a basic production factor in agriculture.

Econometric Model: To quantify the effect of climate change on economic growth in the Arab Republic of Egypt the study period was made to run starting in 1990 up to 2024 to bring the effect into a better focus. This relationship can be generalized as below that indicates the effect of climate change on economic growth:

$$\boldsymbol{GDPPCt} = \boldsymbol{f}(\boldsymbol{CO2t}.\ \boldsymbol{Prect}.\ \boldsymbol{Tast}.\ \boldsymbol{GDIt}.\ \boldsymbol{Lan}.\ \boldsymbol{Rent})$$

The mathematical form of the equation can be written as:

$$\boldsymbol{lGDPPCt} = \boldsymbol{\beta 0} + \boldsymbol{\beta 1}\ \boldsymbol{lCO2t} + \boldsymbol{\beta 2}\ \boldsymbol{lPrect} + \boldsymbol{\beta 3}\ \boldsymbol{lTast} + \boldsymbol{\beta 4}\ \boldsymbol{lGDIt} + + \boldsymbol{\beta} 5\ \boldsymbol{lLandt} + \boldsymbol{\beta} 6\ \boldsymbol{lRentt} + \boldsymbol{\varepsilon t}$$

An error term εt... is included in the equation due to the probabilistic nature of the model.

Where:
GDP per capita (GDPPC): (USD per capita)
CO_2 emissions: Metric tons per capita (t/capita)
Precipitation: Millimeters per year (mm/year)
Temperature (Tasmean): Degrees Celsius (C^O)
Gross domestic investment (GDI): Percent of GDP(%)
Natural resource rents (Rent): Percent of GDP(%)
Arable land (Land): Percent of total land area (%)

Description of the Econometric Method Used: The model used the Autoregressive Distributed Lag (ARDL) model introduced by (Pesaran *et al.*, 2001), which has a number of methodology strengths over the conventional cointegration models. One can use the ARDL model when the variables are of order zero I(0), order one I(1), or a combination of both (Eliw *et al.*, 2019). This flexibility is especially useful in the light of mixed integration properties that are often found in economic and environmental data.

The dependence of the dependent variable Y on the values of the explanatory variable X is not instantaneous. Y is usually dependent on X with a time difference, referred to as a 'lag'. When there is more than one time period, the model is called a distributed lag model and takes the following formula (Pesaran *et al.,* 2001):

$$Y = \alpha + \beta_1 X_t + \beta_2 X_{t-1} + \beta_3 X_{t-2} \ldots\ldots + \beta_k X_{t-k} + u_t \qquad (1)$$

Where k is the number of lag periods, β_1 is the short-run impact because it gives the impact of change in X on Y during the same time period. If the same level of impact carries on, (β_1+ β_2) gives the change that occurs in the average value of Y in the coming period; whereas (β_1+ β_2 + β_3) gives the change that occurs in the average value of Y in period that follows, etc., and is referred to as the separator or average multipliers. The sum of Ks is the long-run or the sum of distributed lagged multiplier is given by:

$$\sum_{i=0}^{K} \beta_i = \beta_1 + \beta_2 + \beta_3 \ldots\ldots\ldots. + \beta_k = \beta \qquad (2)$$

The standard coefficient is a percent of the long-run impact. It gives the impact at a specific period of time using the following formula:

$$y_t = \alpha + \sum_{i=1}^{p} \gamma_i y_i + \sum_{j=1}^{k} \sum_{i=0}^{q_j} X_{j,t-i}{}' \beta_{j,i} + \varepsilon_t \qquad (3)$$

Co-integration: A common single-equation approach for testing co-integration among a set of I(1) variables relies on residual-based tests, while system-based co-integration testing is generally conducted using reduced-rank approaches.

$$\Delta y_t = -\sum_{i=1}^{p-1} \gamma_i * \Delta y_{i-1} + \sum_{j=1}^{k} \sum_{i=0}^{q_j - 1} \Delta X_{j,t-i}{}' \beta_{j,i} * -\hat{\phi} EC_{t-1} + \varepsilon_t \qquad (4)$$

Bounds Testing: Using the cointegration form expressed by equation (4), (Pesaran *et al.,* 2001) developed a new approach to solve the problem of testing for the existence of a level relationship between a dependent variable and a set of regressors, when it is not known with certainty whether the underlying regressors are trend- or first-difference stationary, or the existence of a long-run relationship between the dependent and explanatory variables. Derived from equation (4), bounds testing can be written as (Pesaran *et al.,* 2001):

$$\Delta y_t = -\sum_{i=1}^{p-1} \gamma_i * \Delta y_{i-1} + \sum_{j=1}^{k} \sum_{i=0}^{q_j-1} \Delta X_{j,t-i}{}' \beta_{j,i} * - \rho y_{t-1} - \alpha - \sum_{j=1}^{k} X_{j,t-1}{}' \delta_j + \varepsilon_t \quad (5)$$

Stability Testing: To test the stability of ARDL Models, a proper test should be selected, like cumulative sum of recursive residuals (Cusum), which helps identify the stability of and harmony between long and short-run parameters.

Data Sources: This research relies on secondary data collected from a range of official and internationally recognized sources over the period (1990-2024). Key national sources include the Ministry of Agriculture and Land Reclamation (MALR) through its Economic Affairs Sector (https://www.agri.gov.eg/) the Central Agency for Public Mobilization and Statistics (CAPMAS) (https://www.capmas.gov.eg/home)World Bank (https://climateknowledgeportal.worldbank.org/)

RESULTS

An overview of the current state of Egyptian agriculture

Long-Term Trends in Average Temperature and Annual Rainfall in Egypt (1990–2024): The Table 1 clearly showed that Egypt experienced a noticeable warming trend between 1990 and 2024. The average monthly temperature increased from 19.9°C in 1990 to 22.3°C in 2024, meaning temperatures rose by about 2.4°Cover the period. Minimum temperatures increased even more significantly, which indicate warmer winters compared to the early 1990s. Rainfall, on the other hand, does not follow a perfectly steady decline, but it generally fluctuated at lower levels than in the early years. It decreased slightly from 4.4 mm in 1990 to about 4 mm in 2024, with some unusually high or low years in between.

Table 1: Trends in Average Temperature and Precipitation in Egypt (1990–2024)

Year	Maximum temperature (°C)	Minimum temperature (°C)	Average monthly temperature (°C)	Relative humidity (%)	Rainfall amount (mm)	Thermal range (m)
1990	30.7	9.10	19.90	42	4.4	21.60
1991	32.4	13.70	23.05	42	4.3	18.70
1992	31.2	11.30	21.25	43	4.3	19.90
1993	30.7	11.50	21.10	40	4.2	19.20
1994	29.4	11.30	20.35	45	4.2	18.10
1995	31.2	11.50	21.35	40	4.1	19.70
1996	28.7	11.60	20.15	43	4.1	17.10
1997	34.4	15.40	24.90	49	4.0	19.00
1998	30	11.00	20.50	46	3.9	19.00
1999	31.4	12.80	22.10	50	3.9	18.60
2000	29.8	10.10	19.95	46	3.8	19.70
2001	27.3	11.50	19.40	49	3.8	15.80
2002	26.79	11.38	19.09	50	3.7	15.41
2003	28.28	11.26	19.77	47	3.7	17.02
2004	29.69	10.76	20.23	52	3.6	18.93
2005	28.82	10.74	19.78	47	3.6	18.08
2006	29.91	11.20	20.56	53	3.5	18.71
2007	28.47	15.65	22.06	53	3.33	12.82
2008	28.57	15.66	22.12	53	3.67	12.91
2009	29.43	16.91	23.17	53.98	1.50	12.52
2010	30.52	17.97	24.25	54.61	1.58	12.55

2011	27.80	16.80	22.30	55.08	6.16	11.00
2012	27.84	16.42	22.13	55.38	4.70	11.10
2013	29.29	16.67	22.98	53.48	3.50	12.62
2014	29.00	16.94	22.97	53.89	2.67	12.06
2015	29.03	16.70	22.87	54.32	3.58	12.33
2016	31.00	19.50	25.25	50.40	1.35	11.50
2017	29.00	16.80	22.90	47.40	3.53	12.20
2018	30.20	17.90	24.05	52.60	2.85	12.30
2019	29.40	17.20	23.30	42.20	1.42	12.20
2020	30.20	18.40	24.30	43.00	3.13	11.80
2021	30.30	18.40	24.35	47.20	2.62	11.90
2022	30.60	18.50	24.55	47.48	1.30	12.10
2023	28.56	15.62	22.09	54.78	3.94	12.94
2024	28.88	15.70	22.29	54.90	3.98	13.18

Source: World Bank Climate Change Knowledge Portal; Egyptian Meteorological Authority.
https://climateknowledgeportal.worldbank.org/

Land Use and Irrigation Dynamics under Water Scarcity and Resource Limitations: Table (2) showed how land use and irrigation resources in Egypt evolved structurally between 1990 and 2024 with extreme shortages of natural resources. As the agricultural and cultivated land continued to increase, the rate of increase decreased since 2020, which meant that the horizontal expansion was nearing its economic and environmental boundaries because of water shortage and the increasing cost of reclamation.

Table 2: Land Use and Irrigation Water Resources in Egypt (1990–2024)

Land and Water Resources	**1990**	**2000**	**2010**	**2020**	**2024**
Land Resources					
Total country area (thousand km^2)	100.145	100.145	100.145	100.145	100.145
Agricultural land (thousand ha)	2.648	3.291	3.671	3.971	3.971
Cultivated land (thousand ha)	2.648	3.291	3.671	3.971	3.971
Arable land (thousand ha)	2.284	2.801	2.873	3.365	3.365
Permanent crops area (thousand ha)	364	490	798	606	606
Temporary meadows and pastures (thousand ha)	Not available	647	572	608	608
Forests (planted forests) (thousand ha)	44	59	66	45	45
Irrigation Resources					
Irrigation potential (thousand ha)	4.420	4.420	4.420	4.420	4.420
Area equipped for irrigation (thousand ha)	3.246	3.383	3.610	3.823	3.823
Actually irrigated area (thousand ha)	2.585	3.383	3.422	3.422	3.422
Cropping intensity (%)	166	174	185	185	185
Area affected by salinity due to irrigation (thousand ha)	900	900	900	900	900
Cultivated area equipped with drainage (thousand ha)	3.024	3.024	3.024	3.024	3.024
Area irrigated with treated wastewater (thousand ha)	39	74	71	71	71

Source: CAPMAS, Water Resources and Irrigation Bulletin (1990-2024).

The alterations in land use patterns depicted the growing pressure on arable land and variability in permanent crop, which was indicative of water shortage as well as market-induced adaptation. The comparative standstill of temporary pastures implied a structural imbalance in the livestock development and the availability of feed, which leads to increased production costs in the animal sector.

Indicators of irrigation verified that Egypt is a high reliant area of irrigated agriculture. Despite the growth in the area under irrigation preparation, the really irrigated area had not grown past 2010, which was an indicator of inefficiencies in water use. Increasing intensity of cropping was an adaptation to land shortage but posed a concern on the sustainability of soil and water in the long term.

The constant salinity-impacted regions and the restrained growth of the wastewater reuse highlighted the systematic inefficiency of land and water management.

Egypt's Water Supply and Demand (1990–2024): Table (3) provided a clear view of the water problem in Egypt in the long-term. One of the most noticeable tendencies in the table was the significant decrease of the per capita water level. The total renewable water resources continued to be 57.5 billion cubic meters per year, but the per-capita renewable water resources decreased from 1,020 m^3/year in 1990 to approximately 574 m^3/year in 2024. This depletion then made Egypt far under the global level of water poverty, implicating the fact that the water crisis was not as much caused by absolute scarcity but rather by population pressure and insufficient diversification of resources.

Table 3: Long-Term Water Supply and Demand in Egypt (1990–2024)

Water Resources	1990	2000	2010	2020	2024
Water Supply					
National rainfall index (1990 = 100)	157.3	102.4	106.6	106.6	106.6
Average annual rainfall (mm/year)	18.1	18.1	18.1	18.1	18.1
Internal Resources					
Internally produced surface water (billion m^3/year)	0.5	0.5	0.5	0.5	0.5
Internally produced groundwater (billion m^3/year)	0.5	0.5	0.5	0.5	0.5
Total internal renewable water resources (billion m^3/year)	1.0	1.0	1.0	1.0	1.0
Per capita internal renewable water resources (m^3/year)	34.3	14.5	12.1	10.0	9.0
Non-renewable water resources (billion m^3/year)	0.0	0.1	0.2	0.2	0.2
Treated wastewater (billion m^3/year)	0.0	1.9	3.4	4.3	4.5
External Resources					
Surface water inflow to the country (billion m^3/year)	55.5	55.5	55.5	55.5	55.5
Surface water outflow from the country (billion m^3/year)	0	0	0	0	0
Total external renewable surface water (billion m^3/year)	55.5	55.5	55.5	55.5	55.5
Groundwater inflow to the country (billion m^3/year)	1	1	1	1	1
Groundwater outflow from the country (billion m^3/year)	0	0	0	0	0
External renewable water resources (billion m^3/year)	56.5	56.5	56.5	56.5	56.5
Total					
Total renewable surface water (billion m^3/year)	56	56	56	56	56
Total renewable groundwater (billion m^3/year)	1.5	1.5	1.5	1.5	1.5
Overlap between surface and groundwater (billion m^3/year)	0	0	0	0	0
Total renewable water resources (billion m^3/year)	57.5	57.5	57.5	57.5	57.5
Per capita renewable water resources (m^3/year)	1024.3	835.4	694.8	572.8	574.2
Total water withdrawals (billion m^3/year)	168.2	168.2	168.2	168.2	168.2
Dam capacity (million m^3)	2996.30	2443.60	2032.30	1675.50	1675.50
Water Demand					
Agricultural water withdrawal (billion m^3/year)	47.4	59	67	61.4	60.6
Industrial water withdrawal (billion m^3/year)	4.6	4	2	5.4	5.4
Municipal water withdrawal (billion m^3/year)	3.1	5.3	9	10.8	10.9
Total withdrawal (billion m^3/year)	54	68.3	78	77.5	77.5
Freshwater withdrawal (billion m^3/year)	96.11	99.23	94.25	77.2	77.2
Environmental flow requirements (billion m^3/year)	2.6	2.6	2.6	2.6	2.6
Total population (thousand persons)	56134	68832	82761	100388	108668

Source: CAPMAS, Water Resources and Irrigation Bulletin (1990-2024).

There was also an increasing contribution of other sources of water that were non-conventional. There was a steady rise in treated wastewater, which indicated an adaptive policy reaction to water shortage. Nevertheless, its impact was not significant compared to the overall demand, which implied that reuse had not yet become large enough to cause a significant shift in the national water balance. Equally, the slow consumption of non-renewable groundwater begged the questions of sustainability in the long run and equity between generations.

Projected Rainfall and Its Implications for Egypt's Water Security: Table (4) indicated past and future rainfall in Nile Basin till 2050, for Egypt, the estimates showed that the yearly rainfall would decrease slightly, with an average of 2 mm per year as compared to the past. Even though this decline was relatively insignificant in absolute terms, Egypt already enjoyed very low levels of rain, approximately 15 mm annually, which implied that any slight decline could only worsen the problem of water shortage.

Table 4: Historical and Projected Rainfall in the Nile Basin by 2050

Country	Historical values (mm/year)	GFDL (mm)	HGEM (mm)	IPSL (mm)	Average (mm)
Egypt	15	−1	−2	−3	−2
Sudan (Nile region)	257	60	36	69	55
Sudan (outside Nile)	140	80	53	49	61
South Sudan	959	68	34	153	85
Ethiopia	1173	90	40	472	201

Where:

Historical values (mm/year): Observed or measured annual precipitation data based on historical climate records, expressed in millimeters per year.

GFDL (mm): Precipitation values simulated by the Geophysical Fluid Dynamics Laboratory (GFDL) climate model.

HGEM (mm): Precipitation values generated by the Hadley Centre Global Environmental Model (HadGEM/HGEM) climate model.

IPSL (mm): Precipitation outputs from the Institut Pierre-Simon Laplace (IPSL) climate model.

Average (mm): The mean value of precipitation calculated from the different climate models (GFDL, HGEM, and IPSL) to provide a multi-model ensemble estimate.
Source: CAPMAS, Water Resources and Irrigation Bulletin (1990-2024).

Econometric Framework and Preliminary Tests:

Unit Root Properties and Model Selection: The Phillips–Perron test showed that the variables in the study were a mix of I(0) and I(1). GDP per capita and CO_2 emissions were non-stationary at levels (I(1)), while precipitation, temperature, investment, land, and rents were mostly stationary at levels (I(0)). This trend showed that the ARDL model would be appropriate since it could accommodate both stationary and non-stationary variables.

Climate variables and land resources were relatively stable over the period in which they changing gradually and not being significantly influenced by the short-term shocks. Conversely, GDP per capita and CO_2 emission were more responsive to economic and policy shocks and this indicated changes in the economy. The ARDL model enabled us to address both the short-term dynamics and also to estimate the long-term relationships between the environmental factors and the economy.

Table 5: Results of the Phillips–Perron (PP) Unit Root Test

Variable	Test Level	Calculated Value	Critical Value 1%	Critical Value 5%	Critical Value 10%
GDPPC	At level	0.0516	-3.6702	-2.9639	-2.6210
	First difference	-4.6705***	-3.6793	-2.9677	-2.6229
CO_2	At level	-0.2654	-3.6702	-2.9639	-2.6210
	First difference	-5.6254***	-3.6793	-2.9677	-2.6229
Prec	At level	-4.4517***	-3.6702	-2.9639	-2.6210
	First difference	-15.6434***	-3.6793	-2.9677	-2.6229
Tas	At level	-3.6756***	-3.6702	-2.9639	-2.6210
	First difference	-20.2528***	-3.6793	-2.9677	-2.6229
GDI	At level	-3.5458***	-3.6702	-2.9639	-2.6210
	First difference	-5.4684***	-3.6793	-2.9677	-2.6229
Rent	At level	-2.7775*	-3.6702	-2.9639	-2.6210
	First difference	-8.8723***	-3.6793	-2.9677	-2.6229
Land	At level	-3.4408**	-3.6702	-2.9639	-2.6210
	First difference	-7.2260***	-3.6793	-2.9677	-2.6229

(Note: *stationary at 10% level; *stationary at 5% level; ***stationary at 1% level)*

Source: Calculated based on the data in Tables 1-4.

Optimal Lag Length and Quick Adjustment Dynamics:All the tests in Table 6 agreed that a single lag period is optimal, and all the criteria supported this view, which were Likelihood Ratio (LR), Final Prediction Error (FPE), Akaike Information Criterion (AIC), Schwarz Criterion (SC), and Hannan-Quinn (HQ) criterion. This was statistically effective to ensure that there was no overfitting in the modeling and that the degrees of freedom remained intact and the relevant dynamics were captured.

Table 6: Optimal Lag Length Selection Results

Lag	LogL	LR	FPE	AIC	SC	HQ
0	167.8018	NA	1.28e-16	-13.89581	-13.50085	-13.79648
1	319.2192	184.3342*	9.06e-20*	-21.49732*	-17.94273*	-20.60335*

Where: Lag: Number of lags included in the model; LogL: Log-likelihood value; LR: Likelihood Ratio test statistic; FPE: Final Prediction Error; AIC: Akaike Information Criterion; SC: Schwarz Criterion (Bayesian Information Criterion, BIC); HQ: Hannan–Quinn Information Criterion; (*): Indicates the optimal lag length selected according to each criterion

Source: Calculated based on the data in Tables 1-4.

The single lag optimality implied that the macroeconomic and environmental variables in Egypt responded to shocks and policy changes comparatively fast. This quick adaptation could have been an indication of the direct transfer of climate shocks (like droughts) into agricultural production and how resource bottlenecks impacted production immediately. The one-period lag specification meant that the conditions in the previous year have a strong impact on the current year but other impacts were absorbed by the long-run equilibrium, which was represented by the ARDL cointegration model.

ARDL Model Estimation and Diagnostic Performance

Statistical Adequacy of the ARDL Model: Table 7 showed the estimated ARDL model which had a high level of statistical adequacy. The value of the R-squared of 0.9986 meant that the variables inclided managed to explain 99.9% of the changes in the GDP per capita, and the adjusted R-squared (0.9968) showed that the model was not overfitted. The F-statistic (548.087) was very significant (p<0.0001) which proved the joint significance of all the explanatory variables. The value of DurbinWatson 2.47 indicated that there was no serious autocorrelation and the model residuals were more or less independent with time.

Table 7: Estimation of the Autoregressive Distributed Lag Model (ARDL)
Dependent Variable: **LGDPPC**
Sample (adjusted): 1990–2024
Selected Model: **ARDL (1. 1. 1. 1. 1. 0. 0. 1)**

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LGDPPC(-1)	0.445997	0.164658	2.708625	0.0220
LCO2	0.243834	0.176637	1.380421	0.1975
LCO2(-1)	0.679760	0.232481	2.923944	0.0152
LPRECIPITATION	0.089519	0.026612	3.363788	0.0072
LPRECIPITATION(-1)	0.054912	0.030063	1.826568	0.0977
LTASMEAN	-0.008267	0.418305	-0.019763	0.9846
LTASMEAN(-1)	-1.124195	0.364387	-3.085169	0.0115
LGDITOTL	-0.210523	0.105458	-1.996273	0.0738
LGDITOTL(-1)	0.199582	0.093131	2.143019	0.0577
LTOURISM	0.021189	0.025327	0.836609	0.4224
LLAND	0.378743	0.118681	3.191262	0.0096
LRENTS	-0.025564	0.012024	-2.125973	0.0594
LRENTS(-1)	0.023225	0.007727	3.005534	0.0132
C	8.821400	2.192602	4.023256	0.0024
• R-squared: 0.998598 • Adjusted R-squared: 0.996777	• Prob(F-statistic): 0.000000 • Durbin-Watson stat: 2.473820			

• S.E. of regression: 0.016823 • Sum squared resid: 0.002830 • Log likelihood: 74.49070 • F-statistic: 548.087	• Akaike info criterion: -5.040892 • Schwarz criterion: -4.353694 • Hannan-Quinn criterion: -4.858578 • Mean dependent var: 9.038715 • S.D. dependent var: 0.296314

Source: Calculated based on the data in Tables 1-4.

The estimates of the coefficients gave a number of findings. Current and lagged precipitation, lagged CO_2 emissions had positive effects on GDP per capita in the short run, indicating the significance of water availability and energy-intensive production. On the other hand, the lagged temperature (Tasmean) had a strong negative impact, which agreed with the hypothesis that high temperatures lowered the labor productivity and agricultural yields. The negative value of current domestic investment (GDI) could have seemed counterintuitive at first sight but it might have been an indication of the adjustment cost or consumption displacement in the short run. The high lags of the CO_2 emissions, rents and investment implied that the economy was slow to respond to the variations of these variables and both the short run shocks and the long run equilibrium forces were in action.

Short-Run and Long-Run Dynamics of Economic Growth:

In the short run increases in precipitation and land availability boosted GDP per capita. While temperature shocks reduced growth Lagged effects of CO_2 emissions rents and investment showed that adjustments took time In the long run CO_2 emissions and land positively influenced growth whereas high reliance on rents can harmed stability. Past GDP per capita strongly shaped future growth highlighting the need for policies that balance resource use with environmental sustainability.

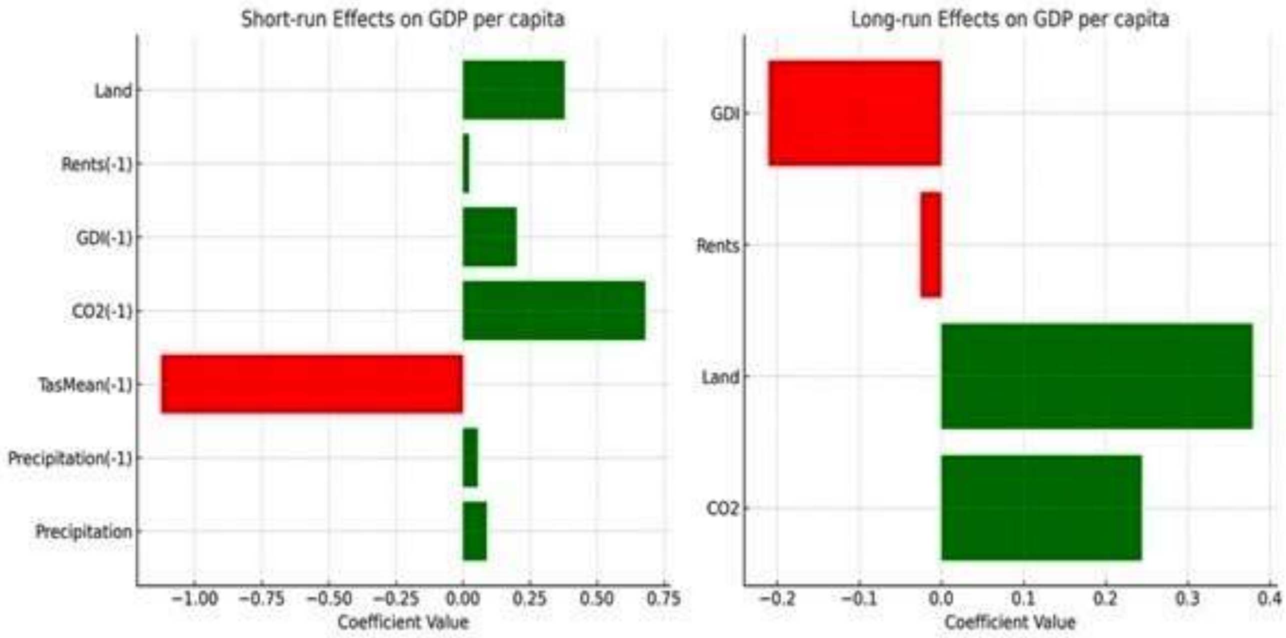

Fig 1: ARDL Short and Long Run Effects on GPD per capita: In the long run, GDI (≈ -0.20) and natural resource rents (≈ -0.05) negatively affect GDP per capita, while land (≈ 0.38) and CO2 (≈ 0.25) remain positive. Overall, temperature reduces growth in the short run and investment inefficiencies matter in the long run, while land and CO2 consistently support economic growth.

Source: Authors work 2025

Cointegration and Long-Run Equilibrium Analysis

Residual Stationarity and Error Correction Mechanism: Table 8 showed that the residuals were stationary at both the level and the first difference at the 1% significance level, which confirmed the stability of the ARDL model. This result indicated that the estimated relationships among the study variables were reliable and not spurious. It also suggested that both climatic variables, such as rainfall and temperature, and economic and water-related variables moved together in a consistent way over time.

Moreover, the significance of the error correction term (ECT) confirmed the existence of a long-run equilibrium relationship among these variables. Any short-run deviations caused by economic shocks or climate variability were gradually corrected, allowing the system to return to its long-term path. In general, this helped to prove the strength of the model and emphasized its applicability to policy analysis and forecasting in the future.

Table 8: Residual Stationary Test Results for the Study Variables

Variable	Level	Test Statistic	Prob.
Residuals (ECT)	At level	-6.042331***	0.0001
	First difference	-6.437046***	0.0000

***Note: * Significance at 10%. ** at 5%. and *** at 1%.**
Source: Calculated based on the data in Tables 1-4.

Bounds Test and Long-Run Cointegration: Table 9 showed that the bounds test F-statistic (7.41) exceeded the upper critical values at all significance levels confirming a long-run cointegration among the variables this rejecting the null of no cointegration. It implied that CO_2 emissions precipitation temperature, land, and rents jointly drove long-term GDP per capita validating the ARDL framework for analyzing both short- and long-run dynamics.

Table 9: Bounds Test and Cointegration Results

K	Value	Test Statistic
7	7.405694	F-Statistic
Critical Value Bounds		
Lower Bound (I0)	Upper Bound (I1)	Significance Level
2.03	3.13	10%
2.32	3.50	5%
2.60	3.84	2.5%
2.96	4.26	1%

Source: Calculated based on the data in Tables 1-4.

Long-Run Economic Impacts of Environmental and Resource Variables

Long-Run Coefficients and Growth Drivers: Table 10 indicated that long-run GDP per capita is most strongly affected by the CO_2 emissions (coefficient = 1.667. $p < 0.01$), which indicated the connection between growth and energy consumption Preciosity and land availability were also significant and positive which reminded about the necessity of the measures aimed at promoting the sustainable use of resources and environmentally friendly management to ensure the enhancement of the long-term growth.

Table 10: Estimated Long-Run Coefficients between the Variables

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LCO2	1.667127	0.107448	15.51573	0.0000
LPRECIPITATION	0.260703	0.107606	2.422754	0.0359
LTASMEAN	-2.044142	1.558545	-1.311571	0.2190
LGDITOTL	-0.019748	0.109753	-0.179932	0.8608
LTOURISM	0.038247	0.048444	0.789510	0.4481
LLAND	0.683647	0.259625	2.633213	0.0250
LRENTS	-0.004221	0.018403	-0.229372	0.8232

Source: Calculated based on the data in Tables 1-4.

Short-Run Dynamics and Adjustment Processes: Table 11 showed that in the short run CO_2 emissions and precipitation positively and significantly affected GDP per capita are supporting the role of environmental and climatic factors in growth. Conversely domestic investment and resource rents negatively impacted short-term performance, while temperature had an insignificant effect indicating a limited role in short-term fluctuations.

Table 11: Short-Run Estimation and Error Correction Model

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	8.821400	0.876152	10.06834	0.0000
D(LCO2)	0.243834	0.089908	2.712028	0.0219
D(LPRECIPITATION)	0.089519	0.011445	7.821727	0.0000
D(LTASMEAN)	-0.008267	0.124930	-0.066174	0.9485
D(LGDITOTL)	-0.210523	0.045368	-4.640340	0.0009
D(LRENTS)	-0.025564	0.005413	-4.722287	0.0008
CointEq(-1)*	-0.554003	0.055203	-10.03581	0.0000
R-squared: **0.887395** Adjusted R-squared: **0.847652** S.E. of regression: **0.012903** Sum squared resid: **0.002830** F-statistic: **22.32832**		Prob(F-statistic): **0.000000** Durbin-Watson stat: **2.473820** Log likelihood: **74.49070** Akaike info criterion: **-5.624225** Schwarz criterion: **-5.280626** Hannan-Quinn criter.: **-5.533068**		

Source: Calculated based on the data in Tables 1-4.

The error correction term (CointEq(-1)) is negative and highly significant indicating a stable long-run equilibrium with about 55% of deviations corrected each period. The model fit well ($R^2 = 0.887$. F-statistic significant), and the Durbin–Watson statistic near 2 confirmed no serious autocorrelation. These results demonstrate the ARDL model's robustness in capturing both short-run dynamics and long-run adjustments.

Model Diagnostic and Stability Tests: The ARCH test showed high p-values for both the F-statistic (0.8885) and Chi-Square (0.8820) indicating no ARCH effects this confirmed homoscedasticity of residuals. The stable variance of shocks ensured the ARDL model was reliable for forecasting and that policy recommendations were not biased by variance instability.

Table 12: Diagnostic Tests for Heteroskedasticity and Serial Correlation (ARCH and LM Tests)

Statistic	Value	Probability
ARCH Test		
F-statistic	0.020145	Prob. F(1.21) = 0.8885
Obs*R-squared	0.022042	Prob. Chi-Square(1) = 0.8820
LM Test		
F-statistic	1.166162	Prob. F(1.9) = 0.3083
Obs*R-squared	2.753043	Prob. Chi-Square(1) = 0.0971

Where:

ARCH Test (Autoregressive Conditional Heteroskedasticity Test): Tests for heteroskedasticity in the error terms (time-varying variance). The null hypothesis assumes constant variance (no ARCH effects). If Prob. > 0.05, the null is not rejected, indicating no heteroskedasticity.

LM Test (Lagrange Multiplier Test for Serial Correlation): Tests for serial correlation in the residuals. The null hypothesis assumes no autocorrelation. If Prob. > 0.05, the null is not rejected, indicating no serial correlation in the model errors.

Source: Calculated based on the data in tables (1, 2, 3, 4).

LM Test and Residual Autocorrelation: Table 12 indicated that the LM test F-statistic (1.166. p = 0.3083) and Obs*R-squared (2.753. p = 0.0971) were insignificant and showed that there was no significant autocorrelation in the residual values. The model was sound but had a minor trace of poor autocorrelation. This justified the effectiveness of the model in capturing the climate-economy relations consistently with past research and did not match the issue of serial correlation in certain macroeconomic models.

Residual Distribution and Model Predictive Reliability: The histogram of the residuals depicted a more or less even distribution about zero, with narrow range (-0.02 to +0.02) which indicated low variation and unbiased estimates. The distribution was near normal that justified t- and F-tests. This indicated that the model could be highly predictive and could be used to give reliable policy decisions.

Structural Stability and Parameter Consistency: In Figure (2), the outcomes of the CUSUM test indicated that the plotted line did not cross the 5% significance limits in the course of the study. This implied that the estimated model was not structurally unstable meaning that the relationship between the economic variables was stable and constant with time. The model provided credible evidence of the economic interpretation and policy implications in the absence of concern about parameter instability.

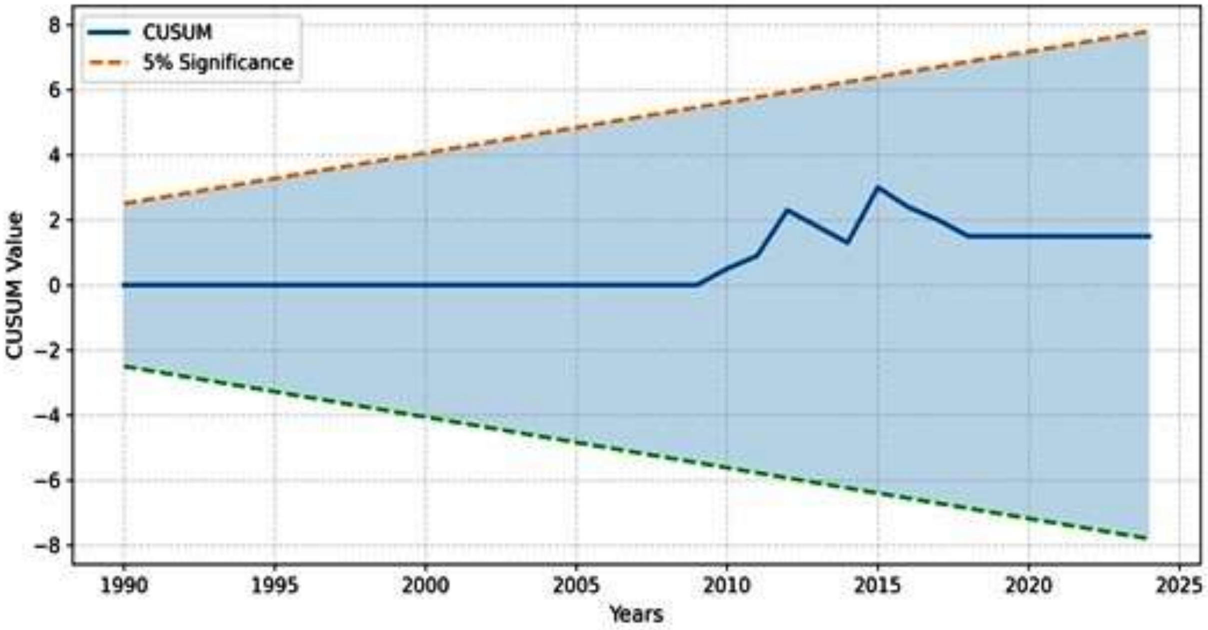

Fig 2: Cumulative Sum Test (The Cumulative Sum (CUSUM) Test is a statistical test used in applied economics and econometrics to assess the stability of a model's parameters over time. It examines the cumulative sum of the recursive residuals from a regression model)

Source: Authors work in this study 2025

CUSUM of Squares test (Figure 3) indicated that the cumulative sum line did not exceed the 5% significance levels throughout the entire period. This meant that the model was not affected by structural breaks or instability which was used to validate the strength of the estimated parameters. Thus, it was possible to say that the model was good enough to explain the economic relations underlying it and to recommend sound policies.

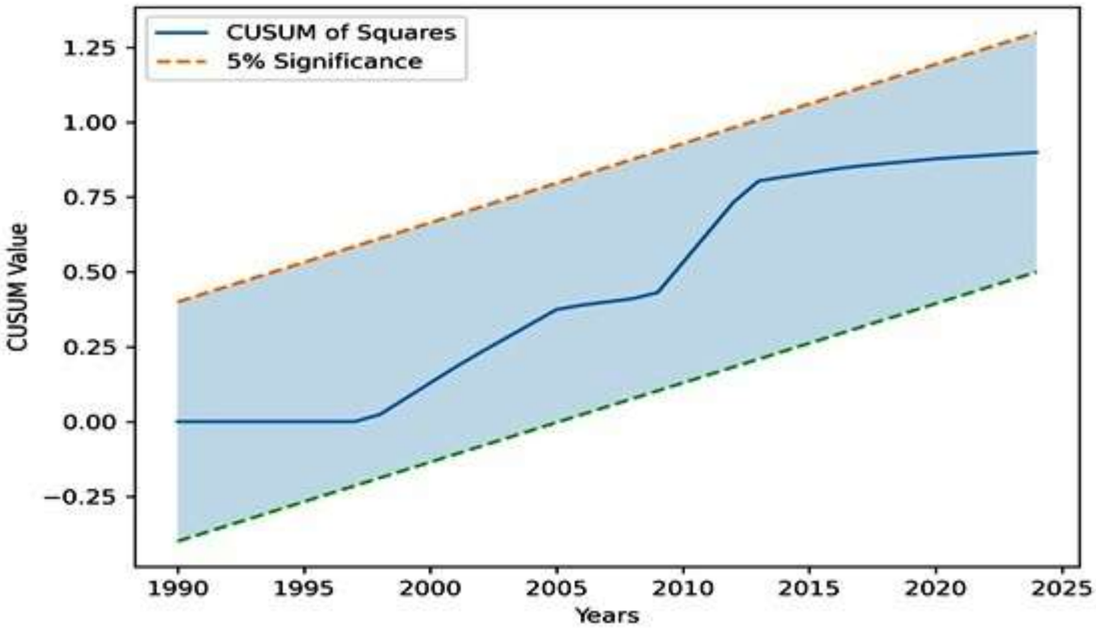

Fig 3: Cumulative of Squares Test (Cumulative of Squares Test: It is a statistical test used in applied economics and economic modeling to verify the structural stability of a model over time. In other words, this test helps the researcher determine whether the parameters of the model remain constant or change during the study period).

Source: Authors work in this study 2025

DISCUSSION

This research paper examines how the economic performance of Egypt is influenced by the climate variables based on thirty years of data and ARDL approach. These findings confirm as well as deviate previous results in the climate economy literature. The negative coefficient of temperature in the short run is in line with (da Silva and Drobinski, 2020; Burke *et al*., 2015) that reported productivity loss with heat exposure in the developing economies. As opposed to (Dell *et al*., 2008; Burke and Tanutama, 2019) who found that long-run effects of temperatures are permanent long-run damages, the current findings suggest that the effects of temperatures in Egypt are not statistically significant in the long run. This implies existence of adjustment measures, like irrigation systems, technological changes, or a changing nature of economic action. This disparity is probably due to the fact that Egypt relies much on the Nile as opposed to agriculture that relies on rainfall.

Precipitation appears to be one of the major sources of economic growth both in the short term as well as in the long term according to (Auffhammer *et al.,* 2012), who stated that rainfall is one of the factors that enhance the productivity of agriculture in the monsoon-dependent areas. Such an outcome is especially necessary when (Ashour *et al*., 2024; Elgohary, 2025) predicts that water availability in Upper Egypt will decrease in the future due to climate change. The drastic reduction in the per capita water resources noted in the descriptive analysis between over 1.020 m^3/year in 1990 and approximately 574 m^3/year in 2024 also contributes to the issues (Abdelazez *et al*., 2024) expressed with respect to rising water stress in Egyptian regions. It is in this respect that the positive value of the precipitation coefficient gives quantitative support that water shortage is a binding factor to the route of the Egyptian development.

A statistically significant and positive coefficient on CO_2 emissions is one of the most policy-relevant results of the research. This result is aligned with (Ali *et al*., 2019) in the case of Pakistan and (Alagidede *et al*., 2016) in the case of Sub-Saharan Africa, where the use of fossil fuels continues to support the growth of the economy. Nonetheless, this correlation should be viewed with some reservations (Diffenbaugh and Burke, 2019) revealed that the warming caused by emissions has increased global inequality in incomes, whereas (Carleton and Hsiang, 2016) reported the increase in social costs of climate change. The estimated coefficient reflects the existing role of energy use in productivity without accounting for the environmental and macroeconomic risks as pointed out by (Zhu and Xie, 2023; Chen and Cui, 2023). Egypt is thus in an apparent trade-off where short-term growth is still closely connected to the supply of energy, but long-term sustainability means decoupling economic growth to the carbon-intensive growth as highlighted by (Crafts & Mills, 2017).

In both model specifications, arable land has a positive impact, which expands the agricultural supply-side results of (Eliw *et al*., 2019) to the macroeconomic scale. Simultaneously, the statistics show a decrease in the pace of land reclamation since 2020, which means that the physical and environmental restrictions are getting stricter. The negative short run coefficients of investment and natural resource rents sound counterintuitive but can be justified by the adjustment costs and transition inefficiency. Investment can take some time before it will give quantifiable returns, a property clearly incorporated into the ARDL model created by (Pesaran *et al*., 2001). The adverse effect of resource rents can be a manifestation of resource-curse processes, according to which a dependence on natural riches may be disastrous to productivity and institutional quality in the short-run.

Methodologically, the single country focus concedes the statistical power of cross country panel studies to institutional and geographic specificity. Although research like (Burke *et al*., 2015; da Silva and Drobinski, 2020) can find global average impacts, Egypt is heavily reliant on Nile water and its dynamics can be lost in the multi-country studies. The ARDL model was suitable to deal with variables with mixed order of integration, which is in line with the results (Eliw *et al.*, 2019). However, utilization of annual data can mask the issue of seasonal vulnerability (Auffhammer *et al*., 2012; Taher, 2019) underlined the value of seasonal timing in the formation of farming and economic results, indicating that further studies need to utilize seasonal or intra-annual information, specifically with reference to Nile floods and cultivation arrangements.

There are a few limitations that ought to be considered. The analysis presupposes linear relationships, although (Burke *et al*., 2015) shows that the effect of temperature becomes non-linear at critical points. It does not explicitly model institutional quality and human capital, which (Crafts and Mills, 2017) define as the key to long-run growth. Moreover, the health effects of temperature, which are reported by (Basu and Samet, 2002; Curriero *et al*., 2002), are not directly taken into account but are implicit. These limitations indicate obvious directions in the future research without contradicting the main findings of the study.

The consequences of the policy are across various sectors. The water management is an immediate concern due to the high impact of precipitations and the future predictions of the decrease of the water supply. Enhancing efficiency of irrigation and increasing wastewater reuse are some viable adaptation measures. The positive CO_2 coefficient in the energy sector represents the economic realities presently, but cannot be used as a future policy guide.

The systemic risks of climate extremes and environmental degradation continue to be built up by the constant reliance on fossil fuels, as (Zhu and Xie, 2023; Chen and Cui, 2023) argue. Even though Egypt has a comparatively low contribution of 0.6% to the global emissions based on the national reporting of domestic co-benefits of renewable energy implementation, there has been a good reason to hasten the shift, which is due to the fact that better air quality and increased energy security is the reward of the deployment of renewable energy sources.

There is also the issue of adjustment to increasing temperatures that should be given special consideration. The fact that there is no important long-run temperature effect implies a certain level of resilience, which may be achieved by adaptive agricultural, infrastructure, or labor organization practices. Nonetheless, Diffenbaugh and Burke (2019) warn against over-reliance on the adaptation without adequate mitigation on the global level. Furthermore, the estimates on the national level can conceal gross regional differences, and like in the case of Upper Egypt, water stress might be more extreme than the aggregate findings, according to (Abdelazez *et al.*, 2024).

Conclusions: The paper demonstrates that climate factors play a key role in determining economic performance of Egypt with water being the most perennial and restrictive factor of growth. The findings support regional data and also offer country-specific information that corresponds to the Egyptian environmental and economic peculiarities. They also reveal that the ARDL approach is easily applicable to the analysis of relationships between climate economics in situations where the data is scarce. The current research ought to be developed in the future with filling the gaps by utilizing more precise data about the season, non-linear modeling, and inclusion of health and institutional factors directly. The biggest issue in the future is evident: Egypt has to enhance its ability to adjust to inevitable climate effects, at the same time making its own contribution to the global mitigation process, not to mention the fact that it has to maintain the economic growth that will enable it to sustain the development and social stability.

Conflict of Interest: The authors declare no conflict of interest.

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