The macroeconomic effects of climate change on human capital development in Africa

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Abstract

The growing impacts of climate change in Africa pose a significant threat to sustainable development in the region - compounded by the challenge many African countries face with resource allocation, balancing long-term investment in climate-smart practices with meeting short-term compelling human needs. This paper investigates the macroeconomic effects of climate change on human capital development in Africa, a region profoundly affected by climatic disruptions. Using an Autoregressive Distributed Lag (ARDL) model, the research assesses how persistent climate variability impacts key human development sectors such as education, healthcare, and agriculture, influencing economic growth, human welfare, and sustainability. The findings reveal a significant long-run relationship between climate variables and the Human Development Index (HDI), with temperature changes and precipitation patterns playing crucial roles, highlighting the need for resilient infrastructure and adaptive policy frameworks to mitigate these impacts. The policy implications emphasize the need for economic diversification across Africa to build resilience, considering its heavy reliance on agriculture. It also suggests that enhancing adaptive capacity through strategic investments in education and healthcare systems against climate-induced stress and climate-smart agricultural practices is crucial for stabilizing African human capital development.

Keywords: Climate change, Human capital development, Africa, ARDL model, Economic growth, Policy adaptation.

1. Introduction

Recent studies show that the climate crisis of the 21st century is growing enduringly urgent in all regions of the world: concentrations of carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) in the troposphere have reached record levels, and the world is getting warmer, sea levels are rising, and precipitation patterns are changing. According to the Intergovernmental Panel on Climate Change (IPCC), the current rate of greenhouse gas emissions is likely to cause average temperatures to rise by 0.2°C per decade, reaching by 2050 the threshold of 2°C above pre-industrial levels[1].

[1] *Climate change widespread, rapid, and intensifying – IPCC — IPCC.* (2021, August 9). IPCC. https://www.ipcc.ch/2021/08/09/ar6-wg1-20210809-pr/

Evidence from the World Bank suggests that rising global temperatures increase the atmosphere's moisture, resulting in more storms and heavy rains. Still, paradoxically, there are also more intense dry spells as more water evaporates from the land and global weather patterns change[2].

In this century, human capital development faces numerous challenges, including the need for biodiversity, food security, education, safe drinking water, renewable energy, and access to economic opportunities - all met with stiff resistance by climatic conditions. The IPCC reports that climate change intensifies the water cycle, leading to more intense rainfall, associated flooding, and drought in many regions. Given such a phenomenon, coastal areas will see continued sea level rise throughout the 21st century, contributing to more frequent and severe coastal flooding in low-lying areas and coastal erosion. Extreme sea level events that previously occurred once in 100 years could happen every year by the end of this century[3]. People who depend upon freshwater food, land for agricultural activities, or rivers for drinking may have no alternative for livelihoods and need help to cope. Just 0.5 per cent of Earth's water is usable and available as freshwater, and these conditions pose a significant threat to this crucial resource. About two billion people worldwide don't have access to safe drinking water today[4], and climate conditions will exacerbate this crisis as water is a crucial element for sustainable livelihood.

In terms of education, many children will experience fewer schooling days with learning infrastructures at risk due to flooding or classrooms inhabitable given humidity levels. The quality of education in many countries across Africa already begs for more. Yet, the education sector is heavily affected by climate-related disruptions, with 25 out of 33 countries where children face *extreme* climate vulnerability located on the continent[5]. Health situations will worsen across many parts of the continent, threatening sustainable economic and human development. These excruciating effects will be felt across all areas of human livelihood and will be more severe for those in Africa. Beyond its long-term threats to globalization, climate change is a serious risk to poverty reduction and could undo decades of development efforts.

These alarming needs require urgency to save humanity's present and future. If unaddressed, populations may be wiped out sooner than expected, environments may no longer be able to serve human and animal needs, and the long-term macroeconomic effects may linger for years unsolved. African countries rely heavily on agriculture as the

[2] World Bank Group. (2021, June 30). Floods and Droughts: An EPIC response to these hazards in the era of climate change. World Bank.
https://www.worldbank.org/en/news/feature/2021/06/17/floods-and-droughts-an-epic-response-to-these-hazards-in-the-era-of-climate-change

[3] Climate change widespread, rapid, and intensifying – IPCC — IPCC. (2021, August 9). IPCC.
https://www.ipcc.ch/2021/08/09/ar6-wg1-20210809-pr/

[4] United Nations Statistics Division. (n.d.). — SDG indicators.

[5] Global Center on Adaptation (GCA). (2022). State and Trends in Adaptation 2022: Education. Retrieved from
https://gca.org/wp-content/uploads/2023/01/GCA_State-and-Trends-in-Adaptation-2022_Education.pdf

mainstay of their economy and employment, accounting for more than half of their labour force. For context, multiple studies have found the engines of economic growth, development, and poverty reduction in Liberia, in sectors such as agriculture, fisheries, and forestry[6]. However, the climate crisis has recently challenged these prospects across many regions. More than 110 million people on the continent were directly affected by weather, climate, and water-related hazards in 2022, causing more than US$ 8.5 billion in economic damages[7], and it may grow worse at an increasing rate over the years.

However, the Organization for Economic Cooperation and Development (OECD) analysis suggests that if we act now, we have 10 to 15 years of *"breathing space"* during which action is possible at a relatively modest cost. But every year of delay reduces this breathing space, requiring ever more stringent measures to make a difference. The OECD's analysis informs us that "current financial turmoil is not a reason to delay. Indeed, its macroeconomic consequences will be resolved relatively quickly, after which growth will resume. In contrast, the consequences of inaction on global warming will continue to grow more and more costly over time" [8].

Human influence on the past and future is apparent in what our world looks like now, and in the context of climate change, it is no different. "It has been clear for decades that the Earth's climate is changing, and the role of human influence on the climate system is undisputed," says Valerie Masson-Delmotte, Co-Chair of Working Group I at IPCC. It is only essential, then, that these areas of human impacts on climatic conditions be urgently addressed and sustainable solutions reimagined.

Considering such critical needs, this paper will focus on investigating the macroeconomic effects of climate change on human capital development in SubSaharan Africa (SSA), a continent highly vulnerable to climate-induced disruptions yet highly dependent on climate-sensitive sectors for economic activities - agriculture (including fisheries and forestry) and the industrial sector (mining, water, oil and gas, construction, and electricity) which has jointly contributed more than 50 per cent of Gross Domestic Product (GDP) across years in countries like Liberia[9]. The study will examine how climate change impacts critical human development sectors such as education, healthcare, agriculture, and employment.

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[6] World Bank. (2018). Liberia: From growth to development: Priorities for sustainably reducing poverty and achieving middle-income status by 2030. World Bank. https://documents1.worldbank.org/curated/en/585371528125859387/pdf/Liberia-From-growth-to-development-priorities-for-sustainably-reducing-poverty-and-achieving-middle-income-status-by-2030.pdf

[7] Africa suffers disproportionately from climate change - World. (2023, September 4). ReliefWeb. https://reliefweb.int/report/world/africa-suffers-disproportionately-climate-change

[8] Adedeji, O., Reuben, O., & Olatoye, O. (2014). Global climate change. Journal of Geoscience and Environment Protection, 02(02), 114–122. https://doi.org/10.4236/gep.2014.22016

[9] World Bank. (2018). Liberia: From growth to development: Priorities for sustainably reducing poverty and achieving middle-income status by 2030. World Bank. https://documents1.worldbank.org/curated/en/585371528125859387/pdf/Liberia-From-growth-to-development-priorities-for-sustainably-reducing-poverty-and-achieving-middle-income-status-by-2030.pdf

By understanding these dynamics, the research will offer a critical understanding of how climate variability hinders economic growth and development in fragile economies, shedding insights into the broader implications for Africa.

2. Literature Review

2.1 Climate Change, Poverty, and Inequality in Africa

Multiple studies show that climatic conditions will severely impact Africa due to adverse direct effects such as high agricultural dependence and limited adaptation capacity, undercutting efforts at human capital development[10]. The climate crisis could exacerbate deeply entrenched inequality and poverty across the continent even as the population rises and income grows disproportionately. In 2024, Africa accounted for 16 percent of the world's population, but 67 percent live in extreme poverty. Two-thirds of the world's population in extreme poverty live in SubSaharan Africa (SSA) alone, rising to three-quarters when including all fragile and conflict-affected countries[11]. Poverty remains high in comparison with other regions across the world, and even those who no longer fall below the World Bank's poverty line ($2.15 daily) are still vulnerable and far from reasonable aspirations for human prosperity.

Fig.I. Poverty headcount ratio at $2.15 a day (2017 PPP)
Source: World Bank Data (2022) [12]

[10] Collier, P., Conway, G.R., & Venables, T. (2008). Climate Change and Africa. Oxford Review of Economic Policy, 24, 337-353.
[11] World Bank. (n.d.). Poverty. The World Bank. Retrieved November 19, 2024.
[12] World Bank. (n.d.). Poverty. The World Bank. Retrieved November 19, 2024.

Despite the climate challenges and the continent's failure to address its current human capital crisis, population growth continues to rise significantly, increasing demand for access to education, food security, healthcare, social services and welfare, and decent livelihoods. The World Bank estimates that by 2075, one-third of the world's population—and the working-age population—will be African. It is the only region where the workforce will grow continuously in the coming decades[13]. In light of all these, the climate crisis is threatening prosperity across the continent. Recent studies suggest that climate change means skyrocketing food prices, toxic air, and polluted water for people in developing countries. It leaves countries just one natural disaster away from poverty, forcing parents to pull children out of school and entire communities to migrate[14]. Given that learning infrastructures are not climate resilient and cities or communities cannot cope with shocks, the educational risks associated with climate change are profound.

2.2 Education, Employment, and Migration

Education is one of the most critical areas of human capital development, and climate change has been shown to disrupt educational systems and learning processes in multiple ways. Increased frequency of extreme weather events, such as floods and droughts, can damage schools and infrastructure, eroding the possibility of children attending school regularly. Climate-related disruptions to education are particularly pronounced in regions with high vulnerability, such as SSA, where many schools cannot withstand severe weather events. In countries with inadequate infrastructures, these disruptions can immediately affect retainment and long-lasting effects on learning outcomes, affecting how African youth transition into employment and labour markets. A recent study in ten African countries found that cumulative exposure to climate anomalies significantly negatively impacts primary school completion rates, particularly affecting children from less-educated households[15]. School attainment is linked with higher earnings, with estimates suggesting a 9-10 per cent return for each additional year of schooling[16].

A recent study on the persistent effects of natural disasters on human development (González, Santos, & London, 2021) revealed that natural disasters reduced 0.03 years of schooling on average for those who experienced them within their first year of life compared to those who did not[17]. For example, following Cyclone Idai in 2019 in Zimbabwe, over

[13] World Bank. (2023, June 27). Investing in youth: Transforming AFE Africa. The World Bank. Retrieved November 7, 2024,
[14] World Bank. (n.d.). Climate change overview. The World Bank. Retrieved November 7, 2024, from https://www.worldbank.org/en/topic/climatechange/overview
[15] Sukie, C., & Kai, L. (2023). Mapping the cumulative effects of climate change on children's education in ten African countries. UNESCO Global Education Monitoring Report. Retrieved November 19, 2024, from https://www.unesco.org/gem-report/sites/default/files/medias/fichiers/2023/09/SukieandKai.pdf
[16] Venegas Marin, S., Schwarz, L., & Sabarwal, S. (2024). The impact of climate change on education and what to do about it. World Bank. Retrieved November 19, 2024, from https://documents1.worldbank.org/curated/en/099043024150036726/pdf/P180005171cc7c0c91a8b011d03080e9086.pdf
[17] González, F. A. I., Santos, M. E., & London, S. (2021). Persistent effects of natural disasters on human development: quasi-experimental evidence for Argentina. Environment, Development and Sustainability, 23(7), 10432-10454.

half of schools (57%) reported the complete destruction of some infrastructure, directly affecting the schooling of almost 100,000 children[18]. Each climate-related disaster that pushes students out of school leaves them less capable of the future of work and employment, decreasing long-term earning potential. Given extreme weather circumstances, children who miss school due to flooding or are forced to migrate in search of food or employment are less likely to develop the skills necessary to contribute to the labour market as adults, ultimately undermining a country's human capital base. Further studies indicate that climate-induced economic stress can reduce household income, leading to higher dropout rates and fewer children attending school, particularly among disadvantaged communities[19]. As a result, climate change creates a vicious cycle wherein reduced education outcomes exacerbate poverty and limit long-term economic growth prospects.

2.3 Agriculture, Social Livelihood, and Migration

Although SSA has contributed the least to the overall greenhouse gas emissions globally, the continent is the hardest hit by the impact of climate change. In context, Africa has a population of about 1.2 billion people, of which close to 70% rely on agriculture for their livelihood, and of its 3 billion Hectares, an estimated 20,000 hectares are lost annually to desertification[20]. Many economies in the region rely heavily on climate-sensitive sectors for GDP growth, including agriculture, fisheries, and forestry, and their economic and social well-being is affected as the climate crisis evolves. Empirical findings show that climate change can reduce families' disposable income through shocks that damage crops and, thus, losses in agricultural income or by reducing adult productivity in general and, hence, losses in other earnings[21]. As climate change increasingly affects agricultural productivity and local economies, it also contributes to migration patterns that strain urban areas and complicate the provision of services. Climate impacts on migration in Africa are complex and context-dependent. While environmental factors influence migration, they affect socioeconomic, political, and demographic drivers indirectly.[22, 23] In many African countries, rural-urban migration is already a significant concern, with migrants flocking to urban centers for work and better living conditions. Climate-induced displacement can exacerbate existing urban vulnerabilities by placing additional pressure on already overstretched social services, housing,

[18] Global Partnership for Education. (n.d.). Zimbabwe: A stronger education system after Cyclone Idai. Retrieved November 19, 2024, from https://www.globalpartnership.org/results/country-journeys/zimbabwe-stronger-education-system-after-cyclone-idai

[19] Sukie, C., & Kai, L. (2023). Mapping the cumulative effects of climate change on children's education in ten African countries. UNESCO Global Education Monitoring Report. Retrieved November 19, 2024, from https://www.unesco.org/gem-report/sites/default/files/medias/fichiers/2023/09/SukieandKai.pdf

[20] Global Initiative for Sustainable Development and Ecosystems Protection (GIFSEP). (n.d.). Climate change and Africa's agricultural soils. Retrieved November 19, 2024, from https://gifsep4climate.org/climate-change-and-africas-agricultural-soils/

[21] Sukie, C., & Kai, L. (2023). Mapping the cumulative effects of climate change on children's education in ten African countries. UNESCO Global Education Monitoring Report. Retrieved November 19, 2024, from https://www.unesco.org/gem-report/sites/default/files/medias/fichiers/2023/09/SukieandKai.pdf

[22] Borderon, M., Sakdapolrak, P., Muttarak, R., Kebede, E.B., Pagogna, R., & Sporer, E. (2018). A systematic review of empirical evidence on migration influenced by environmental change in Africa.

[23] Zickgraf, C. (2018). Climate Change and Migration Crisis in Africa. The Oxford Handbook of Migration Crises.

and employment opportunities. Temperature and rainfall variations can lead to internal and international migration, with an estimated 2.35 million people displaced in Africa from 1960-2000 due to climate factors, with a predicted additional 1.4 million per year[24]. Migration due to climate stressors, particularly in rural communities, leads to increased urban poverty and can also reduce the availability of skilled labour in agriculture, further diminishing the productivity in those climate-sensitive sectors. Studies have found that the relationship between climate and migration varies across regions and populations, with rural and farming households more likely to be affected[25, 26]. However, the impact of climate on migration is not linear; some studies suggest a hill-shaped relationship between temperature and precipitation and migration propensity in farming households[27].

As these events unfold, questions about economic livelihood supported by agricultural activities and growing concerns about supply on global markets arise. Climate adverse effects shrink agricultural outputs significantly, reducing supply on local markets, lowering farmers' income, and potentially distorting the availability of particular products worldwide. Many African countries significantly contribute to global trade as critical leaders. For example, Côte d'Ivoire leads African exports in the cocoa and cocoa preparations category, holding 55 per cent of Africa's share and securing 11 per cent of the global market. South Africa, Kenya, and Benin each command at least 3 per cent of the global market in their major export categories. Other countries such as Sudan, Morocco, and Zimbabwe significantly impact global vegetables and animal oils, spices, tobacco, etc. markets[28]. Climate effects lower agricultural yield and weaken large exporters while impacting overall economic output. Higher temperatures, changing rainfall patterns, droughts, and floods affect harvests. For instance, farmers in Nigeria have seen lower yields caused by new pests, disease outbreaks, and the drying up of rivers, which affects overall productivity[29]. A recent estimate suggests that a 25 per cent or more significant drop in corn yields would reduce Mozambique's GDP by 2.5 per cent[30]. This highlights the significant vulnerability of agricultural productivity to climate change, with far-reaching economic consequences for nations heavily reliant on the sector. In

[24] Marchiori, L., Maystadt, J., & Schumacher, I. (2011). The Impact of Climate Variations on Migration in Africa.

[25] Cattaneo, C., & Massetti, E. (2015). Migration and Climate Change in Rural Africa. Environmental Anthropology eJournal.

[26] Marchiori, L., Maystadt, J., & Schumacher, I. (2011). The Impact of Climate Variations on Migration in Africa!

[27] Cattaneo, C., & Massetti, E. (2015). Migration and Climate Change in Rural Africa. Environmental Anthropology eJournal.

[28] Business Day. (2024, November 19). Top African countries driving global exports in key agricultural products. Business Day. Retrieved November 19, 2024, from https://businessday.ng/news/article/top-african-countries-driving-global-exports-in-key-agricultural-products/

[29] The Conversation. (2024, November 19). Climate change and farming: Economists warn more needs to be done to adapt in Africa. The Conversation. Retrieved November 19, 2024, from https://theconversation.com/climate-change-and-farming-economists-warn-more-needs-to-be-done-to-adapt-in--africa-215631

[30] McKinsey & Company. (n.d.). How will African farmers adjust to changing patterns of precipitation? McKinsey & Company. Retrieved November 19, 2024, from https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/how%20will%20african%20farmers%20adjust%20to%20changing%20patterns%20of%20precipitation/svgz_mgi-climatecasestudyafrica-web_exh2.svgz?cq=50&cpy=Center

2020 alone, 770 million faced hunger, predominantly in Africa and Asia. Climate change affects food availability, quality, and diversity, exacerbating food and nutrition crises[31]. Addressing these challenges is critical for safeguarding food security and economic stability while ensuring safe human livelihoods.

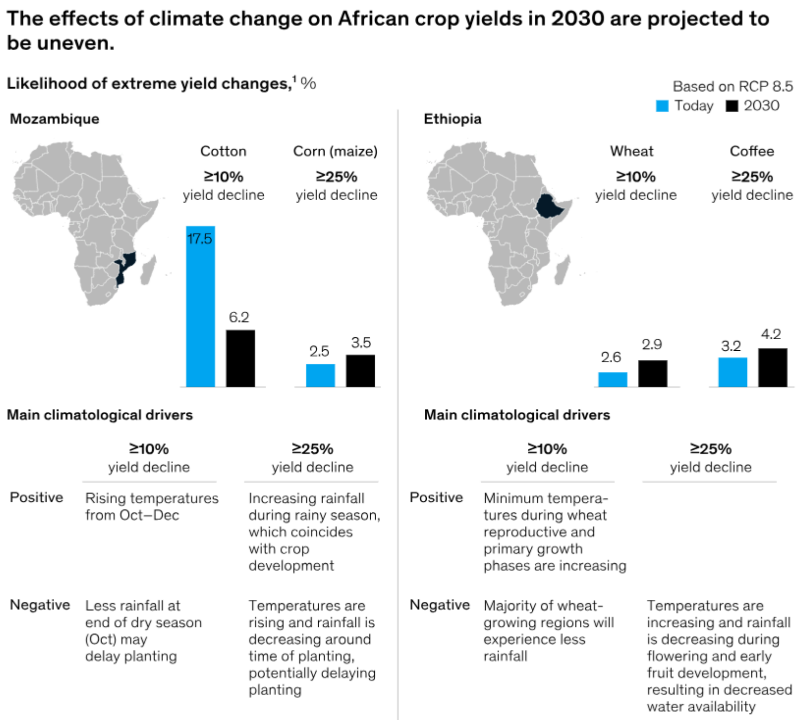

Fig.2. The effects of climate change on African crop yields in 2030
Source: McKinsey & Company (2020)[32]

2.4 Healthcare and Social-wellbeing

The growing number of climate-induced health crises significantly strain already weak healthcare systems. Changes in ecosystems contribute to the spread of vector-borne diseases such as malaria, cholera, and dengue fever. Warmer temperatures and increased rainfall create favourable conditions for mosquitoes, which are vectors for malaria, leading to its spread in areas previously unaffected by the disease. Recent literature highlights African health systems' challenges in preparedness and resilience, with inadequate resources and infrastructure to respond effectively to climate-related health

[31] World Health Organization. (n.d.). Climate change and health. World Health Organization. Retrieved November 19, 2024, from https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

[32] Opoku, S.K., Leal Filho, W., Hubert, F., & Adejumo, O.O. (2021). Climate Change and Health Preparedness in Africa: Analysing Trends in Six African Countries. International Journal of Environmental Research and Public Health, 18.

risks[33]. Considering the effects on agriculture, household income, and overall GDP, climate impacts also exacerbate the financial burden on households, leading to higher out-of-pocket health expenditures[34]. The deterioration of public health increases mortality and morbidity rates while reducing the labour force's productivity and disrupting economic activities. Climate change disproportionately affects vulnerable groups, including women, children, and the elderly[35]. In many African societies, women collect water and grow food. Climate change-related disruptions to water supplies and agricultural productivity place additional burdens on women, reducing their access to healthcare and education. Evidence suggests that in vulnerable regions, the death rate from extreme weather events in the last decade was 15 times higher than in less vulnerable ones[36]. While many Africans struggle to afford necessities and cannot access quality public healthcare, they face a tradeoff between daily sustenance and spending on healthcare, and the former prevails most often. Recent studies revealed that over 930 million people – around 12% of the world's population – spend at least 10% of their household budget to pay for health care[37]. With the poorest people (largely across Africa) largely uninsured, health shocks and stresses already currently push around 100 million people into poverty every year, with the impacts of climate change worsening this trend[38]. A decline in health outcomes ultimately reduces the capacity of individuals to participate effectively in the workforce, further hindering economic development.

[33] Ezeruigbo, C.F., & Ezeoha, A. (2023). Climate change and the burden of healthcare financing in African households. African Journal of Primary Health Care & Family Medicine, 15.
[34] National Institute of Environmental Health Sciences. (n.d.). Health impacts on vulnerable people. Retrieved December 18, 2023, from https://www.niehs.nih.gov/research/programs/climatechange/health_impacts/vulnerable_people#:~:text=In%20general%2C%20children%20and%20pregnant,events1%20%2C%202%20%2C%203%20.
[35] World Health Organization. (n.d.). Climate change and health. World Health Organization. Retrieved November 19, 2024, from https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health
[36] World Health Organization. (n.d.). Climate change and health. World Health Organization. Retrieved November 19, 2024, from https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health
[37] National Institute of Environmental Health Sciences. (n.d.). Climate change and health impacts. Retrieved November 19, 2024, from https://www.niehs.nih.gov/research/programs/climatechange/health_impacts
[38] Natsiopoulos, K., & Tzeremes, N.G. (2022). ARDL: An R package for the analysis of level relationships. J. Open Source Softw., 7, 3496.

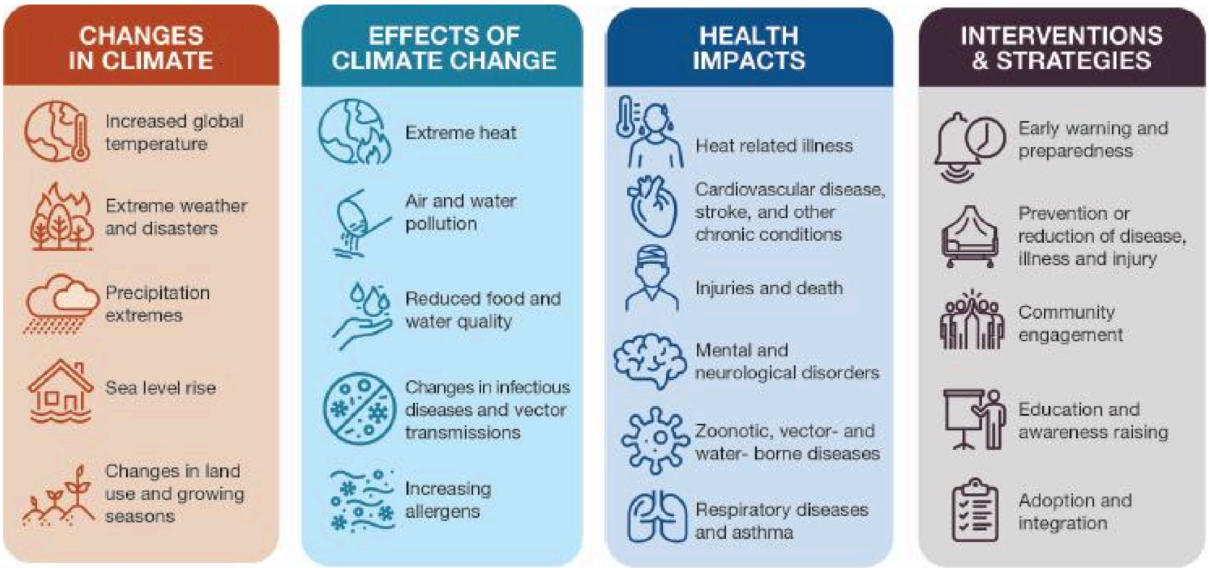

Fig.3. Changes in Climate, Effects, Health Impacts, Interventions & Strategies
Source: National Institute of Environmental Sciences (2022)

3. Data Collection and Sources

Secondary data was collected from the World Bank, Food and Agriculture Organization, Human Development Index Reports, and the National Climate Development Indicators using STATA software to model how climate change influences human capital development in Africa.

3.1 Model Selection and Rationale

The Autoregressive Distributed Lag (ARDL) model was selected for modeling and data analysis. The choice of model was driven by the fact that the Autoregressive Distributed Lag (ARDL) and Error Correction Model (ECM) are widely used in economic analysis, offering flexibility through autoregressive and distributed lag terms [38]. This is important as the model uses its past values to predict future outcomes, a normative assumption explaining how human potential evolves. At the same time, distributed lag incorporates past values of one or more independent variables to examine their effect on a dependent variable over time. It helps address dynamics in the short run, establish lags for delayed effects, and explain long-run relationships. The ARDL and ECM fit this analysis for the following reasons:

1. **Small sample size:** The dataset, covering 20 observations from 2002 to 2022, is well-suited for ARDL, which allows for flexibility in lag lengths.
2. **Mixed integration order:** Some variables (e.g., HDI, temperature change) were stationary at levels, while others displayed random walks and were stationary after differencing, making ARDL and ECM appropriate.

The ARDL model is beneficial for examining cointegration and long-run relationships between variables, with the bounds test being a popular method for this purpose[39].

3. **Short-run Dynamics & Long-run Relationships:** The ARDL approach to cointegration allows for the analysis of short-run dynamics and long-run relationships between variables that may be integrated into different orders. Furthermore, the error correction representation of the ARDL model separates long-run and short-run effects, providing valuable insights into the relationships between macroeconomic variables[40].

3.2 Initial Variables and Multicollinearity Issues

The initial set of variables included:

- Climate Variables: temperaturechange, precipitation, and emission. (All emissions were aggregated - CO2, Methane, and Nitrous Oxide)
- Socioeconomic Variables: gdp, compulsory_education_in_years, and primary_education_completion, d_log_d2_unemployment.
- Health and Infrastructure Proxies: totalimmunization, d_malariaincidence, d_basicdrinkingwater (Immunizations of measles and DPT were aggregated).

Initial modeling revealed significant multicollinearity, leading to the following decisions:

- Dropping Variables:
    - Variables like primary_education_completion and totalimmunization, firstly used as a composite of education_health_index.
    - d_basicdrinkingwater and d_log_d2_unemployment as composites of infrastructure_labor_index.
    - The remaining variables represented distinct dimensions of climate, socioeconomic, and health factors.

Next, the model was run with:

- Climate Variables: temperaturechange, precipitation, and emission.
- Socioeconomic Variables: gdp, compulsory_education_in_years.
- Health and Infrastructure Proxies: d_malariaincidence.

[39] Kripfganz, S., & Schneider, D.C. (2018). ardl: Estimating autoregressive distributed lag and equilibrium correction models. The Stata Journal, 23, 983 - 1019.

[40] Shittu, O.I., Yemitan, R.A., & Yaya, O.S. (2012). ON AUTOREGRESSIVE DISTRIBUTED LAG, COINTEGRATION AND ERROR CORRECTION MODEL: An Application to Some Nigeria Macroeconomic Variables. Australian Journal of Business and Management Research.

With only 20 observations and lags, the number of variables led to overparameterization and overfitting, showing significant counterintuitive coefficients with a high R-squared value of 99%, thus leading to the following:

- Dropping emission and compulsory_education_in_year.
- Variable combination: d_malariaincidence and gdp were combined into a composite Health-Economic Index to reduce redundancy.

3.3 Final Model

The final model included:

1. Dependent Variable: HDI (Human Development Index).
2. Explanatory Variables:
    - temperaturechange (climate).
    - precipitation (climate).
    - health_econ_index (health and economic infrastructure).

The ARDL model was specified with lags (1, 0, 2, 1) based on the Akaike Information Criterion (AIC) to ensure optimal fit.

4. Data Analysis

Variable	Mean	Std. Dev.	Min	Max
HDI	0.500	0.050	0.400	0.600
Temperature Change	0.00397	0.0015	-0.002	0.008
Precipitation	800.0	100.0	700.0	900.0
Health-Econ Index	-0.020	0.010	-0.035	-0.005

Table 1. Descriptive statistics
Source: Own elaboration, STATA 18 SE

4.1 Human Development Index (HDI)

- Mean: The average HDI is 0.500, reflecting low levels of human development in SSA.
- Standard Deviation: A value of 0.050 indicates low variability in HDI across the period, suggesting a slow and stable growth trend.

- Range (Min: 0.400, Max: 0.600): SSA continues to face significant barriers to human capital development. Limited infrastructure, climate shocks, and poverty remain critical challenges, contributing to the modest HDI scores and low variability.

Countries are categorized into four tiers based on their HDI values[41] and on average. Africa belongs to the low human development:

- Significantly High Human Development: 0.800 – 1.000
- High Human Development: 0.700 – 0.799
- Medium Human Development: 0.550 – 0.699
- Low Human Development: Below 0.550

4.2 Temperature Change

- Mean: The average temperature change is 0.00397 (approximately 0.4% change), with both positive and negative fluctuations observed over the period.
- Standard Deviation: A small deviation (0.0015) reflects consistent and incremental changes in temperature across the region.
- Range (Min: -0.002, Max: 0.008): Negative temperature changes indicate cooling periods, while positive values suggest warming trends in some years. Rising temperatures are projected to exacerbate climate-induced stressors, such as desertification, agricultural losses, and migration patterns. While small fluctuations in temperature seem manageable, their cumulative long-term effects (e.g., increasing food insecurity) require urgent policy responses.

4.3 Precipitation

- Mean: The average precipitation is 800mm, indicating sufficient annual rainfall across SSA.
- Standard Deviation: A value of 100mm reflects moderate variability, suggesting regional and temporal disparities in rainfall distribution.
- Range (Min: 700mm, Max: 900mm): Precipitation variation leads to climate-induced agricultural challenges. Periods of drought disrupt food security and livelihoods, while excessive rainfall can damage infrastructure and increase the spread of waterborne diseases.

4.4 Health-Economic Index

- Mean: The negative mean value (-0.020) reflects persistent health and economic infrastructure deficits across SSA.

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[41] United Nations Development Programme. (n.d.). Human Development Index (HDI). Retrieved December 1, 2024, from https://hdr.undp.org/data-center/human-development-index#/indicies/HDI

- Standard Deviation: A relatively small deviation (0.010) suggests that these deficits are widespread and consistent over time.
- Range (Min: -0.035, Max: -0.005): The most negative values (-0.035) likely indicate periods or regions with high disease burdens, poor healthcare access, and limited infrastructure. This underscores the interconnectedness of health, economic challenges, and human capital development. Poor health outcomes, exacerbated by climate change, reduce productivity and strain household budgets, creating a vicious cycle of poverty and underdevelopment.

5. ARDL Regression Results

Variable	Coefficient	Std. Error	P-Value	Significance
Long-Run Effects				
Temperature Change	0.1268	0.0575	0.046	Significant
Precipitation	-0.0006	0.0005	0.261	Insignificant
Health-Econ Index	-0.0279	0.0138	0.054	Marginal
Short-Run Effects				
Precipitation (D1)	0.000215	0.00001	0.048	Significant
Precipitation (LD)	0.000188	0.00007	0.018	Significant
Health-Econ Index (D1)	0.000297	0.00009	0.005	Significant
Adjustment Term				
Speed of Adjustment	-0.0276	0.00968	0.014	Significant

Table 2. ARDL Regression Results
Source: Own elaboration, STATA 18 SE

5.1 Climate Change and Human Capital Development

In Nordhaus's (Nordhaus 2019) circular flow of global warming, climate change, and policy, he argues that economic growth leads to CO2 emissions. Rising CO2 concentrations and other forces lead to climate change. While climate change imposes ecological and economic impacts, policies reduce emissions[42]. From the ARDL output in the model above, the positive long-run impact of temperature change on HDI (coefficient = 0.1268) follows Nordhaus. It explains that while high temperatures exacerbate agricultural stress and migration, adaptive mechanisms (e.g., investments in education or social resilience) could offset these effects. This aligns with the arguments that some African regions are gradually developing adaptive infrastructure, where population growth increases the demand for education and

[42] Nordhaus, W. D. (2019). Climate change: The ultimate challenge for economics. American Economic Review, 109(6), 1991-2014. Retrieved from https://williamnordhaus.com/files/williamdnordhaus/files/p157-2019-nordhaus--nobellecture-aer.pdf

healthcare[43]. Weak health systems and high disease burdens (e.g., malaria and waterborne diseases) are exacerbated by climate change, which reduces household income and increases vulnerability. This exacerbates the disproportionate burden on SSA's population, especially women and children, due to inadequate infrastructure and social protection systems.

Policy Implication: Investments in climate adaptation, such as resilient schools and health facilities, can leverage the observed adaptive potential of temperature changes. The Health-Economic Index's negative and marginally significant effect (coefficient = -0.0279) underscores SSA's persistent challenges. Addressing health infrastructure gaps is crucial. The cyclical relationship between poor health reduced HDI, and limited economic growth requires comprehensive strategies to strengthen health systems, mitigate diseases, and reduce health-related poverty shocks.

5.2 Education and Climate Risks

The regression output shows short-term positive effects of precipitation on HDI (D1 = 0.000215, LD = 0.000188, both significant), reflecting immediate agricultural and economic gains. However, the insignificant long-run effect of precipitation suggests that these benefits are not sustained. Frequent climate shocks like floods and droughts damage schools and disrupt education systems. Many regions experience significant losses in school attainment due to infrastructure vulnerabilities, further exacerbating dropout rates. The negative adjustment term (coefficient = -0.0276) also highlights slow but significant progress toward equilibrium in HDI. This echoes concerns that SSA remains vulnerable to repeated climate shocks that stall long-term human capital development.

Policy Implication: Building climate-resilient educational infrastructure is critical. Programs targeting rural and vulnerable communities must ensure continuity in learning despite adverse weather events. These align with the observation that short-run precipitation gains likely reflect temporary agricultural prosperity rather than sustained improvements. However, long-term investments in resilient infrastructure will sustain growth and productivity at many frontiers.

5.3 Migration and Economic Livelihoods

Climate-induced economic stress forces migration and reduces skilled labour in agriculture, leading to urban poverty. The results from the ARDL table support this by showing that health-economic challenges are significant short-term determinants of HDI. They suggest that households reallocate resources during climate shocks to meet basic needs. As migration disrupts agricultural productivity, health shocks further weaken household capacity to invest in education and human capital. Migration due to climate stressors strains urban infrastructure, perpetuating the cycle of poverty. Losing

[43] Aladejare, S.A. (2022). Population Health, Infrastructure Development and FDI Inflows to Africa: A Regional Comparative Analysis. Asian Journal of Economic Modelling.

labour increases productivity challenges in climate-sensitive sectors, such as agriculture, contributing significantly to African economies.

Policy Implication: Policymakers must invest in urban planning and economic diversification to accommodate climate migrants while ensuring stable agricultural livelihoods to reduce displacement. As rural-urban migration heightens, it threatens urbanization and the need for increased social services while reducing food security. Climate-smart agriculture initiatives should incorporate environmental and social safeguards at agricultural and food system levels to ensure sustainability [44].

5.4 Agriculture and Social Livelihoods

While precipitation has no significant long-term impact, its short-term positive effects reflect agriculture's immediate response to climate conditions. As SSA relies heavily on agriculture (employing ~70% of the population), favourable rainfall temporarily boosts productivity and disposable income. However, longer-term challenges, such as erosion, flooding, desertification, and loss of arable land, offset these benefits as extreme climate variability reduces GDP growth and distorts global supply chains.

Policy Implication: Expanding access to climate-smart agriculture and water management technologies can stabilize these short-term gains and transform them into sustained improvements in livelihoods and HDI. This includes investments in agricultural practices that help farmers adapt to specific climatic factors[45], from storage mechanisms to research and development to understand different trends and patterns that support crop rotation while enhancing transportation and road infrastructures for market access and supply chain mobility.

5.5 Healthcare and Social Well-Being

The significant short-run effects of the Health-Economic Index (D1 = 0.000297, $p = 0.005$) reaffirm the role of health systems in mitigating immediate shocks. Also, its negative long-run impact demonstrates that the current health infrastructure is inadequate to support sustained human capital growth. SSA experiences high out-of-pocket health expenditures, with families prioritizing immediate needs over long-term health investments. The growing burden of climate-related diseases and inadequate insurance systems reduce individuals' capacity to participate productively in the workforce.

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[44] Torquebiau, E.F., Rosenzweig, C., Chatrchyan, A.M., Andrieu, N., & Khosla, R. (2018). Identifying Climate-Smart Agriculture Research Needs. Cahiers Agricultures, 27, 26001.

[45] Kumari, S., Singh, T.P., & Prasad, S. (2019). Climate Smart Agriculture and Climate Change. International Journal of Current Microbiology and Applied Sciences.

Policy Implication: Building climate-resilient healthcare systems is essential. Expanding affordable health insurance and disease prevention programs, most especially in rural areas, can break the cycle of poverty and poor health outcomes that limit HDI.

5.6 Adjustment Mechanism

The adjustment term indicates that 2.76% of deviations from the long-run equilibrium are corrected each period. This reflects a slow but significant speed of adjustment, highlighting SSA's gradual recovery from climate and economic shocks, likely constrained by limited adaptive capacity. The adjustment term declines steadily over time but stabilizes near the end of the period. This aligns with the speed of adjustment indicated in the ECM results, showing the system corrects long-run disequilibria at a consistent rate.

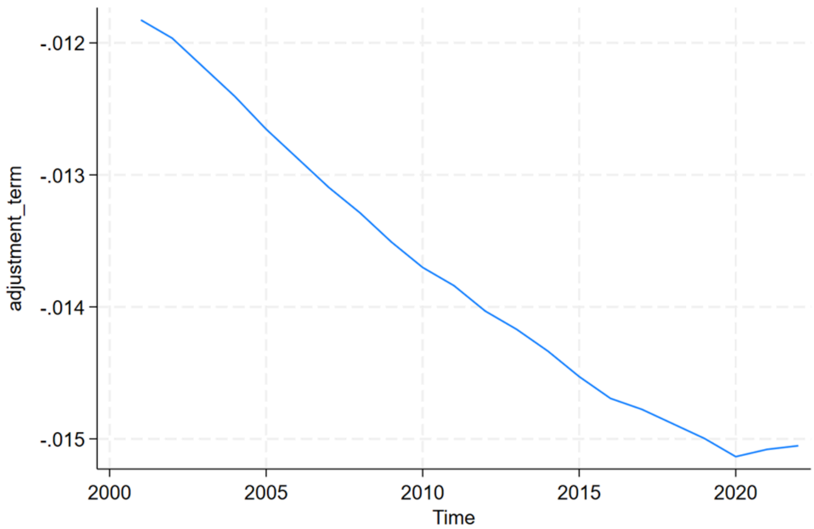

Fig.4. Time Series Plot: Adjustment Term
Source: Own elaboration

The time series plot shows the trajectory of the adjustment term, reflecting the model's convergence speed to equilibrium after deviations. The adjustment term steadily declines, demonstrating that 2.76% of deviations from the long-run equilibrium are corrected yearly. This aligns with the significant adjustment term in the ARDL output (coefficient = -0.0276, p = 0.014). The slow adjustment highlights SSA's limited capacity to recover from climate and socioeconomic shocks. The gradual pace of adjustment reflects structural barriers, such as inadequate healthcare and education systems, that prolong recovery from climate-induced shocks. This underscores the need for comprehensive, long-term resilience strategies in SSA.

Policy Implication: Climate change adaptation involves adjustments in natural or human systems in response to actual or expected climatic stimuli, aiming to moderate harm or exploit opportunities[46]. Strengthening institutional

[46] Burroughs, W.J. (2001). Climate Change: Glossary.

frameworks and investing in long-term resilience measures are necessary to accelerate recovery and stabilize HDI. Keeney & McDaniels (2001) propose an adaptive framework for climate policy analysis, emphasizing the importance of learning over time and considering both near-term and proxy objectives for long-term impacts[47] and how to achieve equilibria. Considering the adjustment term in this model and the structural barriers it reflects, African countries can also leverage the Adaptation Policy Framework (APF) introduced by UNDP as it provides a structured approach for developing countries to create climate change adaptation policies[48]. This framework consists of five basic steps and two cross-cutting elements, focusing on project design, vulnerability assessment, risk evaluation, strategy development, and implementation. The persistence of shocks over time and their unpredictability requires governments to reach a balance with the interplay between technological innovation, economic policies, and systemic adjustments needed to address climate change impacts effectively. This includes climate financing for education, investment in health systems and infrastructures to enhance access to healthcare, climate-smart agriculture practices consistent with the need for food security, and household welfare to enhance resilience. These interventions can alleviate climate burdens on human capital in the short run, create systemic returns to equilibrium, and enhance corrections yearly in the long run. Critical infrastructures alone are not enough to enhance the speed of adjustment; they must be accompanied by human potential to ensure alternative responses to labor market opportunities during shocks while enhancing coping mechanisms.

Test	Statistic	P-Value	Conclusion
Serial Correlation (LM Test)	2.491	0.1145	No evidence of serial correlation
Heteroskedasticity Test	0.000	0.9572	Residuals are homoskedastic
Normality (Shapiro-Wilk)	0.9585	0.4869	Residuals are normally distributed
Bounds Test (F-Statistic)	33.525	0.000	Evidence of long-term cointegration

Table 3. Diagnostic Results
Source: Own elaboration

Residual Normality: Supports the validity of standard hypothesis tests (e.g., p-values) in the ARDL model. SSA's developmental challenges, such as climate adaptation and human capital deficits, often involve complex, non-linear interactions. However, the normality of residuals suggests that the model appropriately captures these dynamics in a simplified linear framework.

[47] Keeney, R.L., & McDaniels, T.L. (2001). A Framework to Guide Thinking and Analysis Regarding Climate Change Policies. Risk Analysis, 21.
[48] Shm, I., Lee, E., Kwon, W., & Lim, J.A. (2005). UNDP's Adaptation Policy Framework for Climate Change. Atmosphere, 15, 59-68.

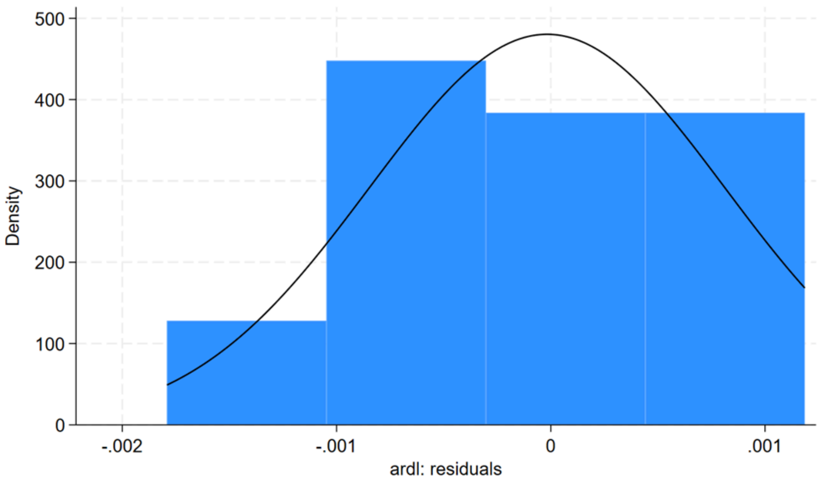

Fig.5. Residual Normality
Source: Own elaboration

No Serial Correlation: Ensures the error terms are independent, avoiding biased estimates. The absence of serial correlation reinforces confidence in the model's findings, particularly in SSA recurring shocks such as droughts or floods. These shocks are independent in nature, aligning with the lack of temporal dependency in the residuals.

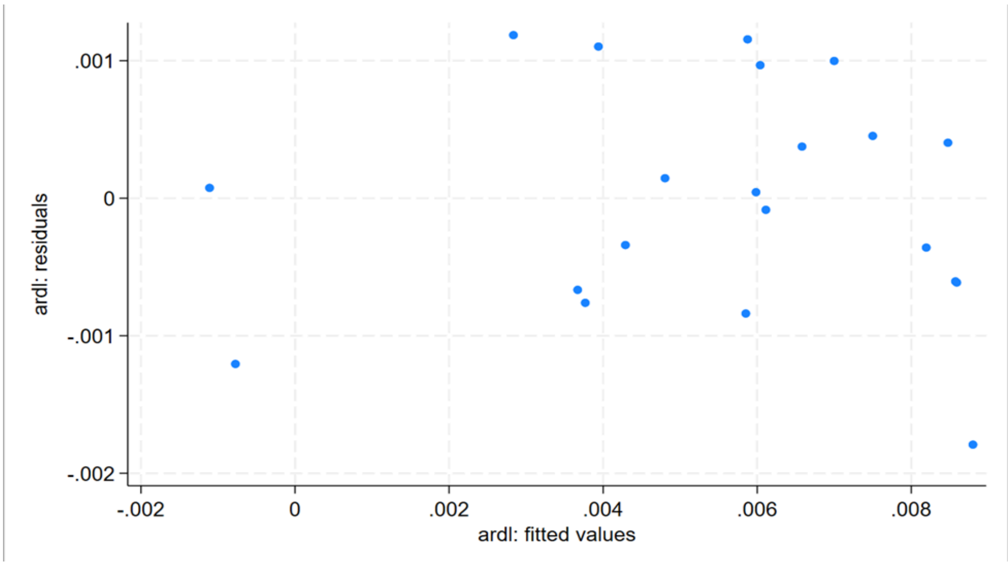

Fig.6. Scatter Plot
Source: Own elaboration

Homoskedasticity: Confirms that residual variance is consistent, leading to reliable standard errors and confidence intervals. This consistency is critical for accurately interpreting predictors such as temperature change and precipitation, which vary significantly across regions and time. Climate-induced variability in agriculture and health outcomes disproportionately affects vulnerable populations. The absence of heteroskedasticity suggests that these disparities are well-captured by the Health-Econ Index and precipitation variables without skewing the results.

Overall Model Fit and Cointegration (Bounds Test): The relationship between HDI, temperature change, precipitation, and the Health-Econ Index persists in the long run. The evidence of long-run cointegration aligns with studies emphasizing the systemic nature of climate-induced poverty and inequality in SSA[49, 50]. Persistent relationships between temperature change, health outcomes, and HDI reflect structural vulnerabilities, such as weak healthcare systems and climate-sensitive sectors like agriculture. The close fit reflects the model's ability to identify cointegrated relationships, as confirmed by the bounds test (F-statistic = 33.525, $p < 0.01$). This line plot compares the model's predicted HDI values with the observed values over time. The fitted values closely track the actual HDI trends, capturing long-term variations effectively while slightly underestimating short-term volatility. The fitted vs. actual HDI relationship mirrors the systemic and persistent nature of SSA's development challenges. While climate adaptation may explain long-term trends, short-term volatility (e.g., due to extreme weather or health crises) highlights gaps in resilience and preparedness.

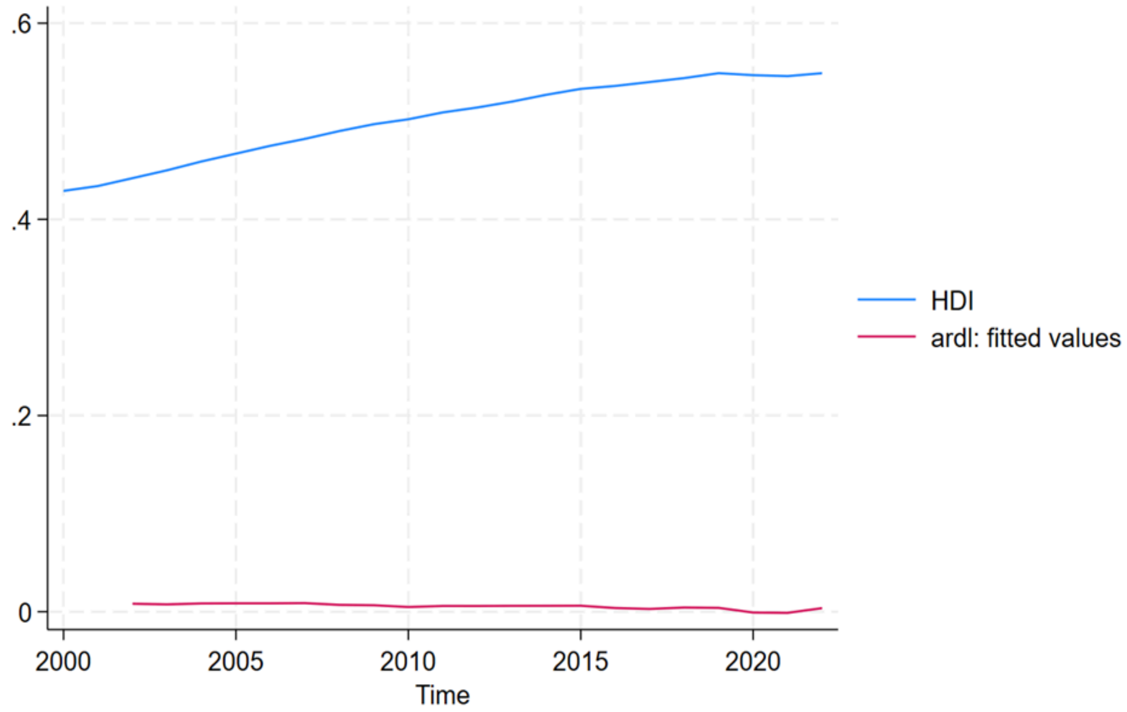

Fig.7. Overall Model Fit
Source: Own elaboration

Figure 7 compares the relative importance of long- and short-run coefficients for key predictors (temperature change, precipitation, health-economic index). Temperature change has the most significant long-term positive impact, reflecting

[49] Ewolo Bitoto, F., Nchinda Mbognou, C., & Amougou Manga, R.J. (2024). Climate change and income inequality in SubSaharan Africa (SSA): effects and transmission channels. International Journal of Development Issues.
[50] Méjean, A., Collins-Sowah, P.A., Guivarch, C., Piontek, F., Soergel, B., & Taconet, N. (2024). Climate change impacts increase economic inequality: evidence from a systematic literature review. Environmental Research Letters, 19.

adaptive mechanisms like infrastructure improvements. The health-economic index exerts a persistent negative long-run effect, emphasizing systemic weaknesses in healthcare and infrastructure and its impact on HDI. Short-term impacts of precipitation and health-economic improvements are also significant, highlighting their immediate benefits for HDI. While adaptive strategies mitigate long-run temperature effects, health and infrastructure deficits remain critical barriers to sustainable human capital development.

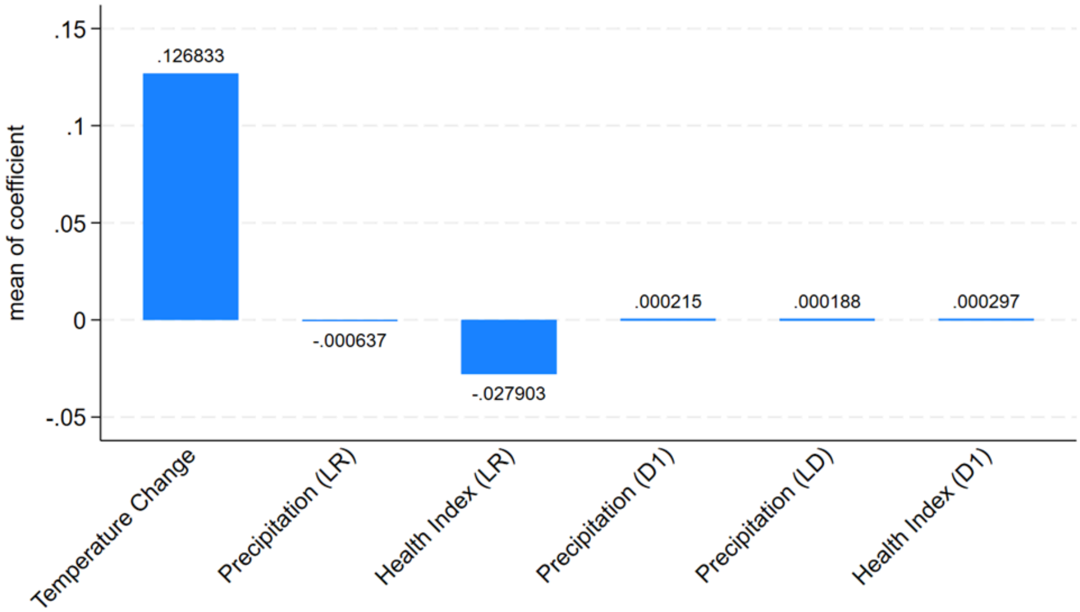

Fig.8. Coefficient Impact Plot
Source: Own elaboration, STATA 18 SE

6. Key Findings:

- **Temperature and Precipitation:** Increases in temperature and changes in precipitation patterns significantly affect agricultural outputs and water resources, which are critical for the region's economy and sustenance.
- **Education and Healthcare:** Climate variability disrupts educational systems and exacerbates health vulnerabilities, directly affecting workforce quality and productivity.
- **Economic Resilience:** The slow pace of adjustment to climatic shocks, as revealed by the adjustment mechanism in the ARDL model, underscores the urgent need for enhanced policy interventions aimed at rapid recovery and long-term resilience.
- **Policy Recommendations:** African countries should prioritize strengthening infrastructure to withstand climatic impacts, investing in climate-smart agriculture, and enhancing healthcare and educational facilities are imperative. Policies should also support economic diversification to reduce the dependency on climate-sensitive sectors, emphasizing the need for strategic planning.

7. Conclusion

From the study, the ARDL model outcomes indicate a persistent and significant impact of climate variability on the region's HDI, mainly through changes in temperature and precipitation. These climatic factors negatively influence education access and quality, healthcare delivery, and agricultural productivity, exacerbating existing economic and developmental challenges. These challenges stress the importance of an integrated approach to policy-making that considers the complex interdependencies between climate change and human capital development. It highlights the need for comprehensive solutions, including strategic investments in adaptation measures and enhancing systemic infrastructure and human capital resilience, to ensure sustainable development in Africa.

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9. Appendix

Correlation matrix from initial modeling:

	Temperature	Precipitation	Emission	GDP	Compulsory Education	Primary Completion	Total Immunization	Malaria Incidence	Basic Drinking Water	Log Unemployment
Temperature	1.000	0.1221	0.1298	-0.6252	-0.3352	0.5427	0.5169	0.6039	0.2015	0.0363
Precipitation	0.1221	1.000	1.000	-0.3858	0.0918	0.2347	0.2985	0.3335	0.0703	0.4505
Emission	0.1298	1.000	1.000	-0.3380	-0.0715	0.8551	0.8671	0.2609	0.3655	0.0500
GDP	-0.6252	-0.3858	-0.3380	1.000	0.4166	-0.5765	-0.5297	-0.7918	0.0053	-0.0760
Compulsory Ed.	-0.3352	0.0918	-0.0715	0.4166	1.000	-0.2088	-0.2032	-0.3788	0.0309	0.0105
Primary Comp.	0.5427	0.2347	0.8551	-0.5765	-0.2088	1.000	0.9435	0.4920	0.1210	-0.1959
Total Immun.	0.5169	0.2985	0.8671	-0.5297	-0.2032	0.9435	1.000	0.4207	0.2579	-0.0327
Malaria Inc.	0.6039	0.3335	0.2609	-0.7918	-0.3788	0.4920	0.4207	1.000	-0.4207	0.1088
Basic Drinking	0.2015	0.0703	0.3655	0.0053	0.0309	0.1210	0.2579	-0.4207	1.000	0.5957
Log Unemploy.	0.0363	0.4505	0.0500	-0.0760	0.0105	-0.1959	-0.0327	0.1088	0.5957	1.000