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A panel data study on the effect of climate change on life expectancy

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Abstract

The life and health of billions of people is endangered by climate change today. Life expectancy is generally used as the best metric for assessing the population health status of a nation. Against this backdrop, this paper investigates the effect of climate change on life expectancy using the panel data model. To do so, imprimis, this paper develops a conceptual framework linking direct and indirect pathways by which climate change affects health. The direct pathways are through weather variables and natural disasters. The indirect pathways are mediated through economic systems and ecosystems. Then this paper estimates the effect of climate change on life expectancy using cross-national data from 191 countries covering the period 1940–2020 and employing the fixed-effect method. The finding of this study suggests that if the annual average temperature increases by 1˚C, then the life expectancy at birth will decline by 0.44 years. Moreover, the temperature rise will further negatively impact life expectancy by interacting with the rainfall cycle. If the composite climate change index, an index of the geometric mean of temperature and rainfall, increases by 10 points, the life expectancy at birth will decline by 0.50 years. Moreover, climate change will disproportionately reduce the life expectancy of females more than the life expectancy of males. A negative relationship between a composite climate change index and life expectancy underscores the urgency of addressing climate change as a public health crisis. Mitigation efforts to reduce greenhouse gas emissions and adapt to changing conditions are essential to minimize the health risks associated with climate change. Thus, countries should come forward with prompt initiatives to contain global temperature rise and protect the health of the population on the verge of climate change.

1. Introduction

The global climate is changing rapidly [1]. Long-term shifts in temperature, rainfall, and other fundamental properties of climate are evident now which is globally recognized as "climate change". The impacts of climate change include but are not limited to warming temperatures, abnormalities in precipitation as well as increases in the frequency and intensity of extreme weather events. These impacts threaten our health by affecting the food we eat, the water we

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drink, the air we breathe, and the weather we experience. Between 2030 and 2050, climate change is expected to cause approximately 250,000 deaths annually and cost US$4 billion of global income loss per year [2].

One of the most noticeable effects of climate change is the increase in global average temperatures. Over the past century, the Earth's surface temperature has risen, with the most significant warming occurring in recent decades. It is splendent that the global surface temperature increased above 1.1˚C in 2011–2020 from 1850–1900 [2]. This change is primarily driven by human activities, particularly the emission of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases trap heat in the Earth's atmosphere, leading to a phenomenon known as the greenhouse effect, which results in rising global temperatures. Higher temperature increases the polar ice shields melting and resulting in the sea level rising which is catastrophic for coastal countries. Moreover, higher temperatures increase water evaporation, which increases the risk of severe droughts in landlocked countries. The potential future effects of escalating temperatures also include more frequent wildfires and tropical cyclones [3]. Moreover, higher temperatures will result in severe costs to society including a fall in output, reduced productivity, damage to food security, and increased mortality [4].

In addition to a higher temperature, more intense and frequent abnormal rainfall is observed [5]. Rainfall anomalies are defined as the deviations of rainfall from longrun averages. Precipitation extremes–in terms of both excess and deficient rainfall—have serious consequences. On the one hand, increased rainfall over extended periods leads to coastal flooding, which results in soil erosion, fatalities, injuries, drownings, crop damage, increased risk of undernutrition resulting from diminished food production, waterborne diseases, and other flooding-related effects on health [6]. On the other hand, the decline in rainfall leads to drought which results in a scarcity of drinking water and irrigation facilities for agriculture production. This can result in rising food prices and food insecurity which ultimately effect of nutrition and health of people. Many of the world's poorest countries which have a disproportionately high dependence on agricultural employment are now experiencing strong negative feedback variability of rainfall including job losses, reduced income for farmers, and decreased health status in affected regions.

Disruption of our climate system along with rising temperature and abnormal rainfall is brought by associated natural calamities like extreme heat waves, powerful storms, hurricanes, tropical cyclones, flooding, droughts, wildfires, and rising numbers of insect and vector-borne diseases [7]. These events can have far-reaching and often devastating consequences for the economy, ecosystem, health, and human society. For instance, rising temperatures can result in more frequent and intense heat waves which can lead to heat-related illnesses and higher mortality. Likewise, droughts can impact water availability for agriculture, industry, and households, leading to water scarcity, crop failures, food shortages, and a fall in expected years of living. Flash floods and river floods can damage infrastructure, displace communities, and result in casualties. Warmer ocean temperatures can fuel the development and intensification of tropical storms, leading to more powerful hurricanes and cyclones. These storms can bring widespread destruction to the lives and livelihoods of people. Rising temperatures, prolonged droughts, and changes in vegetation patterns can also create conditions conducive to wildfires. These fires can devastate forests, destroy homes, and have serious air quality and health implications. Ultimately, these effects of climate disruption are fundamentally health issues and they pose existential risks to all of us which include but are not limited to death, disability, illness and loss or disruption in health care delivery [8].

Life expectancy is the best metric for assessing population health which captures the mortality along the entire life course [9]. Climate change can have a significant impact on life

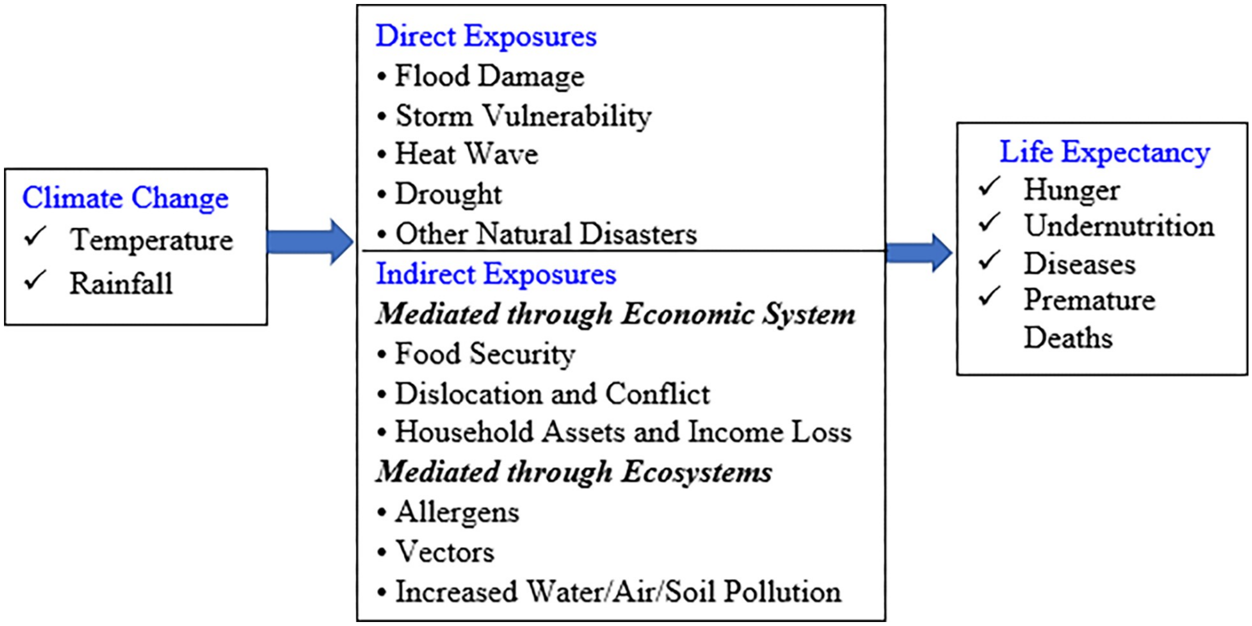

Fig 1. Conceptual relationship between climate change and life expectancy. Source: Authors' build-up based on [10, 11].

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expectancy, both directly and indirectly, through a variety of mechanisms. These effects can vary depending on factors such as geographic location, socioeconomic status, and access to resources. Fig 1 draws the conceptual link between climate change and life expectancy showing two primary exposure pathways by which climate change affects health (following [10, 11]). These impacts are diverse and multifaceted, affecting various aspects of human health and well-being. The direct pathway is through weather variables and natural disasters which relate primarily to changes in the frequency of extreme weather including heat, drought, storms, floods, heavy rain, etc. [12]. Natural disasters can have significant and complex effects on life expectancy. Natural disasters and extreme weather events, rising sea levels, changes in precipitation resulting in flooding and droughts, and intense hurricanes can directly cause injury, illness, and even death and decrease in expected years of living. The impact depends on several factors, including the type and severity of the disaster, the preparedness and resilience of the affected community, access to resources, and the response to the disaster. Natural disasters often cause injuries, some of which can be severe and lead to long-term disabilities. Natural disasters can damage healthcare facilities, disrupt the supply of medications, and strain healthcare systems. This can hinder access to medical care, exacerbate existing health conditions, and lead to preventable deaths. Moreover, crowded shelters and unsanitary conditions in the aftermath of disasters can increase the risk of disease outbreaks, such as cholera, dysentery, and respiratory infections. These outbreaks can lead to additional deaths.

The effects of climate change can also indirectly affect health through alterations to the environment. The indirect pathways are heavily mediated through economic systems such as food security, household assets, income loss, population displacement, conflict over depleted resources, such as water, fertile land, and fisheries, and ecosystems such as disease vectors and pollution [13]. For example, climate change can disrupt agricultural systems, leading to crop failures and reduced food availability. This can result in malnutrition, lack of access to clean drinking water and sanitation, and related health problems among vulnerable populations [14]. Changes in temperature and rainfall can alter the survival, distribution, and behavior of insects and other species which can lead to changes in infectious diseases [15]. Climate change can alter the distribution and behavior of disease-carrying vectors like mosquitoes and ticks. This can lead to the spread of diseases such as malaria, dengue fever, Zika virus, and Lyme disease into new regions [16]. Increases in precipitation, storm surge, and sea temperature can lead to more water-related illnesses. Prolonged exposure to extreme heat can result in heat-related illnesses, such as heat exhaustion and heatstroke, which can be fatal [17]. Climate change can also worsen air quality by increasing the frequency and severity of wildfires, dust storms, and air pollutants. Poor air quality can exacerbate respiratory problems and cardiovascular diseases and cause plummeting life expectancy [18]. Climate change can also affect food safety, exposing people to contaminated foods that can result in foodborne illnesses [19]. In addition, climate change can affect mental health and well-being. Survivors who experience extreme weather events, such as hurricanes, floods, wildfires, or heatwaves, can suffer from direct trauma, including injuries and loss of loved ones or property. The emotional toll of such events can lead to post-traumatic stress disorder (PTSD), anxiety, depression, and other mental health issues and increase the rate of suicides [20]. Economic losses resulting from climate change, such as damage to property, crop failures, and job losses in affected industries, can contribute to financial stress, which can, in turn, impact mental health. Climate change-related disasters can damage healthcare infrastructure and disrupt healthcare services, making it difficult for individuals to access medical care when needed and result in premature death [21]. Resource scarcity driven by climate change can lead to the displacement of communities and conflicts over resources; as a result, the displaced populations would face health risks due to inadequate shelter, sanitation, and clean water, access to healthcare [22]. All these basic pathways lead to how climate change reduces the life expectancy of nations by affecting hunger, nutrition status, diseases, mental health, and premature death profile.

However, there is no empirical research has yet been conducted to estimate the effect of climate change on life expectancy. Against this backdrop, this paper attempts to fill up the knowledge vacuum by empirically analyzing the effect of temperature and rainfall variability on life expectancy using panel data and the fixed effect method. Moreover, it introduces a novel composite climate change index and then estimates the overall impact of climate change on life expectancy. The rest of the paper is organized as follows: section 2 describes the materials and econometric methods used in this study. The next section discusses the results and empirical findings of the study. Finally, section 4 concludes this study with policy suggestions.

2. Materials and methods

2.1 Data and variables description

To study the effect of climate change on the population health of countries, this paper employs cross-national panel data from 191 countries covering the period 1940–2020. The dependent variable of the study is the life expectancy at birth. To check the gender sensitivity of the results, this study further uses the life expectancy at birth of males and life expectancy at birth of females as dependent variables on separate regressions. Data on life expectancy at birth, life expectancy at birth of males, and life expectancy at birth of females are taken from *World Bank World Development Indicators 2023* [23]. Life expectancy at birth indicates the number of years a newborn infant would live if prevailing patterns of mortality at the time of its birth were to stay the same throughout its life [23].

The major explanatory climate variables of the analysis are temperature and rainfall. Data on temperature and rainfall are collected from the *World Bank Climate Change Knowledge Portal 2023* [24], where the temperature is defined as the annual average temperature of a country in a year in degrees Celsius and rainfall is defined as the annual average rainfall of a country in a year in millimeters. Moreover, in order to determine the overall impact of climate change on life expectancy, this study introduces a novel composite climate change index by taking the geometric mean of temperature and rainfall. The geometric mean is used instead of the arithmetic mean in order to avoid perfect substitutability between temperature and rainfall (following [25]). Moreover, the geometric mean has an advantage over the arithmetic mean in that it is less affected by extreme values in a skewed distribution.

$$Climate\ Change\ Index_{it} = \sqrt[2]{Temperature_{it} \times Rainfall_{it}}$$

A climate change index is a valuable tool for several reasons, as it serves multiple important purposes in understanding, addressing, and communicating the challenges and impacts of climate change. A climate change index provides a quantitative way to measure and track progress in addressing climate change. It can assess whether efforts to reduce greenhouse gas emissions and mitigate climate change are effective over time. This information is crucial for evaluating the success of policies and initiatives. A climate change index can also serve as a public awareness tool. It helps convey the urgency and severity of climate change to the general public, policymakers, businesses, and other stakeholders. By providing a clear and easily understandable metric, it can motivate individuals and organizations to take action. It helps identify areas where policy interventions are most needed and assess the effectiveness of existing policies. This can guide the allocation of resources and the development of more targeted and impactful climate policies. Moreover, a climate change index can help prioritize resource allocation by identifying countries that are most vulnerable to climate change or where mitigation efforts can have the most significant impact. In addition, climate change indices allow for international comparisons of climate performance. This can promote healthy competition among nations to reduce emissions and adapt to climate change, as well as foster collaboration in addressing global challenges.

Moreover, the introduction of a novel composite climate change index, achieved through the strategic combination of temperature and rainfall metrics using the geometric mean, marks a significant advancement in climate science. This innovative approach transcends traditional univariate indices by capturing the intricate interplay between multiple climatic variables. The utilization of the geometric mean, as opposed to more conventional methods, brings forth a nuanced measure that encapsulates both the magnitude and proportional changes in temperature and rainfall. This specialized significance lies in the index's ability to provide a more comprehensive and accurate representation of climate conditions, enabling a deeper understanding of the evolving climate dynamics. In the realm of climate change research, the introduction of this composite index addresses the limitations of single-variable indices, which may oversimplify the complexity of climate systems. By incorporating both temperature and rainfall in a geometric mean, the index offers a holistic perspective, acknowledging the interconnected nature of these climatic components. This methodological innovation is particularly crucial in a time where the impacts of climate change manifest in multifaceted ways. Thus, the specialized significance of this novel index lies in its capacity to enhance the precision of climate assessments, fostering more informed decision-making in various sectors that rely on accurate climate data.

In the existing empirical literature, GDP per capita is the most important determinant of life expectancy [26]. GDP per capita increases life expectancy through increased economic growth and development in a country and thus leads to the prolongation of longevity. However, an increase in per capita income does not directly translate into higher life expectancy if it is not utilized for provisioning nutrition, clean drinking water, sanitation, and other public health goods. Thus, we incorporate GDP per capita as the control variable in the study.

Table 1. Descriptive statistics.

Variables	Observations	Mean	S.D.	Min	Max
Life Expectancy at Birth	9,685	64.4342	11.3322	11.9950	84.6156
Life Expectancy at Birth of Males	9,685	62.0579	10.9119	10.054	82.6
Life Expectancy at Birth of Females	9,685	66.9415	11.8774	14.008	87.74
GDP Percapita (GDPPC)	8,733	10567.68	17378.35	144.0314	191193.7
Temperature	11,135	19.0099	8.1231	-9.2166	29.3666
Rainfall	11,135	100.3906	71.0110	1.16667	417.3917
Climate Change Index	10,971	40.9900	21.5718	4.69e-08	104.9058
LDC (Dummy)	14,970	-	-	0	1

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Moreover, to distinguish between developed and developing countries against the least developing countries (LDC), this study includes a dummy variable representing the latter. Data on GDP per capita and LDC are collected from *World Bank World Development Indicators 2023* [23]. Descriptive statistics of the variables under study are reported in Table 1.

The global average life expectancy increased significantly between 1960 and 2020 from 55 years to 72 years [Fig 2]. At the same time, the global average life expectancy of males increased significantly from 48 years to 70 years and the global average life expectancy of females increased significantly from 52 years to 74 years. This longevity is due to access to plentiful and more nutritious food, clean water, better hygiene, and advanced medical care along with innovations in antibiotics and vaccines [27]. However, the due to Covid-19 pandemic, global life expectancy decreased slightly in 2020 [28]. The global average GDP percapita has tripled in the meantime from US$5,000 (PPP) to US$15,000 (PPP) [Fig 3].

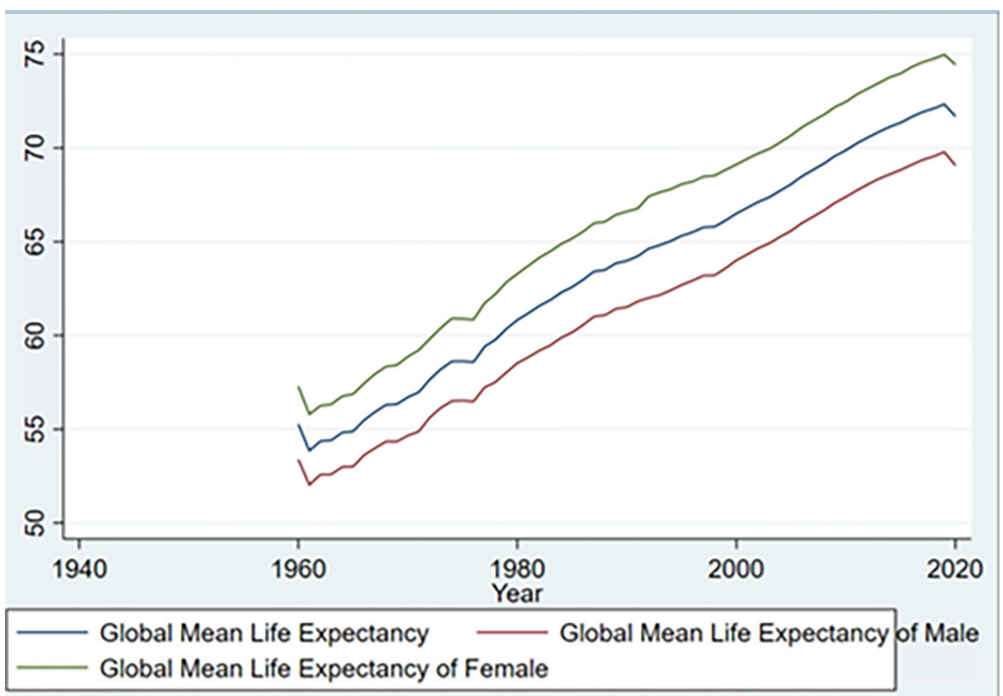

Fig 2. Global average life expectancy from 1960–2020. Source: Authors' plot in STATA based on [17] data.

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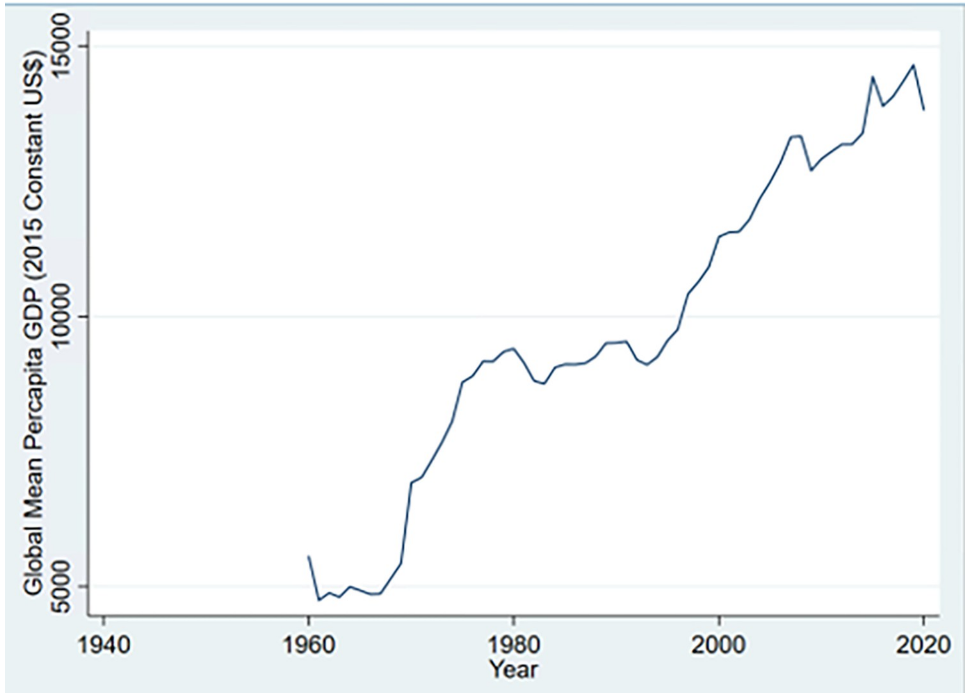

Fig 3. Global average GDP percapita from 1960–2020. Source: Authors' plot in STATA based on [17] data.

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The global mean annual temperature increased sharply between 1940 and 1990 from 15˚C to 21˚C [Fig 4]. The rising temperatures, also known as global warming, are the major externalities of human activities where the overuse of fossil fuels caused the increase in the concentration of greenhouse gases (GHGs) in the atmosphere [29]. However, since 1990 it has declined by 1˚C. The slight reduction in global mean annual temperature is the result of mitigation action taken by countries to reduce GHG emissions by introducing GHG taxes or adopting an emission trading system [30]. In the meantime, the global mean annual rainfall has remained steady at 100±10 millimeters with an increasing trend [Fig 5]. The computed composite climate change index reveals alarming changes in global climate between 1940 and 1990 which are still persisting [Fig 6]. However, a significant decrease in the value of the index is apparent in the twenty-first century owing to the global effort to combat climate change.

2.2 Econometric method

To examine the effect of climate change on life expectancy, this paper employs the panel fixed effect model. The fixed effects model is a statistical method used in econometrics and social sciences to analyze panel data, which is data collected on the same entities (e.g., individuals, firms, countries) over multiple time periods. This model is a type of linear regression model that accounts for both time-invariant and unobserved heterogeneity across the entities in the panel. The panel fixed effects model is particularly useful when you want to control for unobserved time-invariant characteristics that may be correlated with your explanatory variables and affect the dependent variable. By including entity-specific fixed effects, you can better isolate the relationship of interest and make more accurate inferences about the impact of the explanatory variables on the dependent variable while accounting for this unobserved heterogeneity. The panel fixed effects model estimates the parameters (coefficients) of the model using various estimation techniques, such as ordinary least squares (OLS) or the within-

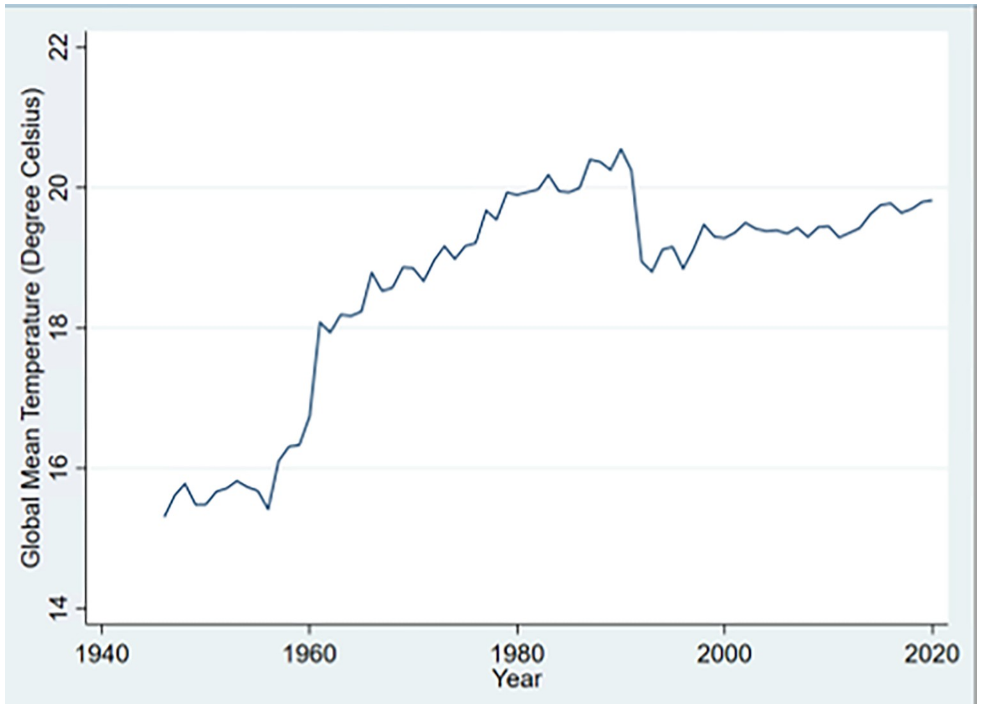

Fig 4. Global average yearly temperature from 1940–2020. Source: Authors' plot in STATA based on [18] data.

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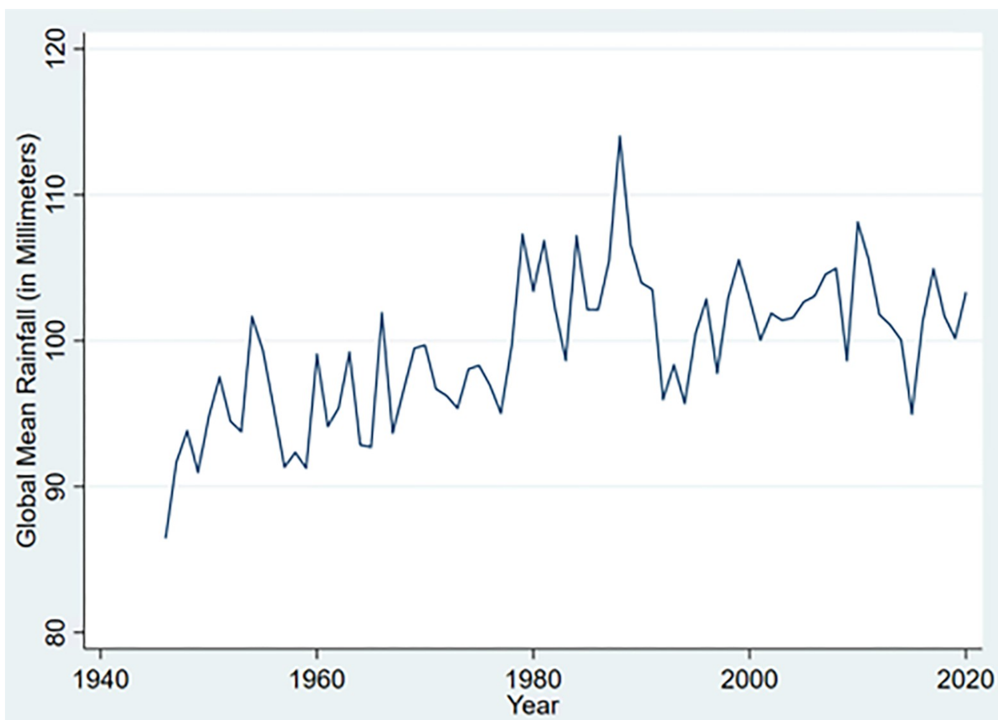

Fig 5. Global average yearly rainfall from 1945–2020. Source: Authors' plot in STATA based on [18] data.

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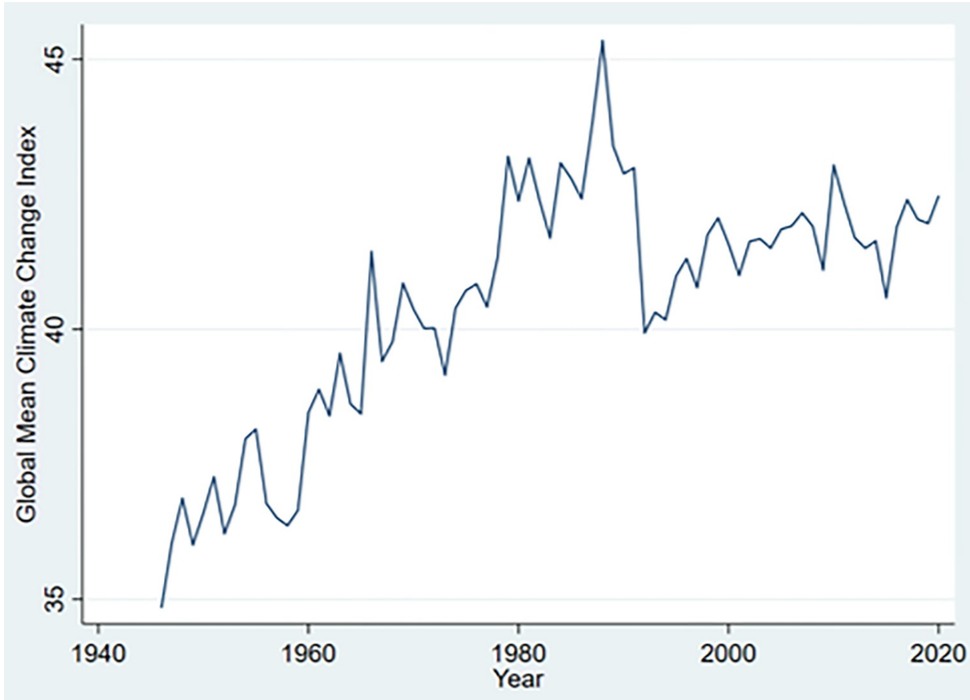

Fig 6. Global average annual climate change index from 1945–2020. Source: Authors' plot in STATA based on calculated data.

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transformation (also known as the fixed effects estimator). The within-transformation subtracts the entity-specific means from the data, effectively eliminating the fixed effects. This paper employs the latter method of estimation as it is more efficient than OLS [31]. For $i = 1,2,\ldots,N$ countries and $t = 1,2,\ldots,T$ time period, a fixed effect model can be expressed as:

$$y_{it} = \alpha_i + \beta_i x_{it} + \varepsilon_{it}$$

Where y_{it} is the dependent variable. α_i captures the fixed effect, that is, the country specific heterogeneity. x_{it} is the vector of explanatory variables. β_i are the parameters to be estimated. ε_{it} is the independently and identically distributed error term. In this analysis, the dependent variable is the life expectancy at birth ($Life\ Expectancy_{it}$). x_{it} is the vector of climate variables, such as, temperature ($Temperature_{it}$) and rainfall ($Rain\ fall_{it}$) as well as control variable GDP percapita ($GDPPC_{it}$). The previous equation can be rewritten in the form as:

$$Life\ Expectancy_{it} = \alpha_i + \beta_i \begin{bmatrix} GDPPC_{it} \\ Temperature_{it} \\ Rainfall_{it} \end{bmatrix} + \varepsilon_{it}$$

where $Life\ Expectancy_{it}$ denotes the life expectancy of birth of ith country on t time and so on.

We also use the composite climate change index as an explanatory variable in separate regression which takes the form as follows:

$$Life\ Expectancy_{it} = \alpha_i + \beta_i \begin{bmatrix} GDPPC_{it} \\ Climate\ Change\ Index_{it} \\ GDPPC_{it} \times Climate\ Change\ Index_{it} \end{bmatrix} + \varepsilon_{it}$$

We also introduce interaction terms between climate and control variables during the empirical analysis in order to determine how much effect climate change has on the effect of GDP percapita on life expectancy. If the interaction coefficient is positive, then the effect of GDP percapita on life expectancy increases as a climate variable increase, if negative the opposite. If the interaction coefficient is zero, then the effect of GDP percapita on life expectancy is independent of the climate variable.

3. Results and discussion

3.1 Effect of climate change (Temperature and rainfall separately) on life expectancy

The results of the empirical analysis are reported in Tables 2–7. Column 1 presents the variables under study. All the models are found statistically significant as the F-statistics exceeds the critical value at 1% level of significance in all cases. Moreover, R-squared reports the overall goodness of fits of the models.

Table 2. Panel fixed effect result. Dependent Variable: Life Expectancy at Birth.

Variables	(1)	(2)	(3)	(4)
GDPPC	0.0003***	0.0002***	0.0001***	0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Temperature	-0.4382***	-0.2836***	-0.7798***	-0.4571***
	(0.0121)	(0.0102)	(0.0213)	(0.0188)
Rainfall	0.0255***	0.0133***	-0.0178***	-0.0040
	(0.0012)	(0.0010)	(0.0066)	(0.0056)
GDPPC × Temperature			0.0000***	0.0000***
			(0.0000)	(0.0000)
GDPPC × Rainfall			0.0000***	0.0000
			(0.0000)	(0.0000)
Temperature × Rainfall			0.0019***	0.0008***
			(0.0003)	(0.0002)
LDC		-10.2977***		-9.5914***
		(0.1620)		(0.1661)
Constant	68.3576***	71.6373***	75.0641***	74.5729***
	(0.2695)	(0.2275)	(0.4792)	(0.4056)
Observations	8,465	8,465	8,465	8,465
F-statistic	2030.68***	3264.55***	1233.79***	1953.28***
R-squared	0.4203	0.6085	0.4685	0.6195
Fixed Effect	Yes	Yes	Yes	Yes

Note: (1) ***, **, * denote 1%, 5% and 10% levels of significance respectively.
(2) Numbers in parentheses are robust standard errors.

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Table 3. Panel fixed effect result of sensitivity analysis. Dependent Variable: Life Expectancy at Birth of Males.

Variables	(5)	(6)	(7)	(8)
GDPPC	0.0003***	0.0002***	0.0001***	0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Temperature	-0.3646***	-0.2209***	-0.6535***	-0.3517***
	(0.0116)	(0.0100)	(0.0206)	(0.0185)
Rainfall	0.0236***	0.0123***	-0.0066	0.0062
	(0.0012)	(0.0010)	(0.0064)	(0.0055)
GDPPC × Temperature			0.0000***	0.0000***
			(0.0000)	(0.0000)
GDPPC × Rainfall			0.0000*	0.0000
			(0.0000)	(0.0000)
Temperature × Rainfall			0.0014***	0.0004*
			(0.0003)	(0.0002)
LDC		-9.5709***		-8.9721***
		(0.1589)		(0.1634)
Constant	64.6406***	67.6888***	70.1948***	69.7353***
	(0.2599)	(0.2230)	(0.4649)	(0.3989)
Observations	8,465	8,465	8,465	8,465
F-statistic	1977.21***	3030.39***	1172.49***	1796.15***
R-squared	0.4139	0.5907	0.4558	0.5996
Fixed Effect	Yes	Yes	Yes	Yes

Note: (1) ***, **, * denote 1%, 5% and 10% levels of significance respectively.
(2) Numbers in parentheses are robust standard errors.

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Table 2 reports the result of the baseline panel fixed effect estimation. From Model (1), we find that GDP percapita (GDPPC) and climate variables have statistically significant on life expectancy individually at 1% level of significance. For instance, the coefficient of GDPPC is 0.0003, which tells us that if the GDP percapita increases by $1000, the life expectancy at birth will increase by 0.3 years or by 4 months, holding all other factors remain the same. The coefficient of temperature is -0.44, which tells us that if the annual average temperature increases by 1˚C, the life expectancy at birth will decline by 0.44 years or by 5 and half months, holding all other factors remain the same. The coefficient of rainfall is 0.03, which tells us that if the annual average rainfall increases by 10 millimeters, the life expectancy at birth will increase by 0.30 years or by 4 months, holding all other factors remain the same. The intercept term of the model is 68.36 which reveals that if all the explanatory variables of the model become zero, the life expectancy at birth would be 68.36 years. To control for the least developing countries (LDC) against the developed and developing countries, we introduce the LDC dummy variable in fixed effect regression (2). LDC coefficient is -10.30 which tells us that if a country is an LDC, its life expectancy at birth is 10.30 years lower than that of the developed and developing world, holding all other factors remain the same. The sign and significance of all variables remain the same in Model (2).

Model (3) incorporates interaction terms between climate and control variables. In this case, the coefficient of GDPPC is reduced to 0.0001, which tells us that if the GDP percapita increases by $1000, the life expectancy at birth will increase by 0.1 years, holding all other factors remain the same. The negative effect of temperature rise on life expectancy has now almost doubled to -0.78 years, holding all other factors remain the same. The interaction terms

Table 4. Panel fixed effect result of sensitivity analysis. Dependent Variable: Life Expectancy at Birth of Females.

Variables	(9)	(10)	(11)	(12)
GDPPC	0.0003***	0.0002***	0.0001***	0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Temperature	-0.5102***	-0.3432***	-0.9119***	-0.5662***
	(0.0128)	(0.0107)	(0.0223)	(0.0196)
Rainfall	0.0276***	0.0144***	-0.0284***	-0.0137**
	(0.0013)	(0.0011)	(0.0069)	(0.0058)
GDPPC × Temperature			0.0000***	0.0000***
			(0.0000)	(0.0000)
GDPPC × Rainfall			0.0000***	0.0000*
			(0.0000)	(0.0000)
Temperature × Rainfall			0.0025***	0.0013***
			(0.0003)	(0.0002)
LDC		-11.1218***		-10.2737***
		(0.1693)		(0.1728)
Constant	72.1242***	75.6664***	80.0757***	79.5495***
	(0.2847)	(0.2376)	(0.5026)	(0.4217)
Observations	8,465	8,465	8,465	8,465
F-statistic	2037.13***	3392.12***	1274.63***	2057.77***
R-squared	0.4211	0.6176	0.4766	0.6317
Fixed Effect	Yes	Yes	Yes	Yes

Note: (1) ***, **, * denote 1%, 5% and 10% levels of significance respectively.
(2) Numbers in parentheses are robust standard errors.

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Table 5. Panel fixed effect result of overall effect of climate change. Dependent Variable: Life Expectancy at Birth.

Variables	(13)	(14)	(15)	(16)
GDPPC	0.0004***	0.0002***	0.0002***	0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Climate Change	-0.0107**	-0.0155***	-0.0511***	-0.0330***
	(0.0043)	(0.0034)	(0.0051)	(0.0041)
GDPPC × Climate Change			0.0000***	0.0000***
			(0.0000)	(0.0000)
LDC		-11.4713***		-11.2763***
		(0.1644)		(0.1656)
Constant	61.9920***	68.1949***	63.4307***	68.7138***
	(0.2225)	(0.1978)	(0.2407)	(0.2079)
Observations	8,388	8,388	8,388	8,388
F-statistic	1962.57***	3697.43***	1413.41***	2808.57***
R-squared	0.3204	0.5713	0.3375	0.5744
Fixed Effect	Yes	Yes	Yes	Yes

Note: (1) ***, **, * denote 1%, 5% and 10% levels of significance respectively.
(2) Numbers in parentheses are robust standard errors.

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Table 6. Panel fixed effect result of overall effect of climate change. (Sensitivity Analysis). Dependent Variable: Life Expectancy at Birth of Males.

Variables	(17)	(18)	(19)	(20)
GDPPC	0.0004***	0.0002***	0.0002***	0.0002***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Climate Change	-0.0045	-0.0090***	-0.0403***	-0.0236***
	(0.0041)	(0.0033)	(0.0048)	(0.0039)
GDPPC × Climate Change			0.0000***	0.0000***
			(0.0000)	(0.0000)
LDC		-10.5456***		-10.3814***
		(0.1586)		(0.1600)
Constant	59.4077***	65.1100***	60.6831***	65.5470***
	(0.2110)	(0.1909)	(0.2286)	(0.2009)
Observations	8,388	8,388	8,388	8,388
F-statistic	2090.11***	3606.00***	1486.73***	2731.02***
R-squared	0.3343	0.5651	0.3489	0.5676
Fixed Effect	Yes	Yes	Yes	Yes

Note: (1) ***, **, * denote 1%, 5% and 10% levels of significance respectively.
(2) Numbers in parentheses are robust standard errors.

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between GDPPC and temperature and rainfall are zero and statistically significant at 1% level of significance which posits the climate variables have no effect on life expectancy through increasing GDPPC. Most surprisingly, the effect of rainfall on life expectancy now becomes negative and statistically significant at 1% level and the interaction term between temperature and rainfall is positive and statistically significant at 1% level which implies the negative effect of temperature rise on life expectancy is compounding through the effect of temperature rise on water cycle and rainfall. In model (4), we reintroduce the LDC dummy and now the effect of rainfall on life expectancy becomes statistically insignificant though the negative effect of

Table 7. Panel fixed effect result of overall effect of climate change. (Sensitivity Analysis). Dependent Variable: Life Expectancy at Birth of Females.

Variables	(21)	(22)	(23)	(24)
GDPPC	0.0004***	0.0002***	0.0002***	0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Climate Change	-0.0165***	-0.0218***	-0.0604***	-0.0407***
	(0.0046)	(0.0036)	(0.0054)	(0.0043)
GDPPC × Climate Change			0.0000***	0.0000***
			(0.0000)	(0.0000)
LDC		-12.4837***		-12.2720***
		(0.1740)		(0.1753)
Constant	64.6566***	71.4068***	66.2203***	71.9699***
	(0.2380)	(0.2094)	(0.2573)	(0.2201)
Observations	8,388	8,388	8,388	8,388
F-statistic	1819.56***	3678.80***	1319.05***	2796.33***
R-squared	0.3042	0.5701	0.3222	0.5734
Fixed Effect	Yes	Yes	Yes	Yes

Note: (1) ***, **, * denote 1%, 5% and 10% levels of significance respectively.
(2) Numbers in parentheses are robust standard errors.

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temperature rise on life expectancy persists. In sum, the effect of temperature rise on life expectancy is consistent and negative, on the other hand, the effect of rainfall variation on life expectancy is ambiguous.

The test the robustness of our findings, we employ two sets of separate fixed effect estimations based on the gender sensitivity of males and females. Table 3 reports the fixed effect estimation for the life expectancy at birth of males. Similar to the previous findings, we find that the increase in GDP percapita has a statistically significant positive effect on the life expectancy at birth of males, holding all other factors constant. Moreover, the temperature rise has a statistically significant negative effect on the life expectancy at birth of males. The coefficient of temperature is -0.65 (Model-7), which tells us that if the annual average temperature increases by 1˚C, the life expectancy at birth of males will decline by 0.65 years or by around 8 months, holding all other factors remain the same. However, the effect of rainfall on the life expectancy at birth of males is ambiguous and statistically insignificant in some cases.

Table 4 reports the fixed effect estimation for the life expectancy at birth of females. Similar to the previous findings, we find that the increase in GDP percapita has a statistically significant positive effect on the life expectancy at birth of females, holding all other factors remain the same. Moreover, the temperature rise has a statistically significant negative effect on the life expectancy at birth of females. The coefficient of temperature is -0.91 (Model-11), which tells us that if the annual average temperature increases by 1˚C, the life expectancy at birth of females will decline by -0.91 years or by around 10 months, holding all other factors remain the same. However, the effect of rainfall on the life expectancy of birth of females is ambiguous but statistically significant.

3.2 Effect of composite climate change index on life expectancy

It is observed in the above findings that temperature rise has a negative effect on life expectancy. Moreover, temperature rise influences rainfall and brings about further negative effects on life expectancy. To test the overall effect of temperature and rainfall variation on life expectancy, we introduce the composite climate change index. Table 5 reports the result of the baseline panel fixed effect estimation for the effect of the climate change index. From Model (15), we find that GDP percapita (GDPPC) and climate change index have statistically significant on life expectancy individually at 1% level of significance. For instance, the coefficient of GDPPC is 0.0002, which tells us that if the percapita income increases by $1000, the life expectancy at birth will increase by 0.2 years, holding all other factors remain the same. The coefficient of the climate change index is -0.05, which tells us that if the annual climate change index increases by 10 points, the life expectancy at birth will decline by 0.50 years or by 6 months, holding all other factors remain the same. The interaction term between GDPPC and climate change index is zero and statistically significant at 1% level which posits that climate change has no effect on life expectancy through increasing GDPPC. We reintroduce the LDC dummy variable in fixed effect regression (16) where the LDC coefficient is -11.28 which tells us that if a country is an LDC, its life expectancy at birth is 11.28 years lower than that of the developed and developing world, holding all other factors remain the same.

The test the gender sensitivity on life expectancy, we estimate the effect of the composite climate change index on the life expectancy of males and the life expectancy of females, and the results are produced in Tables 6 and 7 respectively. The sign and significance of our findings are robust to gender sensitivity. However, results suggest that climate change would reduce the life expectancy of birth of females more than males. For instance, from Model (19), we find that if the annual climate change index increases by 10 points, the life expectancy at birth of males will decline by 0.40 years or by 5 months, holding all other factors remain the same. By contrast, from Model (23), we find that if the annual climate change index increases by 10 points, the life expectancy at birth of females will decline by 0.60 years or by 7 months, holding all other factors remain the same.

3.3 Effect of climate change on life expectancy: Graphical findings

Our above findings are supported by the post-regression fitted line plotted in STATA. For example, Fig 7 depicts a sharp negative tradeoff between temperature and life expectancy. Higher temperatures would bring about higher mortality. However, it is also observable from the graph that there are many regions of the world where increasing temperatures have a positive effect on life expectancy. It implies that higher temperatures can have both positive and negative effects on life expectancy, and the impact depends on several factors, including the magnitude and duration of the temperature increase, geographic location, and the ability of communities to adapt to changing conditions. Higher temperatures can positively influence life expectancy by reducing cold-related mortality during winter seasons in cold extreme countries [32]. Moreover, in some agricultural regions, higher temperatures and longer growing seasons can lead to increased agricultural productivity, hence enhancing food security, reducing malnutrition, and positively impacting public health. Moderate increases in temperature may improve overall comfort and well-being for some individuals, potentially reducing stress-related health issues associated with extreme cold. It's important to note that the health impacts of higher temperatures are not uniform and can vary by geographic region, socioeconomic factors, and individual health status. Vulnerable populations, such as the elderly, children, and those with limited resources, are often more severely affected by extreme heat. Efforts to mitigate the negative health effects of higher temperatures include heat action plans, improved healthcare infrastructure, public education campaigns, and efforts to reduce

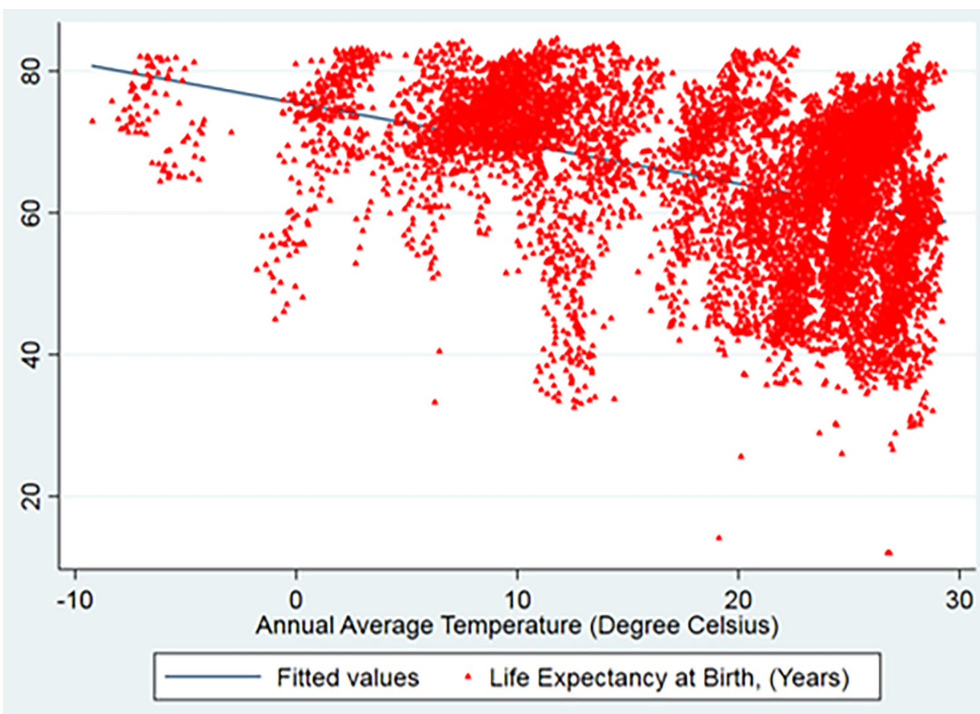

Fig 7. Regression line between temperature and life expectancy. Source: Post Estimation Plot in STATA.

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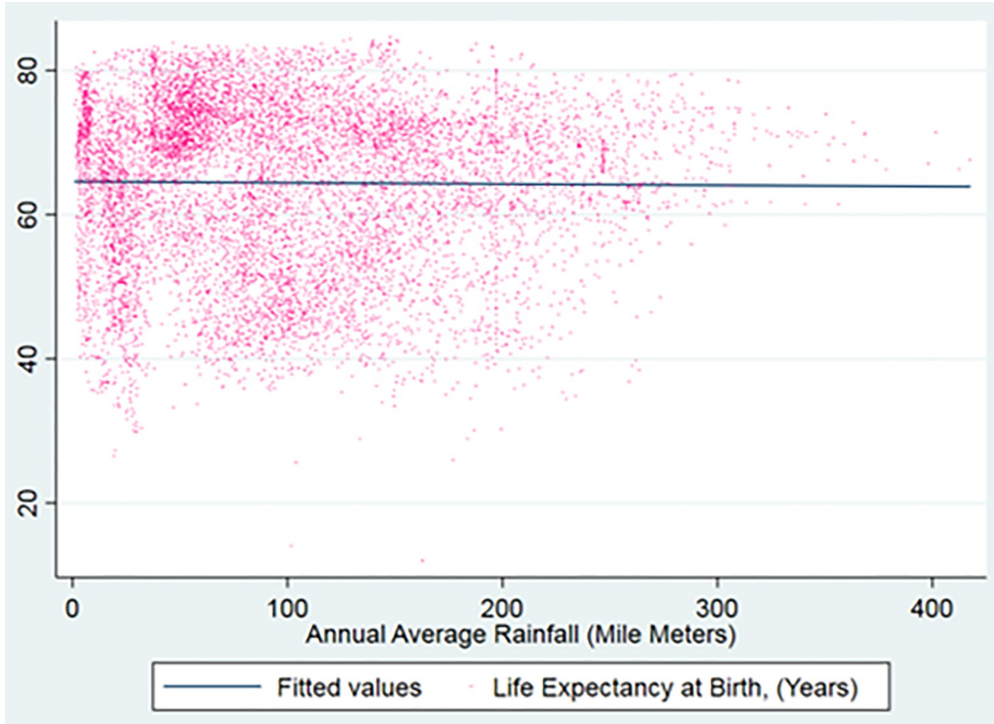

Fig 8. Regression line between rainfall and life expectancy. Source: Post Estimation Plot in STATA.

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greenhouse gas emissions to combat climate change. Adaptation and resilience-building measures are also crucial to protect human health in a warming world.

Fig 8 reveals a flat line between rainfall and life expectancy which is commensurate with findings of the ambiguous effect of rainfall on life expectancy. The relationship between rainfall and life expectancy is complex and can be influenced by numerous factors, including geographic location, temperature variability, socioeconomic conditions, and healthcare infrastructure. It is not uncommon to find mixed or ambiguous findings when studying this relationship, and a "flat line" or lack of a clear correlation is one possible outcome. For example, in regions with arid or semi-arid climates, an increase in rainfall may have a positive effect on agriculture, food production, and water availability, potentially leading to improved health outcomes. Conversely, in regions with high and consistent rainfall, too much rainfall can lead to flooding, waterborne diseases, and other health risks. Access to clean water, sanitation, healthcare, and nutrition can mitigate the negative health effects of inadequate or excessive rainfall. In areas with poor infrastructure and limited resources, the impact of rainfall on health may be more pronounced.

Fig 9, on the other hand, demonstrates a significant negative relationship between the composite climate change index and life expectancy. Higher degrees of climate change, if left unchecked, have the potential to reduce global life expectancy significantly. As temperatures rise and extreme weather events become more frequent and severe, the health risks amplify. A significant negative relationship between a composite climate change index and life expectancy suggests that as the composite climate change index worsens or indicates more severe climate change impacts, life expectancy tends to decrease. This finding implies that the adverse effects of climate change, such as extreme weather events, temperature extremes, changes in disease patterns, and environmental degradation, are having a detrimental impact on human health

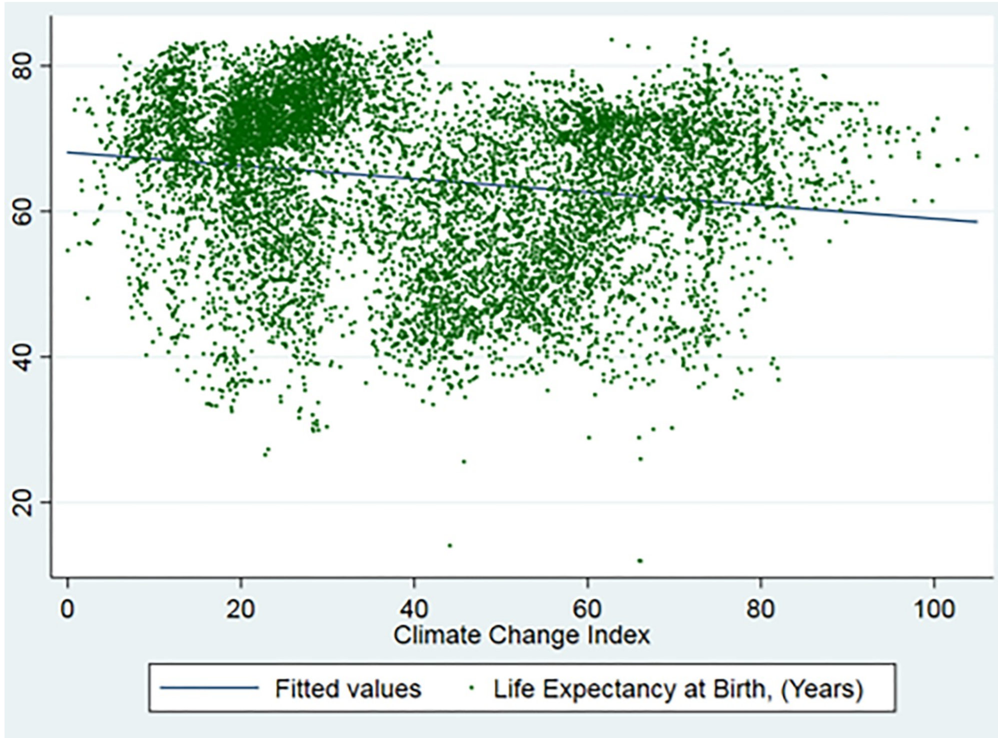

Fig 9. Regression line between climate change index and life expectancy. Source: Post Estimation Plot in STATA.

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and longevity. Such a relationship aligns with the growing body of research that highlights the harmful health consequences of climate change.

Considering the evident inverse relationship between life expectancy and both the climate change index and temperature, along with the consistently unchanging dynamic between rainfall and life expectancy, can we infer that temperature holds a more pronounced influence on life expectancy compared to precipitation. The observed negative correlation between life expectancy and the climate change index, along with the clear association with temperature trends, prompts a compelling question about the relative impact of these climatic factors. The data reveals a distinct pattern, where as temperatures increase or the climate change index rises, life expectancy tends to decrease. Moreover, the consistent flat line observed in the relationship between rainfall and life expectancy suggests that precipitation might not be as influential a factor in determining life expectancy as temperature. This inference is supported by the empirical evidence showcasing a more apparent and consistent influence of temperature on life expectancy. The negative correlation indicates that higher temperatures, often associated with climate change, are linked to a reduction in life expectancy. However, the unaltered relationship between rainfall and life expectancy implies that variations in precipitation might not play a significant role in impacting life expectancy levels. Further exploration and nuanced analyses would be instrumental in comprehensively understanding the intricate interplay between climate variables and their consequences on life expectancy.

4. Conclusion

Climate change is indeed considered one of the most significant global health threats facing humanity today. Its impact on human health is multifaceted and can be far-reaching. Climate change is already impacting health in a myriad of ways through direct and indirect mechanisms. This paper develops a framework to identify and integrate these mechanisms. Moreover, this paper estimates the effect of climate change on life expectancy using cross-national panel data from 191 countries covering the period 1940–2020. Our findings suggest that temperature rise will negatively affect life expectancy. Moreover, an increase in temperature will further negatively impact life expectancy by interacting with the rainfall cycle. Moreover, our findings reveal that climate change disproportionately reduces the life expectancy of females more than the life expectancy of males. Thus, countries should come forward with prompt initiatives to contain global temperature rise and protect the health of the population on the verge of climate change. To address these health impacts, it is crucial to mitigate climate change by reducing greenhouse gas emissions and adapting to the changes that are already occurring [33]. Additionally, public health measures, disaster preparedness, and healthcare infrastructure improvements can enhance resilience and reduce the health risks associated with climate change. Recognizing the interconnectedness of climate and health is essential for developing effective strategies to protect human well-being in a changing climate. Otherwise, climate change threats may also accumulate over time, leading to longer-term changes in resilience and health. Moreover, our findings suggest that climate disruption and its associated natural calamities are not evenly distributed globally. Some regions, particularly, the least developed countries (LDC) are more vulnerable due to their geographic location, socioeconomic factors, and existing levels of resilience and preparedness [34]. Mitigating the impacts of climate change and implementing adaptation strategies are crucial steps in reducing these health risks and protecting human life expectancy [35].

This identified research gap opens up a new avenue for scholarly exploration, encouraging investigators to explore the nuanced relationships between climate-induced disasters and their potential repercussions on life expectancy. By expanding the scope to include a broader array of climate-related events, such as hurricanes, floods, and wildfires, researchers can obtain a more comprehensive understanding of the multifaceted impacts of climate change on human health. Furthermore, it is crucial to recognize that the effect of climate change on life expectancy is not universally uniform. Rather, it varies significantly based on local conditions, vulnerabilities, and geographical specifics. To unravel these complexities, researchers frequently conduct region-specific analyses that carefully consider the unique characteristics of each area under investigation. The study's emphasis on the regional nuances of the climate change-life expectancy relationship is a crucial recognition of the diverse impacts felt by different communities. Future research endeavors could benefit from adopting a localized approach, tailoring investigations to the specific vulnerabilities, adaptive capacities, and environmental contexts of distinct regions. This targeted analysis would provide a more accurate and contextually relevant understanding of the intricate interplay between climate change and life expectancy.

Moreover, it's crucial to acknowledge certain limitations associated with estimating the climate change index, particularly when considering various scenarios that encompass fluctuations in both temperature and rainfall. In instances where temperatures rise while rainfall experiences a decrease, the traditional index may face limitations in distinguishing between the individual contributions of each factor. The geometric mean might not fully encapsulate the nuanced impact of temperature increases and reduced rainfall on the overall climate change scenario. This limitation could potentially lead to underestimating the severity of certain climatic changes. In situations where temperature decreases while rainfall increases, the geometric mean may not distinctly reflect the intricate dynamics at play. The index might not adequately convey the potential complexities arising from contrasting trends in temperature and rainfall. This limitation could result in an oversimplified representation of the climate change scenario, overlooking the intricate interplay between these two factors. When both temperature and rainfall remain within normal ranges, the geometric mean may not effectively discern the absence of extreme climatic variations. The index might not adequately capture the subtleties associated with stable climatic conditions, potentially leading to an overemphasis on the index's sensitivity to extreme changes. This limitation highlights the need for additional indicators or adjustments when assessing scenarios of climatic stability. It is essential to recognize that the proposed composite climate change index, while innovative, may encounter challenges in accurately capturing the diversity of climate change scenarios. These limitations underscore the importance of complementing the index with a comprehensive analysis that considers multiple indicators and accounts for the intricacies associated with varying temperature and rainfall patterns. Addressing these limitations will contribute to a more nuanced and accurate understanding of the impact of climate change in diverse environmental contexts. All remaining errors are of the author and suggestions are welcomed.

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Writing – original draft: Amit Roy.

Writing – review & editing: Amit Roy.

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