El Niño 2023 and future climate change exacerbates public health crises in Kenya

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Abstract

In Kenya, the heavy rains in April 2024, which triggered flash floods that killed at least 228 people, left 72 others missing and displaced more than 212,000 people, were linked to El Niño 2023. El Niño can trigger extreme events around the globe, causing severe damage to people, animals, and ecosystems. This paper examines the vulnerability of Kenya’s regional health sectors to the 2023 El Niño event and future climate change under different CO2 emission pathways. Using a spatio-temporal analysis of temperature, precipitation, and relative humidity, we show that El Niño led to a significant increase in temperature from May to October 2023 compared to 2022, while extreme precipitation and relative humidity were observed in November. The northeastern region is the most vulnerable to extreme weather events, followed by the eastern region, the coastal region, and the upper parts of the Rift Valley. Future projections show that under SSP3 and higher emission scenarios, the risk of these regions being exposed to extreme heatwaves will increase by more than 60% by 2100. There is an urgent need to address the potential health impacts in vulnerable regions and to prepare and intervene early to prevent future health crises related to ENSO events. We recommend prioritizing these regions in the development of health facilities in Kenya, improving emergency medical care, expanding green spaces, practicing regular hydration, and introducing adequate domestic ventilation to combat health crises from future extreme climate events.
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Abstract. In Kenya, the heavy rains in April 2024, which triggered flash floods that killed at least 228 people, left 72 others missing and displaced more than 212,000 people, were linked to El Niño 2023. El Niño can trigger extreme events around the globe, causing severe damage to people, animals, and ecosystems. This paper examines the vulnerability of Kenya’s regional health sectors to the 2023 El Niño event and future climate change under different CO2 emission pathways. Using a spatio-temporal analysis of temperature, precipitation, and relative humidity, we show that El Niño led to a significant increase in temperature from May to October 2023 compared to 2022, while extreme precipitation and relative humidity were observed in November. The northeastern region is the most vulnerable to extreme weather events, followed by the eastern region, the coastal region, and the upper parts of the Rift Valley. Future projections show that under SSP3 and higher emission scenarios, the risk of these regions being exposed to extreme heatwaves will increase by more than 60% by 2100. There is an urgent need to address the potential health impacts in vulnerable regions and to prepare and intervene early to prevent future health crises related to ENSO events. We recommend prioritizing these regions in the development of health facilities in Kenya, improving emergency medical care, expanding green spaces, practicing regular hydration, and introducing adequate domestic ventilation to combat health crises from future extreme climate events.

Plain Language Summary

Following the successive El Niño-related flooding disasters that struck Kenya in 2023 and 2024, resulting in huge material losses and deaths, we examine Kenya’s vulnerability to ENSO-induced public health disasters. A closer look was taken at which of the country’s administrative regions are most vulnerable to the extreme events. Through spatio-temporal analysis of meteorological variables in 2023 compared to the previous year and climatology, we show that El Nino in 2023 led to a significant increase in near-surface temperatures from May to October, while extreme rainfall and humidity were observed in November. Residents of the Northeastern region, followed by the northern parts of the Eastern and Rift Valley regions, are most at risk of extreme heat and humidity-related diseases, while the Northeastern, Coastal, Nairobi, Central, Western, and Nyanza regions are most at risk of extreme rainfall and flood-related disasters and diseases. Future projections show that the number of very hot days will increase in the transition from SSP1 to SSP5 from 2030 to 2100, with residents of the Northeastern
region being most vulnerable to heatwave-related diseases. These findings will help the Kenyan government, non-governmental organizations, and other stakeholders involved in improving public health in Kenya to implement better health policies.

**Keywords**: El Niño 2023, Floods, Heatwaves, Public health, Future projections, Kenya.

1 Introduction

The El Niño Southern Oscillation (ENSO) is a natural phenomenon in which the water in the tropical Pacific warms (El Nino) or cools (La Nina) more than the surrounding water [Climate Prediction Center (2023)]. These extreme conditions can affect ocean currents and atmospheric circulation patterns, cause extreme weather conditions around the world, and cause serious damage to the environment and health ([World Health Organization, 2023](#)). Three of the most common extreme events associated with El Niño are heatwaves, floods, and droughts. Heat waves in particular can cause health problems such as heat strokes, strokes, mental instability, anger and rage, dehydration, the spread of airborne diseases, and death [Flores Ramos (2020); Kapwata et al. (2022); Adigun et al. (2024)](#). Droughts can cause the death of people and animals and the contamination of drinking water systems. Floods can lead to the destruction of houses, public infrastructure and death. For example, in 2023, severe flooding in Kenya due to El Niño displaced hundreds of people and killed others. The floods washed away houses, roads turned into raging rivers, and public infrastructures were destroyed ([Al Jazeera, 2024](#)). The floods also destroyed hundreds of hectares of farmland and caused the death of hundreds of livestock. Sadly, in April 2024, Kenya experienced one of the most devastating floods in its history, killing at least 228 people, leaving 72 others missing, and displacing more than 212,000 people ([Aljazeera, 2024; Larry Madowo and Helen Regan, 2024](#)). This catastrophic event has been linked to El Nino, which began in April 2023. 

El Nino has been shown to alter rainfall patterns, bringing extreme rainfall that leads to flooding and droughts that can seriously affect agricultural activities, infrastructure, and the economy ([Sazib et al., 2020; De Matos, 2023; Ağlamaz, 2023; Xiong et al., 2021; Moore et al., 2017; Who, 2023](#)).

Analysing the impact of El Nino on public health and taking public health measures to mitigate its effects is an important area. [Rony et al. (Rony et al., 2024](#)) conducted a comprehensive literature review that included scientific publications, professional articles, and relevant grey literature to examine the link between El Nino and public health impacts and approaches to improve preparedness. The research found that the occurrence of El Nino events is linked to various health issues such as heat-related diseases, vector-borne diseases, water-borne diseases, and changes in air quality, and also identified which vulnerable groups are at risk. Key preparedness measures proposed include early warning systems, health infrastructure preparedness, and communication strategies. Other researchers have also linked incidents such as vector-borne diseases, heat waves, smoke pollution from forest fires, air pollution, health problems from drought, and nutrition to ENSO events ([Bouma et al., 1997; Gagnon et al., 2001; Kovats et al., 2003; Ototo et al., 2011](#)) as well as outbreaks of infectious diseases. Variations in rainfall, humidity, and temperature patterns associated with climate change affect health by altering the ecology of certain vector-borne diseases such as rift valley fever, malaria, and dengue ([Dhiman et al., 2008; Anyamba et al., 2019](#)). Diseases such as cholera and diarrhea are often caused by contaminated water supplies from floods that result from heavy rainfall, a major factor in the
contamination of surface water with sewage Kovats et al. (2003); Moore et al. (2017). Severe cholera outbreaks occurred in 1997 as a result of heavy rainfall and flooding (Pascual et al., 2000).

Natural disasters associated with ENSO events have varying impacts on public health by disrupting health services, damaging infrastructure, or shifting medical and political priorities (Kovats et al., 2003). Drought occurs twice as often in the years following the onset of El Nino than in non-El Nino years. Drought can lead to an increased concentration of pathogens in surface water and to hygiene-related diseases. In Peru, during the 1997-1998 El Nino event, there was an increased number of children hospitalized with diarrhea, which was linked to the higher than average (Organization et al., 1998). ENSO-related drought also leads to an increased rate of forest fires, resulting in smoke pollution both locally and globally. Respiratory diseases and other harmful effects are caused by inhaling this fire smoke. El Nino events are influenced by changes in the climate, including the concentration of greenhouse gas emissions such as CO$_2$ in the atmosphere. Although the percentage of global greenhouse gas emissions in middle- and low-income countries is low, their populations are likely to be negatively affected by climate change, which in turn will further exacerbate regional health problems (Patz and Olson, 2006; Wiley and Gostin, 2009). The most vulnerable population groups include the elderly, people living in poverty, displaced people, especially women and children, and the urban population (World Health Organization).

Due to the successive floods that hit Kenya in 2023 and 2024, the objective of this work is to conduct a thorough spatio-temporal analysis of climate variables in 2023 and compare them with those of 2022 and climatology to determine the presence and degree of impact of El Nino on public health vulnerability in Kenya, focusing on the most vulnerable regions. This approach provides important insights into which Kenyan regions are more vulnerable to these changes and their impact on public health crises and policies. In addition, the future projections under different CO$_2$ emission scenarios provide valuable insights into long-term planning and mitigation policies and emphasize the importance of adhering to the terms of the Paris Agreement.

Later in the paper, in section 2, we present the data we used, their description, and the methods we employed for our analysis in section 2. Section 3 presents the results and discussion of our findings, and we conclude in section 4.

2 Data and Method

The datasets used in this project have been retrieved from two sources: the ERA5 and the CMIP6 datasets from the Copernicus Climate Data Store (CDS) which is part of Copernicus Change Services (C3S) of the European Centre for Medium-Range Weather Forecasts (ECMWF) and drought data from the Global Drought Crops Monitoring which are both open source platforms.

2.1 ERA5 Dataset

The ERA5 dataset available from 1940 to the present was used (Hersbach et al., 2023). The dataset has horizontal resolution of $0.25^\circ \times 0.25^\circ$ atmosphere and $0.5^\circ \times 0.5^\circ$ ocean waves, for the reanalysis. We have used in this study the monthly average surface temperature, precipitation, and dew point from 1991 to 2023 over Kenya, which is located between latitudes 5°N and 4°S and longitudes 33°E and 42°E with a total area of 582,646 km$^2$. Kenya is bordered to the north by South Sudan.
and Ethiopia, to the east by Somalia, to the west by Uganda, to the south by Tanzania, and to the southeast by the Indian Ocean. Kenya is divided into eight regions namely Central, Coastal, Eastern, Nairobi, North Eastern, Nyanza, Rift Valley, and Western as shown in Figure 1. Kenya has different climatic zones due to its topography, including its nearness to the Indian Ocean, plateaus, high mountains, Rift Valley, and Lake Victoria, the largest freshwater lake in Africa. Temperatures in Kenya vary across the regions with the highlands experiencing cooler temperatures and agricultural riches compared to coastal and lowland regions. Western Kenya which is along Lake Victoria is generally wet with the northeastern and northern regions being arid. Most parts of the country experience two rainy seasons with long rains from March to May and short rains from October to December. The average annual precipitation is around 680 mm which ranges from less than 250mm in the northern areas to about 2000mm in the western regions.

Since the ERA5 dataset doesn’t have relative humidity as a variable, we use the air temperature and dew point temperature to compute the relative humidity. The dew point parameter represents air temperature at 2m above the Earth’s surface that would have to be cooled for the saturation to take place. Using Magnus Dew point formula (Lawrence, 2005)

\[ T_d = \frac{273.04 \times X}{17.625 - X} \]  

and

\[ X = \ln\left(\frac{Rh}{100}\right) + \frac{(17.625 \times T)}{237.3 + T} \]

where \( T \) is air temperature, \( T_d \) is the dew point, \( Rh \) is the relative humidity and 17.625 and 243.04 are revised Magnus coefficients.

### 2.2 Coupled model intercomparison project (CMIP6) dataset

The CMIP6 Model dataset used in this study is the GFDL-ESM4, which is a fourth generation of the Geophysical Fluid Dynamics Laboratory (GFDL) from the National Oceanic and Atmospheric Administration (NOAA) in the United States for our future projections of temperatures under different greenhouse gas emissions scenarios. The mean daily data has a horizontal resolution of 1° for the atmosphere and 0.5° for the ocean Earth System (ESM4). The data covers a historical period from 1850 to 2014. In this work, We focused on the years 2030, 2050, and 2100 to project daily maximum and near-surface temperatures. The emission scenarios considered are SSP1-2.6 (Sustainable development scenario), SSP3-7.0 (Regional rivalry scenario), and SSP5-8.5 (Fossil fuel-driven development scenario) or the "worst case scenario" (Climate Neutral Group, 2021). In general, these SSPs help in understanding how the current levels of greenhouse gas emissions may affect warming in the future years. The emission scenario SSP1-2.6 is a scenario with climate policy while SSP3-7.0 and SSP5-8.5 are scenarios with no climate policy of achieving climate targets.
Figure 1. Map of Africa indicating the location of Kenya (a) (https://images.app.goo.gl/iUUcmztDYXJKRMz8) and (b) (https://images.app.goo.gl/BnenDpAbAakAK1P8) is the map of Kenya showing its administrative regions. In (c), (d), (e), and (f), we examine the 2022 SST, 2023 SST, the 2023 SST anomaly compared to the (1991 to 2020) baseline, and the SST difference between 2023 and 2022 respectively. This figure shows the strong presence of El Nino as indicated in the black rectangular box.
2.3 Global SPEI dataset

The Global SPEI database offers real-time information about drought conditions at the global scale, with a 0.5° spatial resolution and a monthly time resolution (LCSC: Climatology and Climate Services Laboratory). SPEI time-scales range from 0.5 to 48 months which is provided by its multi-scale nature. It is based on monthly precipitation and potential evapotranspiration data from the Laboratory of Climate Services and Climatology (LCSC), starting in January 1901, and it is updated as soon as new data becomes available.

2.4 Descriptive statistics of datasets

Table 1 gives an overview of the summary statistics for the variables used from the ERA5 dataset which are calculated from 1991 to 2023. Sea surface temperature (SST) is for the global dataset while the other variables which are air temperature, precipitation, and relative humidity are for Kenya. The statistics provided include the mean, minimum, maximum, median, and standard deviation which serve as a foundation for our analysis of climate trends and patterns. Units of each variable is also included to quantify physical properties.

Table 1. Summary statistics of meteorological variables

<table>
<thead>
<tr>
<th>SST (°C)</th>
<th>2m air temperature (°C)</th>
<th>Precipitation (mm)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>13.78</td>
<td>24.91</td>
<td>2.19</td>
</tr>
<tr>
<td>Std</td>
<td>8.08</td>
<td>3.61</td>
<td>3.18</td>
</tr>
<tr>
<td>Minimum</td>
<td>-3.88</td>
<td>10.98</td>
<td>-1.39</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>1.09</td>
<td>22.61</td>
<td>0.24</td>
</tr>
<tr>
<td>Median</td>
<td>14.76</td>
<td>25.27</td>
<td>1.10</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>25.54</td>
<td>27.61</td>
<td>3.03</td>
</tr>
<tr>
<td>Maximum</td>
<td>36.53</td>
<td>34.97</td>
<td>125.80</td>
</tr>
</tbody>
</table>

We calculate anomalies by taking the mean of 2023 data and subtracting it from the baseline (1991 to 2020) mean which covers 30 years. The mean changes with the previous year were calculated by subtracting 2022 means from 2023. Heatwaves and hot spells indices have been calculated using the Xclim package in Python (https://github.com/Ouranosinc/xclim/tree/main/docs/notebooks) by setting the threshold maximum daily temperatures to 30°C for the hot spells index, and using the near-surface daily temperature and setting the threshold temperature to 25°C for the heatwave index.

3 Results and Discussions

To reveal the impact of El Nino, we analyze near-surface temperature, total precipitation, relative humidity, and drought indices for 2023 and compare them with those of 2022 and with climatology. Figure 2 shows that the northern parts of the eastern
and northeastern regions and the Rift Valley recorded higher temperatures than in 2022, while all regions recorded higher
temperatures in 2023 than in the climatology. Rainfall anomalies are highest in the Northeast, East, West, and Nyanza regions.
High humidity and droughts are observed around Nyanza, Nairobi, and the Coast region, with more droughts occurring in
most regions compared to climatology. The figure shows that the Northeastern region, followed by the northern parts of the
Eastern and Rift Valley regions are most prone to extreme heat and humidity events, while the Northeastern, Coastal, Central,
Nairobi, Western, and Nyanza regions are most prone to extreme rainfall events. All regions are prone to severe droughts,
with the coastal regions and the northern part of the Rift Valley region being less vulnerable. A large proportion of Kenya’s
population lives in the central region, which includes Nairobi, the southern part of the Rift Valley, Nyanza, the coastal region,
and the western regions. These populations are likely to be more vulnerable to extreme rainfall, humidity, and drought than
those living in the northern part of the country. On the other hand, the inhabitants of the northern and coastal parts of the
country are more exposed to extreme heat waves than the inhabitants of the south and the highland areas of Nairobi.

In figure 3, we examine the development of surface temperature, precipitation, and relative humidity in Kenya and compare
the changes in these variables in 2023 compared to 2022 and the climatology. This figure shows an increasing trend in surface
temperature in Kenya, with 2023 being one of the warmest on record. The monthly time series shows that temperatures from
May to October 2023 were significantly higher compared to 2022. This period coincides with the onset of the El Nino event that
started in April, the previous month. The precipitation development shows a slightly decreasing trend under climate change,
with a positive anomaly in 2023. The monthly time series shows extreme rainfall around November compared to 2022. Relative
humidity shows a similar characteristic to rainfall but with a negative anomaly in 2023. Some parts of Kenya experienced flash
floods in November 2023 leading to the destruction of properties and deaths were recorded. This figure also shows under
increasing regional warming, the probability of more intense El Nino impacts is higher in the future. We have identified the
most vulnerable regions to precipitation extremes and heat waves. This information will help in better decision-making by both
the local Government and the population to prepare against future extreme weather events.

**Future projection**

To assess the health vulnerability of Kenyan regions under future climate change, we analyze the duration of hot spells and
heatwave episodes under different SSP CO2 emission scenarios in 2030, 2050, and 2100. The duration of the hot spell was
calculated using the daily maximum temperature data and by setting 30° as the threshold temperature, while for heatwaves,
the near-surface temperature data was used with 25° set as the threshold temperature. Figure 4 (a) to (i) shows heat maps of
hot spell duration, that is, the number of days when the daily maximum surface temperature exceeds 30° in the years 2023,
2050, and 2100 under SSP1-2.6, SSP3-7.0, and SSP5-8.5, respectively. This figure shows that the number of hot spell days
increases in the transition from SSP1 to SSP5 from 2030 to 2100, with the northeastern region being the most vulnerable,
followed by the eastern region and the northern part of the Rift Valley region. Even controlling for CO2 emissions, the coastal
region will become hotter by 2100, but even hotter under scenarios with higher CO2 emissions. This analysis also shows that
the urbanized region of Nairobi will experience a higher number of very hot days from 2050 under SSP3 and higher emission
scenarios. Figure 5 shows a similar pattern in the duration of heatwave indices, with heatwave exposure increasing under SSP3
Figure 2. The 2m surface temperature (a, b, c), total precipitation (d, e, f), relative humidity (g, h, i), and droughts indices (j, k, l) for 2023 (a, d, g, j), the difference between 2023 and 2022 (b, e, h, k), and anomalies (c, f, i, l) respectively are shown. These figures show higher temperatures recorded in the northern parts of Eastern, Northeastern, and the Rift Valley regions compared to 2022 while all regions experienced higher temperatures in 2023 compared to climatology. Precipitation anomalies are shown to be highest in the Northeastern, Eastern, and Nyanza regions. High humidity and droughts are observed around Nyanza, Nairobi, and the coastal region with most regions experiencing higher droughts compared to climatology.
Onset of El Niño

Figure 3. Multidecadal temperature time series in Kenya (a), anomaly bar charts (b), and monthly time series of 2023 compared to 2022 (c). Precipitation time series (d), anomaly bar charts (e), and monthly time series of 2023 compared to 2022 (f). Relative humidity time series (g), anomaly bar charts (h), and monthly time series of 2023 compared to 2022 (i) are shown. This figure shows an increasing trend in near-surface temperature in Kenya, with the year 2023 as one of the hottest temperatures on record. The monthly time series shows from May to October 2023, temperatures were significantly higher compared to 2022. This coincides with the onset of the El Nino event. Precipitation evolution shows a slightly declining trend under climate change with 2023 recording a positive anomaly. The monthly time series shows extreme precipitation around November compared to 2022. Relative humidity has a similar characteristic as precipitation but with a negative anomaly in 2023.
and higher emission scenarios. Figures 4 (j) and 5 (j) show the mean hot spells and heatwave duration under the different emission scenarios considered. These figures show the number of very hot days will significantly grow by more than 60% under SSP3 and higher emission scenarios by the year 2100.

Many studies have carried out a similar analysis in this paper to associate climate extremes with public health crises. Adigun et al. (2024) investigated the impacts of human activities on the intensification of heatwaves over the historical period and the risk of heat-related mortality under two Representative Concentration Pathways (RCP26) and (RCP60) was projected in Africa. Excess Heat Factor (EHF) was used to measure heatwaves with two heat factors combined in EHF to determine the overall excess heat. Their results verified that the recent intensification is due to anthropogenic activity such as increased concentration of greenhouse gases and shifts in land usage. They highlighted the possible future effects of heatwave conditions which result from climate change and socioeconomic issues as well as the increasing risk of heatwaves in Africa becoming more intense.

The study emphasizes the need for emissions reduction and adaptation strategies, particularly given Africa’s low adaptive capacity. Heatwaves affect human health to an extent that goes beyond illness to death. Health effects related to heatwaves are not only associated with the physical phenomena of heat itself but also other factors like duration, frequency, and intensity of heatwaves. Kapwata et al. (2022) analyzed past heatwave data focused on South Africa where they identified impacts on mortality associated with the diurnal temperature range (DTR) threshold used for defining heatwaves. Severe heatwaves were identified in late 2015 to early 2016 that coincided with the El Niño event which took place during that period. Di Napoli et al. (2022) equally conducted a study whose aim was to monitor and to better understand how climate change affects human health through indicators such as climate change impacts, exposures, and vulnerability indicators (CCIEVIs). The purpose of indicators was to capture ways in which climate change and human health interact. The hazard, exposure, and vulnerability framework was used to define CCIEVIs according to data availability and their significance to both human health and climate change. The findings of the study provide insights into indicator development and application for monitoring and addressing climate-related health impacts.

In this work, through spatio-temporal analysis, we have investigated the El Niño 2023 impacts on surface temperature, precipitation, and relative humidity in Kenya with a focus on the most vulnerable regions to heat, floods, and high humidity-related illnesses. We have used hot spells and heatwave indices to classify these regions according to vulnerability levels. Our results tie in with previous results carried out on the health impacts of El Niño and other extreme weather events.

4 Conclusions

As a result of the successive flood disasters that hit Kenya in 2023 and 2024, we conducted a thorough spatio-temporal analysis of climate variables in 2023 and compared them with 2022 and climatology to determine the presence and degree of El Niño impact on public health vulnerability in Kenya, focusing on the most vulnerable regions. Our approach provides important insights into which Kenyan regions are more vulnerable to these changes and their impact on public health crises and policies. In addition, we conducted an analysis of the potential health impacts of future climate change under different CO₂ emission scenarios. Our approach provides valuable insights into the potential health impacts of future climate change for long-term
Figure 4. The hot spells analysis under different SSP scenarios are shown. The year 2030 for SSP1-2.6 (a), SSP3-7.0 (b), and SSP5-8.5 (c) are presented. The plots (d, e, f) and (g, h, i) are for the years 2050 and 2100 respectively while (j) presents the average number of days in which $30^\circ$ is exceeded under different emission scenarios.
Figure 5. The heatwave duration analysis under different SSP scenarios is shown. The year 2030 for SSP1-2.6 (a), SSP3-7.0 (b), and SSP5-8.5 (c) are presented. The plots (d, e, f) and (g, h, i) are for the years 2050 and 2100 respectively while (j) presents the average number of days in which 30° is exceeded under different emission scenarios.
planning and early implementation of climate change mitigation measures and underlines the importance of adhering to the terms of the Paris Agreement. We have shown that El Niño led to a significant increase in temperature from May to October 2023 compared to 2022, while extreme precipitation and relative humidity were observed in November. The northeastern region is most at risk, followed by the eastern region, the coastal region and the upper parts of the Rift Valley. Future projections showed that under SSP3 and higher emission scenarios, the risk of these regions being exposed to extreme heatwaves and heat spells will increase by more than 60% by 2100. These projected extreme events can lead to health problems such as heat strokes, strokes, mental instability, anger and rage, dehydration, the spread of airborne diseases, and death. A significant proportion of Kenya’s population lives in the central region where the capital Nairobi is located, the southern part of the Rift Valley, Nyanza, the coastal regions, and the western regions. These populations are likely to be more vulnerable to extreme rainfall, humidity, and drought than the inhabitants in the northern part of the country. Health-wise, these regions are more vulnerable to vector and waterborne diseases.

There is, therefore, an urgent need to address the potential health impacts in vulnerable regions and to prepare and intervene early to prevent future health crises related to ENSO events. We recommend prioritizing these regions in the development of health facilities in Kenya, improving emergency medical care, expanding green spaces, practicing regular hydration, and introducing adequate domestic ventilation to combat health crises from future extreme climate events.

4.1 Future works

- To get a more comprehensive understanding of the relationship between El Nino events and impacts on public health, gathering a wide range of climate and health data from various sources, analyzing historical data and health monitoring records is recommended for future works.

- Utilizing spatial analysis techniques like GIS mapping and spatial modeling can also be applied to identify in detail the specific areas that are at the highest risks of El-related health impacts to help in prioritizing them during such events.

- Machine learning algorithms can be integrated to analyze datasets related to climate change and public health in order to identify the correlations, complex patterns, and predictive models for forecasting future health impacts.

Author contributions. NAA conceived the project. EKK and ANN provided the data. All authors carried out the analysis and wrote the paper.

Competing interests. The authors declare no competing interest.

Disclaimer. All the analysis and plots have been generated exclusively by the authors. No graphs or plots or materials have been taken from anywhere without permission or references.
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**Keywords**: El Niño 2023, Floods, Heatwaves, Public health, Future projections, Kenya.

1 Introduction

The El Niño Southern Oscillation (ENSO) is a natural phenomenon in which the water in the tropical Pacific warms (El Niño) or cools (La Niña) more than the surrounding water (Climate Prediction Center, 2023). These extreme conditions can affect ocean currents and atmospheric circulation patterns, cause extreme weather conditions around the world, and cause serious damage to the environment and health (World Health Organization, 2023). Three of the most common extreme events associated with El Niño are heatwaves, floods, and droughts. Heat waves in particular can cause health problems such as heat strokes, strokes, mental instability, anger and rage, dehydration, the spread of airborne diseases, and death (Flores Ramos, 2020; Kapwata et al., 2022; Adigun et al., 2024). Droughts can cause the death of people and animals and the contamination of drinking water systems. Floods can lead to the destruction of houses, public infrastructure and death. For example, in 2023, severe flooding in Kenya due to El Niño displaced hundreds of people and killed others. The floods washed away houses, roads turned into raging rivers, and public infrastructures were destroyed (Al Jazeera, 2024). The floods also destroyed hundreds of hectares of farmland and caused the death of hundreds of livestock. Sadly, in April 2024, Kenya experienced one of the most devastating floods in its history, killing at least 228 people, leaving 72 others missing, and displacing more than 212,000 people (Aljazeera, 2024; Larry Madowo and Helen Regan, 2024). This catastrophic event has been linked to El Nino, which began in April 2023. El Nino has been shown to alter rainfall patterns, bringing extreme rainfall that leads to flooding and droughts that can seriously affect agricultural activities, infrastructure, and the economy (Sazib et al., 2020; De Matos, 2023; Ağlamaz, 2023; Xiong et al., 2021; Moore et al., 2017; Who, 2023).

Analysing the impact of El Nino on public health and taking public health measures to mitigate its effects is an important area. Rony et al. (Rony et al., 2024) conducted a comprehensive literature review that included scientific publications, professional articles, and relevant grey literature to examine the link between El Nino and public health impacts and approaches to improve preparedness. The research found that the occurrence of El Nino events is linked to various health issues such as heat-related diseases, vector-borne diseases, water-borne diseases, and changes in air quality, and also identified which vulnerable groups are at risk. Key preparedness measures proposed include early warning systems, health infrastructure preparedness, and communication strategies. Other researchers have also linked incidents such as vector-borne diseases, heat waves, smoke pollution from forest fires, air pollution, health problems from drought, and nutrition to ENSO events (Bouma et al., 1997; Gagnon et al., 2001; Kovats et al., 2003; Ototo et al., 2011) as well as outbreaks of infectious diseases. Variations in rainfall, humidity, and temperature patterns associated with climate change affect health by altering the ecology of certain vector-borne diseases such as rift valley fever, malaria, and dengue (Dhiman et al., 2008; Anyamba et al., 2019). Diseases such as cholera and diarrhea are often caused by contaminated water supplies from floods that result from heavy rainfall, a major factor in the
contamination of surface water with sewage Kovats et al. (2003); Moore et al. (2017). Severe cholera outbreaks occurred in 1997 as a result of heavy rainfall and flooding (Pascual et al., 2000).

Natural disasters associated with ENSO events have varying impacts on public health by disrupting health services, damaging infrastructure, or shifting medical and political priorities (Kovats et al., 2003). Drought occurs twice as often in the years following the onset of El Nino than in non-El Nino years. Drought can lead to an increased concentration of pathogens in surface water and to hygiene-related diseases. In Peru, during the 1997-1998 El Nino event, there was an increased number of children hospitalized with diarrhea, which was linked to the higher than average (Organization et al., 1998). ENSO-related drought also leads to an increased rate of forest fires, resulting in smoke pollution both locally and globally. Respiratory diseases and other harmful effects are caused by inhaling this fire smoke. El Nino events are influenced by changes in the climate, including the concentration of greenhouse gas emissions such as CO$_2$ in the atmosphere. Although the percentage of global greenhouse gas emissions in middle- and low-income countries is low, their populations are likely to be negatively affected by climate change, which in turn will further exacerbate regional health problems (Patz and Olson, 2006; Wiley and Gostin, 2009). The most vulnerable population groups include the elderly, people living in poverty, displaced people, especially women and children, and the urban population (World Health Organization).

Due to the successive floods that hit Kenya in 2023 and 2024, the objective of this work is to conduct a thorough spatio-temporal analysis of climate variables in 2023 and compare them with those of 2022 and climatology to determine the presence and degree of impact of El Nino on public health vulnerability in Kenya, focusing on the most vulnerable regions. This approach provides important insights into which Kenyan regions are more vulnerable to these changes and their impact on public health crises and policies. In addition, the future projections under different CO$_2$ emission scenarios provide valuable insights into long-term planning and mitigation policies and emphasize the importance of adhering to the terms of the Paris Agreement. Later in the paper, in section 2, we present the data we used, their description, and the methods we employed for our analysis in section 2. Section 3 presents the results and discussion of our findings, and we conclude in section 4.

2 Data and Method

The datasets used in this project have been retrieved from two sources: the ERA5 and the CMIP6 datasets from the Copernicus Climate Data Store (CDS) which is part of Copernicus Change Services (C3S) of the European Centre for Medium-Range Weather Forecasts (ECMWF) and drought data from the Global Drought Crops Monitoring which are both open source platforms.

2.1 ERA5 Dataset

The ERA5 dataset available from 1940 to the present was used (Hersbach et al., 2023). The dataset has horizontal resolution of $0.25^\circ \times 0.25^\circ$ atmosphere and $0.5^\circ \times 0.5^\circ$ ocean waves, for the reanalysis. We have used in this study the monthly average surface temperature, precipitation, and dew point from 1991 to 2023 over Kenya, which is located between latitudes 5°N and 4°S and longitudes 33°E and 42°E with a total area of 582,646 km$^2$. Kenya is bordered to the north by South Sudan
and Ethiopia, to the east by Somalia, to the west by Uganda, to the south by Tanzania, and to the southeast by the Indian Ocean. Kenya is divided into eight regions namely Central, Coastal, Eastern, Nairobi, North Eastern, Nyanza, Rift Valley, and Western as shown in Figure 1. Kenya has different climatic zones due to its topography, including its nearness to the Indian Ocean, plateaus, high mountains, Rift Valley, and Lake Victoria, the largest freshwater lake in Africa. Temperatures in Kenya vary across the regions with the highlands experiencing cooler temperatures and agricultural riches compared to coastal and lowland regions. Western Kenya which is along Lake Victoria is generally wet with the northeastern and northern regions being arid. Most parts of the country experience two rainy seasons with long rains from March to May and short rains from October to December. The average annual precipitation is around 680 mm which ranges from less than 250 mm in the northern areas to about 2000 mm in the western regions.

Since the ERA5 dataset doesn’t have relative humidity as a variable, we use the air temperature and dew point temperature to compute the relative humidity. The dew point parameter represents air temperature at 2 m above the Earth’s surface that would have to be cooled for the saturation to take place. Using Magnus Dew point formula (Lawrence, 2005)

\[
Td = \frac{273.04 \times X}{17.625 - X} \tag{1}
\]

and

\[
X = \ln\left(\frac{Rh}{100}\right) + \frac{(17.625 \times T)}{237.3 + T} \tag{2}
\]

where T is air temperature, Td is the dew point, Rh is the relative humidity and 17.625 and 243.04 are revised Magnus coefficients.

2.2 Coupled model intercomparison project (CMIP6) dataset

The CMIP6 Model dataset used in this study is the GFDL-ESM4, which is a fourth generation of the Geophysical Fluid Dynamics Laboratory (GFDL) from the National Oceanic and Atmospheric Administration (NOAA) in the United States for our future projections of temperatures under different greenhouse gas emissions scenarios. The mean daily data has a horizontal resolution of 1° for the atmosphere and 0.5° for the ocean Earth System (ESM4). The data covers a historical period from 1850 to 2014. In this work, we focused on the years 2030, 2050, and 2100 to project daily maximum and near-surface temperatures. The emission scenarios considered are SSP1-2.6 (Sustainable development scenario), SSP3-7.0 (Regional rivalry scenario), and SSP5-8.5 (Fossil fuel-driven development scenario) or the "worst case scenario" (Climate Neutral Group, 2021). In general, these SSPs help in understanding how the current levels of greenhouse gas emissions may affect warming in the future years. The emission scenario SSP1-2.6 is a scenario with climate policy while SSP3-7.0 and SSP5-8.5 are scenarios with no climate policy of achieving climate targets.
Figure 1. Map of Africa indicating the location of Kenya (a) (https://images.app.goo.gl/iUcmztdSYXJKRMz8) and (b) (https://images.app.goo.gl/BnenDpAbAAakAK1P8) is the map of Kanya showing its administrative regions. In (c), (d), (e), and (f), we examine the 2022 SST, 2023 SST, the 2023 SST anomaly compared to the (1991 to 2020) baseline, and the SST difference between 2023 and 2022 respectively. This figure shows the strong presence of El Nino as indicated in the black rectangular box.
2.3 Global SPEI dataset

The Global SPEI database offers real-time information about drought conditions at the global scale, with a 0.5° spatial resolution and a monthly time resolution (LCSC: Climatology and Climate Services Laboratory). SPEI time-scales range from 0.5 to 48 months which is provided by its multi-scale nature. It is based on monthly precipitation and potential evapotranspiration data from the Laboratory of Climate Services and Climatology (LCSC), starting in January 1901, and it is updated as soon as new data becomes available.

2.4 Descriptive statistics of datasets

Table 1 gives an overview of the summary statistics for the variables used from the ERA5 dataset which are calculated from 1991 to 2023. Sea surface temperature (SST) is for the global dataset while the other variables which are air temperature, precipitation, and relative humidity are for Kenya. The statistics provided include the mean, minimum, maximum, median, and standard deviation which serve as a foundation for our analysis of climate trends and patterns. Units of each variable is also included to quantify physical properties.

Table 1. Summary statistics of meteorological variables

<table>
<thead>
<tr>
<th></th>
<th>SST</th>
<th>2m air temperature</th>
<th>Precipitation</th>
<th>Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C</td>
<td>°C</td>
<td>mm</td>
<td>%</td>
</tr>
<tr>
<td>Mean</td>
<td>13.78</td>
<td>24.91</td>
<td>2.19</td>
<td>61.45</td>
</tr>
<tr>
<td>Std</td>
<td>8.08</td>
<td>3.61</td>
<td>3.18</td>
<td>13.73</td>
</tr>
<tr>
<td>Minimum</td>
<td>-3.88</td>
<td>10.98</td>
<td>-1.39</td>
<td>18.86</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>1.09</td>
<td>22.61</td>
<td>0.24</td>
<td>51.23</td>
</tr>
<tr>
<td>Median</td>
<td>14.76</td>
<td>25.27</td>
<td>1.10</td>
<td>61.80</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>25.54</td>
<td>27.61</td>
<td>3.03</td>
<td>72.98</td>
</tr>
<tr>
<td>Maximum</td>
<td>36.53</td>
<td>34.97</td>
<td>125.80</td>
<td>93.50</td>
</tr>
</tbody>
</table>

We calculate anomalies by taking the mean of 2023 data and subtracting it from the baseline (1991 to 2020) mean which covers 30 years. The mean changes with the previous year were calculated by subtracting 2022 means from 2023. Heatwaves and hot spells indices have been calculated using the Xclim package in Python (https://github.com/Ouranosinc/xclim/tree/main/docs/notebooks) by setting the threshold maximum daily temperatures to 30°C for the hot spells index, and using the near-surface daily temperature and setting the threshold temperature to 25°C for the heatwave index.

3 Results and Discussions

To reveal the impact of El Nino, we analyze near-surface temperature, total precipitation, relative humidity, and drought indices for 2023 and compare them with those of 2022 and with climatology. Figure 2 shows that the northern parts of the eastern
and northeastern regions and the Rift Valley recorded higher temperatures than in 2022, while all regions recorded higher temperatures in 2023 than in the climatology. Rainfall anomalies are highest in the Northeast, East, West, and Nyanza regions. High humidity and droughts are observed around Nyanza, Nairobi, and the Coast region, with more droughts occurring in most regions compared to climatology. The figure shows that the Northeastern region, followed by the northern parts of the Eastern and Rift Valley regions are most prone to extreme heat and humidity events, while the Northeastern, Coastal, Central, Nairobi, Western, and Nyanza regions are most prone to extreme rainfall events. All regions are prone to severe droughts, with the coastal regions and the northern part of the Rift Valley region being less vulnerable. A large proportion of Kenya’s population lives in the central region, which includes Nairobi, the southern part of the Rift Valley, Nyanza, the coastal region, and the western regions. These populations are likely to be more vulnerable to extreme rainfall, humidity, and drought than those living in the northern part of the country. On the other hand, the inhabitants of the northern and coastal parts of the country are more exposed to extreme heat waves than the inhabitants of the south and the highland areas of Nairobi.

In figure 3, we examine the development of surface temperature, precipitation, and relative humidity in Kenya and compare the changes in these variables in 2023 compared to 2022 and the climatology. This figure shows an increasing trend in surface temperature in Kenya, with 2023 being one of the warmest on record. The monthly time series shows that temperatures from May to October 2023 were significantly higher compared to 2022. This period coincides with the onset of the El Nino event that started in April, the previous month. The precipitation development shows a slightly decreasing trend under climate change, with a positive anomaly in 2023. The monthly time series shows extreme rainfall around November compared to 2022. Relative humidity shows a similar characteristic to rainfall but with a negative anomaly in 2023. Some parts of Kenya experienced flash floods in November 2023 leading to the destruction of properties and deaths were recorded. This figure also shows under increasing regional warming, the probability of more intense El Nino impacts is higher in the future. We have identified the most vulnerable regions to precipitation extremes and heat waves. This information will help in better decision-making by both the local Government and the population to prepare against future extreme weather events.

**Future projection**

To assess the health vulnerability of Kenyan regions under future climate change, we analyze the duration of hot spells and heatwave episodes under different SSP CO2 emission scenarios in 2030, 2050, and 2100. The duration of the hot spell was calculated using the daily maximum temperature data and by setting $30^\circ$ as the threshold temperature, while for heatwaves, the near-surface temperature data was used with $25^\circ$ set as the threshold temperature. Figure 4 (a) to (i) shows heat maps of hot spell duration, that is, the number of days when the daily maximum surface temperature exceeds $30^\circ$ in the years 2023, 2050, and 2100 under SSP1-2.6, SSP3-7.0, and SSP5-8.5, respectively. This figure shows that the number of hot spell days increases in the transition from SSP1 to SSP5 from 2030 to 2100, with the northeastern region being the most vulnerable, followed by the eastern region and the northern part of the Rift Valley region. Even controlling for CO2 emissions, the coastal region will become hotter by 2100, but even hotter under scenarios with higher CO2 emissions. This analysis also shows that the urbanized region of Nairobi will experience a higher number of very hot days from 2050 under SSP3 and higher emission scenarios. Figure 5 shows a similar pattern in the duration of heatwave indices, with heatwave exposure increasing under SSP3.
Figure 2. The 2m surface temperature (a, b, c), total precipitation (d, e, f), relative humidity (g, h, i), and droughts indices (j, k, l) for 2023 (a, d, g, j), the difference between 2023 and 2022 (b, e, h, k), and anomalies (c, f, i, l) respectively are shown. These figures show higher temperatures recorded in the northern parts of Eastern, Northeastern, and the Rift Valley regions compared to 2022 while all regions experienced higher temperatures in 2023 compared to climatology. Precipitation anomalies are shown to be highest in the Northeastern, Eastern, and Nyanza regions. High humidity and droughts are observed around Nyanza, Nairobi, and the coastal region with most regions experiencing higher droughts compared to climatology.
Figure 3. Multidecadal temperature time series in Kenya (a), anomaly bar charts (b), and monthly time series of 2023 compared to 2022 (c). Precipitation time series (d), anomaly bar charts (e), and monthly time series of 2023 compared to 2022 (f). Relative humidity time series (g), anomaly bar charts (h), and monthly time series of 2023 compared to 2022 (i) are shown. This figure shows an increasing trend in near-surface temperature in Kenya, with the year 2023 as one of the hottest temperatures on record. The monthly time series shows from May to October 2023, temperatures were significantly higher compared to 2022. This coincides with the onset of the El Nino event. Precipitation evolution shows a slightly declining trend under climate change with 2023 recording a positive anomaly. The monthly time series shows extreme precipitation around November compared to 2022. Relative humidity has a similar characteristic as precipitation but with a negative anomaly in 2023.
and higher emission scenarios. Figures 4 (j) and 5 (j) show the mean hot spells and heatwave duration under the different emission scenarios considered. These figures show the number of very hot days will significantly grow by more than 60% under SSP3 and higher emission scenarios by the year 2100.

Many studies have carried out a similar analysis in this paper to associate climate extremes with public health crises. Adigun et al. (2024) investigated the impacts of human activities on the intensification of heatwaves over the historical period and the risk of heat-related mortality under two Representative Concentration Pathways (RCP26) and (RCP60) was projected in Africa. Excess Heat Factor (EHF) was used to measure heatwaves with two heat factors combined in EHF to determine the overall excess heat. Their results verified that the recent intensification is due to anthropogenic activity such as increased concentration of greenhouse gases and shifts in land usage. They highlighted the possible future effects of heatwave conditions which result from climate change and socioeconomic issues as well as the increasing risk of heatwaves in Africa becoming more intense.

The study emphasizes the need for emissions reduction and adaptation strategies, particularly given Africa’s low adaptive capacity. Heatwaves affect human health to an extent that goes beyond illness to death. Health effects related to heatwaves are not only associated with the physical phenomena of heat itself but also other factors like duration, frequency, and intensity of heatwaves. Kapwata et al. (2022) analyzed past heatwave data focused on South Africa where they identified impacts on mortality associated with the diurnal temperature range (DTR) threshold used for defining heatwaves. Severe heatwaves were identified in late 2015 to early 2016 that coincided with the El Niño event which took place during that period. Di Napoli et al. (2022) equally conducted a study whose aim was to monitor and to better understand how climate change affects human health through indicators such as climate change impacts, exposures, and vulnerability indicators (CCIEVIs). The purpose of indicators was to capture ways in which climate change and human health interact. The hazard, exposure, and vulnerability framework was used to define CCIEVIs according to data availability and their significance to both human health and climate change. The findings of the study provide insights into indicator development and application for monitoring and addressing climate-related health impacts.

In this work, through spatio-temporal analysis, we have investigated the El Niño 2023 impacts on surface temperature, precipitation, and relative humidity in Kenya with a focus on the most vulnerable regions to heat, floods, and high humidity-related illnesses. We have used hot spells and heatwave indices to classify these regions according to vulnerability levels. Our results tie in with previous results carried out on the health impacts of El Niño and other extreme weather events.

4 Conclusions

As a result of the successive flood disasters that hit Kenya in 2023 and 2024, we conducted a thorough spatio-temporal analysis of climate variables in 2023 and compared them with 2022 and climatology to determine the presence and degree of El Niño impact on public health vulnerability in Kenya, focusing on the most vulnerable regions. Our approach provides important insights into which Kenyan regions are more vulnerable to these changes and their impact on public health crises and policies. In addition, we conducted an analysis of the potential health impacts of future climate change under different CO₂ emission scenarios. Our approach provides valuable insights into the potential health impacts of future climate change for long-term
Figure 4. The hot spells analysis under different SSP scenarios are shown. The year 2030 for SSP1-2.6 (a), SSP3-7.0 (b), and SSP5-8.5 (c) are presented. The plots (d, e, f) and (g, h, i) are for the years 2050 and 2100 respectively while (j) presents the average number of days in which $30^\circ$ is exceeded under different emission scenarios.
Figure 5. The heatwave duration analysis under different SSP scenarios is shown. The year 2030 for SSP1-2.6 (a), SSP3-7.0 (b), and SSP5-8.5 (c) are presented. The plots (d, e, f) and (g, h, i) are for the years 2050 and 2100 respectively while (j) presents the average number of days in which 30° is exceeded under different emission scenarios.
planning and early implementation of climate change mitigation measures and underlines the importance of adhering to the terms of the Paris Agreement. We have shown that El Niño led to a significant increase in temperature from May to October 2023 compared to 2022, while extreme precipitation and relative humidity were observed in November. The northeastern region is most at risk, followed by the eastern region, the coastal region and the upper parts of the Rift Valley. Future projections showed that under SSP3 and higher emission scenarios, the risk of these regions being exposed to extreme heatwaves and heat spells will increase by more than 60% by 2100. These projected extreme events can lead to health problems such as heat strokes, strokes, mental instability, anger and rage, dehydration, the spread of airborne diseases, and death. A significant proportion of Kenya’s population lives in the central region where the capital Nairobi is located, the southern part of the Rift Valley, Nyanza, the coastal regions, and the western regions. These populations are likely to be more vulnerable to extreme rainfall, humidity, and drought than the inhabitants in the Northern part of the country. Health-wise, these regions are more vulnerable to vector and waterborne diseases.

There is, therefore, an urgent need to address the potential health impacts in vulnerable regions and to prepare and intervene early to prevent future health crises related to ENSO events. We recommend prioritizing these regions in the development of health facilities in Kenya, improving emergency medical care, expanding green spaces, practicing regular hydration, and introducing adequate domestic ventilation to combat health crises from future extreme climate events.

4.1 Future works

- To get a more comprehensive understanding of the relationship between El Nino events and impacts on public health, gathering a wide range of climate and health data from various sources, analyzing historical data and health monitoring records is recommended for future works.

- Utilizing spatial analysis techniques like GIS mapping and spatial modeling can also be applied to identify in detail the specific areas that are at the highest risks of El-related health impacts to help in prioritizing them during such events.

- Machine learning algorithms can be integrated to analyze datasets related to climate change and public health in order to identify the correlations, complex patterns, and predictive models for forecasting future health impacts.

Author contributions. NAA conceived the project. EKK and ANN provided the data. All authors carried out the analysis and wrote the paper.

Competing interests. The authors declare no competing interest.

Disclaimer. All the analysis and plots have been generated exclusively by the authors. No graphs or plots or materials have been taken from anywhere without permission or references.
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