Discover Sustainability

REVIEW

Open Access

The impact of climate variability and change on environmental health in South Africa

Thabang Maphanga[1*], Xolisiwe Sinalo Grangxabe[1], Benett Siyabonga Madonsela[1], Frederick Mokibelo Mashao[3,4], Innocent L. Mbokodo[5], Boredi Silas Chidi[6], Karabo C. Malakane[7] and Terry Takalani Phungela[1,2]

*Correspondence:
Thabang Maphanga
Maphangat@cput.ac.za
[1]Ecological Biotechnology Research Group, Department of Environmental and Occupational Studies, Faculty of Applied Sciences, Cape Peninsula University of Technology, Corner of Hanover and Tennant Street, Zonnebloem, Cape Town 8000, South Africa
[2]Department of Water and Sanitation, 35 Brown Street, Mbombela 1200, South Africa
[3]Department of Geography and Environmental Studies, University of Limpopo, Sovenga 0727, South Africa
[4]Centre of Global Change, University of Limpopo, Sovenga 0727, South Africa
[5]Climate Service, South African Weather Service, Centurion 0157, South Africa
[6]Ecological Biotechnology Research Group, Department of Biotechnology and Consumer Science, Faculty of Applied Sciences, Cape Peninsula University of Technology, Corner of Hanover, and Tennant Street, Zonnebloem, Cape Town 8000, South Africa
[7]Department of Biodiversity, School of Molecular and Life Sciences, University of Limpopo, Private Bag X1106, Sovenga 0727, South Africa

Abstract
Understanding the importance of climate variability and the potential to predict the impact of climate change at the national level is integral to developing effective and sustainable climate change adaptation and mitigation strategies. This study examines the changes in climate variability and change occurring in the Southern African region, as well as the potential impacts of these changes on environmental health in South Africa. This study analyzed weather-related disasters in South Africa (1941–2021) using media-sourced data from the SAWS Caelum publication, alongside temperature trends from the CRU TS 4 datasets (1941–2020), assessed via spatiotemporal analysis and time-series evaluations for major cities. A systematic literature review, guided by the PRISMA and AMSTAR protocols, synthesized peer-reviewed research on climate impacts in African cities, and 72 publications were included. The visualization was performed using the GrADS software. The results show that in more recent years, particularly from the 2000s onwards, there has been a noticeable increase in positive anomalies, indicating a trend toward warmer temperatures. This aligns with global observations of climate change, in which temperature anomalies have become increasingly positive over time. In essence, of the six variables that characterize climate-related research in SADC, four (> 60%) focus on climate and the burden of disease. Heat-related illnesses associated with vector-borne diseases (25%) in the SADC region preceded waterborne (19%) and respiratory diseases (13%). The hottest region, with a maximum temperature > 28 °C, seems to be expanding over the Northern Cape from period 1941–1970 all-way to 1991–2020, while the extremely cold elevated regions in the east are slowly becoming warmer over time, both during the day and at night. For this reason, understanding the complex relationship between climate variability and public health is not only an academic endeavour but also an important requirement for protecting human lives and promoting resilient communities. Thus, examining the complex effects of climate variability on human health and investigating the interconnected problems and possibilities brings in the pursuit of a better and more sustainable future that aligns with the Sustainable Development Goals.

Keywords Heatwaves, urban areas, Southern africa, Climate change, Climate variability, Sustainable development

1 Introduction

Environmental health in South Africa is significantly impacted by climate change and variability. These factors can have direct effects on human health through heat-related deaths and extreme weather events, such as flooding, which can cause drowning, or indirect effects, such as the geographic spread of vector-borne diseases and mental health issues caused by climate-related trauma [77, 82]. Numerous effects of climate change are being felt by ecosystems and populations that are already at risk. People with disabilities, children, the elderly, and impoverished groups are among the most at risk. The impacts are complex and affect many facets of public health, stemming from social and economic factors such as urban living, natural disasters, and resource-related conflicts. Research indicates that by 2025, two-thirds of the global population, particularly in developing countries, will reside in urban areas [26]. Urban residents, who are already susceptible to the impacts of climate change, face heightened vulnerability due to increased exposure to climate stressors. If current projections hold, by 2030, approximately 60% of the world's population is anticipated to inhabit urban regions. This growth is probably linked to an increase in slum settlements in megacities in developing nations [22, 28, 36, 65]. Damage to infrastructure from extreme events, particularly floods, can worsen the lack of access to health services, which is already a major cause of poor health in slum settlements. Flooding can also make the poor more vulnerable to cholera, pneumonia, and malaria. For instance, significant flooding can increase the prevalence of vector-borne diseases, such as malaria [3, 19, 75].

Southern Africa is particularly vulnerable to climate variability and change, making its effects on environmental well-being critical [85]. According to [35], rising temperatures and storm frequency significantly impact human health in terms of injury and illness. Individuals worldwide are predicted to be impacted by present and future climate change, primarily due to an increased risk of heatwaves and floods [47, 84]. Higher temperatures and UV radiation exposure are associated with higher rates of mortality and illness, especially cardiovascular problems,thus, increases in the frequency and intensity of weather conditions have a negative impact on public health [37]. Furthermore, more research indicates that the effects of climate change on human health are more significant than previously considered. By 2025, 635 million people are predicted to have cardiovascular conditions, the majority of which are linked to strokes and hypertension caused by high sodium intake and low potassium intake, which are frequently linked to urban poverty [22, 24, 36, 65].

Africa is not an exception to the global link between climate change and the spread of infectious diseases. Other direct effects of climate change are mostly manifested in the way that temperature and precipitation interact with infectious and vector-borne diseases. Temperature increases in South Africa have led to the spread and seasonal transmission of several vector-borne infectious illnesses, the most prevalent of which is malaria. According to several studies, one of the first indications of climate change may be the changed range of certain vector species. During the rainy summer months, transmission peaks [1, 81]. According to Mbokodo et al. [50], climate change is predicted to exacerbate existing vulnerabilities. Maximum temperatures in much of the interior may increase by as much as 6 °C by 2070–2099 when greenhouse gas concentrations are high. Particularly for disadvantaged groups, these changes are anticipated to worsen heat-related diseases and fatalities in the future. These extreme events have a substantial impact on public health and a population's capacity to maintain its standard of living, making it necessary to develop methods to alleviate climate-related health risks in urban contexts. The interaction of hazards associated with geographic and climatic variations, the epidemiological trends of infectious diseases [36, 40], and occupational exposure presents a challenge to worldwide readiness and hinders the infrastructure for delivering healthcare services [20, 21].

Climate change presents substantial risks to environmental health in South Africa, manifesting through direct impacts such as heat-related mortality and flood-induced injuries, as well as indirect consequences such as the proliferation of vector-borne diseases and mental health stressors, which disproportionately affect vulnerable populations [77, 82]. Although previous research has elucidated broad linkages between climate and health [37, 84], significant gaps remain in understanding localized climate-health dynamics within Southern African urban centers, particularly concerning the interaction between urbanization, socioeconomic disparities, and climate-induced health outcomes. For example, projections indicating temperature increases of up to 6 °C by 2100 and heightened flood risks [50] lack detailed analysis regarding their intersection with urban health infrastructure, slum conditions, and adaptive capacity, an area this study seeks to address. This study investigates climate variability and changes in the Southern African region and the potential impacts of climate change on environmental health in South Africa. Research Question: How do climate variability and extreme weather events (1941–2021) interact with urbanization trends to exacerbate environmental health disparities in South Africa, and what mitigation strategies can be derived from localized evidence? Objectives: 1) Quantify spatial–temporal trends in temperature extremes and weather-related disasters using SAWS Caelum and CRU TS 4 datasets (1941–2021). 2) Evaluate urban–rural disparities in climate-health impacts through a systematic review (PRISMA/AMSTAR protocols) of peer-reviewed literature (72 studies) and case studies of four major cities. 3) Propose context-specific adaptation strategies by synthesizing vulnerability patterns and policy frameworks. By integrating historical climate data and disaster records, this study transcends generic climate-health assessments to provide place-based evidence for prioritizing interventions in high-risk urban settings.

2 Methodology

2.1 Weather-related disasters

Data on weather-related disasters were obtained from the South African Weather Service (SAWS) Caelum publication, which are collected mainly from newspapers and media clippings. The SAWS maintains and updates the Caelum publication every month [7]. This publication includes notable weather-related disasters recorded by various Newspapers around the country. It contains information on the names and dates of extreme weather occurrences, as well as the resulting socioeconomic impacts and affected regions. Information used is from 1941 to 2021. The limitation of this information is that it is impact-based; therefore, only events with immediate impacts are recorded and archived. This also implies that while Caelum is a reliable source of weather-related disaster information in South Africa, it is important to acknowledge the potential for underreporting, particularly in rural areas where limited media coverage may result in unrecorded events. Caelum publication also focuses more on immediate impact, and is limited in its ability to capture chronic, long-term, or delayed health and socio-economic impacts. Another available source of weather-related disasters is the Emergency Events Database (EM-DAT), which is managed by the World Meteorological Organization (WMO) through the Centre for Research on the Epidemiology of Disasters (CRED). This database usually focuses on regional events and was only launched in 1988 [71].

3 Temperature data

The University of East Anglia's Climatic Research Unit (CRU) Timeseries v4.08 (TS 4, [25]) mean monthly maximum and minimum data was analyzed to gain a better understanding of the spatial changes in both maximum and minimum temperatures in South Africa. This monthly dataset spans from 1901 and is available up to the end of 2003. It covers all land domains on the planet except Antarctica, with a 0.5° latitude by 0.5° longitude grid resolution. It is derived by interpolating monthly climate anomalies using large networks of weather station observations using the angular-distance weighting interpolation method [58]. Spatio-temporal analysis of this CRU temperature data was done in this study for the period 1941–2021 in order to observe spatial temperature changes over time. Analyses were conducted across three 30-year periods: 1941–1970, 1971–1990, and 1991–2020. The Grids Analysis and Display System (GrADS), a free desktop tool compatible with DOS-based computers and available on UNIX workstations [15], was utilized for visualizing the CRU temperature datasets used in this study. Differences in the three 30-year climate periods were calculated and plotted to understand changes across the country in both minimum and maximum temperatures over time.

Time series for mean temperature anomaly based on a 1991–2020 climatological mean was also conducted in this study for four major cities in South Africa (i.e., Cape Town, Durban, Bloemfontein, and Johannesburg) in order to observe changes in mean temperature anomalies over time in these regions. We employed the Mann–Kendall (M–K) non-parametric test, which is commonly used to identify patterns in climatological time series data, to assess the existence and strength of trends in monthly temperature anomalies at the four South African cities. The M–K test is a good fit for environmental datasets because it does not presuppose normalcy and is resilient to outliers and missing values. The M–K test was used to evaluate the statistical significance of trends at the 95% confidence level ($\alpha = 0.05$) for the temperature anomaly time series for each city. Sen's slope estimator, which provides a robust linear rate of change during the research period, was computed in conjunction with significance testing to quantify the trend's amplitude and direction.

4 Literature search

This current study used a systematic review, which allowed the creation of systematic searches in full detail and this method has been widely used by several researchers [6, 20, 45]. For the meta-analysis part of this study, peer-reviewed and published journal articles were used to analyse the impact of climate variability and change in African cities. Literature searches were specifically conducted on English peer-reviewed journals and relevant reports. Data for evaluation and appraisal were collected from project reports, publications, and websites. Search engines primarily used for electronic searches include Google Scholar, Semantic Scholar, Sage, and Research Gate, but are not limited to these. Moreover, the systematic review which was used followed the AMSTAR measurement tool as stated by Shea et al. [70], this was to ensure the quality standards were as described and the PRISMA 2009 checklist [55]. As a result, experienced authors considered the essential steps to be pre-existing knowledge that was already incorporated into the standard process, and they adhered to all of the protocols diligently. Some of the keywords that were included in the thematic search included the impact of climate change in cities, health implications of climate change, climate variability, vulnerability, adaptation assessments, and the Southern African urban environment. A data set was identified, as illustrated in Fig. 1, and a subsequent search of the database produced 72 records. Five different databases were utilised by the authors: Web of Science (16), Google Scholar (110), Scopus (44), Semantic Scholar (10), and PubMed (8). In the course of data processing, the data were stratified and analysed utilising the reference manager software EndNote 21. EndNote 21 assisted in removing duplicates, labelling, and grouping the papers according to their subgroups. During the duplicating process, eight (8) records were removed prior to screening.

5 Search strategy

A comprehensive search was systematically conducted across five electronic databases: Web of Science, Scopus, PubMed, Google Scholar, and Semantic Scholar. This search encompassed publications from 1990 to 2023, aiming to capture contemporary climate-health dynamics in the urbanizing regions of Southern Africa. The search strategy employed Boolean operators and included the following key terms: ("climate change" OR "global warming" OR "climate variability") AND ("urban health" OR "public health" OR "environmental health") AND ("South Africa" OR "Southern Africa") AND ("adaptation" OR "vulnerability" OR "risk assessment").

6 Eligibility criteria

Inclusion Criteria: Empirical studies examining climate-health linkages in urban Southern Africa; Articles reporting quantitative health outcomes (e.g., disease incidence, mortality); Studies published in English in peer-reviewed journals.

Exclusion Criteria: Theoretical models without primary data; Studies focused exclusively on rural contexts; non-English publications.

7 Quality assessment and risk of bias

The quality of the studies was evaluated using the AMSTAR-2 checklist for systematic reviews (Shea et al., 2017) and the Newcastle–Ottawa Scale for observational studies. Two independent reviewers conducted the assessments, with discrepancies resolved through discussion and, when necessary, adjudication by a third reviewer.

8 Data extraction and synthesis

A standardized extraction form was utilized to capture:

- Study characteristics (author, year, location)
- Climate variables examined
- Health outcomes reported
- Key findings on vulnerability and adaptation

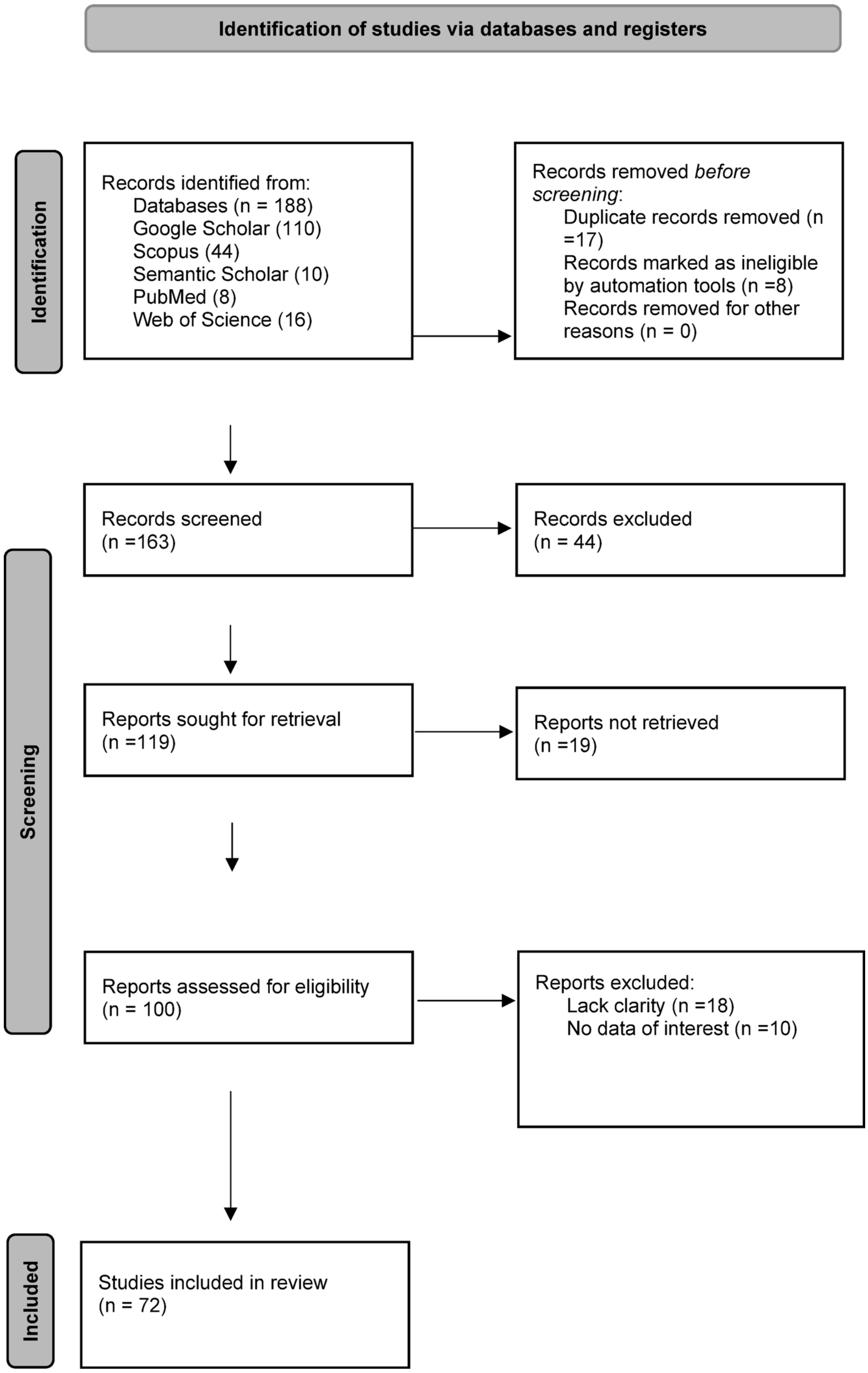

Fig. 1 This paper clarifies the methodology employed in the process of selecting studies from the four most prominent databases. The approach described in this study follows the principles set out by the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA)

9 Limitations

While comprehensive, this review was limited to English-language publications, potentially omitting relevant studies in other languages. The predominance of studies from South Africa may limit the generalizability of findings to other Southern African nations.

10 Results and discussion

10.1 Climate variability (Temperature, rainfall)

Climate variations occur across all time scales and affect every spatial scale, from regional to global levels. The variations in climate already have a significant effect on biological systems and the smallholders, communities, and nations that rely on them [75]. In South Africa, temperature trends are significantly influenced by anthropogenic greenhouse gas emissions [72, 78]. These trends have fluctuated between cooling and warming phases over the past century. According to Jones [32], the country experienced a cooling trend from 1885 to 1915, followed by a warming period between 1915 and 1945. This warming was interrupted by atmospheric cooling until 1970, after which a rapid warming phase began. Easterling et al. [16] also identified a positive trend in both mean daily maximum and minimum temperatures between 1950 and 1993. However, other studies, such as Hulme et al. [30], reported cooling trends in South Africa's coastal regions, with warming predominantly occurring in the central interior from 1901 to 1995.

In addition, observed an increase in both maximum and minimum temperatures in South Africa, with the rate of increase being steeper for maximum temperatures. Likewise, Karl et al. [33] and Mbokodo [51] found an increase in daily maximum and minimum temperatures over most interior parts of the country, while also finding a decline in the diurnal temperature range (DTR). This suggests a disparity in the rates of increase in maximum and minimum temperatures. These results are in disagreement with Muhlenbruch [56], who found increasing minimum, but declining maximum, temperatures over nearly the same study period. Subsequent studies by Kruger and Shongwe [39] and Kruger and Sekele [38] also documented increases in both maximum and minimum temperatures across most of South Africa, enhancing the likelihood of extreme warm temperature events.

A recent study by Mbokodo et al. [52] examined daily extreme temperature trends over a 40-year period, revealing significant decreases in cold nights and cool days, alongside significant increases in warm nights and hot days across much of the country. South Africa is also characterized by extreme temperature events, such as heat waves and cold waves. Heatwaves are more frequent, particularly during drought seasons [44, 52]. While extreme warm temperature events are a common feature of South Africa's climate, extreme low-temperature events can still occur despite the overall warming trend [9]. With global warming, it is expected that heatwaves will not only become more frequent but will also last longer and become more intense [50]. Figure 2 depicts temperature anomalies (in degrees Celsius) from 1941 to 2023 for major South African cities, namely Johannesburg (a), Cape Town (b), Durban (c) and Bloemfontein (d). The graphs indicate that from the 1940s through the early 2000s, there have been fluctuations in temperature anomalies, with both positive and negative values. However, in more recent years, particularly from the 2000s onwards, there is a noticeable increase in positive anomalies, indicating a trend toward warmer temperatures.

Both inland cities, i.e., Johannesburg and Bloemfontein, located in the South African Highveld, exhibit statistically significant warming trends, characterized by positive slopes and p-values below 0.05 (Figs. 2a and d). In contrast, the trends for the coastal cities (Cape Town and Durban) are positive but not statistically robust (Figs. 2b and c) compared to those of the inland cities. This difference is likely due to the influence of mid-latitude frontal systems [48, 73] and ridging high-pressure systems, which can

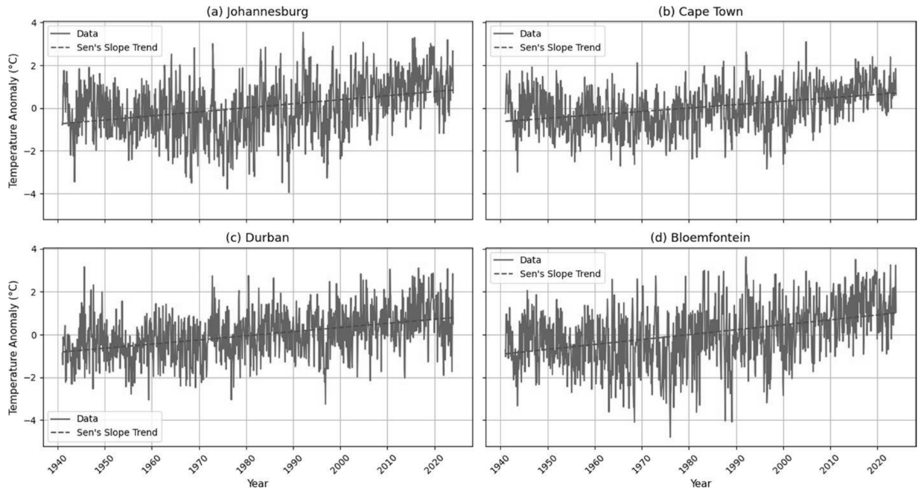

Fig. 2 Observed mean temperature anomalies in four major South African Cities from 1941 to 2021 based on a baseline of 1991–2020. This figure displays mean temperature anomalies from long-term averages in four major South African cities: (**a**) Johannesburg, (**b**) Cape Town, (**c**) Durban, and (**d**) Bloemfontein. Each subfigure shows the deviation from the historical temperature norms, highlighting trends at a 95% confidence interval and variations in the local climate over the observed period

Table 1 Summary of Mann–Kendall trend test results for monthly temperature anomalies at four South African cities

City	Sen's Slope	p-value	Trend	H0 Rejected (5%)
Johannesburg	0.00158	< 0.05	Increasing	Yes
Cape Town	0.001329	< 0.05	Increasing	Yes
Durban	0.001616	< 0.05	Increasing	Yes
Bloemfontein	0.001919	< 0.05	Increasing	Yes

cause temperature drops amid an overall warming climate [9] along the southern coastal region where these cities are located. Table 1 presents Sen's slope estimates (trend magnitude), associated p-values, trend directions, and whether the null hypothesis of no trend is rejected at the 95% confidence level. The positive slopes indicate increasing temperature anomalies. These findings highlight spatial heterogeneity in regional climate change impacts across South Africa, with some urban centers experiencing more pronounced warming than others. However, warm coastal temperatures, when coupled with high moisture contents from the adjacent oceans, are known to have severe health implications such as respiratory problems, particularly to elderly people and young children [34, 64, 79].

11 Overview of the impact of climate variability and change in South Africa

The country is characterized by a wide range of high-impact weather events, as shown in Fig. 3. Based on SAWS Caelum, for the period 1941 to 2021, flooding was by far the most frequent weather-related disaster, with 30% occurrence, followed by strong winds at 14.1%. While these weather extremes are known to destroy infrastructure and lead to fatalities, they can also lead to agricultural losses and even cause health concerns. A recent study by Bopape et al. [5] also showed that floods are the most common extreme over the country. The country is characterized by a wide range of high-impact weather events, as shown in Fig. 3. Based on SAWS Caelum, for the period 1941 to 2021, flooding was by far the most frequent weather-related disaster, followed by strong winds. While

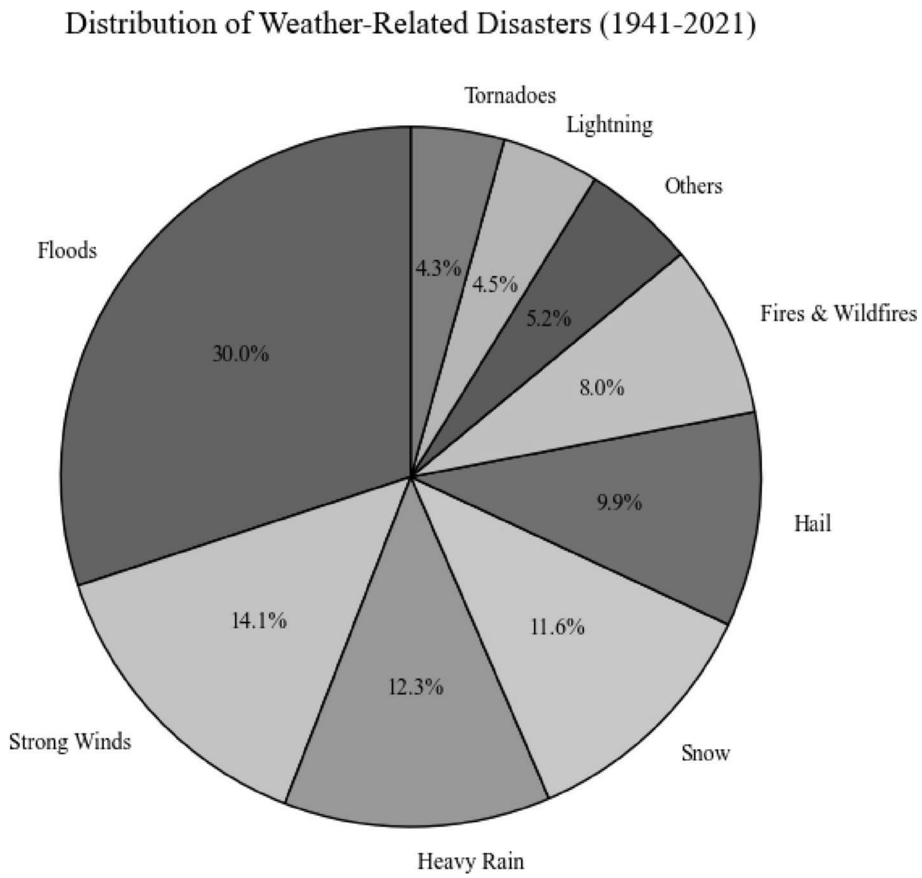

Fig. 3 Weather-related disasters reported on the SAWS Caelum publication (1941–2021)

these weather extremes are known to destroy infrastructure and lead to fatalities, they can also lead to agricultural losses and even cause health concerns. A recent study by Bopape et al. [5] also showed that floods are the most common extreme over the country. Extreme events are frequently influenced by distinct physical mechanisms compared with those that control long-term averages. The primary factor influencing the average change in precipitation is circulation change, whereas extremes are significantly influenced by the thermodynamic state and conditions on specific days. These phenomena are typically associated with unusual temperature and precipitation patterns. Extreme temperature events are significant manifestations of climate change and have a profound impact on all life activities on Earth [53]. According to the IPCC report [76], the southern African region is identified as a significant area where the effects of climate change are particularly severe. The report states that the occurrence of unprecedented extreme temperatures will be the predominant phenomenon in the twenty-first century. In 2018, Cape Town came close to being the first major city in the world to experience water scarcity [17].

South Africa is experiencing severe impacts from climate change, especially in major cities such as Cape Town, Durban, and Johannesburg. These cities are among those most vulnerable to global climate change. The country faces the additional challenge of high levels of poverty and inequality, which makes the effects of climate change even more critical. Extensive literature has shown that Southern Africa is highly vulnerable to the impacts of climate change, primarily because of its geographical location and level of socio-economic development ([47, 53, 69]). Furthermore, over one hundred natural calamities were documented in South Africa between 1900 and 2017 [25, 82]. These events affected approximately twenty-one million individuals, resulting in 2200 deaths and an estimated financial loss of 4.5 billion USD [27]. Similarly, the arrangement of fixed precipitation magnitudes (return levels can be examined in relation to their corresponding return periods. The reciprocal of the return period is occasionally required, as it corresponds to the Annual Exceedance Probability. Extreme events are infrequent occurrences that exhibit distinct characteristics of climate, which differ from the long-term averages. Extreme precipitation occurrences often display distinct signs and, frequently, greater magnitudes of change compared to ordinary precipitation. As the Earth's temperature rises, the capacity of air to hold moisture increases significantly, leading to a higher likelihood of more intense precipitation. This suggests that there is a higher probability of experiencing intense events, which could negatively affect the likelihood of floods. The reversal of the trend towards increased rainfall can only occur in areas where there is a significant reduction in precipitation, leading to an increase in the frequency of big rainfall events instead of a decrease.

Figure 4 shows the spatial distribution of mean temperatures for three 30-year periods over South Africa in order to understand climate variability and change of both mean

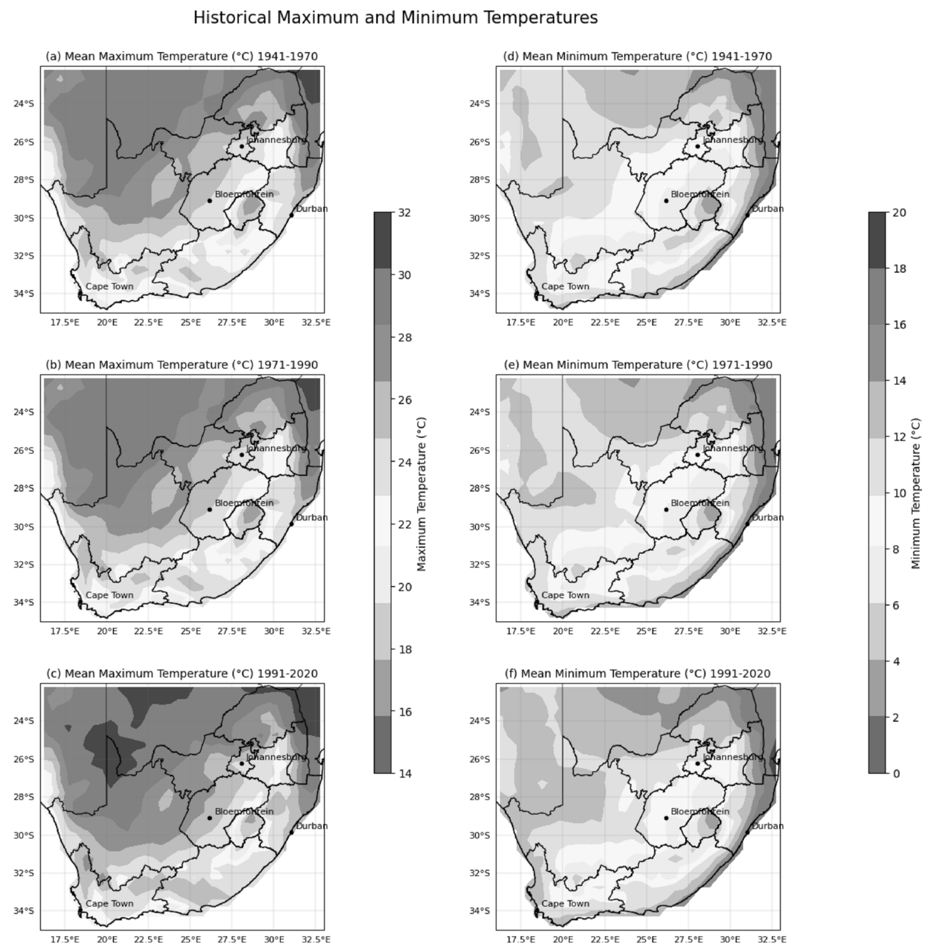

Fig. 4 CRU TS4 mean maximum temperatures between (**a**) 1941–1970, (**b**) 1971–1990, (**c**) 1991–2020 and mean minimum temperatures between (**d**) 1941–1970, (**e**) 1971–1990, (**f**) 1991–2020. Labels in the plots show the location of four major cities in South Africa

maximum and minimum temperatures. Both the mean maximum and minimum temperature distribution over South Africa show a highly spatial distribution over the three 30-year climatological periods, with interior regions showing warming temperatures as compared to coastal regions. The Drakensberg mountainous region on the eastern parts of the country is by far the coldest in all the periods (Fig. 4d-f), while the Northern Cape province, together with the lowvelds of Limpopo and Mpumalanga provinces are hottest in all periods, consistent with earlier findings [9, 78]. The latter regions are characterized by frequent heatwave occurrences during the present-day climate, a pattern which is expected to continue till the end of the twenty-first century [50, 51]. The hottest region (mean maximum temperature > 28 °C, Fig. 4a-c) seem to be expanding over Northern Cape from period 1941–1970 all the way till 1991–2020, while the extreme cold elevated regions over the east are slowly becoming warmer over time both during the day and at night, finding which were also observed in studies such as Mbokodo et al. [52].

12 Human health implications of climate variability and change

The relationships between climatic variability, climate change, and health outcomes are intricate and multifaceted, as they encompass various exposure pathways. Climate change and variability have been recognized as significant threats to human health globally, with particular emphasis on Africa [60]. As such, several studies have extensively documented the various health effects of climate change and variability, as shown in Table 2. These effects include a rise in infectious diseases, respiratory disorders, heat-related illnesses and deaths, malnutrition caused by food insecurity, and negative health outcomes [29, 67, 80]. It is for this reason that understanding the complex relationship between climate variability and public health is not only an academic endeavour but an important requirement for protecting human lives and promoting resilient communities. Thus, examining the complex effects of climate variability on human health and investigating the interconnected problems and possibilities brings to the pursuit of a better and more sustainable future that aligns with the Sustainable Development Goals.

13 Heat-related illnesses and mortality in the Southern Africa development community (major cities)

The morbidity of heat stress and mortality are associated with Climate Variability. This is a cause for concern given that the metropolitan areas are characterized by high population density and limited green spaces, making it more difficult to adapt or mitigate the risks associated with climate variability. As such, Table 3 below summarizes studies from the Southern African Development Community, also known as SADC, regions that have

Table 2 Human health implications associated with climate change and variability

Author (s)	Climate variable	Health implication	Vulnerable population
Tunde et al. [77]	Low temperatures	Typhoid	Susceptible population not defined
Franchini & Mannuci [21]	Low rainfalls	Diarrheal diseases	Children
Wu et al. [83]	Elevated temperatures	Cholera	Children and adults
Chersich et al. [8]	High precipitation	Malaria disease	Children and adults
Wright et al. [82]	Heat stress	Mental disorder	Susceptible population not defined
Jati et al. [31]	Air pollution	Respiratory complications	Infants and children
Lieber et al. [41]	Flooding	Malnutrition	Children and older adults

Table 3 Overview of Southern African Development Community studies that monitor exposure risk of climate change and variability

Southern Africa Authors	**Wright et al. [82]**	**Ropo et al. [68]**		**Panzi et al. [61]**	**Mutombo et al.[57]**	**Mazamay et al. [49]**	**Dlamini et al. [13]**	**Rakotoarison et al. [66]**
Main idea(s) of the study	Major climatic changes facing South Africa and how they can impact human health	Climate variability and heat stress index have increasing ill-health and environmental impacts in East London	Climate change likely to worsens diarrheal disease in Botswana	Forecasting malaria morbidity to 2036 based on geo-climatic factors	Incidence of malaria in Lubumbashi	The environmental drivers of bacterial meningitis epidemics in central DR Congo Africa	Bayesian geostatistical modeling to assess malaria seasonality and monthly incidence risk	Assessment of risk, vulnerability and adaptation to climate change by the health sector in Madagascar.
Burden of disease	Renal disease	Heart failure	Diarrheal disease	Malaria	Malaria	Meningitis	Malaria	Malnutrition
Mortality rate	3.3 deaths per thousand annually	Mortality rate not defined	Mortality rate not defined	Mortality rate not defined	Mortality rate not defined	Mortality rate not defined	Mortality rate not defined	Mortality rate not defined
Country	South Africa	South Africa	Botswana	Democratic Republic of Congo	Democratic Republic of Congo	Democratic Republic of Congo	Eswatini	Madagascar
Southern Africa Authors		**Coates et al. [10]**	**Marghidan [46]**	**Steyn [74]**	**Kunene et al. [40]**	**Paz [63]**		**Luque Fernández et al. [43]**
Main idea(s) of the study	Exploring link between climate variability and mortality in Sub-Saharan Africa	Effects of climate change on human health in Africa	Extreme heat in Mozambique, a rising risk for public health	Analysis of extreme temperature events in Namibia	Association between ambient temperature and daily hospital diarrhoea admissions	Impact of temperature variability on cholera incidence in south-eastern Africa	Extreme heat alerts and impacts across Mozambique	Influence of temperature and rainfall on cholera epidemics in Lusaka, Zambia
Burden of disease	Heat stroke	Chromoblastomycosis	cardiovascular diseases	Dehydration	Diarrhoea	Cholera	Increased heat stress	Cholera
Mortality rate	Mortality rate not defined	Mortality rate not defined	Mortality rate not defined	Mortality rate not defined	Mortality rate not defined	Mortality rate not defined	Eight mortalities	Mortality rate not defined
Country	Malawi	Madagascar	Mozambique	Namibia	South Africa	Tanzania	Mozambique	Zambia

endeavoured to understand the heat-related illnesses and mortality as a result of climate change in metropolitan areas in order to safeguard public health.

Table 3 recorded 10 SADC studies that assessed the heat-related illnesses and mortality in the SADC region. The table provides information regarding the focus of the studies, their geographical location and most importantly, the morbidity and mortality as a result of climate variability in the region. The current meta-analysis indicates that over 65% of the SADC regions conduct exposure risks of climate variability. The risks of climate variability are subsequently detailed in Fig. 5 below.

Figure 5 is an indication that residents in the metros across the SADC region are vulnerable to climate variability as global temperatures continue to change. The scientific evidence in the current study, emanating from Fig. 5 above, shows that climate variability exposure risks in terms of morbidity are not only limited to conventional diseases such as vector diseases, but also water-borne as well as the respiratory burden of diseases. It is for this reason that in the current study, many other diseases that fell out of the parameters of conventional climate variability diseases were identified and classified as 'miscellaneous (44%). That is, diseases such as chromoblastomycosis, renal disease, mental health and many others classified as 'miscellaneous 'collectively dominate the burden of disease in the SADC regions. However, the challenge with the prevalent observation of these diseases is that they are not consistent but occur by chance. For instance, the morbidity of heat stroke associated with climate variability in South Africa is not as pervasively observed as that of malaria vector-borne disease. Hence, the argument that the burden of disease under 'miscellaneous' in the current study is not consistent but rather random. Health professionals in South Africa are actively addressing the consequences of this ongoing crisis [67]. The World Health Organization (WHO) has identified climate change as the most significant health hazard confronting humanity. Rakotoarison et al. [66] anticipate that nations with inadequate health infrastructure will face the greatest challenges.

The effect of climate variability on health is highly dependent on socio-economic factors, including migration patterns, settlement changes, and damage to health

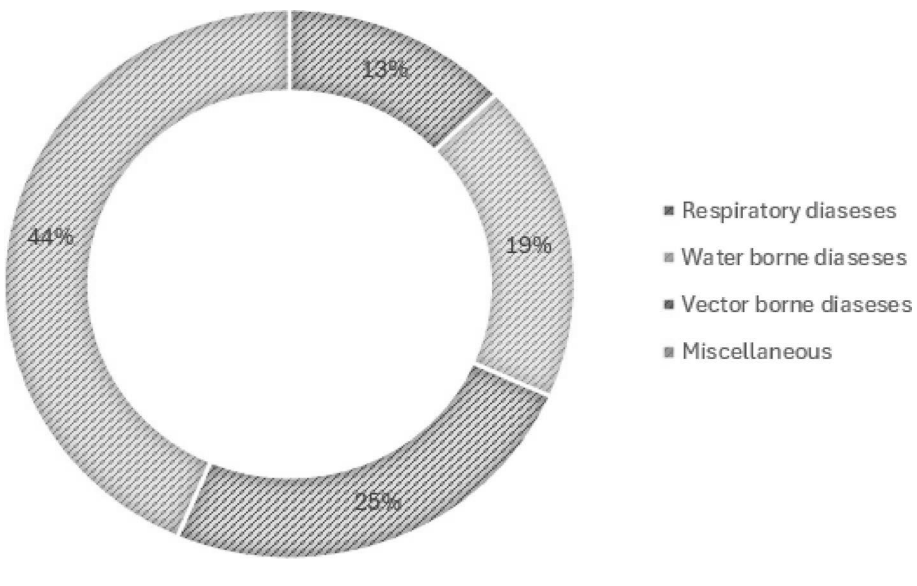

Fig. 5 Climate variability heat heat-related illnesses

infrastructure caused by climate-related events [42]. Climate-sensitive diseases are more prevalent in regions with weak health infrastructures than in regions with advanced health infrastructures [11, 62]. The distribution and lifecycle of vector-borne diseases are particularly affected by climatic changes. Disease vectors in the form of mosquitoes and ticks are directly impacted by temperature and precipitation changes. Malaria and dengue fever have spread to regions beyond their traditional endemic zones due to changing climate conditions [4, 11]. Climate change creates conditions for new infectious diseases to spread to previously uninfected areas, and for old diseases to return to areas they once inhabited [18, 59]) attribute the situation to an increase in international travel and commerce as well as an expansion of urban areas and ecological modifications.

Moreover, in Fig. 6, the heat-related illnesses associated with vector-borne disease (25%) in the SADC region precede waterborne (19%) and respiratory disease (13%). However, important to note that in the SADC region, the burden of disease attributed to climate variability as global temperatures persist is evident. This is concerning, given that the urban population within metros is increasing at an alarming rate. Unless this trend is abated, the SADC metros are at risk of not achieving some of their 2030 sustainable development goals. Especially the sustainable development goals (SDGs 3) associated with good health and well-being within metros. Especially the Sustainable Development Goals (SDGs 3) associated with good health and well-being within metros. Furthermore, the current meta-analysis highlights that there is a willingness to monitor the exposure risks of climate variability in the SADC region, as the frequency of research studies with an interest in this topic is shown in Fig. 5. Increasing global mean temperatures have an influence on individuals of all age groups and communities. Nevertheless, certain groups exhibit a higher susceptibility to heat stress and the exacerbation of pre-existing conditions compared to others. Informality prevails in urban areas and drives economic expansion in Southern Africa, similar to other nations with lower and moderate incomes [14]. Heat stress poses a significant concern for cities, particularly in Southern Africa, where temperatures are increasing at a rate 1.5–2 times higher than the global average [12]. Heat stress hotspots in this region will experience a significant increase [23], which will be worsened by the higher frequency and severity of heatwaves (Russo et al. 2016).

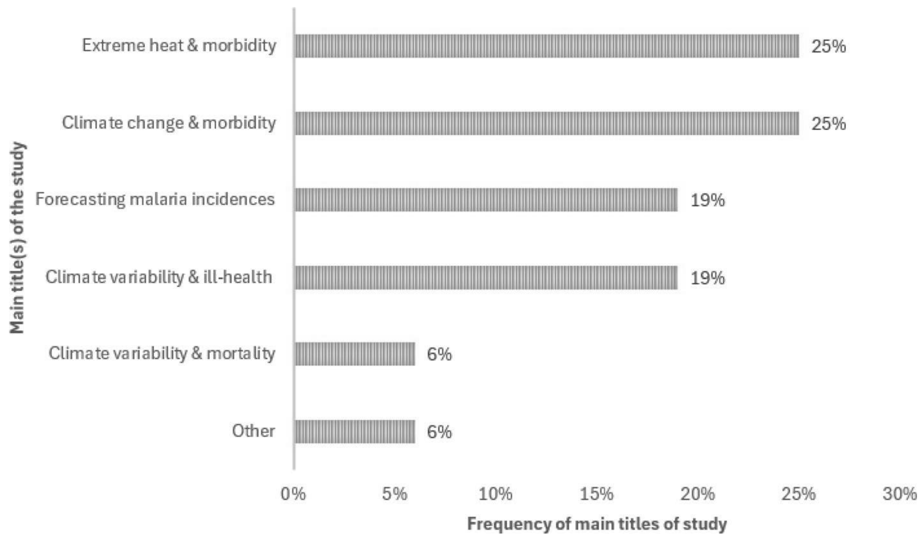

Fig. 6 Proportion of study titles that characterises climate variability and heat-related illnesses

Fig. 7 Southern African Development Community mortality rates reporting

In the SADC region, the studies that monitor the climate variability risk assessment and exposure focus at most on six variables, as depicted in Fig. 6. According to Fig. 5, extreme heat and morbidity, as well as climate and morbidity, top the SADC regional agenda of climate variability and vulnerability to climate change. In essence, out of the six variables that characterise climate-related research in SADC, four (>60%) of them focus on climate and the burden of disease. That is, the research findings indicate that research in this African region is skewed towards morbidity. Subsequently, this presents a research gap which overlooks the mortality rates associated with extreme climate events in the SADC region. This is corroborated by Fig. 7 below.

Although the African continent is susceptible to climate variability and at risk of climate-related events such as heat strokes that exacerbate the chances of mortality, the current findings indicate that there is a paucity of data that focuses on the mortality rate associated with climate variability and vulnerability. It is for this reason that only 13% of the SADC climate variability risk assessment studies conducted monitoring of the mortality rate associated with these extreme weather events, as shown in Fig. 7. While the majority of the studies in the SADC metros prioritize the epidemiological effects. To be precise, in the SADC region, only South Africa and Mozambique recorded the mortality rates associated with heat-related illnesses. In contrast, every investigation that was undertaken to comprehend the impact of climate change and variability in the SADC metros only recorded the morbidity effects. The lack of the mortality rate documented records is a setback for the SADC region metros, given that more than hundred and fifty thousand lives are estimated to be lost due to heat-related illnesses attributed to climate change and variability within the African continent. Therefore, in the metros of the SADC region, there is a need for conclusive evidence that presents susceptibility not only to heat-related illnesses but the mortality rates as well. To achieve this, there is a need to maximize systematic studies directed at the potential impacts of climate variability and temperature-related mortality in the Southern African Development community.

14 Climate variability and health risks in SADC metros: patterns, priorities, and gaps

An examination of morbidity patterns across the SADC metropolitan areas (Fig. 5) indicates a varied health burden associated with climate variability. Vector-borne diseases, such as malaria, remain significant, accounting for 25% of cases, closely followed by waterborne illnesses at 19% and respiratory conditions at 13%. Notably, a considerable 44% of reported climate-related health outcomes are categorized as "miscellaneous," encompassing renal diseases, mental health disorders, chromoblastomycosis, and other less-studied conditions. This predominance of miscellaneous cases suggests that the health impacts of climate variability extend beyond traditional disease categories, yet their irregular occurrence complicates surveillance and prediction. A critical distinction emerges between consistent and sporadic climate-sensitive health outcomes. Vector-borne diseases exhibit clear climatic patterns, whereas conditions such as heat stroke or rare fungal infections occur more randomly. Climate variability affects health differently in SADC metros, so we classified findings by disease types, occurrence patterns, research coverage, and data gaps. In this approach, patterns and imbalances in existing evidence are identified beyond a list of illnesses. This inconsistency limits the ability to design targeted interventions, particularly in regions where health system capacity is already strained. From a research focus perspective, Fig. 6 illustrates that over 60% of SADC climate-health studies prioritize morbidity over mortality. The agenda is dominated by extreme heat and climate–morbidity linkages, while mortality receives minimal attention, with only 13% of studies assessing death rates (Fig. 7). This gap is geographically uneven: South Africa and Mozambique are the only countries reporting mortality from heat-related illnesses. The absence of mortality data impedes a comprehensive understanding of the public health burden and may underestimate the scale of risk. Socio-economic context amplifies these vulnerabilities. Rapid urbanization, informal settlement growth, and inadequate infrastructure heighten exposure to extreme heat and disease vectors, particularly in urban hotspots where temperatures are rising up to twice as fast as the global average. Migratory movements, environmental change, and the expansion of urban footprints further facilitate the spread of infectious diseases into previously unaffected zones.

15 Conclusion

The fundamental causal relationship between climate variability and change is that socio-economic development leads to alterations in land use and land cover. The composition of global atmospheric gases is influenced by land use and land cover changes, vehicle emissions, industrial combustion, and urbanisation. Historical data indicates a warming trend in South Africa, with projections suggesting ongoing temperature increases. The anticipated warming trend is projected to modify rainfall patterns, resulting in water scarcity in certain regions while contributing to increased flooding in others. Comprehending these trends is essential for alleviating the effects on environmental health. The scientific evidence in the current study demonstrated that climate variability exposure risks in terms of morbidity are not only limited to conventional diseases such as vector disease, but also water bore as well as the respiratory burden of diseases. South Africa is experiencing severe impacts from climate change, especially in major cities such as Cape Town, Durban, and Johannesburg. These cities are among those most vulnerable to global climate change. The country faces the additional challenge of high levels of poverty and inequality, which makes the effects of climate change even more critical.

Acknowledgements
The authors would like to acknowledge the anonymous reviewers for taking. Their time and reviewing this work.

Author contributions
T.M.and B.S.M. and F.M.M conceptualized and wrote the manuscriptX.S.G and I.L.M and B.S.C. reviewed the manuscriptK.C.M. and T.T.P. conducted the methodology section.

Funding
This research received no external funding.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethical approval and consent to participate
Not applicable.

Consent to publish
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 10 March 2025 / Accepted: 18 August 2025
Published online: 08 October 2025

References

1. Adeola R. The impact of the African Union convention on the protection and assistance of internally displaced persons in Africa. African Human Rights Law Journal. 2019;19(2):pp.591-607.
2. Alexander KA, Carzolio M, Goodin D, Vance E. Climate change is likely to worsen the public health threat of diarrheal disease in Botswana. International journal of environmental research and public health. 2013;10(4):pp.1202-1230.
3. Anyamba A., Small JL, Britch SC, Tucker CJ, Pak EW, Reynolds CA, Crutchfield J, Linthicum KJ. Recent weather extremes and impacts on agricultural production and vector-borne disease outbreak patterns. PloS one. 2014;9(3):p.e92538.
4. Andersen LK, Davis MDP. Climate change and the epidemiology of selected tick-borne and mosquito-borne diseases: update from the International Society of Dermatology Climate Change Task Force. Int J Dermatol. 2016;56(3):252–9. https://doi.org/10.1111/ijd.13438.
5. Bopape MM, Keebine G, Ndarana T, Mbokodo IL, Hlahane K, Motshegwa T, Amha Y, Ogega OM, Mfopa C, Mahlobo DD, Engelbrecht FA. Weather related disasters in South Africa from 1980 to 2023. Environ Dev. 2025. https://doi.org/10.1016/j.envdev.2025.101254.
6. Bramer WM, De Jonge GB, Rethlefsen ML, Mast F, Kleijnen J. A systematic approach to searching: an efficient and complete method to develop literature searches. J Med Libr Assoc. 2018;106(4):531.
7. Caelum. Notable weather and weather-related events in geo-coded format: 1647–2021. South African Weather Service. 2021. Available online: https://www.weathersa.co.za/Documents/AnnualReports/SA_Weather_Services_Annual_Report_2020_21_Digital_Version_14092021122723.pdf Accessed 15 Apr 2024.
8. Chersich MF, Wright CY, Venter F, Rees H, Scorgie F, Erasmus B. Impacts of climate change on health and wellbeing in South Africa. International journal of environmental research and public health. 2018;15(9):p.1884.
9. Chikoore H, Mbokodo IL, Singo MV, Mohomi T, Munyai RB, Havenga H, Mahlobo DD, Engelbrecht FA, Bopape MJM, Ndarana T. Dynamics of an extreme low temperature event over South Africa amid a warming climate. Weather Clim Extremes. 2024;44: 100668.
10. Coates SJ, Enbiale W, Davis MD, Andersen LK. The effects of climate change on human health in Africa, a dermatologic perspective: a report from the International Society of Dermatology Climate Change Committee. Int J Dermatol. 2020;59(3):265–78.
11. Confalonieri, U. E., Lindsay, S. W., Patz, J. A., & Githeko, A. K. (2000). Climate change and vector-borne diseases: a regional analysis. *Bulletin of the World Health Organization*, *78*(9). https://doi.org/10.1590/s0042-96862000000900009
12. DEA (Department of Environmental Affairs). Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa. Summary for Policy Makers. Pretoria: Department of Environmental Affairs. 2013. https://www.dffe.gov.za/sites/default/files/docs/summary_policymakers_bookV3.pdf Accessed 12 NOV 2024.

13. Dlamini SN, Fall IS, Mabaso SD. Bayesian geostatistical modeling to assess malaria seasonality and monthly incidence risk in Eswatini. J Epidemiol Glob Health. 2022;12(3):340–61.
14. Dodman D, Archer D, and Satterthwaite D. Responding to climate change in contexts of urban poverty and informality. Environment and Urbanization. 2019;31(1):pp.3-12.
15. Doty B. The grid analysis and display system. GRADS Manual. 1995;10:148.
16. Easterling DR, Horton B, Jones PD, Peterson TC, Karl TR, Parker DE, Salinger MJ, Razuvayev V, Plummer N, Jamason P, Folland CK. Maximum and minimum temperature trends for the globe. Science. 1997;277(5324):364–7.
17. Enqvist JP, Ziervogel G. Water governance and justice in Cape Town: an overview. WIREs Water. 2019;6(4): e1354.
18. Boland GJ, Melzer MS, Hopkin A, Higgins V, Nassuth A. Climate change and plant diseases in Ontario. Can J Plant Pathol. 2004;26(3):335–50. https://doi.org/10.1080/07060660409507151.
19. Ebi KL, Frumkin H, Hess JJ. Protecting and promoting population health in the context of climate and other global environmental changes. Anthropocene. 2017;19:pp.1-12.
20. Eriksen MB, Frandsen TF. The impact of patient, intervention, comparison, outcome (PICO) as a search strategy tool on literature search quality: a systematic review. J Med Library Assoc: JMLA. 2018;106(4):420.
21. Franchini M, Mannucci PM. Impact on human health of climate changes. Eur J Intern Med. 2015;26(1):1–5.
22. Gasper R, Blohm A, Ruth M. Social and economic impacts of climate change on the urban environment. Curr Opin Environ Sustain. 2011;3(3):150–7.
23. Garland RM, Matooane M, Engelbrecht FA, Bopape MJM, Landman WA, Naidoo M, Van der Merwe J, and Wright CY. Regional projections of extreme apparent temperature days in Africa and the related potential risk to human health. International journal of environmental research and public health. 2015;12(10):pp.12577-12604.
24. Girard LF, Nocca F. Climate change and health impacts in urban areas: towards hybrid evaluation tools for new governance. Atmosphere. 2020;11(12):1344.
25. Harris I, Osborn TJ, Jones P, Lister D. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Sci Data. 2020;7(1):109.
26. Hebbert M, Jankovic V. Cities and climate change: the precedents and why they matter. Urban Stud. 2013;50(7):1332–47.
27. Herbach EL, Weeks KS, O'Rorke M, Novak NL, and Schweizer ML. Disparities in breast cancer stage at diagnosis between immigrant and native-born women: A meta-analysis. Annals of epidemiology. 2021;54:pp.64-72.
28. Hewitson BC, Crane RG. Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa. Int J Climatol: J Royal Meteorol Soc. 2006;26(10):1315–37.
29. Hsiang SM, Burke M, Miguel E. Quantifying the influence of climate on human conflict. Science. 2013;341(6151):1235367.
30. Hulme M, Doherty R, Ngara T, New M, Lister D. African climate change: 1900–2100. Clim Res. 2001;17(2):145–68.
31. Jati SP, Ginandjar P. Potential impact of climate variability on respiratory diseases in infant and children in Semarang. In IOP Conference Series: Earth and Environmental Science. 2017;55(1):p.012049). IOP Publishing.
32. Jones PD. Hemispheric surface air temperature variations: a reanalysis and an update to 1993. J Climate. 1994;7(11):1794–802.
33. Karl TR, Jones PD, Knight RW, Kukla G, Plummer N, Razuvayev V, Gallo KP, Lindseay J, Charlson RJ, Peterson TC. A new perspective on recent global warming: asymmetric trends of daily maximum and minimum temperature. Bull Am Meteorol Soc. 1993;74(6):1007–24.
34. Kishanrao S. Extremes of weather conditions and child health. Open J Pediatrics Child Health. 2024;9(1):050–7.
35. Kim KH, Kabir E, Ara Jahan S. A review of the consequences of global climate change on human health. Journal of Environmental Science and Health, Part C. 2014;32(3):pp.299-318.
36. Kjellstrom T. Impact of climate conditions on occupational health and related economic losses: a new feature of global and urban health in the context of climate change. Asia Pac J Public Health. 2016;28(2_suppl):28S-37S.
37. Kovats S, Akhtar R. Climate, climate change and human health in Asian cities. Environ Urban. 2008;20(1):165–75.
38. Kruger AC, Sekele SS. Trends in extreme temperature indices in South Africa: 1962–2009. Int J Climatol. 2013. https://doi.org/10.1002/joc.3455.
39. Kruger AC, Shongwe S. Temperature trends in South Africa: 1960–2003. Int J Climatol. 2004;24(15):1929–45.
40. Kunene, Z., Kapwata, T., Mathee, A., Sweijd, N., Minakawa, N., Naidoo, N. and Wright, C.Y., 2023, April. Exploring the association between ambient temperature and daily hospital admissions for diarrhea in Mopani District, Limpopo Province, South Africa. In Healthcare (Vol. 11, No. 9, p. 1251). Mdpi.
41. Lieber M, Chin-Hong P, Kelly K, Dandu M, Weiser SD. A systematic review and meta-analysis assessing the impact of droughts, flooding, and climate variability on malnutrition. Glob Public Health. 2022;17(1):68–82.
42. Louis S, Carlson AK, Suresh A, Rim J, Mays M, Ontaneda D, Dhawan A. Impacts of climate change and air pollution on neurologic health, disease, and practice: a scoping review. Neurology. 2022;100(10):474–83. https://doi.org/10.1212/wnl.0000000000201630.
43. Luque Fernández MÁ, Bauernfeind A, Jiménez JD, Gil CL, Omeiri NE, Guibert DH. Influence of temperature and rainfall on the evolution of cholera epidemics in Lusaka, Zambia, 2003–2006: analysis of a time series. Trans R Soc Trop Med Hyg. 2009;103(2):137–43.
44. Lyon B. Southern Africa summer drought and heat waves: observations and coupled model behavior. J Climate. 2009;22(22):6033–46.
45. Madonsela BS, Maphanga T, Mahlakwana G. Advancement in the monitoring techniques of Particulate Matter and Nitrogen Oxides in African states: a systematic review with meta-analysis. Int J Environ Impacts. 2023;6(1):37–47.
46. MARGHIDAN, C.P., 2022. EXTREME HEAT IN MOZAMBIQUE: A RISING RISK FOR PUBLIC HEALTH (Doctoral dissertation,Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for thedegree of Master of Science in Spatial Engineering SUPERVISORS: Prof. dr. Maarten van Aalst Prof. dr. Justine Blanford THESISASSESSMENT BOARD: Prof. dr. Norman Kerle (Chair) dr. Maud Huynen (External Examiner, Maastricht University).
47. Mashao FM, Mothapo MC, Munyai RB, Letsoalo JM, Mbokodo IL, Muofhe TP, Matsane W, Chikoore H. Extreme rainfall and flood risk prediction over the East Coast of South Africa. Water. 2023;15(1):50.
48. Mahlalela PT, Blamey RC, Reason CJC. Mechanisms behind early winter rainfall variability in the southwestern Cape, South Africa. Climate Dynamics. 2019;53(1):pp.21-39.

49. Mazamay S, Broutin H, Bompangue D, Muyembe JJ, Guégan JF. The environmental drivers of bacterial meningitis epidemics in the Democratic Republic of Congo, central Africa. PLoS Negl Trop Dis. 2020;14(10): e0008634.
50. Mbokodo I, Bopape MJ, Chikoore H, Engelbrecht F, Nethengwe N. Heatwaves in the future warmer climate of South Africa. Atmosphere. 2020;11(7):712.
51. Mbokodo, I.L., 2017. Heat waves in South Africa: Observed variabilty, structure and trends. Master's dissertation, University of Venda.
52. Mbokodo IL, Bopape MJM, Ndarana T, Mbatha SM, Muofhe TP, Singo MV, Xulu NG, Mohomi T, Ayisi KK, Chikoore H. Heatwave variability and structure in South Africa during summer drought. Climate. 2023;11(2):38.
53. Mengistu AG, Woyessa YE, Tesfuhuney WA, Steyn AS, Lee SS. Assessing the impact of climate change on future extreme temperature events in major South African cities. Theor Appl Climatol. 2024;155(3):1807–19.
54. Mier IAM, Zhuo L. Current status of municipal solid waste management in Juba city, south Sudan. Int. J. Sci. Res. Publ. 2020;10: pp.671-684.
55. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 2009;6: e1000097.
56. Muhlenbruch-Tegen A. Long-term surface temperature variations in South Africa. S Afr J Sci. 1992;88(4):197–205.
57. Mutombo AM, Mukomena E, Kanteng G, Kakisingi C, Mankan G, Mukuku OK. Incidence of malaria in Lubumbashi, Democratic Republic of the Congo: an assessment of eight years. African J Heal. 2018;2018:2.
58. New M, Hulme M, Jones P. Representing twentieth-century space–time climate variability. Part II: Development of 1901–96 monthly grids of terrestrial surface climate. Journal of climate. 2000;13(13):pp.2217-2238.
59. Ogden N, Gachon P. Climate change and infectious diseases: what can we expect? Can Commun Dis Rep. 2019;45(4):76–80. https://doi.org/10.14745/ccdr.v45i04a01.
60. Orimoloye IR, Mazinyo SP, Kalumba AM, Ekundayo OY, Nel W. Implications of climate variability and change on urban and human health: a review. Cities. 2019;91:213–23.
61. Panzi EK, Kandala NI, Kafinga EL, Tampwo BM, Kandala NB. Forecasting malaria morbidity to 2036 based on geo-climatic factors in the Democratic Republic of Congo. Int J Environ Res Public Health. 2022;19(19):12271.
62. Patz JA, Foley JA, Holloway T, Campbell-Lendrum D. Impact of regional climate change on human health. Nature. 2005;438(7066):310–7. https://doi.org/10.1038/nature04188.
63. Paz S. Impact of temperature variability on cholera incidence in southeastern Africa, 1971–2006. EcoHealth. 2009;6(3):340–5.
64. Peng RD, Bobb JF, Tebaldi C, McDaniel L, Bell ML, Dominici F. Toward a quantitative estimate of future heat wave mortality under global climate change. Environ Health Perspect. 2011;119(5):701–6.
65. Proust K, Newell B, Brown H, Capon A, Browne C, Burton A, Dixon J, Mu L, Zarafu M. Human health and climate change: leverage points for adaptation in urban environments. Int J Environ Res Public Health. 2012;9(6):2134–58.
66. Rakotoarison N, Raholijao N, Razafindramavo LM, Rakotomavo ZAPH, Rakotoarisoa A, Guillemot JS, Randriamialisoa ZJ, Mafilaza V, Ramiandrisoa VAMP, Rajaonarivony R, Andrianjafinirina S. Assessment of risk, vulnerability and adaptation to climate change by the health sector in Madagascar. Int J Environ Res Public Health. 2018;15(12):2643.
67. Rocque RJ, Beaudoin C, Ndjaboue R, Cameron L, Poirier-Bergeron L, Poulin-Rheault RA, Fallon C, Tricco AC, Witteman HO. Health effects of climate change: an overview of systematic reviews. BMJ Open. 2021;11(6): e046333.
68. Ropo OI, Perez MS, Werner N, Enoch TI. Climate variability and heat stress index have increasing potential ill-health and environmental impacts in the East London, South Africa. Int J Appl Eng Res. 2017;12(17):6910–8.
69. Scholes PB, Engelbrecht F, and Vogel C. EFFECTIVE ACTION BASED ON ENHANCED UNDERSTANDING. www.safsc.org.za/wp-content/uploads/2020/06/Climate-Science-Doc_June-2020.pdf.
70. Shea BJ, Grimshaw JM, Wells GA, Boers M, Andersson N, Hamel C, Porter AC, Tugwell P, Moher D, Bouter LM. Development of AMSTAR: a measurement tool to assess the methodological quality of systematic reviews. BMC Med Res Methodol. 2007;7:1–7.
71. Shen, G. and Hwang, S.N., 2019. Spatial–Temporal snapshots of global natural disaster impacts Revealed from EM-DAT for 1900–2015. Geomatics, Natural Hazards and Risk.
72. Solomon, S., Qin, D., Manning, M., Averyt, K., Marquis, M. (Eds.) *Climate Change 2007—The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC (Vol. 4)*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2007
73. Stager JC, Mayewski PA., White J, Chase BM, Neumann FH, Meadows ME, King CD, Dixon DA. Precipitation variability in the winter rainfall zone of South Africa during the last 1400 yr linked to the austral westerlies. Climate of the Past. 2012;8(3):pp.877-887.
74. Steyn, C., 2021. An analysis of extreme temperature events (ETEs) of Namibia (Doctoral dissertation).
75. Thornton PK, Ericksen PJ, Herrero M, Challinor AJ. Climate variability and vulnerability to climate change: a review. Glob Change Biol. 2014;20(11):3313–28.
76. Trisos C, Totin E, Adelekan I, Lennard C, Simpson N. IPCC's sixth assessment report: impacts, adaptation options and investment areas for a climate-resilient Central Africa. 2022.
77. Tunde AM, Adeleke EA, Adeniyi EE. Impact of climate variability on human health in Ilorin. Nigeria Environ Nat Resour Res. 2013;3(1):127.
78. van der Walt AJ, Fitchett JM. Exploring extreme warm temperature trends in South Africa: 1960–2016. Theor Appl Climatol. 2021;143(3):1341–60.
79. Vandentorren S, Bretin P, Zeghnoun A, Mandereau-Bruno L, Croisier A, Cochet C, Ribéron J, Siberan I, Declercq B, Ledrans M. August 2003 heat wave in France: risk factors for death of elderly people living at home. Eur J Public Health. 2006;16(6):583–91.
80. Watts N, Amann M, Arnell N, Ayeb-Karlsson S, Beagley J, Belesova K, Boykoff M, Byass P, Cai W, Campbell-Lendrum D, Capstick S. The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. The lancet. 2021;397(10269):pp.129-170.
81. Weiss AJ, Wier LM, Stocks C, Blanchard J. Overview of emergency department visits in the United States. 2014;2011
82. Wright CY, Kapwata T, Du Preez DJ, Wernecke B, Garland RM, Nkosi V, Landman WA, Dyson L, Norval M. Major climate change-induced risks to human health in South Africa. Environ Res. 2021;196: 110973.

83. Wu X, Lu Y, Zhou S, Chen L, Xu B. Impact of climate change on human infectious diseases: empirical evidence and human adaptation. Environ Int. 2016;86:14–23.
84. Zhou L, Kori DS, Sibanda M, Nhundu K. An analysis of the differences in vulnerability to climate change: A review of rural and urban areas in South Africa. Climate. 2022;10(8):118.
85. Ziervogel G, New M, Archer van Garderen E, Midgley G, Taylor A, Hamann R, Stuart-Hill S, Myers J, Warburton M. Climate change impacts and adaptation in South Africa. Wiley Interdisciplinary Rev: Climate Change. 2014;5(5):605–20.

Publisher's note