

**Assessing the inter-annual and inter-seasonal climate-induced variation
in caseload of respiratory diseases**



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1129160

*A thesis submitted in fulfilment of the academic requirements for the degree of Doctor
of Philosophy*

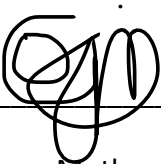
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June 2024

DECLARATION

I declare that this thesis is my own, unaided work, except where otherwise acknowledged. It is being submitted for the Degree of Doctor of Philosophy in Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for examination for any degree at this or any other university.



Ogone Motlogeloa

27 June 2024 at Johannesburg

ABSTRACT

In South Africa, acute upper respiratory diseases pose a significant public health challenge, influenced heavily by climatic factors. Recognizing the critical need for detailed seasonal analysis. This thesis delves into the inter-annual and inter-seasonal impacts of climate on disease caseloads, offering four pivotal contributions to health biometeorology. The first contribution refines the understanding of the acute upper respiratory disease season in South Africa, previously recognized as the winter months of May to September. This research provides a more granular analysis by pinpointing specific onset timings and fluctuations within the season that are crucial for optimizing healthcare responses, particularly in vaccination schedules. The second contribution is an in-depth analysis of climatic variables affecting acute upper respiratory disease prevalence. Utilizing Spearman's correlation analyses and the Distributed Lag Non-linear Model across Johannesburg, Cape Town, and Gqeberha, this study identifies negative correlations between temperature and disease cases, pinpointing significant risk thresholds most prevalent during the winter peak. The third contribution investigates the impact of extreme climate events (ECEs) over twelve years, elucidating how, while individual ECEs influence medical aid claims and disease incidence, it is the broader seasonal patterns that predominantly dictate acute upper respiratory disease prevalence. The fourth contribution offers a nuanced exploration of the climate-health nexus, demonstrating that routine weather variations play a more significant role in the peak transmission of acute upper respiratory viruses than extreme events. This thesis elucidates the substantial yet nuanced influence of climate on respiratory health in South Africa. By specifying the disease season with greater precision and clarifying the relationship between temperature variations and disease prevalence, the research provides essential data for health practitioners to plan targeted interventions. This study moves beyond the focus on extreme weather events to expose the subtler, yet more consistent, impact of seasonal climate shifts on health outcomes, enriching our understanding and serving as a vital reference for enhancing disease preparedness in an era marked by climatic uncertainty.

Keywords: Health Biometeorology, Respiratory Diseases, Climate Variation, Seasonality, Public Health Policy, South Africa

LIST OF WORKS

This study is organised in X chapters, four of which are stand-alone research papers. Of these, three have been accepted for publication in peer-reviewed journals, and one is currently under review. These are compiled into the full thesis, supplemented by an introduction, study region, methodology, general discussion, and conclusion chapters. The four papers include:

1. **Motlogeloa O** and Fitchett JM (2023) Climate and human health: a critical review of publication trends in the International Journal of Biometeorology. *International Journal of Biometeorology*, 67

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70% contribution to the work: collected and analysed the data, produced the figures and tables in the text, and led the writing of the manuscript and revisions with input from the project leader.

2. **Motlogeloa O**, Fitchett JM and Sweijd N (2023) Defining the South African Acute Respiratory Infectious Disease Season. *International Journal of Environmental Research and Public Health*, 20, 1074. DOI: 10.3390/ijerph20021074

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72% contribution to the work: collected and analysed the data, produced the figures and tables in the text, and led the writing of the manuscript and revisions with input from the project leader.

3. **Motlogeloa O**, Fitchett JM and Sweijd N (2023) Exploring the role of Extreme Climate Events (ECEs) in the incidence of respiratory disease in South Africa. *Submitted to Weather Climate and Society*.

Current status: Under Review – Resubmitted 18 January 2024

Impact factor for 2023 - 2024: 3.019, five-year impact factor: 2.878.

74% contribution to the work: collected and analysed the data, produced the figures and tables in the text and led the writing of the manuscript and revisions with input from the project leader.

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75% contribution to the work: collected and analysed the data, produced the figures and tables in the text and led the writing of the manuscript and revisions with input from the project leader.

Conference presentations:

1. **Motlogeloa O**, Fitchett JM, and Sweijd S (2022). Exploring the role of climate on temporal seasonality in the incidence of influenza and respiratory disease hospitalizations in Gauteng South Africa. Society of South African Geographers Biennial Conference, Pretoria, 12-14 September 2022.
2. **Motlogeloa O**, Fitchett JM, and Sweijd S (2023). Exploring the role of climatic seasonality in the peak incidence of respiratory disease in South Africa. Global Change Conference, Bloemfontein, 30 January-February 2023.
3. **Motlogeloa O**, Fitchett JM, and Sweijd S (2023). Exploring the role of Extreme Climate Events (ECEs) in the incidence of respiratory disease in South Africa. International Society of Biometeorology Congress, Tempe Arizona, 14-17 May 2023.
4. **Motlogeloa O**, Fitchett JM, and Sweijd S (2023). Exploring the intersection of climate and health: Analyzing seasonal patterns in acute respiratory diseases post-extreme climate events in South Africa. Climate and Health Research Conference, Nagasaki, 25 November - 2 December 2023.

Science Communication Outputs

1. Mail and Guardian newspaper article: <https://mg.co.za/article/2023-07-18-its-flu-season-but-why-does-it-happen-in-winter/>
2. Cape Times newspaper article: <https://www.iol.co.za/capetimes/opinion/why-the-flu-season-is-not-to-be-sneezed-at-we-all-get-it-some-time-147c8668-2c65-4984-99d7-1cb55f468f2a>
3. Khaya FM Radio Interview: 16 June 2021

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TABLE OF CONTENTS

ABSTRACT.....	iii
LIST OF WORKS	iv
ACKNOWLEDGEMENTS.....	vii
TABLE OF CONTENTS	xi
LIST OF FIGURES.....	xiii
LIST OF TABLES	Error! Bookmark not defined.
LIST OF ACRONYMS AND SCIENTIFIC TERMS	xvii
CHAPTER 1: INTRODUCTION.....	1
1.1 Background	1
1.1.1 Global Climate Impacts on Health	3
1.1.2 Climate and Respiratory Diseases Globally	4
1.1.3 Environmental Factors and Their Impact on Respiratory Health in South Africa	8
1.1.4 Policy Implications.....	9
1.2 Rationale	12
1.3 Study Aim and Objectives.....	12
1.4 Structure of the Thesis.....	13
CHAPTER 2: STUDY REGION.....	15
2.1 Introduction.....	15
2.2 Geographic Location and Topography.....	16
2.3 Climatic Characteristics of South Africa.....	17
2.4 Socioeconomic Conditions and Health Outcomes: The Poverty Index.....	20
CHAPTER 3: METHODOLOGICAL CONSIDERATIONS	25
3.1 Introduction.....	25
3.2 Datasets	26
3.2.1 Data Acquisition	Error! Bookmark not defined.
3.3 Meteorological Data.....	29
3.4 Key Methods Used	31
3.5 Scale of Analysis: Provincial vs. Local Perspectives.....	32
3.6 Ethical Considerations	34
CHAPTER 4: CLIMATE AND HUMAN HEALTH: A REVIEW OF PUBLICATION TRENDS IN THE INTERNATIONAL JOURNAL OF BIOMETEOROLOGY.....	35
4.1 Brief Synopsis	35
CHAPTER 5: DEFINING THE SOUTH AFRICAN ACUTE RESPIRATORY INFECTIOUS DISEASE SEASON.....	60

5.1 Brief Synopsis	60
CHAPTER 6: EXPLORING THE ROLE OF EXTREME CLIMATE EVENTS (ECES) IN THE INCIDENCE OF RESPIRATORY DISEASE IN SOUTH AFRICA.	78
6.1 Brief Synopsis	78
ABSTRACT	81
SIGNIFICANCE STATEMENT	82
Acknowledgements	108
Data Availability Statement	108
REFERENCES	109
CHAPTER 7: ASSESSING THE IMPACT OF CLIMATIC VARIABILITY ON ACUTE RESPIRATORY DISEASES ACROSS DIVERSE CLIMATIC ZONES IN SOUTH AFRICA	118
7.1 Brief Synopsis	118
CHAPTER 8: DISCUSSION	132
8.1 Introduction.....	132
8.2 Seasonality of Respiratory Diseases: Global to Local Perspectives Error! Bookmark not defined.	
8.3 Looking Forward: Future Trajectories of Acute Respiratory Disease in South Africa.....	144
8.4 Limitations of the Study	149
CHAPTER 9: CONCLUSION	152
9.1 Synthesis	152
9.2 Achievement of Study Aim and Objectives	152
9.3 Directions for Future Research	155
COMPREHENSIVE REFERENCE LIST	157
APPENDIX 1: ETHICS CLEARANCE	210

LIST OF FIGURES

Figure 2.1: Location and Topography of South Africa.....	17
Figure 2.2: Koppen- Geiger Climate Classification.....	18
Figure 2.3: Evaporation Range Zones of South Africa.....	19
Figure 2.3: Poverty Index of South Africa.....	23
Figure 4.1. (Appearing in the paper as Fig. 1): Flow diagram of the process of the article identification, screening, eligibility, and inclusion in this review.....	39
Figure 4.2. (Appearing in the paper as Fig. 2): Number of empirical studies and papers related to climate and human health published per year in the <i>International Journal of Biometeorology</i>	41
Figure 4.3. (Appearing in the paper as Fig. 3): Countries of interest in health biometeorological studies.....	49
Figure 4.4. (Appearing in the paper as Fig. 4): Diseases studied per continent and WHO's top ten list of leading causes of death globally.....	49
Figure 4.5 (Appearing in the paper as Fig. 5): Bibliometric visualization map of all 180 paper.....	51
Figure 4.6 (Appearing in the paper as Fig. 6): Meteorological variables studied per disease category.....	51
Figure 5.1 (Appearing in the paper as Fig. 1): Map of the study site of South Africa indicating the nine provinces, topography, the surrounding oceans, and their respective currents.....	64

Figure 5.2. (Appearing in the paper as Fig. 2): Caseloads of the hospitalized patients with the positive tests for (a) influenza (b) RSV (2015-2019).....	67
Figure 5.3. (Appearing in the paper as Fig. 3): Weekly medical insurance claims for South Africa and the 5-point running mean (2008-2019).....	69
Figure 5.4. (Appearing in the paper as Fig. 4): Discovery medical scheme claims in Gauteng, with a 5-point running mean.....	69
Figure 5.5. (Appearing in the paper as Fig. 5): Medical Insurance claims and running mean for Eastern Cape, Free State, KwaZulu-Natal, Limpopo, Mpumalanga, Northern Cape, North West Province and Western Cape.....	70
Figure 5.6 (Appearing in the paper as Fig. 6): Applying Vega et al.'s 5% threshold for South Africa's nine provinces.....	72
Figure 5.7 (Appearing in the paper as Fig. 7): Threshold graphs showing the different thresholds for the nine South African provinces respectively.....	73
Figure 6.1. (Appearing in the paper as Fig. 1): Map illustrating the number of ECEs that have occurred in South Africa between 2008-2019.....	87
Figure 6.2. (Appearing in the paper as Fig. 2): Significance of ECEs in South Africa from 2008-2019 at a two-week period.....	103
Figure 7.1. (Appearing in the paper as Fig. 1): Spatial distribution of rainfall season zones (Roffe et al., 2019) across South Africa with locations of Cape Town, Johannesburg and Gqeberha.....	122
Figure 7.2. (Appearing in the paper as Fig. 2): Comparative monthly climate trends – Illustration of the monthly variations in temperature and rainfall for Johannesburg (a), Cape Town (b), and the Gqeberha(c) in South Africa.....	124

Figure 7.3. (Appearing in the paper as Fig. 3): Acute respiratory claims plotted against daily a) mean temperature, b) maximum temperature, c) minimum temperature and d) daily rainfall in Johannesburg, South Africa. Red bars indicate one standard deviation from the mean.....	125
Figure 7.4. (Appearing in the paper as Fig. 4): Acute respiratory claims plotted against daily a) mean temperature, b) maximum temperature, c) minimum temperature and d) daily rainfall in Gqeberha, South Africa. Red bars indicate one standard deviation from the mean.....	125
Figure 7.5. (Appearing in the paper as Fig 5): Acute respiratory claims plotted against daily a) mean temperature, b) maximum temperature, c) minimum temperature and d) daily rainfall in Cape Town, South Africa. Red bars indicate one standard deviation from the mean.....	126
Figure 7.6. (Appearing in the paper as Fig 6): Johannesburg relative risk for acute respiratory disease medical insurance claims at, a) maximum temperature, b) mean temperature, c) daily rain and d) minimum temperature over a 14-day lag.....	127
Figure 7.7. (Appearing in the paper as Fig 7): Gqeberha relative risk for acute respiratory disease medical insurance claims at a) maximum temperature, b) mean temperature, c) daily rain and d) minimum temperature over a 14-day lag.....	128
Figure 7.8. (Appearing in the paper as Fig 8): Cape Town relative risk for acute respiratory disease medical insurance claims at a) maximum temperature, b) mean temperature, c) daily rain and d) minimum temperature over a 14-day lag.....	129

LIST OF TABLES

Table 4.1. (Appearing in the paper as Table 1): Papers on the intersection of specific diagnosable diseases and meteorological variables in the <i>International Journal of Biometeorology</i> 1957-2022.....	42
Table 6.1. (Appearing in the manuscript as Table 1): Overview of ECEs occurring in South Africa from 2008 -2019.....	93
Table 6.2. (Appearing in the manuscript as Table 2): Changes in Medical Insurance Claims Relative to Baseline in the Events of ECEs.....	100
Table 7.1. (Appearing in the manuscript as Table 1): Spearman Correlation Coefficients and P-values for Weather Variables and Medical Insurance Claims in Johannesburg, Cape Town, and Gqeberha.....	124

LIST OF ACRONYMS AND SCIENTIFIC TERMS

CDC: Centers for Disease Control and Prevention

CO₂ : Carbon Dioxide

COLs: Cut-Off Lows

COPD: Chronic Obstructive Pulmonary Disease

COVID-19: Coronavirus Disease 2019

DHMS: Discovery Health Medical Scheme

DLNM: Distributed Lag Non-linear Model

ECEs: Extreme Climate Events

EM-DAT: Emergency Events Database

GIS: Geographical Information Systems

GP: General Practitioner

HIV: Human Immunodeficiency Virus

HREC: Human Health Research Ethics Committee

ICD-10 codes: International Classification of Diseases, Tenth Revision

ICU: Intensive Care Unit

IJB: International Journal of Biometeorology

ITCZ: Intertropical Convergence Zone

MERS: Middle East Respiratory Syndrome (MERS-CoV)

M.asl: Meters above sea level

NICD: National Institute for Communicable Diseases

NHI: National Health Insurance

PM 2.5: Particulate Matter 2.5

RR: Relative Risk

RSV: Respiratory Syncytial Virus

SARS: Severe Acute Respiratory Syndrome

SAWS: South African Weather Services

SRZ: Summer Rainfall Zone

$T_{\max}$: Maximum Temperature

T_{mean} : Mean Temperature

$T_{\min}$: Minimum Temperature

USA: United States of America

WHO: World Health Organization

WRZ: Winter Rainfall Zone

YRZ: Year-Round Rainfall Zone

CHAPTER 1: INTRODUCTION

1.1 Background

Infectious diseases pose a formidable challenge to global health, with acute lower respiratory infections notably standing as the second leading cause of death and the foremost contributor to disability-adjusted life years worldwide (Pinner et al., 1996; WHO, 2000). Among these infections, diseases such as influenza, respiratory syncytial virus (RSV), and the common cold significantly contribute to morbidity and mortality, exerting significant strain on healthcare systems, particularly in resource-limited settings (Fauci, 2001; Tempia et al., 2019). This study narrows its focus to acute respiratory diseases, deliberately excluding COVID-19 to preserve the integrity of the data up to 2019. Such a historical approach enables a clear analysis of pre-pandemic patterns and establishes a foundational baseline for future epidemiological assessments (David and Hansen-Flasche, 2019; NICE, 2008). The burden of these diseases is acute in Africa, where the prevalence of severe illness and mortality rates associated with influenza far exceed those in other regions, posing a significant economic and health challenge (Lafond et al., 2017; Iuliano et al., 2018). In South Africa, the annual toll of influenza is substantial, with estimates indicating that millions of people are affected by mild but work-impeding symptoms, hundreds of thousands by severe illness, and thousands of deaths annually are attributed to influenza-related complications (Cohen et al., 2018; Tempia et al., 2019).

Respiratory infections exhibit a distinct seasonality, often associated with colder weather. Research has consistently linked lower temperatures to a surge in respiratory diseases, especially influenza (Lowen and Steel, 2007; Troeger et al., 2017). Yet, in the context of South

Africa—with its dense population, high incidence of comorbidities such as HIV and tuberculosis, and a geographical span from subtropical to mid-latitudes—it becomes crucial to determine if these established global patterns hold (Lofgren et al., 2007; WHO, 2016; Statistics SA, 2017). This research aims to address this gap, examining the seasonality of respiratory infections in South Africa and exploring the extent to which global patterns align with local epidemiological data.

Biometeorology, bridging atmospheric science with biology and health, investigates how climate affects organisms, particularly human health (Hondula et al., 2017). This field uses time-series and Distributed Lag Non-linear Models (DLNMs) to analyze the timing and intensity of weather-related health outcomes (Hajat et al., 2002; Gasparrini et al., 2010). Remote sensing provides wide-scale environmental monitoring, critical for understanding large-scale health impacts (Hay et al., 2000), while Geographic Information Systems (GIS) enable the mapping of climate-health data, crucial for pinpointing disease hotspots and directing health resources (Rocklöv and Dubrow, 2020).

Integrating diverse data, biometeorology applies big data analytics to discern complex climate-health links (Lowe et al., 2011; Bhaskaran et al., 2013). For instance, GIS has been used to model dengue fever risks (Acharya et al., 2018) and assess the impact of air pollution on respiratory health (Chai et al., 2020), enhancing our grasp of how climate factors affect health and aiding in emergency response to extreme weather events.

1.1.1 Global Climate Impacts on Health

The impact of climate on global health extends beyond direct outcomes to a range of indirect effects that compound the challenge of managing public health (Campbell-Lendrum et al., 2015). Exposure to extreme weather events has been linked with a spectrum of health outcomes, notably affecting the incidence and severity of diseases. While the direct effects of phenomena such as heatwaves intensify the burden of heat-related illnesses and mortality (Balato et al., 2014), cold spells present contrasting challenges by inducing a rise in respiratory complications, a relationship that has been substantiated by recent studies (Davis and Enfield, 2018). The indirect effects of climatic shifts are profound and multifaceted. For example, changes in temperature and humidity have been observed to influence the geographic distribution of disease vectors, contributing to an increased spread of vector-borne diseases, such as dengue fever, with substantial public health implications (Bal and Sodoudi, 2020; Cheng et al., 2021). Additionally, climate-induced alterations in air quality can exacerbate respiratory diseases, as air pollution serves as a crucial mediator between climatic conditions and respiratory health (Chai et al., 2020).

Furthermore, climate-driven changes in food production and water quality may lead to nutritional deficits and an uptick in the spread of water-borne diseases, compounding the indirect health consequences of climate variability (Phung et al., 2015; Cheng et al., 2019). The need for robust public health frameworks that can adapt to these diverse challenges is crucial, and researchers continue to emphasize the importance of incorporating climate considerations into global health policies to effectively mitigate and manage emerging health risks (Tapak et al., 2018; Hossain et al., 2019). The complex relationship between climate and health requires a nuanced understanding of both direct and indirect pathways. The

contemporary literature underscores the critical need for integrated climate health policies and interventions that can withstand and address the multifaceted impacts of climate change on human health.

1.1.2 Climate and Respiratory Diseases Globally

The relationship between climate factors and respiratory diseases is complex and multifaceted (Davis and Enfield, 2018; Chai et al., 2020). Temperature and humidity, for example, directly affect the survival and transmission of respiratory pathogens. Studies such as those by Lowen et al. (2007) have shown that influenza virus transmission is optimized at low temperatures and low relative humidity, facilitating the virus's survival and increasing its transmission potential during colder months (Moriyama et al., 2020). This phenomenon helps explain the seasonal peaks of influenza in temperate climates during winter (Motlogeloa et al., 2023). In contrast, tropical regions often experience a different pattern, where higher humidity and rainfall are associated with increased respiratory ailments (Neumann et al., 2022). This can be attributed to enhanced growth of moulds and proliferation of other allergens due to moist conditions, which aggravate respiratory conditions, particularly among susceptible populations (Moriyama et al., 2020).

Moreover, precipitation plays a dual role. While excessive rainfall can lead to increased humidity and mould growth, thereby exacerbating respiratory conditions, it can also temporarily reduce the concentration of airborne pollutants, including particulate matter (Gamba-Sanchez et al., 2016). However, the latter scenario can lead to a rebound effect where, post-rainfall, evaporated pollutants become more concentrated, potentially leading to increased respiratory distress (Uttajug, 2023).

Arid regions present unique challenges for respiratory health due to the low moisture content in the air (Kalankesh et al., 2022). Dry air leads to the drying of the nasal passages and respiratory mucosa, which are first-line defences against airborne pathogens (Ahlawat et al., 2020). When these mucosal barriers are compromised, their ability to trap and clear viruses and bacteria is significantly reduced, leading to increased susceptibility to respiratory infections (Ahlawat et al., 2020; Kalankesh et al., 2022).

Research by Kudo et al. (2019) has highlighted that mucosal dryness can lead to an increased risk of infectious diseases, including common respiratory viruses. The physiological impact of arid conditions extends to the aggravation of chronic respiratory conditions such as asthma, where dry air can trigger pulmonary distress.

Extreme weather events, including heatwaves, cold spells, and floods, significantly impact respiratory health (Bal and Sodoudi, 2020; Feng et al., 2021). Each type of event contributes differently based on its nature and the environmental changes it brings. Heatwaves often exacerbate respiratory problems in individuals with pre-existing conditions like chronic obstructive pulmonary disease (COPD) and asthma (Cheng et al., 2016). The high temperatures increase the formation of ground-level ozone, a potent respiratory irritant, and elevate levels of airborne particulates, especially in urban areas (Chai et al., 2020). Research indicates that during heatwaves, there is a noticeable increase in hospital admissions for respiratory issues due to exacerbated symptoms and direct irritation of the respiratory tract (Anderson et al., 2013).

Cold spells are particularly harsh on respiratory health, promoting conditions that favour the survival and transmission of common respiratory pathogens such as the influenza virus (Mourtzoukou and Falagas, 2007). The cold air itself can trigger asthma attacks and other respiratory conditions by causing airway constriction and increased mucosal irritation. Moreover, people tend to spend more time indoors during cold spells, which increases the risk of transmitting infections within crowded settings.

Floods contribute to respiratory health issues by promoting the growth of mould and mildew in water-damaged buildings and homes (Hoppe et al., 2012). Inhalation of mould spores can lead to severe respiratory symptoms, allergic reactions, and asthma exacerbations. Additionally, standing water and increased humidity can enhance the proliferation of other biological allergens, affecting air quality and respiratory health (Cann et al., 2013).

The linkage between air pollution and respiratory infections is well-documented, with climate change playing a significant role in exacerbating this issue (Glenn et al., 2022). Air pollutants such as particulate matter (PM), nitrogen dioxide (NO₂), and sulfur dioxide (SO₂) from industrial emissions, vehicle exhaust, and other sources are known to irritate the airways,

reduce lung function, and impair the body's ability to clear respiratory pathogens (Ortega-Garcia et al., 2020). Furthermore, climate change contributes to increased air pollution in several ways. For instance, higher temperatures can enhance the chemical reactions that form ground-level ozone, while wildfires, which are becoming more frequent and severe due to climate change, produce significant amounts of smoke and fine particulate matter (Deng et al., 2020). A study by Anenberg et al. (2018) demonstrated that wildfire-related PM_{2.5} exposure is associated with increased rates of respiratory infections, particularly in children and the elderly, who are more vulnerable to air quality issues.

Climate change significantly impacts the production, distribution, and allergenicity of pollen and other airborne allergens, with direct consequences for respiratory diseases such as asthma and allergic rhinitis. Higher atmospheric carbon dioxide levels and rising temperatures stimulate the growth of many allergenic plant species, leading to an increase in pollen production (Paudel et al., 2021). Studies have shown that plants like ragweed exhibit longer growing seasons and produce more pollen in response to higher CO₂ concentrations (Ziska et al., 2019). Additionally, warmer temperatures advance the start of the pollen season and extend its duration, which can increase exposure times and potentially worsen allergy and asthma symptoms (D'Amato et al., 2020). Altered precipitation patterns can also affect pollen production. For example, increased rainfall in certain areas can boost plant growth and subsequent pollen output, whereas drought conditions might lead to reduced overall pollen counts but could increase the concentration of airborne pollen during dry spells (Barnes, 2018).

Climate change is also causing shifts in the geographic distribution of plants, which can introduce new allergens to areas where they were previously absent (Tran et al., 2023). This not only affects local biodiversity but also poses new health risks to populations that may not have prior exposure or immunity to these new allergenic plants. The geographic distribution of respiratory diseases is profoundly influenced by local climate conditions, which can vary dramatically across different regions (Andersen et al., 2023). For instance, urban areas might experience higher levels of air pollutants, exacerbating respiratory conditions, while rural areas might face different challenges such as increased exposure to agricultural dust and pollen. In regions experiencing rapid industrialization, increased emissions from factories and

vehicles degrade air quality, impacting respiratory health (Odo et al., 2022). Conversely, in areas where deforestation is prevalent, there may be less pollen but increased dust levels, which can also affect respiratory health (Odo et al., 2022). Climate change can exacerbate these regional disparities, as some areas may become hotter and drier, increasing the prevalence of dust and particulate matter, while others may become wetter, leading to higher humidity and mould growth, both of which can worsen respiratory conditions (Mirsaeidi et al., 2016).

Comparative studies, such as those examining respiratory health impacts in different climatic zones of Europe compared to those in the tropics, reveal significant variations in the type and frequency of respiratory ailments, underscoring the need for region-specific public health strategies (Motlogeloa and Fitchett, 2024). Adapting to the changing climate and its impact on respiratory health requires comprehensive strategies that encompass surveillance, public education, and healthcare infrastructure enhancements (Fox et al., 2019). Effective adaptation strategies involve multiple stakeholders, including government bodies, healthcare providers, and communities.

Improved surveillance systems are essential for tracking climate-related changes in respiratory disease patterns (Moulton and Schramm, 2017). This includes monitoring air quality, pollen counts, and respiratory disease outbreaks. For example, real-time air quality monitoring and pollen alerts can help individuals with respiratory conditions make informed decisions about outdoor activities, thereby minimizing exposure and preventing exacerbations. Educating the public about the risks associated with climate change and respiratory health is critical (Frumkin et al., 2008). Programs designed to inform individuals about how to manage their conditions during poor air quality days, heatwaves, or pollen seasons can significantly reduce emergency room visits and improve quality of life.

Enhancing healthcare infrastructure to cope with the expected increase in respiratory cases is another crucial strategy. This may involve increasing the availability of respiratory specialists and allergists, expanding emergency room capacities, and ensuring that primary care providers are well-trained in managing climate-related respiratory issues. Predictive modelling plays a pivotal role in understanding and responding to the impacts of climate change on respiratory health (Pizzulli et al., 2021). These models integrate data from

climatology, epidemiology, and public health to forecast future trends and inform policy decisions (Ku et al., 2021).

The study on the seasonality of respiratory infections in South Africa, focusing on diseases such as influenza and RSV, is poised to fill several critical gaps in the current understanding of climate-health interactions. By leveraging biometeorology to integrate atmospheric science with health data through Distributed Lag Non-linear Models (DLNMs) and Geographic Information Systems (GIS), the research specifically elucidates how diverse climatic zones within South Africa influence respiratory disease outbreaks. This approach not only provides a localized perspective on global patterns of disease seasonality but also offers a crucial pre-pandemic baseline for future epidemiological assessments. Additionally, the spatial mapping of disease hotspots through GIS and remote sensing significantly enhances resource allocation and health policy formulation, particularly in regions burdened by comorbidities such as HIV and tuberculosis. Ultimately, the study improves the understanding of the timing and intensity of weather-related health outcomes, aiding in the refinement of emergency responses and preparedness for climate-induced health crises, thereby advancing both local and global public health strategies.

1.1.3 Environmental Factors and Their Impact on Respiratory Health in South Africa

In South Africa, the relationship between climate and respiratory diseases is of particular interest due to the country's wide range of climatic zones, from the dry, arid regions of the Karoo to the moist, subtropical climate of the eastern coastline (Engelbrecht and Engelbrecht, 2016). This diversity results in a complex interaction between environmental factors and health outcomes, especially respiratory conditions which are affected by both temperature fluctuations and humidity levels. While Wright et al. (2014) and Myers et al. (2013) have provided valuable insights, there is a need for more nuanced research that considers the local and short-term variations in climate and their impacts on respiratory health.

Temperature fluctuations, particularly in vulnerable populations, have been shown to influence respiratory diseases. In the South African context, studies have observed that heatwaves can significantly exacerbate respiratory distress, while cold snaps may amplify the risk of respiratory infections (Coetzee et al., 2016). The multifaceted role of humidity in modulating the prevalence of respiratory illnesses has been observed, with studies indicating that high humidity levels may facilitate the spread of diseases, and conversely, low humidity conditions could exacerbate respiratory symptoms (Blumberg et al., 2015). Urbanization and its consequent air pollution represent a notable risk for respiratory health, with a clear association between high pollutant levels and the exacerbation of respiratory conditions (Thomson et al., 2017). Industrial activities in urban centres contribute to poor air quality, thus necessitating effective environmental and health policies to mitigate these impacts (Johnston et al., 2018). Urban air pollution in South Africa has been recognized as a significant contributor to respiratory health problems, with industrial and vehicular emissions impacting urban populations (Garland et al., 2013). Although research into indoor air pollution has advanced, further study is needed on the health outcomes of using 'dirty' fuels like paraffin, particularly in urban areas, and the term 'biomass burning' should be clearly distinguished from veld fires in discussions of domestic air quality issues (Bruce et al., 2000).

1.1.4 Policy Implications

The imperative for effective policy formulation, anchored in climate health research, is underscored by the dynamic interplay between climatic variables and respiratory disease epidemiology. In South Africa, biometeorological research has significantly informed the development of respiratory health policies. These include the optimisation of influenza vaccination campaigns, which are calibrated according to the seasonality of the virus and the

prevailing climatic conditions (Ebi and Semenza, 2008; Cohen et al., 2015; Tempia et al., 2019). Additionally, climate health research has been instrumental in shaping emergency preparedness strategies in response to extreme weather events, and in formulating long-term responses to the health impacts of climate change.

Translating complex and nuanced scientific findings into actionable policies, however, presents substantial challenges. The persistent divide between research outputs and policy enactment necessitates continued attention (Ebi et al., 2006; McMichael and Lindgren, 2011). This research endeavours to assess the integration of biometeorological research within health policy frameworks and to appraise the current policies' effectiveness in mitigating climate-related health risks.

In the context of South Africa, the National Department of Health's influenza vaccination campaign prioritizes high-risk groups, reflecting an understanding of climate-health interactions. The 2022 influenza guidelines articulate the need for vaccination prioritization, especially among healthcare workers, individuals over 65 years of age, and those with underlying chronic conditions, considering the concurrent risks posed by COVID-19 (National Department of Health, South Africa, 2022). This targeted approach is instrumental in reducing the healthcare burden, particularly when facing the likelihood of simultaneous influenza and SARS-CoV-2 transmission, underscoring the importance of climate-health research, as explored in this thesis.

This thesis provides empirical evidence supporting the need for specific policy enhancements related to influenza management in South Africa. The findings suggest that integrating

climate-health research data into the annual update of vaccine compositions and review of vaccination target groups can significantly enhance the protection of vulnerable populations. This is particularly crucial in light of the variability in influenza strain prevalence and environmental factors affecting disease transmission, as documented in the research findings (National Department of Health, South Africa, 2022). Additionally, the thesis underscores the benefits of expanding the availability of quadrivalent vaccines in public healthcare settings. The data presented demonstrate how broader protection against prevalent influenza strains can reduce transmission rates, which is essential for protecting high-risk groups such as children and healthcare workers (National Department of Health, South Africa, 2022). The research also highlights the effectiveness of evidence-based isolation, cohorting, and vaccination practices in managing influenza outbreaks, particularly in closed community settings. These strategies are informed by the documented patterns of outbreak dynamics and could be essential components of a proactive public health response (National Department of Health, South Africa, 2022). Finally, the integration of influenza vaccination strategies within comprehensive pandemic preparedness plans is advocated. This thesis draws on the experiences from the COVID-19 pandemic, showing how robust preparedness plans can enhance the healthcare system's resilience against concurrent disease outbreaks (National Department of Health, South Africa, 2022).

While current policies in South Africa address the intersection of influenza and climatic factors, ongoing research in biometeorology presents opportunities for further policy refinement. Future updates must consider the fluid nature of influenza viruses, the lessons from the COVID-19 pandemic, and the detailed insights from biometeorological studies. The

objective is to foster the development of flexible and responsive health policies that are well-equipped to address both present and emerging climate-related health challenges.

1.2 Rationale

The interplay between climate and health outcomes is increasingly critical in light of evolving global climate patterns (Pecl et al., 2017). In South Africa, this interaction is compounded by a unique climatic heterogeneity and the burden of diseases like HIV and tuberculosis, which may be influenced by climatic variables, affecting disease seasonality and transmission (Lofgren et al., 2007; WHO, 2016; Statistics SA, 2017). Despite a strong policy framework, execution in the context of the South African health system often struggles due to legacy management and stewardship issues (Coovadia et al., 2009; Burger and Christian, 2018). Addressing a lacuna in the extant literature, this research delineates the ornate connections between respiratory diseases and climate in South Africa, aiming to bolster health system readiness and inform policy. This alignment not only supports the Sustainable Development Goals but also serves the insurance industry by providing essential data on the risks associated with climate-sensitive health conditions (Hák, et al., 2016; Sach et al., 2019).

1.3 Study Aim and Objectives

The primary aim of this research is to investigate the interplay between climatic factors and the seasonality of acute respiratory diseases in South Africa, underpinned by an in-depth analysis of various climatic influences. To address the primary aim of this research, the specific objectives of this research are:

1. To define seasonality: Establish the timing of the onset and cessation of the primary period during which acute upper respiratory diseases occur across South Africa, using both public-sector hospitalization data and private-sector medical aid scheme data.
2. To assess the impact of mean climatic conditions on the incidence of acute upper respiratory diseases:
3. To determine the influence of climatic factors, including extreme weather events and variability, on the incidence and prevalence of acute upper respiratory diseases.

In addition to these data-driven objectives, this thesis will also include a comprehensive review of the literature on climate and health in the *International Journal of Biometeorology*, as this forms the foundation of this research.

1.4 Structure of the Thesis

This thesis is presented as a PhD by publication, incorporating four core papers that contribute to the body of knowledge on the impact of climatic variations on respiratory health, with three of these papers having been published to date. Following this introductory chapter, the second chapter provides a detailed description of the South African study region, covering aspects such as topography, climate, and socioeconomic conditions. The third chapter, while not a standalone methodological chapter due to the inclusion of detailed methodologies within each paper, offers a synopsis of the overarching methodological approaches that underpin the research. Chapters four to six are dedicated to the individual papers, each a peer-reviewed piece that addresses specific aspects of the research questions. The seventh chapter engages in a general discussion that weaves together the themes across the four papers, situating them within the wider academic discourse and acknowledging the limitations of the study. The eighth and final chapter concludes the thesis by reflecting on the

research objectives, summarizing the key findings, and their significance, and suggesting directions for future research. A comprehensive reference list follows, collating all citations from the journal papers and thesis chapters, with specific reference lists for chapters three to six adhering to the citation styles of their respective journals. The appendices provide the necessary ethical clearance documentation, underscoring the stringent ethical adherence throughout the research.

CHAPTER 2: STUDY REGION

2.1 Introduction

This chapter describes South Africa, showcasing the reasons for its selection as the focal point of this study. South Africa is distinguished by its diverse geographic location and topography, which creates a unique mosaic of climatic and environmental conditions across the country. The choice of South Africa, as opposed to neighbouring countries like Lesotho or Botswana, or vastly different contexts such as the United States of America (USA), is rooted in its distinctive blend of climatic diversity, disease burden, and varied socioeconomic conditions, including a wide range of evaporation rates and a nuanced poverty index. The rationale for concentrating on the provincial scale is twofold. First, it allows for an examination of respiratory diseases within diverse but defined climatic zones, offering a balance between specificity and generalizability. Second, the provincial focus aligns with the administrative and health service structures in South Africa, facilitating relevant public health insights. The study region's land use zones are particularly pertinent to this research, as they influence human settlement patterns, environmental exposure, and consequently, the epidemiology of respiratory diseases.

It is important to note that while the individual papers included in this thesis provide succinct study site descriptions relevant to each paper's focus, this chapter expands upon those details. Here, we explore the geographic, climatic, and socioeconomic characteristics of the study region more comprehensively. This detailed overview provides the contextual backdrop necessary for a nuanced understanding of the complex interplay between environmental

factors and health outcomes, thereby underpinning the research's provincial focus and justifying the selection of South Africa as the study site.

2.2 Geographic Location and Topography

South Africa occupies the southernmost part of the African continent, extending from 22-35° S and 17-33° E, with a total land area of 1,219,602 km² (Figure 2.1; Mokoena, 2019). It shares national borders with Namibia, Botswana, Zimbabwe, Mozambique, and Eswatini, and entirely encloses Lesotho (Mokoena, 2019). The Atlantic Ocean borders the western and southwestern coastline of the country, where the Benguela Current, a cooler current, influences the maritime climate (Davis-Reddy and Vincent, 2017). The Indian Ocean borders the southern and eastern coastlines, where the warm Mozambique and Agulhas Currents influence the coastal climate up to Cape Agulhas (Davis-Reddy and Vincent, 2017; Mokoena, 2019).

The country's topography is characterized by the presence of the Great Escarpment, a significant geological feature that marks the division between the high interior plateau and the lower coastal plains (Grab and Knight, 2018; Mokoena, 2019; Roffe et al., 2019). The escarpment sweeps through Limpopo and south-eastern Mpumalanga, and ascends to its peak along the border between Lesotho and KwaZulu-Natal province, with the Drakensberg region reaching elevations of up to 3,482m.asl (Figure 2.1; Grab and Knight, 2018; Mokoena, 2019). The vast interior plateau stands at an average elevation of 1,200 meters, while the higher plateau regions, including the western, eastern, and southern escarpments, average around 1,250 m.asl (Figure 2.1; Landman et al., 2017). The Cape Fold Belt mountain range in

the southwestern Cape and along the southern coast reaches elevations of approximately 2,249 m.asl (Grab and Knight, 2018).

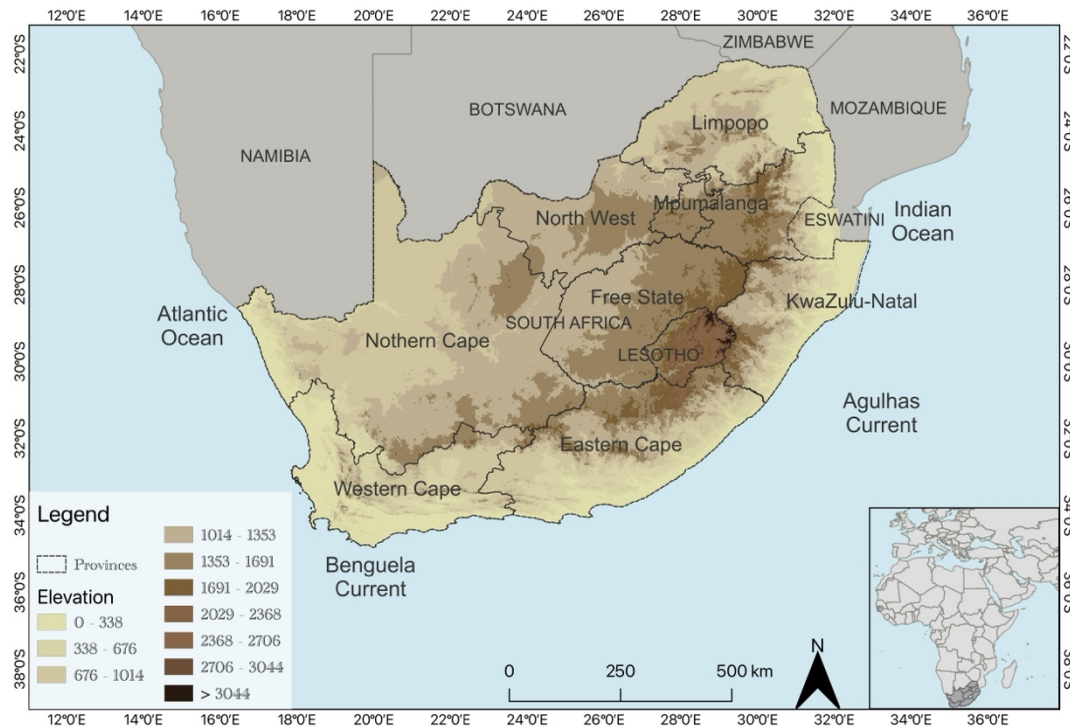


Figure 2.1: Location and Topography of South Africa.

2.3 Climatic Characteristics of South Africa

Before examining the evaporation range within South Africa, an exposition of the fundamental climatic components is warranted. The Köppen-Geiger climate classification delineates the diverse climatic zones of the region, categorizing them into desert, semi-arid, subtropical, and oceanic climates (Engelbrecht and Engelbrecht, 2016). This classification is useful in interpreting the heterogeneous temperature and precipitation profiles throughout the nation. Thermal variations within South Africa are substantial and are predominantly attributed to the nation's distinct topography coupled with maritime influences (Akinyemi et

al., 2019). The elevated interior plateau is typically subject to higher thermal readings in contrast to the coastal regions, which experience moderated temperatures due to oceanic currents (Lennard, 2019). Precipitation distribution is similarly variable, with the eastern seaboard receiving substantial rainfall, in stark contrast to the markedly arider western areas. (Landman et al., 2017; Roffe et al., 2021).

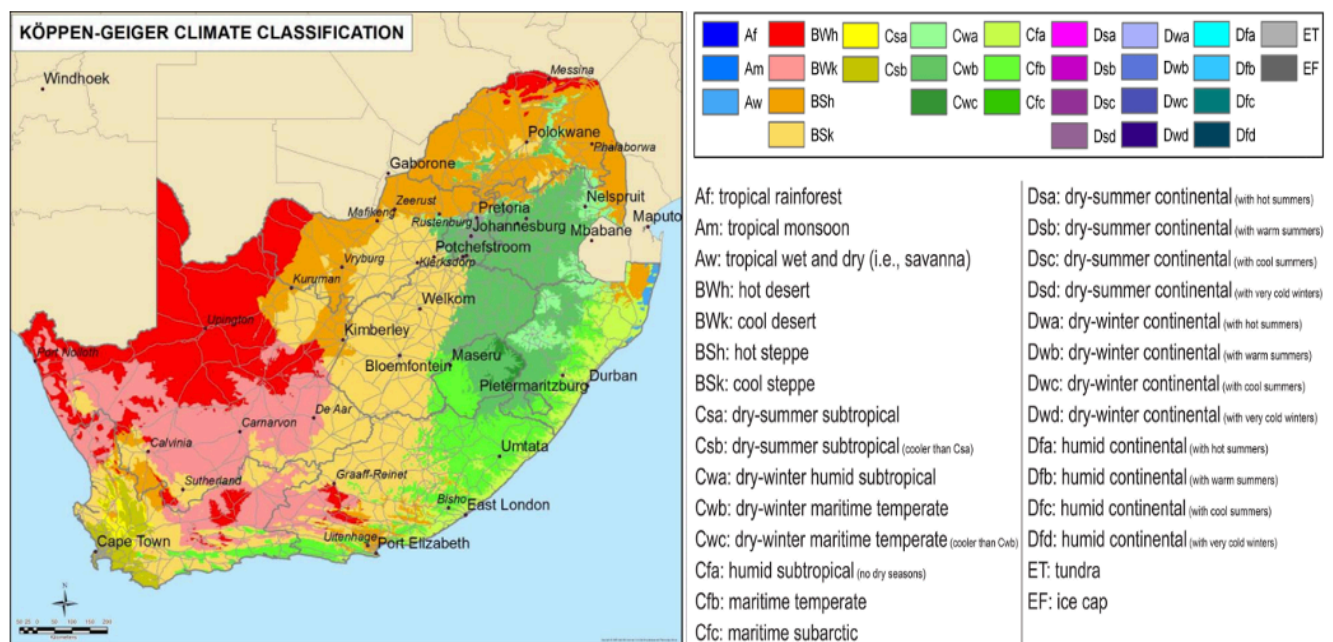


Figure 2.2: Köppen-Geiger Climate Classification (Engelbrecht and Engelbrecht, 2016)

Within the climatic framework of South Africa, the parameter of evaporation is particularly salient when considering the balance between evaporation and precipitation (Culiis et al., 2015). As depicted in the Evaporation Range map (Figure 2.3), a gradient of aridity traverses the country, highlighting zones where limited water availability may serve as a surrogate for potential respiratory health risks (Silvermane et al., 2021). Areas with pronounced evaporation rates suggest arid conditions and correlate with a heightened presence of airborne dust and particulate matter (Arenas-Diaz et al., 2022). In South Africa, the correlation between arid conditions and the presence of airborne dust and particulate matter does not

align with patterns observed in other regions (Manisalidid, 2020). Here, higher particulate matter levels are often found in densely populated areas rather than regions with high evaporation rates, highlighting the need for a specific focus on urban and industrial emissions in air quality studies (Gili et al., 2022). Although arid conditions are associated with increased airborne dust globally, in South Africa, particulate matter's impact on respiratory health is more strongly linked to emissions from urban and industrial activities (Glenn et al., 2022). This link is particularly pronounced in socioeconomically disadvantaged populations, where exposure to industrial pollutants rather than natural aridity contributes to a higher incidence of respiratory conditions such as transient irritation and COPD (Figure 2.3; Gordon, 2003; Thompson, 2005).

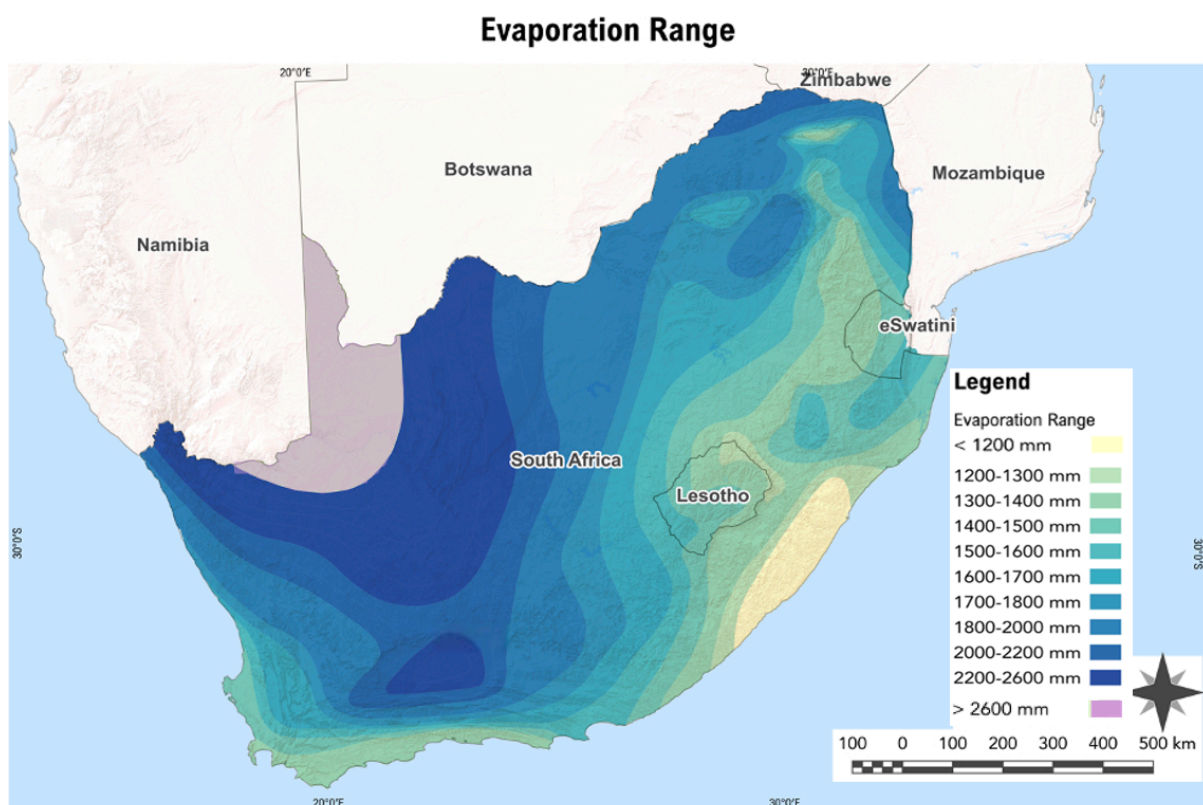


Figure 2.3: Evaporation Range Zones of South Africa

The transmission dynamics of respiratory pathogens are modulated by environmental variables, notably temperature and humidity (Wang et al., 2021). The Evaporation range map affords a predictive perspective on the regions where climatic conditions may enhance the persistence and propagation of respiratory viruses, thus influencing epidemiological patterns of disease manifestation and spread (Lofgren et al., 2007). It is imperative to show that aridity is not solely contingent upon evaporation rates; rather, it is the interplay between evaporation and precipitation that is determinative.

The primary focus of this thesis is the examination of specific climatic variables concerning respiratory diseases. Therefore, the emphasis placed on evaporation should be contextualized within its association with the primary variables under study. Although the evaporation data was not a direct variable of investigation, its relevance lies in its interaction with other climatic factors. This understanding furnishes a foundational context for the research and contributes to the discourse on potential indirect climatic influences on respiratory health outcomes.

2.4 Socioeconomic Conditions and Health Outcomes: The Poverty Index

The Poverty Index offers a stark visual representation of the socioeconomic disparities that pervade the South African landscape (Figure 2.4). Figure 2.4 indicates that the highest levels of poverty, represented by the darkest shades (above 81% poverty index), are predominantly found in the northeastern regions of South Africa. Additionally, certain central and eastern regions also show high poverty levels, within the 71-81% range. Such disparities have profound implications for the nation's health profile, particularly concerning respiratory diseases. Research has consistently demonstrated a correlation between socioeconomic

status and health outcomes, emphasizing that higher poverty indices are often associated with increased respiratory disease incidence due to a multitude of interrelated factors (Ataguba et al., 2011).

In South Africa, healthcare delivery ranges from primary services to advanced, specialized care across public and private sectors (Harris et al., 2011). Despite the state contributing 40% of the total health expenditure, the public sector is burdened with serving 80% of the population. This dichotomy in healthcare financing means access to private care is largely contingent on one's financial means—either through direct payment or insurance—while the public sector struggles with challenges such as protracted waiting times, outdated facilities, and compromised quality of care (Naiker et al., 2009; Burger and Christian, 2018). The over 400 public hospitals contrast with more than 200 private facilities, reflecting a disparity in healthcare resources, particularly pronounced in impoverished regions where limited infrastructure contributes to delayed diagnosis and treatment of diseases, including respiratory conditions (Mayosi et al., 2012; Coovadia et al., 2009).

The land use patterns in South Africa, particularly urbanization, have significant health implications. Urban areas, with their dense populations and industrial activities, are often implicated in the formation of urban heat islands, which may amplify the prevalence and severity of respiratory diseases among susceptible populations (Ackerman, 1985; Harlan and Ruddell, 2011). Urbanization alters the environment in ways that can directly impact respiratory health. The conversion of natural landscapes to built environments predominantly exacerbates air quality degradation through increased emissions in urban areas. This deterioration is exacerbated by the accumulation of particulate matter and pollutants from

vehicular and industrial sources, creating conditions conducive to respiratory diseases (Pope III et al., 2002).

Conversely, the integration of green spaces within urban areas has been shown to enhance air quality and reduce respiratory ailments, underscoring the health benefits of maintaining natural vegetation within cityscapes (Hartig et al., 2014). In contrast, deforestation and the loss of natural vegetation detrimentally affect air quality and biodiversity. While some types of vegetation can indeed trigger allergies, the broader implications of reduced biodiversity and altered air quality contribute significantly to the increase in allergy and asthma prevalence (Hanski et al., 2012). Incorporating land use considerations into public health strategies is crucial for addressing the varied health challenges across different zones. By understanding the land use-health nexus, policies can be tailored to mitigate the adverse health effects of environmental and lifestyle factors prevalent in both urban and rural settings.

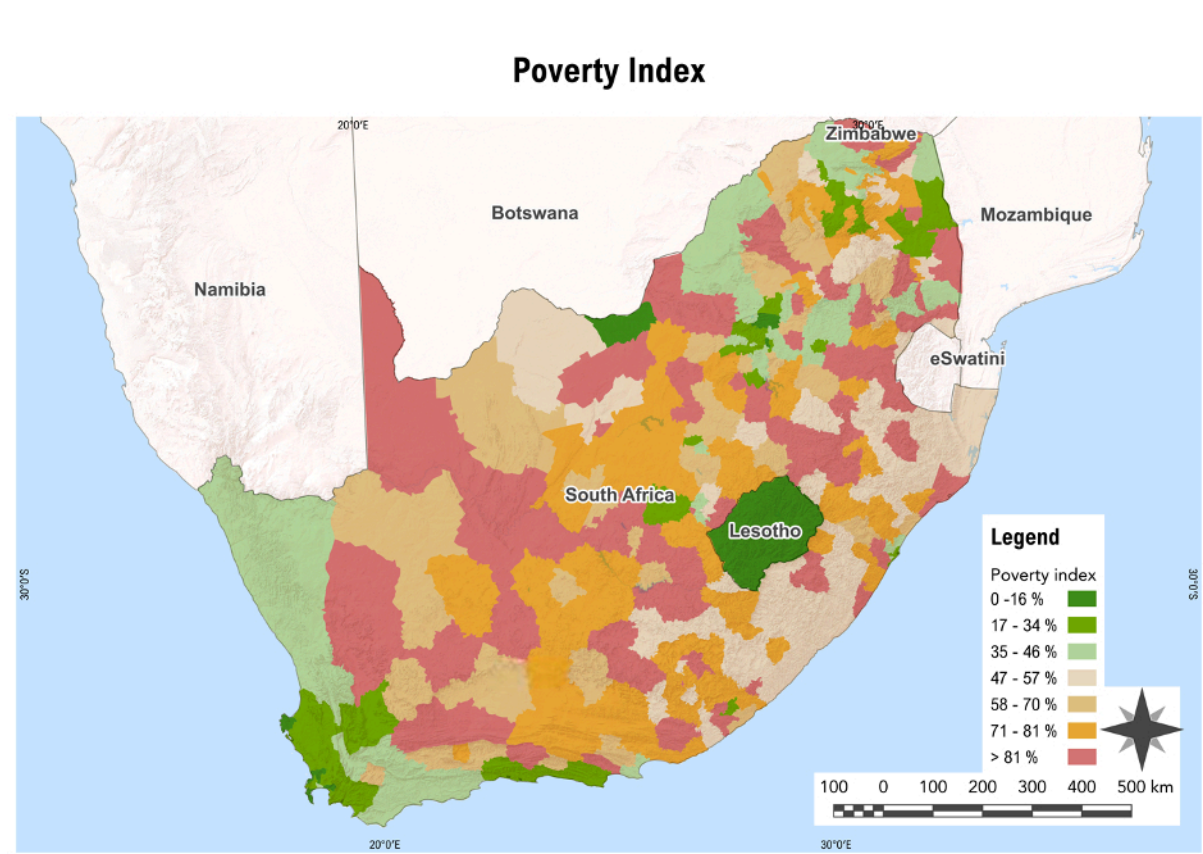


Figure 2.4: Poverty Index of South Africa

South Africa is an exemplary setting for a study focused on the climate-related fluctuations in respiratory disease patterns due to several distinct attributes. The country's climatic diversity spans Mediterranean to subtropical climates, offering a range of environmental conditions for analysis. The clear seasonal transitions in South Africa provide a structured framework to investigate the temporal relationship between climate and respiratory health. Additionally, the nation's healthcare infrastructure yields high-quality data, essential for such a study. Socio-economic variability across the region may affect disease incidence and outcomes, allowing for a comprehensive examination of environmental and social determinants of health. The rich biodiversity, including a variety of allergens, further enriches the study context, enabling an in-depth exploration of the ecological factors contributing to respiratory

health. Together, these elements position South Africa as an ideal location for research into the climate dynamics of respiratory disease prevalence.

CHAPTER 3: METHODOLOGICAL CONSIDERATIONS

3.1 Introduction

This chapter delineates the methodological framework adopted to analyze the impact of inter-annual and inter-seasonal climate variations on respiratory disease prevalence in South Africa. The exposition begins with an overview of the data collection methods, specifying the data sources, selection criteria, and the measures implemented to verify data accuracy. Subsequent to this, the discussion transitions to the ethical considerations integral to the study, focusing on confidentiality, informed consent, and the ethical approval processes upheld during the research.

Central to the data analysis were the statistical tools and programming techniques employed, particularly the use of R—a statistical computing environment favoured for its capacity to handle complex data and perform detailed statistical modelling. The analysis also made supplementary use of Excel for its versatile data manipulation and visualization capabilities. The chapter provides a detailed account of the selection and application of various statistical models, including those used to elucidate the nuanced relationships between climate variables and disease patterns.

The chapter then addresses the inherent challenges encountered in the research process, such as data heterogeneity and bias, articulating the strategies adopted to manage these issues effectively. In particular, it emphasizes the use of R for its advanced package ecosystem and robust data handling features, which were pivotal in ensuring the integrity and robustness of the research results. The chapter culminates with a reflection on the

methodological significance of the study within the broader context of climate health research.

3.2 Datasets

This section details the dual-dataset approach used in analyzing acute respiratory diseases by combining data from public and private healthcare sectors in South Africa. Data from Chris Hani Baragwanath Hospital provides insights into public healthcare trends and diseases' seasonality. Complementarily, data from the Discovery Health Medical Scheme offers a broader spectrum of respiratory conditions treated in the private sector, from mild to severe cases. Together, these datasets enable comprehensive analysis of respiratory disease prevalence and trends across socio-economic settings, enhancing understanding and aiding public health strategy development. The study employs meticulous temporal and geographical data analysis to identify patterns and inform effective interventions. It is important to note that all datasets used in this study include data from 2008 to the end of 2019, specifically chosen to avoid the confounding impact of the COVID-19 pandemic. This timeframe allows for a comprehensive analysis of respiratory disease prevalence and trends across socio-economic settings, enhancing understanding and aiding public health strategy development.

This study employed a dual-dataset approach for the analysis of acute respiratory diseases, incorporating data from both public and private healthcare sectors in South Africa. The dataset from Chris Hani Baragwanath Hospital, a significant public healthcare provider as one of the largest hospitals in the world, was utilized for three fundamental reasons:

1. Representation of Public Healthcare: As the largest hospital in Africa and one of the most extensive in the world, Chris Hani Baragwanath Hospital caters to a large portion

of the South African population. It is estimated that around 80% of the population relies on public healthcare services.

2. **Specificity of Respiratory Disease Data:** The dataset includes test-confirmed cases of respiratory diseases, such as Influenza, Respiratory Syncytial Virus (RSV), and coronaviruses. The specificity of the data for named respiratory diseases enhances the precision of the study, allowing for a focused investigation into the incidence and seasonality of these particular illnesses.
3. **Global Comparability for Seasonality and Climatic Impact Assessment:** Hospitalization data is a widely recognized measure in global health research for assessing the seasonality and climatic influences on acute upper-respiratory diseases. By utilizing this dataset, the study aligns with international research methodologies, facilitating comparisons and benchmarking with global data.

These data were paramount in offering a granular view of the disease burden within a hospital setting, allowing for an examination of the severity of cases, response to treatments, and patient outcomes. This comprehensive analysis provided a solid foundation for understanding the progression, impact, and seasonal trends of respiratory diseases in a public hospital environment, offering a valuable comparison with private healthcare data and contributing to a holistic understanding of respiratory health in varied socio-economic settings.

The dataset from the Discovery Health Medical Scheme (DHMS) complemented the hospital data by providing a panoramic view of acute respiratory disease cases within the private healthcare sector. This dataset is comprehensive, documenting instances that span from minor symptoms treated with over-the-counter medications at local pharmacies, general

practitioner consultations for common colds identified by the ICD-10 code J00 (Acute nasopharyngitis), to severe cases of Influenza, some of which necessitated Intensive Care Unit (ICU) admission, denoted by codes J118 (Influenza with other manifestations, virus not identified), J111 (Influenza with other respiratory manifestations, virus not identified), and J110 (Influenza with pneumonia, virus not identified).

This variety in data captures the full distribution of acute upper respiratory diseases—beyond just the severe cases that result in hospitalization—across individuals who have medical aid coverage through DHMS. Although medical aid covers approximately 20% of South Africans, with DHMS being only one among various providers, their dataset is notably expansive. It surpasses the hospitalization data in volume, even when considering the Johannesburg region served by Baragwanath Hospital.

The inclusion of such a spectrum of cases—from the common cold to more severe influenza—is crucial to understanding the broader impact of respiratory diseases. It allows for a more comprehensive analysis of disease prevalence, the effectiveness of public health interventions, and the overall health status of the community with respect to respiratory conditions. Moreover, the use of ICD-10 codes ensures a precise and consistent classification of diseases, which is imperative for the analytical accuracy and relevance of the study to its research questions.

By incorporating both the specific, test-confirmed hospital data with the more comprehensive symptom-based medical scheme data, a more holistic view of acute respiratory diseases in South Africa is revealed. To facilitate comparison of these two datasets, the DHMS data were

aggregated to weekly total claims, with the weekday starting on a Sunday, to align with the format of the Baragwanath data.

The data analysis in this study meticulously examined both temporal and geographical dimensions. Data was analyzed at daily and weekly intervals, tailored to the specific analysis being performed and the desired outcomes. This flexible approach provided a comprehensive temporal perspective, enabling a detailed understanding of the fluctuating patterns of respiratory diseases over time. By varying the temporal scale of analysis, the study effectively captured both short-term fluctuations and longer-term trends in disease occurrence, ensuring that unique disease patterns were accurately reflected in changing environmental and climatic conditions. Additionally, the geographical span of the study covered multiple locations within South Africa, offering a nuanced understanding of the spatial dynamics of disease incidence. This granular approach to analyzing data across time and space was pivotal in identifying regional variations and temporal trends in respiratory diseases.

3.3 Meteorological Data

The study period for our analysis spanned from 2008 to 2019. During this time, the meteorological data was collected with a daily temporal resolution, including measurements of minimum, maximum, and calculated mean temperatures, as well as rainfall data. The geographical distribution of the meteorological data involved a total of 24 weather stations strategically situated in and around Cape Town, Gqeberha, and Johannesburg, selected to represent areas with similar climatic conditions. This configuration provided a comprehensive dataset that allowed for detailed analysis of the environmental factors affecting respiratory health across these diverse yet climatically comparable regions.

We obtained meteorological data from the South African Weather Service (SAWS), including temperature, humidity, rainfall, and wind speed. To ensure the reliability of the data, a comprehensive verification process was conducted. This involved quality checks to identify anomalies and correct them, enhancing data consistency and accuracy. When faced with missing or inconsistent data, we employed interpolation techniques. These statistical methods estimated missing values based on the temporal and spatial trends of the meteorological variables, using sophisticated algorithms to minimize errors and accurately fill gaps in the dataset.

The alignment of meteorological data with health data involved both temporal and spatial considerations. Temporally, we matched health record timestamps with corresponding meteorological data dates and times. This precise synchronization allowed for an accurate analysis of the correlation between weather conditions and respiratory disease occurrences. Spatially, we mapped the geographical coordinates of weather stations to the locations of health data records. This step ensured that the analysis reflected the impact of local weather conditions on health outcomes in specific regions. Spatial alignment was crucial for identifying potential links between environmental factors and disease prevalence at a regional level.

We also addressed the different scales of meteorological and health data through geostatistical methods, aggregating weather data to match the health data's scale. This careful alignment and aggregation allowed us to conduct a detailed analysis of the relationship between weather conditions and respiratory disease patterns, revealing potential seasonal trends and disease prevalence variations linked to specific meteorological conditions.

3.4 Key Methods Used

This study employed a diverse range of methods to thoroughly address its multifaceted research objectives. The methods varied across different papers within the study to suit the specific analytical needs:

1. **Systematic Literature Review:** The study began with a systematic literature review to establish a foundation of existing knowledge and identify gaps in current research. This review informed the direction of subsequent analysis (Hossain et al., 2018).
2. **Threshold Analysis:** Following the literature review, threshold analysis was employed to identify specific climatic conditions that significantly increase the risk of respiratory diseases. In the context of the study on respiratory diseases, a percentage threshold refers to a specific point or limit in the data analysis that indicates when climatic conditions become significantly associated with an increased risk of respiratory diseases. This method of threshold analysis involves determining a percentage level at which certain climatic variables—such as temperature, humidity, or pollutant concentration—reach a critical point beyond which there is a measurable and statistically significant increase in the incidence of respiratory diseases. This method was pivotal for determining critical risk points relevant to public health advisories and policymaking (Eurich et al., 2008; CDC, 2022).
3. **Percentage Differences in the Extreme Climate Events (ECE) Paper:** After establishing thresholds, we used the percentage differences approach in the ECE paper to quantify relative changes in disease incidence associated with extreme weather events. This method provided a clear representation of the impacts of extreme weather on health (Hay et al., 2000).

4. Distributed Lag Non-linear Models (DLNM): Lastly, DLNMs were utilized to examine the relationship between temperature and respiratory disease incidence. This method was particularly effective in accounting for non-linear relationships and delayed effects, key aspects in environmental health studies (Dixon et al., 2014).

Each method was informed by key papers in the field, ensuring that the study's application of these statistical techniques was grounded in established research. The details and application of these methods are described in the respective papers, with each paper focusing on a different aspect of the climatic impact on respiratory diseases. The methods were applied in a sequence that built upon the insights gained from each step, culminating in a comprehensive understanding of the complex relationship between climate variability and respiratory health.

3.5 Scale of Analysis: Provincial vs. Local Perspectives

The research adopted a dual-scale approach, analyzing data at both provincial and local levels. This strategy was pivotal in addressing the diverse aspects of the study's objectives. By examining the data at these two distinct scales, the research was able to capture the heterogeneity inherent in climatic conditions, healthcare infrastructure, and health outcomes across South Africa. At the provincial level, the analysis provided a macroscopic view of respiratory disease trends across different provinces. This broad perspective was crucial for identifying overarching patterns and regional variations in disease incidence and prevalence. The provincial scale analysis helped in understanding how different climatic zones across the country correlate with respiratory health outcomes, offering insights that are vital for formulating regional public health strategies and resource allocation.

Whilst the local scale analysis conducted in this study focused on specific geographical and demographic contexts within urban and rural settings. This detailed examination was targeted at distinct levels. This granular approach was crucial for understanding how local environmental factors, demographic compositions, and variations in healthcare access influence the patterns and impacts of respiratory diseases.

This analysis was part of a multi-tiered approach to the research:

1. Threshold Analysis was performed at the provincial level, providing an overview of the broader climatic impacts on respiratory health.
2. Distributed Lag Non-Linear Models (DLNM) focused specifically on metropolitan areas, analyzing the temporal dynamics between environmental variables and health outcomes in urban centres.
3. Percentage Differences in the Extreme Climate Events (ECE) was applied to specific areas, assessing the localized effects of environmental factors in defined urban and rural settings.

The choice of conducting analyses at both provincial and local scales was guided by the objective to comprehensively understand the impact of climatic variables on respiratory diseases. Recognizing South Africa's varied climatic, demographic, and healthcare landscapes, it was essential to adopt a multi-scale approach. This method ensured that the study's findings were not only broadly applicable at the national and provincial levels but also deeply relevant and actionable at the local community level. By encompassing both provincial and local perspectives, the study's findings offer valuable insights for public health policymakers at multiple administrative levels. The dual-scale analysis allows for the development of both broad-reaching policies and targeted local interventions, ensuring that public health

strategies are effectively aligned with the specific needs and challenges of different regions and communities.

In summary, the scale of analysis in this research was carefully chosen to ensure that the findings provide a comprehensive understanding of the relationship between climatic variables and respiratory diseases. This approach facilitated the generation of insights that are critical for informed decision-making in public health, catering to both provincial and local healthcare planning and intervention strategies.

3.6 Ethical Considerations

Our research followed ethical guidelines from the Wits University Human Research Ethics Committee (Medical), with clearance certificate number M210617. This approval reflects our commitment to ethical research, guiding all stages including data handling and analysis. Wits University's ethics committee endorsement indicates our study's design and conduct met high ethical standards, especially concerning patient confidentiality. We strictly protected individuals' identities by anonymizing data throughout the research process. Our procedures complied with ethical norms and underscored the importance of privacy in medical research.

Every phase of the research, from initial data gathering to detailed analysis, adhered to ethical practices. This consistent application of ethical guidelines across all research stages ensured the integrity of our work and the ethical treatment of all participants. Adherence to these standards is essential to maintain the trustworthiness of our research outcomes and contribute responsibly to scientific knowledge.

CHAPTER 4: CLIMATE AND HUMAN HEALTH: A REVIEW OF PUBLICATION TRENDS IN THE INTERNATIONAL JOURNAL OF BIOMETEOROLOGY

4.1 Brief Synopsis

This review article, "Climate and Human Health: a review of Publication Trends in the International Journal of Biometeorology," explores the confluence of meteorological factors and specific health conditions. Surveying the 180 papers from the International Journal of Biometeorology that empirically tested the relationship between diagnosed medical conditions and climate, this corpus represents 8.3% of the total 2183 publications that more broadly focused on human health and climate. The review underscores a burgeoning interest in the nexus of climate and health since 2011, with research intensifying in 2017. It highlights a predominance of studies emanating from the Global North, especially Asia and Europe, juxtaposed against a scant output from African and South American scholars. Predominant health concerns explored include respiratory, cardiovascular, and cerebrovascular diseases. The piece accentuates the exigency for persistent inquiry, particularly in territories with low and lower-middle incomes, which bear the brunt of climate-sensitive health conditions. This analysis underpins the rationale for this doctoral study, which seeks to delve into the existing body of knowledge specific to biometeorology and underscores the necessity for geographically tailored studies in Africa. It also brings to light the evolution in research methodologies, advancing from elementary linear regression and correlation assessments to more sophisticated Distributed Lag Non-linear Models (DLNM). This academic progression mirrors the objectives of this PhD research, which aims to not only fill the geographical gaps

identified but also to enhance the analytical techniques applied in the field of climate and health.

Author contributions:

Contributor role	Author contribution
Conceptualisation	Fitchett JM
Methodology	Motlogeloa O and Fitchett JM
Validation	Motlogeloa O
Formal analysis	Motlogeloa O
Investigation	Motlogeloa O
Resources	Motlogeloa O
Data Curation	Motlogeloa O
Writing – the original draft preparation	Motlogeloa O
Writing – review and editing	Motlogeloa O and Fitchett JM
Visualisation	Motlogeloa O
Supervision	Fitchett JM and Sweijd N
Project Leader	Fitchett JM

According to the above-mentioned CRediT system the author contribution was calculated as follows:

Motlogeloa O – 70%

Fitchett JM – 30%

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Climate and human health: a review of publication trends in the International Journal of Biometeorology

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Abstract

The climate-health nexus is well documented in the field of biometeorology. Since its inception, Biometeorology has in many ways become the umbrella under which much of this collaborative research has been conducted. Whilst a range of review papers have considered the development of biometeorological research and its coverage in this journal, and a few have reviewed the literature on specific diseases, none have focused on the sub-field of climate and health as a whole. Since its first issue in 1957, the *International Journal of Biometeorology* has published a total of 2183 papers that broadly consider human health and its relationship with climate. In this review, we identify a total of 180 (8.3%, $n=2183$) of these papers that specifically focus on the intersection between meteorological variables and specific, named diagnosable diseases, and explore the publication trends thereof. The number of publications on climate and health in the journal increases considerably since 2011. The largest number of publications on the topic was in 2017 (18) followed by 2021 (17). Of the 180 studies conducted, respiratory diseases accounted for 37.2% of the publications, cardiovascular disease 17%, and cerebrovascular disease 11.1%. The literature on climate and health in the journal is dominated by studies from the global North, with a particular focus on Asia and Europe. Only 2.2% and 8.3% of these studies explore empirical evidence from the African continent and South America respectively. These findings highlight the importance of continued research on climate and human health, especially in low- and lower-middle-income countries, the populations of which are more vulnerable to climate-sensitive illnesses.

Keywords Health biometeorology · Climate and health · Diseases · Meteorological variables · Publications · Human

Introduction

The history and the development of the International Society of Biometeorology are well documented in the *International Journal of Biometeorology* (Tromp 1957; International Society of Biometeorology 1975, 1981; Keatley 2017). Since its inception, the *International Journal of Biometeorology* has not only been true to its international scope, but also to the variety of studies it has published that span across various fields of research (Sheridan and Allen 2017; Fitchett 2021). The role of climate on health has been known for millennia, yet the deliberate study of the aetiology and statistical analysis have been more recent, and a key component of biometeorology, since the inception of the society and the

first issue of the journal (Tromp 1956). Increased incidence of respiratory and cardiovascular disease (CDC 2022), injuries and early deaths from extreme weather events (CDC 2022), changes in the prevalence and geographic distribution of food- and water-borne illnesses and other infectious diseases, and threats to mental health are some of the health effects that are worsened by a change in climate (CDC 2022; Krüger et al. 2022). Changes in climate and climatic variability, particularly changes in the frequency, intensity, and distribution of weather extremes, affect the environment that provides us with clean air, food, water, shelter, and security (Wu et al. 2016; Wang et al. 2017). Given that the impacts of climate change are projected to increase over the next century, existing climate-sensitive health threats will intensify and new health threats may emerge particularly in regions situated in the Southern Hemisphere and regions in Europe with an ageing population (Caini et al. 2018). The studies published in the *International Journal of Biometeorology* on the impact of various meteorological variables on disease are important as their findings not only help classify the

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severity of the situation but also assist in better understanding how climatically sensitive these diseases are (Hewitt and Griggs 2004). This journal serves as an important platform, encouraging from its inception the collaboration between climatologists, health practitioners, and a range of other interdisciplinary actors (Sheridan and Allen 2017). This subsequently allows for the development of effective methods for minimizing the effects of climate change on health (Tromp 1957).

Three review papers on health biometeorology have been published in the *International Journal of Biometeorology*. Cheng et al. (2019) reviewed the impacts of exposure to ambient temperature on the burden of diseases; Hossain et al. (2019) examined the relationship between sociodemographic factors, climate, and respiratory tract infections in the literature; and Jahan et al. (2020) published a review on the relationship between schizophrenia and seasonality. These papers made important contributions in synthesizing the research for specific medical conditions. However, this study presents the first systematic review that considers the subdiscipline of health biometeorology as a whole, reflecting on the geographic distribution of studies, the diseases investigated, the specific meteorological variables investigated, and the growth in this thematic area within the journal from 1957 to April 2022. This review paper contributes to the ongoing reflective and reflexive efforts of this journal and relatively new discipline in tracking the growth and impact of research. It is also valuable in evaluating whether the trends in the literature align with the key global challenges faced at present.

The establishment of health biometeorology research

The meteorologist Franz Linke (1878–1944) formalized the academic theme of medical meteorology (Tromp 1963). Rather than concentrating on independent meteorological components, Linke examined the connection between complexes of weather conditions factors, for example, such as frontal passages and air masses with biological events (Tromp 1977). To acquire vital information, Linke established bioclimatological stations across Germany and started to give clinical meteorological gauges in light of measurable meteorological examinations (Tromp 1967, 1977). To convey the outcomes, Linke established, along with Austrian partners, the main journal committed to bioclimatology, the 'Bioklimatische Beiblätter' as an enhancement to the Austrian 'Meteorologische Zeitschrift' (de Rudder 1931; International Society of Biometeorology and Bioclimatology 1957). The journal integrated a few previously divergent disciplines, including physics, medicine, botany, and geography, that were relevant to the interdisciplinary study of biology and the climate

(International Society of Biometeorology and Bioclimatology 1957). Parallel to the holistic movement, a few German meteorologists and doctors concentrated on the Hippocratic theories on the connection between weather and health through unbiased and more logical methodologies (Tromp 1963, 1966). Regardless of the revolution in medication that brought about germ theory, bacteriology, and parasitology as focal ideas in medication, more established Hippocratic convictions about the natural reasons for sickness continued (Lieth 1988). These thoughts were communicated in various structures, subject to the nearby setting and the expectations of the people who embraced them (Tromp 1966; Brezina 1938).

Holistic values underscored an organic perspective on man as a patient, creating opportunities for natural healing, for example, climatotherapy (Bynum 1994). The theoretical, order Hippocratic idea that climatic fluctuation caused sickness was embraced in the logically arranged approaches of Petersen (1935), de Rudder (1931), and others, which became known as 'bioclimatology' or 'biometeorology'. Considering the longing to understand the link between man and his environment, it is not surprising that this concept was selected amongst the many other Hippocratic theories (Weihe 1967). To follow the onset of disease, which is a diversion from the healthy state, it was sensible to look for related changes in the environment, the climate, or the weather (Tromp 1977). It was unanticipated that during the 1920s meteorologists would have made great leaps forward in how they might interpret changes in the climate; thus, scientists such as de Rudder (1931) and Petersen (1935) began to concentrate on how the onset of diseases is related to large scale atmospheric movements (de Rudder 1931; Petersen 1935). However, it is less certain how more subtle environmental factors play a role in the origin of diseases (Wu et al. 2016).

Biometeorology is the field that studies relationships between living organisms and their surroundings, with its sub-branch of human biometeorology dedicated to issues concerning human health (Tromp 1977). These fields are multidisciplinary, combining biology or medicine with meteorology and climatology (Folk 2013). Around 1950, biometeorological topics were studied by dispersed and isolated individual scientists with various backgrounds (McGregor 2012). A need was felt to organize these efforts into a new discipline with its institutions in the form of a society, a journal, dedicated conferences, and study groups (Folk 2013). The discipline was formalized in the 1950s with the establishment of the *International Society of Biometeorology* and its flagship journal in 1956 and 1957 respectively (Folk 2013). Studies such as these bring us to the modern-day and subsequently increase in recognition of the need to statistically engage in the relationship between climate and human health. For this reason, this study focuses specifically on empirical papers that use a statistical approach with meteorological data and case data.

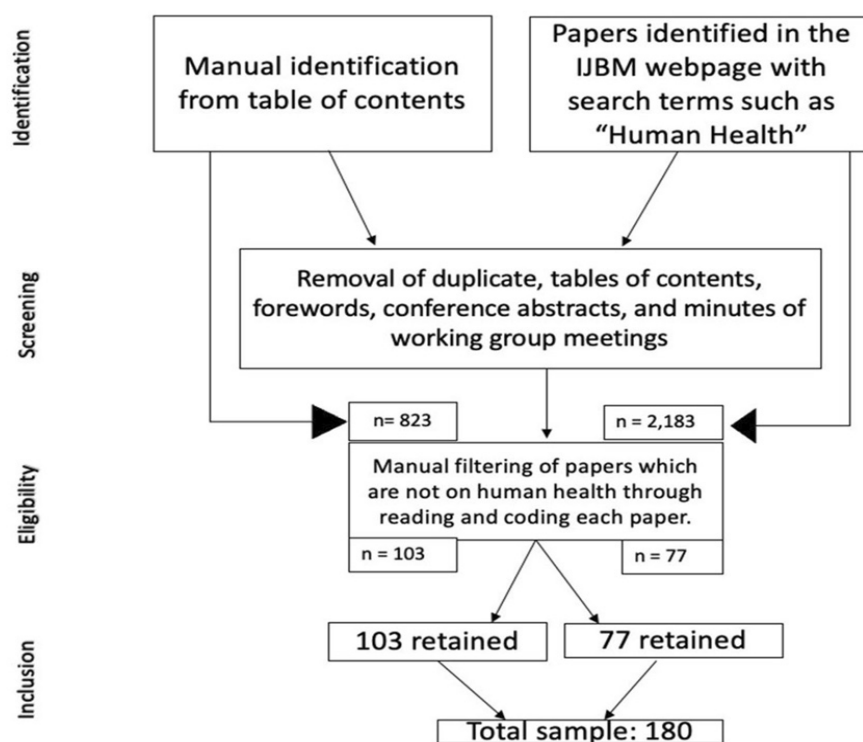
Methods

The methodology employed in this review is adapted from previous discipline-specific reviews in the *International Journal of Biometeorology*, which consider only those papers published within the journal (Beggs et al. 2017; Donnelly and Yu 2017; Hondula et al. 2017; Sheridan and Allen 2017). The SpringerLink search function on the *International Journal of Biometeorology* webpage was used in the data acquisition process of this review, from which search words were applied across all published papers within the journal. An initial search was conducted for research papers using the phrase ‘human health’, returning all papers in which both ‘human’ and ‘health’ are mentioned at least once in the title, abstract, and main text of the manuscript. This yielded a total of 2183 papers (Fig. 1).

Search results that included conference abstracts, review papers, minutes from working group papers, corrections, and forewords of issues were excluded in the first round of screening. At this point, 2183 studies broadly considering climate and health through empirical research were identified (Fig. 1). A descriptive analysis of the thematic areas of these studies was

performed, which included a manual review of each paper to ascertain whether the analysis related directly to health and climate. As this review paper specifically focuses on the intersection between specific, diagnosable diseases and meteorological variables through the use of statistical methodologies such as regressions, time series analysis, and distributed lag nonlinear models, generalized additive models with Poisson distribution, the second round of manual screening excluded all papers on broader health issues such as thermal comfort, thermal stress, fertility, and balneotherapy. Thermal comfort and stress have been the focus of prior reviews (e.g., Vanos et al. 2010; Baruti et al. 2019), and whilst certain diseases are precipitated and exacerbated by thermal stress, it is not independently considered a disease. Likewise, whilst issues of fertility may be exacerbated or triggered by the climate, this review only considers cases where specific diagnosed diseases are considered. Although balneotherapy was one of the key areas of interest in early health biometeorology (McGregor 2012), it is focused largely on general well-being rather than a specific disease, and so these themes have likewise been excluded even where balneotherapy is considered in relation to a diagnosed disease if meteorological factors have not been considered.

Fig. 1 Flow diagram of the process of article identification, screening, eligibility, and inclusion in this review



Of the 2183 studies, initially identified, only 77 were retained following this exclusion process (Fig. 1). This was then proceeded by manually reading through the table of contents for each issue of the journal since its inception, identifying all papers related to a specific, diagnosable disease, and meteorological variables. The sample was thereafter narrowed to papers that applied statistical techniques to empirically test the relationship between specific, measured meteorological variables, and diagnosed diseases solely. A total of 823 papers were initially identified through this process (Fig. 1). After careful consideration of each of the 823 papers, based on the exclusion criteria that were applied to the papers identified on the SpringerLink search, of these, 720 papers were excluded (Fig. 1). This brought the total down to 103 papers (Fig. 1). These papers were then manually read to determine whether they were indeed studies related to a specific disease and meteorological variables. Those that met the inclusion criteria were then captured in the database, according to the authors, year of publication, country, continent, meteorological variable, disease, and whether or not there was statistical significance. The two databases were then combined, and duplicates were removed. After careful inspection a final total of 180 papers remained in the database (Fig. 1). This represents 4.13% of the 4357 published papers in the *International Journal of Biometeorology* as of April 2022.

The 180 papers were manually coded, extracting and recording details on the diseases that were examined, in which country, with which meteorological variables, and in which year, to establish any spatial, thematic, and temporal trends in health biometeorology publications in the journal. The results of these findings have been displayed in tables, maps, and graphs, similar to those of Sheridan and Allen (2017) and Fitchett (2021). Additionally, a bibliometric network visualization was produced using VOSviewer, through the manual compilation of the same list of 180 papers. VOSViewer then generated a network visualization of the clustered articles. The nodes in the network are coloured based on their cluster membership, and the edges indicate the strength of the relationships between the nodes. The size of the nodes represents the number of articles associated with that membership. This review paper aims to track the bibliometric trends in the literature, and therefore it does not present a critique of the papers or review their approach or findings; rather, it aims to explore the publication trends within this theme of the journal.

Results and discussion

Publication trends

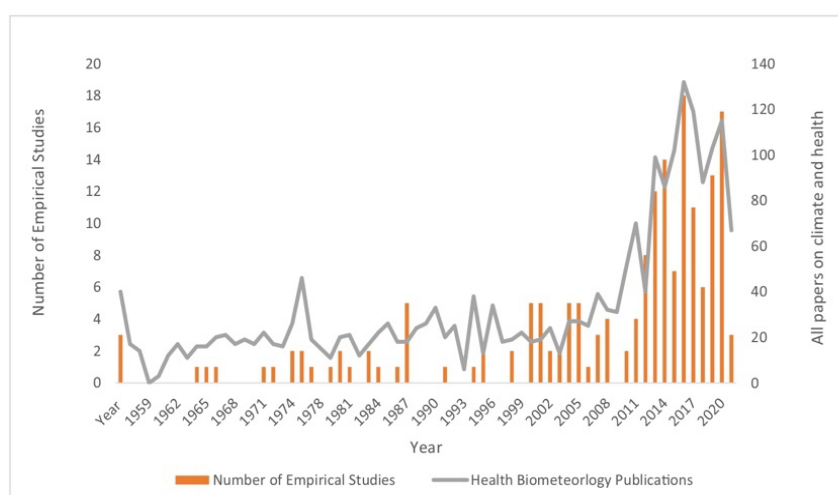
A total of 2183 papers in the *International Journal of Biometeorology* published between 1957 and 2022 make mention

of ‘human health’ at some point in the title, abstract, or manuscript, representing a substantial 50.2% of papers in the journal. Papers that explored thermal comfort account for 32.4% ($n=708$) of this total, whilst publications assessing balneotherapy account for 5.4% ($n=117$). There have been special issues in the journal dedicated to Balneology (Volume 64, Issue 6, June 2020) and the Universal Thermal Climate Index (Volume 56, Issue 3, May 2012 and Volume 65, Issue 9, September 2021). There is an overall increase in publications on climate and human health in the journal over the period 1957–2012. This coincides with changes in the total number of papers in the journal (Sheridan and Allen 2017). The increased number of issues per volume during the 2000s, from four issues a year until 2004, consist of 10–18 papers to six issues until 2012, and thereafter 12 issues which coincide with the months of the year (Fig. 2). These increases in health publications coincide with the inception of the constitution of the climate and human health commission (CHC) proposed in 2005 at the International Congress on Biometeorology in Germany (Fdez-Arroyabe and Robau 2017). Since its inception, the CHC has held a total of six meetings to date in 2006, 2007, 2008, 2010, 2011, and 2014 (Fdez-Arroyabe and Robau 2017). These patterns are also consistent with the temporal patterns in the total number of papers on human health in the journal over this period, attributed to advancements in technologies, moving to online publications and reviews, and the move to the Editorial Manager system in 2006 (Sheridan and Allen 2017).

The 180 papers that empirically explore the statistical relationship between meteorological variables and diagnosed disease case numbers, and which form the focus of this review (Table 1), represent 4.1% of the total 4350 papers published in the *International Journal of Biometeorology* since its inception in 1957 and 8.26% of the total 2183 papers that mention ‘human health’.

Over the first three decades of the journal, only 21 publications (11.7%, $n=180$) focused on a specific disease in the context of a meteorological variable (Fig. 2). As is the case for all papers on climate and health generally, from the early 2000s there has been a considerable increase in studies that use statistical methodologies to assess the relationships between climate and human health, aligning with the findings of McGregor (2012), with 18 published in 2017 alone (Fig. 2). Before this, the highest peak for 1 year at five papers (2.8%, $n=180$) was for 1988 (Fig. 2). These outcomes are ascribed to the journal’s overall rise in articles as a result of its rise in the number of issues per volume. The increase in health and climate publications in the journal may potentially also be in response to disease outbreaks. Following 1988, there was the COVID-19 pandemic from 2020, the Zika virus epidemic in South America in 2015, and the Ebola outbreak in central Africa in 2015. There are 39

Fig. 2 Number of empirical studies and papers related to climate and human health published per year in the *International Journal of Biometeorology*



papers on COVID-19 and the Zika virus in the journal that were published after 2015. Health and climate publications substantially increased during this time.

Geographical distribution of the research regions

The 180 papers empirically studying climate and health since the inception of *The International Journal of Biometeorology* in 1957 to April 2022 are largely concentrated across much of the Northern Hemisphere (Fig. 3). The greatest proportion of the studies have been conducted in Asia (42.2%, $n=180$). On the scale of individual countries, the greatest number of studies have been conducted in China (19.4%, $n=180$), followed by Japan (8.5%, $n=180$). In 2008, the CHC held a meeting in Japan, and in 2019 the *International Journal of Biometeorology* dedicated a special issue to Asian Biometeorology (Fdez-Arroyabe and Robau 2017), both of which may contribute to the large focus on Asia. These publications focused on a range of diseases. Some included chronic and acute respiratory diseases (24%, $n=75$), genetic disorders (2.6%, $n=75$), and vector-borne diseases (9%, $n=75$) (Table 1).

The second largest continental representation in the published research is in Europe (35.6%). This may be because researchers were predominantly based in Europe before the ISB expanded to other parts of the world. Studies conducted in Europe have been concentrated in Spain (6.1%, $n=180$) and Lithuania (3.3%, $n=180$). European studies particularly dominated the earlier volumes of the *International Journal of Biometeorology* (Table 1). This was perhaps as Tromp was from Europe and worked predominantly in this field of research. In 2021, a special issue was dedicated to the first

European Biometeorologists' meeting, following which five papers on climate and health in the region were published. For the same year, however, a greater number of studies were conducted in North America (25), namely the USA (18) and Canada (7). Overall, papers from North America account for 13.3% ($n=180$) of papers on climate and health in the *International Journal of Biometeorology*.

A small proportion of the literature on health biometeorology in the journal originates from the Southern Hemisphere. Only 10 studies have been conducted in Australia, and four in Africa. The latter comprises three studies in Nigeria and one in Kenya, leaving 52 African countries that have not been studied. Studies conducted in Africa comprise 4.1% ($n=180$) of all papers in the journal in total. However, whilst this fits proportionately with the journal figures (Fitchett 2021), it is surprising given the heightened disease load in Africa, particularly to climate-sensitive conditions such as malaria, Ebola, and yellow fever (Sen Roy 2018; de Villiers 2021).

Studies based in South America comprise 8.3% of the total 180 papers (Fig. 3). It is interesting to note that although there was a special issue on Latin America/Caribbean Biometeorology in 2018 and a special issue on the Brazilian Congress in 2019, very few of the publications from either special issue explored health biometeorology of specific diseases (Fdez-Arroyabe and Robau 2017).

Diseases under investigation

Across the 180 papers (1957–2022), a total of 14 disease groups were explored: neurological, cardiovascular, skin, rheumatic, intestinal, metabolic, psychiatric, vector-borne, genetic, cerebrovascular, respiratory, renal, and bacterial

Table 1 Papers on the intersection of specific diagnosable diseases and meteorological variables in the *International Journal of Biometeorology* 1957–2022

Author	Year	Disease	Country	Meteorological variable	Statistical significance
Canto Borreguero	1957	Allergic diseases	Spain	Weather	Yes
Tromp	1957	Bronchial asthma and mental diseases	Netherlands	Weather	Yes
Whiten	1957	Rheumatism	Great Britain	Weather	Yes
Derrick	1965	Asthma	Australia	Weather	Yes
Tromp and Bouma	1966	Arthritic pain	Netherlands	Weather	Yes
Paulus and Smith	1967	Allergic bronchial asthma	USA	Weather and air pollutants	Yes
Hansen and Pedersen	1972	Perforated duodenal ulcer	Denmark	Barometric pressure	No
Gomersall and Stuart	1973	Migraines	Scotland	Temperature	Yes
Bodhe and Mokashi	1975	Peptic ulcer	India	Relative humidity	Yes
Specht et al	1975	Asthma	Australia	Wind	No
Von Deschwanden and Jungmann	1975	Mental illness (schizophrenia and depression); hay fever; asthma	Germany; London; USA	Temperature	Yes
Shiffman et al	1976	Intestinal disease (diarrhoea)	Guatemala	Rainfall and temperature	Yes
Fleischer and Asnani	1978	Asthma	Kenya	Rainfall and temperature	Yes
Schulman et al	1980	Headaches	USA	Barometric pressure	No
Osterman et al	1981	Headaches	Sweden	Temperature	Yes
Goldstein	1981	Asthma	New York City and New Orleans	Weather	Yes
Deacon and Williams	1982	Sudden infant death syndrome	8 metropolitan communities	Temperature and rainfall	Yes
Formiconi and Tagliaferri	1984	Urinary stone colic	Italy	Temperature, rainfall and barometric pressure	Yes
Mukammal et al	1984	Cardiovascular disease (ischaemic heart disease)	Canada	Temperature	Yes
Bellossi et al	1985	Myocardial infarction	France	Relative humidity	No
Fujita	1987	Urinary stone colic	Japan	Temperature and barometric pressure	Yes
Fletcher	1988	Föhn illness	Canada	Temperature and wind	Yes
Garvey et al	1998	Depression	USA	Temperature	No
Mannino and Washburn	1989	Cardiovascular disease	USA	Temperature and rainfall	Yes
Morton	1988	Headaches	Canada	Relative humidity	Yes
Suzuki et al	1988	Asthma	Japan	Temperature and barometric pressure	Yes
Collier	1992	Meningococcal meningitis	United Kingdom	Temperature	Yes
Ohtsuka et al	1996	Diabetes mellitus	Japan	Temperature	Yes
Halpern et al	1995	Foetal chromosome abnormalities (trisomy-21)	Israel	Solar activity	No
Thompson et al	1996	Myocardial infarction	England	Temperature and relative humidity	Yes

Table 1 (continued)

Author	Year	Disease	Country	Meteorological variable	Statistical significance
Aikman	1997	Arthritis (rheumatoid and osteoarthritis)	Australia	Temperature, rainfall and barometric pressure, relative humidity	Yes
McGregor et al	1999	Respiratory disease	England	Barometric pressure	Yes
Rutherford et al	1999	Asthma	Australia	Wind	Yes
Bentham and Langford	2001	Food poisoning	England and Wales	Temperature	Yes
Laaidi	2001	Pollinosis	France	Wind, relative humidity, rainfall, and temperature	Yes
Schreiber	2001	Dengue	Puerto Rico	Temperature and relative humidity	Yes
Vaitl et al	2001	Headaches and migraines	Germany	Temperature	Yes
Vocks et al	2001	Atopic eczema	Switzerland	Temperature	Yes
Gagnon et al	2002	Malaria	Colombia, Ecuador, French Guiana, Guyana, Peru, Suriname, and Venezuela	Temperature and rainfall	Yes
Makie et al	2002	Cerebrovascular disease, respiratory disease, digestive diseases	Japan	Temperature and barometric pressure	Yes
Rusticucci et al	2002	Cerebrovascular disease, respiratory disease, digestive diseases, muscle pains, skin and allergies, neurological diseases, and psychopathological disorders	Argentina	Temperature and precipitation	Yes
Schlink et al	2002	Respiratory disease	Germany	Solar radiation, temperature, relative humidity	Yes
Wang et al	2002	Stroke	Japan	Temperature	No
Kolivas and Comrie	2003	Coccidioidomycosis (valley fever)	USA	Temperature and rainfall	Yes
Tobias et al	2013	Asthma	Spain	Wind	No
Ebi et al	2004	Cardiovascular diseases (myocardial infarction, angina pectoris, congestive heart failure) and stroke	USA	Temperature and rainfall	Yes
Ohwaki et al	2004	Hypertensive intracerebral haemorrhage	Japan	Temperature	No
Bulbena et al	2005	Anxiety	Spain	Wind, rainfall, temperature, relative humidity, and solar radiation	Yes
Gyan et al	2005	Asthma	Trinidad	Wind	Yes
Kovats et al	2005	Campylobacter	Canada, Scotland, Australia, Malta, Denmark, Spain, Czech Republic, Estonia, Greece, Ireland	Temperature	Yes
Stoupel et al	2005	Down syndrome	Israel	Solar radiation	Yes
Villeneuve et al	2005	Asthma	Canada	Relative humidity, temperature, rainfall	Yes
Fleury et al	2006	Bacterial enteric infection	Canada	Temperature	Yes
Hrushesky et al	2006	Uterine cervical human papilloma virus	Holland	Temperature, rainfall, relative humidity	Yes

Table 1 (continued)

Author	Year	Disease	Country	Meteorological variable	Statistical significance
Nastos and Matzarakis	2006	Respiratory infection	Greece	Temperature, relative humidity, sunshine hours, wind, and barometric pressure	Yes
Ohshige et al	2006	Stroke	Japan	Temperature, relative humidity, and barometric pressure	Yes
Zender and Talamantes	2006	Coccidioidomycosis (valley fever)	USA	Rainfall and temperature	Yes
Liang et al	2008	Acute coronary syndrome	Taiwan	Temperature	Yes
Nakaguchi et al	2008	Intracerebral haemorrhage	Japan	Barometric pressure, temperature, relative humidity, rainfall, and wind	Yes
Prospero et al	2008	Asthma	Caribbean	Wind	No
Suárez-Varela et al	2008	Atopic eczema	Spain	Rainfall, temperature, and relative humidity	Yes
García-Marcos et al	2009	Asthma	Spain	Relative humidity and temperature	Yes
Liang et al	2009	Chronic obstructive pulmonary disease	Taiwan	Temperature	Yes
Styra et al	2009	Cardiovascular disease	Lithuania	Barometric pressure	No
Wang et al	2009	Stroke	Australia	Temperature	Yes
Arnedo-Pena et al	2011	Asthma and allergies	Spain	Sunshine hours	Yes
Azevedo et al	2011	Respiratory and cardiovascular diseases	Portugal	Sunshine hours	Yes
Omonijo et al	2012	Measles	Nigeria	Temperature	Yes
Goggins et al	2012	Stroke	China	Temperature, humidity, sunshine hours, precipitation, and barometric pressure	Yes
Ferrari et al	2012	Obstructive pulmonary disease	Germany	Relative humidity, solar radiation, temperature	Yes
Coelho and Massad Alexander	2012	Leptospirosis	Brazil	Weather temperature and rainfall	Yes
	2013	Heart disease, arrhythmia, heart failure, cardiopulmonary arrest, angina, pectoris, psychiatric diseases, stroke, transient ischemic attack	Argentina	Temperature and rainfall	Yes
McWilliams et al	2013	Psychotic illnesses	Ireland	Wind, rainfall, temperature, relative humidity, solar radiation, and barometric pressure	No
Scheidt et al	2013	Migraines	Germany	Temperature	Yes
Bakal et al	2013	Acute coronary syndrome	Global	Temperature and relative humidity	Yes
Arnedo-Pena et al	2013	Asthma	Western Europe	Temperature, rainfall, sunshine hours, and relative humidity	Yes
Lim et al	2013	Cardiovascular disease	Korea	Temperature	Yes
Soyiri et al	2013	Asthma	England	Temperature	No

Table 1 (continued)

Author	Year	Disease	Country	Meteorological variable	Statistical significance
Akinbobola and Omotosho	2013	Malaria	North Central Nigeria	Temperature, rainfall, and relative humidity	Yes
Yackerson et al	2014	Schizophrenia	Israel	Wind and barometric pressure	Yes
de Weger et al	2014	Allergic rhinitis	Netherlands	Temperature	Yes
Wanka et al	2014	Respiratory disease	Germany	Temperature and relative humidity	No
Smedslund et al	2014	Fibromyalgia pain	Norway	Barometric pressure, temperature, and relative humidity	Yes
Shaposhnikov et al	2014	Myocardial infarction and brain stroke	Russia	Barometric pressure	Yes
Plavcová and Kyselý,	2014	Cardiovascular disease	Czech Republic	Barometric pressure	Yes
Palmisano et al	2014	Bradyarrhythmia	Italy	Temperature	Yes
Ng et al	2014	Heatstroke	Japan	Temperature	Yes
McWilliams et al	2014	Mania and depression	Ireland	Wind barometric pressure, rainfall, temperature, and sunshine hours	No
Li et al	2014	Respiratory infection	China	Temperature	Yes
Chen et al	2014	Hand, foot, and mouth disease	China	Relative humidity, temperature, and rainfall	Yes
Flight et al	2014	Viral respiratory infection	England	Temperature and relative humidity	Yes
Wang and Lin	2015	Respiratory diseases, asthma, and chronic airway obstruction	Taiwan	Temperature	Yes
Vencloviene et al	2017	Acute coronary syndrome	Lithuania	Temperature, barometric pressure, relative humidity, and wind	Yes
Phung et al	2015	Diarrhoea	Vietnam	Relative humidity, temperature, and rainfall	Yes
Ozeki et al	2015	Headaches	Japan	Barometric pressure, temperature, relative humidity, and rainfall	Yes
Onozuka and Hagiwara	2015b	Tuberculosis	Japan	Temperature	Yes
Onozuka and Hagiwara	2015a	Influenza	Japan	Rainfall and relative humidity	Yes
Makra et al	2015	Asthma	Hungary	Temperature and humidity	Yes
Lim et al	2015	Dehydration	Korea	Temperature	Yes
Li et al	2015	Lung infection	China	Temperature	Yes
Khalid and Ghaffar	2015	Dengue	Pakistan	Rainfall, temperature, and wind	Yes
Condemi et al	2015	Renal colic and urinary calculi	Italy	Temperature	Yes
Çevik et al	2015	Stroke	Turkey	Temperature	Yes
Akpınar-Elci et al	2013	Asthma	Caribbean	Rainfall and wind	Yes
Yang et al	2016	Renal colic and urinary calculi	China	Temperature	Yes
Taheri Shahraini et al	2016	Acute aortic dissection	Berlin	Temperature and cloud cover	Yes
Royé et al	2016	Respiratory disease	Spain	Temperature, rainfall, and relative humidity	Yes

Table 1 (continued)

Author	Year	Disease	Country	Meteorological variable	Statistical significance
Hervás et al	2016	Streptococcal pharyngitis	Spain	Temperature, relative humidity, rainfall, atmospheric pressure, and wind	Yes
Gao et al	2016	Hepatitis A virus	China	Rainfall	Yes
Duan et al	2016	Scarlet fever	China	Temperature	Yes
Cheng et al	2016	Hand, foot, and mouth disease	China	Temperature	Yes
Zhao et al	2017	Hand, foot, and mouth disease	China	Relative humidity, barometric pressure, and rainfall	No
Wang et al	2017	Influenza	China and Canada	Relative humidity, temperature	Yes
Vencloviene et al	2017	Acute coronary syndrome	Lithuania	Temperature	Yes
Tamerius et al	2017	Influenza	Nicaragua	Temperature	No
Rowell et al	2017	Parkinson's disease	Australia	Temperature	Yes
Peulnier et al	2017	Knee osteoarthritis pain	France	Temperature, rainfall, sunshine hours, relative humidity, atmospheric pressure, and wind	Yes
Näyhä et al	2017	Cardiorespiratory disease	Finland	Temperature	Yes
Mu et al	2017	Chronic obstructive pulmonary disease	China	Relative humidity and temperature	Yes
Kim and Kim	2017	Cardiac arrhythmias	Korea	Temperature	Yes
He et al	2017	Allergic rhinitis	China	Temperature and relative humidity	Yes
Gou et al	2017	Hand, foot, and mouth disease	China	Temperature	Yes
Gestro et al	2017	Otitis media	Italy	Temperature, relative humidity, atmospheric pressure, and wind	Yes
Elcik et al	2017	Migraine headaches	USA	Wind	No
Čulić	2017	Cardiac arrhythmias	Croatia	Temperature	No
Azcárate and Mendoza	2017	Hypertension	Mexico	Temperature	Yes
Almendra et al	2017	Circulatory system diseases	Portugal	Temperature and wind	No
Acquaotta et al	2017	Haemolytic-uraemic syndrome	Italy	Temperature, rainfall, and relative humidity	Yes
Abbas et al	2017	Crimean-congo hemorrhagic fever	Pakistan	Temperature	Yes
Davis and Enfield	2018	Influenza	USA	Temperature	Yes
Tapak et al	2018	Depressive disorder, bipolar, and schizophrenia	Iran	Rainfall, snowfall, relative humidity, and cloud cover	Yes
Russo et al	2018	Legionnaires' disease	Portugal	Relative humidity and temperature	Yes
Liu et al	2018	Hand, foot, and mouth disease	China	Temperature	No
Li et al	2018	Influenza	China	Temperature	Yes
Lam et al	2018	Chronic obstructive pulmonary disease and pneumonia	China	Relative humidity and temperature	Yes

Table 1 (continued)

Author	Year	Disease	Country	Meteorological variable	Statistical significance
Goldie et al	2019	Cardiovascular disease, respiratory disease, and renal disease	Australia	Relative humidity, wind, and temperature	Yes
Gie et al	2018	Rheumatic heart disease	China	Weather temperature	Yes
Davis and Enfield	2018	Respiratory disease	USA	Relative humidity and temperature	Yes
Brandl et al	2018	Psychiatric disorders	Germany	Temperature	Yes
Acharya et al	2018	Dengue fever	Nepal	Temperature	Yes
Yuan et al	2019	Dengue	Taiwan	Temperature and humidity	Yes
Xie et al	2019	Respiratory disease	China	Relative humidity	Yes
da Silva et al	2019	Asthma and bronchitis	Brazil	Temperature, barometric pressure, relative, and humidity	Yes
Romaszko et al	2019	Respiratory infection	Poland	Temperature	Yes
Liu et al	2019	Influenza	China	Relative humidity	Yes
Cui et al	2019	Cardiovascular disease	China	Temperature	Yes
Zhao et al	2020	Chronic pharyngitis	China	Relative humidity	Yes
Zhang et al	2020	Pertussis infection	China	Temperature and rainfall	Yes
Xie et al	2020	Rheumatoid arthritis	China	Rainfall	Yes
Wang et al	2020	Allergic rhinitis	China	Temperature and humidity	Yes
Vencloviene et al	2020	Acute myocardial infarction	Lithuania	Wind	Yes
Oh et al	2020	Benign paroxysmal positional vertigo	Korea	Humidity, temperature, atmospheric pressure, cloud cover, and sunshine	Yes
Nguyen et al	2020	Hand, foot, and mouth disease	Vietnam	Temperature, humidity, and rainfall	Yes
Mathew	2020	Malaria	Nigeria	Rainfall	Yes
Madaniyazi et al	2020	Cholesterol	China	Temperature	Yes
Hossain et al	2020	Pneumonia	Bangladesh	Relative humidity and temperature	No
Chang et al	2020	Asthma	China	Relative humidity	Yes
Chai et al	2020	Respiratory disease	China	Temperature	Yes
Bal and Sodoudi	2020	Dengue	India	Temperature	Yes
Xin et al	2021	Dysentery	China	Rainfall	Yes
Wang et al	2021	Bacillary dysentery	China	Temperature	Yes
Silva et al	2021	Respiratory disease	Portugal	Wind	Yes
Riancho et al	2021	Neurodegenerative diseases (Alzheimer disease, Parkinson's disease, and amyotrophic lateral sclerosis)	Spain	Temperature	No
Nili et al	2021	Cutaneous leishmaniasis	Iran	Precipitation, temperature, and relative humidity	No

Table 1 (continued)

Author	Year	Disease	Country	Meteorological variable	Statistical significance
Ngo et al	2021	Acute lower respiratory infection	Vietnam	Temperature	Yes
Molina-Gómez et al	2021	Respiratory disease	Bogotá	Relative humidity	Yes
Meng et al	2021	Dengue	China	Rainfall	Yes
Martinaitiene and Raskauskiene	2021	Coronary artery disease	Lithuania	Temperature	Yes
Lindner-Cendrowska and Bröde	2021	Influenza	Poland	Temperature air pollutants	Yes
Lei et al	2021	Asthma	China	Temperature	Yes
Jahan et al	2021	Schizophrenia	Australia	Temperature, rainfall, and relative humidity	No
Gutiérrez	2021	Leptospirosis	Colombia	Temperature and rainfall	Yes
Fdez-Arróyabe et al	2021	Influenza	Spain	Circulation weather	No
Dong et al	2021	Respiratory disease	China	Wind	Yes
Cheng et al	2021	Dengue	China	Temperature, rainfall, and relative humidity	Yes
Chaturvedi and Dwivedi	2021	Malaria	India	Temperature	Yes
Huang et al	2022	Rheumatoid arthritis	China	Temperature	Yes
Ma et al	2022	Influenza A and B	China	Temperature, relative humidity, and wind	Yes
Vaičiulis et al	2022	Stroke	Lithuania	Temperature	Yes

diseases and others such as measles (Fig. 4). According to WHO (2020) respiratory diseases are the fourth-ranked leading cause of death notably respiratory diseases represented the greatest proportion studied (37.2%, $n = 180$), with research on all six of the habitable continents, including both chronic respiratory conditions such as asthma and acute respiratory conditions such as influenza. As there has been a lot of research conducted on respiratory diseases and it is well-understood that climate and weather influence their transmission dynamics. These studies, similar to the overall trends, were concentrated in the Northern Hemisphere, with 25 papers on respiratory health from Asia and 23 from Europe (Fig. 4). The dominance of research from Asia in this domain is accounted for, in part, by the SARS and MERS epidemics in the region (Reichert et al. 2004). According to the WHO top 10 causes of death, stroke (a neurological disease) is the second leading cause of death globally; however, only 5% ($n = 180$) of the studies published in the International Journal of Biometeorology examined strokes.

Cardiovascular diseases are the leading cause of death according to the WHO (2020) and were responsible for 8.9 million deaths globally in 2019. However, studies on cardiovascular diseases such as myocardial infarctions only represent the second most frequently explored group (17.2%, $n = 180$). This is likely as a result of an increase in research on non-communicable diseases in the twenty-first century and the fact that cardiovascular diseases are the major cause of mortality (Münzel et al. 2022). These were conducted predominantly in Europe (48.4%, $n = 15$). This is likely due to the ageing population of the region, heightening the vulnerability to these diseases (Murphy 2017).

Studies conducted in South America predominantly explored vector-borne diseases such as dengue and Malaria and intestinal diseases such as diarrhoea which are ranked eighth on the WHO top 10 causes of death lost, due to both socioeconomic and geographical factors (WHO 2020; Ruano et al. 2021). By contrast, whilst most of the disease categories were investigated in Europe, vector-borne diseases were not, again a result of the climatic and geographical factors determining disease prevalence (Roclov and Dubriw 2020). The four studies for Africa explored measles, malaria, and asthma.

Psychiatric conditions, which represent 6.1% of the total 180 papers, are concentrated in the European region, with none from Africa or South America (Fig. 4). All disease groups were explored in at least one Asian country except for dermatological conditions, which were only investigated in Europe, since the skin is the organ that is exposed to the environment the most (Balato et al. 2014; Richard et al. 2022). Although stroke and chronic obstructive pulmonary disease are the second and third leading causes of death respectively according to the WHO (2020) no studies

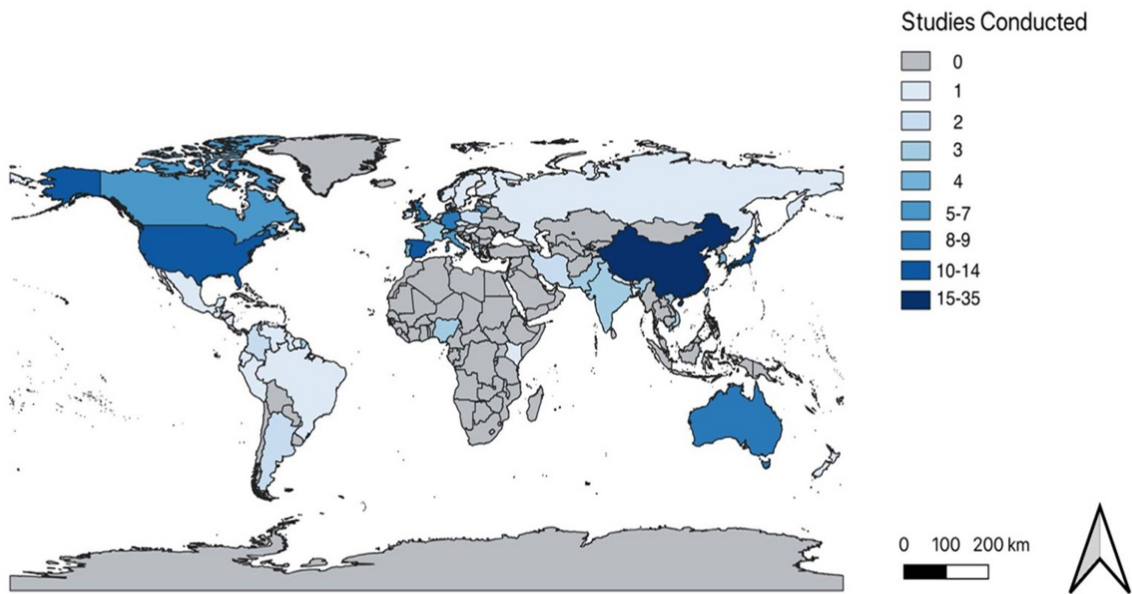
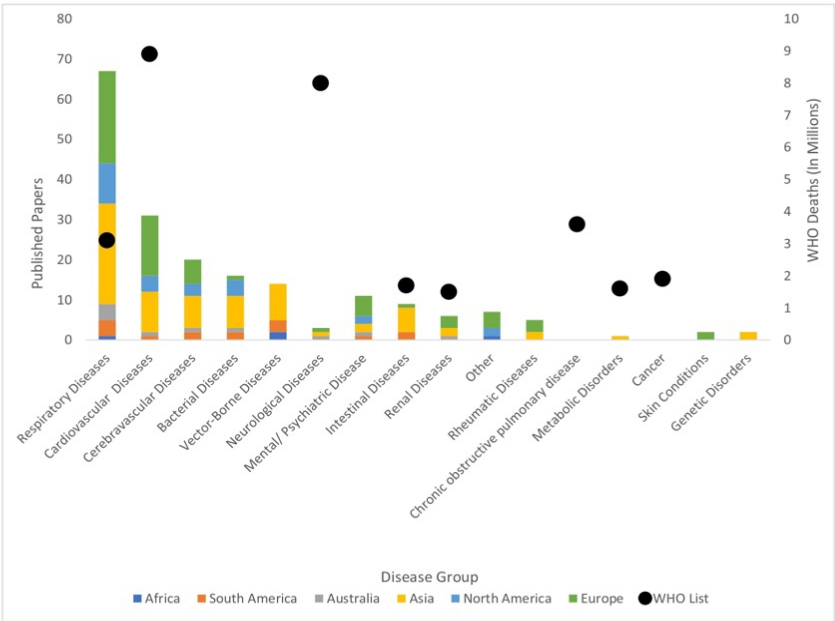


Fig. 3 Countries of interest in health biometeorological studies

published in the International Journal of Biometeorology examined chronic obstructive pulmonary disease, these publication trends are interesting as they do not coincide with the WHO top ten list of the leading causes of death globally

(Fig. 4: WHO 2020). Cancer is ranked sixth on the list of leading causes of death; however, no study examined cancer. This review also assessed if the 180 studies conducted respectively yielded any statistical significance between

Fig. 4 Diseases studied per continent and WHO’s top ten list of leading causes of death globally



the variable under investigation in each paper. Of the tests for relationships between the disease and specific meteorological variables only 14.4% ($n = 180$) of the papers being investigated in this review report results that are not statistically significant (Table 1). This may reveal the bias in publication towards only those studies which reveal statistically significant relationships, in the expected direction, that have been recorded in the biometeorological research on phenology (Menzel et al. 2006). If this is the case, it would obscure results of repeated studies that may contest relationships between specific diseases and meteorological conditions, whether generally or for a specific region.

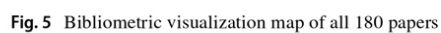
An increasing body of evidence exists regarding how climate change may affect human health, notably the emergence and spread of diseases. Understanding this connection is crucial because it will increase the already heavy burden that diseases place on the country's economy and public health. For instance, heat and acute coronary syndromes, climate change and malaria, solar activity, and chromosome aberrations (Fig. 5). These findings illustrate further that research outputs were situated greatly in China (Asia) and the weather was the dominant meteorological variable, and the majority of the papers utilized statistical methodologies in the form of regression analysis to determine the relationship between climate and health (Fig. 5). Researchers achieved this by utilizing hospitalization data (Fig. 5). Researchers examined the link between temperature and cardiovascular disease in nations like Italy and Korea, and those in the Middle East (Israel) evaluated the link between solar activity and chromosome abnormalities (Fig. 5). Overall diseases differ by demographic and geographic location, and they evolve with time.

A range of meteorological variables is explored across the 180 papers spanning from the year 1957 to April 2022. In each of the disease types, average temperature, relative humidity, and rainfall were most commonly examined (Fig. 6). With the exception of genetic disorders, studies examining all disease categories used the meteorological variable temperature. Whilst only the category of mental/psychiatric diseases used cloud cover as a meteorological variable. Temperature, precipitation, and relative humidity variables were evaluated for both skin conditions and cerebrovascular diseases. All the meteorological variables were examined in studies on respiratory and cardiovascular diseases, but not snowfall. Studies investigating vector-borne diseases looked at the amount of sunshine, the relative humidity, the amount of rain, and the temperature. Temperature, rainfall, relative humidity, and barometric pressure were all evaluated in studies on bacterial and rheumatic diseases (Fig. 6).

Key research directions in biometeorology of health

This review explores the publications that analysed the relationship between specific, diagnosable diseases, and meteorological variables. Since the inception of the journal, there has been an increase in publications that assess the relationship between meteorological variables and diagnosable diseases. This increase in research is imperative in the context of climate change and concerns about the climatic sensitivity of conditions such as COVID-19 (Smit et al. 2020). Warming and increases in humidity are projected to create new habitats for diseases like malaria in Africa (Epstein et al. 1998; Martens 1999), parasitic nematodes in the Arctic (Kutz et al. 2005), West Nile virus (Reisen et al. 2006), Lyme disease in North America (Ogden et al. 2008), and schistosomiasis in China. These projections are largely based on studies (Zhou et al. 2008). In the East African highlands, for instance, reported altitudinal increases in falciparum malaria over the past 30 years have been linked to rising temperatures and are compatible with theories of anopheline mosquito vector development (Pascual et al. 2006). This will be exacerbated by climate change's effects on the length of seasons.

This review has highlighted that research on climate and health in the *International Journal of Biometeorology* is highly concentrated in the Northern Hemisphere (Fig. 6), whilst many countries in the Southern Hemisphere carry a greater disease burden (Valodia and Taylor 2022), have an overburdened public health sector, and are projected to experience an above-average rate of climate warming in decades to come (IPCC 2022 6AR). The importance of health research in low- and middle-income nations has been highlighted by recent incidences of developing and reemerging infectious illnesses, commitments to obtaining universal health coverage, and increased interest in global health (Ranabhat et al. 2020). Additional factors to take into account in the context of evolving population health demands include the requirement for contextualized evidence to produce local solutions, innovation to increase efficiency, and the creation of more effective treatment regimens given the rise in drug resistance (Nabyonga-Orem et al. 2021). Contextual elements such as conflict settings (Bowsher et al. 2019), multilayered governance in implementation research (Patel et al. 2017), and rapidly developing digital technologies necessitate ongoing adaptation of health research systems to ensure relevance and effectiveness (Kostkova 2015). Since they are currently the least studied, these nations need the greatest attention both now and in the future. Health research is

[illegible]

essential for advancing development, equity, and health (Nuyens 2005). Inadequate financing, infrastructure, and skill levels, disproportionate rates of climate change and lack of adaptation given its unique disease burden as well as poor governance of health research are the key causes of Africa's subpar research capacity, which has long been a cause for concern (Fig. 5; Chu et al. 2014; Rusakaniko et al. 2019; Simpkin et al. 2019). This may help to explain why so little research is produced; Africa only contributes 2% (Schemm 2013) to global research output and 1.3% to worldwide publications (Uthman et al. 2015). Whilst this can be facilitated through regional conferences, special issues, and collaborative research (WHO 2018; Fitchett 2021), this will also need greater focus in funding for research in these regions.

It is also important that local researchers from African and South American countries be included and involved in this research. The increase in research from the Northern Hemisphere has resulted in the development of strong methodological approaches that can be replicated in studies in regions such as Africa (Sen Roy 2018; Marincola and Kariuki 2020; de Villiers 2021). Whilst it does increase the total research output it often misses nuances (Marincola and Kariuki 2020). Particularly in Africa and South America, key nuances in health related to the prevalence of endemic and regionally occurring diseases (Moreira et al. 2020), such as malaria, Ebola, yellow fever, Zika virus, and chikungunya virus (de Villiers 2021; Roclöv and Dubriw 2020; Ruano et al. 2021). It is therefore critical that collaboration is inclusive, and conducted on the ground, rather than perpetuating parachute science that lacks local context (Stefanoudis et al. 2021).

Whilst research on climate and health has been central to the focus of both the International Society of Biometeorology and the *International Journal of Biometeorology*, many other journals do publish research on these topics, including but not limited to *Health Communication*, *the International Journal of Environmental Research and Public Health*, *The Lancet*, and *Global Health Action*, in addition to local and international interdisciplinary journals. This review does not consider those papers, as the aim is to explicitly track trends within the journal. However, these key avenues for future research would be implemented across research published in this much wider range of journals. Important in further developing Biometeorology as a discipline that includes climate and health is raising awareness amongst researchers who are working in this nexus of the International Society of Biometeorology as a forum for engagement, and the *International Journal of Biometeorology* as an outlet for publication. As an international journal, it is important to strive towards greater and more balanced international representation in published research.

As a factor of the inclusion criteria, all 180 papers considered in this review employed statistical methodologies to quantify the impacts of climate on health (Table 1). This makes the studies more robust than earlier more qualitative assessments of this nexus, but often, it ignores the qualitative or experiential and aetiological aspects of these relationships (Mehta 2022). Firstly, purely statistical and empirical studies do not study the nature of the phenomenon itself; it does not engage with individual items thus making it difficult to infer causation and are limited to correlation only (Musani et al. 2007; Mehta 2022).

Secondly, a wide range of statistical methods is being employed across these studies (e.g., Poisson regression, times series analysis, linear regression, generalized additive models, and distributed-lag nonlinear model). This makes the comparison of results from studies difficult to perform. So, whilst statistical analyses of empirical case data are important, they do not negate the importance of laboratory work in understanding aetiology, and qualitative work on experiential components of seasonality. An important future direction, in this regard, is to employ a less reductive approach and to focus more holistically on the physiological reasons that underpin any relationships found and reported from the data. This would be most effectively achieved through greater collaboration between climatologists, healthcare practitioners, and data scientists. Indeed, this was one of the key aims of the society at its inception (Tout 1987; Sheridan and Allen 2017).

Conclusion

A significant increase in human health papers has been published in the last decade in the *International Journal of Biometeorology*. Over the full period of publication of the journal, studies dedicated to the intersection between specific, diagnosable diseases and meteorological variables account for only 4.1% of the 4350 works of the journal to date. Although the criteria for this review were specific, the 180 papers analysed are an indication that the *International Journal of Biometeorology* has indeed stuck to its scope in documenting such studies. Researchers in Europe and Asia have done an excellent job in documenting their studies in the journal since its inception, contributing a combined 77.8% to the total 180 studies. It is important to have more studies explore the extent to which diseases are climate sensitive. Of the 180 papers reviewed, only four (2.22%) studies were based in Africa. A total of 15 (8.3%) studies were based in South America. This means that regionally endemic conditions such as Ebola, yellow fever, and malaria are largely unstudied in this journal. Given a change in climatic conditions, continents such as South America and

Africa, which are affected greatly by climate change have minimal to no studies on climate and health. In Africa and South America, dysfunctional health systems and the collision of epidemics of communicable and non-communicable diseases have exacerbated this. The paucity of research on human biometeorology conducted in Africa and South America was exposed by this systematic literature review, which also identified shortcomings that may serve as the basis for future studies. The study had the advantage of making it clear which sectors should receive the majority of the funding for research in the near future. In this way, gaps in publication production can promote the expansion of research in specific subregions of South America and Africa.

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CHAPTER 5: DEFINING THE SOUTH AFRICAN ACUTE RESPIRATORY INFECTIOUS DISEASE SEASON

5.1 Brief Synopsis

The paper titled "Defining the South African Acute Respiratory Infectious Disease Season" aims to determine the start and end dates of the acute respiratory infectious disease season in South Africa. The study utilizes public-sector hospitalization data and private-sector medical insurance claims, applying the intensity threshold methodology to define the season. The CDC first case onset, and European Union 5% thresholds yielded year-round seasons; the thresholds that aligned with the NICD 19-week threshold was found to be at 11 - 25%. It finds that the respiratory disease season in South Africa typically starts in May and ends in September, with significant regional variations. This research aids in improving surveillance and preparedness in both public and private healthcare sectors.

Author contributions:

Contributor role	Author contribution
Conceptualisation	Fitchett JM and Sweijd N
Methodology	Motlogeloa O, Fitchett JM
Validation	Motlogeloa O
Formal analysis	Motlogeloa O
Investigation	Motlogeloa O
Resources	Motlogeloa O
Data Curation	Motlogeloa O
Writing – the original draft preparation	Motlogeloa O
Writing – review and editing	Motlogeloa O, Fitchett JM and Sweijd N
Visualisation	Motlogeloa O
Supervision	Fitchett JM and Sweijd N
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Motlogeloa O – 72%

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Article

Defining the South African Acute Respiratory Infectious Disease Season

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Abstract: The acute respiratory infectious disease season, or colloquially the “flu season”, is defined as the annually recurring period characterized by the prevalence of an outbreak of acute respiratory infectious diseases. It has been widely agreed that this season spans the winter period globally, but the precise timing or intensity of the season onset in South Africa is not well defined. This limits the efficacy of the public health sector to vaccinate for influenza timeously and for health facilities to synchronize efficiently for an increase in cases. This study explores the statistical intensity thresholds in defining this season to determine the start and finish date of the acute respiratory infectious disease season in South Africa. Two sets of data were utilized: public-sector hospitalization data that included laboratory-tested RSV and influenza cases and private-sector medical insurance claims under ICD 10 codes J111, J118, J110, and J00. Using the intensity threshold methodology proposed by the US CDC in 2017, various thresholds were tested for alignment with the nineteen-week flu season as proposed by the South African NICD. This resulted in varying thresholds for each province. The respiratory disease season commences in May and ends in September. These findings were seen in hospitalization cases and medical insurance claim cases, particularly with influenza-positive cases in Baragwanath hospital for the year 2019. These statistically determined intensity thresholds and timing of the acute respiratory infectious disease season allow for improved surveillance and preparedness among the public and private healthcare.



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Keywords: influenza; common cold; RSV; seasonality; winter; public health

1. Introduction

Acute respiratory diseases broadly refer to any infectious diseases of the upper or lower respiratory tract [1]. The body’s respiratory system includes the nose, sinuses, mouth, throat (pharynx), voice box (larynx), windpipe (trachea), and lungs [1]. Upper respiratory infections affect the nose, sinuses, and throat, while lower respiratory infections affect the airways and lungs [1,2]. Influenza and respiratory syncytial virus (RSV) infections are common causes of lower respiratory tract infections [3–5]. Although not all instances of influenza infection seek medical attention and are thus not all detected by the surveillance systems, the annual rate of influenza infection is estimated to be between 5 and 10% in adults and between 20 and 30% in children during a typical season [6].

Studies reveal that the burden of influenza is particularly high in sub-Saharan Africa, particularly in South Africa, where influenza-associated mortality rates are greater than in other areas [7]. Between 7000 and 12,000 seasonal influenza-related deaths are estimated to occur annually in South Africa [7]. It is generally agreed that the following goals should be covered by influenza surveillance: keeping track of the circulating viral strains, the frequency, intensity, and severity of epidemic waves; letting people know about the risk factors that contribute to severity; and providing epidemiological and virological assistance for pandemic early warning and readiness [8]. Indicators, both quantitative and qualitative,

that measure the impact of seasonal outbreaks are used to support influenza surveillance [8,9]. Clinical consultations in general practice, hospitalized laboratory-confirmed cases, sentinel and non-sentinel positive specimens, mortality, and local epidemics are the main sources of these indicators [10]. The estimated incidence of the percentage of consultations in a population in a certain period, which is connected to the severity of seasonal epidemics, is one of the most crucial indicators in influenza surveillance. For analyzing the dynamics of influenza epidemics and comparing patterns within or across countries, overall seasonal or weekly influenza intensity levels are helpful [11]. It is important to maintain a comprehensive system for influenza surveillance for the following reasons: (1) vaccines must be administered annually and are updated regularly based on surveillance findings, (2) the need to inform the public to be cautious, and (3) the need for hospital medical practice readiness [10]. There is increasing evidence that suggests that the length of a single flu season on regional scales has changed under global warming, but a hemispherical-scale response to the four seasons in the past and future remains unknown [12]. Therefore, influenza surveillance needs to take into account the climate change effect of these trends in the seasonal timing and intensity of this disease [12–14].

There is a broad consensus that in countries with distinct climatic seasonality, there is an increase in the incidence of acute infectious respiratory disease caseload during winter as meteorological conditions are more suitable for the survival of acute infectious respiratory viruses [10,15,16]. Despite a widespread understanding of this winter seasonality in acute infectious respiratory diseases, there is little standardization in how to define the onset or timing of the season. The acute respiratory infectious disease season is seldom quantified, and when it is, there is no standardization in the quantification methodologies.

In 2017, the Centers for Disease Control and Prevention (CDC) outlined and adopted a new methodology for classifying flu season severity [17]. Based on data from past flu seasons, the CDC used key flu indicator data to develop intensity thresholds (ITs) to classify the severity of flu seasons and set a specific threshold to delineate the start of the influenza season [17,18]. An intensity threshold is a value developed using data from past flu seasons that help assess the probability that an influenza indicator, such as influenza-like-illness (ILI) or influenza percent positive, will go above a certain threshold [17,18]. The National Institute of Communicable Diseases (NICD) in South Africa states that the average duration of the influenza season over the past thirteen years has been nineteen weeks [7] but has not set an intensity threshold nor published any methodologies for the delineation of the influenza season. Globally, the definitions for the acute respiratory infectious disease season and its onset thresholds vary. These include regions that refer to the season being defined by a ‘significant spike’ but do not indicate how that is quantified. Other regions define the season by the month of the largest number of cases, but in these instances one can only define the timing of the season retrospectively, affording little value in adapting the health sector response through the season [17,19]. Where thresholds have been used, they vary widely. Eurich et al. [20] argue that the respiratory disease season commences from the first case and ends with the last case in the year, whilst a European study advocates for a 5% threshold. Using a range of data sets from the public and private healthcare sectors in South Africa, this study applies the CDC [17] method of intensity thresholds, combined with the NICD stipulated length of the influenza season to explore the timing of onset and cessation of the acute infectious respiratory disease season and the relevant thresholds across the region.

2. Materials and Methods

2.1. Study Site

The southernmost country in Africa, South Africa, has 9 provinces and a land area of 1,220,000 km². It is situated between the latitudes of 22–35° S and 16–33° E. (Figure 1) [21–23]. There is considerable climatic heterogeneity across the country: hot, dry, and arid conditions in the west and warm, wet, and humid conditions in the east [21,23,24]. Rainfall occurs in

summer across much of the country, but the southwestern tip is characterized by winter rainfall, and the southern coast by year-round rainfall (Figure 1) [25–29].

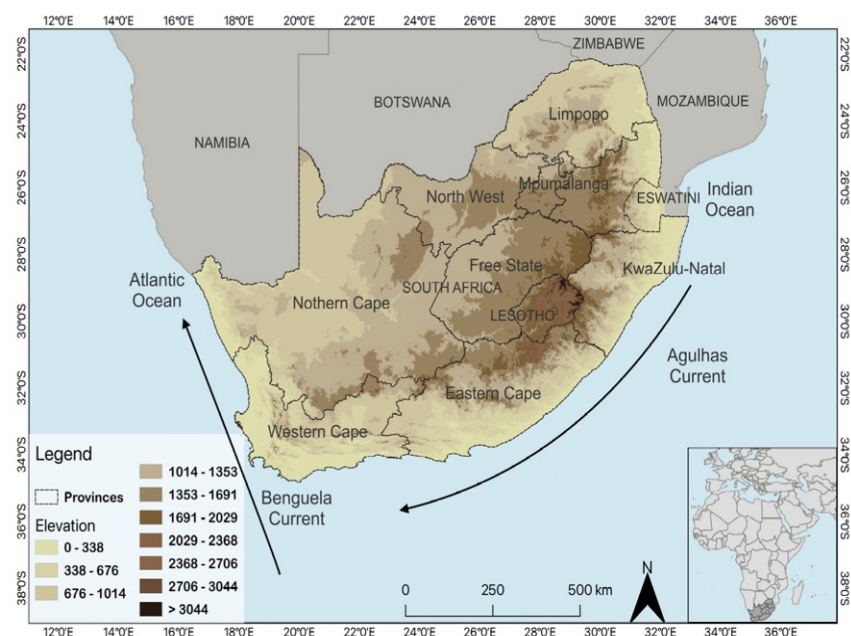


Figure 1. Map of the study site of South Africa indicating the nine provinces, topography, the surrounding oceans, and their respective currents.

The National Department of Health (NDoH) in South Africa is in charge of overseeing, coordinating, and setting policies for the nation's health services, while the nine provincial departments are primarily in charge of providing those services [30]. A two-tiered, severely unequal healthcare system exists in South Africa. The majority of the population (71%), which is served by the public sector, is funded by the government [30,31]. Around 27% of the population is served by the private sector, which is mostly financed by individual payments to health insurance or medical insurance plans [30–33].

2.2. Data Sources

Acute respiratory diseases, in the context of this paper, are defined as infections of the respiratory system caused by viruses or bacteria that develop in less than fifteen days and show symptoms such as coughing, nasal congestion, airway obstruction, sore throat, dysphonia, or respiratory distress, whether they are accompanied by fever [1]. The conditions under this wide classification that are the subject of this study include influenza, respiratory syncytial virus (RSV), acute nasopharyngitis, influenza with pneumonia, influenza with other respiratory manifestations, and influenza with other features. The most frequent reasons for primary care visits are influenza and other respiratory viral illnesses, which place a significant financial strain on the global economy [2–5].

To explore definitions for the start and finish of the South African acute respiratory infectious disease season, this study utilized two data sets. One data set encompassed a time series of five years of laboratory-tested and confirmed RSV and influenza hospitalization cases, and the other consisted of a time series of medical insurance scheme claims where claimants were diagnosed and treated symptomatically for acute respiratory disease. The two data sets are important for the following reasons: (1) from the magnitude of the medical insurance claims data, a seasonal temporal pattern can be ascertained; (2) the hospitalization cases—although a conservative estimate—indicate the actual number of extreme cases when people were hospitalized for an acute respiratory infectious disease.

Although the data sets do not capture those cases that are self-diagnosed and treated with over-the-counter (OTC) medication; these two data sets are a sound index of incidence and enable us to compare hospitalizations cases and medical insurance claims which would be representative of the population levels of infection. It is important to note that both these data sets include data up to the end of 2019, specifically to avoid COVID-19 as it could potentially reflect on the medical insurance scheme claims under the ICD 10 code considering that these individuals are being treated symptomatically. Furthermore, it is yet to be proven that COVID-19 has a distinct seasonality in South Africa [13,34]. Ethical clearance to work with both data sets was obtained from the University of Witwatersrand Health Research Ethics Committee (HREC) with ethics clearance no: M210617 approved on 4 August 2021 and is valid up until 4 August 2026.

2.3. Hospitalization Cases

The hospitalization data utilized in this study were applied for and obtained through the South African Medical Research Council (SAMRC) Respiratory and Meningeal Pathogens Research Unit which has been conducting surveillance for respiratory viruses for over 20 years at Chris Hani Baragwanath Hospital. This research unit has recorded laboratory-confirmed influenza and RSV-associated hospitalization cases under ethics clearance no: 131109 through the Human Research Ethics Committee (HREC). Chris Hani Baragwanath Hospital is located in Soweto, a South African suburb southwest of central Johannesburg. It is Africa's largest hospital and the world's third-largest hospital, occupying 170 acres of land and housing 3400 beds and 6760 employees [35]. It is one of the 40 Gauteng provincial hospitals, and it is funded and managed by the Gauteng Provincial Department of Health [36]. It also serves as a teaching hospital for the University of the Witwatersrand Medical School [35,36]. Although these data were obtained from the largest hospital in Africa, its patients are still only a small proportion of all influenza and RSV cases in South Africa as it is only one hospital and accounts only for cases that are severe enough for hospitalization and laboratory testing to guide diagnosis. Therefore, these data are a conservative estimate of the pattern of the seasonality of hospitalization cases confirmed to be a result of an acute respiratory infectious disease.

2.4. Medical Insurance Scheme Claims

Discovery Medical Insurance Scheme is a private medical insurance company catering to 3.3 million clients across South Africa. The scheme retains all data on medical claims submitted to them, each of which is made against a specific ICD 10 code. These ICD 10 codes can relate to claims for visits with medical practitioners, any medical tests conducted, and medication dispensed for that condition. The medical practitioner bases the ICD 10 code listed for that consultation based on their diagnosis, but these do not require laboratory testing for confirmation. For this study, we obtained Discovery claims data for ICD 10 codes J00, J110, J111, and J118, which incorporate all cases of acute nasopharyngitis, influenza with pneumonia, influenza with other respiratory manifestations, and influenza with other manifestations. Data were provided as individual daily claims among all clients across the country from 2008 to 2019. Included in the metadata for each claim is the town in which the claim was made, the date of the claim, the age band the claimant belongs to, the claimant's gender, and the number of doctor visits the claimant attended.

2.5. Data Analysis

To determine the acute respiratory infectious disease season in South Africa, various methods were employed. First, it was important to identify if there was a seasonality in medical insurance claims and hospitalization cases. In the interests of the comparability of the different data sets, the medical insurance claim data were converted to weekly totals, starting on Sunday of each week. These totals were then tabulated and plotted, commencing from the first week of the year 2008 to the last week of the year 2019. This process was repeated for all nine provinces from 2008 to 2019 to assess the seasonality of

each province, respectively, given their distinct geographical location and climatologies, and independently for the Baragwanath hospitalization cases (Figure 1). This was proceeded by calculating and plotting a five-point running mean for each province. Exploratory data analysis was employed to determine whether there were any erroneous values in any of the data sets.

Once both data sets were represented graphically and a seasonality in claims and hospitalization cases were identified and confirmed, the start and end dates of the seasons were explored. While the NICD [7] states that the average duration of the influenza season over the past thirteen years has been nineteen weeks, no objective criteria have been established to determine the onset and cessation thresholds. We considered that internationally the acute respiratory infectious disease season has been defined through a variety of approaches. For example, Eurich et al. [20] argue that the respiratory disease season commences from the first case and ends with the last case in the year, whilst a European study [11] advocated for a 5% threshold. In light of this, we explored thresholds that resulted in the suggested nineteen weeks of acute respiratory disease season in South Africa.

To achieve this, we calculated the total number of cases for each year in each province and averaged those for the study period (2008–2019). The thresholds were calculated as percentages of the annual mean total number of cases for each province. When the percentage had been applied to the mean annual total for that province, a threshold value was returned. The weekly data were then coded as either exceeding this threshold or not and plotted accordingly. The start of the respiratory disease season was then defined as the week from which the threshold in cases is exceeded, and the end of the season is defined as the week from which the threshold is not exceeded. In the interests of comparability, we began by exploring the 5% threshold used for defining the onset and cessation of the influenza season in Europe [10]. We thereafter applied thresholds of 10%, 15%, 20%, 33.3%, 60%, and 90% to the data for each province to identify the threshold that returned a respiratory disease season that most closely aligned with the 19 weeks duration defined by the NICD [7]. The respiratory disease season defined by the respective threshold for each province was then also plotted as an indication of weeks that either exceeded or fell below that threshold.

3. Results

3.1. Weekly Trends in Hospitalization Cases and Medical Insurance Claims

Influenza and RSV hospitalization rates at Baragwanath hospital indicate that cases peaked during early autumn to winter from 2015 to 2019 and influenza cases increased during winter in South Africa (Figure 2). A distinct single peak in cases per year is observed in RSV- positive cases and influenza-positive cases (Figure 2). However, these peaks are better observed in the RSV-positive cases in comparison to the influenza-positive cases (Figure 2). The RSV cases utilized in this study were obtained from the paediatric ward at Baragwanath hospital and show a distinct seasonality for the following reasons: (1) RSV is the most common cause of bronchitis and lower respiratory tract illness among young children, (2) infants and young children often have underdeveloped immune systems, and (3) transmissions often occur more frequently due to shared spaces such as schools and playgrounds [37]. Cases increase from close to 0 each week to over 7 a week for influenza and over 35 a week for RSV (Figure 2). Cases of influenza started to increase from week 20 in 2015, with the highest number of cases being during week 24 with a total of 13 hospitalizations (Figure 2a). In that same year, a spike in RSV is seen between weeks 8 and 9, 14 and 15 with the highest cases being observed in week 20 with a total of 43 cases (Figure 2b).

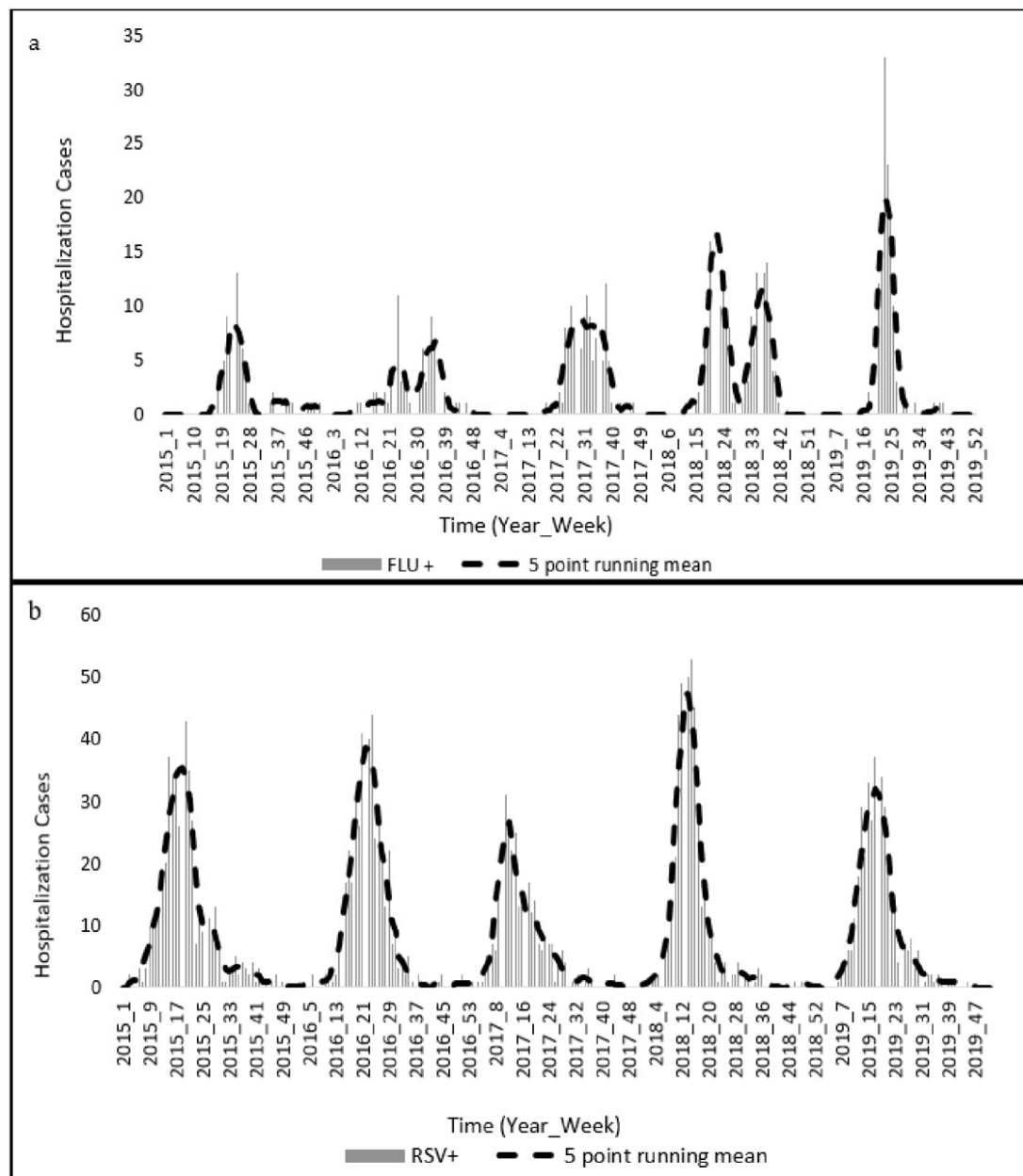


Figure 2. Caseloads of hospitalized patients with positive tests for (a) influenza and (b) RSV (2015–2019).

In 2016, influenza cases were relatively low. However, they spiked in week 24 with 11 cases and gradually increased again from week 31, and almost no cases were reported post-week 39 (Figure 2a). The prevalence of cases was observed for RSV from weeks 14 to 29, with the highest cases being observed in week 24 with 44 cases (Figure 2b). In 2017, RSV cases started to gradually increase from the first week, and during weeks 10 and 11, RSV cases were highest with a total of 31 cases for each, week respectively, and they gradually decreased after week 11 where almost no cases were reported from 30 until the remainder of the year (Figure 2b). Similarly, influenza case prevalence was low in 2017 with the highest

number of cases being in week 38 with a total of 12 cases (Figure 2a). In 2018, cases started to increase from week 18, and week 22 reported the highest number of influenza cases which was 23, and RSV cases started to increase with the highest number of cases being observed in week 15 with a total of 53 cases after which it started to gradually decrease (Figure 2). Lastly, in 2019 influenza cases started to increase during week 21 and peaked during week 23 with 33 reported cases, and RSV cases started to increase during week 11 and peaked in week 17 with 37 cases (Figure 2). In 2019, there was a spike in influenza cases during week 23 that is not apparent for RSV (Figure 2). Overall, both influenza and RSV cases begin to gradually increase during the colder seasons and start to gradually decrease during the warmer seasons. However, in 2017 cases of influenza and RSV started to increase early, and overall, fewer people were hospitalized for both these two acute lower respiratory diseases.

RSV-positive hospitalized patients at Baragwanath hospital exceeded those who tested positive for influenza overall (Figure 2b). Across all the years, we were in the influenza season by week 21 and out of it roughly between weeks 37 and 40 and in the RSV season by week 13 and out of it roughly between weeks 32 and 34 (Figure 2). The peak in cases for influenza on average was experienced in weeks 21–25, and for RSV cases the peak was usually between weeks 17 and 23 (Figure 2). In 2015, RSV cases began to increase as early as week 9 and peaked at week 20 with a total of 43 cases. In 2016, RSV cases started to increase from week 15 and peaked at 44 cases in week 24. In 2017, cases exhibited similar patterns to those of 2015 and started increasing from week 6 and peaked in weeks 10 and 11 with 31 cases in each week. The number of cases per week increased in 2018. This increase started in week 7 and peaked in week 15 with 53 cases, and cases started to increase from week 11 in 2019 and peaked in week 19 with 34 cases.

Figure 3 is a graphical representation of the national claim totals for the Discovery medical insurance scheme. It is easy to deduce that there is a distinct seasonality in claims for the whole country. Nationwide claims peak in the colder seasons (autumn and winter) and decrease during the warmer seasons (spring and summer). There is an overall increase in claims from 2008 to 2019. In 2008, claims peaked at week 29. In 2009, claims peaked in week 34. In 2010, claims peaked in week 33. In 2011, claims peaked at week 25. In 2012, claims peaked at week 22, and in 2013, claims peaked in week 22. In 2014, claims peaked in week 26. In 2015, claims peaked in week 21. In 2016, claims peaked in week 21. In 2017, claims peaked in week 40. In 2018, claims peaked in week 25, and in 2019, claims peaked in week 22. It is clear that cases start to increase during colder seasons and decrease during the warmer seasons (Figure 3).

Exploring each province individually, a distinct seasonal pattern is observed in Gauteng province (Figure 4). It is the most densely populated province in South Africa, and it is also the economic hub of the country and consists of individuals that have more financial means and can subsequently afford medical insurance (Figure 4). Acute lower respiratory diseases spread mainly through droplets when infected people cough or sneeze making it a disease that spreads easily [17]. Given that the geographical space of Gauteng is the smallest in comparison to the other nine provinces, this subsequently means that there are more people per square kilometer. From 2015–2019, RSV or flu cases on average peaked in the winter season, roughly around week 21 (Figure 2). However, unlike Baragwanath hospitalization data, there are claims every week including the off-peak seasons which are the warmer seasons (Figure 4). However, like Baragwanath influenza cases, Discovery medical insurance claims in Gauteng were exceedingly higher in 2019 during the colder seasons (Figure 2). South Africa in general, experiences a climate that varies temporally and spatially across several scales, and this is because of its topography, surrounding oceans, and latitudinal location [26]. Therefore, not all nine provinces will exhibit a distinct seasonal pattern (Figure 5).

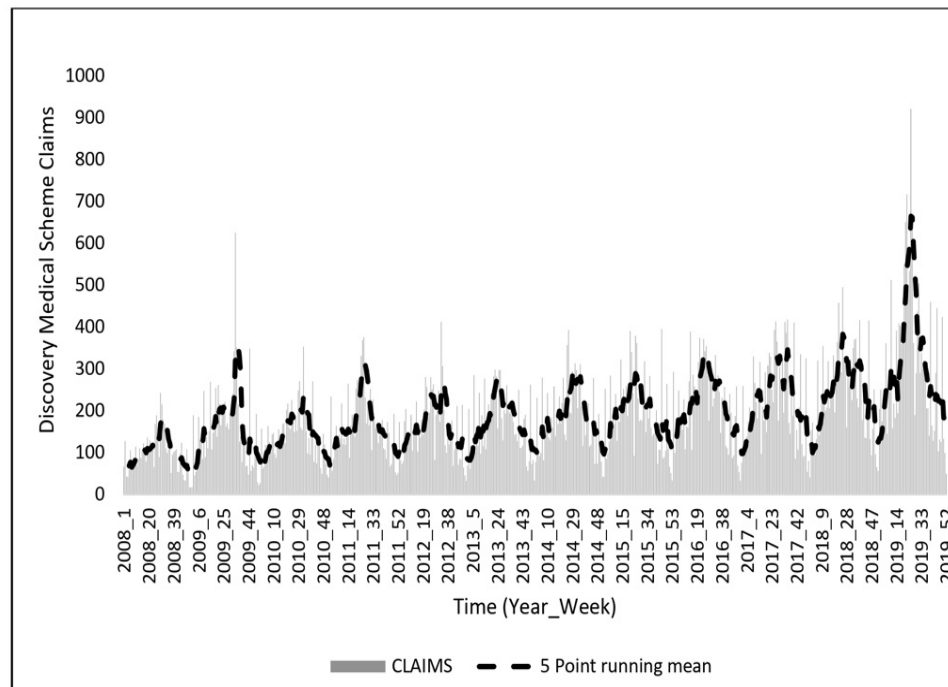


Figure 3. Weekly medical insurance claims for South Africa and the 5-point running mean (2008–2019).

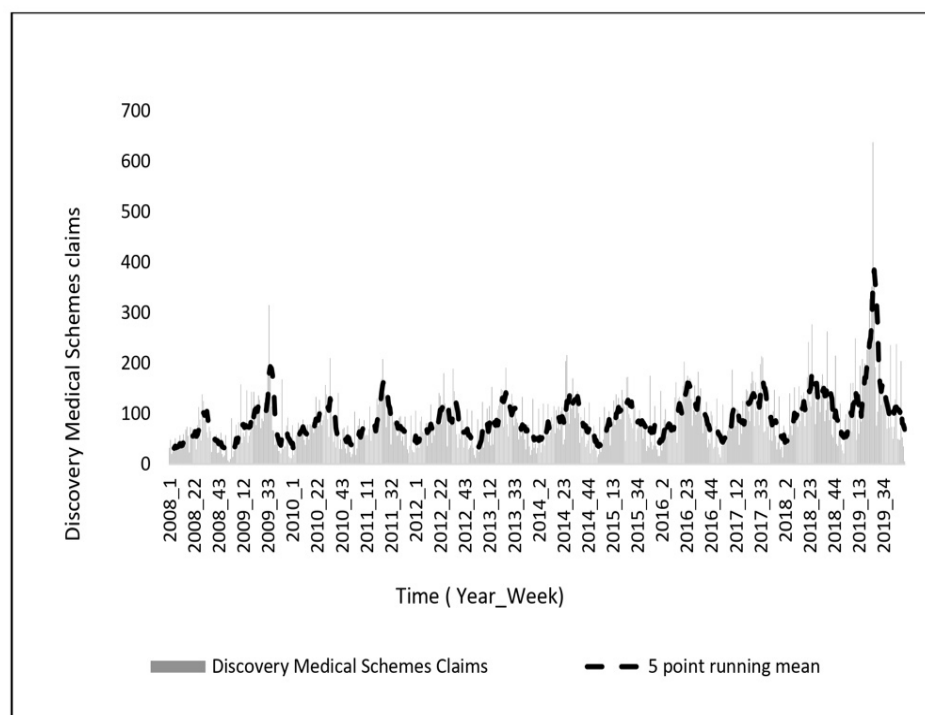


Figure 4. Discovery medical scheme claims in Gauteng, with a 5-point running, mean.

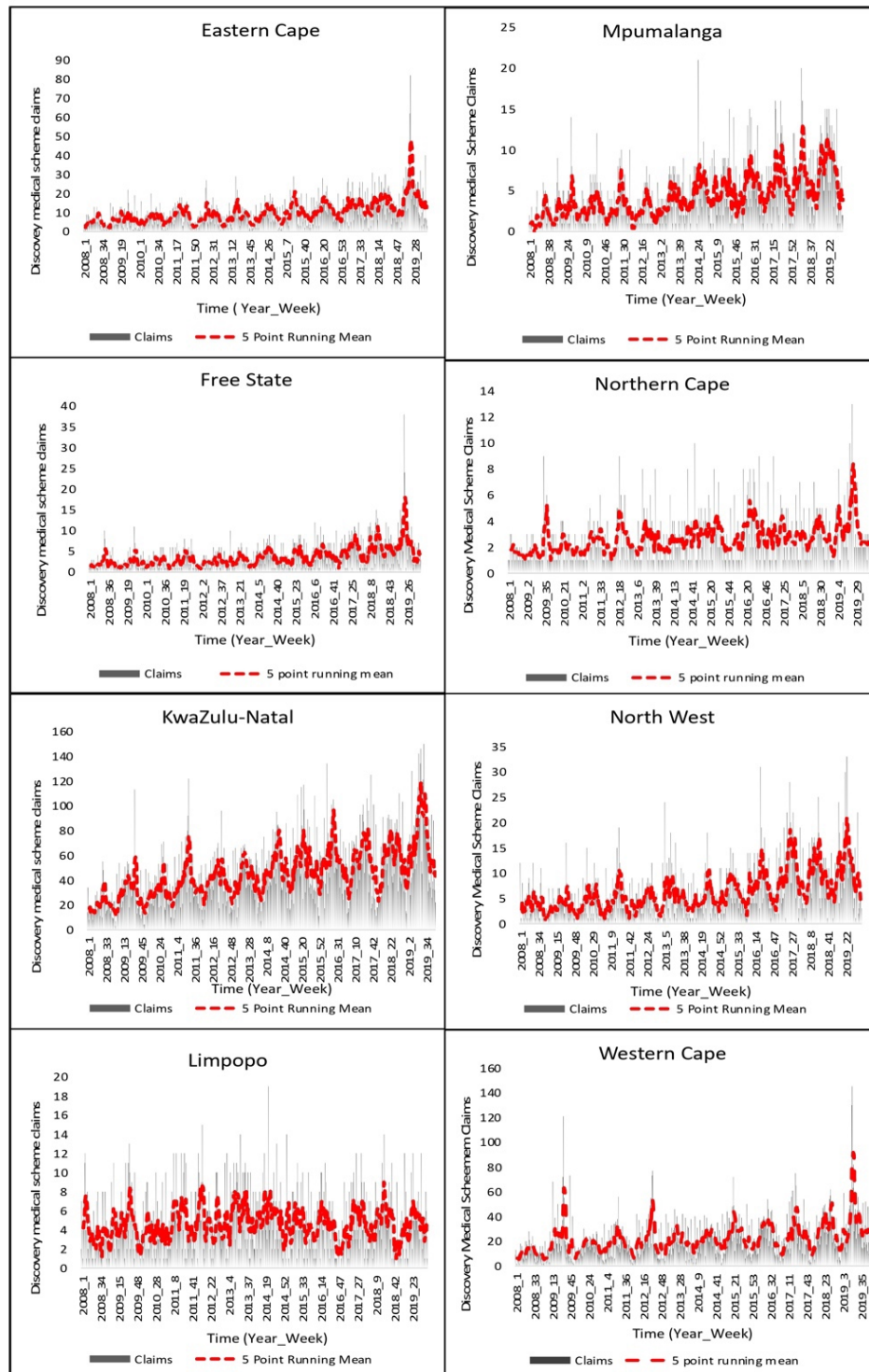


Figure 5. Medical insurance claims and running mean for Eastern Cape, Free State, KwaZulu-Natal, Limpopo, Mpumalanga, Northern Cape, North West Province, and Western Cape.

The Western Cape, Eastern Cape, and KwaZulu-Natal also show a distinct seasonality with the peak seasons being in the colder seasons and the off-peak seasons being the warmer seasons compared to the remainder of the other provinces (Figure 5). It is interesting to note that all three provinces are situated along the coast (Figure 1). However, the North West province exhibits a distinct seasonal pattern in comparison to the remaining provinces, which consist of the Free State, Limpopo, Mpumalanga, and the Northern Cape all situated inland and not exhibiting a distinct seasonality (Figures 1 and 5).

Limpopo, the northernmost province of South Africa, exhibits no seasonal pattern in claims as the claims peaked in both peak and off-peak seasons from 2008 to 2019 (Figures 1 and 5). This is also the case for the Northern Cape; however, in comparison to Gauteng province, many people cannot afford the luxury of health care insurance, and this province has the lowest number of claims (Figure 5). The Free State has a low number of claims similar to the influenza cases from Baragwanath hospital and from Gauteng. There was, however, a spike in claims during the winter season of 2019 (Figures 2a, 4 and 5). Mpumalanga also does not exhibit a distinct seasonality. A slight pattern can, however, be observed when assessing the five-point running mean graph (Figure 5).

3.2. Defining the Acute Infectious Respiratory Disease Season

Eurich et al. [20] argued that the respiratory disease season spans from the first case to the last case each year. This methodology would be effective for the Baragwanath hospitalization data for RSV and influenza. However, for the medical insurance claim data, there are claims for every week of the year in each of the provinces, and this method would return a respiratory disease season that spans the full 52 weeks of the year. As the first positive test for the hospitalization data is very unlikely to be the first person to contract an acute infectious respiratory disease in South Africa, the hospitalization data cannot be considered a clear indicator of disease prevalence in Gauteng province and definitely cannot be generalized to the full country.

More consistent with the CDC methodology of intensity thresholds, Vega et al. [10] advocate a 5% threshold. This threshold was applied to the data across all nine provinces from 2008 to 2019, and it is clear that the acute respiratory infectious disease season spans a considerably longer period than 19 weeks (Figure 6). This was particularly the case for provinces that had higher medical insurance members; Eastern Cape, Gauteng, KwaZulu-Natal, and Western Cape well exceeded the 19-week duration from 2008 to 2019 (Figure 6). All of the abovementioned provinces' cases started as early as the first week and finish in week 51 of the year, meaning that there indeed is no flu season, and South Africans in these province display flu-like symptoms throughout the year (Figure 6). This threshold is also not appropriate for the Free State, Limpopo, Mpumalanga, the Northern Cape, and the North West as in some years the acute lower respiratory disease season is only nine weeks, and in other years it is the entire year and is experienced through warmer seasons and not colder (Figure 6).

After testing a series of different thresholds for each of the provinces, the most appropriate threshold was determined for each province, respectively, that yielded results that were close to a 19-week flu season from 2008 to 2019: Eastern Cape (17%), Free State (15%), Gauteng (20%), KwaZulu-Natal (25%), Limpopo (15%), Mpumalanga (15%), North West (13%), Northern Cape (11%), and Western Cape (18%) (Figure 7). The provinces had a distinct seasonal pattern. None of the provinces yielded precisely nineteen weeks, but the threshold selected for each province was close to the nineteen-week season proposed by the NICD. Gauteng, Western Cape, KwaZulu-Natal, and Eastern Cape had the most suitable thresholds. All three provinces have acute respiratory infectious disease seasons that start in the winter season (Figure 7). The Northern Cape, Limpopo, Mpumalanga, and Free State yielded seasons that start very early in the year for certain years.

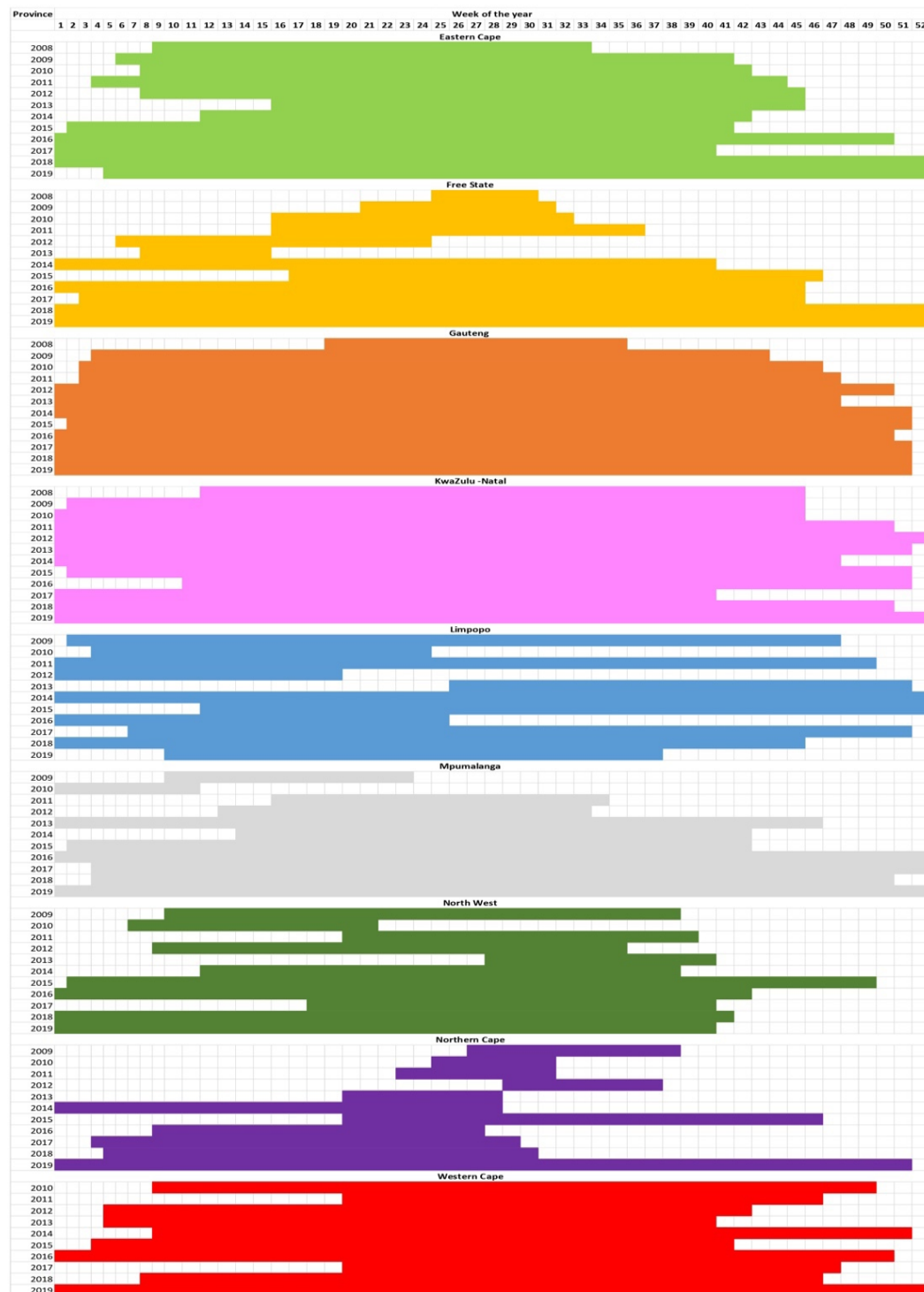


Figure 6. Applying Vega et al.'s [10] 5% threshold for South Africa's nine provinces.

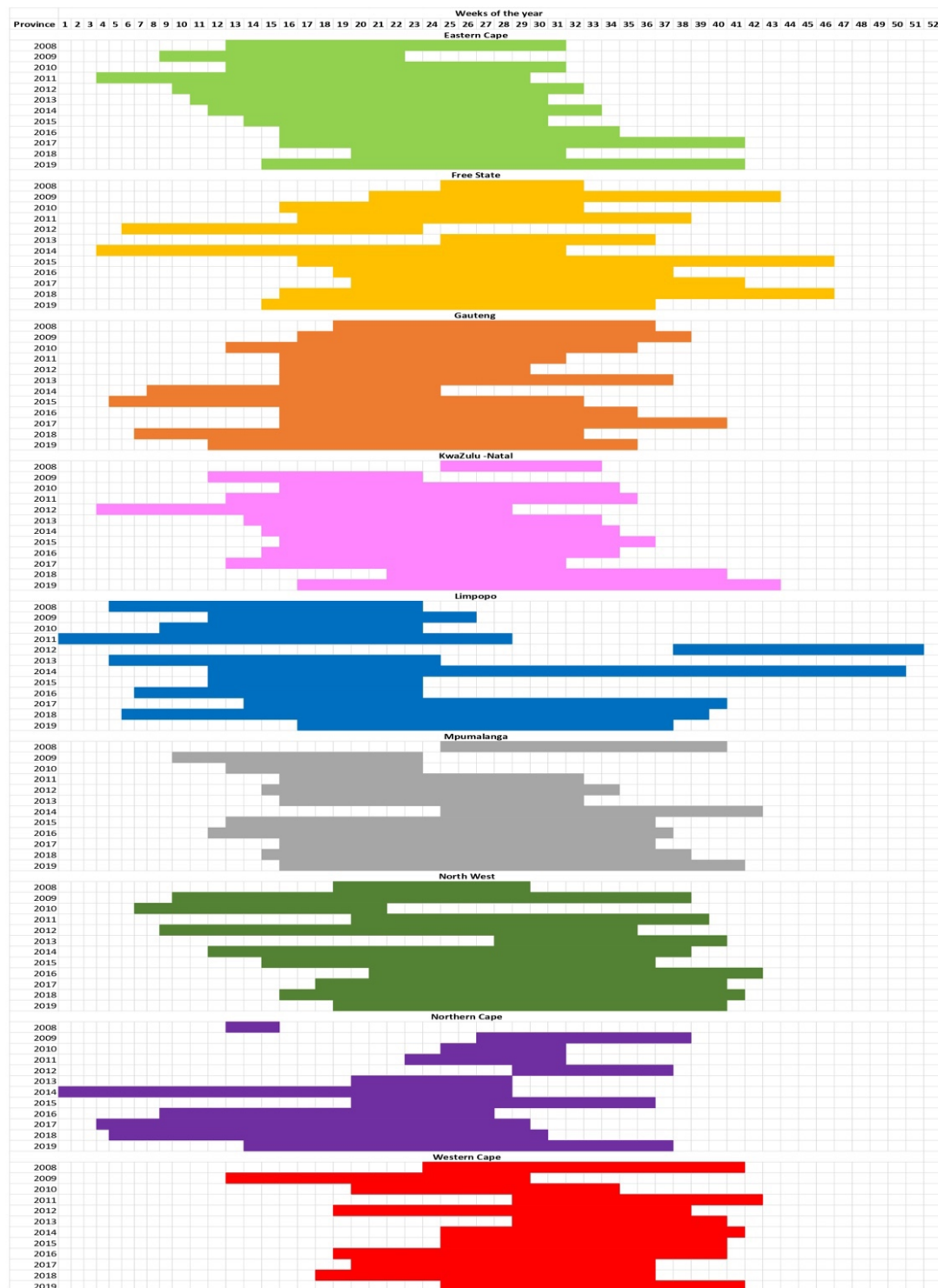


Figure 7. Threshold graphs showing the different thresholds for the nine South African provinces, respectively.

The timing of seasons differed interannually for each season per province, and when comparing provinces, the start and finish times also differed. Limpopo's season was distinct from other provinces as not only were overall seasons shorter than nineteen weeks, but the season also commenced as early as week 1 in some years, only started in week 38 in 2012 and managed to last almost the entire year in 2014 (Figure 7). In the Free State, the respiratory disease season was exceptionally short in 2008 and 2013 and started earlier in 2014 (Figure 7). The Northern Cape also had some unusual start and finish dates, particularly for 2008 and 2014 (Figure 7). In 2008, Mpumalanga had a respiratory disease season that commenced much later in the year (Figure 7). Gauteng, KwaZulu-Natal, Eastern Cape, and Western Cape on average had respiratory disease seasons that started early in some years but ran through the whole winter season and ended between weeks 37 and 46 (Figure 7).

4. Discussion

Annual acute respiratory infectious disease epidemics result in an estimated three to five million cases of severe illness, and about 290,000–650,000 deaths globally [6]. In South Africa, influenza (commonly known as flu) kills between 6000 and 11,000 people every year [37]. About half of these deaths are in the elderly, and about 30% are in HIV-infected people [7,37]. The highest rates of hospitalization are in the elderly (65 years and older), HIV-infected people, and children less than 5 years of age [37]. Pregnant women are also at increased risk of hospitalization and death from flu infections. People with chronic illnesses such as diabetes, lung disease, tuberculosis, and heart disease are also at increased risk of being hospitalized from the flu. During the flu season in South Africa, about 8–10% of patients hospitalized for pneumonia and 25% of patients with flu-like illness (fever and cough) will test positive for influenza.

Across South Africa, seasonality influences a wide range of activities that contribute largely to the economy; however, there is little consensus on the timing of seasonal boundaries [38–43]. This is due to the inconsistencies in different ad hoc approaches to defining seasonal boundaries across South Africa [44]. The NICD [7] states that for the past thirteen years, the South African flu season has lasted for approximately 19 weeks. Using the CDC's approach of intensity thresholds methodology [17], different thresholds had to be applied to the Discovery medical insurance claim data to quantify the South African acute respiratory infectious disease season. Based on the above findings, it is clear that the acute respiratory disease season is most intense during the winter season. Each province had different thresholds; however, all of them increased in the fall and winter based on Van der Walt and Fitchett's [44] seasons classification. These thresholds vary significantly across provinces. The most appropriate threshold was determined for each province that yielded results that were close to a 19-week flu season: Eastern Cape (17%), Free State (15%), Gauteng (20%), KwaZulu-Natal (25%), Limpopo (15%), Mpumalanga (15%), North West (13%), Northern Cape (11%), and Western Cape (18%) (Figure 7). This could be due to several various reasons: (1) the number of medical insurance members, certain provinces are considered to have more affluent residents who can afford medical insurance, whilst others cannot; (2) the geographical location of the province can contribute to the seasonality of acute respiratory infectious diseases.

A disease's potential to cause an outbreak determines whether it should be under surveillance [45]. An epidemic threshold indicates the level of incidence above which a disease requires an urgent response [18,45]. Each disease has a specific threshold that depends on its infectiousness, other determinants of transmission, and the degree to which it is locally endemic. Surveillance is often focused on diseases that could cause an outbreak and be a major public health concern. However, there is value in monitoring case numbers in less severe diseases. This allows for better communication with the public and the preparation of health facilities [46]. While it would be very costly to have high-resolution surveillance of the type instituted for COVID-19 where people were extensively tested, medical insurance data provide a proxy by which this can be carried out [47,48].

These thresholds can be evaluated weekly, and when approaching them, the public can be alerted [48]. The NICD already sends out warnings for flu seasons, but this could expand the process at a relatively low cost.

While this study has identified the thresholds that align with the NICD nineteen-week flu season and provides the mean timing of the season, it does not explore the causes of this seasonal pattern. Adequate thresholds will allow for future research to look at other drivers of seasonal trends in acute respiratory infectious disease cases. Cases and claims increase during the winter season which also coincides with school holidays, a time when people migrate, and cluster in spaces, such as airports and tourist destinations, where diseases spread easily. Therefore, it is important for future studies to look at the causal factors.

5. Conclusions

In a developing country such as South Africa, pivotal facets of primary healthcare are not in place, and there is a substantial human resources crisis facing the healthcare field [49]. Climatic changes will exacerbate the existing problems experienced by the public healthcare sector in the country [14]. The respiratory disease season is predominantly in the winter season and ends in summer for all nine provinces in South Africa. Each province has a different threshold that yields a respiratory disease season that is roughly 19 weeks long, Eastern Cape (17%), Free State (15%), Gauteng (20%), KwaZulu-Natal (25%), Limpopo (15%), Mpumalanga (15%), North West (13%), Northern Cape (11%), and Western Cape (18%).

This study provided insight into the complexities of varying quantification of the acute respiratory infectious disease season in South Africa, and although the NICD has been able to determine the duration of the influenza season, the start and finish date of the influenza season needs to be determined to better plan for seasonal acute respiratory disease epidemics. Thus, advocating for a particular classification of the acute respiratory disease season is important. This may be beneficial to the public as they can better understand their risk of disease and are subsequently able to mitigate it accordingly and get vaccinated on time. This has the potential to lessen the disease load and risk to human health. It is also of benefit to the medical insurance schemes in planning for surges in claims, thus enhancing their financial sustainability.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The authors do not have authority to share the data. Requests for access to the data should be made directly to Discovery Health Medical Aid and to the South African Medical Research Council Respiratory and Meningeal Pathogens Research Unit.

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CHAPTER 6: EXPLORING THE ROLE OF EXTREME CLIMATE EVENTS (ECES) IN THE INCIDENCE OF RESPIRATORY DISEASE IN SOUTH AFRICA.

6.1 Brief Synopsis

The manuscript titled "Exploring the Role of Extreme Climate Events (ECes) in the Incidence of Respiratory Disease in South Africa" examines the association between extreme climatic phenomena—such as storms and heatwaves—and the incidence of respiratory diseases. This research constitutes a segment of the broader National Research Foundation (NRF) project on ECes, which provided funding for this doctoral study. The investigation focuses on the immediate and direct implications of ECes on public health. Through the analysis of health insurance claims corresponding to 48 documented ECes, the study observes that respiratory disease claims are influenced by both the presence and absence of these climatic events. Crucially, the analysis reveals that seasonal weather variations exert a more significant impact on the patterns of respiratory diseases than the extreme events themselves. The implications of this research underscore the importance of strategic health planning that anticipates seasonal climatic variations, rather than solely reactive measures to ECes. Such insights are pivotal for the development of effective public health policies and resource allocation strategies aimed at mitigating the burden of respiratory diseases.

Author contributions:

Contributor role	Author contribution
Conceptualisation	Fitchett JM and Sweijd N
Methodology	Motlogeloa O, Fitchett JM
Validation	Motlogeloa O
Formal analysis	Motlogeloa O

Investigation	Motlogeloa O
Resources	Motlogeloa O
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**Exploring the role of Extreme Climate Events (ECEs) in the incidence of respiratory disease
in South Africa.**

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ABSTRACT

In recent decades, escalating extreme climate events (ECEs) have raised concerns regarding their impact on South African public health, particularly respiratory health. This study investigates the complex link between ECEs and respiratory health. 48 ECEs were analysed, with 28 in regions with over 100 medical claims for respiratory disease. The events, including storms, heat waves, cold waves, floods, and tornadoes, underwent a thorough examination. A two-week lag period assessed their connection to medical claims. The findings indicated notable correlations between specific storms, heatwaves, cold waves, floods, and tornado occurrences and medical claims, both positive and negative. However, seasonal patterns had a more substantial impact on respiratory health than individual events. Positive percentage variations for significant events ranged from about 16% to 121%, while negative differences spanned approximately -178% to -5%. Despite some significant individual events, the overall seasonal context more profoundly affected respiratory health. Significant events were dispersed across municipalities and provinces from 2008 to 2019, lacking distinct clustering in seasons or time frames. Consequently, the study suggests prioritizing seasonal preparedness to enhance respiratory health instead of focusing on isolated extreme events. These outcomes hold vital policy and public health intervention implications. Effective strategies are necessary to mitigate extreme event impacts and enhance respiratory health in South Africa. Prioritizing seasonal readiness aligns with evidence that collective effects during specific periods wield a more substantial influence on respiratory health than isolated incidents. Developing comprehensive, targeted public health measures is pivotal to safeguarding vulnerable populations and enhancing overall respiratory health in South Africa amid changing climate and increased extreme weather frequency.

SIGNIFICANCE STATEMENT

The findings of this study underline the complex interplay among extreme weather events, flu seasons, and acute respiratory disease claims in South Africa. Although certain events exhibited significant changes in respiratory claims, the overall analysis reveals varying impacts. Seasonal effects on respiratory health surpass the influence of individual events, underscoring the importance of prioritizing seasonal preparedness in policy and public health strategies. Addressing cumulative seasonal variations can enhance preparedness and response measures to mitigate the consequences of extreme events. This research highlights the ongoing need to comprehensively address public health challenges in the context of a changing climate. The insights garnered can contribute to strengthening South Africa's healthcare system to better navigate extreme weather events and their associated health impacts.

1. Introduction

An extreme climate event (ECE) can be defined as a notable deviation from the historical mean or anticipated weather conditions within a specific geographic area, manifesting itself over a relatively limited temporal period, usually hours to days (Stephenson and Mtsweni, 2008; Smith, 2011; Van Der Walt and Fitchett, 2022). These events exhibit distinctive features in terms of their intensity, duration, or frequency, and frequently have substantial ramifications for human societies, ecosystems, and the environment at large (Smith, 2011). It is anticipated that climate change will increase the frequency and severity of ECEs globally, posing a significant danger to food security, water security, and economic stability in Southern Africa (Abrams et al., 2018; IPCC, 2021; Lahsen and Ribot, 2022). In Southern Africa, ECEs such

as droughts, heat waves, and floods are becoming more frequent and severe (Davis-Reddy et al., 2017; Van Der Walt and Fitchett, 2022). These events already have substantial effects on South Africa, including decreased agriculture yields, limited access to clean water, and property destruction (Apraku et al., 2021). The most vulnerable populations, including those living in rural communities and informal settlements, are often disproportionately affected (Curtis et al., 2017). ECEs have also been associated with an increase in the spread of infectious diseases and exacerbate existing health problems (McMichael, 2015).

Infectious respiratory diseases are a major public health problem in South Africa due to the high prevalence of influenza and pneumonia (Tempia et al., 2020; Fraser et al., 2022), and the challenges posed by co-morbidities of HIV/AIDS and Tuberculosis (Bates et al., 2015). Influenza results in thousands of hospitalizations and fatalities annually (Duque et al., 2014; Tempia et al., 2019, 2020). Influenza typically has a seasonal pattern, with most cases occurring during the autumn and winter months in temperate regions of the world (Iuliano et al., 2018; Smit et al., 2020). In South Africa, the respiratory disease season spans 19 weeks (NICD, 2019), spanning approximately May to August with considerably inter-annual and spatial variability (Motlogeloa et al., 2023). Common respiratory viral epidemics, such as influenza and respiratory syncytial virus (RSV), as well as concomitant bacterial pneumonia, display marked seasonal and interannual variability (Tellier, 2006; Palache, 2011; Weinberger, 2021). The occurrence, total duration, and severity of infectious pandemics may become unpredictable as a result of climate change, including the effects of extreme climate events. (Towers et al., 2013).

ECEs can have a significant impact on the spread and incidence of diseases (McMichael, 2015; Davis-Reddy, 2017). These events temporarily heighten adverse weather conditions, and can disrupt the natural environment and increase the risk of exposure to disease-causing organisms or vectors, leading to outbreaks of infectious diseases (Matsumoto et al., 2012; Towers et al., 2013). Floods can result in the dissemination of waterborne diseases and the formation of favourable conditions for disease-carrying vectors like mosquitoes, as highlighted by Loevinsohn (1994). Heatwaves can directly result in heat exhaustion, heat stroke, and dehydration, particularly in vulnerable populations such as the elderly, children, and those with pre-existing health conditions (Campbell et al., 2018; Van Der Walt and Fitchett, 2021a). ECEs can also have an impact on the spread of respiratory diseases such as influenza (Feng et al., 2021). Events such as tropical cyclones and floods can lead to overcrowding in emergency shelters, thereby increasing the risk of the spread of respiratory diseases (Beveridge, 1991; Cavallo and Noy, 2010), and it has been observed that the number of pneumonia cases may increase following tornadoes (Forshee-Hakala, 2015; Chapungu, 2020). Furthermore, studies have shown that the disruption caused by such events can exacerbate the incidence of respiratory conditions (Kontowicz et al., 2022). Climate change is projected to result in an increase in the frequency and severity of extreme weather events, leading to further impacts on human health and the spread of disease (Hathaway and Maibach, 2018, IPCC, 2021). While the direct mortality from ECEs is often recorded and published, the impacts on specific medical conditions are less frequently explored.

This study examines changes in respiratory disease burden following ECEs using proxy case data in the form of private-sector medical aid claims from Discovery Health Medical Scheme. Using the EM-DAT list of ECEs that have occurred in South Africa, coupled with Google News

reports, this study compares the timing of ECEs to incidence peaks observed in medical insurance claims data post the occurrence of an ECE. These findings will enable the correct prediction of the change in respiratory disease after an extreme climate event.

2. Material and Methods

a. Study Site

South Africa is the southernmost country in Africa, situated between 22-35°S and 16-33°E. It has a land area of 1,220,000 km² (Figure 1) bordered by Botswana, Mozambique, Namibia, and Zimbabwe. A mountainous escarpment separates the coastal plain from a high plateau in the interior (Grab and Knight, 2018). South Africa, with its diverse geography, experiences various extreme climate events (ECEs) across different regions. During the summer months, the interior areas, particularly the Northern Cape, Free State, and North West Province, are more susceptible to intense heatwaves, with temperatures often exceeding 30°C and occasionally surpassing 40°C (Figure 1; Van Der Walt and Fitchett, 2021a; LeComte, 2020). In contrast, the southern coast and interior regions, including the Free State, Gauteng, and Mpumalanga province, are more prone to cold spells during the winter months, as cold fronts from the southern Atlantic Ocean bring colder air to these areas (Schulza and Maharaj, 2007; Roffe et al., 2019; Lone and Ahmad, 2020; Van Der Walt and Fitchett, 2021b). Some South African locations also face significant flooding during the summer due to cut-off lows (COLs) and synoptic-scale baroclinic systems, while tornadoes are more common in the north-eastern regions, such as Mpumalanga, Gauteng, and KwaZulu-Natal, albeit relatively rare compared to other parts of the world (Figure 1; Milford et al., 1994; Roffe et al., 2019; Grab and Nash, 2023). Moreover, the country experiences recurring droughts, particularly in the

western and central parts, characterized by semi-arid and arid conditions, resulting in significant impacts on agriculture, water resources, and the economy (Figure 1; Zucchini and Adamson, 1984; Rouault and Richard, 2005; Sousa et al., 2018). The Day Zero drought in South Africa was one of the country's most significant droughts, particularly impacting Cape Town (Wolski, 2018; Ziervogel, 2019).

Urban areas in South Africa, which are the focus of this study can experience particularly severe impact of ECEs. The presence of built infrastructure in cities and towns makes them vulnerable to destruction or damage during severe weather events, including floods, tornadoes, and storms. Additionally, the urban heat island effect can exacerbate heat waves, accelerating infrastructure deterioration and increasing energy demands for cooling (Salimi and Al-Ghamdi, 2020). As urbanization continues to grow in South Africa, addressing the effects of ECEs on built environments becomes imperative for enhancing community resilience and promoting sustainable urban development.

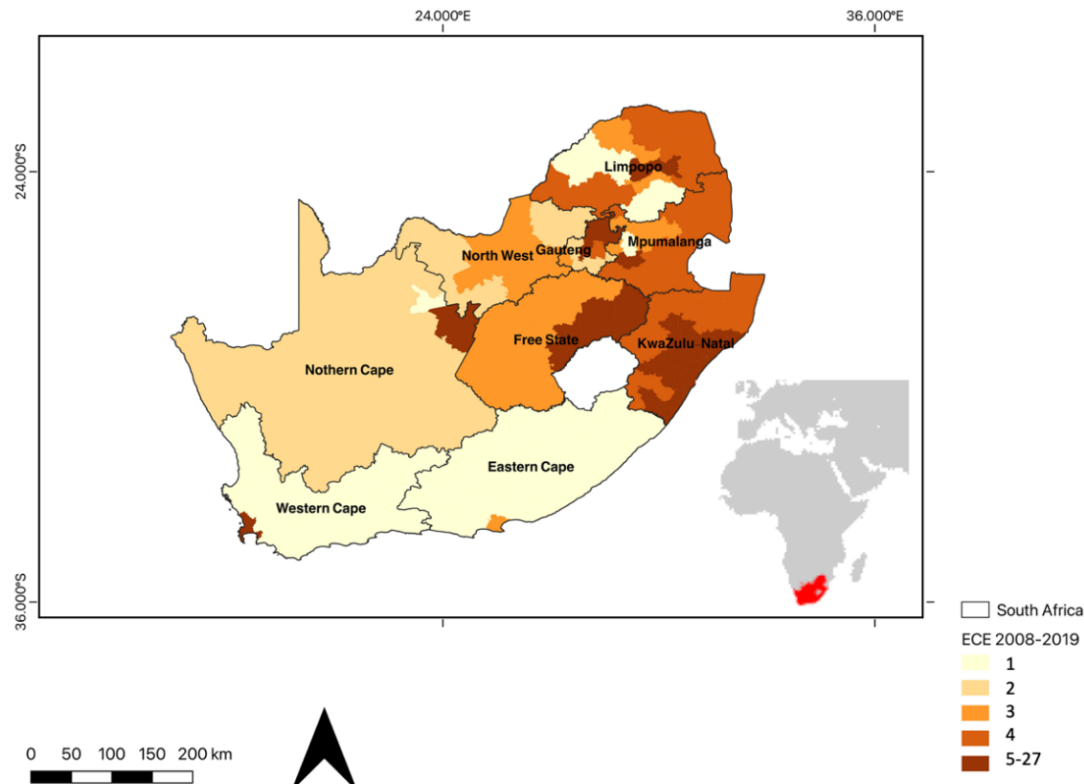


Fig. 1. Map illustrating the number of ECEs that have occurred in South Africa between 2008-2019.

b. Data Sources

1) CASE DATA

In this study, we analyzed two datasets to explore the correlation between extreme climate events (ECEs) and the incidence of respiratory diseases in South Africa. The primary dataset comprised a 12-year series (2008-2019) of medical insurance claims, specifically for individuals diagnosed with acute respiratory diseases as classified by ICD-10 codes J00 (Acute nasopharyngitis), J110 (Influenza with pneumonia), J111 (Influenza with respiratory infection), and J118 (Influenza with other infestations). This data was sourced from Discovery Health Medical Scheme and detailed daily claims from various municipalities, towns, and cities nationwide. Each record included the location of the claim, the filing date, and

demographic details of the claimant such as age and gender. We aggregated the data weekly, starting each Sunday, and consciously excluded data post-2019 to prevent COVID-19 cases from distorting the analysis of seasonal and climatic trends. The research received ethical approval from the University of the Witwatersrand's Human Health Research Ethics Committee (HREC), with the reference number M210617.

While it is recognized that medical aid coverage in South Africa extends to less than 20% of the population as of 2022, the dataset of medical insurance claims used in this study serves as a valuable proxy for monitoring trends in respiratory disease following extreme climate events (ECEs). This dataset, derived from a leading health insurance provider, captures a substantial volume of systematic data over a 12-year period, offering a robust foundation for analyzing temporal patterns and associations with ECEs. The insured population's claims data can reflect broader public health trends because insured individuals are distributed across various municipalities, towns, and cities, and their increasing demographic diversity provides a heterogeneous sample. Moreover, claims data represent the full spectrum of symptomatic responses to acute upper respiratory infections, from mild symptoms requiring over-the-counter medication at a pharmacy, through to severe cases leading to hospitalization up to the level of intensive care units. Although the results reflect the health outcomes of insured individuals, these individuals are part of the wider community ecosystem that includes both urban and rural settings. Therefore, the patterns observed in this segment can offer important insights into the potential health impacts of ECEs at a larger scale. Comparisons of these medical aid claims against hospitalization data for Baragwanath Hospital, the largest hospital in Africa, confirm consistency in the trends in the seasonality of the data observed (Motlogeloa et al., 2023).

2) EXTREME CLIMATE EVENT DATA

The complementary dataset utilized in our investigation documented the occurrence, geography, and classification of extreme climate events (ECEs). This information was extracted from the Emergency Events Database (EM-DAT), which catalogues natural disasters dating back to 1900 and is curated by the Centre for Research on the Epidemiology of Disasters (CRED) at the Université Catholique de Louvain's School of Public Health in Brussels, Belgium. EM-DAT compiles extensive details on disasters, including their nature, location, dates, affected populations, casualties, injuries, and financial impact. Its reliability and comprehensiveness make EM-DAT an indispensable resource for scholars, policy formulators, and humanitarian groups. It supports the monitoring and analysis of disaster patterns, assisting in the formulation of measures for disaster risk mitigation and management of disaster response initiatives.

The methodology for classifying extreme climate events (ECEs) in this study was strategically aligned with the categorizations used by the EM-DAT database. This choice diverges from the approaches outlined by Jong et al. (2023) and Perkins and Alexander (2013), which rely on a percentile-based analysis of historical weather data to define extreme events. Instead of determining ECEs by percentile thresholds for significant meteorological phenomena such as heavy rainfall or extreme temperatures, our method leveraged the established classifications and descriptive keywords provided by EM-DAT. This facilitated a comprehensive and targeted search for relevant ECEs within the South African context, spanning from 2008 to 2019.

Further enriching our methodology, we expanded our data gathering through Google News to include additional reports on ECEs, using keywords like 'flood', 'drought', 'heatwave', and

'cold wave'. This approach allowed us to build on the EM-DAT records and address potential under-reporting issues, noted in studies by Rataj et al. (2016) and Van Der Walt and Fitchett (2021a). To effectively collect and manage this information, a custom web scraping tool was developed. This tool was designed with advanced algorithms capable of accurately identifying and extracting relevant news content about ECEs, which were then saved in a structured CSV format for detailed analysis.

The collected data underwent a rigorous cleaning process, including a manual review to verify the relevance and severity of the events, ensuring the elimination of duplicates and maintaining a focus strictly on climatic ECEs pertinent to our research objectives. This meticulous approach to data collection has resulted in a robust and comprehensive dataset, crucial for analyzing the impacts of ECEs on respiratory health outcomes accurately and comprehensively.

3. Data Analysis

In our analysis of the claims data, we used a detrending process to isolate the impact of extreme climate events (ECEs) on respiratory diseases, independent of seasonal variations. We applied the Seasonal and Trend decomposition using Loess (STL) method within R, suitable for non-stationary time series data (Cleveland et al., 1990). This involved decomposing the data into trend, seasonal, and irregular components, and removing the trend component to stabilize the time series mean across the study period. The STL method was chosen for its non-parametric nature, allowing for accurate modeling and removal of both linear and non-linear trends without assuming a specific form for the seasonal

component (Cleveland et al., 1990). After detrending, we analyzed the residual component to identify deviations due to ECEs. The procedure was validated to ensure that the detrended data did not retain long-term trends, confirming the effectiveness of our seasonality removal and enabling precise analysis of the ECEs' effects.

Following the detrending, our analysis proceeded with inferential statistical methods to examine the relationship between ECEs and the frequency of medical insurance claims for respiratory diseases. To ensure the robustness of our findings, we excluded events from locales with fewer than 100 total claims. This exclusion minimizes the impact of statistical anomalies or outliers that can distort the analysis, particularly in less populated areas. By setting this threshold, we focused on areas with sufficient data to yield statistically meaningful insights, enhancing the statistical integrity of our findings and focusing on substantial, actionable insights suitable for public health interventions. For the included ECEs, we conducted a comparative analysis where the number of claims during the ECE week and the following two weeks was measured against the average number of claims for the same calendar weeks over the previous nine years (Roshan et al., 2022). This approach provided a baseline that accounted for normal fluctuations in disease incidence. We incorporated a two-week lag period in our analysis to capture the incubation and typical symptom duration of respiratory illnesses, which is critical for assessing the delayed effects of ECEs on health.

In our analysis, we quantified the impact of each Extreme Climate Event (ECE) on the number of medical claims for respiratory diseases by calculating the percentage deviation from a baseline of claims established from historical data. To assess the variability of claims data

around this mean deviation, we computed the standard deviation for each type of ECE. This measure provided insight into the spread of the data and helped in understanding the consistency of the impact across different occurrences of the same type of event.

To evaluate the statistical significance of the observed deviations from the baseline, we applied a t-test to each ECE (Roshan et al., 2022). This analytical approach enabled us to identify any statistically significant fluctuations—either increases or decreases—in the number of respiratory disease cases that could be directly attributed to specific ECEs. The t-test results helped to ascertain whether the changes in claim numbers during ECEs were likely due to random variation or were statistically significant reflections of the impacts of these climate events. After establishing significance and assessing data variability, we further analyzed the data to understand how different types of ECEs and their geographic locations influenced the volume of respiratory disease cases. This detailed scrutiny allowed us to uncover nuanced insights about the spatial and event-type specific impacts of ECEs on public health, particularly respiratory health outcomes.

3. Results

a. ECEs in South Africa 2008-2019

The EM-DAT database records 32 ECEs in South Africa between 2008 and 2019. Each of these events was covered in at least one news article captured by Google News. Excluding earthquakes, fires, and ecological extreme events, the dataset was reduced to 29 ECEs. An additional 19 ECEs were identified from Google News, of which ten were extreme temperature events and nine were tornadoes (Table 1). A total of 47 ECEs were therefore included in the combined database. These included droughts (3), tornadoes (9), heatwaves (5), cold waves (5), storms (11), and flooding (14; Table 1). The eThekweni district of KwaZulu-

Natal has experienced the greatest number of storms and flood events (4). Droughts occurred frequently in the Western Cape over the period 2008-2019 (3), including the ‘Day Zero Drought’ which made global headlines. The mortality associated directly with these ECEs varied over the years; flood and storm events resulted in the greatest loss of life, resulting in a total of 363 deaths from 2008 to 2019 (Table 1).

Table 1. Overview of ECEs occurring in South Africa from 2008-2019.

Year_Week	Disaster Type	Location	Duration (days)	Source
2008_25	Cold wave	Cape Town (Western Cape); Gqeberha, East London (Eastern Cape); Durban (KwaZulu-Natal); Johannesburg (Gauteng)	7	Google News
2008_46	Storm	Durban City (KwaZulu-Natal)	1	EM-DAT, Google News
2008_47	Tornado	Molweni (KwaZulu-Natal)	1	Google News
2008_25	Flood	eThekweni district (KwaZulu-Natal)	1	EM-DAT, Google News
2009_1	Storm	Inchanga town - eThekweni district, Umzimkhulu area - Sisonke district, Richmond area - Umgungundlovu district (KwaZulu-Natal)	1	EM-DAT, Google News
2009_4	Heatwave	Johannesburg, Pretoria (Gauteng); Durban (KwaZulu-Natal); Cape Town (Western Cape)	1	Google News
2009_9	Flood	Kwadukuza (KwaZulu-Natal)	1	EM-DAT, Google News
2009_45	Tornado	Bulwer (KwaZulu-Natal)	1	Google News
2009_47	Storm	Cacadu district (Eastern Cape); Central Karoo district (Western Cape)	1	EM-DAT, Google News

2009_29	Flood	City of Cape Town district (Western Cape)	4	EM-DAT, Google News
2010_51	Storm	Free State, Mpumalanga, North West, Northern Cape, Limpopo, Gauteng, KwaZulu-Natal, Eastern Cape	2	EM-DAT, Google News
2011_1	Flood	Buffalo City, Amathole, Joe Gqabi, O. R, Tambo, Alfred Nzo, Chris Hani districts (Eastern Cape); Fezile Dabi, Thabo Mofutsanyane, Xhariep districts (Free State); City of Johannesburg, Ekurhuleni, Sedibeng, West Rand districts (Gauteng)	4	EM-DAT, Google News
2011_1	Flood	Amajuba, eThekweni, iLembe, Sisonke, Ugu, Uthukela districts (KwaZulu-Natal); Mopani, Sekhukhune, Vhembe, Waterberg districts (Limpopo); Frances Baard, Namakwa, Pixley ka Seme, Siyanda districts (Northern Cape); North West Province	4	EM-DAT, Google News
2011_41	Tornado	Duduza (Gauteng)	1	Google News
2011_41	Tornado	Ficksburg (Free State)	1	Google News
2011_54	Storm	KwaZulu-Natal	1	EM-DAT, Google News
2011_41	Storm	Meqheleng area-Ficksburg, Thabo Mofutsanyane district (Free State); Duduza town-Ekurhuleni district (Gauteng)	1	EM-DAT, Google News
2011_46	Heatwave	Johannesburg, Pretoria (Gauteng); Polokwane (Limpopo)	16	Google News
2011_47	Cold wave	Kimberley (Northern Cape); Cape Town (Western Cape); Gqeberha (Eastern Cape)	8	Google News

2012_1	Storm	Limpopo, Mpumalanga	1	EM-DAT, Google News
2012_19	Cold wave	Cape Town (Western Cape); Gqeberha (Eastern Cape); Kimberley (Northern Cape)	7	Google News
2012_25	Tornado	Bethlehem, Deneysville (Free State)	1	Google News
2012_43	Flood	Bathurst, Port Alfred, Kenton-on-Sea, Grahamstown (Eastern Cape)	5	EM-DAT, Google News
2013_22	Storm	Bishop Lavis, Hout Bay, Gugulethu, Strand, Khayelitsha, City of Cape Town (Western Cape)	1	EM-DAT, Google News
2014_9	Flood	Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, North West	1	EM-DAT, Google News
2014_46	Heatwave	Johannesburg, Pretoria (Gauteng); Polokwane (Limpopo); Kimberley (Northern Cape)	7	Google News
2015_1	Drought	KwaZulu-Natal, Free state, Limpopo, Mpumalanga, North-West, Cape Town (Western Cape)	~730	EM-DAT, Google News
2016_1	Heatwave	Ngaka Modiri Molema (North West)	9	EM-DAT, Google News
2016_31	Flood	Cape Town, Phillipi, Khayelitsha (Western Cape); Durban, Cato Manor, Amazimtoti, Inanda, Ntuzuma, KwaMashu, uMlazi, Yellow Wood Park, Chatsworth -eThekweni Metropolitan Municipality, Ugu district (KwaZulu- Natal)	1	EM-DAT, Google News
2016_31	Tornado	Tembisa (Gauteng)	1	Google News
2016_46	Flood	Gauteng, KwaZulu Natal	1	EM-DAT, Google News
2016_51	Tornado	Standerton (Mpumalanga)	1	Google News

2016_52	Tornado	Standerton (Mpumalanga); Vaal Marina (Gauteng)	1	Google News
2017_23	Storm	Kraaifontein, Lavender Hill, Strand, Kalkfontein, Delft, Mfuleni, Mandalay, Hout Bay, Kraaifontein, Cape Town, Rheenendal, Welbedacht, Knysna, Pacaltsdorp, Mossel Bay, George to Plettenberg Bay - Eden, Welbedacht - Cape Winelands (Western Cape)	1	EM-DAT, Google News
2017_41	Storm	Durban, Bluff, Jacobs, Montclair, Glenwood, Umlazi, Merebank, Isipingo, Nquthu, Umzinyathi (KwaZulu-Natal); Johannesburg, Ekurhuleni-West Rand District Municipality (Gauteng)	1	EM-DAT, Google News
2017_18	Drought	Cape Town, Cape occidental, Cape oriental, North Cape (Western Cape)	~365	EM-DAT, Google News
2017_46	Cold wave	Johannesburg, Pretoria (Gauteng)	7	Google News
2017_20	Flood	Kquthu-Umzinyathi District, Zinkwazi-Ilembe District, Mzingwenya-Uthungulu District, uMzumbe municipality, uMdoni, uMuziwabantu (KwaZulu-Natal)	5	EM-DAT, Google News
2018_6	Heatwave	Johannesburg, Pretoria (Gauteng); Klerksdorp, Potchefstroom (North West)	7	Google News
2018_25	Cold wave	Cape Town (Western Cape)	1	Google News
2019_10	Flood	KwaZulu-Natal, Eastern Cape, Free State	4	EM-DAT, Google News
2019_17	Flood	Ntuzuma, Verusalam, Inanda, KwaMashu (KwaZulu-Natal)	4	EM-DAT, Google News
2019_18	Flood	Eastern Cape	1	EM-DAT, Google News

2019_46	Storm	Inanda (KwaZulu-Natal)	1	EM-DAT, Google News
2019_1	Drought	Western Cape, Eastern Cape, Northern Cape	12	EM-DAT, Google News
2019_49	Flood	Pretoria (Gauteng)	9	EM-DAT, Google News
2019_51	Tornado	New Hanover (KwaZulu- Natal)	1	Google News

b. ECEs and the incidence of acute respiratory diseases

Of the 48 ECEs (Table 1), only 28 occurred in regions which had more than 100 total DHMS medical aid claims and were thus retained for further analysis. Importantly, some ECEs affected more than one area, resulting in duplicate entries of the event where the local medical aid claim response is tested (Table 2). Extreme climate events, such as storms, heat waves, cold waves, floods, and tornadoes, have significant implications for public health and medical health insurance claims. To examine the association between these extreme climate events and medical health insurance claims, a comprehensive analysis was undertaken, incorporating a two-week lag period for each event. The findings from this study are summarized below.

A subset of storm events correlated with significant fluctuations in medical health insurance claims, as reflected by p-values ranging from <0.001 to 0.1, detailed in Table 2. These events resulted in a range of insurance claim adjustments, with increases between 16% to 121% and decreases from -5% to -178%. The incidences of these storm events were distributed across various locations and spanned from 2008 to 2019, exhibiting no discernible seasonal or temporal trends. Notably, the standard deviations for claims in other years and the standard deviations for claims in the test year provide additional context, indicating the variability of

claims associated with each event, as seen in the entries for each city and event in Table 2. For instance, the storm in Inanda in 2019 showed a standard deviation of 1.55 for other years and 0.78 for the test year, highlighting the variability in claim amounts.

Similarly, heatwave events were associated with notable variations in insurance claims, evidenced by p-values in the same statistical range. Heatwaves led to a rise in claims by 18% to 27% and a reduction by -7% to -40%, without a focused spatial or temporal distribution. The standard deviations in claims for other years and in the test year for these events show the fluctuations in claim amounts during heatwaves, providing insight into the variability of claims, which ranges from 0.72 to 2.51 for other years and 0.89 to 2.02 for the test year. Cold wave events were linked to significant changes in claims, with increases noted from 16% to 85%, and decreases ranging from -83% to -178%. The occurrence of significant cold wave events did not show any regular patterns in their distribution. The standard deviations for claims during cold wave events demonstrate considerable variability, with figures ranging from 0.50 to 3.90 for other years and 1.15 to 2.90 for the test year, underscoring the unpredictable nature of insurance claims related to cold waves.

Flood-related events also showed a significant correlation with changes in insurance claims, with p-values ranging from <0.001 to 0.1. These events accounted for claim increases from 75% to 86% and decreases ranging from -5% to -178%, occurring without a consistent pattern in location or timing. The standard deviations for these events highlight the variability in claims, with figures ranging from 0.65 to 3.12 for claims in the test year and 1.48 to 4.36 for claims in other years, emphasizing the unpredictable nature of insurance claims associated with flood events. Tornado events displayed a similar trend, with significant impacts on

insurance claims ranging from positive changes of 38% to 135% to negative changes between -61% to -70%. Like other ECEs, tornado events did not present any particular spatial or temporal patterns. The variability in claims related to tornadoes is evident in the standard deviations, with figures ranging from 0.46 to 5.93 for claims in the test year and 1.40 to 3.94 for claims in other years. These statistics underscore the substantial fluctuations in insurance claims associated with tornado occurrences .

1 Table 2. Changes in Medical Insurance Claims Relative to Baseline in the Event of ECEs

Municipality/City	Week	Year	Disaster Type	Province	Baseline Claims	Change in Claims	% Change from Baseline	95% CI for Change	P Value	Sd Claims Other Years	Sd Claims Year Test
Pretoria	49	2019	Flood	Gauteng	54	-3	-5	54	0,0004	1,87	0,65
Inanda	46	2019	Storm	KwaZulu-Natal	34	-14	-42	17	0,0549	1,55	0,78
Inanda	17	2019	Flood	KwaZulu-Natal	87	75	86	42	0,0773	3,98	3,12
Durban	41	2017	Storm	KwaZulu-Natal	113	-38	-34	42	0,0799	1,68	1,48
Johannesburg	41	2017	Storm	Gauteng	82	18	22	151	0,0007	1,79	0,72
Inanda	42	2017	Storm	KwaZulu-Natal	51	-27	-53	10	0,8318	1,71	1,96
Kempton Park	42	2011	Storm	Gauteng	21	17	85	12	0,1348	1,28	2,52
Johannesburg	1	2011	Flood	Gauteng	85	-5	-5	31	<0.0001	1,48	0,79
Durban	2	2011	Flood	KwaZulu-Natal	135	-40	-29	58	0,0180	2,45	1,51
Durban	46	2008	Storm	KwaZulu-Natal	113	-28	-25	54	0,0109	1,87	1,28
Durban	25	2008	Flood	KwaZulu-Natal	328	-178	-54	37	0,3030	4,36	2,42
Pinetown	27	2008	Flood	KwaZulu-Natal	23	-2	-7	10	0,7008	2,17	1,51
Durban	1	2009	Flood	KwaZulu-Natal	139	-64	-46	26	0,9264	2,29	1,29

Pretoria	4	2009	Heatwave	Gauteng	98	-38	-39	58	<0.0001	2,51	1,36
Johannesburg	4	2009	Heatwave	Gauteng	117	-7	-6	67	0,0412	1,88	2,02
Durban	4	2009	Heatwave	KwaZulu-Natal	150	-25	-16	59	0,6856	2,36	1,70
Johannesburg	46	2011	Heatwave	Gauteng	72	-12	-17	43	0,2096	1,21	0,89
Pretoria	46	2011	Heatwave	Gauteng	61	-40	-66	16	0,0144	2,01	0,87
Johannesburg	6	2018	Heatwave	Gauteng	143	27	19	98	0,0515	2,27	1,81
Pretoria	6	2018	Heatwave	Gauteng	103	23	23	62	0,8234	2,49	1,55
Gqeberha	33	2008	Coldwave	Eastern Cape	29	-24	-83	2	0,1831	2,15	1,15
Durban	35	2008	Coldwave	KwaZulu-Natal	237	-127	-54	43	0,0159	2,93	1,67
Johannesburg	36	2008	Coldwave	Gauteng	226	-101	-45	137	<0.0001	3,23	1,22
Gqeberha	21	2012	Coldwave	Eastern Cape	42	-13	-31	15	0,1089	3,74	2,13
Pretoria	46	2017	Coldwave	Gauteng	56	16	28	35	0,5330	1,83	2,90
Johannesburg	47	2017	Coldwave	Gauteng	65	-15	-23	83	<0.0001	1,20	0,50
Johannesburg	31	2016	Tornado	Gauteng	319	121	38	58	0,0002	3,94	5,93
Kempton Park	41	2011	Tornado	Gauteng	24	32	135	12	0,0081	1,40	2,67
Durban	47	2008	Tornado	KwaZulu-Natal	115	-70	-61	149	<0.0001	1,94	0,46

The results, detailed in Figure 2 and Table 2, consistently reveal no statistically significant relationships between medical health insurance claims and extreme climate events. While some events showed statistically significant associations, both positive and negative, there were no discernible trends or patterns regarding spatial or temporal clustering. For example, the flood in Pretoria in 2019 and the tornado in Durban in 2008 both show p-values well below 0.05, indicating statistically significant impacts on insurance claims for those specific weeks. However, when considering broader trends within groups of similar ECEs (like all floods or all heatwaves across multiple events and years), the data does not show consistent trends that reach statistical significance. This suggests that while individual events can have significant impacts, these effects do not uniformly manifest across all occurrences of the same type of ECE. These findings emphasize the complexity of the relationship between extreme climate events and medical health insurance claims, warranting further research and consideration for policy and healthcare planning (Figure 2). The comprehensive analysis presented provides valuable insights into the diverse impact of extreme weather events on the health insurance system.

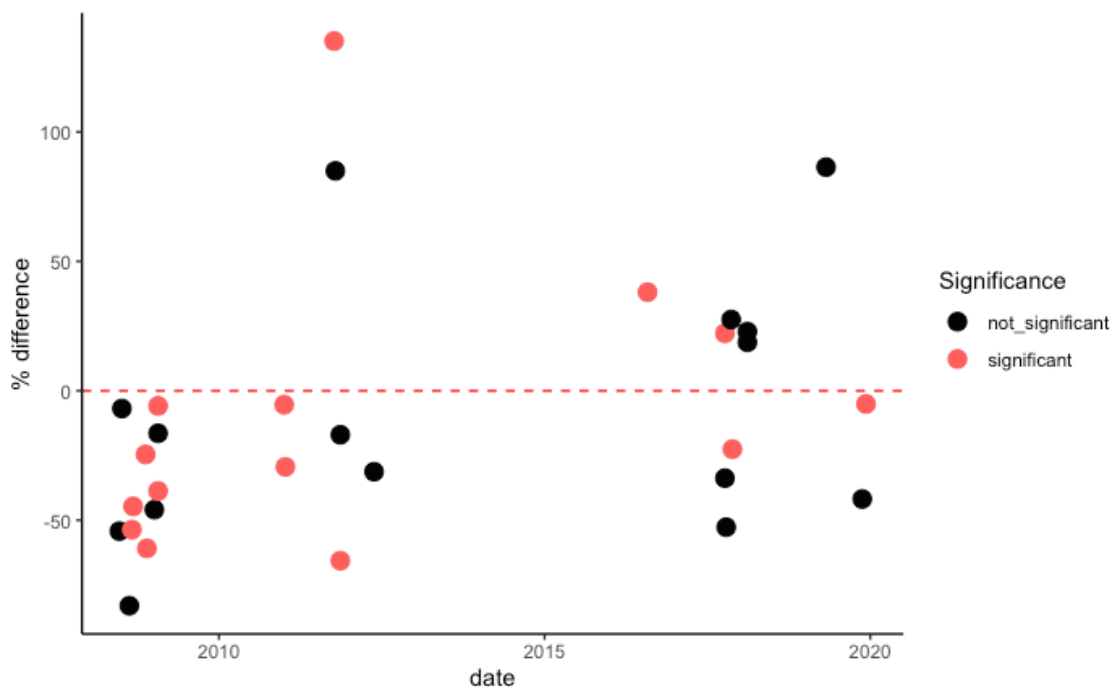


Fig. 2. Significance of ECEs in South Africa from 2008-2019 at a two-week lag period.

5. Discussion

a. Variations in Medical Claim Patterns Following Extreme Climate Events (ECEs)

The primary observation of this study is the consistent absence of statistically significant relationships between extreme climate events (ECEs) and fluctuations in medical health insurance claims, suggesting a more complex interplay of factors than initially hypothesized. This consistency points to the potential influence of other, as yet unexplored variables that may modulate the health outcomes of such climatic events (Table 2; Figure 2). This lack of consistency is evident as certain ECEs elicited noteworthy changes in respiratory disease claims, while others demonstrated negligible effects (Table 2; Figure 2). Furthermore, among the significant ECEs, disparate trends emerged, with both increases and decreases in claims recorded across different event types (Table 2; Figure 2). To understand the underlying factors of these results, we must investigate the diverse influences that ECEs may have on medical health insurance claims. To understand the underlying factors of these results, it is

important to consider how ECEs affect the practical aspects of seeking medical care. Extreme weather conditions, such as floodwaters or severe cold, can impede travel to healthcare facilities, influencing whether individuals decide to seek medical help during such times. This factor needs to be considered as it could suppress the number of claims despite potential increases in respiratory illnesses.

Firstly, ECEs engender transient alterations in local weather conditions, which can either augment or hinder the survival and transmission of respiratory viruses (Iwasaki and Pillai, 2014). For instance, certain ECEs, such as storms and floods, can heighten the risk of exposure to respiratory pathogens and allergens, consequently leading to escalated respiratory infections (Iwasaki and Pillai, 2014; von Gottberg et al., 2014). Conversely, cold temperatures during cold waves may foster the penetration of viruses into the respiratory system, owing to the provocation of dry and irritated airways (Leon-Gomes et al., 2015; Carmona et al., 2016). However, the variable impact of ECEs on local weather conditions and viral survivability may account for the observed divergences in medical health insurance claim patterns (Kovats et al., 2004).

Secondly, the response of medical health insurance claims to ECEs is also influenced by human behaviour and transient shifts in individual immunity (Kovats et al., 2004). During heatwaves, individuals tend to seek shelter indoors within air-conditioned environments, potentially culminating in escalated transmission rates in densely populated spaces (Gaillat et al., 2008). Conversely, flooding and the subsequent evacuation procedures may facilitate person-to-person contact and thereby contribute to the dissemination of influenza viruses (Kontowicz et al., 2022). These behaviour-related factors are contingent upon the severity and scale of

the ECE, thus contributing to the pronounced heterogeneity evident in medical health insurance claim responses (Killingley and Nguyen-Van-Tam, 2013). Furthermore, short-term changes in individual immunity following ECEs may play a role in the variation of respiratory disease claims. Severe weather events and the associated stressors may weaken the immune system, making individuals more susceptible to infections. However, the extent of this impact can vary depending on the baseline health status of the population and the overall healthcare infrastructure.

The complex interplay of meteorological variables, human behaviour, and individual immunity makes it challenging to predict the precise impact of ECEs on respiratory health outcomes. The observed variations underscore the influence of specific contextual factors on the relationship between ECEs and medical health insurance claims for respiratory diseases, as shown in Table 2 and Figure 2. Generalizing the impact of ECEs on respiratory disease claims may not be appropriate, as the effects can be counteractive and vary based on a myriad of interrelated factors (von Gottberg et al., 2014; Mendelson, 2020). For example, the time of the year, the presence of holidays, the scale of the ECE, the severity of the ECE, the level of infrastructural damage, and the baseline climate can all influence the responses observed. Additionally, different regions may exhibit more consistent responses to ECEs, and further research is needed to understand the reasons behind such variations (Booyesen, 2003; Busayo et al., 2022).

b. Implications for Respiratory Disease Preparedness

The findings of this study highlight the variability in the impact of extreme climate events (ECEs) on respiratory disease claims, reinforcing the assertion that seasonal patterns of respiratory illness exert a more significant influence than individual ECEs (Motlogeloa et al., 2023). Hence, healthcare initiatives should concentrate on managing the direct impacts of ECEs, such as heatstroke from heatwaves, hypothermia due to cold snaps, and injuries or fatalities from tropical cyclones (Campbell et al., 2018; Codjoe and Atiglo, 2020). While ECEs have a role in respiratory health outcomes, their effects are often eclipsed by the dominant seasonal patterns (Forshee-Hakala, 2015; Kimambo, 2018).

However, in the face of climate change, where shifts in mean climate conditions and an increase in the frequency and severity of ECEs are expected, it is imperative to continue monitoring their impact on respiratory health (Beniston and Stephenson, 2004). Climate change is projected to amplify both the occurrence and intensity of ECEs, potentially leading to novel interactions between weather patterns and respiratory pathogens (Guha-Sapir et al., 2016; Codjoe and Atiglo, 2020). Therefore, sustained surveillance and preparedness are essential to mitigate future risks to respiratory health.

The observed inconsistency in health insurance claim responses to ECEs underscores the complexity of factors such as meteorological conditions, human behavior, and individual immunity. This multifaceted, context-dependent relationship necessitates a sophisticated approach to understand and mitigate the impacts of ECEs on respiratory health. Despite the overarching influence of seasonal disease trends, it is crucial to maintain vigilance and tailor respiratory disease preparedness strategies to the evolving realities of climate change and

the increasing prevalence of ECEs (Iuliano et al., 2018; Tempia et al., 2019). A more profound comprehension of these dynamics will empower public health authorities to develop more effective responses to protect respiratory health during extreme climate occurrences

6. Conclusion

In conclusion, the results of this study underscore the complex dynamics between extreme climate events and the pattern of acute respiratory disease claims in South Africa.. While certain extreme climate events demonstrated statistically significant changes in respiratory disease claims, the overall analysis points to a lack of uniformity and consistency in their impact. Moving forward, it is evident that the seasonal impacts on respiratory health are much stronger and more consistent than the isolated effects of individual extreme events (Apraku et al., 2021; Rataj et al., 2016). Therefore, it is crucial for policy and public health interventions to prioritize seasonal preparedness rather than solely focusing on individual extreme events. Preparedness efforts should be geared towards addressing the cumulative impacts of seasonal variations, as these have a more substantial influence on respiratory health outcomes (Onuma et al., 2017). Incorporating strategies that consider the broader patterns and trends in weather and disease during specific seasons will enable more effective preparedness and response measures, ultimately mitigating the impact of extreme events on respiratory health (Curtis et al., 2017; Salimi and Al-Ghamdi, 2020; Fraser et al., 2022).

While this study provides valuable insights into the implications of extreme weather events on respiratory health in South Africa, it also underscores the importance of continued research and vigilance in addressing public health challenges posed by extreme weather

events in the context of a changing climate (Codjoe and Atiglo, 2020). By understanding the interplay of multiple factors and the significance of seasonality, authorities can develop proactive policies and guidelines aimed at protecting vulnerable populations and minimizing the health burden associated with acute respiratory diseases during extreme weather events (Apraku et al., 2021; Rataj et al., 2016). This study highlights that the impact of extreme weather events on respiratory health is complex and influenced by various factors. Seasonal preparedness and response strategies should be prioritized over a singular focus on individual events to promote better respiratory health outcomes in the context of climate change. The lessons from this research can contribute to building a more resilient healthcare system in South Africa, equipped to address the challenges posed by extreme weather events and safeguard the well-being of its population (Monirul Qader Mirza, 2003).

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Data Availability Statement.

Due to confidentiality agreements, supporting data can only be made available to bona fide researchers subject to a non-disclosure agreement.

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CHAPTER 7: ASSESSING THE IMPACT OF CLIMATIC VARIABILITY ON ACUTE RESPIRATORY DISEASES ACROSS DIVERSE CLIMATIC ZONES IN SOUTH AFRICA

7.1 Brief Synopsis

The publication "Assessing the Impact of Climatic Variability on Acute Respiratory Diseases Across Diverse Climatic Zones in South Africa" investigates the connection between climate variables (like temperature and rainfall) and the prevalence of acute respiratory diseases in Johannesburg, Cape Town, and Gqeberha. It uses Spearman's correlation analyses and the Distributed Lag Non-linear Model (DLNM) to explore this relationship. The findings indicate complex, non-linear influences of climate on respiratory health and emphasize the need for region-specific public health strategies in South Africa.

Author contributions:

Contributor role	Author contribution
Conceptualisation	Fitchett JM
Methodology	Motlogeloa O and Fitchett JM
Validation	Motlogeloa O
Formal analysis	Motlogeloa O
Investigation	Motlogeloa O
Resources	Motlogeloa O
Data Curation	Motlogeloa O
Writing – the original draft preparation	Motlogeloa O
Writing – review and editing	Motlogeloa O and Fitchett JM
Visualisation	Motlogeloa O
Supervision	Fitchett JM and Sweijd N
Project Leader	Fitchett JM

According to the above-mentioned CRediT system the author contribution was calculated as follows:

Motlogeloa O – 75%

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Assessing the impact of climatic variability on acute respiratory diseases across diverse climatic zones in South Africa

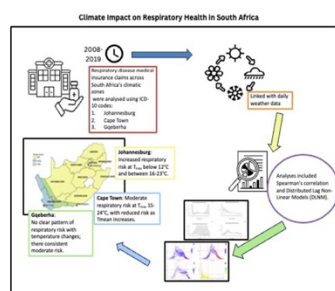
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HIGHLIGHTS

- Johannesburg: Elevated respiratory disease risk linked to extreme cold and moderate winter temperatures.
- Cape Town: Stable respiratory risk across a moderate temperature range; increased risk with extreme heat.
- Gqeberha: Indistinct temperature-respiratory disease relationship due to moderate climate with year-round rainfall.
- Spikes in claims are closely associated with relative changes in weather patterns, rather than specific absolute thresholds.
- There are complex, non-linear interactions between climate and respiratory health risks for South Africa.

GRAPHICAL ABSTRACT



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ABSTRACT

Acute respiratory diseases are a significant public health concern in South Africa, with climatic variables such as temperature and rainfall being key influencers. This study investigates the associations between these variables and the prevalence of acute respiratory diseases in Johannesburg, Cape Town, and Gqeberha (Port Elizabeth), representing distinct climatic zones. Spearman's correlation analyses showed negative correlations in Johannesburg for respiratory disease claims with maximum temperature ($r = -0.12$, $p < 0.0001$) and mean temperature ($r = -0.13$, $p < 0.0001$), and a negative correlation with daily rainfall ($r = -0.12$, $p < 0.0001$). Cape Town demonstrated a negative correlation with maximum temperature ($r = -0.18$, $p < 0.0001$) and a positive correlation with rainfall ($r = 0.08$, $p < 0.0001$). Utilizing Distributed Lag Non-linear Models (DLNM), the study revealed that in Johannesburg, the relative risk (RR) of respiratory claims increases notably at temperatures below 12°C , and again at a T_{max} between 16 and 23°C . The risk escalates further at $>30^{\circ}\text{C}$, although with a considerable error margin. For Cape Town, a stable level of moderate RR is seen from T_{max} 15 – 24°C , with a significant increase in RR and error margin above 30°C . In Gqeberha, the DLNM results are less definitive, reflecting the city's moderate climate and year-round rainfall. The RR of acute respiratory diseases did not show clear patterns with temperature changes, with increasing error margins outside the 22°C threshold. These findings emphasize the imperative for region-specific public health strategies that account for the complex, non-linear influences of climate on respiratory health. This detailed understanding of the climate-health nexus

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provides a robust basis for enhancing public health interventions and future research directed at reducing the impacts of climate factors.

1. Introduction

Acute respiratory diseases have a marked impact on public health globally, with pronounced effects in South Africa, where socioeconomic conditions heighten the vulnerability of a large proportion of the population (Cohen et al., 2015a, 2015b; Wright et al., 2021). The intricate relationships between acute respiratory diseases and various environmental factors, especially weather conditions, have been observed worldwide (Tempia et al., 2017). Understanding these associations at local scales is crucial as they offer valuable insights into the determinants of disease prevalence, and the variations across different regions (Cannell et al., 2006). Studies have underscored specific associations between climate variables like temperature and humidity and respiratory diseases, highlighting the crucial role of localized research in effectively understanding and addressing these health impacts within particular regions or communities (Fuhrmann, 2010; Motlogeloa et al., 2023). In South Africa, the substantial disease burden and economic costs attributed to acute respiratory diseases necessitate an in-depth understanding of these dynamics to develop effective public health strategies and interventions (Van Noort et al., 2012).

Globally, weather conditions over periods of days to weeks have been demonstrated to significantly influence the incidence and severity of acute respiratory diseases (Roussel et al., 2016). These climatic factors influence the viability of respiratory pathogens and human behaviour, both crucial determinants of respiratory health outcomes. Weather conditions significantly influence the incidence and severity of acute respiratory diseases through two main pathways. First, they affect pathogen survival and transmission by altering the environment in which pathogens thrive (Harlan and Ruddell, 2011). Second, varying weather conditions impact human susceptibility and exposure to these pathogens, as they influence human behaviour and immune system performance (D'Amato et al., 2014). Given the intricate nature of these relationships, an investigation is imperative for developing effective and precise public health interventions aimed at alleviating the burden of acute respiratory diseases (Takaro et al., 2013; Vega et al., 2015). Maximum, minimum, and mean temperatures ($T_{\max}$, $T_{\min}$ and T_{mean}), and rainfall, are vital meteorological parameters influencing the transmission and prevalence of acute respiratory diseases. (Roussel et al., 2016; Mirsaedi et al., 2016; Weaver et al., 2022). Changes in these weather variables can directly alter the transmission rates and viability of respiratory pathogens, thereby affecting disease incidence and severity within various populations (Patz et al., 2003). South Africa presents a complex climate system characterized by a variety of rainfall regions and seasonality patterns, further complicating the relationship between weather and acute respiratory diseases (Engelbrecht and Landman, 2016; Roffe et al., 2019). Three distinct rainfall seasonality zones have been identified, namely the Winter Rainfall Zone (WRZ), Summer Rainfall Zone (SRZ), and Year-Round Rainfall Zone (YRZ; Tyson and Preston-Whyte, 2000; Engelbrecht and Landman, 2016; Roffe et al., 2021). These zones, resulting from South Africa's unique geographical position, exhibit different weather patterns and hence possess distinct implications for the transmission of acute respiratory diseases (Pica and Bouvier, 2012; Engelbrecht and Engelbrecht, 2016).

In an exploration of the interplay between meteorological variables and respiratory diseases, global studies have revealed nuanced insights (Alahmad et al., 2019; Zhang et al., 2022; Dumanoglu et al., 2021; de Sousa et al., 2019; Liu et al., 2021; Cui et al., 2003; Zhang et al., 2021; Shen et al., 2010; Stojanovic et al., 2019). For instance, Alahmad et al. (2019) performed a case-crossover analysis in Saudi Arabia, revealing a higher likelihood for the coronavirus linked to severe respiratory symptoms, formerly known as Middle East Respiratory Syndrome, to

present predominantly under colder and drier conditions. Concurrently, studies emanating from China have underscored the susceptibility of paediatric populations to respiratory diseases amidst temperature extremes, elucidating a pronounced emphasis on the detrimental impacts of lower temperatures (Zhang et al., 2022; Liu et al., 2021).

Key meteorological variables, such as temperature, humidity, and air pollution metrics including PM10 and NOx concentrations, have been recurrently identified as pivotal influencers across these studies (Shen et al., 2010; Stojanovic et al., 2019; Cui et al., 2003; Dumanoglu et al., 2021; Liu et al., 2021). For instance, Dumanoglu et al. (2021) reported a nuanced interplay between weather parameters such as temperature and air pressure and the incidence of COVID-19 cases in Turkey. Furthermore, research from the Russian Far East has highlighted the modulation of immune responses in respiratory diseases by weather variations, thereby underscoring the intricate interplay between atmospheric conditions and respiratory health (Stojanovic et al., 2019).

The Distributed Lag Non-linear Models (DLNM) framework has been a crucial asset in epidemiological studies, enabling researchers to delve deeply into the intricate associations between environmental exposures, such as temperature and air pollution, and respiratory diseases (Bi et al., 2007; Alahmad et al., 2019; Chai et al., 2020). The DLNM is adept at capturing and modelling the nonlinear and delayed effects of these exposures, providing a comprehensive understanding of their impact on respiratory health outcomes over time (Gasparrini, 2011, 2014; Gao et al., 2023). Gasparrini (2011) utilized the DLNM to explore the exposure-response and lag-response associations, allowing for a detailed exploration of how health effects evolve over lagged times following exposure. For Lanzhou, China, the DLNM was applied to assess the effects of extreme temperatures on respiratory diseases, offering insights into temperature-related health risks (Meng et al., 2023). Another study, applied in São Paulo, Brazil, employed the DLNM to investigate the relationships between meteorological variables, air pollution, and paediatric respiratory disease hospitalizations, demonstrating the applicability of the model in various geographical and demographic contexts (de Sousa et al., 2019). Zhang et al. (2020a) applied the DLNM to explore the associations between sulphur dioxide exposure and respiratory disease hospitalizations in Ganzhou, China, highlighting its effectiveness in revealing relative risks essential for public health policy-making.

Through exploring univariate linear relationships and applying the DLNM, this study aims to illuminate the lagged and nonlinear relationships between maximum, minimum, and mean temperatures, rainfall, and the incidence of acute respiratory diseases in different climatic zones across South Africa. The insights garnered will be instrumental in informing targeted public health interventions, crafting climate-resilient healthcare strategies, and developing policy frameworks for mitigating acute respiratory diseases across various climate zones in South Africa.

2. Material and methods

2.1. Study site

South Africa, with coordinates ranging from 22 to 35°S in latitude and 16–33°E in longitude, covers an area of about 1,220,000 km² and exhibits a variety of climates due to its geographical diversity (Landman et al., 2017). The country is positioned where subtropical and mid-latitude climates converge, resulting in different rainfall patterns such as the Summer Rainfall Zone (SRZ) and Winter Rainfall Zone (WRZ; Fitchett and Bamford, 2017; Sousa et al., 2018; Roffe et al., 2021). These patterns are influenced by the seasonal latitudinal displacement of the

Intertropical Convergence Zone (ITCZ) and the Southern Hemisphere Westerlies (Lennard, 2019; Landman et al., 2017; Roffe et al., 2021).

The study focuses on three cities: Johannesburg, Cape Town, and Gqeberha (formerly Port Elizabeth), each with distinct climatic characteristics (Fig. 1). Johannesburg, located in the north-eastern part of South Africa, experiences a subtropical highland climate, characterized by dry winters and rainy summers (Crétat et al., 2012). Cape Town, situated in the southwestern part, has a Mediterranean climate with mild, wet winters and warm, dry summers (Favre et al., 2016). Gqeberha, on the south-eastern coast, experiences an oceanic climate, receiving a more evenly distributed rainfall throughout the year (Roffe et al., 2019). These cities were selected to represent different climatic conditions in South Africa, providing a diverse range of environments to study the impact of weather on acute respiratory diseases. The focus on cities relates to the data requirements to run the DLNM, which would not be met for smaller towns.

2.2. Data sources

2.2.1. Medical insurance scheme claims

The study utilized data from the Discovery Health Medical Scheme (DHMS), South Africa's leading private medical insurance provider, which covers approximately 3.3 million clients. DHMS has a comprehensive database of medical claims, each classified by an International Classification of Diseases ICD-10 code corresponding to the diagnosed condition (Hohl et al., 2014). These codes are assigned by medical practitioners based on patient symptoms during consultations, often without the need for laboratory confirmation (Stausberg and Hasford, 2010). For our analysis, we focused on claims linked to ICD-10 codes for acute respiratory diseases: J00 (acute nasopharyngitis), J110 (influenza with pneumonia), J111 (influenza with other respiratory manifestations), and J118 (influenza with other manifestations). While the dataset

spans claims from 2008 to 2019, our study specifically targeted claims from Johannesburg (28,114), Cape Town (11,372), and Gqeberha (3898) to represent three distinct rainfall zones. Claims from smaller regions within these cities, such as spatially contiguous but discretely named suburbs, were aggregated to provide a holistic view of the data for each city.

2.2.2. Meteorological data

Daily resolution meteorological data were sourced from the South African Weather Services for the period 2008–2019. The dataset included daily maximum, minimum, and mean temperatures (T_{max} , T_{min} , T_{mean}), and rainfall, recorded at ground-based meteorological stations located in Johannesburg, Cape Town, and Gqeberha. During the data cleaning process, the initial step involved exploratory data analysis, checking for inconsistencies, errors, and outliers in the dataset, ensuring that the data were accurate and reliable for analysis. The data were then processed to manage missing values. In cases where data were missing, various imputation methods could be applied, such as mean imputation or interpolation, to maintain the dataset's integrity and usability (Ding et al., 2010). We employed imputation methods best suited to the characteristics of the missing data, selecting the most appropriate technique based on the proportion and the observed pattern of the missing values (Scheffer, 2002). The cleaned and processed meteorological data were then added to the database containing the medical aid claims data, ensuring consistency and accuracy in the temporal matching of the two datasets.

3. Data analysis

Integrating the meteorological and claims data, Spearman's correlation coefficients were calculated to identify simplistic linear correlations between meteorological variables and occurrences of acute

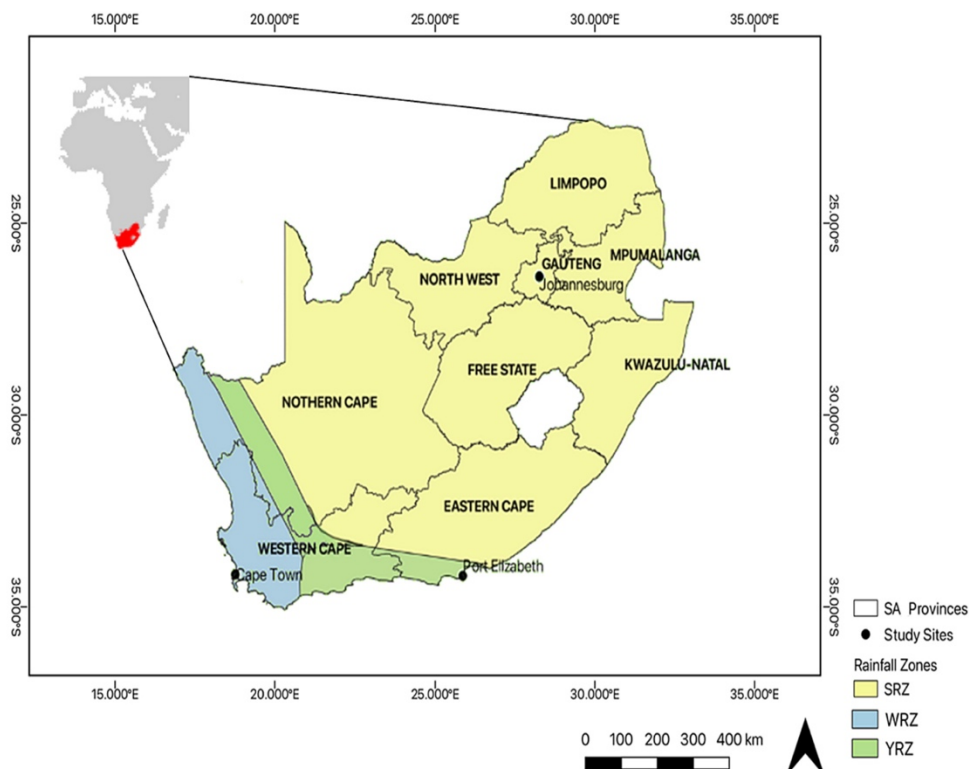


Fig. 1. Spatial distribution of rainfall season zones (Roffe et al., 2019) across South Africa with locations of Cape Town, Johannesburg and Gqeberha.

respiratory diseases (Pica and Bouvier, 2012; Jackson et al., 2021; Motlogelo et al., 2023) in Johannesburg, Cape Town, and Gqeberha. Scatter plots were produced to graphically represent the distribution of acute respiratory disease incidences in relation to temperature and precipitation data. Points exceeding two standard deviations from the mean were marked to denote significant anomalies from expected values, indicative of potential extreme weather effects on health outcomes.

Subsequently, a time series quasi-Poisson regression and the DLNM were applied using the 'dlnm' package in R. In the DLNM, a quadratic B-spline was used for temperature, and a natural cubic spline was applied for the lag-response curve (Gasparrini and Leone, 2014; Zhao et al., 2018). The model was adjusted for time-varying confounders such as weekdays and holidays. Following the approach by Zhao et al. (2018), three degrees of freedom were assigned to exposure variables within the model, and a maximum lag of fourteen days (0–14 days) was incorporated to assess the meteorological impacts on respiratory disease-related claims in each city (Ozeki et al., 2015; Motlogelo et al., 2023), which are delayed from infection by the period of incubation of the disease, the onset and worsening of symptoms, and delays in accessing healthcare (Lessler et al., 2009).

The output from the DLNM was primarily focused on the relative risk of acute respiratory diseases associated with meteorological variables. This approach is consistent with several studies that have utilized the DLNM outputs to assess and visualize the relative risks associated with environmental exposures (Armstrong et al., 2014; Phung et al., 2016). The relative risks were plotted against each meteorological variable to provide a clear representation of the associations between weather variables and the likelihood of respiratory disease occurrences, facilitating a nuanced interpretation of the potential health risks posed by varying meteorological conditions (Zhang et al., 2016; Sera et al., 2019). Recent applications of DLNM in the field (Li et al., 2023; Crank et al., 2023; Lam et al., 2024) support its continued relevance and suitability for our study. The DLNM is calculated by:

$$RR = \exp \left(\alpha + CB_{min_temp}(T_{min}, t, lt) + CB_{max_temp}(T_{max}, t, lt) + CB_{mean_temp}(T_{mean}, t, lt) + C_{Brain}(Rt, lt) + \gamma_1 \cdot \text{Weekday} + \gamma_2 \cdot \text{Holiday} + NS(\text{Time}, df) + \epsilon \right)$$

where:

- **RR:** Relative Risk. This is the outcome of interest, often representing the risk of an event (like respiratory disease) occurring. In the context of the model, it's the expected count of the outcome given the predictors, relative to a baseline count.
- **exp():** Exponential function. It's used to ensure that the model's predictions are positive, as counts cannot be negative. This is the link function for the quasi-Poisson regression model.
- **α :** Intercept. This is the log-relative risk when all predictors are at their reference levels (typically zero for continuous variables).
- **B:** Cross-basis function. This is used to model the relationship between a predictor (like temperature or rainfall) and the outcome across different lags. It's a combination of two functions: one for the relationship at each time point (like a B-spline) and one across lags (like a natural cubic spline).
- **$T_{min}, t, T_{max}, t, T_{mean}, t$:** These represent the minimum, maximum, and mean temperature values at time t , respectively.
- **Rt :** This represents the rainfall value at time t .
- **lt :** Lag time at time t , indicating how many days in the past the model looks to assess the effect of temperature and rainfall on the current risk.
- **γ_1, γ_2 :** Coefficients for categorical variables. These are the parameters estimated for the effects of weekdays and holidays, respectively.
- **$\cdot$:** Multiplication sign. It's used to indicate that the coefficient (like γ_1) multiplies the predictor (like Weekday).

- **NS(Time, df):** Natural spline function of time with a specified degree of freedom. This is used to control for time-varying confounders and trends that are not captured by other variables in the model.
- **ϵ :** Error term. It accounts for the variation in the outcome that is not explained by the model.
- **+**: Plus sign. It's used to indicate that terms are added together in the model.

4. Results

In Johannesburg, the average daily maximum summer temperature registered at 27.19 °C, and the winters, while wettest, reached up to 171.09 mm of rain per day, which is less than expected for a summer rainfall zone (Fig. 2a). Cape Town, however, exhibited a daily maximum summer average of 27.34 °C and a cooler winter daily maximum average of 19.84 °C, with the highest rainfall in summer, not winter, averaging 171.46 mm per day, challenging the typical Mediterranean climate pattern (Fig. 2b). Gqeberha experienced minor temperature fluctuations year-round — the summer and winter daily maximum averages were 26.09 °C and 20.59 °C, respectively, with a more uniform rainfall distribution, peaking at 29.77 mm in winter (Fig. 2c). These findings illustrate the distinct climatic dynamics within South African regions, as influenced by their specific geographical and topographical features (Fig. 2).

4.1. Correlation between meteorological variables and respiratory disease claims

Spearman's correlation coefficients (Table 1) reveal relatively weak, but statistically significant, linear univariate relationships between meteorological variables and acute respiratory disease claims across Johannesburg, Cape Town, and Gqeberha. T_{max} and T_{mean} consistently show statistically significant negative correlations with disease claims across all cities, with coefficients ranging from $r = -0.10$ to $r = -0.18$ ($p < 0.0001$). Conversely, T_{min} displays varied associations; a weak but statistically significant positive correlation is observed in Johannesburg $r = 0.10$, $p < 0.0001$, while in the other two cities analyzed, the relationships are either slight or statistically insignificant (Table 1). An interesting observation is the decrease in respiratory disease risk with colder T_{min} , necessitating further exploration (Table 1). Daily rainfall correlations also vary, with significant relationships observed in some cities, such as Johannesburg and Cape Town, and non-significant correlations in others like Gqeberha (Table 1).

4.2. Meteorological influences on acute respiratory diseases

The second stage of analysis explores non-linear relationships between meteorological variables and medical aid claims, exploring the distribution of total claims at each given temperature or daily total rainfall amount. In Johannesburg, the highest number of claims are recorded from at a T_{max} of 18–23 °C, T_{min} of 3–8 °C, and T_{mean} of 11–15 °C (Fig. 3), meteorological conditions which dominate during the winter season and during autumn, spring and early summer season cold snaps associated with cut-off low systems. The rainfall data (Fig. 3d) exhibit a right-skewed distribution, due to the large number of days with no rainfall in Johannesburg; with many dry days and no clear increase in claims on days with higher rainfall totals or extreme events.

In Gqeberha, the largest number of claims are recorded for T_{max} of 17–24 °C, T_{min} of 5–13 °C, and T_{mean} of 12–18 °C, again consistent with conditions during the winter season, and cooler conditions during the autumn and spring (Fig. 4). For rainfall, although the data remain right skewed, there is a greater variation in rainfall totals associated with heightened claims. This is likely due to the position of Gqeberha in the year-round rainfall zone, where the winter months are not characterized by an absence of rainfall that is common in Johannesburg.

For Cape Town, the peak in respiratory disease claims is associated

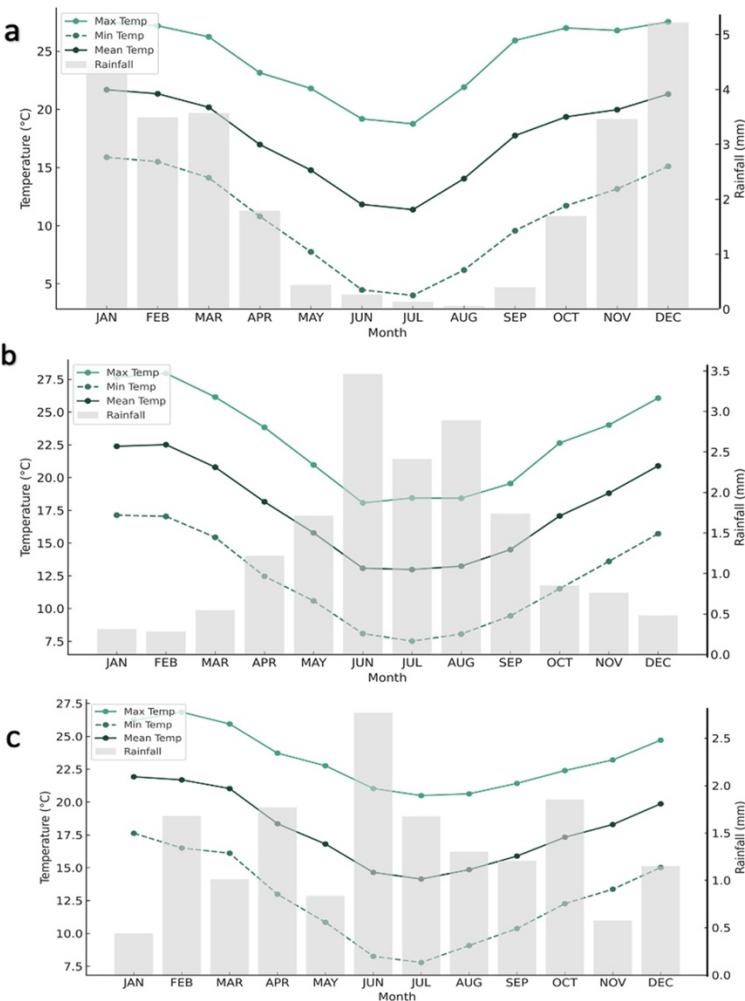


Fig. 2. Comparative monthly climate trends – Illustration of the monthly variations in temperature and rainfall for Johannesburg (a), Cape Town (b), and the Gqeberha(c) in South Africa.

Table 1
Spearman correlation coefficients and *P*-values for weather variables and medical insurance claims in Johannesburg, Cape Town, and Gqeberha.

City	Variable	Correlation (<i>r</i>)	<i>P</i> -value
Johannesburg	T_{max}	−0.12	$p < 0.0001$
	T_{min}	0.10	$p < 0.0001$
	Daily Rainfall	−0.12	$p < 0.0001$
	T_{mean}	−0.13	$p < 0.0001$
Cape Town	T_{max}	−0.18	$p < 0.0001$
	T_{min}	0.02	0.1836
	Daily Rainfall	0.08	$p < 0.0001$
	T_{mean}	−0.17	$p < 0.0001$
Gqeberha+	T_{max}	−0.10	$p < 0.0001$
	T_{min}	0.02	0.4428
	Daily Rainfall	−0.01	0.8743
	T_{mean}	−0.13	$p < 0.0001$

with T_{max} ranging from 18 to 2215 °C, T_{min} ranging from 5 to 14 °C, and T_{mean} from 12 to 16 °C (Fig. 5), again characteristic of the winter months. In Cape Town, the analysis of rainfall data reveals a wider spread in the volume of rainfall compared to Gqeberha and

Johannesburg. This aligns with Cape Town's winter rainfall climate, where periods of higher rainfall coincide with lower temperatures. The seasonal temperature shifts and their impact on medical claims highlight the need for a non-linear statistical model that accounts for lag time between weather exposure and claims. Hence, the DLNM is applied to dissect these intricate relationships further.

4.3. Nonlinear associations between meteorological variables and acute respiratory disease incidence

The outputs of the DLNM do not dispute the broad relationships between meteorological variables and medical aid claims for acute upper respiratory disease demonstrated previously, but provide more nuanced non-linear reflections in light of the influence of lags and influencing periods such as holidays. In Johannesburg, the relative risk (RR) of respiratory claims increases significantly at T_{max} below 12 °C, which corresponds to extremely cold events. There is also a notable peak in RR at T_{max} between 16 and 23 °C, aligning with typical winter daytime temperatures. Above 30 °C, the RR increase is less certain, as indicated by a larger error margin (Fig. 6a). T_{min} shows the highest RR

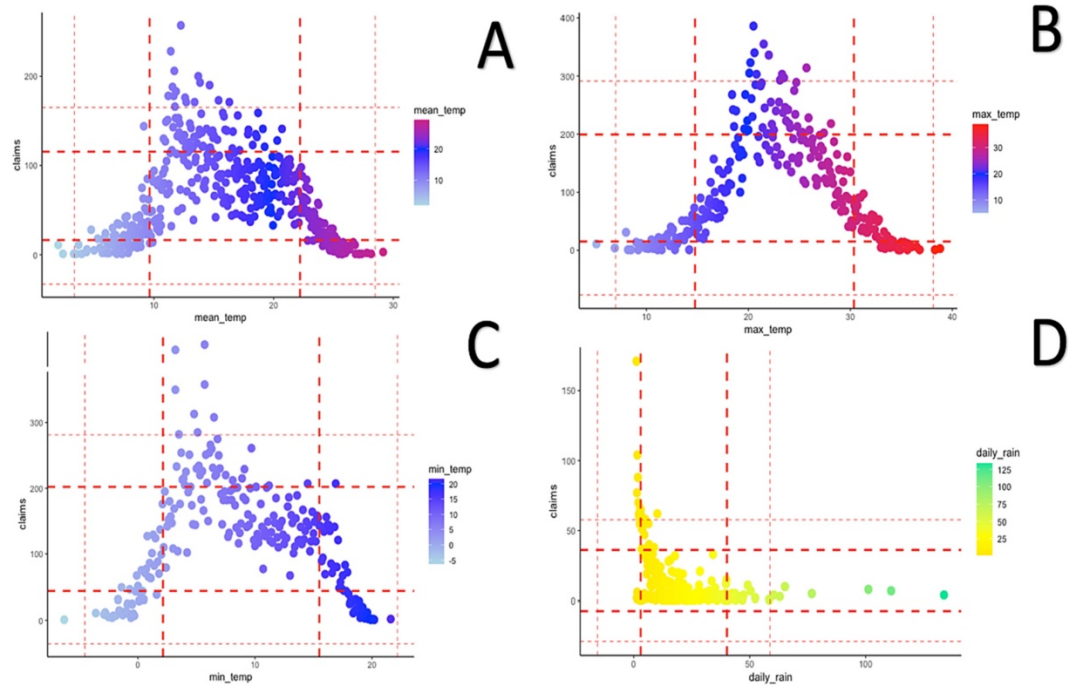


Fig. 3. Acute respiratory claims plotted against daily a) mean temperature, b) maximum temperature, c) minimum temperature and d) daily rainfall in Johannesburg, South Africa. The thick red bars indicate one standard deviation from the mean and the thin red bars indicate two standard deviations from the mean.

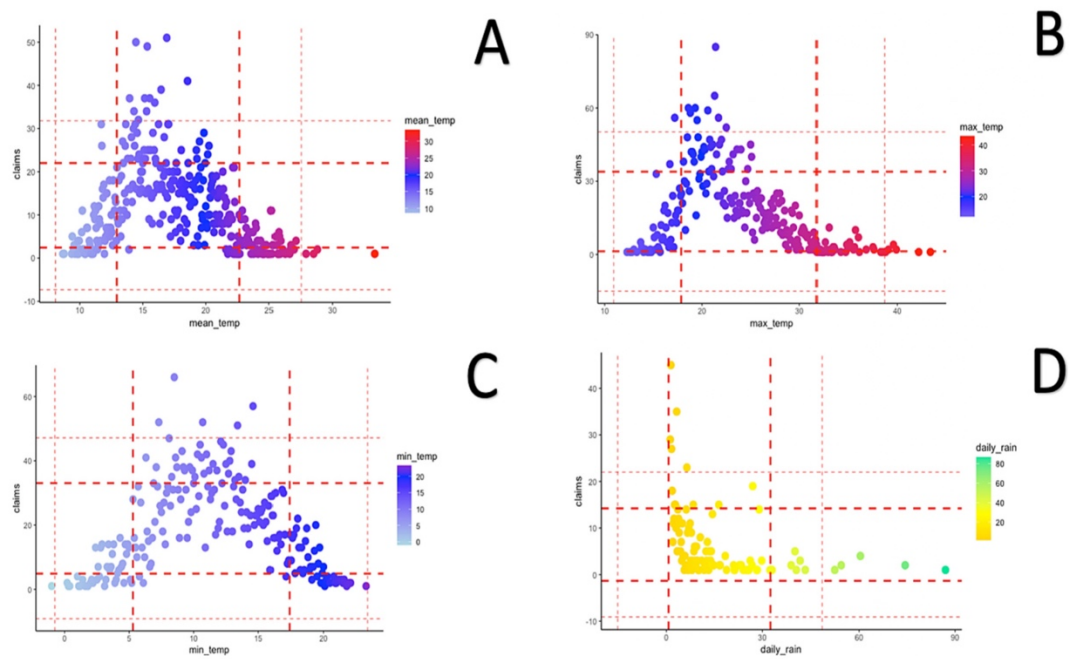


Fig. 4. Acute respiratory claims plotted against daily a) mean temperature, b) maximum temperature, c) minimum temperature and d) daily rainfall in Gqeberha, South Africa. The thick red bars indicate one standard deviation from the mean and the thin red bars indicate two standard deviations from the mean.

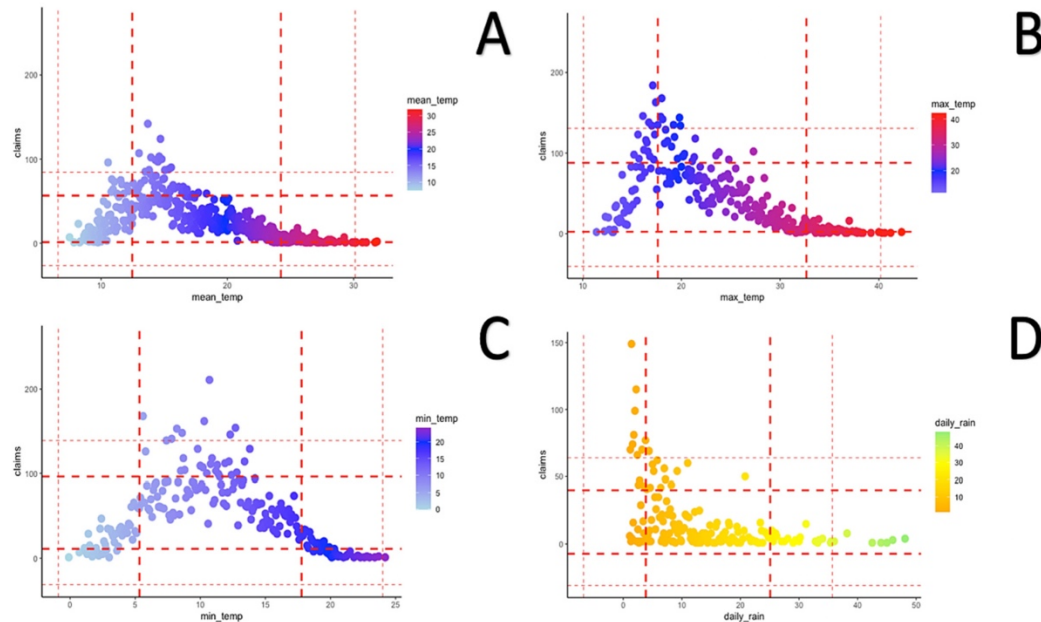


Fig. 5. Acute respiratory claims plotted against daily a) mean temperature, b) maximum temperature, c) minimum temperature and d) daily rainfall in Cape Town, South Africa. The thick red bars indicate one standard deviation from the mean and the thin red bars indicate two standard deviations from the mean.

between 0 and 5 °C, and it tapers off in very low temperatures unusual for Johannesburg or above 12 °C, common in warmer seasons (Fig. 6d). T_{mean} indicates a decrease in RR with rising temperatures, suggesting lower risk at warmer average temperatures (Fig. 6b). Rainfall RR exhibits high variability, with a possible increase around 60 mm daily rainfall (Fig. 6c).

For Gqeberha, the results of the DLNM provide a less clear indication of the key meteorological conditions associated with a heightened risk of acute upper respiratory disease. This may be as a result of the year-round rainfall conditions at the city, and the relatively moderate seasonal temperature range as a result of the proximity to the Indian Ocean and warm Agulhas current. There is no discernible change in the RR of acute respiratory diseases with increases (or decreases) in T_{max} , although notably there are rapidly increasing levels of the error margin of the model above and below 22 °C (Fig. 7a). For T_{min} , the DLNM suggests a heightened risk between temperatures of 16–18 °C, although importantly this is coupled with a considerable error margin. The error margin is lowest for a moderate level of risk from 3 to 12 °C. For T_{mean} , the peak in RR is similarly associated with the greatest error margin; the lowest error margin is associated with a moderate level of risk at ~17 °C (Fig. 7b). As for temperature, the modelled peaks in risk for rainfall coincide with the greatest error margins. Overall, for Gqeberha, no definitive patterns in the risk of meteorological conditions can be determined using the DLNM, likely due to the suppressed seasonality in both temperature and rainfall for the city.

For Cape Town, a similar pattern in RR is modelled for T_{mean} as for Johannesburg: as T_{mean} increases, the RR of acute respiratory disease claims decreases (Fig. 8). For T_{max} , RR increases to a relatively stable level of moderate risk from 15 to 24 °C. As for Johannesburg, at >30 °C there is an increase in RR, but this is associated with a very large error margin, a function of the rarity of these extreme temperatures. For T_{min} , the relative risk remains relatively constant, with a small increase between 5 and 10 °C, and similar to the hotter T_{max} , an increase in the margin of error from $T_{\text{min}} > 18$ °C (Fig. 8a). In the Johannesburg and

Gqeberha regions, relative risk (RR) analysis for rainfall-related respiratory claims indicates increased uncertainty. However, there's a discernible uptick in claim risk at rainfall levels of 5–20 mm/day. The confidence in the model's predictions is higher for daily rainfall amounts of 0–5 mm and 25–32 mm, as reflected by the lower error margins in these ranges (Fig. 8c).

In this study, Distributed Lag Non-linear Models (DLNM) were applied to explore the associations between meteorological variables and the RR of acute respiratory diseases. Traditional correlation methods suggest a negative correlation between T_{max} and disease incidence. However, the DLNM analysis provides a more detailed depiction, revealing variations and complexities not captured by simple correlation coefficients. The DLNM approach unveils specific temperature and rainfall thresholds associated with changes in RR, emphasizing that a simplistic correlation may not adequately represent the relationships within extensive datasets (Gasparrini, 2011; Armstrong et al., 2014). Utilizing the DLNM for analysis facilitates a more comprehensive understanding of the data, allowing for more accurate public health interpretations and strategies based on the diverse environmental influences present in extensive meteorological and health datasets.

5. Discussion

5.1. Meteorological impact on acute respiratory diseases

Our analysis delves deeper into the associations between climate and respiratory illness across three distinct South African climatic zones. In Cape Town, the colder and wetter winter conditions appear to correlate with increased respiratory disease claims, a pattern consistent with global findings. Johannesburg's cold but drier winters suggest a different interaction between temperature and moisture in disease prevalence. Gqeberha presents a unique case with its year-round rainfall, which may dilute the pronounced seasonal effect seen in other regions.

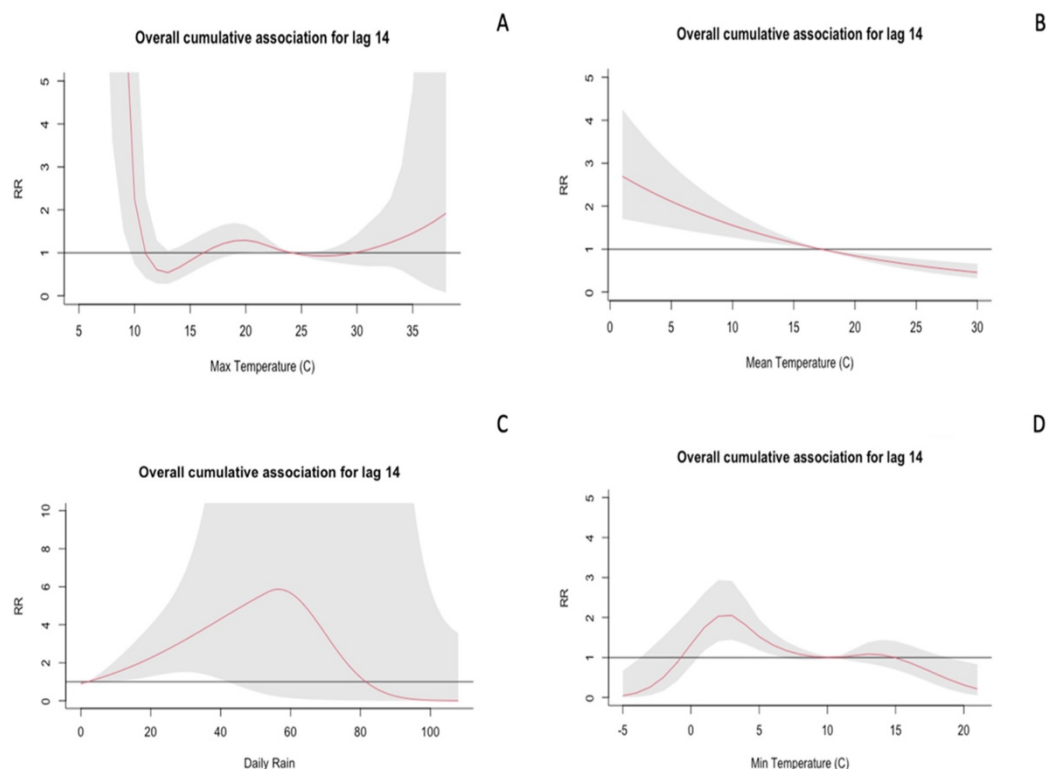


Fig. 6. Johannesburg relative risk for acute respiratory disease medical insurance claims at, a) maximum temperature, b) mean temperature, c) daily rain and d) minimum temperature over a 14-day lag.

The relatively consistent temperature across the zones contributes to subtler variations in disease prevalence than anticipated, underscoring the complex interplay of climate factors. The consistent temperature ranges across these zones, coupled with their distinct rainfall patterns, suggest that regional adaptations in public health strategies are necessary. Further examination of these complex relationships is warranted, considering local environmental and social factors that may modulate these associations.

Understanding the meteorological influences on acute respiratory diseases is essential for effective public health planning and interventions (D'Amato et al., 2015; Liu et al., 2020). Global research has demonstrated various temperature and rainfall ranges that influence the local risk of respiratory diseases (Takaro et al., 2013; Nsoesie et al., 2014; Zhang et al., 2020b; Ma et al., 2022). In winter rainfall zones, such as those studied in parts of Australia and the Mediterranean, a rise in respiratory diseases has been observed during colder and wetter conditions (Ebi and Forsberg, 2009; Rocklöv et al., 2014). This holds true for Cape Town, South Africa, where the distribution of climatic conditions and claims reveal that colder conditions and relatively wet conditions are associated with the heightened risk of acute upper respiratory disease claims (Thraustarson et al., 2017). In Johannesburg, a summer rainfall zone, cold temperatures and lower rainfall conditions are found to be associated with the highest risk of claims for respiratory diseases (Javanian et al., 2021; Kronfeld-Schor et al., 2021). For Gqeberha, a less distinct relative risk distribution is modelled, likely a function of the year-round rainfall, and less pronounced seasonal temperature differences. The subtleties in respiratory disease prevalence across South Africa's diverse climatic zones were less pronounced than expected,

possibly due to the relatively consistent temperature ranges experienced across these regions that are distinguished primarily by their differences in rainfall seasonality (Philippon et al., 2012; Favre et al., 2016; Roffe et al., 2019). The analysis within our manuscript focuses on temperature and its correlation with respiratory disease prevalence. While rainfall was included in our evaluation, the data did not exhibit a strong correlation independent of temperature variations. We have not analyzed the impact of air pollutants due to the unavailability of consistent, region-wide data for the period of our study.

Our study provides a comprehensive analysis of the intricate relationship between various weather variables and the transmission dynamics of respiratory viruses, particularly influenza, in South Africa. The findings reveal that rather than extreme climatic conditions, it is the subtle interplay between temperature and humidity that significantly influences the prevalence and transmission patterns of these viruses (Pica and Bouvier, 2012). The virus appears to thrive during the weather conditions commonly experienced in winter, and during colder weeks in autumn and spring (Motlogeloa et al., 2023). This revelation is instrumental in redefining our approach towards influenza preparedness and response strategies, emphasizing the need for pre-emptive measures ahead of the identified high-risk periods (Fuhrmann, 2010).

5.2. Public health implications

A multifaceted public health approach, considering the various influences on respiratory disease prevalence (Shea et al., 2008), is supported by the findings of this study. A generalized seasonal strategy, rather than a focus on specific meteorological thresholds, appears more

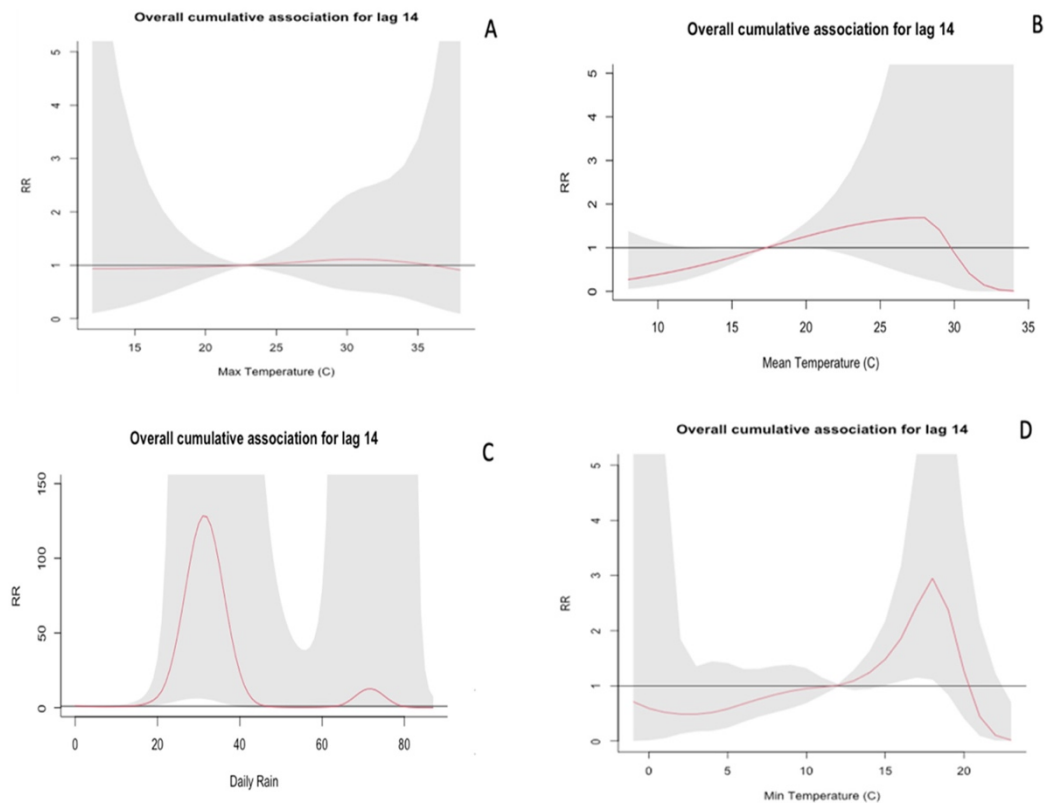


Fig. 7. Gqeberha relative risk for acute respiratory disease medical insurance claims at a) maximum temperature, b) mean temperature, c) daily rain and d) minimum temperature over a 14-day lag.

pragmatic due to the complex interplay between temperature, rainfall, humidity, and societal behaviours (Nsoesie et al., 2014; Jackson et al., 2021; Bi et al., 2007). The study underscores the significance of rainfall in influencing respiratory disease cases, suggesting a proactive public health stance during periods of increased rainfall (Motlogelo et al., 2023; Treanor, 2016). Given the newfound understanding of the timing of influenza peaks, there is a pressing need to rethink and optimize vaccination strategies. The initiation of vaccination campaigns should be recalibrated to precede the early autumn period, which has been identified as a conducive environment for influenza transmission (Treanor, 2016). Such a proactive approach in administering vaccines could bolster community immunity, reduce susceptibility, and curtail the spread of the influenza virus (Tempia et al., 2017). Our findings underscore the imperative of developing adaptive public health strategies that resonate with the prevailing weather patterns conducive to the transmission of respiratory viruses (Watts et al., 2015). This involves a meticulous tailoring of various public health interventions, such as vaccination schedules, public health messaging, and the allocation of healthcare resources, to align with the nuanced weather patterns identified in the study (Shea et al., 2008). This study underscores the pivotal role of routine weather patterns in shaping the transmission dynamics of respiratory viruses in South Africa. It advocates for a re-evaluation and recalibration of existing public health strategies, particularly vaccination campaigns, to align more closely with the identified weather patterns. Such alignment could enhance the efficacy of preventive measures, fostering a more resilient community against the onslaught of respiratory viruses, including influenza. In light of the forecasting limitations, we propose a flexible vaccination strategy that incorporates short-term weather predictions, enabling rapid response to forecast

cooler and wetter conditions, which are conducive to increased respiratory diseases. This insight necessitates a paradigm shift in our preparedness and response strategies, advocating for a more nuanced and weather-aligned approach to mitigate the impact of respiratory viruses, particularly influenza (Weaver et al., 2022).

6. Conclusion

In conclusion, this study clarifies the relationships between meteorological variables and the prevalence of claims for acute respiratory diseases in major South African cities. The findings are instrumental for enhancing public health planning and interventions, particularly in the unique context of a developing country like South Africa (Thrustarson et al., 2017). Our study reveals that temperature and rainfall variations in Johannesburg, Cape Town, and Gqeberha influence the patterns of respiratory disease claims, aligning with global research that indicates a correlation between meteorological variables and respiratory diseases (Javanian et al., 2021; Kronfeld-Schor et al., 2021). The insights derived from this study are pivotal for developing targeted communication strategies, early warning systems, and vaccination campaigns that are sensitive to the unique climatic and epidemiological profiles of each city (Motlogelo et al., 2023; Nsoesie et al., 2014).

Strategic public health communication, based on the identified temperature and rainfall thresholds, can facilitate better preparedness and response to seasonal variations in respiratory diseases (Bi et al., 2007; Treanor, 2016). Tailoring these strategies to the specific needs and contexts of each city will enhance their effectiveness and relevance, ensuring a more resilient healthcare system and improved public health outcomes in the face of varying meteorological conditions (Jackson

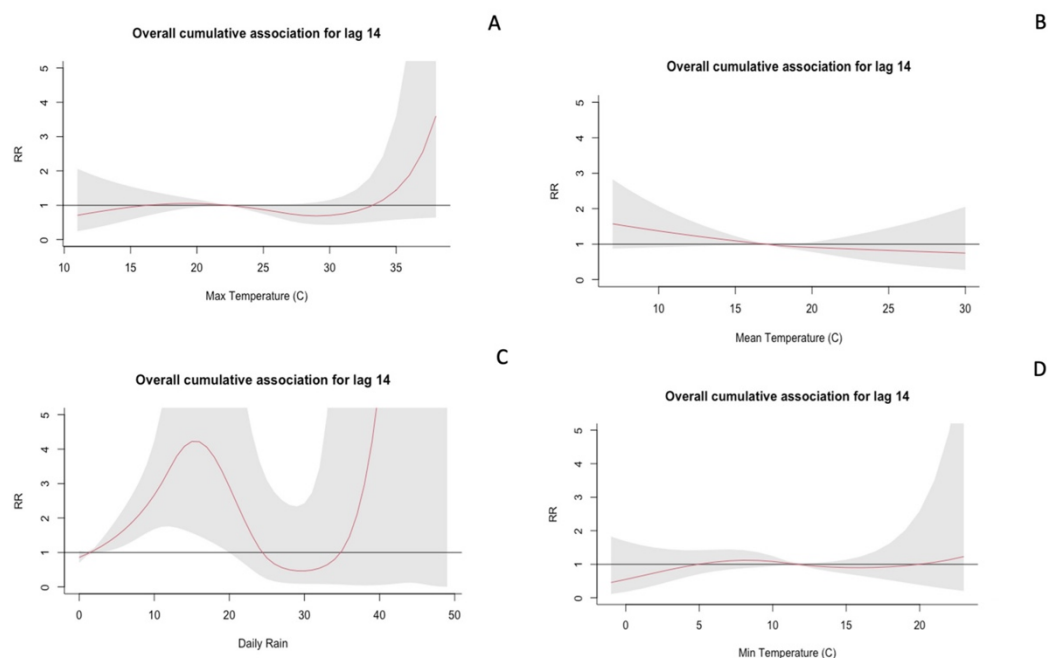


Fig. 8. Cape Town relative risk for acute respiratory disease medical insurance claims at a) maximum temperature, b) mean temperature, c) daily rain and d) minimum temperature over a 14-day lag.

et al., 2021). In light of these findings, it is essential to continue exploring and understanding the multifaceted impacts of meteorological variables on health, to inform more nuanced and effective public health strategies and interventions in various geographical and climatic contexts.

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Research ethics

Ethics clearance was obtained from the Witwatersrand Human Medical Research Ethics Committee, clearance number M210617. Authorization for data acquisition was obtained by DHMS. Data from Baragwanath Hospital were collected under the Respiratory and Meningeal Pathogens Research Unit's database compiled for the study "Surveillance on pathogen-specific causes of pneumonia and diarrhoea hospitalization in children" HREC reference no: 131109.

CRedit authorship contribution statement

Ogone Motlogeloa: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Jennifer M. Fitchett:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

We declare that the authors have no competing interests, financial or otherwise.

Data availability

The data that has been used is confidential.

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CHAPTER 8: DISCUSSION

8.1 Introduction

The nexus between climate and respiratory health forms a critical focus within health biometeorology, particularly in the climatically diverse context of South Africa (Wright et al., 2021). This discipline, situated at the intersection of atmospheric science and public health, offers invaluable insights into how weather and climate variations impact human health, especially concerning respiratory conditions that exhibit clear seasonality and variability (Smit et al., 2020). South Africa, with its wide range of climates from the Mediterranean in the southwest to subtropical in the northeast, provides a unique natural laboratory for studying these dynamics (Lennard, 2019).

The initial aims and objectives of this research were to uncover the nuanced ways in which climatic factors influence the incidence and severity of respiratory diseases in South Africa (Engelbrecht et al., 2015). By applying specific intensity thresholds and conducting a comprehensive examination of regional data, this study aimed to illuminate the complex, heterogeneous climatic influences across various provinces (Lazenby et al., 2014). These efforts are particularly critical in light of the socio-economic disparities that exacerbate health vulnerabilities in the region (Maphumulo and Bhengu, 2019).

Through the methodology adopted, this thesis has distilled insights from extensive research into the seasonality and variability of respiratory diseases, moving beyond mere epidemiological statistics to a nuanced understanding of the complex relationships between climate and public health outcomes (Tempia et al., 2017). It has critically examined the

interplay between meteorological conditions and the prevalence of respiratory ailments, highlighting the importance of integrating meteorological data with health surveillance for effective public health strategies (Meerhoff et al., 2004).

This discussion begins by reviewing the aims and objectives of the research, critically evaluating the methodology for its ability to comprehensively capture the complex dynamics at play. Furthermore, the analysis of the results will be contextualized within the wider framework of their implications for policy formulation and healthcare planning (Landman et al., 2017). This section aims to provide a concise yet thorough analysis, setting the stage for subsequent research and policy formulation that addresses the multifaceted challenges of climate and respiratory disease dynamics in South Africa. The ultimate goal is to contribute to a body of knowledge that supports more resilient and adaptive health systems in the face of climatic uncertainties.

8.2 Seasonality of Respiratory Diseases: Global to Local Perspectives

Climate change emerges as a significant global challenge with profound implications for human health, particularly in the realm of acute respiratory diseases (Davis, 2018). The relationship between the changing climate and the prevalence of these diseases is complex, influenced by a multitude of factors beyond just the increase in atmospheric carbon dioxide (CO₂) levels and pollen production (D'Amato et al., 2015). Instead, the emphasis is on the broader impacts of climate change, including shifts in seasonal patterns and how these changes exacerbate respiratory conditions (Wang et al., 2021). The seasonality of respiratory viral diseases, such as the common cold and influenza, aligns closely with environmental changes, with annual epidemics peaking during the winter months in temperate climates

(Moriyama et al., 2020). This pattern extends to more recent viral outbreaks like SARS-CoV and SARS-CoV-2, which also show a tendency to surge during colder periods (Scholes and Engelbrecht, 2021). These observations underscore the critical role of environmental parameters, including temperature and humidity, in driving the seasonality of respiratory infections (Lennard, 2019).

The intricate relationship between climate change and respiratory health is further highlighted by the exacerbating effects of air pollution (Cui et al., 2003; Tran et al., 2023). Airborne pollutants, such as particulate matter and ozone, are significant triggers for respiratory conditions such as asthma and COPD (Engelbrecht et al., 2015). These pollutants, often intensified by climate-related factors such as increased temperature and altered precipitation patterns, can interact with respiratory viruses to amplify the severity of diseases (Wright et al., 2021). Urbanization and the shift towards urban lifestyles contribute to this problem by increasing exposure to vehicle emissions and other sources of urban pollution, aggravating the risk of respiratory allergies and infections (Tempia et al., 2017).

Crucially, the marked seasonality of acute respiratory diseases is shaped by an array of factors including, but not limited to, temperature fluctuations, changes in humidity, and variations in human behaviour (Cohen et al., 2015). These elements collectively influence the transmission dynamics of respiratory viruses and the immune response of hosts, highlighting the deep-seated connections between environmental changes and respiratory health (Zhang et al., 2020). The development and implementation of comprehensive mitigation strategies become paramount (Landman et al., 2017).

The exploration of this thesis, through the lens of seasonality and through the use of the DLNM to model the impacts of daily weather, unveils intricate patterns of disease incidence significantly influenced by climatic variations (Gasparrini et al., 2015). This analysis, compared with similar studies, provides a rich understanding of how geographical and climatic nuances shape the public health landscape concerning acute upper respiratory diseases (Engelbrecht et al., 2016). Chapter 5, "Defining the South African Acute Respiratory Infectious Disease Season," embarked on identifying the precise timeframe of heightened acute upper respiratory disease prevalence, motivated by the pressing need to optimize public health interventions, particularly vaccination timing, by accurately delineating the start and end of the acute upper respiratory diseases season (NICD, 2022). Utilizing hospitalization and medical insurance claim data, the study adeptly used intensity threshold methodologies to demarcate the acute upper respiratory diseases season as spanning from May to September, a period characterized by lower temperatures and aligned with the universally observed uptick in respiratory infections during colder months, a pattern corroborated by other studies through its national survey approach, emphasizing winter as the peak season for acute upper respiratory diseases (WHO, 2012).

Chapter 7, "Assessing the impact of climatic variability on acute respiratory diseases across diverse climatic zones in South Africa," further enriches our understanding by dissecting the complex relationship between climatic factors and acute upper respiratory disease incidence. Spearman Correlation Analysis and DLNM application revealed an inverse relationship between temperature and disease incidence, showcasing the non-linear and delayed effects of climatic variables on health, offering deep insights into how specific weather conditions precipitate variances in disease patterns across Johannesburg, Cape Town, and Gqeberha

(Motlogeloa and Fitchett, 2024). Such region-specific findings underscore the imperative for public health interventions to be acutely tailored to local climatic idiosyncrasies, mirroring adaptation strategies that might be inferred elsewhere (Patz et al., 2003).

The comparative analysis with other studies underscores the universal impact of climatic conditions on acute upper respiratory disease seasonality, yet also emphasizes the critical importance of localized, climate-informed public health strategies (Cannell et al., 2006; Chen and Kirk, 2013). Both the South African and Australian contexts reveal a clear seasonal pattern in acute upper respiratory disease incidence, peaking during colder months, which corroborates the global understanding of temperature and humidity as pivotal environmental drivers (Chen and Kirk, 2013; Takaro et al., 2013).

The influence of climate on the seasonality and incidence of acute upper respiratory diseases varies significantly with geographical latitude (Motlogeloa et al., 2023; 2024). Regions situated further from the equator, sharing similar temperate climates, often exhibit a pronounced seasonality in the incidence of acute upper respiratory diseases, characterized by peak periods during the colder months (Cannell et al., 2006). This pattern contrasts with areas in the tropics, where the absence of significant temperature fluctuations leads to a less distinct seasonality in acute upper respiratory disease patterns (Zhang et al., 2020).

In temperate regions, such as parts of Australia and South Africa, the colder seasons bring about a marked increase in acute upper respiratory disease cases (Chen and Kirk, 2013). The cooler, drier air facilitates the survival and transmission of respiratory viruses, such as influenza and the respiratory syncytial virus, leading to seasonal outbreaks (Lennard, 2019).

The distinct drop in temperature during the winter months in these regions creates conditions conducive to indoor crowding, further enhancing the transmission dynamics of acute upper respiratory diseases (Engelbrecht et al., 2015).

Conversely, tropical regions experience relatively consistent temperatures throughout the year, with seasonal variations in disease incidence more closely tied to rainfall patterns than to temperature changes (Nicholson, 2000). The lack of a cold season means that acute upper respiratory diseases do not exhibit the same pronounced seasonality seen in temperate zones. Instead, acute upper respiratory disease incidence in these areas may peak during the rainy season, driven by different environmental and social factors (Gasparrini et al., 2015).

The contrasting patterns of acute upper respiratory disease seasonality between temperate and tropical regions underscore the importance of tailoring public health interventions to specific climatic and geographical contexts (Wang et al., 2021). In temperate regions, vaccination campaigns and public health advisories can be timed to precede the expected seasonal increase in acute upper respiratory disease incidence, maximizing their effectiveness (NICD, 2022).

In tropical regions, where acute upper respiratory disease seasonality may be less pronounced or tied to different environmental factors, disease surveillance and public health strategies need to be adaptable, focusing on monitoring and responding to disease outbreaks about variable factors like rainfall and humidity (WHO, 2012; Mosegui et al., 2022). This approach ensures that interventions are responsive to the unique epidemiological patterns of acute upper respiratory diseases in these regions, potentially involving year-round vigilance

and targeted measures during periods of increased risk associated with specific climatic conditions (Tempia et al., 2017).

The distinct trends in acute upper respiratory disease seasonality between temperate and tropical regions highlight the complex interplay between climate, geography, and disease dynamics (Jin et al., 2021). Understanding these patterns is crucial for developing effective public health strategies tailored to the specific needs of each region, ensuring that interventions are both timely and contextually appropriate. This knowledge enables health authorities to anticipate and mitigate the impact of seasonal disease peaks, ultimately reducing the public health burden of acute upper respiratory diseases across diverse climatic zones.

The influence of climate on the seasonality of acute upper respiratory diseases not only varies with geographical latitude but also significantly depends on hemispheric location (Cannell et al., 2006). While South Africa and other countries in the Southern Hemisphere experience seasonal peaks in these diseases during their winter months (June to August), countries in the Northern Hemisphere observe similar seasonal patterns, albeit during the boreal colder months of December through February (Wang et al., 2021). This hemispheric difference means that the drivers of acute upper respiratory disease seasonality—primarily temperature and indoor crowding—are consistent across both hemispheres, with the seasonality of these diseases manifesting at opposite times of the year (Lennard, 2019).

In the Southern Hemisphere, the winter season, which includes months like June, July, and August, marks a significant increase in the incidence of acute upper respiratory diseases. This

is due to the colder, drier weather that facilitates virus survival and transmission, coupled with the tendency for people to spend more time indoors, which enhances virus spread among the population (NICD, 2022). Conversely, the Northern Hemisphere experiences its winter season during December, January, and February, during which there is also an observed increase in acute upper respiratory diseases for the same reasons (WHO, 2012). The replication of these conditions across hemispheres, albeit at different times of the year, underscores the universal impact of specific climatic factors on the transmission dynamics of these diseases (Engelbrecht et al., 2015).

The predictable seasonality of acute upper respiratory diseases, driven by climatic conditions that are consistent in both hemispheres but occur at opposite times, has significant implications for global public health strategies. It necessitates a coordinated approach to disease surveillance, vaccination campaigns, and public health advisories that are tailored to the seasonal patterns of each hemisphere (Moriyama et al., 2020). For instance, flu vaccination efforts are ramped up in anticipation of the winter season in both hemispheres, ensuring populations are immunized before the peak transmission periods begin (Gasparrini et al., 2015).

This staggered seasonality also allows for the sharing of surveillance data and resources between hemispheres. (Abbas et al., 2017; Motlogeloa et al., 2023) As one hemisphere exits its peak disease season, it can offer insights and support to the other hemisphere that is approaching its seasonal increase in disease incidence. This global perspective enhances the ability to forecast disease trends, allocate resources efficiently, and implement timely public health interventions (Alahmad et al., 2019).

The mirrored lag in the seasonality of acute upper respiratory diseases between the Northern and Southern Hemispheres highlights the global nature of these health challenges (Shea et al., 2014; Jackson et al., 2020). Understanding and anticipating these seasonal trends are crucial for the development of effective, timely public health responses that can mitigate the impact of these diseases worldwide. By recognizing the shared drivers behind disease seasonality and leveraging the staggered timing of seasons across hemispheres, global health authorities can foster collaboration and enhance preparedness for seasonal peaks in acute upper respiratory diseases, ultimately aiming to protect public health across diverse climatic and geographical landscapes (Tempia et al., 2017).

Chapter 4, emphasizes the increasing attention toward the climate-health nexus, particularly the impact of climate on human health (Watts et al., 2015). While the excerpt does not directly mention South Africa or developing countries' specific challenges related to climate change and health, it highlights a broader concern for the global disparity in research focus and empirical evidence, particularly the underrepresentation of studies from the global South, including Africa (Wright et al., 2021).

Given the context provided and the broader implications of climate change on health as discussed in various research, including the underrepresented regions like South Africa, we can infer the importance of addressing climate change's health impacts in developing countries (Ebi & Forsberg, 2009). Here is a detailed section that addresses why a developing country like South Africa must be cautious as climate change persists, incorporating general insights from biometeorological research trends and the specific challenges faced by such regions (Landman et al., 2017).

As climate change continues to manifest through global warming, altered precipitation patterns, and more frequent extreme weather events, its impact on human health becomes increasingly significant, especially in developing countries like South Africa (McMichael et al., 2006). The underrepresentation of empirical evidence from such regions in global research, as highlighted in the review of publications in the *International Journal of Biometeorology*, underscores the need for a focused and cautious approach to understanding and mitigating these impacts (Wright et al., 2021).

Developing countries, due to their limited resources, often have healthcare systems that are less equipped to handle the surge in disease incidence and environmental health hazards associated with climate change (Mosegui et al., 2022). For South Africa, a nation already grappling with significant health challenges, including high rates of communicable diseases and a growing burden of non-communicable diseases, the added stress of climate-related health impacts poses a critical threat (Maphumulo & Bhengu, 2019).

Chapter 4 emphasis on the climate-health nexus points to the significance of understanding seasonal disease patterns, which are likely to shift as global climates change. In South Africa, climate change could alter the seasonality of acute upper respiratory diseases, potentially leading to longer seasons or increased disease incidence outside traditional peak periods. This shift necessitates adaptable public health strategies that can respond to changing disease dynamics in real-time (Engelbrecht et al., 2015).

The socioeconomic disparities prevalent in developing countries like South Africa mean that the health impacts of climate change are likely to be felt most acutely by the most vulnerable

populations (Watts et al., 2015). Urban poor, rural communities, and those already facing health inequities are at greater risk. A focused approach to climate change and health in South Africa must address these disparities, ensuring that adaptation and mitigation strategies are equitable and inclusive (Wright et al., 2021).

The call for more empirical research from under-represented regions, including South Africa, is crucial for informing policy and intervention strategies (Ebi & Forsberg, 2009). As the global focus shifts towards addressing the climate-health nexus, developing countries need to prioritize research that reflects their unique climatic, environmental, and socioeconomic contexts (Landman et al., 2017). This research is essential for developing targeted, effective public health interventions and for informing policy decisions that can mitigate the adverse health impacts of climate change (Engelbrecht et al., 2015).

The persistence of climate change presents a complex array of challenges for human health, particularly in developing countries like South Africa. The insights from the review in the *International Journal of Biometeorology*, while highlighting the global scope of climate-health research, also underscore the critical gaps in knowledge and evidence from the global South (Cohen et al., 2015; Fitchett, 2021). For South Africa, a cautious, proactive approach to understanding and addressing the health impacts of climate change is not only necessary but urgent. This approach requires a commitment to increasing research output, enhancing healthcare system resilience, and implementing equitable public health strategies that can adapt to the changing climate landscape (Maphumulo & Bhengu, 2019).

Summary of Key Findings from Research Articles on Climate and Health:

From "Climate and Human Health: A Review of Publication Trends in the International Journal of Biometeorology" (Chapter 4):

1. Growth in Publications: Increased publications since 2011, with peaks in 2017 (18 publications) and 2021 (17 publications).
2. Disease Focus: Respiratory diseases (37.2%), cardiovascular diseases (17%), and cerebrovascular diseases (11.1%) are the main focus.
3. Geographical Imbalance: Predominantly features studies from Asia and Europe, with limited research from Africa (only 2.2% of studies).
4. Methodological Advancements: Utilization of sophisticated statistical methods like regressions and distributed lag nonlinear models.
5. Interdisciplinary Collaboration: Encourages cooperation among climatologists, health practitioners, and others to mitigate climate change's health impacts.

From "Defining the South African Acute Respiratory Disease Season" (Chapter 5):

1. Season Onset and Duration: Identifies May to September as the respiratory disease season in South Africa using intensity threshold methodologies.
2. Provincial Variations: Notable variations across provinces, with Gauteng displaying a pronounced seasonal peak.
3. Impact on Public Health Strategy: Supports effective influenza vaccination timing and resource allocation.
4. Data Utilization and Methodology: Combines public and private sector data for robust seasonal trend analysis.

From "Exploring the Role of Extreme Climate Events (ECEs) in the Incidence of Respiratory Disease in South Africa" (Chapter 6):

1. Correlation of ECEs with Health Claims: Specific ECEs like storms and floods significantly impact respiratory disease claims, both positively and negatively.
2. Geographical and Temporal Distribution: Health impacts of ECEs are dispersed across various municipalities without clear seasonal patterns.

From "Assessing the impact of climate variability on acute respiratory diseases across diverse climatic zones in South Africa" (Chapter 7):

1. Differential Impact by City:
 - Johannesburg: Higher respiratory disease risk with extreme cold and moderate winter temperatures.
 - Cape Town: Increased respiratory risk with extreme heat; positive correlation with rainfall.
 - Gqeberha: Indistinct temperature-respiratory disease relationship due to moderate, rainy climate.
2. Temperature and Respiratory Disease Correlation: Negative correlations in Johannesburg and Cape Town, with varying impacts based on specific climatic conditions.

These findings collectively underline the critical interactions between climate conditions and respiratory health, pointing towards necessary adaptations in public health strategies and further research needs, especially in underrepresented regions like Africa.

8.3 Looking Forward: Future Trajectories of Acute Respiratory Disease in South Africa

Climate change poses significant risks to public health, with an especially acute impact on respiratory disease patterns. South Africa faces a forecasted rise in average temperatures of up to 2°C by 2050, accompanied by modifications in rainfall patterns, which are likely to

extend the transmission seasons for respiratory pathogens (Baker et al., 2022). These environmental changes are intricately linked to public health outcomes, necessitating a strategic and adaptable response from health policy and infrastructure.

Baker et al. (2022) highlight the anticipated warming in South Africa, suggesting a direct correlation with altered disease dynamics. This warming trend, alongside the projected increase in the frequency and intensity of extreme weather events like heatwaves and severe storms, could lead to a higher incidence of respiratory diseases and the introduction of novel pathogens to the region (Codjoe et al., 2020; Cheng et al., 2021). The health challenges posed by these changes are further exacerbated by the potential for increased air pollution and the disruption of healthcare systems during extreme weather events, a concern raised by researchers (Stephenson, 2004; Guha-Sapir et al., 2016.. (2016).

To counteract the anticipated rise in respiratory diseases, it is imperative to enhance infrastructure resilience against extreme weather and to develop healthcare models that are adaptable to the emerging patterns of climate-induced diseases. The establishment of vaccine production centres in South Africa during the COVID-19 pandemic marks a strategic shift towards healthcare resource self-sufficiency (Maphumulo and Bheng, 2019). Furthermore, the planned implementation of the National Health Insurance (NHI) is set to revamp the healthcare landscape, aiming to provide equitable health services to all South Africans (Gqirana, 2015). This system seeks to pool resources to ensure that every citizen and resident has access to essential healthcare services, mitigating the financial hardship often associated with healthcare (SA News, 2015).

Health policies must evolve to keep pace with the rapid climatic shifts and their implications for disease prevalence. Moving away from a reliance on static historical data, these policies should integrate real-time climatic data and forecasts into the health planning process. Such an approach is advocated by Fuhrmann (2010), who emphasizes the need for health planning that anticipates and responds to current and future climatic conditions. Adjusting vaccination campaigns to align with emerging disease incidence patterns, such as early autumn peaks, can enhance the efficacy of these preventive measures (Shea et al., 2014; Nsoesie et al., 2014).

A comprehensive response to the health impacts of climate change requires an interdisciplinary approach. Collaborations across various domains, including meteorology, healthcare, urban planning, and policy, are crucial for developing strategies that address predictive modelling, emergency planning, and public education. Jury (2018) underscores the importance of such a cross-sectoral strategy in effectively managing the health impacts of climate change. Based on the insights provided in Chapter 7, it is recommended that vaccination campaigns in South Africa should be initiated before the early autumn period. This timing is suggested because early autumn has been identified as conducive to influenza transmission. Adopting such a proactive vaccination strategy can enhance community immunity, reduce susceptibility to infection, and limit the spread of the influenza virus. The chapter also emphasizes the importance of developing adaptive public health strategies that are attuned to the prevailing weather patterns, which are significant in the transmission dynamics of respiratory viruses. Therefore, a flexible vaccination strategy that includes short-term weather predictions could enable a rapid response to the forecasted cooler and wetter conditions associated with an increase in respiratory diseases. This approach would require a

re-evaluation and recalibration of current public health strategies, especially vaccination campaigns, to closely align with the weather patterns identified in the study

The relationship between climate change and respiratory health in South Africa calls for an integrated, proactive public health strategy. The South African health policies, including the prospective NHI, must be robust and adaptable to protect and enhance respiratory health amid a changing climate. By reinforcing infrastructure, revising healthcare models, and fostering interdisciplinary collaboration, South Africa can build resilience against the health impacts of climate change and secure a healthier future for its population. The insights from several researchers, including Baker et al. (2022), Beniston and Stephenson (2004), Guha-Sapir et al. (2016), Maphumulo and Bhengu (2019), SA News(2015), Fuhrmann (2010), Shea et al. (2014), Nsoesie et al. (2014), and Jury (2018), to underscore the complex nature of climate change's impact on health. It highlights the need for a multifaceted and responsive healthcare system capable of addressing the challenges posed by climate change on respiratory health.

In summation and in light of this analysis conducted in this study, it is possible to project changes in the incidence of respiratory diseases in South Africa in response to climate change. Here are scientifically grounded inferences:

1. **Temperature Variability and Respiratory Illnesses:**The research documented in the Seasonality and DLNM papers indicates a significant correlation between respiratory diseases and temperature fluctuations. With climate change likely to increase temperature variability, an escalation in respiratory disease incidence during both

unusually cold spells and heatwaves can be anticipated, especially in densely populated urban areas susceptible to the urban heat island effect.

2. Frequency and Impact of Extreme Climate Events (ECEs): Findings from the ECE manuscript reveal that extreme weather events, such as storms, floods, and heatwaves, directly affect respiratory health. With projections suggesting an increase in both the frequency and severity of these events due to climate change, respiratory illnesses are expected to display more frequent and intense fluctuations.
3. Changes in Seasonality and Disease Duration: Climate change may alter the traditional timing and prolong the duration of respiratory disease seasons, as indicated by the Seasonality study. Such shifts could extend periods of high respiratory disease incidence, necessitating adjustments in healthcare planning and resource distribution.
4. Regional Variations in Disease Incidence: The impact of climate change on respiratory diseases will likely vary regionally across South Africa, reflecting the country's diverse climatic conditions. This variability calls for localized health surveillance and tailored response strategies to manage the differential impacts effectively.
5. Enhancing Public Health Preparedness: The expected increase in severity and unpredictability of climate-related impacts on respiratory health emphasizes the need for improved public health infrastructure. This includes enhanced disease surveillance systems, broader public health education on preventive measures, and optimized resource and vaccination distribution strategies.

Collectively, these projections highlight the necessity for South Africa to develop an adaptive public health framework that incorporates advanced predictive modeling and robust scenario

planning. This strategic approach will enable proactive responses to the evolving challenges posed by climate change on the patterns of respiratory diseases.

8.4 Limitations of the Study

The study exploring the impact of climate on respiratory diseases, particularly within the South African context, presents numerous challenges that can constrain the breadth and depth of research findings. These constraints necessitate a candid discussion about the limitations of current studies, acknowledging the gaps and exploring how they can be addressed to refine future research.

One of the primary limitations is the geographical focus of the data, which has centred on the urban hubs of Cape Town, Gqberha and Johannesburg. Although these metropolitan areas provide a rich source of climate and health data, the paucity of information from rural and peri-urban areas introduces a significant bias. This urban-centric view overlooks the variability in climate impacts across different regions, which is crucial for a nuanced understanding of climate's role in respiratory health. To partially address this gap, the study was supplemented with regional climate and health data where available, offering a broader yet still incomplete picture (Philippon et al., 2012; Favre et al., 2016). By incorporating data from neighbouring peri-urban suburbs, an attempt was made to bridge this divide. However, the limitations remain, as the unique seasonality and climate impacts in rural areas—exacerbated by factors such as the urban heat island effect—are still under-represented. Consequently, when considering the implications for public health interventions, such as vaccination programs and healthcare centre preparedness, it is advisable to incorporate a margin of error and adopt a more conservative stance (Roffe et al., 2019).

Another limitation arises from the reliance on medical insurance claims data. While this data is invaluable, it is not wholly representative of the population, especially not of the underinsured or those dependent on public health services. Efforts were made to cross-reference insurance claims with hospital admission records to mitigate this limitation, yet disparities persist. This reliance on medical claims can lead to an underrepresentation of respiratory disease incidents in less affluent areas, causing potential underestimations of disease burdens in the findings (Motlogeloa et al., 2023).

The research also grapples with external variables like socioeconomic status, healthcare access, and individual behaviours, all of which are recognized as potential confounders in understanding the impact of climate on respiratory diseases. Statistical controls and comparative analyses were employed to manage these variables' effects. Nonetheless, the controls' effectiveness is limited by the available data and the inherent complexity of these socio-economic factors. These limitations suggest that while the study provides valuable insights, there is a need for caution when interpreting the relationship between climate variables and respiratory diseases (Iwasaki and Pillai, 2014; Kovats et al., 2004).

For future research, a more comprehensive approach is required. Expansive data collection efforts that encompass broader demographics and geographic areas are essential. Methodological enhancements should also include qualitative analyses to augment quantitative data, thereby providing a more complete understanding of the climate's impacts on health. Interdisciplinary and collaborative research efforts are paramount in transcending the current study's limitations and enabling more sophisticated and holistic findings (Tout,

1987; Sheridan and Allen, 2017). While the research conducted provides valuable insights into the urban impact of climate change on respiratory diseases, the acknowledged limitations point to a clear need for ongoing scrutiny and methodological refinement. These limitations must be carefully considered in the context of public health policy and planning. Future studies should strive for inclusivity and comprehensiveness, ensuring that the intricate relationship between climate and health is thoroughly examined, and the findings can be applied to safeguard the health of all South Africans, irrespective of their locale or socio-economic status.

CHAPTER 9: CONCLUSION

9.1 Synthesis

The research studies compiled in the thesis titled "Assessing the Inter-annual and Inter-seasonal Climate-Induced Variation in Caseload of Respiratory Diseases" offer pivotal insights into the multifaceted yet profound effects of climatic factors on respiratory disease patterns within the diverse climatic zones of South Africa. This synthesis underscores the climatic complexities affecting public health and contributes to the strategic development of health interventions.

In synthesis, the collected body of work within this thesis elucidates the intricate relationship between climatic factors and respiratory disease trends in South Africa. It advocates for adaptable and nuanced public health responses attuned to climatic subtleties and seasonalities. By combining these research insights, the thesis "Assessing the Inter-annual and Inter-seasonal Climate-Induced Variation in Caseload of Respiratory Diseases" significantly contributes to the foundation for future policy formulation, research, and public health initiatives both within the South African context and in the broader scope of climate change and health globally.

9.2 Achievement of Study Aim and Objectives

The quest to understand the interplay between climatic factors and respiratory diseases in South Africa has led to a multifaceted investigation within this research. Grounded in a rigorous methodological framework, the study sought to unpack the seasonality and climatic impacts on the patterns of disease incidence. This section articulates how the specific

objectives of the research align with the overarching aim to provide a comprehensive analysis of climatic influences on acute respiratory diseases.

The primary aim of this research is to investigate the interplay between climatic factors and the seasonality of acute respiratory diseases in South Africa, underpinned by an in-depth analysis of various climatic influences. To address the primary aim of this research, the specific objectives of this research are:

- 1. To Define Seasonality: Establish the timing of the onset and cessation of the primary period during which acute upper respiratory diseases occur across South Africa, using both public-sector hospitalization data and private-sector medical aid scheme data.*

The research successfully established clear patterns of seasonality for acute respiratory diseases by analysing hospitalization and medical insurance claims data. It was ascertained that the respiratory disease season predominantly spans from May to September, aligning with the colder months, which concur with increased incidence rates. This finding was corroborated by employing statistical intensity thresholds that highlighted inter-annual and spatial variability.

- 2. To Assess Climatic Impacts: Determine the influence of climatic factors, including extreme weather events and variability, on the incidence and prevalence of respiratory diseases.*

A thorough examination of climatic data in conjunction with medical claims revealed that while extreme climate events (ECEs) have an impact on respiratory disease claims, these are not as pronounced as the shifts attributable to more subtle, routine weather patterns. The study's findings suggest that seasonal trends have a stronger influence on respiratory health outcomes than individual extreme events. This conclusion was drawn from a comprehensive analysis that included Spearman's correlation and Distributed Lag Non-linear Models (DLNM), which elucidated the non-linear and delayed effects of climatic factors.

3. To determine the influence of climatic factors, including extreme weather events and variability, on the incidence and prevalence of acute upper respiratory diseases.

By examining the effects of both routine climatic conditions and extreme weather events, the research has clarified the complex interdependencies between climate and disease incidence. This has reinforced the need for an integrated approach to public health planning that takes into account both climatic variability and extreme events.

This body of work has illuminated the complex relationship between climatic factors and the incidence of respiratory diseases in South Africa, thereby fulfilling the primary aim of the research. The evidence gathered underscores the need for a nuanced understanding of seasonality and its implications for public health strategies. It emphasizes the importance of considering climatic variability and extreme events in the planning and execution of health interventions, such as vaccination campaigns and resource allocation for healthcare services.

9.3 Directions for Future Research

The investigation into the climatic factors affecting the prevalence and seasonality of respiratory diseases in South Africa has provided valuable insights, yet it also highlights the need for further research. Future studies should broaden demographic inclusivity to encompass more comprehensive healthcare data across urban and rural settings. This will allow for an equitable understanding of the climate-health nexus across different population groups and inform tailored public health strategies.

A deeper analysis of the interactions between air pollution and climatic variables is warranted given their synergistic effects on respiratory conditions. Understanding these relationships will be crucial for developing robust preventive measures and health interventions. Research into the perceptions and behaviours of healthcare practitioners and the general public regarding the links between climate and health can offer valuable insights. Such studies could improve the effectiveness of public health messaging and intervention uptake, contributing to the overall health resilience of communities.

The application of advanced epidemiological models, such as Distributed Lag Non-linear Models, to a wider range of medical conditions could shed light on the broader implications of climate variability. This approach could be particularly insightful for conditions with varying transmission dynamics, offering a more comprehensive understanding of the health impacts of climatic factors.

Longitudinal studies on the impacts of climate change are essential for proactive public health planning. These studies should track changes in disease patterns over time and consider

climate change projections to ensure the adaptability and resilience of healthcare systems. The adaptability of healthcare systems to the growing burden of climate-related diseases also presents an area ripe for research. Evaluating the resilience of healthcare infrastructure and the capacity of health services to meet climate-related health demands will be critical for future planning and response.

Integrating research findings into policy-making and healthcare practice is another important direction. Future research should explore how evidence from climate-health studies can be translated into policy frameworks to enhance disease surveillance and healthcare planning. The potential of emerging technologies, including big data, machine learning, and artificial intelligence, should be harnessed to improve disease surveillance and predictive capabilities. These technologies could revolutionize how health systems anticipate and respond to climate-related health challenges. Lastly, it is crucial to consider the socioeconomic determinants that interplay with climatic factors to affect health outcomes. Research in this area can lead to more comprehensive public health strategies that address both the symptoms and root causes of vulnerability to climate-sensitive illnesses.

In summary, the synthesis of these research directions underscores the need for an integrated and interdisciplinary approach to future studies. Such a concerted effort will be key to addressing the multifaceted challenges posed by climate change to public health, ensuring that populations, especially in vulnerable regions like South Africa, are prepared to thrive amidst climatic uncertainties.

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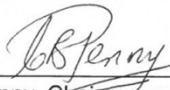
APPENDIX 1: ETHICS CLEARANCE



R14/49 Miss Ogone Motlogeloa

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

CLEARANCE CERTIFICATE NO. M210617

NAME: Miss Ogone Motlogeloa
(Principal Investigator)
DEPARTMENT: Geography Archeology and Environmental Sciences
PROJECT TITLE: Assessing the inter-annual and inter-seasonal climate-induced variation in case load of respiratory diseases
DATE CONSIDERED: 25/06/2021
DECISION: Approved unconditionally
CONDITIONS:
SUPERVISOR: Dr J Botai, Prof J Fitchett and Dr N Sweijd
APPROVED BY: 
Dr CB Penny, Chairperson, HREC (Medical)
DATE OF APPROVAL: 04/08/2021

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office Secretary on the Third Floor, Faculty of Health Sciences, Phillip Tobias Building, 29 Princess of Wales Terrace, Parktown, 2193, University of the Witwatersrand. I/we fully understand the conditions under which I am/we are authorized to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated, from the research protocol as approved, I/we undertake to resubmit the application to the Committee. **I agree to submit a yearly progress report.** The date for annual re-certification will be one year after the date of convened meeting where the study was initially reviewed. In this case, the study was initially reviewed in **June** and will therefore be due in the month of **June** each year. Unreported changes to the application may invalidate the clearance given by the HREC (Medical).


Principal Investigator Signature

4/8/2021
Date

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES