CITIZEN SCIENCE EARLY WARNING TOOLS FOR WEATHER AND CLIMATE RISK AWARENESS

Report
to the Water Research Commission

by

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EXECUTIVE SUMMARY

Rationale

The impacts of climate change and variability are being experienced globally, especially in climate-sensitive sectors such as water, agriculture, health, human settlements, and energy. In South Africa, the triple challenges of inequality, poverty, and unemployment further exacerbate the impacts of climate change, as a significant proportion of South African communities in both rural and urban areas have limited adaptive capacity to respond to frequent extreme weather events such as floods and droughts. Extreme weather events such as intense storms, heavy rain, extreme winds, heatwaves, and an increase in the number of hot days affect the livelihoods of the most vulnerable communities in both rural and urban areas. Therefore, to minimise impacts on these communities, it is essential to involve citizens and build their capacity to respond to the inherent impacts of weather and climate by providing simplified tools that can support citizen engagement in disaster risk reduction and management, including the dissemination of early warnings. Citizen Science (CS) involves the engagement of volunteers in scientific investigations and their participation in framing research questions, collecting data, or interpreting results. In the context of disaster preparedness and response, there is a need to ensure that the technical language around weather and disaster risk reduction is simplified to ensure a shared understanding of the risks while enabling informed participation in designing and implementing risk management measures. Citizen science is not just public participation based on attendance at workshops or meetings, but a genuine participation and contribution of non-professionals in scientific research. The involvement of voluntary community members or citizen scientists in environmental monitoring has been happening for many years and has enabled scientists and academia to achieve scientific advancements that inform effective policy and decision-making.

A number of studies have indicated that indigenous and local communities have long used traditional knowledge to make various adaptive responses for generations to changes in their environment, climate and risks by developing situation-specific livelihood practices and building the resilience of their households and communities. Consequently, in order to effectively adapt to and cope with the impacts of weather variability and climate change, modern scientific knowledge should be integrated with indigenous and local knowledge systems, drawing on the lived experiences of communities that have long adapted to environmental changes. In this study, the citizen scientists (CSs) included learners, farmers and youth who had acquired indigenous knowledge at various levels and shared this to support learning and knowledge sharing. This knowledge included indicators for impending extreme weather events and adaptation actions that were used in the various communities. This second phase of the citizen science project aimed to assess knowledge of climate risks, early warning systems, current response mechanisms, local Indigenous Knowledge Systems (IKS), and to train CSs to collect, interpret, and disseminate weather information. Additionally, the project aimed to co-design a community-based early warning system (EWS) and communication tool.

This study employed a case study approach to support CSs in selected study sites of Malamulele (Limpopo Province), Cullinan (Gauteng Province), Cofimvaba (Eastern Cape Province), Swayimane (Kwa-Zulu Natal Province) and Manenberg (Western Cape Province). Engaging the CSs enabled the project team to co-develop a shared vision with the volunteers that would facilitate building their resilience to extreme weather events. Workshops were held in all study sites to build the capacity to understand and communicate early warning messages and empower local communities to prepare and respond to weather-related hazards. The project also focused on building the capacity of citizens to engage in weather and environmental management initiatives to mitigate the impacts of extreme weather events, including those based on indigenous and local knowledge. In addition, CSs were trained on how to collect local weather information using Citizen Weather Stations (CWSs). Enhanced collaboration between scientists, CSs, and local communities creates a skilled community of citizen scientists. The establishment of an extended weather and climate change monitoring network, along with a community-based EWS created in collaboration with CSs, enhances understanding and provides long-term data sources and sustainability. Furthermore, efforts were directed towards establishing a monitoring network that empowers citizens, including schools, youth, and community-based organisations, to predict and address extreme weather events, while also fostering community involvement through accessible platforms like WhatsApp groups. Mobile technology is one of the key ways that can facilitate faster dissemination of early warnings to vulnerable groups, ensuring that nations contribute efficiently to the UN's Early Warnings for All Initiative (EW4All). Furthermore, the implementation of an extensive monitoring network and community-based EWS will benefit various climate-sensitive sectors and stakeholders including: South African Weather Service (SAWS); Disaster Management; Department of Forestry, Fisheries and the Environment; Department of Agriculture, Land Reform and Rural Development; Department of Water and Sanitation; farmers; local municipalities; Non-Governmental Organisations, as well as multilateral agencies like UNESCO and UNICEF. The SAWS will utilise the data from the project to verify forecasts and issue impact-based warnings to the communities through the EWS.

Objectives

The project aimed to:

1. Perform an intercomparison field study of low-cost CWSs against standard professional weather stations to quantify bias and errors associated with CWSs
2. Conduct community engagements to assess risk knowledge and response capability based on Indigenous Knowledge Systems (IKS)
3. Develop training materials for stakeholder outreach activities to build the capacity of citizen scientists and community knowledge of highly technical concepts and information on weather, climate, and early warning.
4. Co-design disaster early warning monitoring tools and network
5. Test or simulate the proposed disaster warning tools developed to improve community-based early warning systems and the community's response procedures.

Methodology

The concept of the co-created CS approach (e.g., an open collaborative approach) is used in this study, where citizens have a specific problem, question, or issue they would like to investigate (Bonney et al., 2009; WMO, 2021). The project was carried out through four phases of citizen science engagements, i.e., initiation phase, development phase, live or participatory science phase, and analysis and reporting phase. In the first phase the project team, consisting of scientists from the South African Weather Service (SAWS), University of Cape Town (UCT), and University of KwaZulu-Natal (UKZN) in partnership with local civil society organisations, departments of disaster management and education, engaged with CSs from the five communities in the study sites, where four schools and a science centre were selected as sites for the project. These are the Viva Foundation Schools in the City of Tshwane Metropolitan Municipality, Swayimane High School in KwaZulu-Natal, The Leadership College (Manenberg), Cape Town, E.P.P. Mhinga Secondary School in Malamulele (Limpopo), and The Albertina Sisulu Science Center in Cofimvaba (Eastern Cape). All five study sites have experienced extreme weather events that have caused loss of human lives and livestock as well as damage to agricultural fields, homes, and other infrastructure.

Virtual and in-person meetings were used to get permission/approval from relevant authorities, such as provincial education departments, school principals, and disaster management departments. The enrollment of CSs from the study sites was done during the first phase of citizen science engagement. The first workshop was held with CSs to co-create an early warning shared vision for their respective communities. The participants got to share their knowledge on weather, extreme weather, and identify volunteers who would like to be CSs, and explain the benefits (incentives) for the participants/ communities. Between 15 and 25 volunteers were selected from each site, and these included learners from both primary and high schools, youths, farmers, and educators. During the development phase, community engagement workshops were conducted to evaluate the community's understanding of climate risks, vulnerability factors, early warning systems, and existing adaptation strategies, including insights from IKS. This phase involved interactive sessions with community members to exchange information on weather, climate, and impact-based early warning concepts, as well as collaboratively design a community-based EWS that would be used to alert the community of impending disasters, building on the capacities and assets available in their community.

The third phase was the live phase and involved training citizen scientists to collect, interpret, and share weather information from the Citizen Weather Stations (CWSs - HP2551 and HP2000). Citizen scientists were engaged to identify, co-develop, and select tools and implement the most effective tool for sharing early warning information from SAWS, such as impact-based warnings tailored to their communities. The study also involved a field study comparing low-cost CWSs (HP 2551, HP 2000, HP1000, Logia 7 in 1, Acurite Atlas, Davis Vantage Pro2, Decagon Complete Weather Station) with standard professional weather stations. This comparison was important for assessing instrument performance, biases, and dependencies. The fourth phase of the CS approach involved compiling the activities and lessons learned from each of the study sites into a report. The findings were disseminated to the communities in the selected sites through various platforms, including posters and pamphlets in local languages such as IsiZulu, IsiXhosa, Xitsonga, and Sepedi, to enhance usability within the communities. Citizen scientists were also awarded certificates to recognise their role and contribution to the project.

Results and Discussion

Several capacity-building workshops were conducted to strengthen the development and sharing of an early warning system with citizen scientists and their respective communities. The workshops ensured that CSs had a clear understanding of the project objectives and their roles and responsibilities. Activities included: training on accessing and interpreting weather forecasts, seasonal outlooks, and climate change projections; group discussions on extreme weather events; and knowledge-sharing sessions on climate change, early warning systems, and the documentation and archiving of weather- and climate-related indigenous knowledge.

Participants also engaged in facilitated discussions to share their experiences of weather patterns, extreme weather events, climate change, and IKS related to weather and climate. They provided valuable input on local weather conditions, the impacts of extreme weather and climate events, community coping mechanisms and safety strategies, the use of indigenous knowledge, and access to and use of weather forecasts, seasonal outlooks, and early warning information. The extreme events reported included hailstorms, strong winds, high temperatures, heavy rainfall leading to flooding, frost, and drought. These events resulted in widespread impacts such as roof damage or destruction, loss of crops and livestock, soil erosion, damage to property and infrastructure, financial losses, increased incidence of crop pests and diseases, weakened livestock, water scarcity, damage to feedstock, rising costs associated with purchasing feed, declining agricultural yields, drying of fields, and the occurrence of veld fires. CSs proposed a range of coping strategies to mitigate these impacts. These included planting trees to act as windbreaks, securing roofs with bricks to prevent wind damage, installing protective nets over crops, constructing drainage systems and embankments to manage excess water during heavy rainfall. Other suggested actions included using sandbags to protect gardens from flooding and installing durable fencing to prevent livestock from being swept away. Farmers in Swayimane and Cofimvaba indicated other actions that include monitoring livestock body temperatures using short-term weather forecasts, covering crops with plastic sheeting to protect them from frost, regulating temperatures in animal shelters using dry grass, and vaccinating livestock. Participants emphasised the critical importance of timely and reliable early warning systems to enable farmers to anticipate and prepare for extreme weather events.

The integration of IKS into weather and climate early warning systems within the project demonstrated considerable potential, as reflected in engagements with indigenous communities in South Africa. A combination of meteorological, ecological, and astronomical IKS indicators was identified as valuable for monitoring local weather patterns, extreme events, and seasonal climate variability. However, several challenges threaten the sustainability of these systems, including weak knowledge transfer mechanisms, limited documentation, the loss of experienced knowledge holders, modernisation and urbanisation, the disappearance of key indicator species, land-use changes, population growth, and the growing impacts of climate change. Farmers stressed the importance of accessible, localised early warning systems tailored to agricultural planning, as well as the provision of more precise, context-specific forecasts to support local decision-making and policy development. Further work is required to enhance the proactive documentation, record, and systematize IKS-based early warning indicators (e.g., animal behavior, plant phenology), and traditional coping strategies. Additionally, there is a need to strengthen EWS with IKS by linking meteorological data with local environmental indicators (e.g., observing celestial bodies or animal behavior) to improve accuracy and relevance. The use of modern communication tools (e.g., WhatsApp) to collect real-time data from community observers can bridge the gap between local observations and formal EWSs. For instance, the CSs in Malamulele shared that the warning issued for their community regarding rainfall showing high chances of rain was inaccurate, as the weather in their community was clear and sunny. The validation by CSs helps verify the forecast information issued by the SAWS. It also highlights the need for more weather stations to provide local weather information. The data provided by the CWSs could be used to support the SAWS network to have more accurate weather information.

The study also conducted a field-based intercomparison of low-cost CWSs and standard professional weather stations (AWSs) to evaluate instrument performance and biases. An intercomparison analysis of the average and total measured values of weather parameters and derived variables obtained from the CWSs and those from standard AWSs at 5-minute, hourly, and daily intervals at the SAWS Irene Office and the UKZN site in Pietermaritzburg was undertaken. Results of air temperature and relative humidity measured using CWSs depicted very good agreement with the standard AWS measurements. Wind speed comparisons illustrated relatively poor agreement, with most of the CWSs recording consistently higher values, except for the Acurite Atlas station. Rainfall measurements across all CWSs exhibited significant variations compared to the standard rain gauge readings. The observed variations could be attributed to poor calibration leading to bias in some of the CWSs right from the start, as well as differences in the measurement heights between the CWSs and the standard AWSs at which the rain gauges are placed, which may be influenced by increased wind speeds. Intercomparison between variables derived from CWSs (e.g., heat index, wind chill, and reference evapotranspiration) and those from the standard AWSs showed fairly good agreement between heat index from the CWSs and that from the standard AWS measurements. In addition, the HP2551, Accurite Atlas, and Decagon CWS wind chill estimates depicted good correlation with the standard AWS estimates. Furthermore, daily reference evapotranspiration estimates from CWSs were consistently lower than those from standard AWS stations. The HP2551, HP2000, and Decagon reference evapotranspiration estimates showed better correlation with the standard AWS estimates.

An effective EWS comprises four interconnected components: risk knowledge, technical monitoring and warning services, communication and dissemination mechanisms, as well as community response capability. These components collectively support hazard monitoring, risk assessment, timely warning issuance, and preparedness actions. The CSs actively participated in the co-design of community-based EWSs across the study sites. Their involvement included identifying climate-related hazards, analysing local climate patterns, evaluating warning communication channels, and assessing the relevance and applicability of IKS tools. The CSs demonstrated strong awareness of climate risks and trends, and their identification of local hazards provided an essential baseline for understanding existing early warning tools and communication practices. Workshop discussions revealed that communities rely on a combination of technological and traditional communication tools, depending on accessibility. Among these, WhatsApp was identified as the most effective and preferred platform for disseminating early warnings issued by the SAWS. The SAWS utilises multiple platforms to disseminate warnings, including social media, TV, radio, and disaster management structures. The widespread use of WhatsApp in South Africa makes it a particularly suitable platform for the rapid sharing and receipt of urgent, community-based weather alerts. However, this platform has its own limitations, including information overload, which causes notification fatigue to users who then ignore or miss critical, time-sensitive alerts, which can be augmented by using other channels, such as radio and community leaders.

Conclusions and Recommendations

The findings from the five study sites illustrate that the frequency, intensity, and duration of climate-related risks are increasing, with far-reaching impacts on South African communities. These extreme weather events amplify existing socio-economic and environmental vulnerabilities, such as a reduction in arable land and food insecurity. Addressing these challenges requires adaptation actions that are user-specific, inclusive and well coordinated by involving a broad range of stakeholders, including government institutions, the private sector, and local communities, particularly those most at risk. This project sought to raise awareness of weather and climate risks and to develop early warning tools for monitoring and detecting natural hazards, thereby supporting timely warnings and effective response actions. Key project outputs included community-based knowledge-sharing activities to enhance understanding of current and future climate-related extreme events, assessments of impacts, and adaptation options. The deployment of reliable low-cost CWSs enabled CSs to have access to local weather information that enhanced learning activities at schools and empowered local communities to understand their local weather and use this knowledge to prepare for and respond to weather-related hazards. Empowered CSs are now able to comprehend and interpret the colour-coded risk matrix used by the SAWS to communicate impact-based warnings and associated risks.

Several training workshops ensured that participants had a clear understanding of the project objectives and their roles and responsibilities. Activities included training on accessing and interpreting weather forecasts, seasonal outlooks, and climate change projections, as well as facilitated discussions to document indigenous weather knowledge. A recurring concern was the absence of effective EWSs for farmers and the need for support to strengthen preparedness and response to extreme weather events. Overall, community engagements demonstrated that South African communities possess strong knowledge of local hazards and existing warning practices. While scientific forecasting systems are widely trusted for their accuracy, IKS remain essential for community engagement and contextual interpretation. The convergence of scientific and indigenous approaches offers a valuable opportunity to enhance the relevance, inclusivity, and effectiveness of EWSs, provided that communication, community participation, and capacity building are strengthened.

The simple, low-cost, and robust CWSs enabled citizen scientists to collect and monitor local weather without compromising data accuracy and quality. Measurements of solar radiation, air temperature, and relative humidity from the CWSs showed very good agreement with standard AWS observations. Wind speed measurements, however, exhibited relatively poor agreement, with most CWSs recording consistently higher values than the AWSs, except for the Acurite Atlas station. Rainfall measurements from all CWSs showed significant variability when compared to the standard rain gauge. These discrepancies are likely attributable to calibration biases present from installation, as well as differences in sensor placement and measurement height between CWSs and AWSs, which may be further influenced by wind effects. Intercomparisons of derived variables, including heat index and wind chill, demonstrated good agreement between CWS- and AWS-derived values. Overall, the results indicate strong agreement between CWS and AWS measurements, with the HP2551, HP2000, and Decagon Complete Weather Stations exhibiting superior performance relative to other CWSs used in this study (HP1000, Logia 7 in 1, Acurite Atlas, Davis Vantage Pro2).

An effective EWS is built on four interrelated components: risk knowledge, technical monitoring and warning services, communication and dissemination mechanisms, and community response capability. In line with this framework, the project focused on the co-design of disaster early warning monitoring tools and the evaluation of their effectiveness in strengthening community-based EWSs and response procedures at the selected study sites. Citizen scientists identified WhatsApp as the most suitable platform for disseminating early warnings issued by the SAWS, given its widespread use and capacity for rapid information sharing. For EWSs to function effectively, it is essential to actively engage at-risk communities, promote public education on hazards, ensure the timely and clear dissemination of alerts, and sustain a state of preparedness. The findings underscore the critical role of CSs in facilitating both bottom-up and top-down knowledge exchange, thereby enhancing collective learning and resilience to extreme weather events. Integrating scientific forecasting with indigenous knowledge systems offers a powerful pathway toward more inclusive, context-sensitive, and culturally grounded disaster preparedness and climate resilience.

South Africa has many communities that remain highly vulnerable to extreme weather and climate-related hazards. The lessons and insights generated through this citizen science project should be scaled up and replicated across additional schools and communities to strengthen people-centred EWSs in diverse geographic and socio-economic contexts, thereby expanding the SAWS monitoring network.

Pillar 1: Disaster risk knowledge

- Future research should prioritise community-based disaster risk education programmes delivered in local languages and through culturally appropriate platforms. Integrating indigenous and local risk knowledge with scientific and technical information is essential to improving hazard awareness, risk perception, and preparedness at the community level.
- Particular emphasis should be placed on empowering vulnerable and marginalised groups, including women, older persons, and people living with disabilities, as active contributors to risk knowledge generation and dissemination through citizen science approaches.

Pillar 2: Detection, monitoring, analysis, and forecasting

- Citizen science initiatives should be further explored as complementary mechanisms to support hazard monitoring and data collection, particularly in underserved and data-scarce areas.
- Future studies should assess how locally generated observations can be ethically, reliably, and sustainably integrated with national and regional forecasting systems to enhance the timeliness and relevance of early warnings.

Pillar 3: Warning dissemination and communication

- Research is needed to identify and evaluate the effectiveness of multiple, redundant, and accessible communication channels for warning dissemination, including digital platforms, community networks, schools, and local institutions.
- Clear, consistent, and actionable messaging is critical to building trust and ensuring warnings reach vulnerable populations in a timely and understandable manner, while accounting for socio-economic barriers to access.

Pillar 4: Preparedness and response capabilities

- Future work should focus on strengthening community preparedness and response capacities by linking early warnings to locally relevant actions, drills, and response plans. Schools and community-based organisations play a central role as hubs for preparedness activities and last-mile response.

Long-term and predictable funding, alongside sustained technical and institutional support, is essential to maintaining citizen science initiatives and ensuring the durability and effectiveness of community-based EWSs over time.

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ACRONYMS & ABBREVIATIONS

AFRA	Association for Rural Advancement
ASO	August September October
AWS	Automatic Weather Station
CS	Citizen Science
CWS	Citizen Weather Station
DRR	Disaster Risk Reduction
ETo	Reference Evapotranspiration
EWS	Early Warning Systems
IBF	Impact-Based Forecasting
ICMHEWS	Integrated Climate-Driven Multi-Hazard Early Warning System
IFRC	Federation of Red Cross and Red Crescent Societies
IKS	Indigenous Knowledge Systems
IRSA	Islamic Relief South Africa
OND	October November December
P	Rainfall
RCP	Representative Concentration Pathway
RH	Relative Humidity
Rs	Solar Radiation
SAWS	South African Weather Service
SON	September October November
Ta	Air Temperature
TLC	The Leadership College
UKZN	University of KwaZulu-Natal
UNDRR	United Nations Office for Disaster Risk Reduction
WD	Wind direction
WMO	World Meteorological Organisation
WS	Wind Speed

GLOSSARY

The term **citizen science** is confined to studies on environmental monitoring, including weather and climate change. The term is used in this context to refer to the engagement of non-professional volunteers in scientific investigations, commonly in data collection, asking questions, quality assurance, data analysis and interpretation, problem definition and the dissemination of results (Gura, 2013; Bonney et al., 2014; Turrini et al., 2018).

Climate – Weather conditions prevailing in an area in general over a long period (SAWS Dictionary, 2021).

Climate change – The change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere, and which is in addition to natural climate variability observed over comparable periods.

Climate variation – A significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years (SAWS Dictionary, 2021).

Citizen scientist – A person who participates in a project by helping define its focus, collecting and/ or analysing data at the local level and this work is unpaid.

Disaster – A serious disruption of the functioning of a community or a society involving widespread human, material, economic, or environmental losses and impacts that exceed the ability of the affected community or society to cope using its own resources (UNDRR, 2017).

Disaster risk reduction – The concept and practice of preventing new and reducing existing disaster risk and managing residual risk, all of which contribute to strengthening resilience and therefore to the achievement of sustainable development (UNDRR, 2017).

Early warning system – An integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities, systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events (UNDRR, 2017).

Hazard – A process, phenomenon, or human activity that may cause loss of life, injury, or other health impacts, property damage, social and economic disruption, or environmental degradation (UNDRR, 2017).

Resilience – The ability of a system, community, or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management (UNDRR, 2017).

Risk – The probability of an event and its negative consequences (UNDRR, 2017).

Vulnerability – The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards (UNDRR, 2017).

Weather is the state of the atmosphere, particularly concerning its immediate effects upon human affairs, plants, animals and to a lesser extent upon the inanimate objects and processes (SAWS Dictionary, 2021).

Box 1: Atmospheric and Meteorological terminology in Tswana, Xitsonga, Sepedi, IsiZulu and Afrikaans

Climate: Tlelaemete/Tlilayimete/ Tlelaemete, bosatelele/ /Isimomvama sezulu/Klimaat
Climate change: Phegotlelaemete /Ncincatlilayimete/ Phetogotlemaemete, phetogobosotolele/Uguquko lwesimomvama sezulu/ klimaatsverandering; klimaatverandering
Climate variation: Dipharologanotlelaemete/Ncincancinco wa tlilayimete/ Pharologanyobosotelele/ Ukuquguquka lwesimomvama sezulu/ Klimaartvariasie; klimaatsvairisie
Weather: Bosa/Maxelo/Boso/ Isimo sezulu/ Weer

(Source: SAWS Dictionary, 2021)

CHAPTER 1: BACKGROUND

1.1. INTRODUCTION

The impacts of climate change and variability are becoming more pronounced, especially in climate-sensitive sectors such as water, agriculture, health, human settlements, and energy. There is evidence that extreme weather events attributed to climate change are becoming more frequent, severe, and erratic (Masson-Delmotte et al., 2021). These events are a threat to economic stability, natural systems, as well as human health, well-being, and safety (Whitmee et al., 2017). Communities at the local level, including the poor and marginalised, are the most vulnerable to high-impact weather events (Karim and Theil, 2017). Communities in South Africa have had varied experiences of climate change-related extreme weather events such as droughts, intense storms that cause flooding, hailstorms, and heatwaves. The recent floods in KwaZulu-Natal and droughts in the Eastern Cape have highlighted the social vulnerability of our communities. There is therefore a need to support policy and decision-making in support of ameliorating the impact of extreme high-impact weather events at the local level through the integration of the weather and climate information and socio-economic systems. Albagli and Iwama (2022) indicate that effective climate change response interventions require coordinated efforts from different stakeholders, including the various levels of government, the private sector, and the community level.

Citizens are key stakeholders as they live in the space in which the impacts of climate change are felt. Contributions from Citizen Science (CS) communities may range from providing their understanding of local climate problems, to identifying solutions that governments can support to adapt, mitigate and build resilience to climate change, as well as collecting both locally based and scientific knowledge and integrating, analysing, and reporting weather-related information and observations within their surroundings (Tauginienė et al., 2020; Katapally, 2019). Hence, they can contribute to managing and reducing extreme weather risks that affect them by supporting bottom-up and top-down knowledge transfer and learning approaches. It is also essential to establish partnerships with influential or key stakeholders in communities to implement participatory approaches, which will help improve early warning knowledge and response by including representative groups from the society who bring different types of knowledge. Indigenous and local peoples' in-situ knowledge practices have the potential to make significant contributions to meeting contemporary sustainability challenges both locally and globally (Mistry and Berardi 2016, Fernández-Llamazares et al., 2020).

In this project, the involvement of citizens in collecting local weather data encouraged greater participation in the generation of new knowledge to support early warning and response. The project outcomes included community knowledge-sharing activities to increase local knowledge on current and future climate-related extreme weather events, their impacts, and adaptation options; provision of reliable low-cost CWSs for a weather monitoring network; capacity building; and empowering the local communities to prepare, communicate, and respond to weather-related hazards. The project also aimed to improve engagement between scientists, citizen scientists, and the local communities, thereby building a capacitated community CSs. Additionally, the project sought to improve the knowledge base and long-term data sources through an expanded weather and climate change monitoring network developed and informed in collaboration with citizen scientists. The overall impact was enhanced resilience of communities and their livelihoods to the impacts of weather and climate-related extreme events. The information collected by citizen scientists in the selected study sites was validated by the SAWS and its collaborative partners and was valuable for disaster monitoring and response, scientific research, policy and decision-making, as well as awareness raising in the selected vulnerable communities.

1.2. PROJECT AIMS

The project aimed to:

- Perform an intercomparison field study of low-cost CWSs against standard professional weather stations to quantify bias and errors associated with CWSs.
- Community engagement to assess risk knowledge and response capability based on Indigenous Knowledge Systems (IKS).
- Develop training materials for stakeholder outreach activities to build the capacity of citizen scientists and community knowledge of highly technical concepts and information on weather, climate, and early warning.
- Co-design disaster early warning monitoring tools and network.
- Test or simulate the proposed disaster warning tools developed to improve community-based early warning systems and the community's response procedures.

1.3. SCOPE AND LIMITATIONS

The project was implemented in five sites: the Viva Foundation Schools in the City of Tshwane (Gauteng), Swayimane High School in uMgungundlovu District Municipality (KwaZulu-Natal), Leadership College Manenberg (Western Cape), Albertina Sisulu Science Center in Cofimvaba (Eastern Cape), and E.P.P. Mhinga Secondary School in Malamulele (Limpopo). All five study sites have experienced extreme weather events that have caused loss of lives as well as damage to livestock, agricultural fields, homes, and other infrastructure.

This study adopted a case study approach focusing on learners and youth, which presents several limitations that should be considered when interpreting the findings. First, as a case study conducted in a specific geographic and institutional context, the findings are not statistically generalisable to all schools, communities, or youth populations in South Africa. However, the study provides rich, context-specific insights that may be analytically transferable to similar settings facing comparable climate and disaster risk challenges. Second, the sample was limited to learners and youth participants, which may not fully capture the perspectives, capacities, and decision-making dynamics of other key actors involved in EWSs, such as caregivers, educators, community leaders, or local authorities. As a result, the findings primarily reflect youth experiences and may overlook intergenerational or institutional dimensions of early warning and response. Third, participation levels and engagement may have been influenced by factors such as age, literacy levels, language proficiency, and access to technology. These factors may have shaped how learners and youth understood risk information, engaged with citizen science activities, or interpreted early warning messages. Fourth, the reliance on self-reported data through participatory activities, discussions, or surveys introduces the possibility of response bias, including social desirability bias or recall bias. Participants may have overstated their understanding, interest, or preparedness due to the educational setting or perceived expectations of the researchers.

Finally, the time-bound nature of the study limited the ability to assess longer-term learning outcomes, behavioural change, or sustained engagement in EWSs. Longitudinal research would be required to evaluate whether observed knowledge gains and participation translate into lasting preparedness and response capacities over time.

CHAPTER 2: CITIZEN SCIENCE FOR WEATHER AND CLIMATE HAZARDS AND EARLY WARNING SYSTEMS

2.1. INTRODUCTION

Citizen science is proving to be beneficial in disaster risk reduction (DRR) and has shown success, especially in providing early warning of hazards, scientific knowledge advancement, and impact assessment and management. Currently, most disaster risk management activities focus on post-disaster recovery actions and less on prevention and mitigation (Marchezini et al., 2018; Hicks et al., 2019). Albagli and Iwama (2022) stated that policies and actions at different levels, through the participation and sensitisation of the most affected and vulnerable social groups, policymakers, and private actors, are expected to provide communities with greater capacity and safety to tackle some of the effects of climate change. According to Garcia and Fearnley (2012), there are two main approaches to EWS: the people-centered (bottom-up) and the hazard-centered (top-down) approaches. This project has adopted the people-centred EWS where the vulnerable communities to extreme weather events will generate knowledge and be part of the citizen science-based EWS. This aligns with the World Meteorological Organisation (WMO) and the United Nations Office for Disaster Risk Reduction (UNDRR), which co-lead the Early Warnings for All initiative that seeks to ensure everyone is informed and prepared for climate hazards. The study will apply the four components of EWS highlighted in Marchezini et al. (2018) and WMO (2023): 1) risk knowledge; 2) detection, observation, monitoring, analysis, and forecasting; 3) warning dissemination and communication; and 4) preparedness and response capabilities.

2.2. THE WARNING VALUE CHAIN CONCEPT

The value chain concept has gained popularity as a tool for describing and assessing the production and use of weather warnings that are often established through co-design, co-creation, and co-provision (Golding et al., 2022; Tan et al., 2022). The aim of the production of warnings as a value chain is to provide information that enables the best decisions to be taken before and during an event, both by individuals and by those with the responsibility to protect others, with the common goal of enabling timely action to reduce risks (Golding et al., 2019). The warning value chain is characterised and visualised by Golding et al. (2019) as a sequence of peaks and valleys (Figure 1) where the peaks represent expertise. The valleys ("valley of death") represent communication gulfs between different areas of expertise, coined as a metaphor of the failure of research to lead to successful innovation (Tan et al., 2022). Each part of the chain is typically associated with an expert community that delivers that function (Figure 1). The figure shows the warning value chain between expertise in observations, weather, hazards, and impacts, including their forecasts, warning communication, and decision making and response.

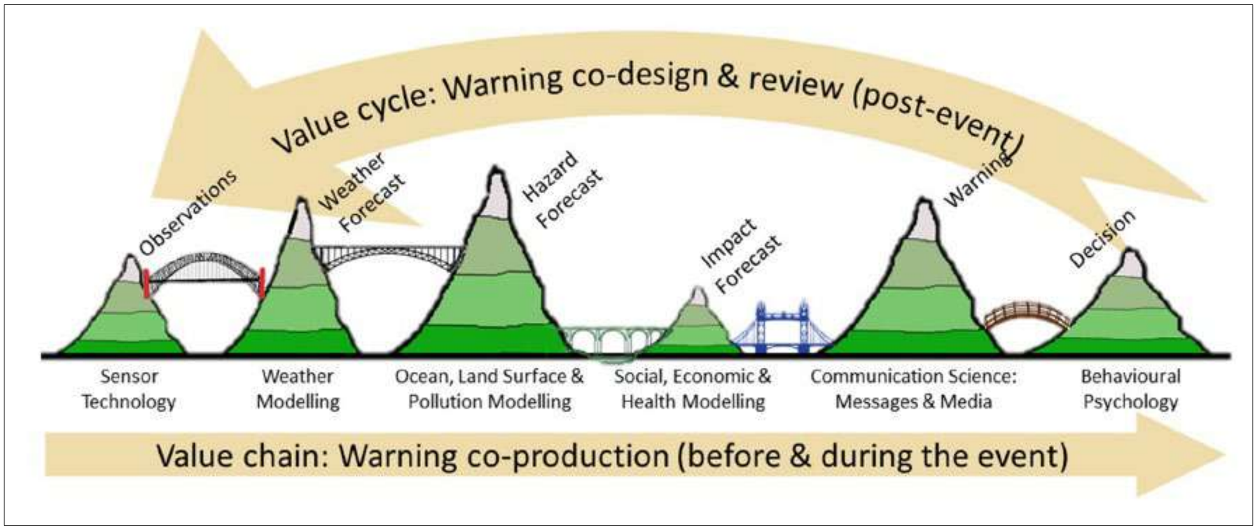


Figure 1. The warning value chain concept proposed by Golding et al. (2019) was adapted (Tan et al., 2022). The peaks of expertise, valleys of death, and bridges of communication between them, in a conceptual value chain for a weather-related hazard warning**.**

According to Tan et al. (2022), data transmission and information sharing between units at each stage of this warning value chain are often imperfect. They noted that citizen science has been proven useful in bridging gaps by providing local and on-the-ground data for research; however, there is limited understanding of citizen science's role in bridging gaps in the warning value chain. Highly participatory projects actively involve citizens in the project design, data collection, analysis, and co-production (WMO, 2021). Similarly, in other citizen science projects, scientists can take a more leading role in designing and coordinating projects, and citizens contribute passively or actively through data collection or analysis (WMO, 2021). The citizen science project design depends on the citizens' and scientists' level of engagement, and both contribute to the dynamics of how projects operate.

The argument is that each component of the warning value chain visualised by Golding et al. (2019) in Figure 1, such as hazard monitoring, modelling and forecasting, risk assessment, communication, and preparedness activities, is associated with an expert community that executes that function. The challenges that are encountered between the communities represented by bridges show the importance of communication in linking the expert communities to promote an efficient flow of information and data to inform models and other decision-making processes. According to Harrison et al. (2022), the value chain consists of various associated data inputs and outputs for each point where hazard, exposure, and vulnerability data are required in the different warning chain stages to ensure that it operates effectively. By continuously improving communication and tools that are used by weather services, the value can be further enhanced, resulting in increased confidence, accuracy, lead time, and engagements. On the other hand, value may also be decreased when all the information available is not utilised due to the fact that each stakeholder within the chain has their own objectives, resources, and constraints (Golding et al., 2019). The authors argue that roadblocks or bridges can be created by the lack of data, access, and data processing and management skills, but experience and innovations can improve the value cycle, increasing the number of people contributing to the system design and operation.

WMO (2021) summarised the different typologies and simplified the roles of citizens and scientists into a matrix (Figure 2) based on the citizens' and scientists' level of engagement. It describes citizen scientists as sensors, interpreters, engagers, or collaborators, and scientists as instructors, collaborators, or co-creators, on different citizen science project types as well as their influence.

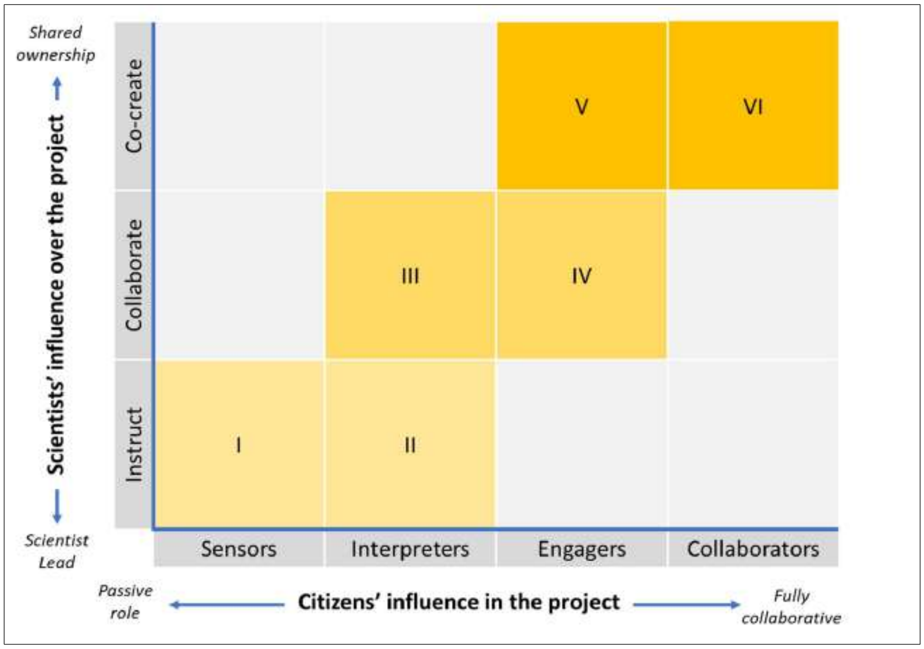


Figure 2. Matrix on the typology of citizen science projects based on citizens' and scientists' levels of influence (WMO, 2021).

According to WMO (2021), in their capacity as sensors, citizen scientists can observe and gather data for the projects, as interpreters, they can be actively involved in both data collection and analysis, as engagers, they can be involved in the development of the problem and project design, and as collaborators, they can be involved in the co-production process. The sensor role can also be passive, such as downloading an app that allows data gathering via phone, or active, such as taking photos or daily logs of information. Even though citizens can actively engage in the project design and data collection, they still require scientists' expertise in the analysis and interpretation of the results. Scientists can influence the citizen science projects by taking the instructional and leading roles while integrating the citizens' participation and facilitating co-creation. In the instructional role, they exercise primary authority depending on their expertise and take responsibility for the entire research design, while the citizens contribute data. In the collaborative role, they initiate the research design, while citizens contribute to data gathering and, in some cases, also help to design, analyse, or disseminate. In co-creation, both scientists and citizens work together throughout the project (WMO, 2021).

While it is generally accepted that self-motivation, interest, and willingness to learn are some of the key drivers for the participation of citizen scientists in projects, it is important to consider the challenges of citizen science projects that need to be managed carefully to ensure effectiveness and inclusivity. In some cases, a certain level of expertise is expected depending on the type of data to be gathered and analysed, which may require training and monitoring of the data quality, and this may have associated costs. Sauermann and Franzoni (2015) note that the citizen scientists' interests and willingness to participate may change or decrease as the project progresses. They may feel overwhelmed by the commitments, or feel that their contributions are not valued, or feel less empowered to continue, or sometimes their expectations may lead to conflicts among participants and/or with project organisers (Walker et al., 2021). Pan (2020) highlights that citizen scientists have the potential to assist in the handling of misinformation during events, thereby playing an important role in the value chain, and also using multiple channels can help to improve decision-making when communicating risks. Citizen science can play a key role as an engagement tool to bridge gaps and enhance communication between authorities and the public, and also as a platform for awareness and inclusivity for disadvantaged groups within communities. Furthermore, education and awareness play a key role in responding to weather hazard warnings, and while school is the ideal place to learn (Scolobig et al., 2022), there should always be ongoing education about hazards and their impacts, warnings, and capabilities. According to Scolobig et al. (2022), there are different approaches to educating the public, ranging from talks and workshops to communicating forecast certainty and finding new ways to inspire the public to take necessary precautions during extreme weather events.

2.3. SUMMARY

The warning value chain concept highlights how crucial it is to comprehend how warning signals come from are processed and eventually affect how complex systems make decisions. This idea emphasizes that timely, understandable, and actionable signals are just as important to effective warnings as information transmission. Organisations can find possible points of failure or delay that could jeopardize the efficacy of warnings in preventing or mitigating adverse events by examining the complete value chain from detection to dissemination. The warning value chain also emphasizes how different parts of the warning process are interconnected. It highlights the functions of sensors, communication channels, interpretive frameworks, and decision-makers, showing how each step can affect warning systems' overall effectiveness. Acknowledging these interdependencies enables focused enhancements like improving sensor accuracy, optimising communication channels, or educating decision-makers on proper signal interpretation. In the end, this all-encompassing perspective aids in the creation of warning systems that are stronger and more resilient, able to handle intricate threats. The warning value chain concept is an essential framework for assessing and enhancing warning systems. It promotes an all-encompassing strategy that takes into account each link in the chain, guaranteeing that warning signals are not only produced but also successfully received and responded to. By putting this idea into practice, organisations can enhance their ability to safeguard people and property from a variety of threats, optimise their warning systems, and more accurately predict possible malfunctions. In order to improve overall safety resilience and advance proactive risk management, this systemic approach is crucial.

CHAPTER 3: STUDY SITES AND METHODOLOGY

3.1. STUDY SITES

3.1.1. Swayimane

Swayimane is a rural and peri-urban community in the uMshwathi Local Municipality under the uMgungundlovu District Municipality in KwaZulu-Natal (Figure 3). The area is located about 40 km outside Pietermaritzburg and falls under the Gcumisa Traditional Authority. The main language spoken is IsiZulu. It is part of the greater uMgeni Catchment, which is considered one of the important water catchments in the country and provides water to almost half of the province's population (Adaptation Fund, 2014; Ndlovu et al., 2021). Land in Swayimane is mainly used for small-scale farming of crops such as maize, beans, amadumbe, sweet potatoes, and sugarcane.

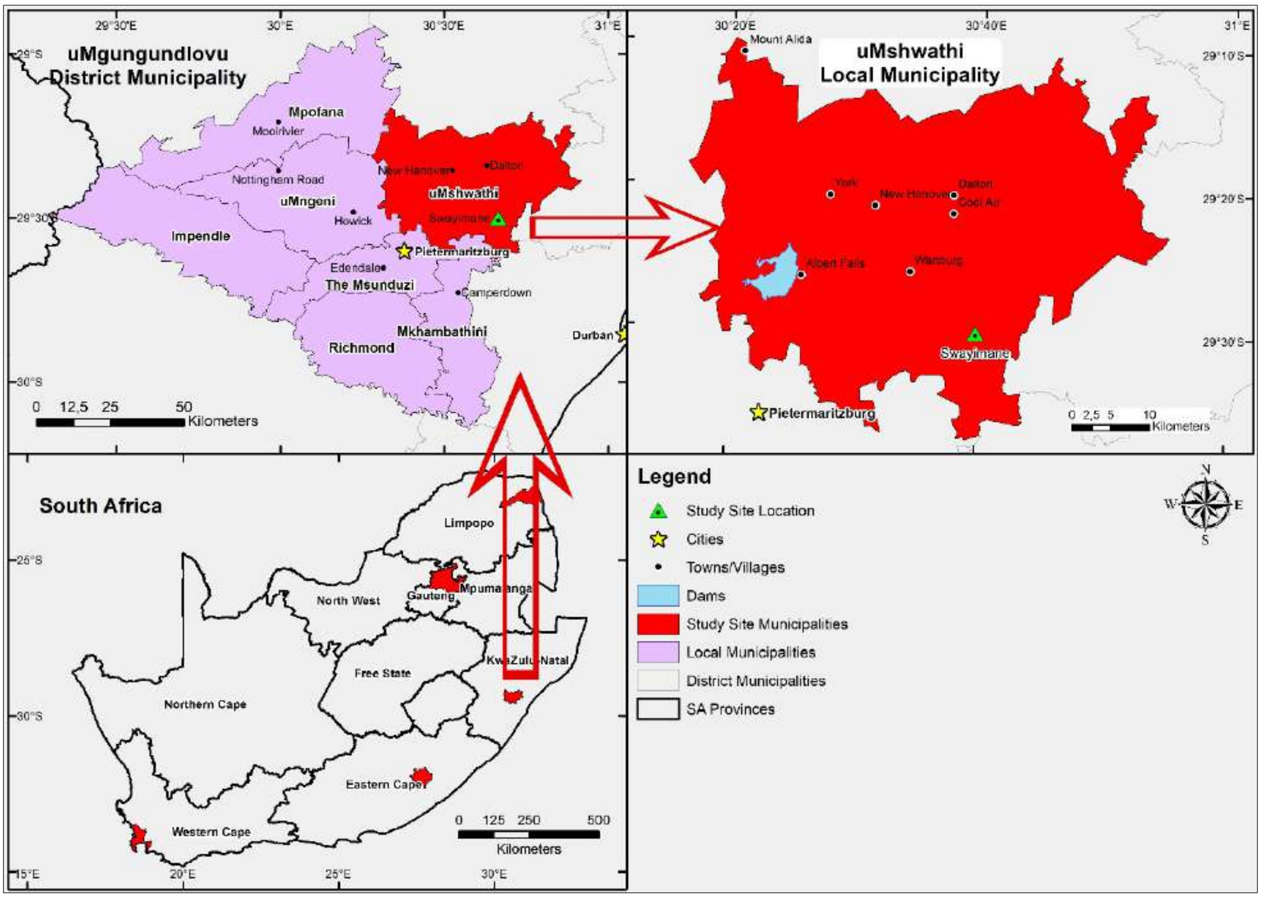


Figure 3. Map showing the location of Swayimane in the uMshwathi Local Municipality.

Food production in this municipality has been affected by shifts in seasonal patterns and increased rainfall variability; however, some programmes have been implemented in the area with variable outcomes to support conservation agriculture for the smallholder farmers (Mathebula et al., 2018). Other extreme weather experienced in the area includes floods, strong winds, and wildfires. The uMgungundlovu District Municipality faces other challenges, such as poverty, poor land use management resulting in land degradation, and over-exploitation of natural resources. The most vulnerable groups in the district are women, children, youth, and the elderly. Future projections indicate warming, while rainfall changes are uncertain, but there is an increased incidence of floods and droughts. Swayimane High School was chosen as the location for the installation of the CWS for weather data collection, and the students from the school and the local community participated as citizen scientists in the project.

3.1.2. Cullinan

Cullinan is a small diamond mining and farming town located about 44 km east of Pretoria Central, and is located in the City of Tshwane Metropolitan Municipality in the Gauteng Province (Figure 4). The main languages spoken in Cullinan are Afrikaans, Sepedi, English, and Sotho. Cullinan is predominantly rural, and it includes a township, i.e., Refilwe, established as a mine residence for African mine workers. Agricultural activities in Cullinan include livestock farming, poultry, and maize production. There are some tourism activities based on the mine. The town is in the upper catchment areas of the Premiermynloop and the McHardyspruit, which form part of the Pienaars River sub-system (IFC, 2015). There has been conflict between farming and mining communities due to increased environmental degradation (including pollution, loss of flora and fauna, and loss of wetlands) and competition for water (Kings, 2013; Kritzinger, 2018; Munnik et al., 2018). Extreme weather events identified in Cullinan include floods, hailstorms, and heatwaves. Climate change projections indicate a potential for these extreme weather events to increase in the future. The school selected for this project is Viva Connect in Refilwe, Cullinan.

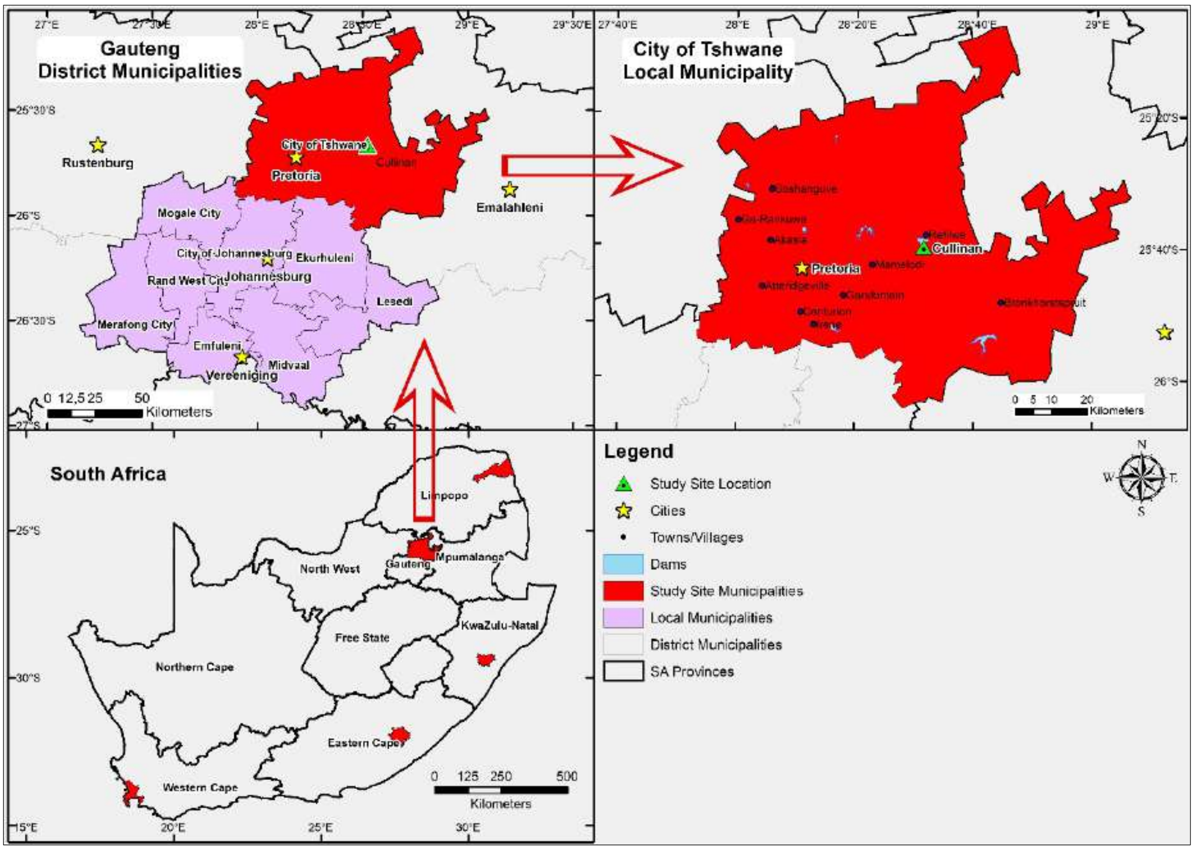


Figure 4. Map showing the location of Cullinan in the City of Tshwane Metropolitan Municipality.

3.1.3. Manenberg

Manenberg is a township in the City of Cape Town Metropolitan Municipality located in the southern peninsula of the Western Cape Province (Figure 5). It is located about 20 km from central Cape Town and is one of the most disadvantaged communities that was established during apartheid to accommodate coloureds on the Cape Flats (Jacobs, 2013). The main languages spoken are Afrikaans, English, and IsiXhosa. The community has high rates of unemployment, gang violence, and drug abuse that can be attributed to factors such as historical social displacement and socio-economic circumstances like high crime rates, domestic violence, overcrowding, and poverty (Davids, 2020). Manenberg also includes canals such as the Vygekraal Canal that feed into rivers in the province, but often get flooded during the rainy season, mostly due to blockages of stormwater gullies (Badroodien, 2022).

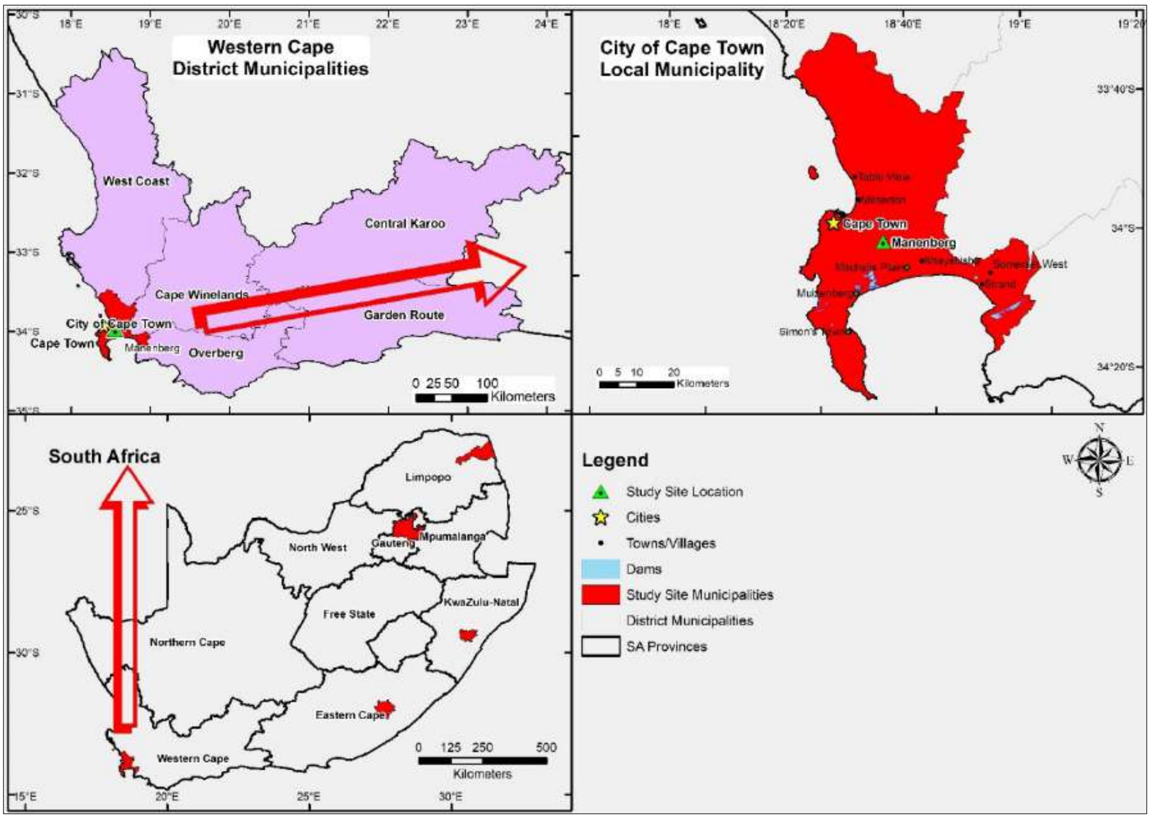


Figure 5. The location of Manenberg in the City of Cape Town Metropolitan Municipality.

Key challenges that communities face in the area include limited access to basic services, including education, water and sanitation, as well as healthcare. Residents in Manenberg are currently affected by floods and heat waves, and projections indicate that there is potential for these extreme weather events to increase in the future, with impacts on human lives and urban infrastructure. Records show that in August 1999, the community was affected by a microburst popularly known as the Manenberg tornado, which was caused by downdraught winds, or air that falls out of a thunderstorm system, resulting in damage to homes, leaving some people homeless (RADAR Western Cape, 2010). The school selected for this project in Manenberg is the Leadership College (TLC), and support was provided by the Islamic Relief South Africa (IRSA), a non-profit organisation working in the community.

3.1.4. Malamulele

Malamulele is located in the Collins Chabane Local Municipality, within the Vhembe District Municipality in the Limpopo Province, bordering Zimbabwe and Botswana to the northwest and Mozambique to the southeast (Figure 6).

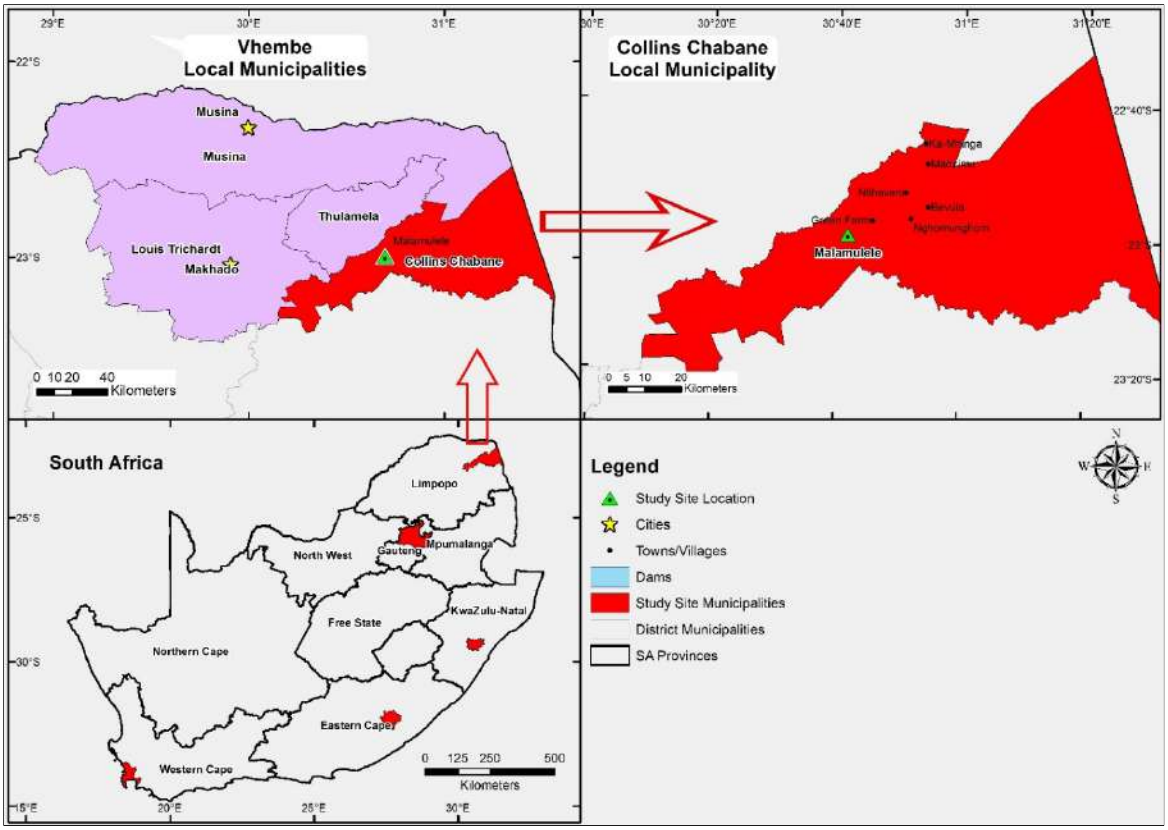


Figure 6. Location of Malamulele in Collins Chabane Municipality.

Xitsonga is the most widely spoken language in Malamulele. The main economic activities include agriculture, mining, and tourism, with the Kruger National Park as one of the major tourist attractions. While agriculture is a key economic activity that supports many livelihoods in the district through vegetable, citrus, subtropical fruits, and nut production, it has also resulted in overexploitation of surface and groundwater for irrigation, for example, in the Sand Catchment, Nzhelele Catchment, and Albasini Dam (Petrie et al., 2014; VDM, 2022). The concerns for water security are compounded by the expansion of mining, which also uses a large proportion of the water in the municipality, with impacts on water quality downstream, with the Olifants River being highlighted as one of the most polluted rivers in the Limpopo River Basin (LIMCOM, 2020).

Current extreme weather events in Malamule include floods, drought, and heatwaves, which are exacerbated by socio-economic issues such as poverty, unemployment, and limited access to education. Extreme weather events are projected to increase in the future and, if unabated, will continue to impact water, food, and energy security. In addition, the site is vulnerable to health risks such as vector-borne and waterborne diseases, including malaria and cholera, the latter of which is worsened by poor access to safe drinking water, inadequate sanitation facilities, and poor personal hygiene. The E.P.P. Mhinga Secondary School in Malamulele has been selected as one of the project sites.

3.1.5. Cofimvaba

Cofimvaba is a rural town in the Intsika Yethu Local Municipality that is under the Chris Hani District Municipality in the Eastern Cape Province (See Figure 7). It is located about 80 km from Queenstown and serves as a hub for surrounding villages and communities (Tshaka et al., 2023). The most common language spoken in this area is IsiXhosa. Community services, trade, and agriculture are the main economic activities. Small-scale livestock farming and crop production are some of the prominent livelihood activities at the community level, with most of the land falling under the communal land tenure system (CoGTA, 2020).

There is potential to increase agricultural production in this area; however, this is currently constrained by a lack of funding and equipment, land degradation, soil erosion, skills shortages, and poor infrastructure (Meyiwa et al., 2014; Intsika Yethu Local Municipality, 2022). Cofimvaba is vulnerable to high temperatures, which have implications for agricultural productivity, water availability, and human and animal health. Other extreme weather events affecting this area include floods, drought, and heatwave events, which are exacerbated by socio-economic issues such as poverty, unemployment, inequality, and limited access to basic services (CoGTA, 2020).

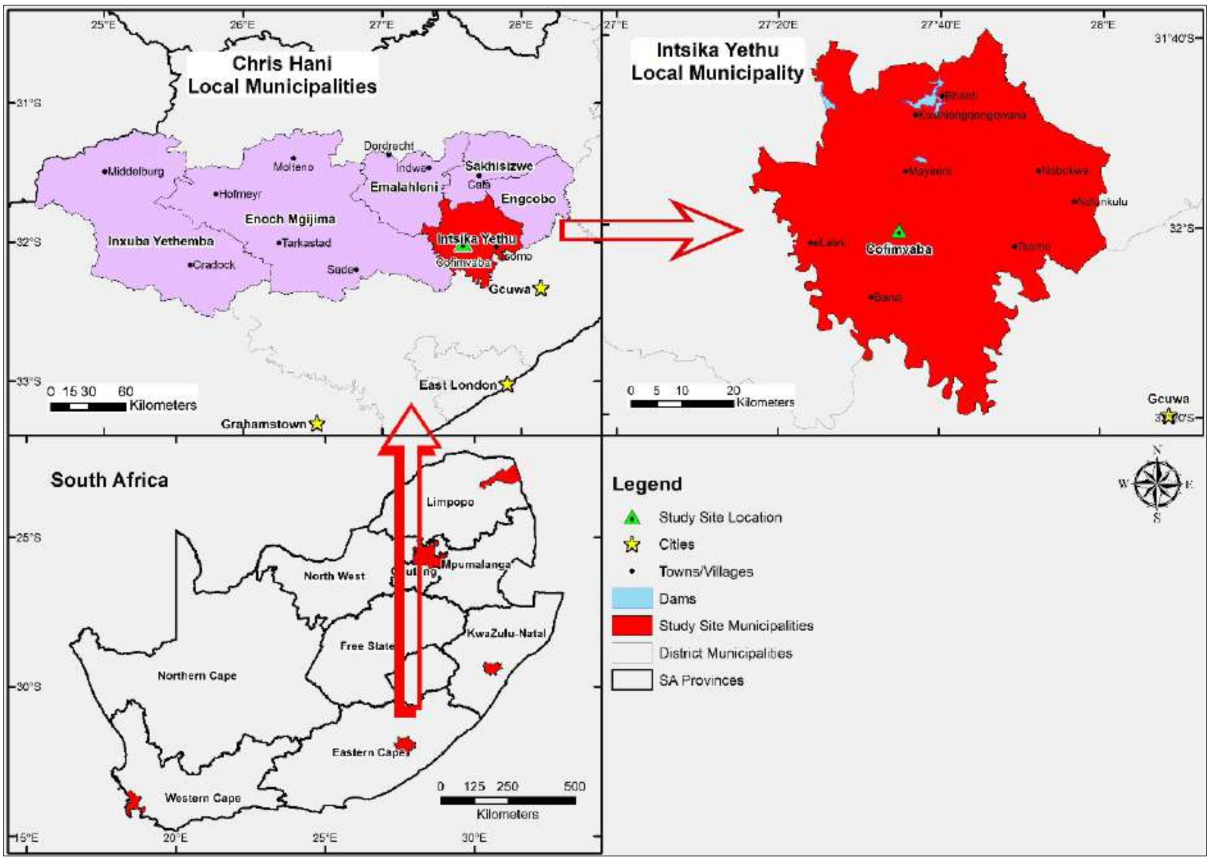


Figure 7. Location of Cofimvaba in the Intsika Yethu Local Municipality.

3.2. METHODOLOGY

The concept of the co-created citizen science approach is used in this study, which is an open collaborative approach, where citizens have a specific problem, question, or issue they would like to investigate (Bonney et al., 2009; WMO, 2021). The project was carried out through four phases of citizen science engagement, i.e., initiation phase, development phase, live or participatory science phase, and analysis and reporting phase. The project team, consisting of scientists from the SAWS, UCT, and UKZN, engaged with citizen scientists from the five communities in the study sites, namely, the Viva Foundation Schools in the City of Tshwane, Swayimane High School in KwaZulu-Natal, The Leadership College (Manenberg), Cape Town, The Albertina Sisulu Science Center, Cofimvaba (Eastern Cape), and E.P.P. Mhinga Secondary School in Malamulele (Limpopo). All five study sites have experienced extreme weather events that have caused damage to lives, livestock, agricultural fields, homes, and other infrastructure.

3.2.1 Enrollment and capacity building of citizen scientists

As stated above, the study was implemented with Citizen Scientists from five case study sites, including schools and community centres in KwaZulu-Natal, Eastern Cape, Limpopo, Gauteng, and the Western Cape provinces. The enrollment of citizen scientists from the study sites was done using the citizen science engagement, comprising four phases. The first phase included the use of workshops and interviews in the study sites to first get permission/approval from relevant authorities, for example, municipal councillors and/or traditional leaders. Virtual and in-person meetings have been used to get permission/approval from relevant authorities such as provincial education departments, school principals, and disaster management departments. A follow-up workshops were held with participants to co-create an early warning shared vision for their respective community, share the objectives of the study, identify volunteers who would like to be CS, and explain the benefit/s (incentives) for the participants/ communities. About 10 to 15 volunteer citizen scientists were selected from each site, including learners from primary and high schools, tertiary institutions, and community members.

The second phase of the CS process was the development phase, whereby community engagement workshops were held to assess their knowledge of climate risks in their respective communities (community risk assessment), drivers of vulnerability, early warning, and current adaptation or response mechanisms (assets and capabilities) available, which includes the knowledge from local Indigenous Knowledge Systems (IKS). This phase also included participatory activities with communities to share simplified weather, climate, and impact-based early warning terminology, and co-design a community-based early warning system that would be used to alert the community of impending disasters, building on the capacities and assets available in their community. The success of these activities required support from different stakeholders, including the local government, disaster management centres, community leaders, and SAWS, to disseminate the information through the different community structures. The third phase was the live phase. Specific activities included training citizen scientists to collect, interpret, and disseminate weather information from their simple automated weather stations and early warning tools. The following weather parameters were monitored: solar radiation, air temperature, relative humidity, wind speed and direction, rainfall, lightning detection, and UV. The community co-led the process of developing and identifying different tools and implementing the best tool for disseminating early warning information from SAWS, i.e., impact-based warnings relevant to their community, through the citizen scientists.

To keep track of how IKS informs knowledge of changes in seasons, the project team, together with volunteers, engaged community members such as the elderly, traditional leaders, and traditional health practitioners through targeted vital informant interviews, transect walks, and focus group discussions to share stories and highlight areas affected by extreme weather events based on their experiential knowledge. These narratives were used to document indigenous and local knowledge from each community and illustrate possibly how they foretell the upcoming seasons (IKS-based seasonal forecasts), and the weather changes that they have experienced. The information was compared with seasonal forecasts from SAWS and will be used to compile the IKS information sheet/pamphlet for each study site. The fourth phase of the CS approach was the reporting phase, whereby the activities and lessons drawn from the study sites were compiled into a report. The findings will also be shared with the communities through different platforms, and these can include community workshops and pamphlets in the local languages (e.g., IsiZulu, IsiXhosa, and Xitsonga) to increase uptake in the respective communities. Citizen scientists will receive certification to commend them for their role and competence in CS. In addition, the citizen scientists were trained to monitor the stations and will continue with this role with support from relevant stakeholders upon completion of the project to ensure the sustainability of the early warning system. The Viva Foundation school in Cullinan is using low-cost CWS data to teach learners for academic purposes and also sharing information with nearby farmers.

3.2.2 Intercomparison of low-cost citizen weather stations

In addition to the simple AWS, the study also included an intercomparison field study of low-cost Citizen Weather Stations (CWSs) against standard professional weather stations. This intercomparison study was necessary to identify instrument performances, biases, and dependencies. Different models of popular low-cost CWSs and standard SAWS AWS were used in the intercomparison study. Measurements and intercomparisons of the weather monitoring sensors were undertaken to check data quality and bias of CWS data covering varying weather patterns and synoptic conditions. The sensor intercomparison study was conducted in collaboration with a team from the University of KwaZulu-Natal.

The project had originally intended to include locally produced weather monitoring tools (such as the sensors utilised in the GroundTruth for the Citizen Science Tools Development project) in the intercomparison study. However, this was not feasible because these sensors are not specifically designed for early warning purposes and their data is not sufficiently accurate to be included in the comparison. Data is collected manually using these GroundTruth sensors and is not digitized for real-time transmission to be used in EWS. For the intercomparison study, the following low-cost CWS stations with estimated costs per station were selected: 7-in-1 Wireless Weather Station With 4-Day Forecast (R7,500), AcuRite Iris Weather Station + My AcuRite Access + Lightning Detector (R10,200), HP 2000 Wireless Weather Station Kit (R12,000), and HP2551CA kit + WH57 Lightning Detector + WH51 Soil Moisture Sensor (R7,500).

CHAPTER 4: INTERCOMPARISON OF CITIZEN WEATHER STATIONS

4.1 INTRODUCTION

One of the approaches to understanding our environment and adapting to changing weather patterns and climate is to improve weather prediction by using weather instruments to provide accurate and timely local weather data, which is necessary to capture small-scale variations and extreme events. This can be achieved using automatic weather stations (AWSs) for accurate and timely weather data collection and transmission, with an increased density of AWS networks covering large areas under observation (Cooper et al., 2008). Generally, weather parameters are monitored and measured by observers using manual and automatic stations at several sites every day. The most common weather parameters that are observed include solar radiation, air temperature, relative humidity, precipitation, wind speed and direction, and air pressure (WMO, 2003). At present, AWSs are available as commercial products with a variety of facilities, specifications, options, and prices. However, the high cost of available AWSs makes it a challenge to buy them in large numbers in most developing countries (Nsabagwa et al., 2019).

Generally, the measurement of weather parameters and data collection has been performed by professional meteorological organisations. However, in the last decade, with technological advancement, there has been a continuous increase in the number of low-cost AWSs, which come in a variety of designs and configurations. This has enabled other organisations, industries, individuals, and citizen scientists to collect weather data for various purposes. The World Meteorological Organization (WMO) recognises these types of Low-Cost Automatic Weather Stations. These stations are characterised by their relatively low cost, low power consumption, the transmission of data in real-time (with or without logging), and their small and compact size (WMO, 2018). Nevertheless, data quality remains a significant concern for some CWS stations; hence, there is a need for intercomparison of CWSs against standard professional weather stations to identify the best-performing CWSs.

One of the project goals was to implement simple, low-cost, and robust AWSs or CWSs that can be easily used by citizen scientists for data collection. Therefore, it was crucial to identify the affordable CWSs that could help achieve this goal without compromising data quality, timely collection, and transmission of the data, which would be beneficial for many applications. Uncertainty about CWSs data can arise from calibration issues, design flaws, communication and software errors, metadata issues, and representativity errors (Bell et al., 2015). To address some of these uncertainties, an intercomparison field study of selected low-cost CWSs was done against standard professional weather stations to quantify bias and errors associated with CWSs.

4.2 AUTOMATIC WEATHER STATION: SPECIFICATIONS AND REQUIREMENTS

An AWS is an instrument that measures and records weather parameters using sensors, stores the data in a data logger, or automatically transmits records to a remote location via a communication link. In an AWS, the measurements are converted into electrical signals through sensors, then processed and transformed into meteorological data, and finally transmitted by wire or radio, or automatically stored in the data logger (Ahmad et al., 2017). The specifications and requirements of AWS and best practices are presented in phase 1 of this citizen science project (Mengistu et al., 2022). The project team conducted a desktop review of commercially available low-cost AWSs and recommended the HP2000 professional wireless weather station to be used as a citizen weather station (Mengistu et al., 2022). The requirements for an acceptable AWS system depend on a proper understanding of the needs, which include the satisfaction of both end-user and system expectations. Nsabagwa et al. (2019) analysed the requirements of a typical AWS and categorised these requirements under functional and non-functional requirements. Functional requirements capture the behavior of the system and are expressed as tasks or services of the system, such as basic data collection, captured data processing and buffering, and data transmission. The non-functional requirements include external interfaces, attributes, design constraints, and performance constraints (Nsabagwa et al., 2019). All AWSs must have meteorological sensors that produce analog signals, electronics to convert these signals into digital values, and the capacity to store and transmit the measured data (Tanner, 1990).

Although AWS collects and transmits data automatically, an interface is required to monitor and configure its operations. Benchmarking the AWS against a standard instrument is necessary to determine the accuracy of the AWS. Furthermore, proper siting of an AWS and sensor calibration are crucial for data accuracy and should be checked to ensure and conform to standards (WMO, 2018). According to the WMO, data acquisition using an AWS involves the following main functions: data sampling, data processing, and converting the data into digital numeric values that can be manipulated by a computer or data processors. AWS should have low power consumption, powerful remote communication capability, high-precision sensor interfaces, and high reliability measures to ensure timely weather data processing. Based on the means of data acquisition, WMO categorises AWSs into Offline and Online AWSs. Offline AWSs are described as stations recording data on-site without any automatic transmission. These types of AWSs are used less nowadays, mainly because data is not available in real-time, and stations do not allow fast detection of possible failures. Therefore, WMO recommends the use of online AWSs even for climatological data. The online data acquisition system uses wired and wireless communication technologies and should be designed taking into account the ease of change of the telecommunication interface, both in terms of physical hardware and software (WMO, 2018).

Most standard AWSs collect sub-hourly, hourly, and daily basic weather parameters such as precipitation (mm), air temperature (^{o}C), relative humidity (%), air pressure (hPa), wind speed (m/s), direction (^{o}), and many other parameters with a data logger measuring at a higher sampling frequency (e.g., a 60-second interval), and data files are then transferred or downloaded in an ASCII text format.

4.3 DATA AND METHODOLOGY

The intercomparison study evaluated weather parameters measured with selected commercially available CWSs against variables obtained using standard reference South African Weather Service (SAWS) and University of KwaZulu-Natal (UKZN) stations. These experiments were conducted at the SAWS Irene Weather Office, Irene, Gauteng (altitude, 1525 m; 25.911° S, 28.210° E) and the School of AEES, UKZN, Pietermaritzburg, KwaZulu-Natal (altitude, 648 m; 29.628° S, 30.403° E). A detailed description of the standard AWSs and CWSs used in this study is presented in the following sections.

For the evaluation and comparison, 5-minute, hourly, and daily data of the weather variables measured and derived by both the CWSs and standard AWSs were used. A regression analysis was conducted on the average 5-minute, hourly, and daily values obtained from the CWSs, with the corresponding values measured and calculated by the standard AWSs. The CWS values were plotted as the dependent variable (y) against the standard AWS values as the independent variable (x) to determine the slope, intercept, and R^2 values.

4.3.1 Reference Automatic Weather Stations

The standard SAWS AWS instruments installed at Irene (Figure 8) include a HMP155 Vaisala air temperature and relative humidity sensor, a Kipp & Zonen CMP11 pyranometer, a KISTERS TB3 Tipping bucket rain gauge, and an RM Young Wind Monitor-AQ 05305 for wind speed and direction (Figure 9, Table 1). The AWS sensors used as a standard at the UKZN site (Figure 10, Table 2) include a Campbell Scientific CS215 temperature and relative humidity probe, a Kipp & Zonen CMP3 pyranometer, a Texas Electronics TE525 Tipping bucket rain gauge, and an RM Young Model 03002 Wind Sentry Anemometer and Vane for wind speed and direction (Figure 11). These reference AWS sensors used at both sites were calibrated and maintained regularly, meet WMO and other international standards, and can be used as a reference to evaluate the CWS stations used in this study.

4.3.2 Citizen Weather Stations

The Citizen Weather Stations (CWSs) used at the South African Weather Service Irene Office for the intercomparison experiment comprise four different commercially available models: the HP 2551 Professional WiFi weather station; the HP 2000 Professional Wireless Weather Station; the Logia 7 in 1 Wireless Weather Station with WiFi; and the Acurite Atlas Professional Weather Station. Details of the CWS stations are presented in Table 3, with images of the stations shown in Figure 12.

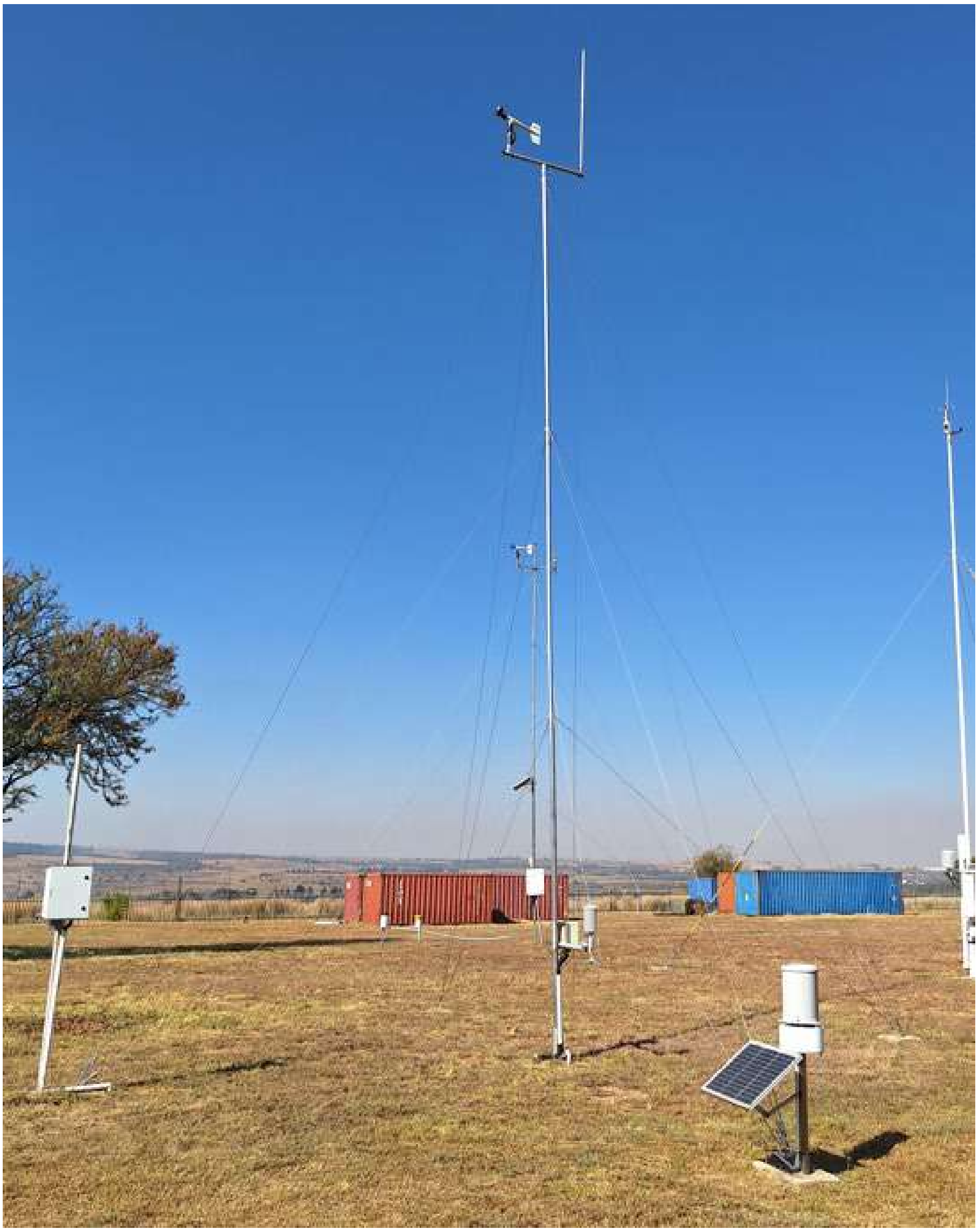


Figure 8. An automatic weather station (AWS) installed with standard sensors used to measure weather parameters at the South African Weather Service Irene Office.

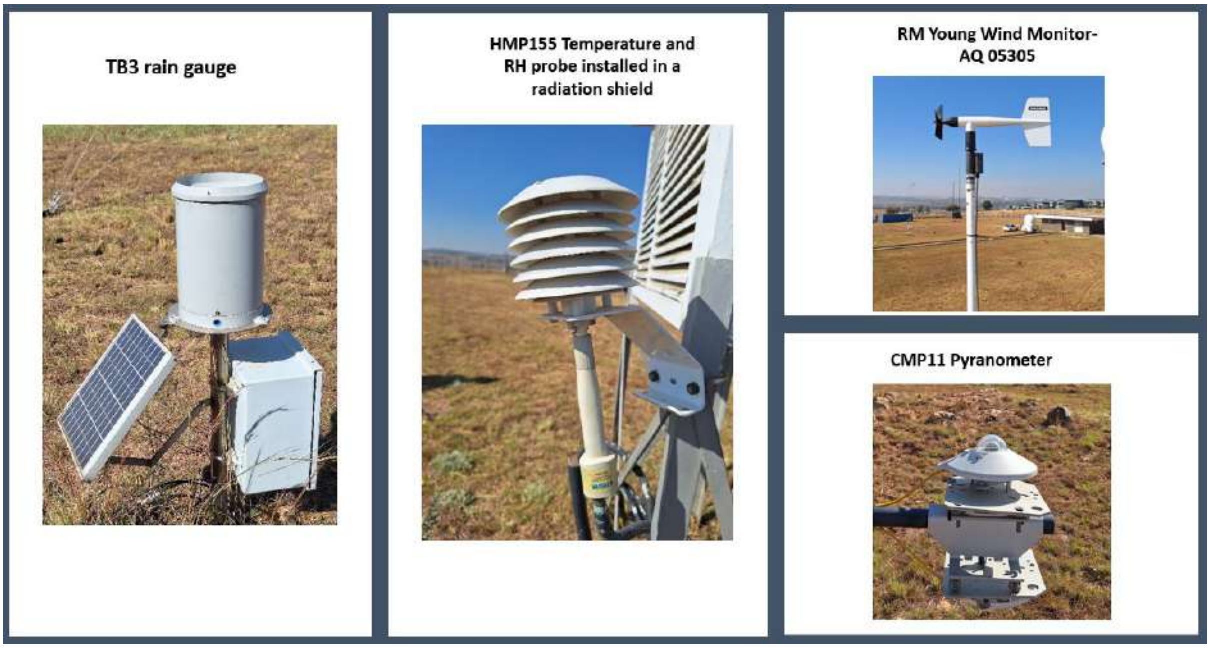


Figure 9. Standard sensors used as references to evaluate CWS stations at the South African Weather Service Irene Office.

Table 1. Weather sensors used in the AWS at the South African Weather Service Irene Office.

Variable	Model No.	Manufacturer	Accuracy
Solar Radiation (R_s)	CMP 11	Kipp & Zonen	± 1 %
Air temperature (T_a)	HMP155	Vaisala	± (0.1 + 0.0017* T_a)
Relative Humidity (RH)	HMP155	Vaisala	± 0.6 to 1.0 % RH
Wind Speed (WS)	05305 Wind Monitor-AQ	R. M. Young	± 0.2 m/s
Wind Direction (WD)	05305 Wind Monitor-AQ	R. M. Young	± 3°
Rainfall (P)	TB3 Rain Gauge	Kisters	± 2 %

Figure 10. An automatic weather station (AWS) installed with standard sensors used to measure weather parameters at the UKZN site in Pietermaritzburg.

Figure 11. Standard sensors used as references to evaluate CWS stations at the UKZN site in Pietermaritzburg.

Table 2. Weather sensors used in the AWS at the UKZN site in Pietermaritzburg.

Variable	Model No.	Manufacturer	Accuracy
Solar Radiation	CM 3	Kipp & Zonen	± 1 %
Air temperature	CS215	Campbell Scientific	± 0.4 °C
Relative Humidity	CS215	Campbell Scientific	± 2 to 4 % at 25 °C
Wind Speed	03002 Wind Sentry	R. M. Young	± 0.5 m/s
Wind Direction	03002 Wind Sentry	R. M. Young	± 5°
Rainfall	TE525 Rain Gauge	Texas Electronics Inc	± 3 %

Table 3. An overview of the sensor capabilities of the CWSs used at the South African Weather Service Irene Office.

Station Name	Model No.	Temperature	RH	Rain	Wind Speed	Wind Direction	Solar Radiation
Professional WiFi weather station	HP2551	±0.1°C	±5%	± 10%	±10%	N/A	±15%
Professional Wireless Weather Station	HP2000	± 0.3°C	±5%	± 10%	±5%	±7°	± 15%
Logia 7-in-1 Wireless Weather Station	LOWSC713SWB	± 0.4°C	±3.5%	± 7%	± 6%	± 4°	0.1 W/m2
Acurite Atlas Professional Weather Station	Model 06059	± 1°F	± 2%	± 5%	± 10%	± 3°	N/A

Figure 12. Commercially available Citizen Weather Stations (CWSs) used at the South African Weather Service Irene Office.

Three widely used models of CWSs were used at the UKZN site in Pietermaritzburg for the intercomparison experiment: the Davis Vantage Pro2 Weather Station, the Decagon Complete Weather Station, and the HP1000 Professional Wireless Weather Station. Table 4 presents a summary of the sensor capabilities of the CWSs, while Figure 13 displays pictures of the stations.

Table 4. An overview of the sensor capabilities of the CWSs used at the UKZN site in Pietermaritzburg.

Station Name	Model No.	Temperature	RH	Rain	Wind Speed	Wind Direction	Solar Radiation
Davis	Vantage Pro2	±0.5°C	±3%	±5%	±5%	± 3°	±5%
Professional Wireless Internet Weather Station	HP1000	± 1°C	±5%	±10%	±10%	N/A	±15%
Decagon Complete Weather Station	Em50g logger	±0.1°C	±5%	±2%	±3%	± 3°	±5%

Figure 13. Citizen Weather Stations (CWSs) used at the UKZN site in Pietermaritzburg.

4.4 ADDITIONAL DERIVED VARIABLES

4.4.1. Heat Index

The heat index (HI), also referred to as the apparent temperature, is the perceived temperature to the human body when the air temperature is combined with relative humidity (Steadman, 1979). It serves as a measure to assess heat exposure, representing the temperature felt by humans, and is crucial for the human body's comfort considerations (Anderson et al., 2013). When the relative humidity (RH) is high, the body's evaporation rate decreases, causing the human body to feel warmer in humid conditions. Conversely, when the RH decreases, the body's perspiration rate increases, leading to a cooler sensation. The heat index is directly influenced by both air temperature and relative humidity, with higher (lower) temperatures and humidity levels resulting in a higher (lower) heat index (Steadman, 1979).

Various heat index algorithms are found in environmental research literature, ranging from simple equations with single terms for air temperature and relative humidity (RH) to more complex equations with exponential or quadratic terms for air temperature and RH. Some algorithms also include correction factors for specific weather conditions (Anderson et al., 2013). In this study, the Blazejczyk et al. (2012) algorithm for calculating heat index in degrees Celsius (HI) is used, based on hourly measurements of air temperature (T) and RH obtained from CWSs and AWSs. The following formula is used to determine the heat index (HI) when the temperature is given in degrees Celsius:

$$HI = -8.784695 + 1.61139411*T + 2.338549*RH - 0.14611605T*RH - (1.2308094*10^{-2})*T^{2} - (1.6424828*10^{-2})*RH^{2} + (2.211732*10^{-3})*T^{2}*RH + (7.2546*10^{-4})*T*RH^{2} - (3.582*10^{-6})*T^{2}*RH^{2} \tag{1}$$

where *HI* = heat index (in degrees Celsius), *T* = air temperature (in degrees Celsius), and *RH* is relative humidity (percentage value between 0 and 100). Correction factor: *HI* = *T* when T ≤ 20°C.

4.4.2. Wind Chill

Wind chill is the feeling of cold caused by the wind for a given ambient air temperature on exposed skin, as the wind speed accelerates the rate of heat transfer from the body to the surrounding atmosphere (NOAA, 2008). It is a measure of how cold the weather feels to the average person and is calculated by combining temperature and wind speed values into a single number that represents the perceived temperature.

There are multiple wind chill formulas in use, as opposed to temperature, due to the lack of a universally accepted standard definition or measurement for wind chill (Osczevski and Bluestein, 2005). The standard Wind Chill formula for Environment Canada is used to calculate Wind chill in metric units of measurement (Kozlowski, 2022):

$$WC = 13.12 + 0.6215*T - 11.37*V_{10m}^{0.16} + 0.3965*T*V_{10m}^{0.16} \tag{2}$$

where, WC is the wind chill index, based on the Celsius temperature scale, T is the air temperature in degrees Celsius (°C), and V_{10m} is the wind speed at 10 metres (standard anemometer height), in kilometres per hour (km/h).

4.4.3. Reference Evapotranspiration

Numerous scientists worldwide have developed a variety of empirical methods in recent decades to estimate evapotranspiration from different climatic variables. These relationships often required rigorous local calibrations and were found to have limited global applicability. A group of experts recommended the adoption of the Penman-Monteith combination method as the new standard for reference evapotranspiration and guided the calculation of the necessary parameters (Allen et al., 1998). This method was later standardized by the Food and Agriculture Organization as the FAO-56 Penman-Monteith model (Allen et al., 1998). The modified Penman method was deemed to provide the most accurate results with minimal error in relation to a living grass reference crop (Allen et al., 1998). It is a method that is highly likely to accurately predict ETo in a wide range of locations and climates, and it can be applied in situations where data is limited.

Reference evapotranspiration (ET_o) is the evapotranspiration from a specified reference surface. The FAO Penman-Monteith method was developed by defining the reference crop as a hypothetical crop with a height of 0.12 m, a surface resistance of 70 s m-1, and an albedo of 0.23. This reference crop closely resembles the evaporation of a green grass surface of uniform height that is actively growing and well-watered (Allen et al., 1998). The equation uses standard climatological records of solar radiation, air temperature, relative humidity, and wind speed. For accurate calculations, the weather measurements should be taken at a height of 2 meters (or converted to that height).

The FAO Penman-Monteith method to estimate ET_o can be derived:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (3)$$

where, ET_o is reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is average air temperature at 2 m height (°C), u_2 wind speed at 2 m height (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), e_s - e_a is saturation vapour pressure deficit (kPa), D is the slope of vapour pressure curve (kPa °C^{-1}), g is psychrometric constant (kPa °C^{-1}).

4.5 COMPARISON OF CITIZEN WEATHER STATIONS WITH STANDARD AUTOMATIC WEATHER STATIONS

The average measured values of solar radiation (R_s), air temperature (T_a), relative humidity (RH), rainfall (P), wind speed (WS), and direction (WD) obtained from the CWSs were compared with values measured using the standard AWSs at 5-minute, hourly, and daily intervals at the SAWS Irene Office and the UKZN site in Pietermaritzburg. Additional derived variables using the weather parameters are also included to observe the impact on the calculated variables and indices. The subsequent sections present the results of the comparison experiment between the CWSs and the standard AWSs.

4.5.1 Solar Radiation

A comparison of the 5-minute solar radiation (R_s) measurements using the different CWSs and the standard reference sensors is presented in Figure 14 for the SAWS Irene site and in Figure 15 for the UKZN site, respectively. In general, the results show good agreement; however, considerable scatter is observed for the Acurite Atlas, Logia (Figure 14), and Decagon CWSs (Figure 15). The Acurite Atlas measurements have shown poor agreement (slope = 0.53) compared to the reference R_s measurements (Figure 14). However, there is a strong correlation between the Acurite Atlas measurements and the standard sensor (R^2 = 0.98), indicating that calibration is needed to correct the measurements. The HP2551 measurements (Figure 14) and Davis (Figure 15) performed best with slopes and R^2 close to 1.

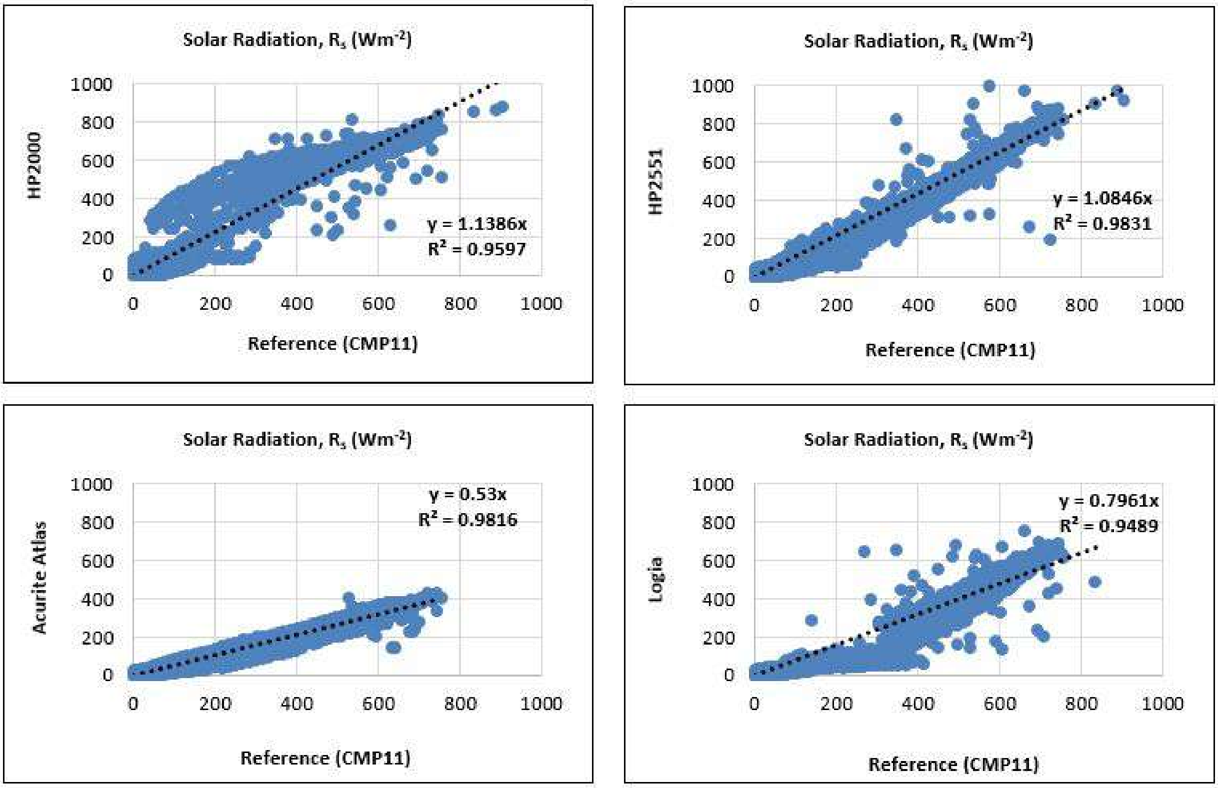


Figure 14. Comparison of the average 5-minute solar radiation (Rs) measured at the South African Weather Service Irene Office using the CWSs and the Rs obtained using the reference sensor (CMP 11, Kipp & Zonen).

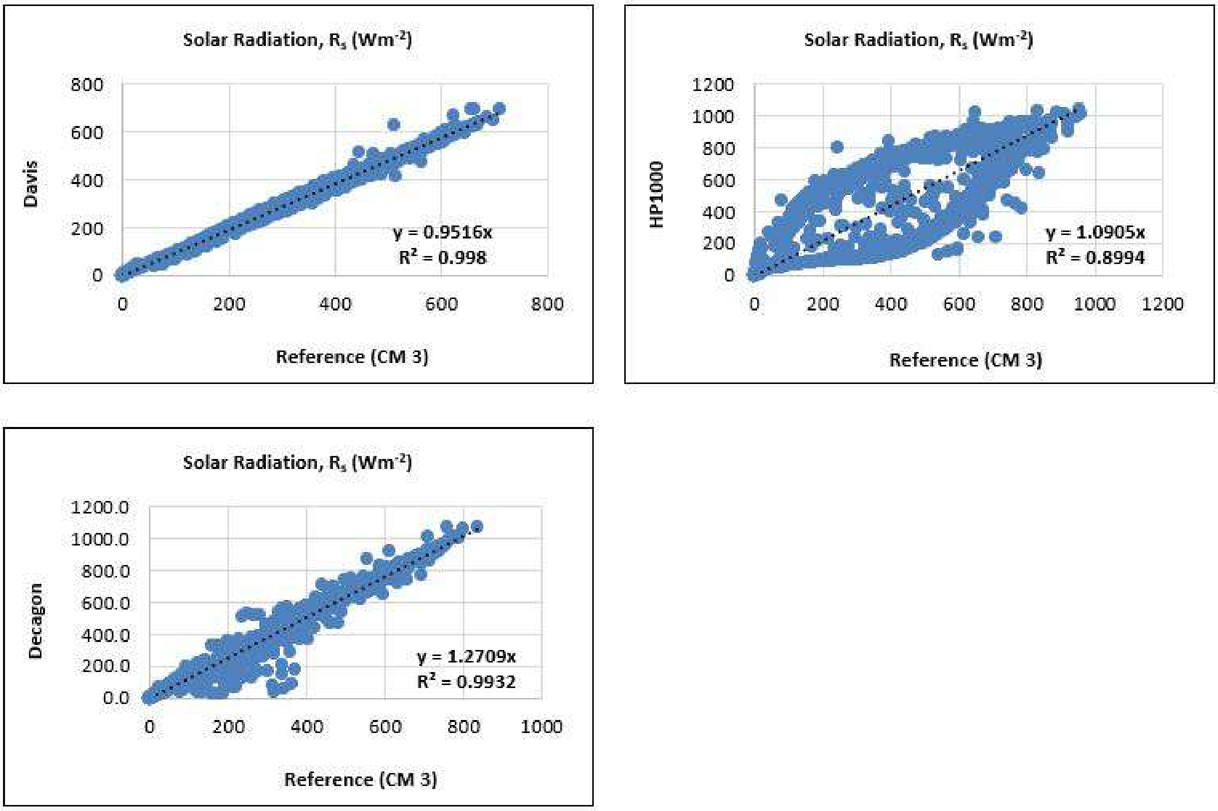


Figure 15. Comparison of the average 5-minute solar radiation (Rs) measured at the UKZN site in Pietermaritzburg using the CWSs and the Rs obtained using the reference sensor (CM 3, Kipp & Zonen).

Figure 16 shows the comparison of the average hourly Rs measurements between the different CWSs and the standard reference sensor at the SAWS Irene site. Figure 17 displays the same comparison for the UKZN site. Similarly, there is a significant amount of variation seen in the data for the Acurite Atlas, Logia (Figure 16), and Davis CWSs (Figure 17). The Acurite Atlas hourly R_s measurements exhibited poor agreement when compared to the reference R_s measurements (Figure 16). The HP2000, HP2551 measurements (Figure 16), and HP1000 (Figure 17) showed the best performance with slopes and R^2 values close to 1.

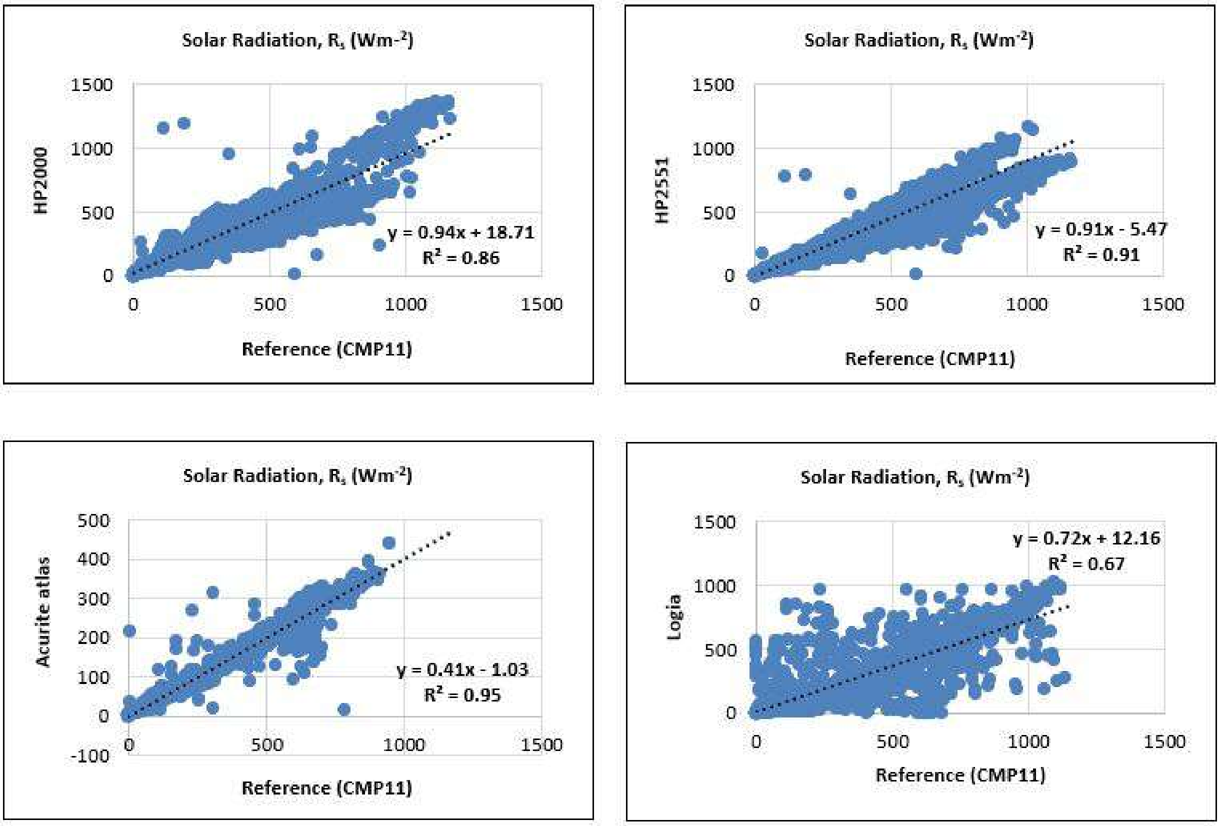


Figure 16. Comparison of the average hourly solar radiation (Rs) measured at the South African Weather Service Irene Office using the CWSs and the Rs obtained using the reference sensor (CMP 11, Kipp & Zonen).

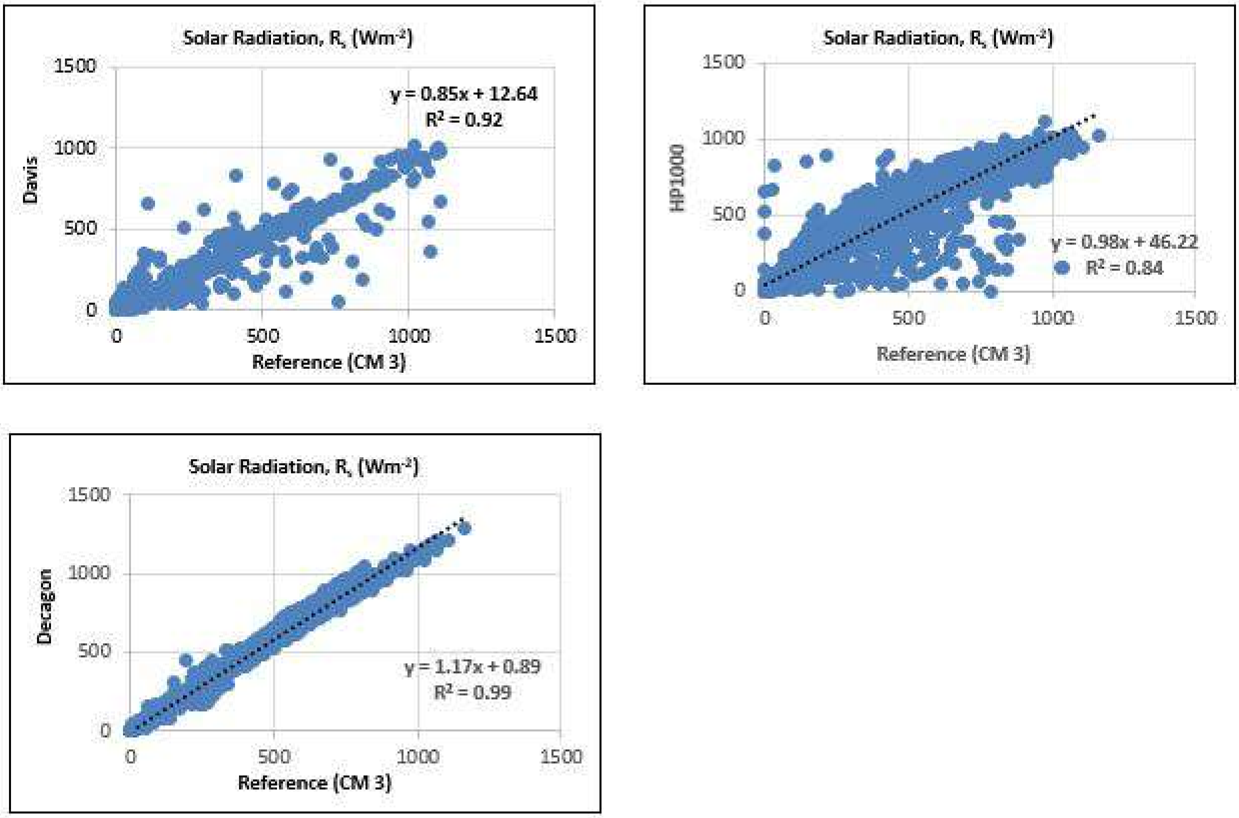


Figure 17. Comparison of the average hourly solar radiation (Rs) measured at the UKZN site in Pietermaritzburg using the CWSs and the Rs obtained using the reference sensor (CM 3, Kipp & Zonen).

4.5.2 Air Temperature and Relative Humidity

The reliability of the air temperature (T_a) and relative humidity (RH) measurements from the CWSs was also assessed against values obtained using the reference sensors (HMP155 and CS215 temperature and relative humidity probes) from the standard SAWS and UKZN AWSs. Figure 18 and Figure 19 display the comparisons between the CWSs' 5-minute T_a measurements and the reference measurements at the SAWS Irene and UKZN sites, respectively. Additionally, hourly comparisons of T_a are shown in Figure 20 and Figure 21 for the SAWS Irene and UKZN sites, respectively.

All CWSs' T_a measurements show very good agreement with the reference sensors. As shown in Figure 18 and Figure 19, the CWSs measurements are strongly linearly related to the standard sensor measurements, with slopes and R^2 close to unity and smaller biases compared to the solar radiation measurements. The hourly comparisons of T_a also showed strong agreement with the reference measurements, except for the Logia, which had a slope of less than 0.90 (Figure 20).

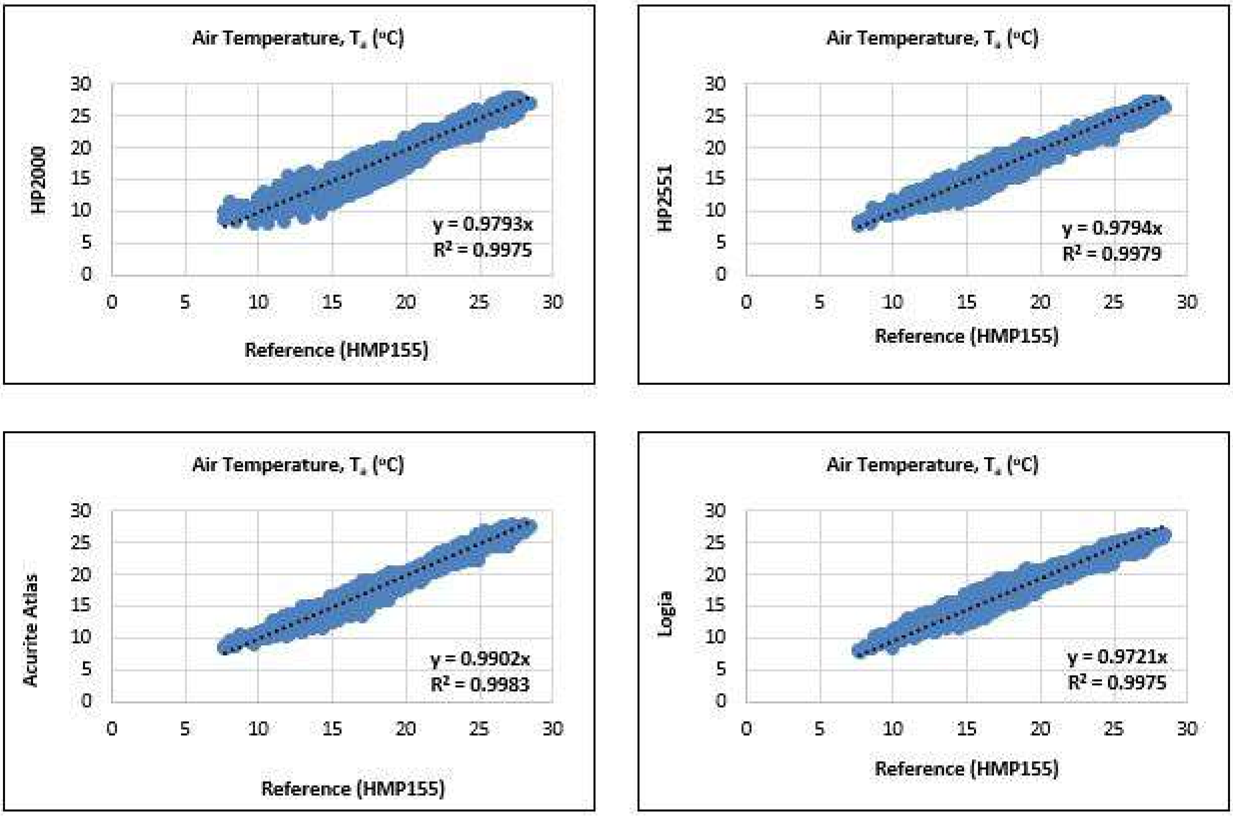


Figure 18. Comparison of the average 5-minute air temperature (Ta) measured at the South African Weather Service Irene Office using the CWSs and the Ta measured using the reference sensor (HMP155).

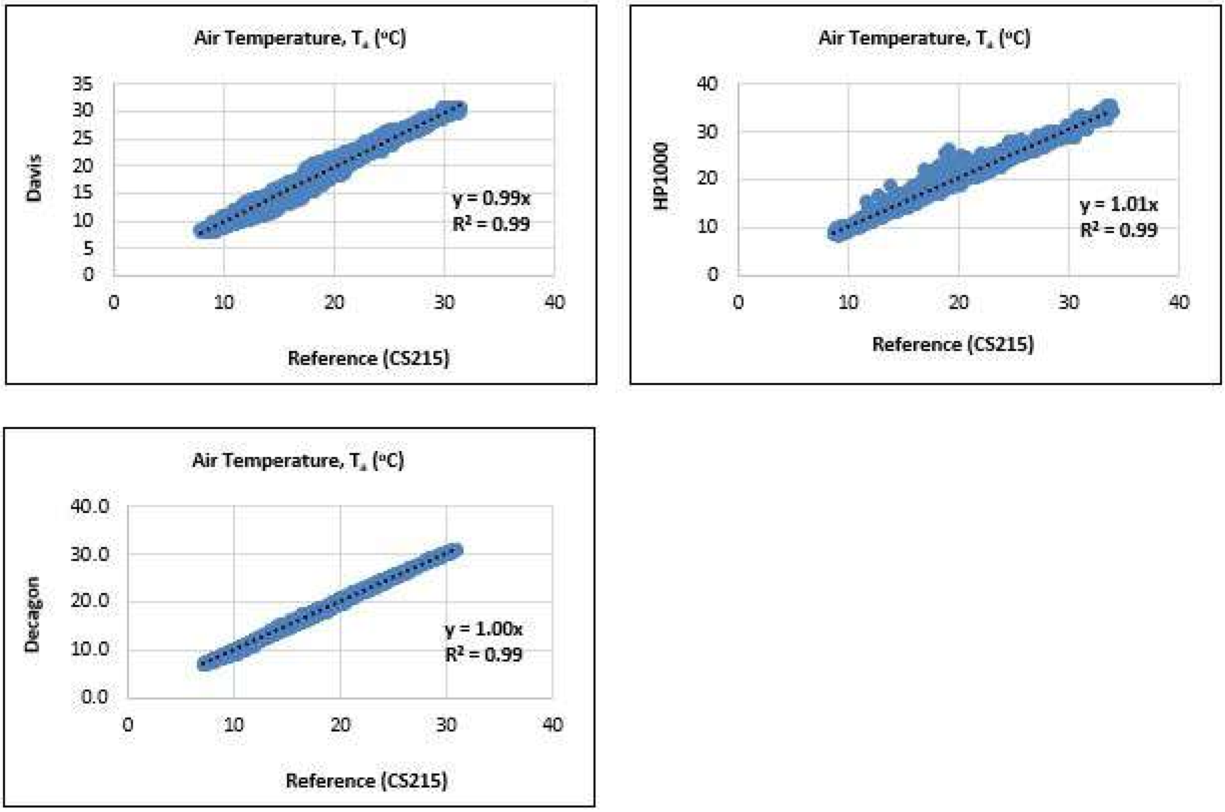


Figure 19. Comparison of the average 5-minute air temperature (Ta) measured at the UKZN site in Pietermaritzburg using the CWSs and the Ta measured using the reference sensor (HMP155).

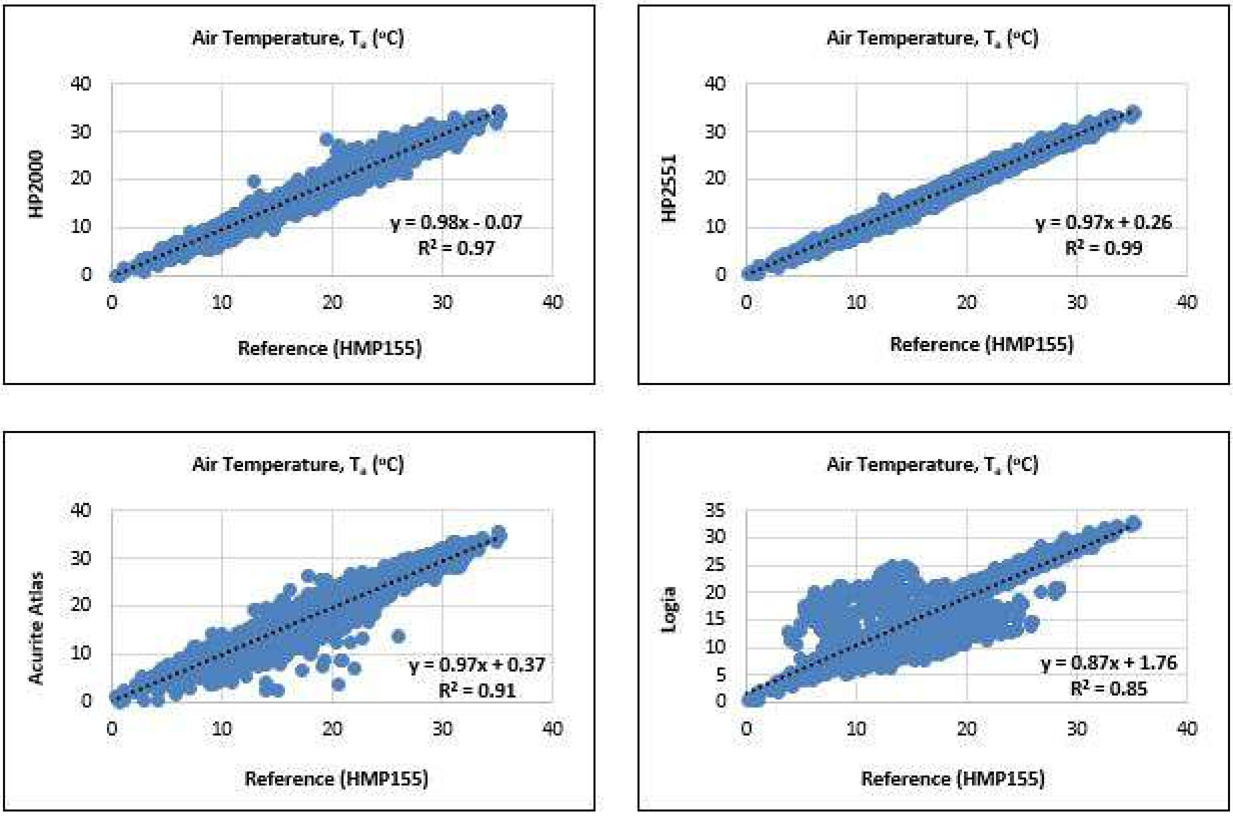


Figure 20. Comparison of the average hourly air temperature (Ta) measured at the South African Weather Service Irene Office using the CWSs and the Ta measured using the reference sensor (HMP155).

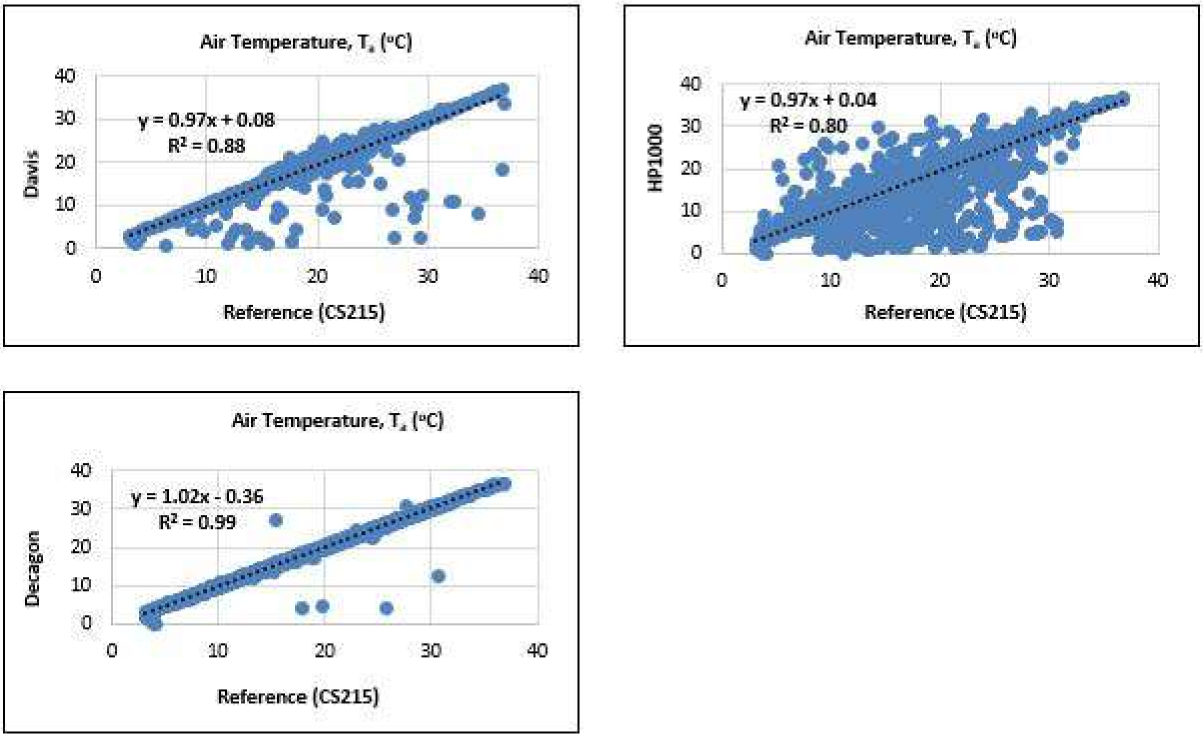


Figure 21. Comparison of the average hourly air temperature (Ta) measured at the UKZN site in Pietermaritzburg using the CWSs and the Ta measured using the reference sensor (HMP155).

The 5-minute relative humidity (RH) measurement comparisons are presented in Figure 22 and Figure 23 for the SAWS Irene and UKZN sites, respectively. The CWSs' RH measurements have shown very good agreement with the measurements from the reference sensors. In addition, hourly comparisons of RH are shown in Figure 24 and Figure 25 for the SAWS Irene and UKZN sites, respectively. Similarly, the hourly CWSs measurements exhibited a strong linear relationship with the standard sensor measurements, except for the Logia sensor, which had a slope of less than 0.90 (Figure 24 and Figure 25).

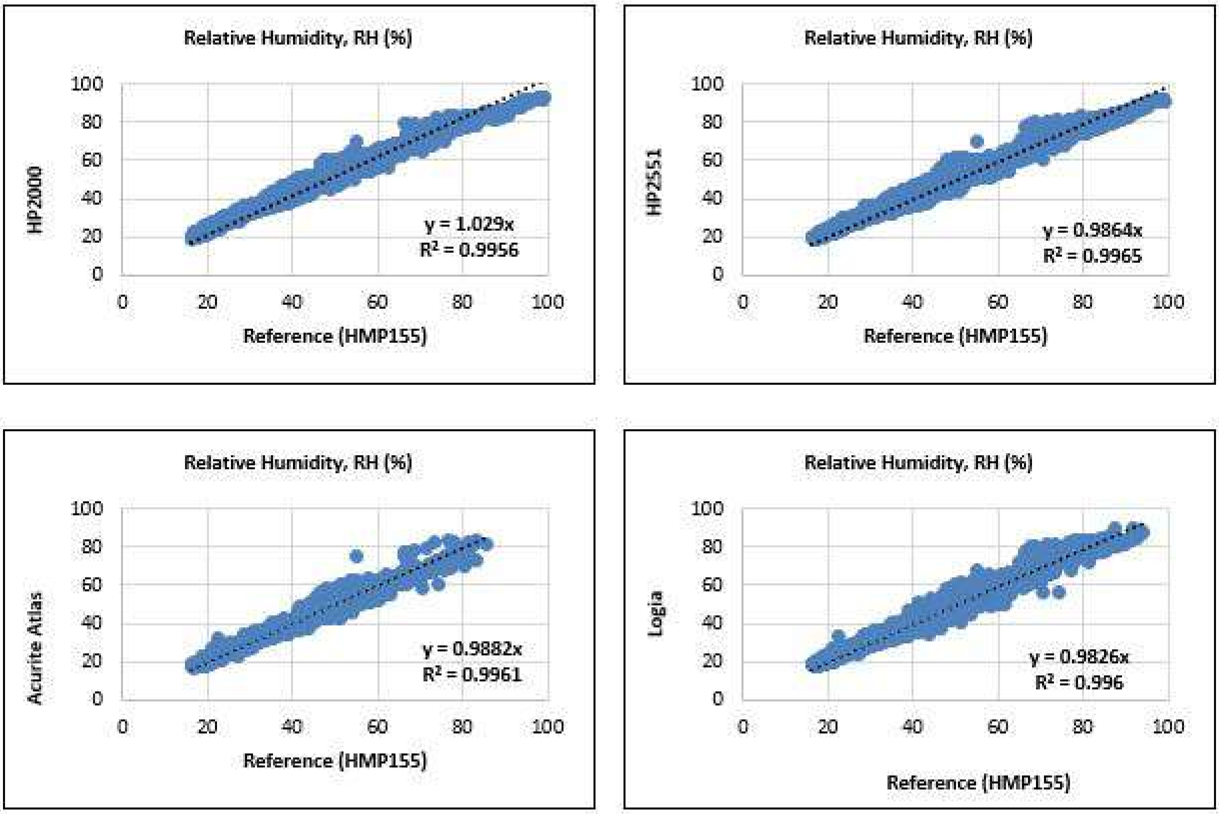


Figure 22. Comparison of the average 5-minute relative humidity (RH, %) measured at the South African Weather Service Irene Office using the CWSs and the RH measured using the reference sensor (CS215 probe).

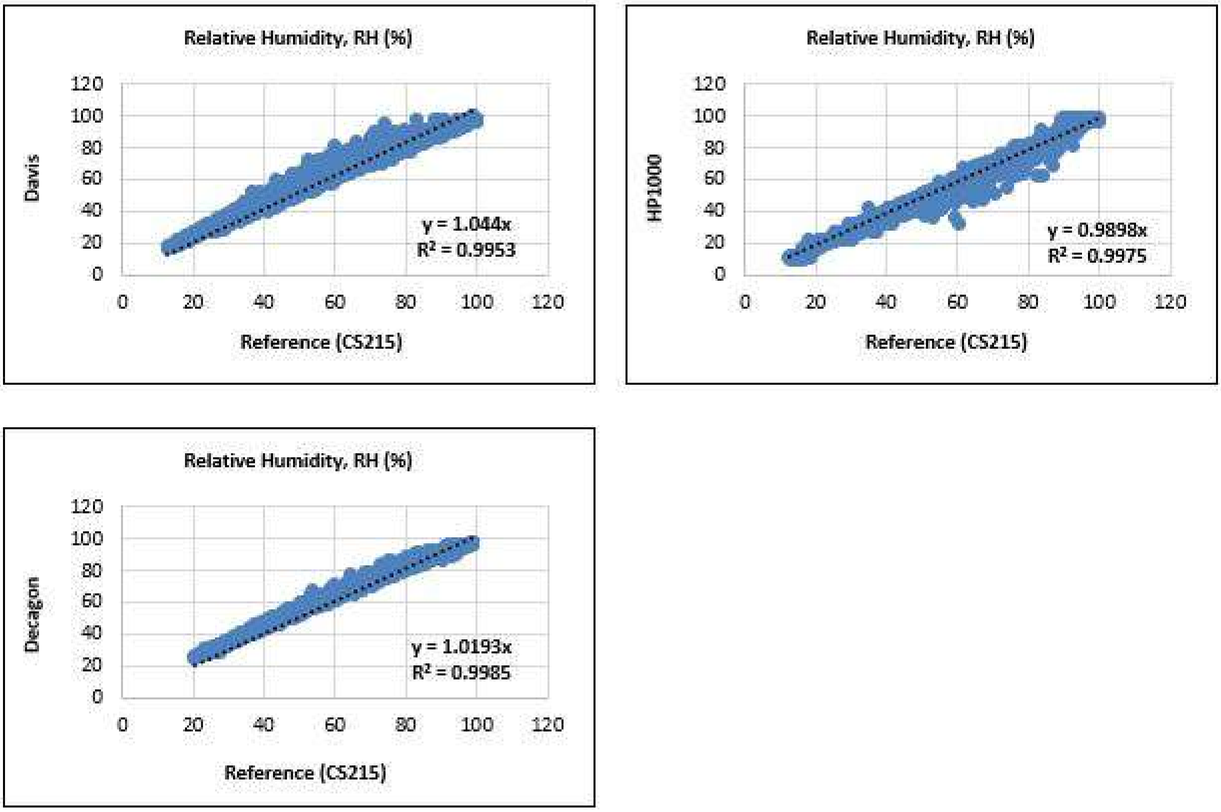


Figure 23. Comparison of the average 5-minute relative humidity (RH, %) measured at the UKZN site in Pietermaritzburg using the CWSs and the RH measured using the reference sensor (CS215 probe).

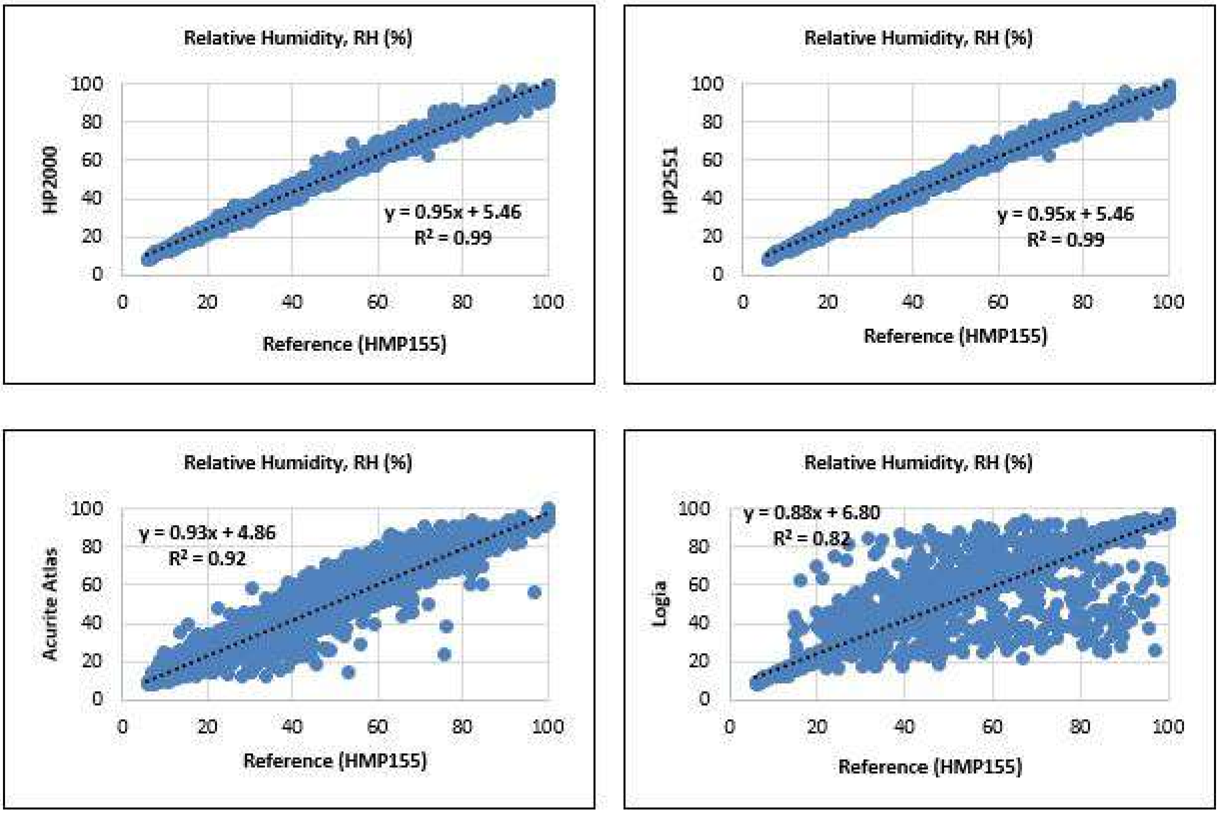


Figure 24. Comparison of the hourly relative humidity (RH, %) measured at the South African Weather Service Irene Office using the CWSs and the RH measured using the reference sensor (CS215 probe).

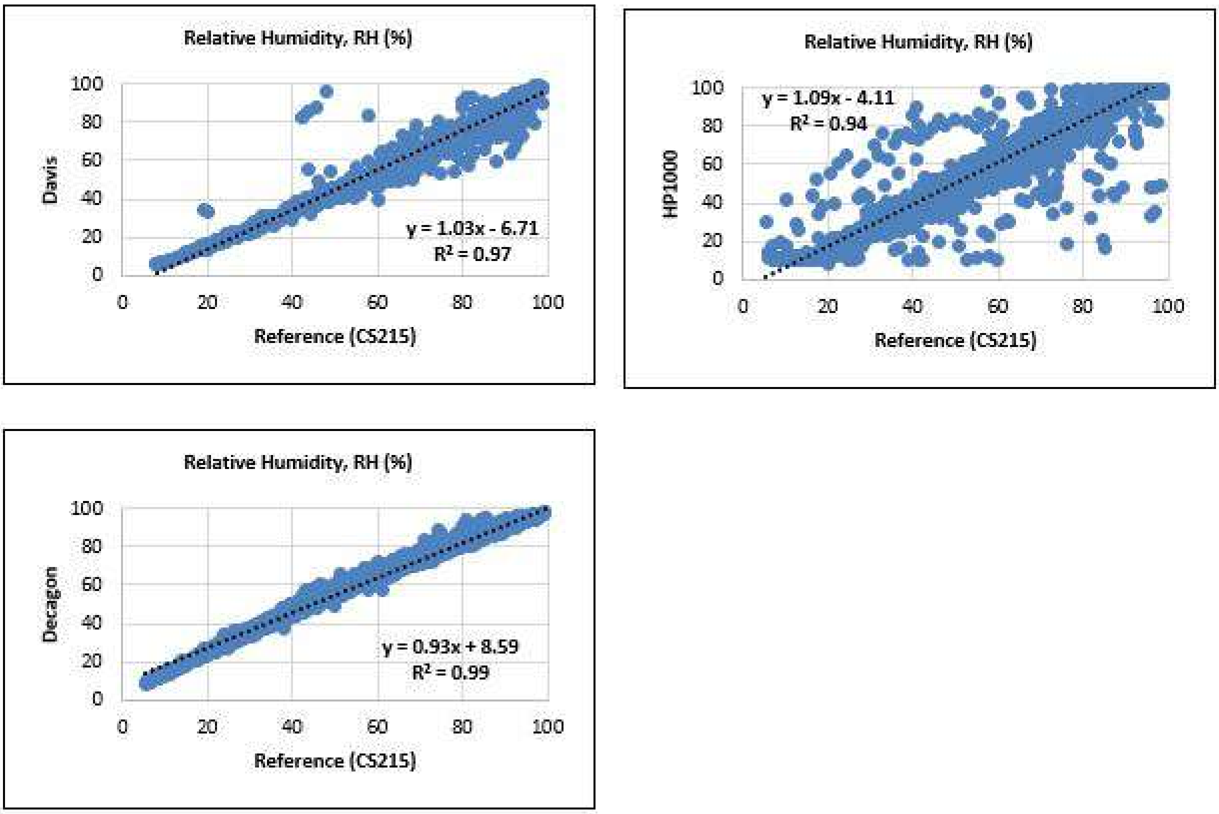


Figure 25. Comparison of hourly relative humidity (RH %) measured at the UKZN site in Pietermaritzburg using the CWSs and the RH measured using the reference sensor (CS215 probe).

4.5.3 Wind Speed and Wind Direction

Comparisons of the CWS anemometers with the standard R.M. Young (Wind Monitor-AQ and Wind Sentry) sensors are shown in Figure 26 and Figure 27 for the SAWS Irene and UKZN sites, respectively. A point-by-point comparison of the 5-minute wind speed values between the CWS and standard AWS stations showed a large amount of scatter (Figure 26 and Figure 27). This could be partly attributed to the different ways the average wind speed is calculated and logged for the different CWSs and the standard sensors. The CWS wind speeds were consistently lower than the standard sensors, except for the Acurite Atlas station, which recorded higher values, as shown in Figure 26. The Decagon CWS wind speed measurements showed better correlation with the measurements of the standard sensor, with a slope of 0.82 and an R^2 of 0.96 (Figure 27).

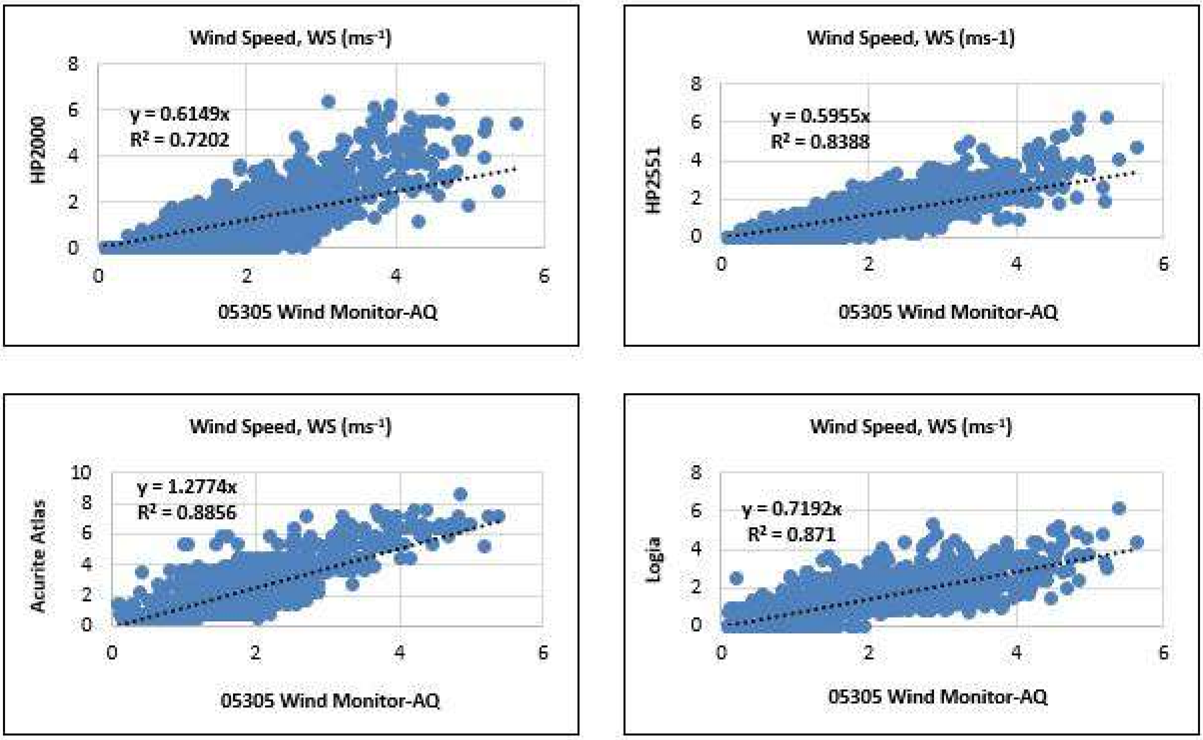


Figure 26. Comparison of the average 5-minute wind speed, WS (ms-1), measured at the South African Weather Service Irene Office using the CWSs and the reference sensor (05305 Wind Monitor-AQ).

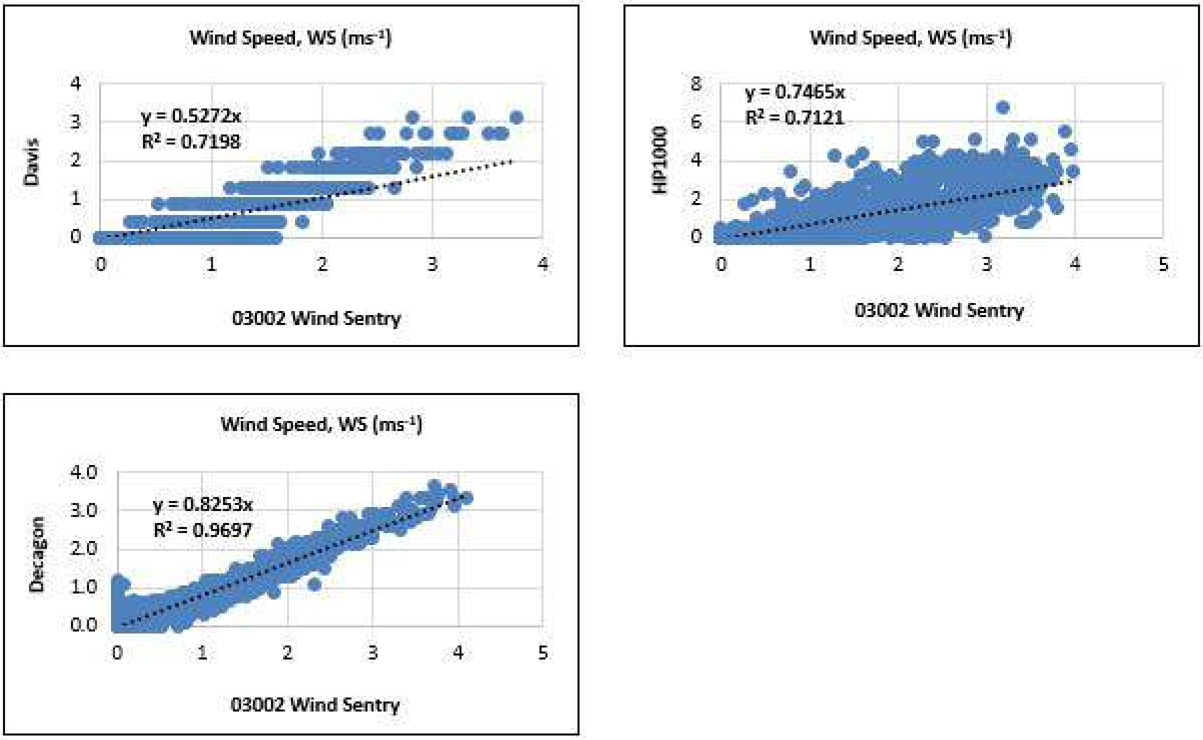


Figure 27. Comparison of the average 5-minute wind speed, WS (ms-1), measured at the UKZN site in Pietermaritzburg using the CWSs and the WS measured using the reference sensor (03002 Wind Sentry).

Comparisons of the hourly average wind speed values between the CWS and standard AWS stations also showed significant scatter (Figure 28 and Figure 29). The CWS hourly wind speeds were also lower than the standard sensors, except for the Acurite Atlas station. The wind speed measurements from the Davis, Decagon, and HP2551 CWS stations exhibited a stronger correlation with the standard sensor measurements, with slopes exceeding 0.75 and R^2 values surpassing 0.70.

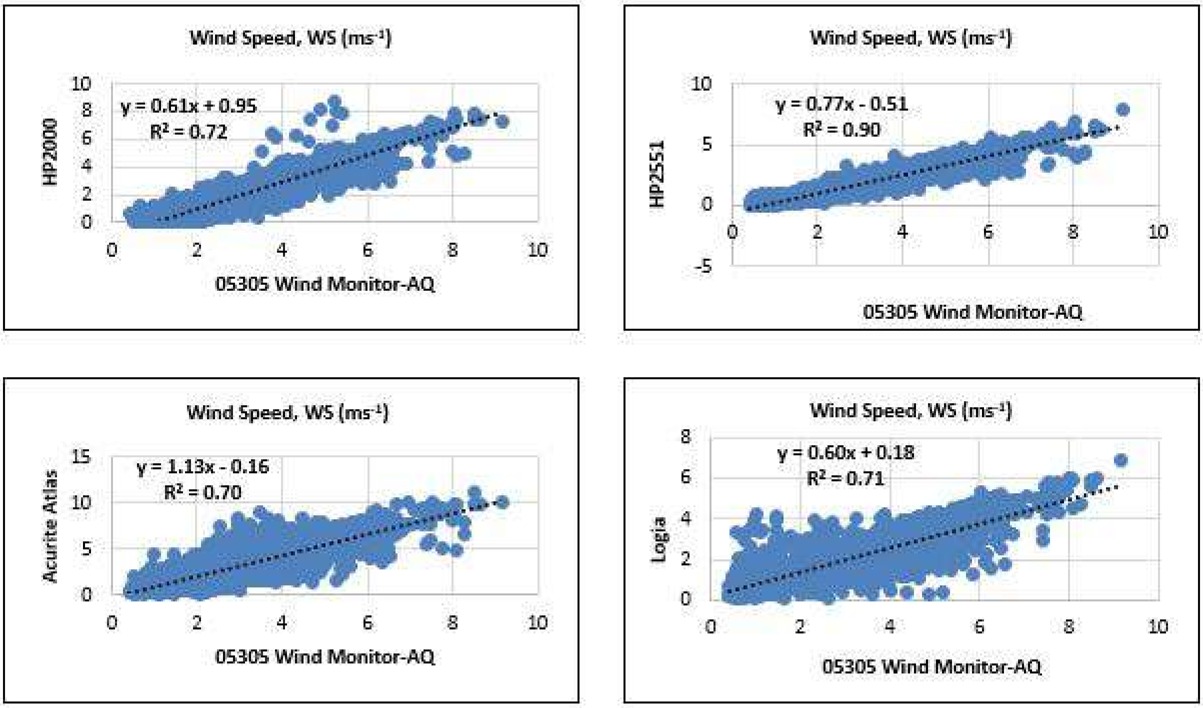


Figure 28. Comparison of the average hourly wind speed, WS (ms-1), measured at the South African Weather Service Irene Office using the CWSs and the reference sensor (05305 Wind Monitor-AQ).

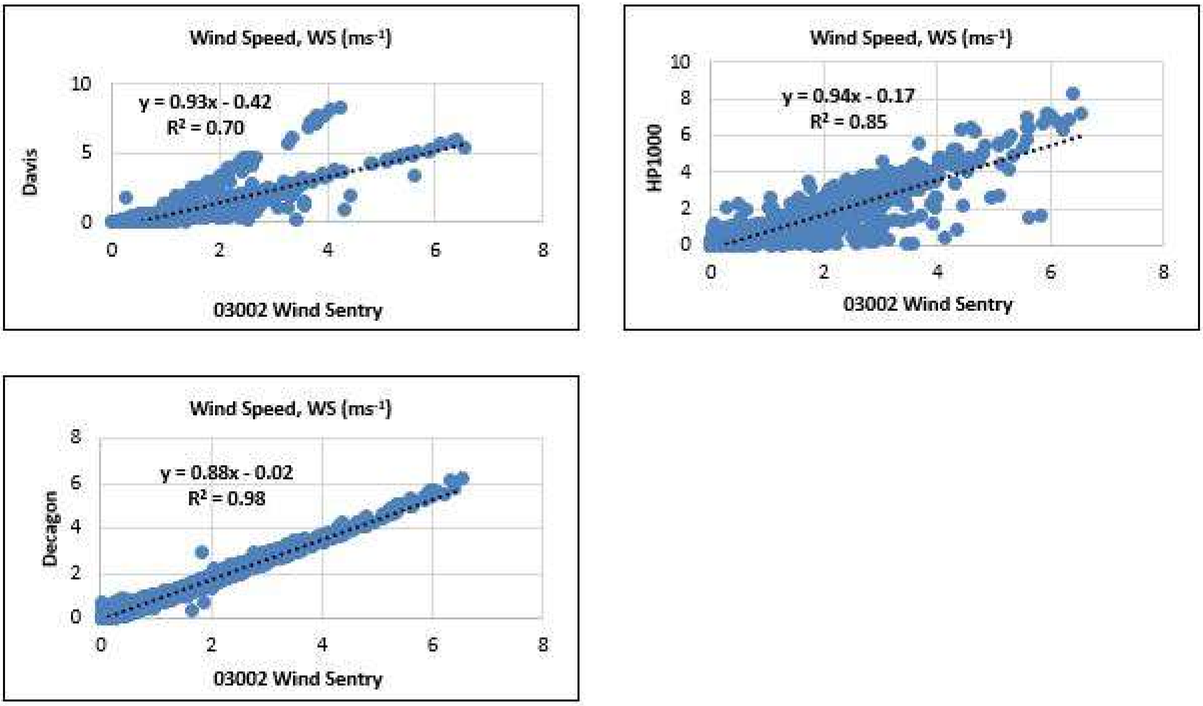


Figure 29. Comparison of the average hourly wind speed, WS (ms-1), measured at the UKZN site in Pietermaritzburg using the CWSs and the WS measured using the reference sensor (03002 Wind Sentry).

Wind direction measurements are difficult to compare, and it is not easy to perform point-by-point comparisons because a lack of synchronization between measurements allows turbulent motion to make the directions sampled quite different (Jenkins, 2014). Figure 30 to Figure 33 display time-series plots of the wind direction obtained with the standard R.M. Young (Wind Monitor-AQ) sensor and the CWSs at the SAWS Irene site. The CWS wind directions closely followed the wind direction measurements of the standard sensor.

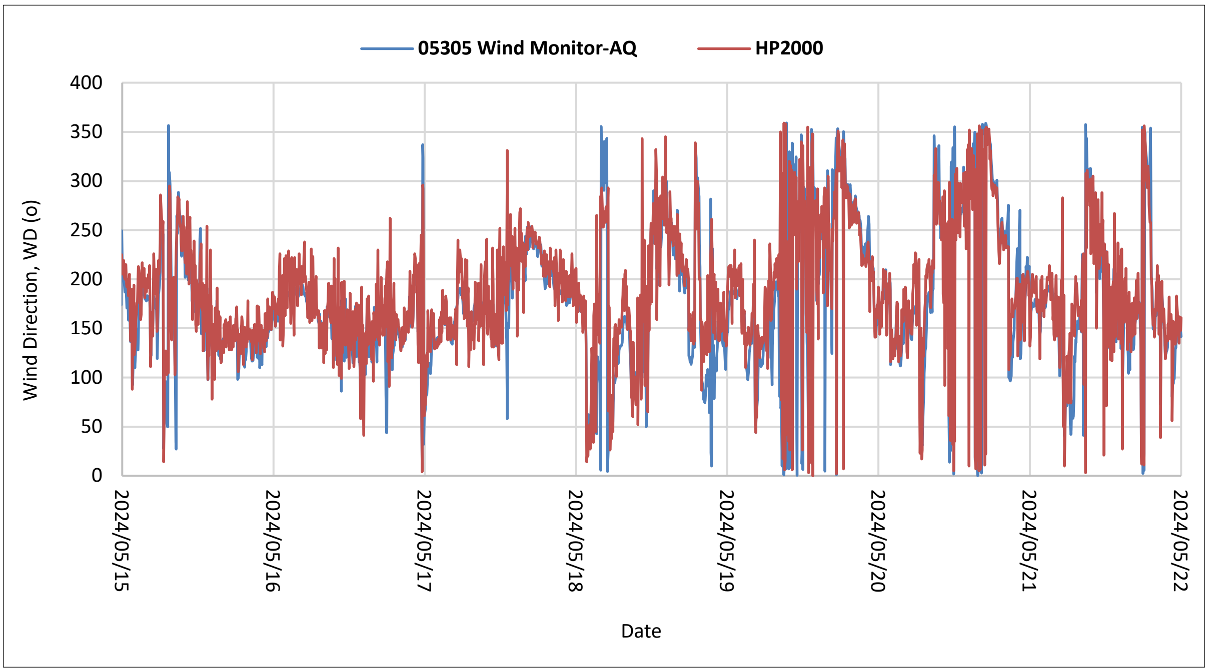


Figure 30. Wind direction as a function of time recorded using the HP2000 CWS station (brown) and the standard Wind Monitor-AQ sensor (blue) over the period May 5–15, 2024.

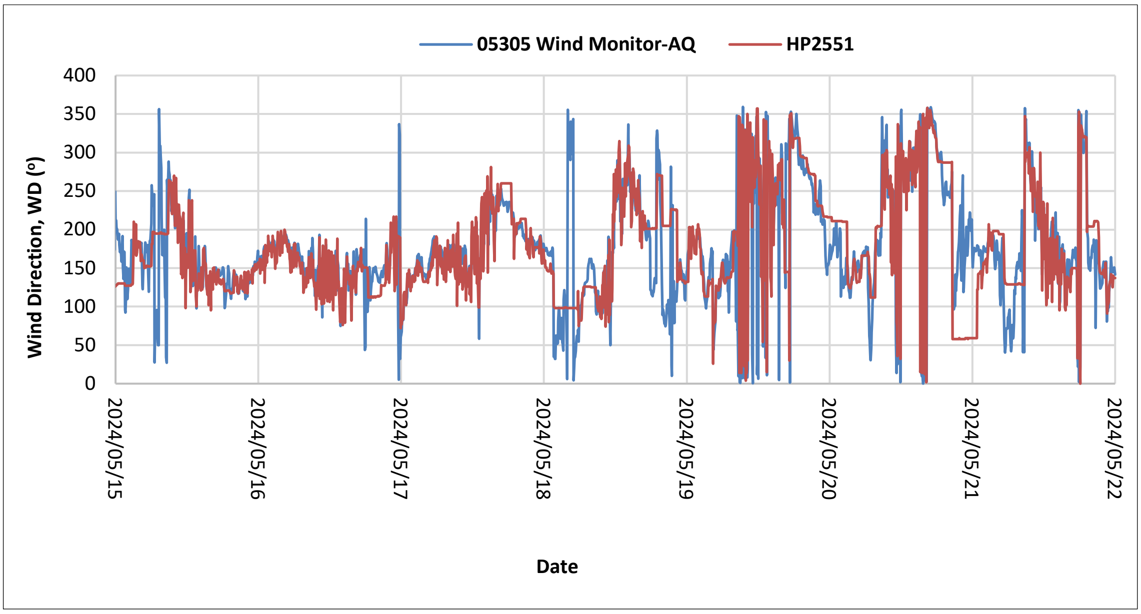


Figure 31. Wind direction as a function of time measured using the HP2551 CWS station (brown) and the standard Wind Monitor-AQ sensor (blue) over the period May 15–22, 2024.

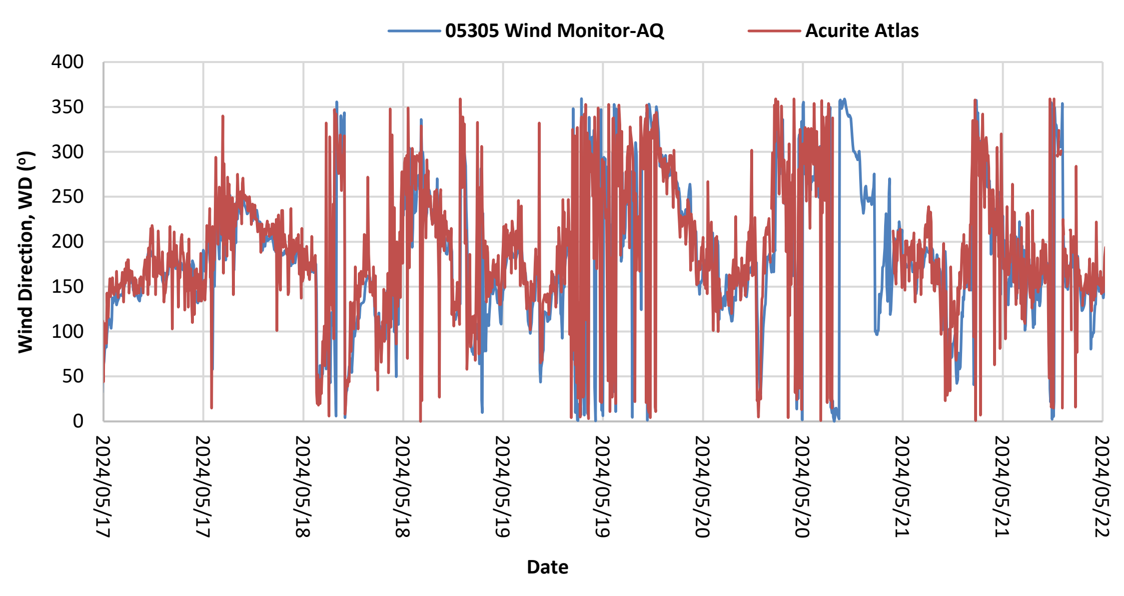


Figure 32. Wind direction as a function of time measured using the Acurite Atlas CWS station (brown) and the standard Wind Monitor-AQ sensor (blue) over the period May 17–22, 2024.

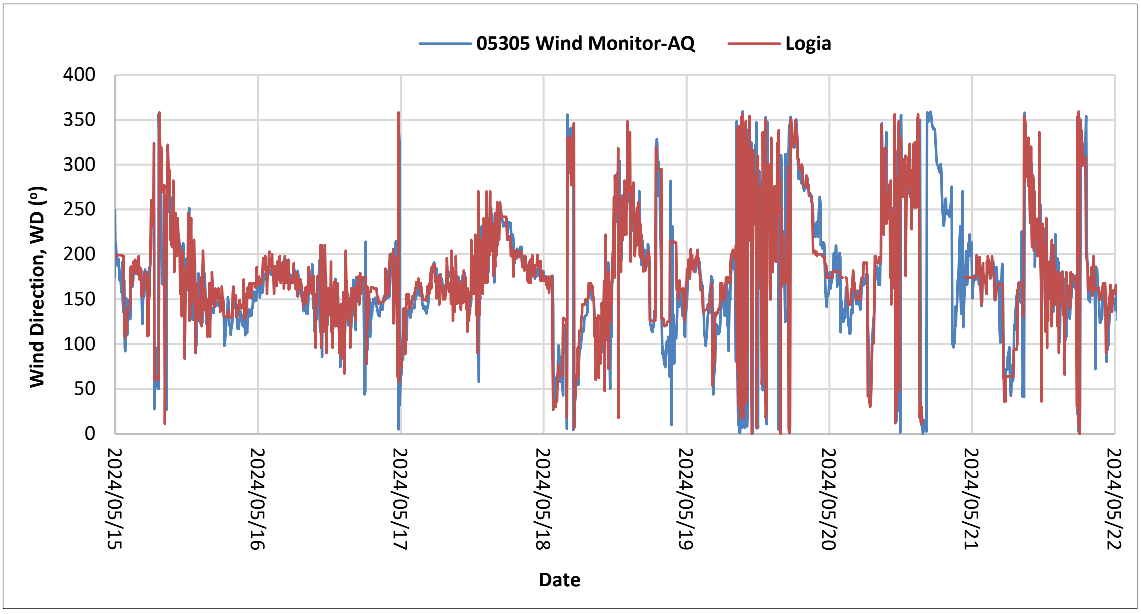


Figure 33. Wind direction as a function of time measured using the Logia CWS station (brown) and the standard Wind Monitor-AQ sensor (blue) over the period May 15–22, 2024.

4.5.4 Rainfall

The plots of daily rainfall measured with the CWSs versus daily rainfall measured with the standard AWSs are shown in Figure 34 and Figure 35 for the SAWS Irene and UKZN sites, respectively. Overall, there was poor agreement between the CWSs and AWSs, as most of the CWSs recorded lower daily values than the standard rain gauges. The HP2000, HP2551, and Logia rain gauges, however, showed better agreement, with values that were 10 to 15% higher.

Figure 36 and Figure 37 display graphs of the total cumulative rainfall recorded by the seven CWSs in comparison to the cumulative rainfall measured by the standard reference rain gauges at the SAWS Irene and

UKZN sites during the measurement period, respectively. Most CWSs measured totals less than the standard rain gauge. The rain gauge readings from Accurite Atlas, Decagon, and Davis were lower compared to the other CWSs and standard rain gauges (Figure 36 and Figure 37). It is important to highlight that the rainfall measurements from all CWSs showed significant differences ranging from 10% to 50% compared to the standard rain gauge readings, and these differences were observed in different directions.

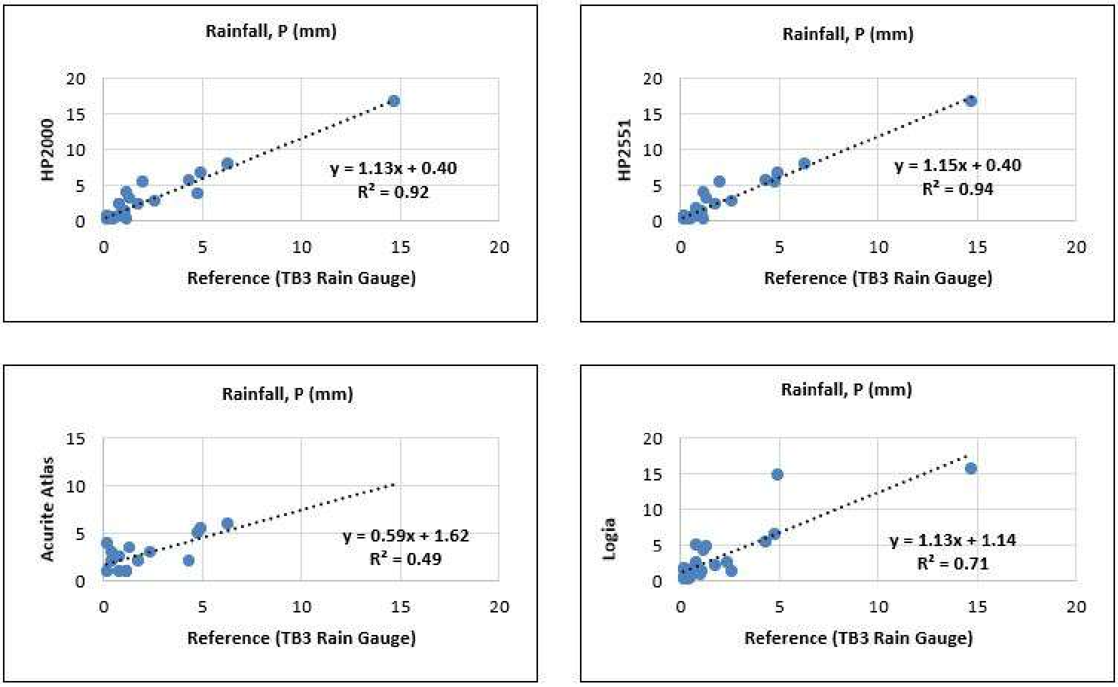


Figure 34. Comparison of the total daily rainfall, P (mm), measured at the South African Weather Service Irene Office using the CWSs and the reference rain gauge (TB3).

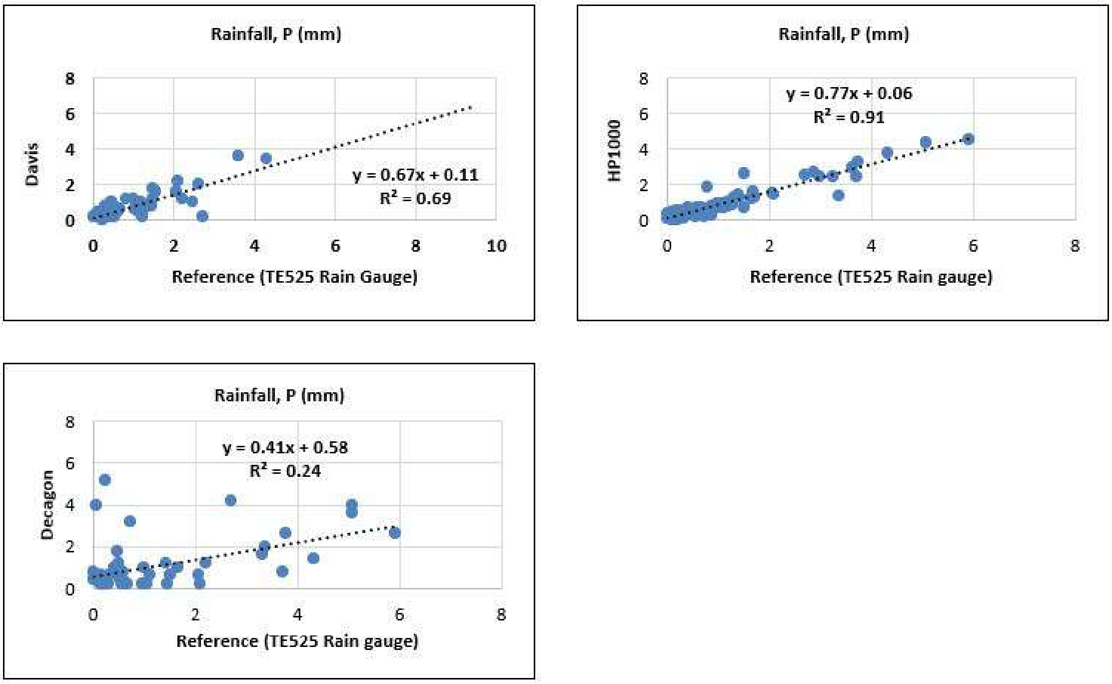


Figure 35. Comparison of the total hourly rainfall, P (mm), measured at the UKZN site in Pietermaritzburg using the CWSs and the reference rain gauge (TE525).

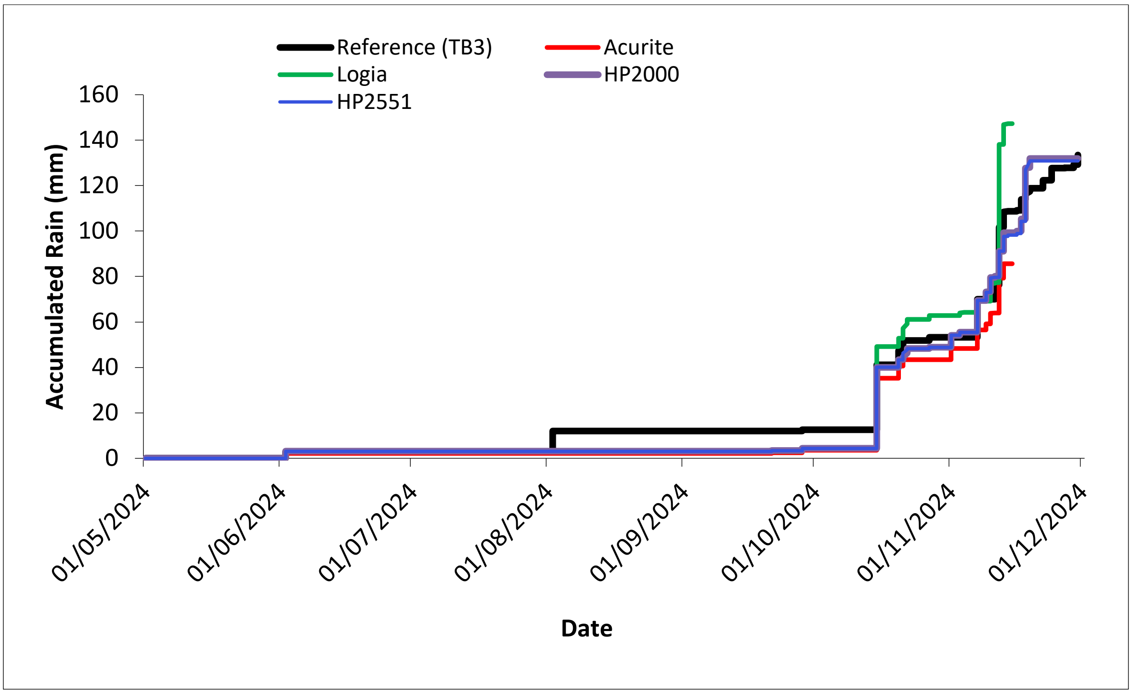


Figure 36. Cumulative rainfall totals from the four CWSs and the standard reference rain gauge (TB3) at the South African Weather Service Irene Office.

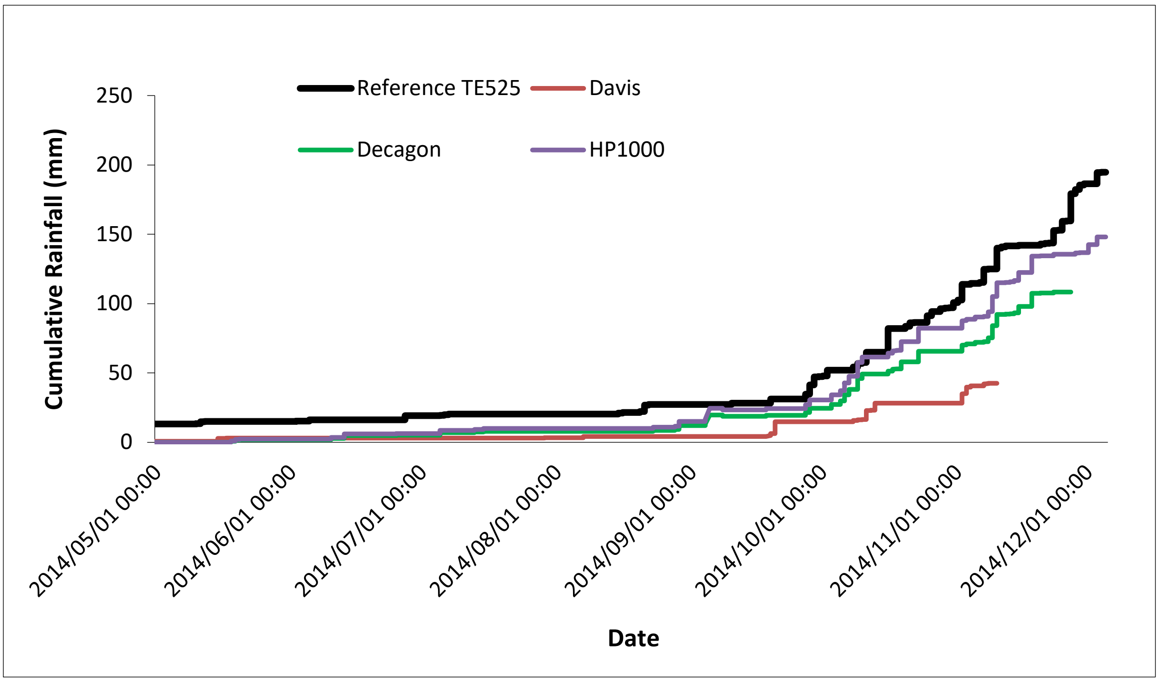


Figure 37. Cumulative rainfall totals from the three CWSs and the standard reference rain gauge (TE525) at the UKZN site in Pietermaritzburg.

4.6 DERIVED VARIABLES

4.6.1 **Heat Index**

The heat index is the perceived temperature felt by the human body when the air temperature is combined with relative humidity. It is calculated using air temperature and relative humidity data and helps in evaluating heat exposure, playing a crucial role in human comfort. Figure 38 displays the comparison of the hourly heat index (in degrees Celsius) calculated using the CWSs and the reference AWS at the South African Weather Service Irene Office. Additionally, Figure 39 shows the hourly comparisons of the calculated heat index using the CWSs and the reference AWS at the UKZN site in Pietermaritzburg. All CWSs' heat index comparisons showed very good agreement with the reference sensors. Figure 38 and Figure 39 illustrate a strong linear relationship between the CWSs' heat index values and the standard sensor calculations, with slopes and R^2 values close to unity, except for the Logia and HP2000 models, which had slopes below 0.90 (Figure 39).

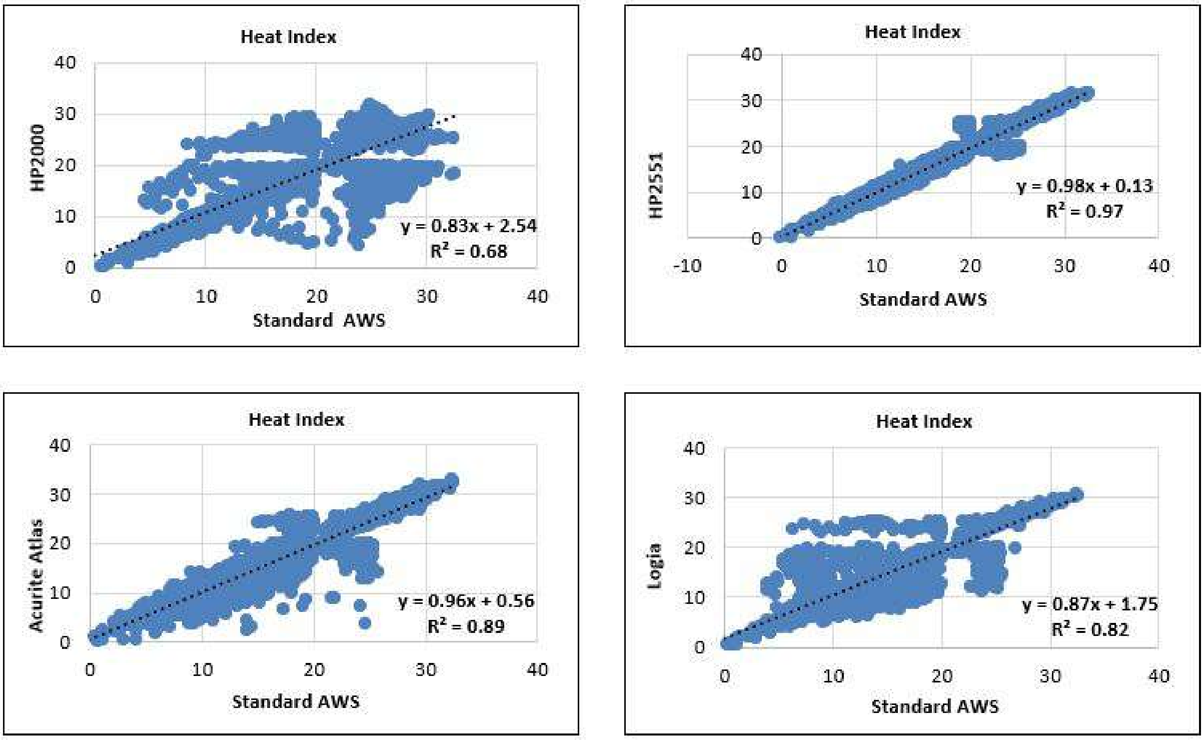


Figure 38. Comparison of the hourly heat index (oC) calculated using the CWSs and the reference AWS at the South African Weather Service Irene Office.

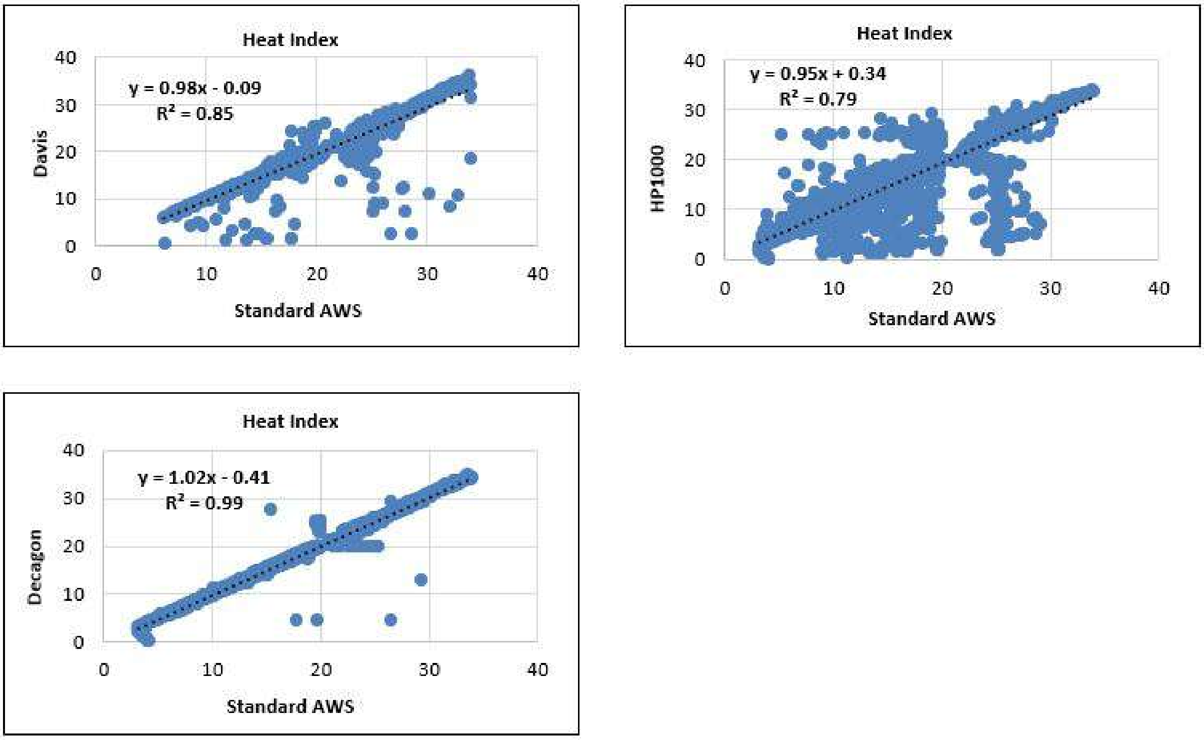


Figure 39. Comparison of the hourly heat index (oC) calculated using the CWSs and the reference AWS at the UKZN site in Pietermaritzburg.

4.6.2 Wind Chill

Wind chill is the sensation of cold experienced on exposed skin due to the combination of wind and ambient air temperature. The wind chill temperature is a measure of how cold it feels to people and animals when they are outside. This perceived temperature is calculated using both the air temperature and wind speed values. Comparisons of the hourly wind chill calculated using the CWSs and the reference AWS sensors at the South African Weather Service Irene Office and the UKZN site in Pietermaritzburg are shown in Figure 40 and Figure 41, respectively.

The HP2551, Accurite Atlas, and Decagon CWS wind chill estimates showed good correlation with the standard AWSs estimates, with slopes and R^2 values close to unity (Figure 40 and Figure 41). Comparisons of the hourly wind chill values between the rest of the CWSs and standard AWS stations showed significant scatter, with the HP1000 showing the worst performance (Figure 41). These discrepancies may be due to the wind speed CWSs measurements, which exhibited poor agreement with the standard sensors (Figure 28 and Figure 29) used for these wind chill calculations.

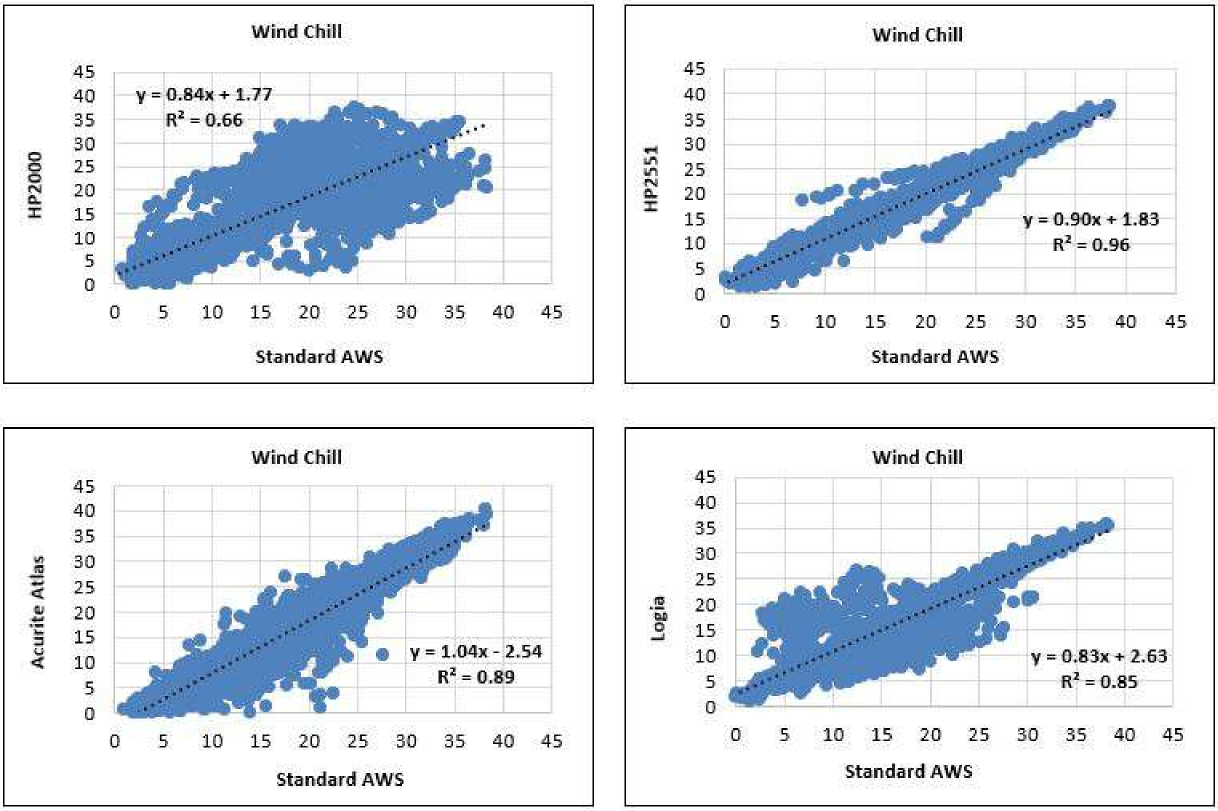


Figure 40. Comparison of the hourly wind chill calculated using the CWSs and the reference AWS at the South African Weather Service Irene Office.

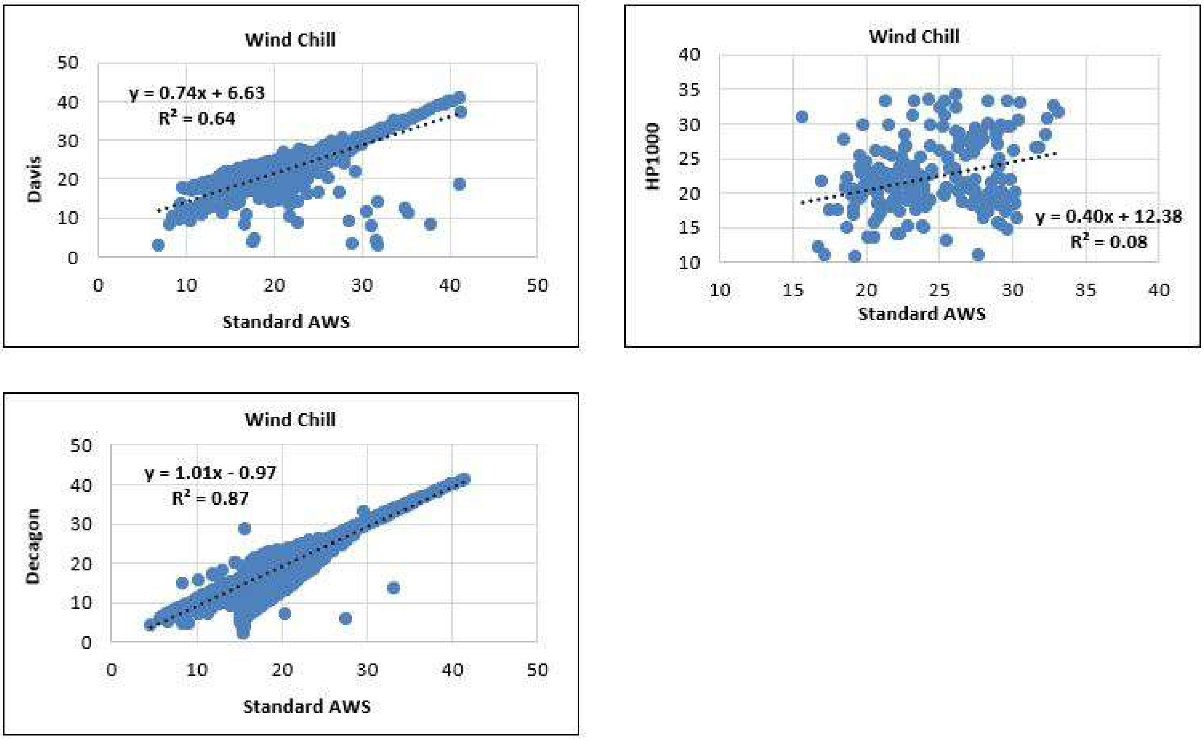


Figure 41. Comparison of the hourly wind chill calculated using the CWSs and the reference AWS at the UKZN site in Pietermaritzburg.

4.6.3 Reference Evapotranspiration

Reference evapotranspiration (ET_o) is the amount of water lost through evapotranspiration from a specific reference surface. The FAO Penman-Monteith (PM) method, developed for a short, well-watered green grass surface, was used to calculate ET_o. The PM utilises standard meteorological data such as solar radiation, air temperature, relative humidity, and wind speed. Reference evapotranspiration is used in various applications, such as improving the efficiency of irrigated agriculture and managing water resources.

Figure 42 illustrates the comparison of daily ET_o estimates (mm) calculated using the CWSs and the reference AWS at the South African Weather Service Irene Office. Figure 43 also shows comparisons of daily calculated ETo (mm) using the CWSs and the reference AWS at the UKZN site in Pietermaritzburg. Comparisons of the daily ET_o estimates between the CWSs and standard AWS stations showed a notable scatter, with all CWSs' estimates consistently lower (20 to 40%) than the standard AWS estimates. These differences could be attributed to discrepancies in wind speed and solar radiation measurements from the CWSs, which exhibited relatively poor agreement with the standard sensors used for the ET_o calculations. The HP2551, HP2000, and Decagon ETo estimates displayed a stronger correlation with the standard AWSs estimates, with slopes and R^2 values exceeding 0.7 (Figure 42 and Figure 43).

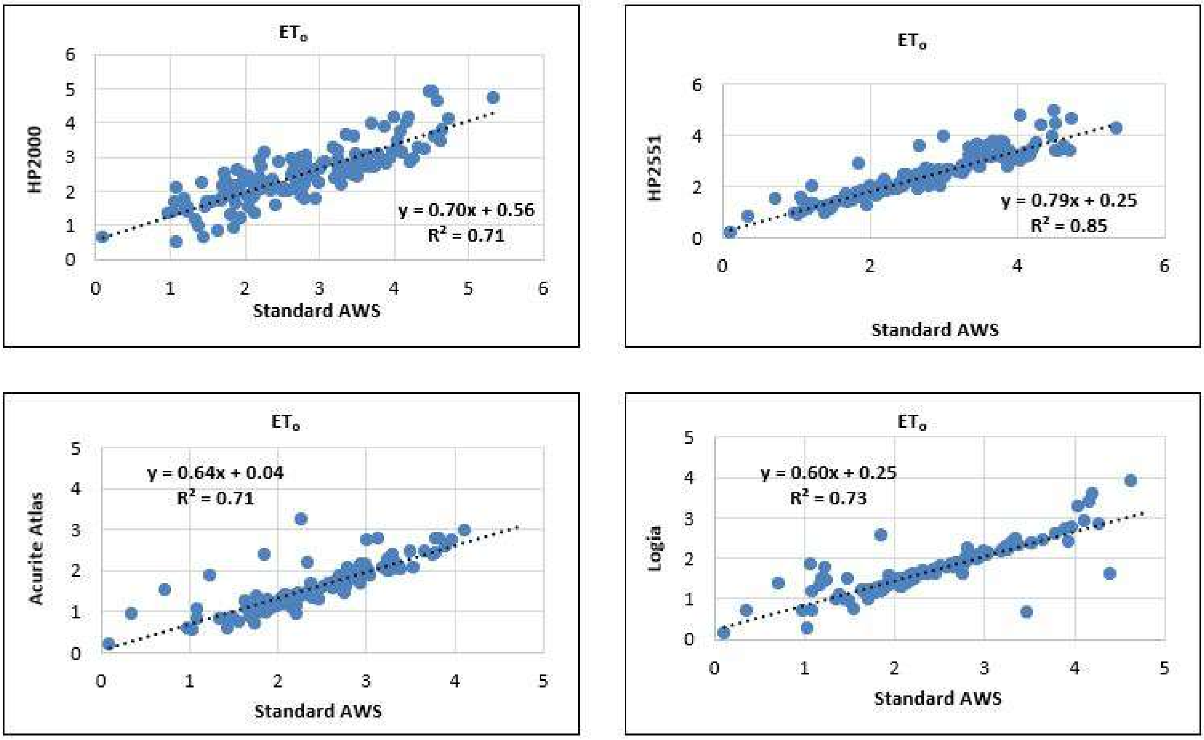


Figure 42. Comparison of the daily reference evapotranspiration, ET_o (mm), calculated using the CWSs and the standard AWS at the South African Weather Service Irene Office.

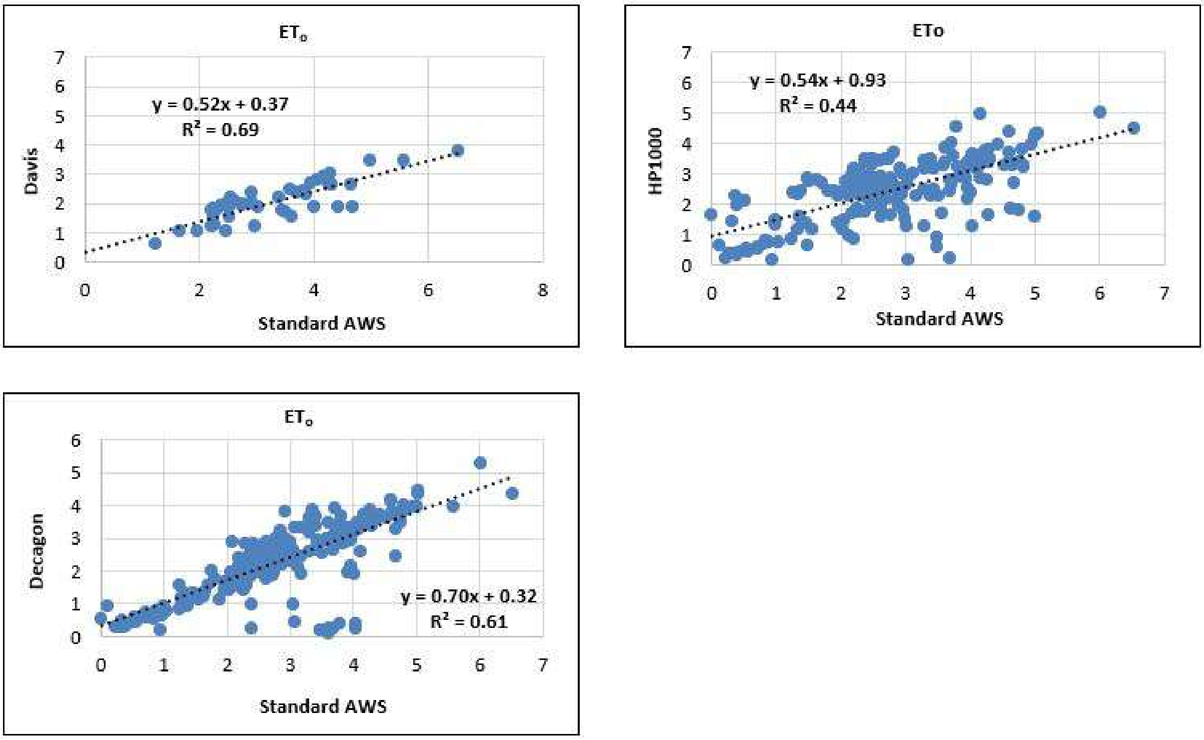


Figure 43. Comparison of the daily reference evapotranspiration, *ET*o (mm), calculated using the CWSs and the standard AWS at the UKZN site in Pietermaritzburg**.**

4.7 SUMMARY AND CONCLUSIONS

An intercomparison field study of selected low-cost CWSs against standard professional weather stations was conducted to evaluate the performance of the CWSs. The average and total measured values of weather parameters and derived variables obtained from the CWSs were compared with values from standard AWSs at 5-minute, hourly, and daily intervals at the SAWS Irene Office and the UKZN site in Pietermaritzburg.

The results indicate that air temperature and relative humidity measured using CWSs showed very good agreement with the standard AWS measurements. In general, most of the CWSs' solar radiation measurements also showed good agreement with the standard AWS measurements. However, wind speed comparisons have shown relatively poor agreement, with most of the CWSs recording consistently higher values, except for the Acurite Atlas station. Rainfall measurements from all CWSs exhibited significant variations compared to the standard rain gauge readings. These variations in rainfall could be attributed to poor calibration leading to bias in some of the CWSs right from the start, as well as differences in the measurement heights between the CWSs and the standard AWSs at which the rain gauges are placed, which may be influenced by increased wind speeds.

Variables derived from CWSs, such as heat index, wind chill, and reference evapotranspiration, were also compared with variables from the standard AWSs. The heat index calculated using the CWSs showed very good agreement with the heat index from the standard AWS measurements. The HP2551, Accurite Atlas, and Decagon CWS wind chill estimates showed good correlation with the standard AWS estimates. However, there was considerable variability in the hourly wind chill values between the other CWSs and standard AWS stations. Daily reference evapotranspiration estimates from CWSs were consistently lower than those from standard AWS stations. The HP2551, HP2000, and Decagon reference evapotranspiration estimates showed better correlation with the standard AWS estimates.

In general, there was good agreement between the standard AWS and the CWS measurements. The data collected by the CWSs in this study provide sufficient information on hourly and daily values for most weather parameters and derived indices. However, it is important to note a possible concern regarding the accuracy of CWS's daily rainfall measurements. It is advisable to calibrate the CWS rain gauges and establish instrument bias correction for accurate rainfall data. Overall, the results show that the Professional Wireless Weather Station HP2551, HP2000 (previously recommended in Phase one of this project), and the Decagon Complete Weather Station outperformed the other CWSs. The other CWSs included in this study showed lower levels of accuracy.

The weather parameters assessed in the study are useful in supporting communities with their day-to-day activities, including planning social events, farming, and preparing for extreme weather to mitigate impacts. However, using CWS data for any purpose will necessitate a robust quality control system to identify and correct errors, account for instrument bias, and provide an uncertainty assessment. As a result, accurately determining CWS station bias and errors depends on obtaining reliable estimates of the weather parameters spanning all seasons. One of the benefits of CWSs is their low cost and ease of use, offering real-time weather information almost instantly. The popularity of affordable CWSs that are internet and WiFi-enabled is growing, especially as internet access becomes more widespread, even in remote locations. However, if the internet connection is interrupted, data collection and storage are also disrupted in certain CWSs. For instance, in this study, data collection and storage from the Logia and Acurite Atlas stations were interrupted several times when WiFi connectivity was lost. The HP2551 and HP2000 stations have an advantage because they are equipped with a backup data storage system using microSD cards, allowing for data storage even when the stations are not connected to the internet.

CHAPTER 5: KNOWLEDGE OF CLIMATE RISKS, EARLY WARNING, AND CURRENT RESPONSE MECHANISMS

5.1. INTRODUCTION

In developing nations like South Africa, where unemployment, poverty, and inequality are prevalent, climate change and variability will have a substantial impact on sectors that are sensitive to climate change, including human settlements. Climate control, biodiversity conservation, food and water security, and ecosystem sustainability are all at risk from the impacts of climate change. Human capital and decision-making tools are therefore required to develop successful strategies for climate change adaptation and mitigation. A better understanding, effective predictions, and preparedness of anticipated changes in weather and climate variables are essential, particularly for the most vulnerable local communities whose livelihoods depend on weather and climate conditions, yet they continue to frequently experience harsh climatic changes within their environments (Balehegn et al., 2019). While there have been weather and climate monitoring systems put in place to monitor and forecast weather conditions, there is a notion that observed increases in climate variability influence the accuracy and reliability of weather forecasts, including seasonal rainfall prediction (Chang'a et al 2010). Another predicament is poor network coverage, particularly in areas vulnerable to harsh weather and climate conditions. With projections indicating increased climate variability over most of Africa, including South Africa, there is a need to enhance efforts to improve weather and climate monitoring systems.

According to Cooper et al. (2008), increasing the density of automatic weather stations (AWSs) networks to cover vast areas under observation can assist in the timely collection and transmission of accurate weather data. For instance, the use of in situ weather monitoring instruments and low-cost meteorological sensors within local communities is considered an alternative way to increase spatial coverage and contribute to data collection useful for environmental monitoring. Through this collaborative approach, capacitated citizen scientists become more proactive and are likely to build resilience towards extreme weather events across areas such as weather monitoring, seasonal forecasts, and climate change. Another promising initiative that can improve data collection and support decision-making is systematic documentation and integration of Indigenous Knowledge (IK) in weather and climate monitoring and prediction. Indigenous Knowledge Systems (IKS) encompass social and ecological knowledge practices and beliefs about how living things, including humans, relate to their surroundings and each other (Cuyler 2020, Tengo 2021). For instance, IK has been used in many rural areas in Tanzania to predict the weather by observing and monitoring the behaviour of animals, plants, and insects (Mhita, 2006; Kijazi et al., 2013). According to Hiwasaki et al. (2014), indigenous knowledge of the local communities can play a major role in reducing the number of fatalities and property damage caused by disasters. The authors add that successful climate change adaptation and disaster preparedness plans can result from fusing indigenous knowledge with scientific understanding. Equipping citizen scientists with both scientific and indigenous knowledge gathered at the grassroots level can therefore help communities prepare for, mitigate, prevent, and recover from climate change disasters.

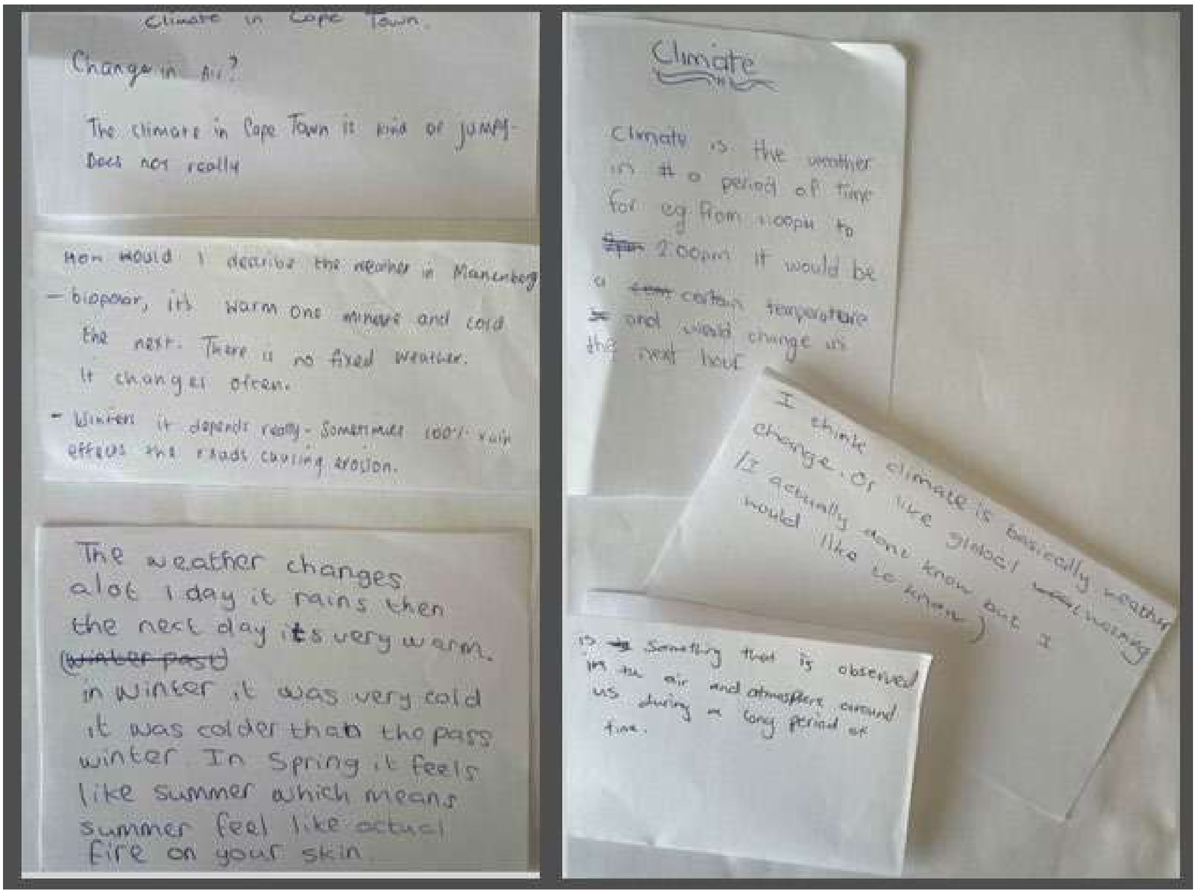
The role of citizen science and its contribution to the field of climate change research by enabling scientists to better understand the effects of the phenomenon and create practical mitigation plans cannot be overemphasised. This report focuses on outcomes of the workshops and training of citizen scientists at the five project sites (Swayimane, Cullinan, Malamulele, Cofimvaba, and Manenberg) on weather monitoring, seasonal forecasts, climate change, and capturing and archiving weather and climate-related IKS. To promote a common understanding of the risks, the citizen science approach was implemented by simplifying the technical language surrounding disaster risk reduction and weather, enabling informed participation in activities such as mapping community risks and assets, exchanging indigenous knowledge, and co-designing and implementing an early warning system. Citizen scientists used tools such as questionnaires to gather information from community members on IKS-based weather data, which was used to create an information sheet for each study site. Citizen scientists were trained to gather local weather data from the citizen weather stations that were installed in the study sites. The resulting weather data and documented IK will contribute to the development of effective adaptation measures to minimize the inherent impacts of climate change in each of the study sites.

5.2. CITIZEN SCIENCE TRAINING ON WEATHER MONITORING, SEASONAL FORECASTS, CLIMATE CHANGE

Extreme weather events and climate change are intricate global issues that necessitate the collaboration of scientists, policymakers, and the public. Citizen science enables individuals to engage in weather and climate change research, actively contributing to efforts to address extreme weather events and adapt to climate change. Citizen science involves simplifying technical language related to weather and disaster risk reduction to ensure a common understanding of the risks, allowing for informed participation in designing and implementing risk management measures (Mille-Rushing et al., 2012). Participating in citizen science projects enables volunteers to collect data, enhance their scientific knowledge, and contribute valuable insights into local climate patterns by filling gaps in traditional monitoring networks (Conrad and Hilchey, 2011). While citizen science offers many benefits in raising awareness of weather and climate risks and building climate change resilience, it also comes with specific challenges and limitations that must be addressed. One of the main challenges in citizen science projects is the validity and reliability of data generated by citizen scientists. To address this challenge, citizen science projects should offer clear instructions, implement training protocols for volunteers, and quality control measures to ensure data accuracy (Balázs et al., 2021).

5.2.1. Introducing CS to the Basics of Weather-related Terminology

During the development phase, citizen scientists received training to improve their skills in collecting, comprehending, and disseminating early warning information within their communities. As part of this process, the CS's comprehension of specific key terms was assessed to guide subsequent knowledge-sharing activities by the project team. Consequently, CS were asked to articulate their understanding of weather and climate before the project team presented a formal definition of these terms. The feedback revealed that some citizen scientists were mistakenly using "weather" and "climate" interchangeably to describe short-term temperature fluctuations, while others associated these terms with global warming. Figure 44 illustrates this confusion.



Climate in Cope Town.

Change in Air?

The climate in Cape Town is kind of jump-
Does not really

How would I describe the weather in Manenberg
– biopolar, it's warm one minute and cold
the next. There is no fixed weather.
It changes often.
- Winters it depends really - Sometimes 100% rain
effects the roads causing erosion.

The weather changes
alot 1 day it rains then
the next day its very warm.
(~~winter past~~)
in winter it was very cold
it was colder than the pass
winter. In Spring it feels
like summer which means
summer feel like actual
fire on your skin

Climate

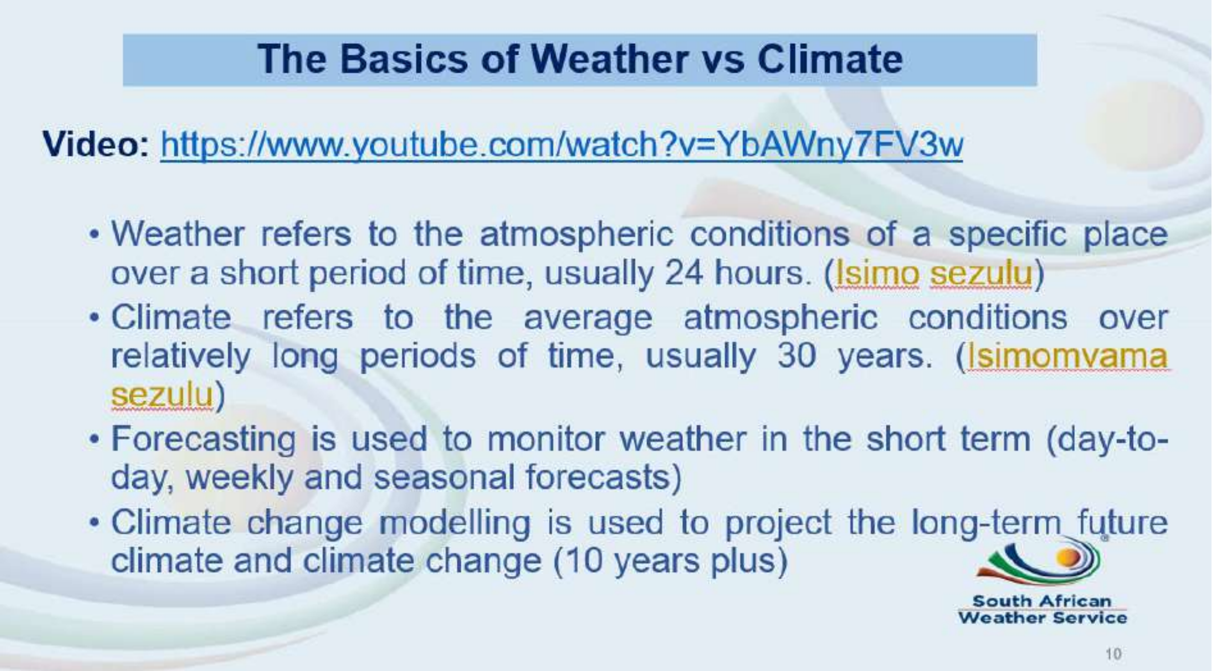
Climate is the weather
in ~~it~~ a period of time
for eg. from 1:00pm to
~~3pm~~ 2:00pm it would be
a ~~cer~~ certain temperature
~~x~~ and would change in
the next hour

I think climate is basically weather
change. Or like global ~~war~~ warming
(I actually don't know but I
would like to know)

is ~~a~~ Something that is observed
in the air and atmosphere around
us during a long period of
time.

Figure 44. Contributions by CS on their understanding of weather and climate.

The SAWS team then provided citizen scientists at all five sites with training on fundamental weather and climate concepts, ensuring that they were well-informed and able to contribute meaningfully to the project's planned activities (Figure 45 to Figure 48). Key terms such as weather, climate, climate change, forecasting, early warning, disaster, hazard, risk, and extreme weather events were clarified for the CS through this training. The terms were also presented in the local indigenous languages most spoken in the different sites, for example, IsiZulu in Swayimane, IsiXhosa in Cofimvaba, and Xitsonga in Malamulele. Posters were also used during the workshops to describe weather, extreme weather events, and early warning systems in the local languages at the study sites. The SAWS was involved in a Government of Flanders-funded Integrated Climate-Driven Multi-Hazard Early Warning System (ICMHEWS), where booklets with weather and climate terminology in indigenous languages have been published (See Figure 46). These booklets were also distributed to citizen scientists to facilitate continued learning and knowledge sharing in their community.



The Basics of Weather vs Climate

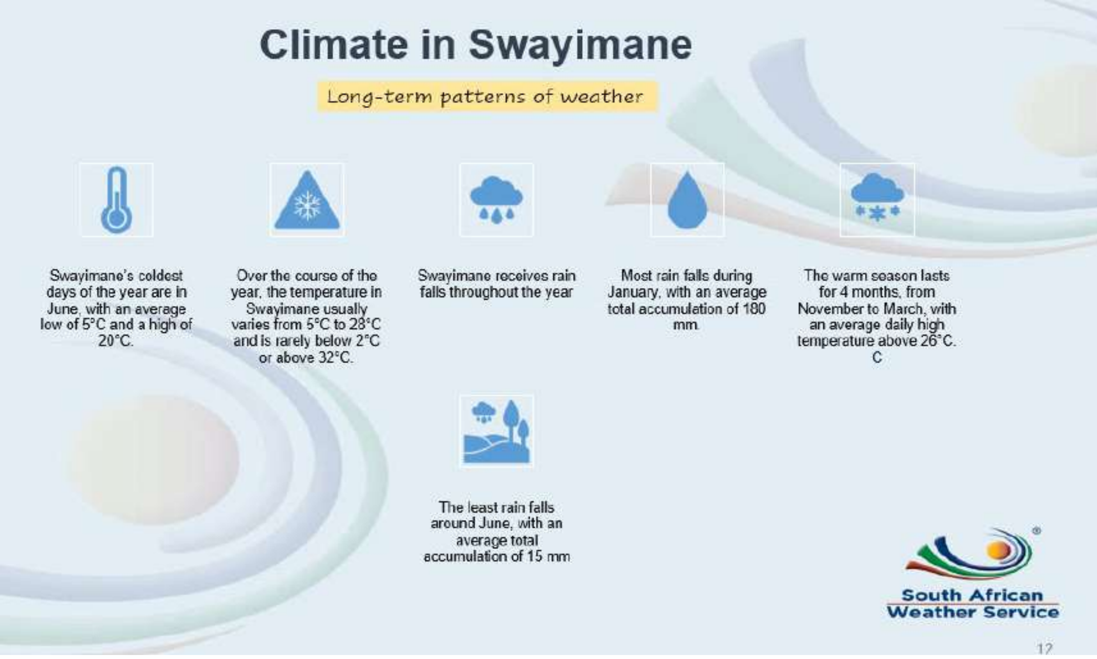
Video: https://www.youtube.com/watch?v=YbAWny7FV3w

- Weather refers to the atmospheric conditions of a specific place over a short period of time, usually 24 hours. (Isimo sezulu)
- Climate refers to the average atmospheric conditions over relatively long periods of time, usually 30 years. (Isimomvama sezulu)
- Forecasting is used to monitor weather in the short term (day-to-day, weekly and seasonal forecasts)
- Climate change modelling is used to project the long-term future climate and climate change (10 years plus)

South African Weather Service

Figure 45. Presentation on the basics of weather and climate shared with citizen scientists in Swayimane.

Figure 46. Weather and climate information booklet shared with Citizen Scientists.



Climate in Swayimane

Long-term patterns of weather

Swayimane's coldest days of the year are in June, with an average low of 5°C and a high of 20°C.

Over the course of the year, the temperature in Swayimane usually varies from 5°C to 28°C and is rarely below 2°C or above 32°C.

Swayimane receives rain falls throughout the year

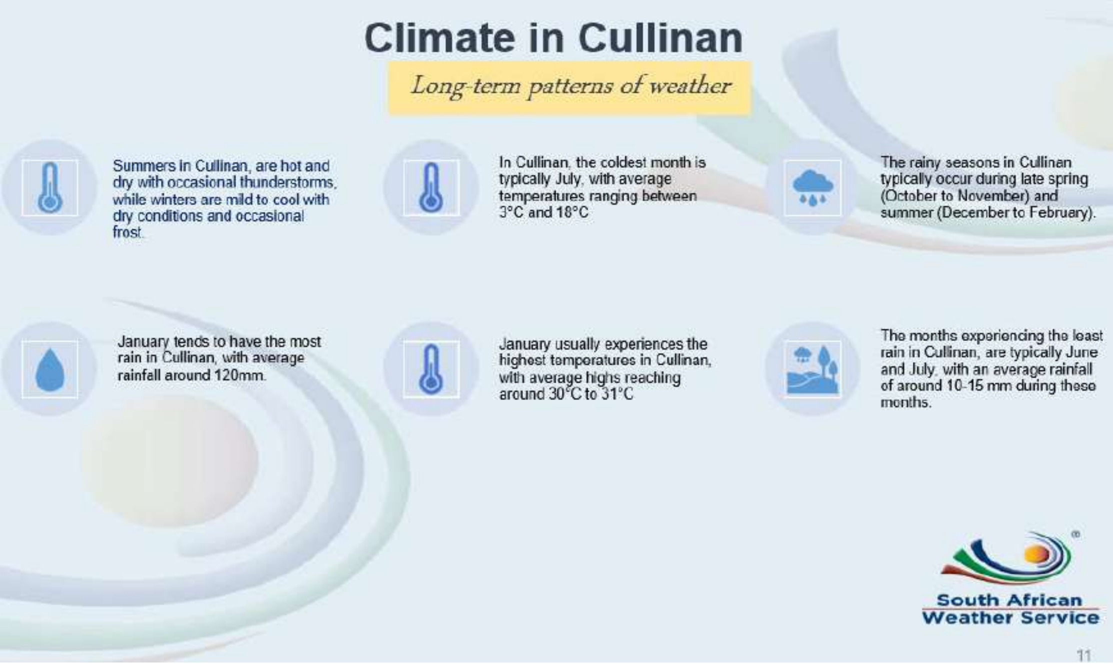
Most rain falls during January, with an average total accumulation of 180 mm.

The warm season lasts for 4 months, from November to March, with an average daily high temperature above 26°C. C

The least rain falls around June, with an average total accumulation of 15 mm

South African Weather Service

Figure 47. Citizen Scientists also received climate information for Swayimane based on information from SAWS historical data.



Climate in Cullinan

Long-term patterns of weather

Summers in Cullinan, are hot and dry with occasional thunderstorms, while winters are mild to cool with dry conditions and occasional frost.

In Cullinan, the coldest month is typically July, with average temperatures ranging between 3°C and 18°C

The rainy seasons in Cullinan typically occur during late spring (October to November) and summer (December to February).

January tends to have the most rain in Cullinan, with average rainfall around 120mm.

January usually experiences the highest temperatures in Cullinan, with average highs reaching around 30°C to 31°C

The months experiencing the least rain in Cullinan, are typically June and July, with an average rainfall of around 10-15 mm during these months.

South African Weather Service

Figure 48. Citizen Scientists also received climate information for Cullinan based on information from SAWS historical data.

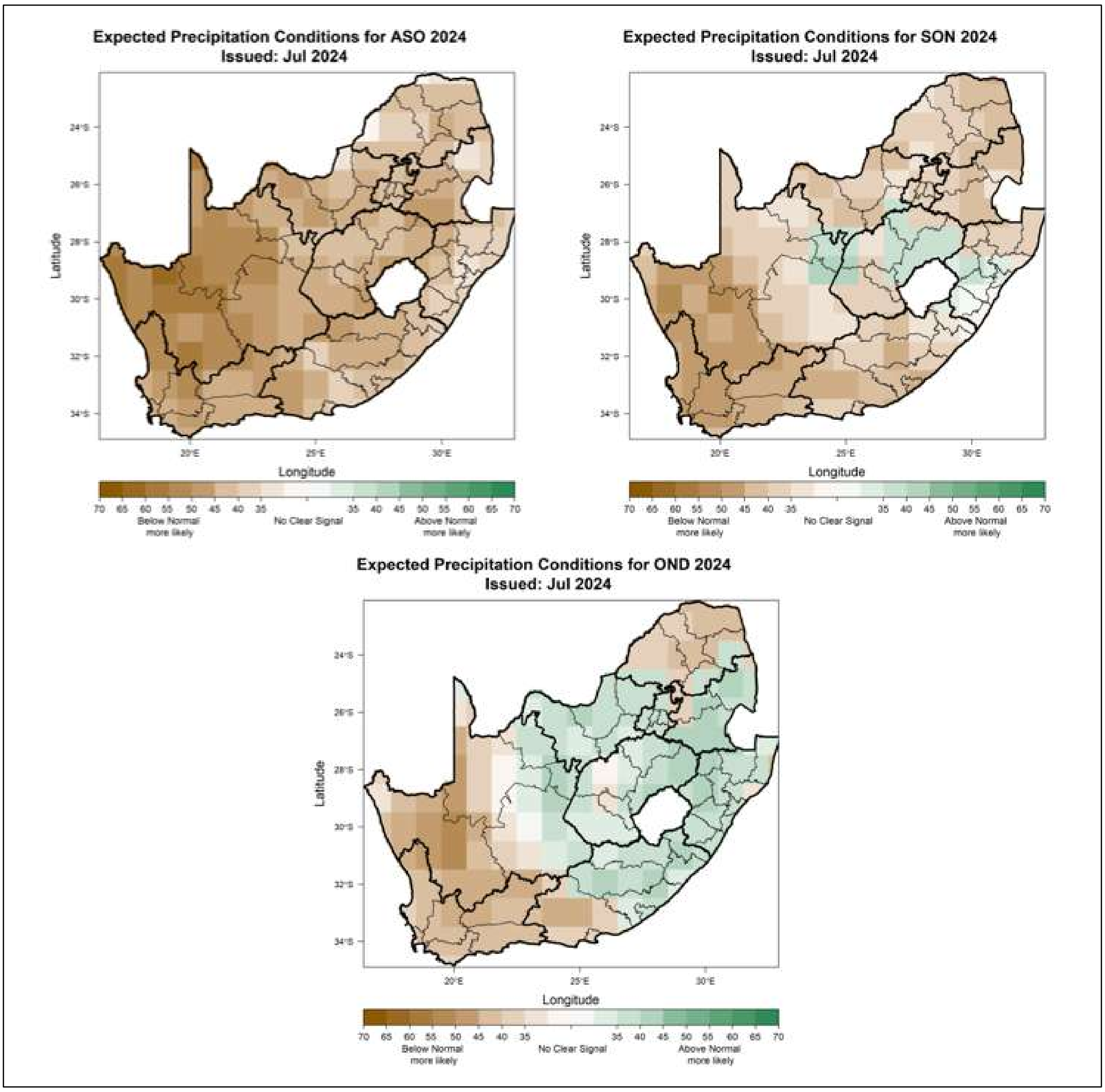
5.2.2. Knowledge Sharing on Seasonal Forecasts

Extreme weather events such as droughts and floods are projected to become more frequent and severe, affecting multiple sectors, especially agriculture, and disproportionately impacting smallholder farmers in sub-Saharan Africa (Sarr et al., 2015). It is recommended that the development of weather and climate services be considered an essential component in managing the risks associated with climate variability and change

(Vaughan & Dessai, 2014). Recent scientific advancements enable the provision of short- and long-term climate information services to assist farmers in making decisions (Mullen, 2007). Seasonal-to-interannual variations in rainfall across southern Africa are crucial for predicting extreme climatic events. Utilising rainfall data from farmers to develop and validate seasonal forecast models could enhance the accuracy of seasonal forecasts tailored for farm management. This collaborative approach between forecast modellers and end-users has the potential to increase the forecast uptake (Landman et al., 2020).

Farmers and youth from two farming communities in the Umshwati Municipality (KwaZulu-Natal) and Cofimvaba (Eastern Cape) were trained on the use of weather forecasts and seasonal outlook to improve decision-making in agriculture. The project team presented and discussed the knowledge and interpretation of local climate and the available weather and climate information; plans to manage weather and climatic extremes, such as drought and flooding; and the use of climatic information provided by the SAWS for decision-making. The three types of weather forecasts offered by the SAWS, namely, the short-range forecast valid for 48 hours, the medium-range or extended forecast valid for five days, and the long-range or seasonal forecast valid from a month to a season, were presented to the participants. Each of these forecasts plays a crucial role in agriculture; for instance, short-range forecasts are most valuable in daily farm operations, whereas medium-range and seasonal forecasts are important in long-term farm operations and planning. Farmers were trained on how to make the best use of favorable weather conditions and adjustments for extreme weather and climatic events based on these forecasts.

The seasonal climate outlook for the coming summer season was shared with the CS as presented in Figure 49 to Figure 51. The forecasts indicated that the El Niño-Southern Oscillation (ENSO) is in a La Niña state, and early indications of above-normal rainfall over most of the summer rainfall areas during October-November-December (OND). Minimum and maximum temperatures were expected to be mostly above-normal countrywide for the forecasted period.



Expected Precipitation Conditions for ASO 2024
Issued: Jul 2024

Expected Precipitation Conditions for SON 2024
Issued: Jul 2024

Expected Precipitation Conditions for OND 2024
Issued: Jul 2024

Figure 49. August-September-October 2024 (ASO; left), September-October-November 2024 (SON; right), October-November-December 2024 (OND; bottom) seasonal precipitation prediction. Maps indicate the highest probability of the above-normal and below-normal categories.

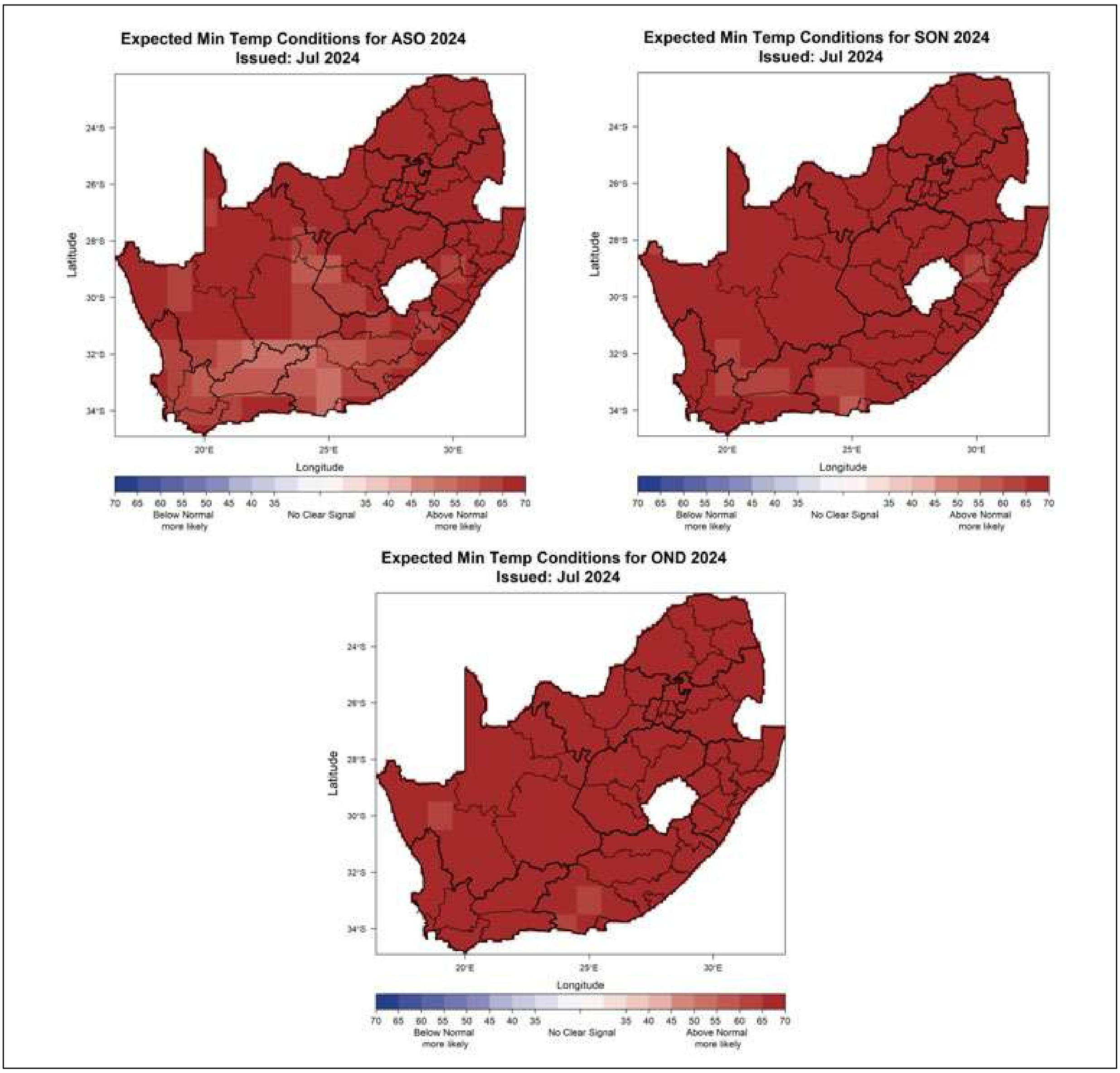


Figure 50. August-September-October 2024 (ASO; left), September-October-November 2024 (SON; right), October-November-December 2024 (OND; bottom) seasonal minimum temperature prediction. Maps indicate the highest probability of the above-normal and below-normal categories. Please refer to Appendix Figure A2 for forecast skill levels.

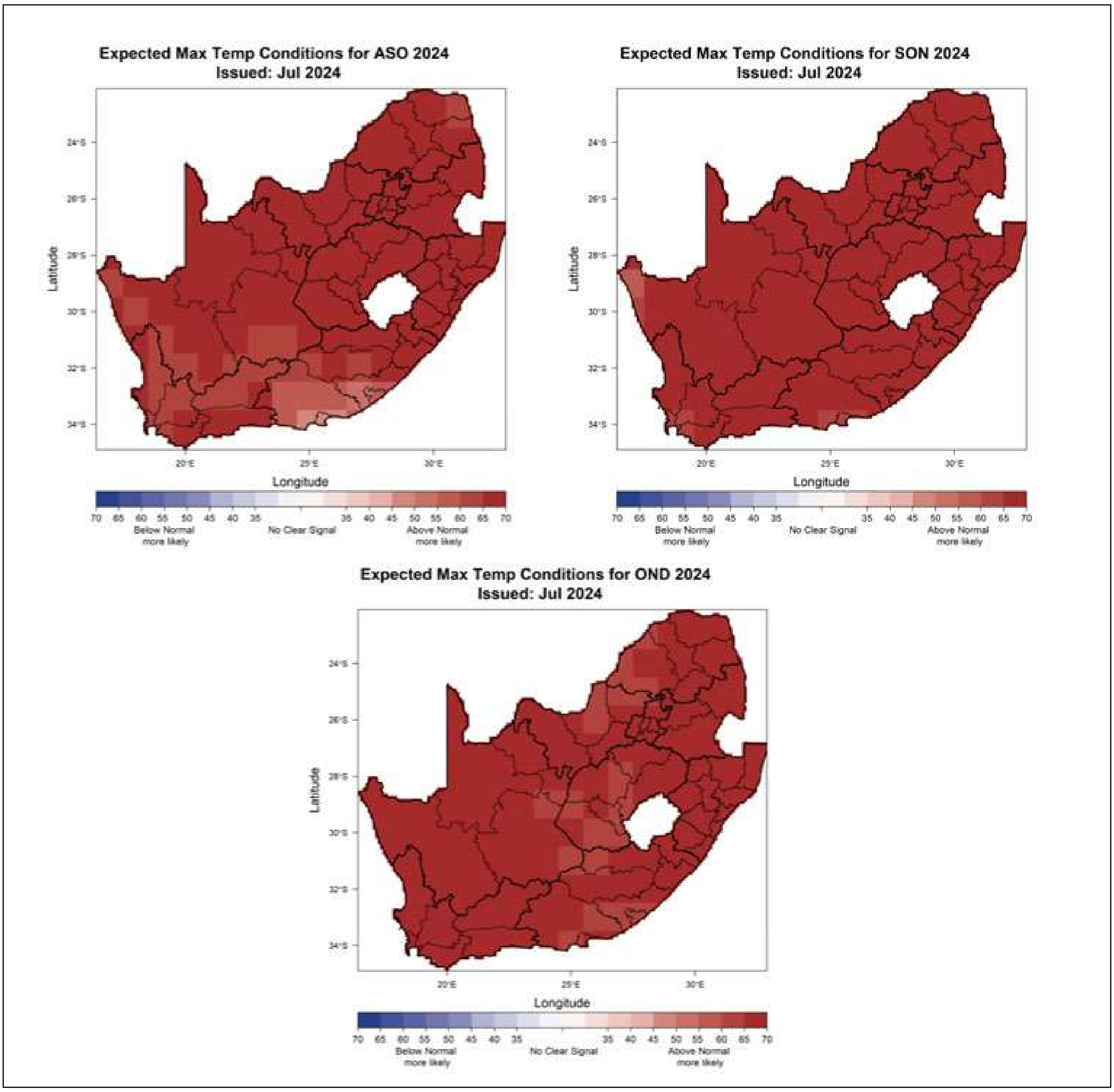


Figure 51. August-September-October 2024 (ASO; left), September-October-November 2024 (SON; right), October-November-December 2024 (OND; bottom) seasonal maximum temperature prediction. Maps indicate the highest probability of the above-normal and below-normal categories. Please refer to Appendix Figure A3 for forecast skill levels.

Following the presentations and training on weather monitoring and forecasts, as well as seasonal outlook, the participants discussed and provided feedback on how to effectively use this information for livestock and crop production. The short-range and medium-range forecasts can be used for many field operations and activities such as fertilizer application, spraying, haymaking, preventing damage from frost, irrigation scheduling, and mitigating heat and cold stress in poultry and livestock production. According to the workshop participants, the seasonal forecasts are beneficial and can be used for planning and management in crop and animal production, including:

- onset of the rainy and planting season and impending droughts;
- change crop variety (short or long duration);

- change crop species or mix of species;
- implement soil and water conservation techniques;
- increase or decrease the area planted;
- adjust the timing of land preparation;
- and sell or purchase livestock, depending on the anticipated costs and availability of feeds

In addition to the training on weather and seasonal forecasts, CSs also received training on climate change, and the projections for their respective provinces (Appendix A) were shared, and these are summarised in the subsequent section.

5.2.3. Climate Change and Variability

CSs and farmers were trained on the use and interpretation of climate change and variability products from SAWS. The training session focused on knowledge sharing and dissemination through participatory interactions with learners, youth, and farmers based on their climate knowledge and experiences. The sessions also focused on the development of metrics of preparedness for the farmers under a changing climate. The presentation on climate change and variability focused on the future projections of climate. The project team explained the difference between weather and climate to establish a common understanding when referring to the two terms. The definition of weather was shared with the participants as the short-term state of the atmosphere that can change rapidly, and it includes, but is not limited to rain, cloud cover, sunshine, winds, thunderstorms, and more. While climate is the long-term pattern of weather, it is the average weather over many years in a specific area. In addition, the project team explained global warming, greenhouse gases, and climate change. Furthermore, the use of climate models for climate change projections and climate change scenarios was presented to the participants. Two important climate change scenarios, the moderate scenario and the business-as-usual (no mitigation) scenario, were presented and discussed at the workshops. For the moderate scenario, the radiative forcing is expected to stabilize at $4.5Wm^{-2}$ in the year 2100, as a result of reductions in greenhouse gas emissions. In the no mitigation scenario, also referred to as the “business as usual”, greenhouse gas emissions will continue, where radiative forcing reaches $8.5Wm^{-2}$ by 2100 and continues to rise for some amount of time (Appendix A).

5.3. REPORT ON THE ENGAGEMENT OF FARMERS AS KEY STAKEHOLDERS IN EARLY WARNING SYSTEMS

A training workshop to build the capacity of farmers to understand weather, climate change, and early warning systems was also conducted with farmers from Swayimane and Cofimvaba. The uMshwati Municipality Disaster Management and AFRA supported the training in Swayimane, whilst the Cofimvaba Science Centre facilitated the project team to engage with farmers in Cofimvaba. Feedback from these two sessions is summarised below.

5.3.1. Swayimane

In July 2024, 18 farmers participated in the workshop held at the uMshwathi Thusong Centre boardroom in New Hanover. The farmers were divided into groups for a discussion, where they shared and responded to questions about the weather in their communities if they had been affected by extreme weather events, and what the impact of these extreme weather events was. The discussions also covered what communities are doing to stay safe, how they use indigenous knowledge for weather information, and how everyone in the community can receive early warning information to ensure safety for all. Table 5 shows the responses of the participants to the extreme weather events experienced, the impacts, and the coping mechanisms. Currently, there is no early warning system available for farmers to use to prepare for extreme weather events. The suggestions from farmers regarding the early warning tools that could be utilised to disseminate early warning information in their community are presented in Table 6. This includes the advantages and disadvantages of some of the tools.

Table 5. Participant responses on their experiences of extreme weather events, impacts, and coping mechanisms in Swayimane (KZN).

Extreme Events	Impacts	Coping Mechanisms
Hail	• Loss of plants, and it was not easy to replant • Chicken drowned	• Protect the crops with nets. • Place vehicles under a shelter/garage • Build a shelter for animals like chickens.
Strong winds	• Roofs were blown away/damaged • Crops were damaged • Fertile soil eroded, leading to plants not thriving	• Plant trees for protection against the winds • Place bricks on the roof to ensure it's not blown off • Place a net to protect the crops
High temperatures	• Plants damaged • Veldfires	• Irrigate crops at night Recycle (irrigating using grey water)
Floods	• Damage to property and infrastructure • Loss of profit for small-scale farmers • Plants such as cabbage and tomatoes were exposed to pests and diseases • Plants were washed away	• Open a furrow to allow water to flow through and divert it from the gardens. • Place sandbags around the garden to prevent excessive water from the rain • Use strong fencing to avoid the livestock being washed away
Frost	• Livestock feed was affected as the frost damaged the fields.	• Place dry grass on the ground of the animal shelter • Look for ways to keep animal shelters warm (heaters), especially for young animals and poultry • Cover the plants with a plastic sheet
Drought	• Loss of crops and livestock • Livestock become frail • Water scarcity	• Irrigate crops at night • Recycle water/use grey water for irrigating

Table 6. Early warning tools, their advantages and disadvantages.

EWS Tools	Advantages	Disadvantages
Loud hailing	Accessible to everyone, even those without cell phones or radios	• This would require a dedicated person(s) to go around with the loud hailer. If the person is not in the community, then the message might not reach people on time.
Blowing a whistle	Accessible to everyone, even those without cell phones or radios	• It would require a dedicated person(s) to blow the whistle. If the person is not in the community, then the message might not reach people on time.
Ring the bell to alert the community.	Accessible to everyone, even those without cell phones or radios	• This would require a dedicated person(s) to ring the bell. If the person is not in the community, then the message might not reach people on time.
Word of mouth: pass the message/warning to others after receiving it	Accessible to everyone	• The message can take a long time to reach other people and may be distorted along the way.
Raise a flag to alert others.	Accessible to everyone, even those without cell phones or radios	• This would require a dedicated person(s) to raise the flag. If the person is not in the community, then the message might not reach people on time.
WhatsApp/SMS	WhatsApp groups formed can build community engagement and quick dissemination of weather information.	• It is not accessible to everyone; certain areas do not have electricity, and they only charge their phones when they go to town. Several people are not using smartphones and hence do not have WhatsApp. • The phone signal is also poor in some communities; hence, messages are not received on time.
Community Radio	Quick dissemination of information	• It is not accessible to everyone; certain areas do not have electricity. For radios that operate on batteries, sometimes the signal is bad, or it takes time for owners to replace the batteries. • Not everyone believes the information shared on the radio because sometimes the weather shared is not what they experience on the ground.
Public meetings (organised by the traditional leaders)	Controlled dissemination of information from a trusted source	• EW requires timely dissemination, hence it might be too late to gather people, especially for fast-approaching extreme weather events such as thunderstorms and lightning.

5.3.2. Cofimvaba

Thirty-two farmers participated in a workshop held in July 2024 at the Albertina Nonstikelelo Sisulu Science Centre in Cofimvaba. The farmers identified frost, heatwaves, high temperatures, wildfires, and drought as the main extreme weather events that affect the area. The impacts and some of the coping mechanisms they use are summarised in Table 7. The participants also identified some possible tools that could be used to disseminate EWS in their community, which include using the community radio station (Vukani Community Radio), SMS, loud hailers, traditional leaders' imbizos, local newspaper (Skawala News), Isikoba Community Facebook page, Community WhatsApp groups, and word of mouth through, for example, Ward Committee members.

Participants indicated that some communities in Cofimvaba have weekly community meetings, which could help with sharing warnings if they are issued before the extreme weather event occurs. The pros and cons of these tools are similar to those in Table 6 above. Some community members in Cofimvaba have challenges with electricity and cell phone networks, hence tools like social media will not be effective, so loud hailers and sirens would be more effective.

Table 7. Participant responses on their experiences of extreme weather events, impacts, and coping mechanisms in Cofimvaba.

Extreme Events	Impacts	Coping Mechanisms
Frost, *e.g, Cofimvaba town, Qamata, Albertina Sisulu Science Centre*	• Damage to feedstock/grass. Animals starve, affecting livestock fertility, and sometimes livestock have frostbite. • Farmers spend more money buying feedstock • Water can freeze, and animals struggle to get drinking water. • Loss of and damage to crops • Loss of chickens	• Use a short-term forecast to regulate livestock temperature • Cover the plants with plastic sheeting • Cover the ground with dry grass to regulate the temperatures in animal shelters. • Build a shelter for the lamb and other livestock.
Heavy rains that result in floods, *e.g., in Mncuncuzo, Mahlubini, Chamama, and Malangazana*	• Bridges were swept away • Loss of animals such as cattle, sheep, and goats • Damage to homes • Increase in pests and diseases • Soil erosion • Damage to and loss of crops • People get injured	• Vaccinate animals • Prepare drains to direct water during rainfall events • Construct embankments and encourage people to plant trees to reduce soil erosion • Repair of bridges using stronger materials • Some farmers have insurance to cover their farming activities from extreme weather events. • Some relocate to other towns/provinces.

High temperatures, *e.g., in Gxwalubomvu, Qamata, Ntshingeni*	• Decline in agricultural yields, especially for rainfed agricultural activities • Heat stress for livestock and poultry. Temperatures greater than 26 degrees Celsius lead to windy conditions • Fields dry up and sometimes result in veld fires.	• Use the forecast to plan farming activities • Use a forecast to regulate livestock temperature • Use irrigation systems (like dam running or flood irrigation)
Veld fires, *e.g., Mancuncuzo, Tsakane forests*	• Loss of biodiversity, crops, grazing lands, and infrastructure	• Some farmers have evacuation plans in place • Farmers do controlled fires to avoid veld fires
Drought affects all areas in Cofimvaba.	• Livestock starve and die. • Loss of and damage to plants • Loss of profit as the crop yield decreases and livestock die	• Plant drought-resistant crops • Recycle water and use it for irrigation • Stock feed for livestock • Build more dams • People migrate to other areas
Strong winds *e.g., in Nyazela, Magwala, Skhobeni forest*	• Damage to roofs, electricity cables, wifi poles and cables • Promote the spread of veld fires • Trees get uprooted	• Farmers create windbreaks to protect crops

5.4. SUMMARY AND CONCLUSIONS

The project team organised training workshops for citizen scientists to collaborate on developing an early warning shared vision for their respective communities by ensuring that citizen scientists have a clear understanding of the project objectives and their role. Citizen scientists in the project are volunteers from each study site, including 25-35 learners from primary and high schools, youths, educators, and farmers. The project team held citizen science training workshops at the five project study sites in October, November, and December 2023. The project team has been engaging and sharing warnings issued by SAWS with all the volunteer citizen scientists selected from the five study sites. Furthermore, training workshops were held in July 2024 in partnership with the Association for Rural Advancement (AFRA) and the Department of Science and Innovation (DSI). The workshops took place at the Umshwathi Thusong Service Centre in New Hanover (KZN) for farmers from Umshwati Municipality, and at the Albertina Sisulu Science Center in Cofimvaba (Eastern Cape) for youth and farmers in collaboration with the Science Center.

The agenda of the workshops included training sessions on accessing and interpreting weather forecasts, seasonal outlooks, climate change projections, group discussions on extreme weather events, and sharing knowledge and experiences on climate change, early warning systems, and archiving weather and climate-related indigenous knowledge. After the presentations, participants were split into groups to discuss their experiences with weather, extreme weather events, climate change, and indigenous knowledge systems related to weather and climate.

The CSs and farmers provided input on the weather conditions in their communities, the impact of extreme weather and climate events, coping mechanisms to stay safe, the use of weather and climate-related Indigenous knowledge, and access and use of weather forecasting, seasonal outlook, and early warning information. Participants emphasized the lack of an early warning system for farmers to use and prepare for extreme weather events, highlighting the need for support in improving readiness and response to these events.

CHAPTER 6: HARNESSING CITIZEN SCIENCE TO DOCUMENT INDIGENOUS EARLY WARNING INDICATORS: PATHWAYS FOR INTEGRATING LOCAL KNOWLEDGE IN DISASTER RISK REDUCTION

6.1. INTRODUCTION

The frequency, spatial extent, and intensity of extreme weather events have increased over the years, affecting communities worldwide. The World Meteorological Organisation (WMO, 2021) noted a fivefold increase in incidents of climate change-related disasters over the past 50 years. Globally, there are 11778 weather, climate, and water extreme-related disasters that were reported between 1970 and 2021, resulting in more than two million deaths and economic losses of over US$4.3 trillion (WMO, 2023a). Given the devastating impact of extreme weather, forecasting has become central in providing early warning information to aid disaster preparedness and response. Useful information for predicting weather changes is not only generated by the National Meteorological and Hydrological Service (NMHS); there is a growing consensus that Indigenous Knowledge Systems (IKS) are also vital sources of context-informed and relatable forecasts (Balay-As et al., 2018; Hadlos et al., 2022). Understandably, there is no single fixed definition of indigenous knowledge, as it is shaped by various factors — including the recognition that Indigenous peoples perceive and apply their knowledge in multiple ways, grounded in distinct value systems and cosmovisions (UNESCO, 2024).

However, many Indigenous communities, particularly in the Global South, are at risk of losing their rich knowledge as it remains largely undocumented and is preserved only through memory and oral transmissions across generations. Even more, indigenous knowledge has been dismissed in science-driven climate knowledge generation, often deemed as not universal or easily replicable. Instead, weather forecasts, nowcasts, and early warnings issued by NMHSs have become the dominant scientific methods used to inform the public of natural hazards. Evidence suggests that despite advances in providing accurate and timely warnings of severe weather hazards, these warnings do not always elicit an adequate public response, resulting in loss of life, displacement, and significant economic disruption. The gap lies in the mismatch between the divergent indigenous ways of knowing and understanding information, and the remoteness of knowledge generated and transmitted by scientists, affecting public trust in weather information from NMHSs.

In South Africa, for example, the South African Weather Service (SAWS) uses impact-based forecasting (IBF) that informs the public of impending extreme weather, its likelihood and associated impacts. This is disseminated through partners in disaster management at the national and subnational levels, as well as through radio, television, and social media. However, in 2022, parts of KwaZulu-Natal Province experienced flash floods resulting from a low-pressure system for which several weather warnings were issued, but many were unprepared (Presidential Climate Commission, 2023). The event led to the loss of approximately 435 lives, with 80 people reported missing, disrupted operations for 826 companies (IFRC, 2025), and caused an estimated R17 billion in damages (Presidential Climate Commission, 2023). An awareness of this misnomer helps to acknowledge the need for community-level initiatives for disaster preparedness and response to ensure scientific weather knowledge reaches everyone, whilst also allowing for indigenous knowledge holders to also share their local observations with disaster officials and NMHSs. This is because for many centuries, Indigenous communities have navigated weather and environmental changes relying on their relationship and understanding of the environment and cosmologies (Hewitt, 1983; Balay-As et al., 2018; UNESCO, 2024). As such, there is an urgent need to bridge misconceptions about IKS to foster sustainable relationships between humans and the natural environment (Balay-As et al., 2018; Department of Science and Innovation, 2019).

This chapter builds on these efforts of bridging the gap between science and IKS by sharing insights on the contributions of indigenous communities of Malamulele in Limpopo Province, Cofimvaba in the Eastern Cape Province, and Swayimane in KwaZulu-Natal Province to building relatable context-informed early warnings and responses to extreme weather. The citizen scientists involved include school learners, post-secondary youths, farmers, members of local civic organisations, educators, and community members.

6.2. METHODOLOGY

Citizen scientists selected from Malamulele, Cofimvaba, and Swayimane included education authorities, farmers, disaster management officials, learners, educators, youths, and community members, who were identified through a combination of purposive and snowball sampling. The study employed an interpretive research approach, centering citizen scientists from the three sites as knowledgeable contributors to understanding indigenous knowledge systems for early warning of extreme weather events. Focus was on establishing local insights of short-term (daily weather) and seasonal variations that inform their weather forecasting trends. Thus, data collection relied on participatory methods such as interviews, surveys, storytelling, and workshops, following the four phases of citizen science engagement.

In the first phase, purposive sampling was used to identify key organisations working on disaster management, education, agriculture, and indigenous knowledge custodians in the three sites. Meetings and interviews with these participants enabled snowballing sampling, as they identified other participants, where some volunteered to be enrolled as citizen scientists for this project. Participatory workshops with citizen scientists were used to co-create an early warning shared vision for their respective communities, share the objectives of the study, and plan for future engagements.

In the second phase, known as the development phase, stakeholder engagement workshops were held over several days at each site to assess citizen scientists' knowledge of climate risks in their communities, including IKS, drivers of vulnerability, early warning systems, and current adaptation or response mechanisms. Sharing citizen scientists' life stories and experiences facilitated discussions, highlighting the rich local and indigenous knowledge that remains undocumented but exists within these communities. To improve the information gathered from citizen scientists during the workshops, a survey was provided for each participant to take home and complete with other elderly family members, traditional leaders, and health practitioners, focusing on local and indigenous indicators used to forecast weather changes and extreme events. The workshops also served to share simplified weather, climate, and impact-based early warning information from the SAWS and to evaluate perceptions of the reliability of forecasts and warnings issued by the national meteorological office.

The third phase, the live phase, involved integrating science and IKS by training citizen scientists to collect, interpret, and disseminate weather data obtained from the simple automated weather stations installed at each site, thereby enhancing their understanding of local weather conditions. Targeted key informant interviews with disaster management officials and transect walks with volunteers and local leaders facilitated knowledge sharing through stories that reflect local wisdom, cultural beliefs, and customs influencing people's understanding and experiences of weather and extreme weather events.

6.3. REFLECTIONS FROM CITIZEN SCIENTISTS

The reflections from the Citizen Scientists, surveys, and interviews with participants from the three sites highlighted the connection that these communities have with their environment. This knowledge has shaped their understanding of daily weather patterns, planning of daily activities, and preparation for extreme weather events. The three communities are predominantly agrarian, and studies show that there is a close relationship between agriculture and the natural, human, and spiritual world (Dankelmon, 2002).

6.3.1. Meteorological Indicators

Meteorological indicators commonly used by community members to forecast weather and seasonal changes include observations of cloud formation, wind patterns, and temperature fluctuations (Table 8).

Table 8. Examples of Meteorological indicators that are used to forecast the changes in weather, extreme weather events, and seasons collected from stakeholder engagements in Swayimane (KwaZulu-Natal), Cofimvaba (Eastern Cape), and Malamulele (Limpopo), 2024.

Community	Observations
Swayimane	• Darkening clouds signal impending rainfall. • The transition from winter to spring is marked by warmer temperatures, clear skies, and occasional thunder. • During winter, light rains and strong winds are common, often associated with increased flu and fever due to cold conditions. • The sun sets earlier in winter compared to summer, accompanied by cold temperatures and gusty winds. • Autumn marks the shift from hot to mild weather, indicating the approach of winter. • Mist and frost commonly occur during autumn mornings. • Summer is the hottest season, characterised by thunderstorms and heavy rainfall.
Malamulele	• Spring is identified by warmer temperatures and occasional windy rains. • In summer, the sun sets later, and temperatures are generally high throughout most days. • Summer represents the main rainy season, often accompanied by heatwaves and floods.
Cofimvaba	• Changes in cloud formations indicate the onset of strong winds. • The presence of cumulonimbus (large, towering) clouds signals that rainfall is imminent.

In Swayimane, participants reported that the appearance of dark, dense clouds is interpreted as a sign of imminent rainfall, while strong winter winds are understood to herald the arrival of rain associated with cold fronts. Across all three study sites, participants consistently noted that temperature variations serve as reliable cues for seasonal transitions, summer being characterised by longer days and shorter nights, whereas winter brings shorter days and longer nights.

These meteorological indicators reflect systematic, experience-based observations aligned with established atmospheric processes. For instance, darkening or cumulonimbus cloud formations correspond to convective activity preceding rainfall, while temperature and light variations across seasons mirror solar radiation and atmospheric circulation changes. The coherence between indigenous meteorological knowledge and scientific principles underscores the empirical validity and local precision of IKS in interpreting weather dynamics.

6.3.2. Ecological Indicators

Indigenous communities rely on a range of ecological indicators, particularly animal behaviour and plant phenology, to anticipate weather patterns, seasonal shifts, and extreme weather events (Table 9). These indicators are deeply rooted in local environmental observations and have been refined through generations of experiential learning.

In Swayimane, participants identified several biological cues used to predict rainfall. The appearance of bats flying around, the sighting of the *Southern Ground Hornbill* (*Bucorvus leadbeateri*), and the distinct chirping of the *Fukwe* bird (*Burchell's Coucal*) were noted as signs of imminent rain. The nesting behaviour of the *Amahlohloko* bird also serves as an early warning for rainfall intensity: nests built high in trees indicate a season of heavy rainfall and potential flooding, whereas nests constructed lower suggest a drier season ahead. In Cofimvaba, rainfall prediction relies on multiple ecological indicators, including the unusual appearance of black ants on walls, the presence of *Intubi* (butterflies), *Inkonjane* (swallows), *Ing'angane* (Hadada ibis), and *Intsikizi* (*Southern Ground Hornbill*). Conversely, sightings of the *Bhobhoyi* bird and locust swarms are interpreted as signs of impending drought.

In Malamulele, indicators are largely drawn from animal behaviour. Participants explained that when donkeys and calves behave abnormally, such as running around or rolling on the ground, it signals the coming of rain. Cattle lying down in open pastures are similarly seen as indicators of early summer rainfall. The presence of "*Peolwane*" (*Red-breasted Swallow*) birds flying erratically in multiple directions is also associated with approaching rain.

Table 9. Examples of Ecological indicators used to forecast the changes in weather, extreme weather events and seasons shared during the stakeholder engagements in Swayimane (KwaZulu-Natal), Cofimvaba (Eastern Cape), and Malamulele (Limpopo), 2024.

Indicator (Species/Sign)	Community	Observed Behaviour	Associated Weather or Seasonal Interpretation
Southern Ground Hornbill (*Bucorvus leadbeateri*) /*Intsikizi*	Swayimane, Cofimvaba	Presence or frequent calls	Imminent/ Onset of rain
Fukwe bird (*Burchell's Coucal*)	Swayimane	Increased chirping or calls	Imminent rainfall
Birds and bats (general)	Swayimane	Increased flight activity before rainfall	Approaching rain; rising humidity
Village Weaver (*Ploceus cucullatus*)	Swayimane	Nest building and loud morning calls in summer	Beginning of summer; breeding season
Mahlokohloko birds	Swayimane	Seasonal migration and arrival in villages. The nesting height of *amahlokohloko* birds indicates rainfall intensity	Start of summer and rainy season. The high nests signal heavy rains/floods, while low nests suggest light rain.
Inkonjane (Swallows)	Cofimvaba	Increased flight activity	Approaching rain
Ing'angane (Hadada Ibis)	Cofimvaba	Seen flying or calling frequently	Approaching rain
Bhobhoyi bird	Cofimvaba	Increased presence	Impending drought
Black ants	Cofimvaba	Appearing on walls or in houses	Rain approaching
Intubi (Butterflies)	Cofimvaba	Increased visibility	Approaching rain
Grasshoppers	Cofimvaba	Unusually high numbers	Impending drought or dry spell
"*Peolwane" (Red-breasted Swallow*	Malamulele	Flying in multiple directions	Imminent rainfall
Bees, flies, and other insects.	All sites	Increased activity and buzzing	Hot weather or the onset of summer
Insects (general)	Malamulele	Chirping for prolonged periods	Very high temperatures

Ants	All sites	Building new colonies in the spring	Onset of warmer season
Spiders	All sites	Formation of large webs	Approaching a cold winter season
Small birds and parrots	Swayimane	Increased visibility during autumn	Transition to cooler season
Migratory birds (falcons, white storks/*unogolantethe*)	Swayimane	Arrival in the summer months	Warm conditions and the start of summer
Laying hens	All sites	Reduced egg production in winter	Extreme cold or onset of winter
Birds (various species)	All sites	Gathering and storing food	Preparation for winter scarcity

Beyond rainfall, participants in Malamulele observed that prolonged insect chirping during summer is linked to very high temperatures. At the same time, an increase in flies and mosquitoes is seen as a sign of an approaching heatwave. In Swayimane, poultry farmers noted that reduced egg production during winter coincided with extreme cold conditions. Across all three sites, participants reported that a noticeable decline in the presence of birds and ants signals the arrival of winter and suggests the likelihood of cold spells.

Seasonal transitions were also linked to specific ecological cues. In Swayimane, the abundance of *Amadumbe* (*Colocasia esculenta*) plants following summer rainfall marks the arrival of autumn, as these tubers become common in local markets and household meals. In Cofimvaba, the growth of aloe plants signifies the onset of autumn, while the blooming of yellow flowers on the *UmuNga* (sweet thorn, *Vachellia karroo*) tree indicates the approach of summer and the beginning of land preparation for planting. In Malamulele, the shift from winter to spring is heralded by the reappearance of insects such as bugs, moths, and butterflies.

Overall, these observations illustrate how indigenous communities across the three sites continue to rely on interconnected biological and environmental indicators to forecast weather and seasonal changes. These indicators not only guide agricultural and livelihood activities but also reinforce community-based resilience to climate variability. Behaviours such as increased bird activity before rainfall align with shifts in atmospheric pressure and humidity, which influence animal movement and feeding patterns. Similarly, reduced egg production in winter is often a result of reduced light hours and cold stress (Hu and Cheng, 2021; Kim et al., 2023), and bird migration during cold periods reflects adaptive responses to temperature decline and resource scarcity (Birdlife South Africa, 2020, 2025). These observations reveal that IKS captures ecological feedback that mirrors scientific explanations of animal and plant responses to meteorological and climatic fluctuations, offering a locally grounded complement to formal forecasting models.

6.3.3. Astronomical Indicators

Astronomical indicators, including the position and appearance of the sun, moon, and stars, were traditionally used to forecast weather patterns and seasonal transitions, often intertwined with cultural practices, oral traditions, and storytelling (Table 10). Participants across the three sites described the moon and stars as key celestial guides for predicting seasonal changes. Citizen scientists noted that during September and October, community members closely observe the moon to anticipate the onset and intensity of the summer rainfall season. In Swayimane and Cofimvaba, a tilted moon with its crescent facing downward is interpreted as a sign of abundant rainfall in the coming months, whereas a crescent facing upward suggests limited rainfall or potential drought conditions.

Engagements with traditional leaders and traditional health practitioners in Limpopo revealed the historical use of stars, namely the *Xirimela* (or *Selemela*), which was traditionally associated with forthcoming rainfall, while the *Gongomela* star signalled the likelihood of disasters such as heavy rains, thunderstorms, or droughts, although participants noted that these stars are no longer visible today. From an astronomical perspective, stars may become invisible from Earth due to natural life cycle changes (such as dimming or supernovae), gradual shifts in Earth's axial tilt that alter constellation positions, or the Milky Way's rotation, moving stars beyond the observable horizon. These processes contribute to the cultural perception that some stars have "*disappeared*" from view.

Table 10. Examples of Astronomical indicators (Observations of stars, moon, and sun) used to forecast the changes in weather, extreme weather events, and seasons based on field data collected from stakeholder engagements in Swayimane (KwaZulu-Natal), Cofimvaba (Eastern Cape), and Malamulele (Limpopo), 2024.

Community	Observations
Swayimane	• When the moon's crescent faces downward, it indicates heavy rainfall during the upcoming summer; when it faces upward, it suggests reduced rainfall or possible drought. • The arrival of spring is marked by a full moon surrounded by stars appearing closer together.
Malamulele	• A first-quarter moon is typically observed highest in the sky around the spring equinox. • Stars appear brighter during spring nights. • In winter, the moon remains visible for longer periods, and the skies are clearer. • During summer, a new moon appears higher and brighter in the sky. • When the crescent moon points upward, it is believed to "hold water," signalling a dry spell or low rainfall for the coming season. • In summer, celestial visible triangular alignment (Mars, Venus, and the moon). • Summer nights are characterised by a prominent, dense field of stars and a fully developed moon.
Cofimvaba	• A red-tinged moon is interpreted as a sign of strong winds to come. • The earlier sunrise marks the onset of summer, continuing until winter, when the sun begins to rise later.

The astronomical indicators identified by Indigenous communities show strong parallels with established meteorological and astronomical principles. For instance, variations in the moon's orientation and illumination correspond to lunar phases and the tilt of the ecliptic, which influence night-time brightness. Observations of the sun's shifting position and duration above the horizon align with the Earth's axial tilt angle and seasonal transitions (NASA, 2020).

6.4. RELIGIOUS AND TRADITIONAL RITUALS THAT CAN BE DONE TO MITIGATE THE IMPACT OF EXTREME WEATHER

In addition to recognizing the IKS indicators for predicting seasons and upcoming weather events, farmers in Swayimane and Cofimvaba also shared some religious and traditional rituals performed in their communities to reduce the impact of or end extreme weather.

Swayimane

- Community members go to the mountain to ask for rain
- If it is raining, ring the bell at the door, and it will stop raining
- If you hit the traditional pot, you can prevent the occurrence of hail
- To stop rainfall, add salt to the seawater
- Dig in front of the door and place the bottle with seawater to prevent a rainfall event.
- Burn a tyre to prevent rain
- Put a tyre on top of the roof to avoid being struck by lightning
- Cover all mirrors in the house and stay away from windows to avoid being struck by lightning

Cofimvaba

- When there is too much rain, and you want it to stop, you get twins to go out and bang metal tins.
- Yelling '*Embo Embo'* to chase away the rain
- Religious leaders go to the mountains to pray when there is a drought.

Religious and traditional practices documented through this citizen science project contribute to local risk understanding but have not been formally validated and should be integrated cautiously alongside scientifically grounded early warning and preparedness approaches.

6.5. PATHWAYS FOR THE INTEGRATION OF LOCAL KNOWLEDGE

The findings underscore the depth and richness of IKS within South African communities, which hold significant potential to enhance disaster risk reduction (DRR) and climate change adaptation. However, this knowledge remains at risk of erosion, as much of it is tacitly transmitted orally and held within the memories of community elders. Factors such as rural-to-urban migration, cultural assimilation, and the influence of modernization disrupt traditional systems of knowledge transmission, weaken social networks, and limit opportunities for intergenerational learning. Preserving and revitalising IKS is therefore essential to strengthen community-based environmental management, disaster preparedness, and response.

A key pathway for integration involves strengthening institutional mechanisms for documentation and knowledge management. Partnerships with library and information professionals can facilitate the systematic cataloguing, indexing, and archiving of IKS materials, ensuring accessibility and long-term preservation (Ngulube, 2002). Encouragingly, the Department of Forestry, Fisheries, and the Environment has initiated a pilot study to collect baseline data on climate risk information and IKS to inform provincial risk profiling under the National Climate Change Information System (NCCIS). Findings from this initiative highlight Indigenous communities' willingness to share their knowledge and emphasise the value of integrating IKS with scientific data to enhance local resilience. Similarly, in KwaZulu-Natal, the provincial disaster management department has also started a process of collating and validating IKS from the province to support disaster management (KZN-PDMC, 2021; 2022). However, such documentation processes are resource-intensive and require adequate financial support, flexibility, and inclusive participation across sectors.

Currently, IKS is not formally embedded within South Africa's national climate change or disaster risk reduction policies, posing a challenge for its application in local adaptation and resilience planning. Including IKS holders and community representatives in municipal-level DRR and climate adaptation planning processes can ensure that locally observed weather patterns and early warning indicators inform formal systems. The involvement of citizen scientists in this study illustrates the potential of such integration. Through the installation of low-cost automatic weather stations, communities were able to generate localised meteorological data while simultaneously recording IKS indicators related to rainfall, temperature extremes, and other environmental cues. This participatory approach not only validated scientific forecasts issued by the South African Weather Service (SAWS) but also enhanced community ownership and responsiveness to weather warnings.

Importantly, this study engaged youth and learners as citizen scientists, fostering intergenerational knowledge exchange between young people and community elders. This approach ensured that valuable Indigenous knowledge, much of which had never been formally recorded, was captured and transmitted to younger generations. Integrating IKS into school curricula and community-based education programmes could further institutionalise this process, ensuring that Indigenous weather forecasting knowledge continues to inform adaptation and resilience strategies for generations to come.

6.6. SUMMARY

Indigenous Knowledge Systems (IKS) offer valuable insights that can support broader societal objectives, while their preservation and dissemination promote the continuity of traditional practices and lifestyles. Beyond cultural significance, IKS can contribute meaningfully to weather and climate early warning systems (Kugara et al., 2021). Indigenous communities maintain a holistic relationship with their environment, encompassing both metaphysical and physical dimensions. This relationship enables them to sense, observe, and interpret environmental changes, thereby anticipating and preparing for weather variations.

Findings from this study indicate that indigenous communities in South Africa employ a combination of meteorological, ecological, and astronomical IKS indicators to monitor local weather patterns, extreme events, and seasonal climate variations. These traditional knowledge systems are particularly valuable for predicting and interpreting climate phenomena in areas where formal forecasts may be unavailable. However, IKS-based forecasting faces significant challenges, including inadequate knowledge transfer mechanisms, limited documentation, loss of experienced knowledge holders, and the pressures of modernisation. Additional threats include the disappearance of key plants and animals, land-use changes, urbanization, population growth, and the impacts of climate change.

Through the training of citizen scientists from these communities in the use of low-cost automatic weather stations and the interpretation of forecasts and climate projections, participants emphasised the importance of accessible, localised early warning systems for agricultural planning. Integrating indigenous and scientific knowledge offers a practical pathway for enhancing climate resilience, providing more precise, context-specific forecasts that can guide local decision-making and policy.

CHAPTER 7: COMMUNITY-BASED TOOLS FOR EARLY WARNING

7.1 DEVELOPING EARLY WARNING SYSTEMS

Early warning is a crucial component of disaster risk reduction, as it helps prevent loss of life and minimizes the economic impact of disasters. To be effective, early warning systems (EWS) must engage the communities at risk, promote public education and awareness of risks, disseminate messages and warnings effectively, and maintain a state of preparedness (WMO, 2018). A community-based or people-centred multi-hazard early warning system empowers individuals and communities facing hazards to take timely and appropriate actions to minimize the risk of harm, injury, loss of life, and damage to property, assets, and the environment (WMO, 2018). An effective EWS must be: MULTI-HAZARD: capable of detecting various hazards that may occur independently, concurrently, or in succession. END-TO-END: covering all aspects from hazard identification to response, including delivering clear and actionable warning messages. PEOPLE-CENTERED: designed with a focus on individuals, enabling them to take timely and appropriate actions to minimize risks (WMO, 2024). An effective EWS consists of four key components: risk knowledge, technical monitoring and warning service, communication and dissemination of warnings, and community response capability. These essential and interconnected components involve collecting data and conducting risk assessments, monitoring hazards, issuing timely and accurate warnings, and ensuring preparedness to respond to warnings at all levels (UNDRR, 2023). The schematic representation of the four key elements of an EWS is presented in Figure 52.

Disasters are not always the main concern for vulnerable communities, so the sustainability of EWSs relies on incorporating components that serve multiple purposes within a community. According to the International Federation of Red Cross and Red Crescent Societies (IFRC), disaster risk management organisations often find that the priorities of the communities they assist differ from what they expect. Instead of focusing on a recent deadly natural disaster like floods that claim a few lives each year, poor communities in developing countries prioritise daily survival, food security, and meeting basic and socio-cultural needs such as education expenses, healthcare costs, access to water, religious ceremonies, or funerals regularly. Therefore, it is crucial for EWS initiatives to recognise and address the specific priorities and requirements of local communities (IFRC, 2012).

Effective EWSs rely on diverse knowledge systems, and the most robust EWS will leverage a variety of knowledge systems, including indigenous, local, and scientific knowledge. Language plays a crucial role in the transmission of knowledge. Exploring the unique qualities of a language can reveal interesting insights about the users that are instrumental in guiding decisions, which can be valuable in enhancing EWSs (IFRC, 2012). Globally, EWSs form a cornerstone of climate resilience by enabling communities to anticipate, prepare for, and respond to climate-related hazards. In South Africa, community-based approaches that combine scientific tools and IKS are especially important for localised and culturally relevant early warning. This chapter presents findings from the project study sites on community EWSs where citizen scientists participated in identifying hazards, analysing climate patterns, evaluating warning communication channels, and assessing the relevance and usefulness of IKS tools.

Disaster risk knowledge

- Are key hazards and related threats identified?
- Are exposure, vulnerabilities, capacities and risks assessed?
- Are roles and responsibilities of stakeholders identified?
- Is risk information consolidated?

Detection, monitoring, analysis and forecasting of the hazards and possible consequences

- Are there monitoring systems in place?
- Are there forecasting and warning services in place?
- Are there institutional mechanisms in place?

Warning dissemination and communication

- Are organizational and decision-making processes in place and operational?
- Are communication systems and equipment in place and operational?
- Are impact-based early warnings communicated effectively to prompt action by target groups?

Preparedness and response capabilities

- Are disaster preparedness measures, including response plans, developed and operational?
- Are public awareness and education campaigns conducted?
- Are public awareness and response tested and evaluated?

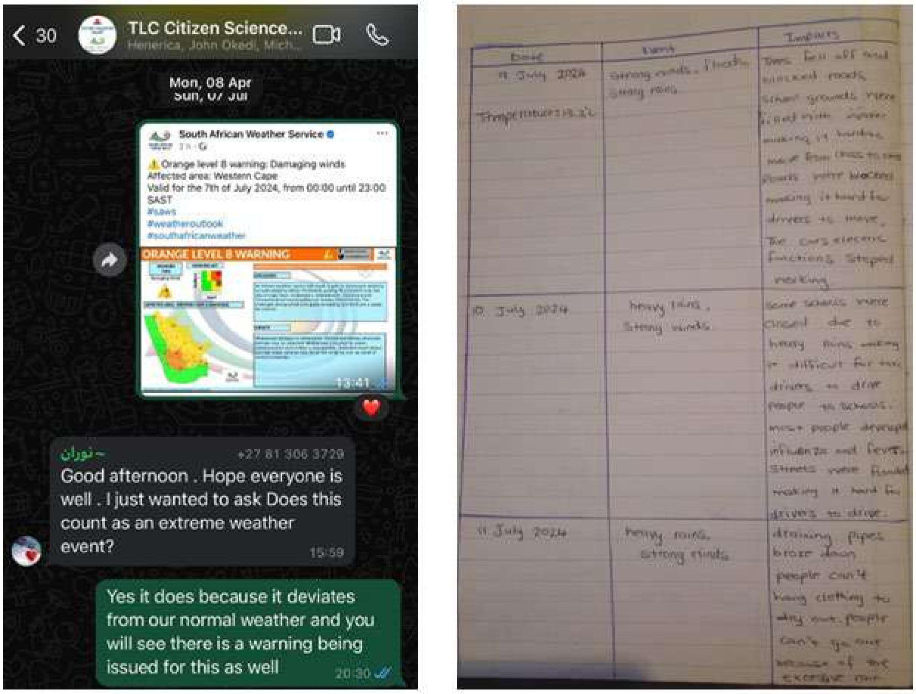
Figure 52. Four elements of people-centred early warning systems (WMO, 2018).

Furthermore, the warning value chain concept highlighted in this report shows the importance of comprehending how warning signals are processed and affect how decisions are made within complex systems. The emphasis is on timely, understandable, and actionable signals to support effective warnings and information transmission. Organisations can find possible points of failure or delay that could jeopardise the efficacy of warnings in preventing or mitigating adverse events by examining the complete value chain from detection to dissemination. The warning value chain also emphasizes how different parts of the warning process are interconnected. It highlights the functions of sensors, communication channels, interpretive frameworks, and decision-makers, showing how each step can affect warning systems' overall effectiveness. Acknowledging these interdependencies enables focused enhancements like improving sensor accuracy, optimizing communication channels, or educating decision-makers on proper signal interpretation. In the end, this all-encompassing perspective aids in the creation of warning systems that are stronger and more resilient, able to handle intricate threats. The warning value chain concept promotes an all-encompassing strategy that takes into account each link in the chain, guaranteeing that warning signals are not only produced but also successfully received and responded to. By putting this idea into practice, organisations can enhance their ability to safeguard people and property from a variety of threats, optimise their warning systems, and more accurately predict possible malfunctions. In order to improve overall safety resilience and advance proactive risk management, this systemic approach is crucial.

7.2 CAPTURING EXTREME WEATHER EVENTS AND FEEDBACK FROM CITIZEN SCIENTISTS

Daily weather information in the five sites is being collected using Citizen Weather Stations (CWSs), and data is stored in memory cards. During the training, the CSs were also asked to collect information on the extreme weather events that affect their communities during the project lifecycle. CSs identified WhatsApp as one of the platforms that can be used to share the early warnings issued by SAWS, and CSs would provide feedback to validate these warnings and also share images of the impact of extreme weather in their community, where possible. WhatsApp groups were created for all of the study sites, including Cullinan, Cofimvaba, Malamulele, Manenberg, and Swayimane. CSs were encouraged to share these early warnings with their communities. For Cullinan, the volunteers were all primary school learners who did not have cell phones; hence, information was shared through their educators, and feedback was collated in a book.

While CS received warnings when they were issued by SAWS for their respective areas, feedback from Cofimvaba, Malamulele, and Swayimane was poor due to challenges with the network, and some CSs did not have data. Therefore, other ways of obtaining their feedback were explored. All sites received a book that they used, and engagements with the CSs to discuss this feedback were conducted during follow-up workshops. The CSs from each site elected two people to lead the team in collecting extreme weather information for their community, which was captured in the book. Some of the feedback received by CSs is presented in this section. The CSs from Manenberg, for example, shared that they have experienced heatwaves, strong winds, and heavy rainfall resulting in floods. On 8 July 2024, the SAWS issued an Orange level warning for the City of Cape Town to prepare residents for damaging winds due to an intense weather system, and this information was shared with the CSs (See Figure 53 below-left image). The CSs indicated that they experienced heavy rains and strong winds between 9 and 11 July, which caused some schools to close down for a few days.



South African Weather Service

⚠️ Orange level 8 warning: Damaging winds
Affected area: Western Cape
Valid for the 7th of July 2024, from 00:00 until 23:00 SAST
#saws
#weatheroutlook
#southafricanweather

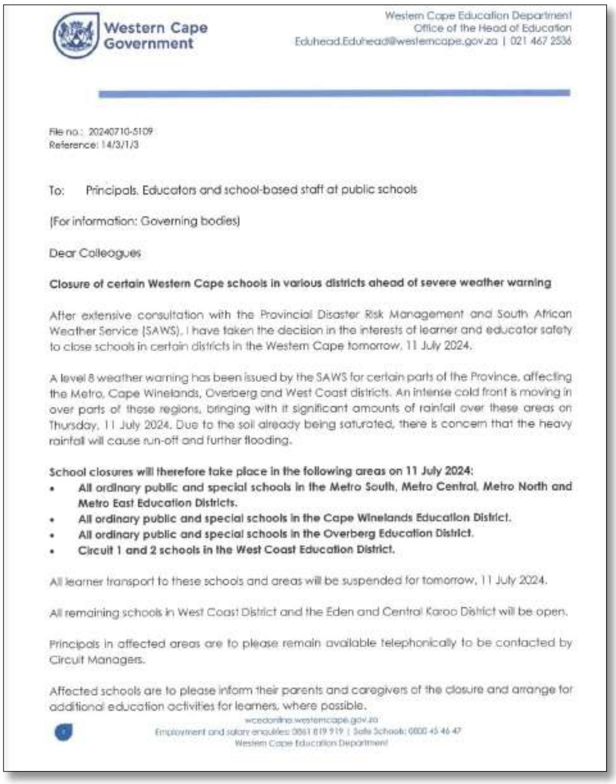
~ نوران +27 81 306 3729
Good afternoon . Hope everyone is well . I just wanted to ask Does this count as an extreme weather event? 15:59

Yes it does because it deviates from our normal weather and you will see there is a warning being issued for this as well 20:30

Date	Event	Impacts
9 July 2024 Temperature:13.2°C	strong winds, floods, strong rains	Trees fell off and blocked roads, school grounds were filled with water making it hard to move from class to class. Roads were blocked making it hard for drivers to move. The city's electric functions stopped working
10 July 2024	heavy rains, strong winds	Some schools were closed due to heavy rains making it difficult for the drivers to drive people to schools. Most people developed influenza and fever. Streets were flooded making it hard for drivers to drive.
11 July 2024	heavy rains, strong winds	draining pipes broke down people can't hang clothing to dry out. People can't go out because of the excessive rain

Figure 53. Orange-level Impact-based warning issued for the Western Cape, including the City of Cape Town on the left and the feedback captured in the book by CSs from Manenberg (on the right).

The CSs also shared a notice that was issued by the Western Cape Department of Education in consultation with the Provincial Disaster Management, alerting schools to close on the 11th of July to ensure the safety of learners and educators (Figure 54). The Leadership College was inaccessible following the heavy rains and strong winds. The CSs also shared some images below of the impacts in their community, with some roads getting blocked and some houses damaged by this extreme weather event (Figure 55).



Western Cape Government

Western Cape Education Department
Office of the Head of Education
Eduhead.Eduhead@westerncape.gov.za | 021 467 2536

File no.: 20240710-5109
Reference: 14/3/1/3

To: Principals, Educators and school-based staff at public schools

(For information: Governing bodies)

Dear Colleagues

Closure of certain Western Cape schools in various districts ahead of severe weather warning

After extensive consultation with the Provincial Disaster Risk Management and South African Weather Service (SAWS), I have taken the decision in the interests of learner and educator safety to close schools in certain districts in the Western Cape tomorrow, 11 July 2024.

A level 8 weather warning has been issued by the SAWS for certain parts of the Province, affecting the Metro, Cape Winelands, Overberg and West Coast districts. An intense cold front is moving in over parts of these regions, bringing with it significant amounts of rainfall over these areas on Thursday, 11 July 2024. Due to the soil already being saturated, there is concern that the heavy rainfall will cause run-off and further flooding.

School closures will therefore take place in the following areas on 11 July 2024:
- **All ordinary public and special schools in the Metro South, Metro Central, Metro North and Metro East Education Districts.**
- **All ordinary public and special schools in the Cape Winelands Education District.**
- **All ordinary public and special schools in the Overberg Education District.**
- **Circuit 1 and 2 schools in the West Coast Education District.**

All learner transport to these schools and areas will be suspended for tomorrow, 11 July 2024.

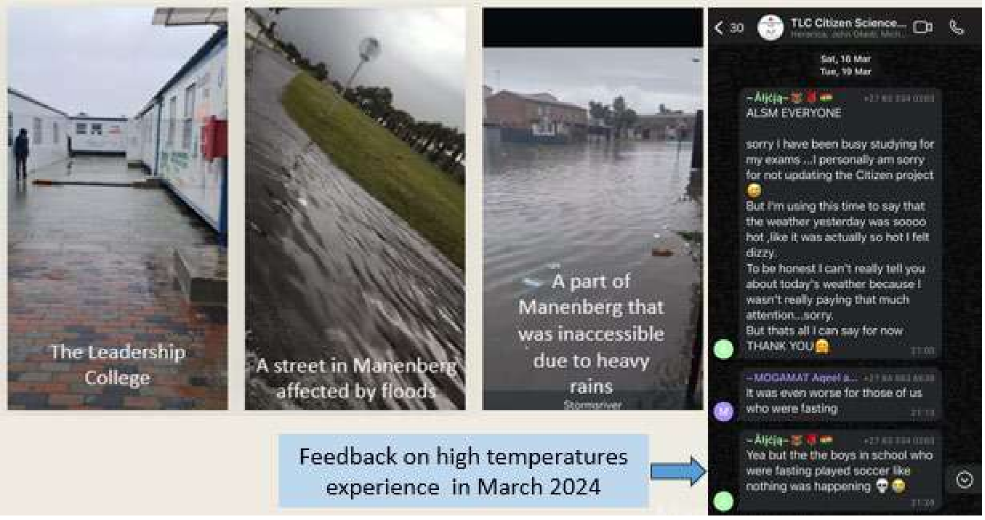
All remaining schools in West Coast District and the Eden and Central Karoo District will be open.

Principals in affected areas are to please remain available telephonically to be contacted by Circuit Managers.

Affected schools are to please inform their parents and caregivers of the closure and arrange for additional education activities for learners, where possible.

wcedonline.westerncape.gov.za
Employment and salary enquiries: 0861 819 919 | Safe Schools: 0800 45 46 47
Western Cape Education Department

Figure 54. Notice issued by the Western Cape Department of Education advising schools to close following the Orange Level Impact-Based warning for strong winds and heavy rainfall, which caused damage to roads, schools, and other infrastructure.



-Aliçia-
ALSM EVERYONE

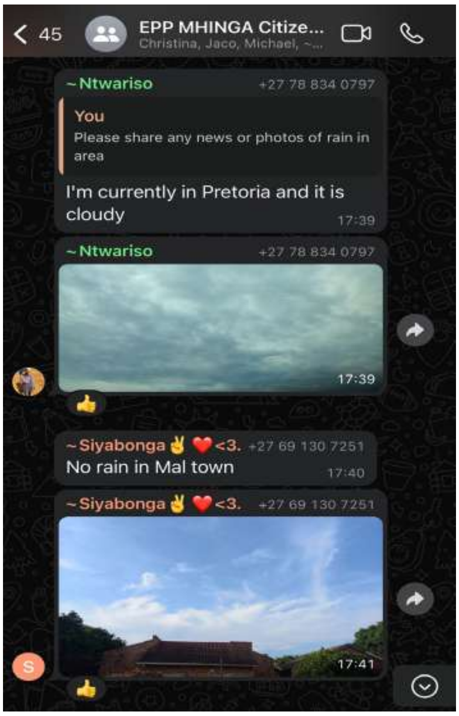
sorry I have been busy studying for my exams ...I personally am sorry for not updating the Citizen project 😓
But I'm using this time to say that the weather yesterday was soooo hot ,like it was actually so hot I felt dizzy.
To be honest I can't really tell you about today's weather because I wasn't really paying that much attention...sorry.
But thats all I can say for now
THANK YOU🤗

-MOGAMAT Aqeel a...
It was even worse for those of us who were fasting

-Aliçia-
Yea but the the boys in school who were fasting played soccer like nothing was happening 💀😂

Figure 55. Images shared by CS of the impact of the heavy rains in Manenberg, following the heavy rains between 9-11 July 2024; Image on the far-right CS shares experiences of extreme high temperatures that they experienced in March 2024.

The CSs from Malamulele also reported through a WhatsApp group that they have experienced very high temperatures and incidents of heatwaves in the past 8 months since the project began. During a follow-up workshop in April 2024, learners shared that their community received less rain last summer (2023/24), which affected fruit and crop production. Mangoes, a common fruit in many households, were in short supply, and some were sunburned and were not suitable for sale in local markets. In one incident, the CSs shared that the warning issued for their community regarding rainfall was inaccurate, as the weather in their community was clear and sunny (Figure 56). The validation by CSs helps verify the forecast information issued by SAWS. It also highlights the need for more weather stations to provide local weather information. The data provided by the CWSs could be used to support the SAWS network to have more accurate weather information.



~Ntwariso +27 78 834 0797

You
Please share any news or photos of rain in area

I'm currently in Pretoria and it is cloudy 17:39

~Ntwariso +27 78 834 0797

17:39

~Siyabonga ✌️ ❤️<3. +27 69 130 7251
No rain in Mal town 17:40

~Siyabonga ✌️ ❤️<3. +27 69 130 7251

17:41

Figure 56. Images shared by CS on the weather in Malamulele, verifying no rain on the 9th of January 2024.

7.3 COMMUNITY-BASED EARLY WARNING TOOLS FOR THE STUDY SITES

Citizen scientists across the study sites actively participated in identifying hazards, weather patterns, communication channels, and the perceived usefulness of warning systems. This scoping process helped to highlight context-specific tools and practices that communities currently use, as well as those they value or mistrust. The Citizen Scientist demonstrated substantial knowledge of climate-related hazards and trends. Their identification of local hazards served as an important baseline for understanding the types of early warning tools and communication platforms currently in use. From the workshops, communities indicated that they rely on a mix of technological and traditional tools depending on accessibility. Citizen scientists were also able to describe weather patterns and trends, such as seasonal floods in Cofimvaba, sudden temperature changes in Cullinan, and frequent heavy winter rains in Cape Town. Table 11 provides a summary of hazards and early warning tools identified across the study sites. These tools formed the basis for assessing both the reach and reliability of existing early warning communication pathways and gaps across the study areas. Summary of the focus group discussions and responses on hazards and early warning tools identified for the study sites are presented in Tables 12 to 15.

Table 11: Summary of hazards and early warning tools identified across sites

Study Site	Hazards Identified	Weather Patterns/Trends	Early Warning Tools
Cullinan (Gauteng)	Heavy rains, heatwaves, strong winds, thunderstorms, hail, drought	Sudden temperature changes – increased temperatures; heavy rain leading to floods	Radio, WhatsApp, word of mouth, smartwatches, phones, social media, TV
Cofimvaba (Eastern Cape)	Drought, heatwaves, thunderstorms, strong winds, floods	Seasonal floods; strong winds at night; unusual cold spells sometimes, and increased temperatures resulting in heatwaves	WhatsApp, radio, and limited by network connectivity
Swayimane (KwaZulu-Natal)	Mist, floods, heatwaves, fog, heavy winds, thunderstorms	Temperature changes, heavy rains leading to floods, and frequent strong winds and lightning.	TV, radio, WhatsApp, word of mouth (loadshedding and weak signals challenges)
Malamulele (Limpopo)	Drought, heatwaves, floods	Temperature changes - increased temperatures resulting in heatwaves, and dry spells	TV, radio, WhatsApp, word of mouth, phones, social media
Manenberg (Western Cape)	Cold fronts, heatwaves, heavy rains, flooding, strong winds	Frequent heavy rains cause flooding; heat strokes	Radio, TV, WhatsApp, SMS, weather apps

Table 12: Summary of hazards and early warning tools identified for Cullinan – Viva Connect School: focus group discussions and responses.

Risk Knowledge	
Questions	**Answers**
Are the hazards and the vulnerabilities well known?	Climate related hazards and the vulnerabilities are well known by the citizen scientists (primary school learners from Grades 3 up to 7 who were between the ages of 9 and 12 years old). Hazards identified were: • Heavy rains • Heatwaves • Strong winds • Thunderstorm/ lightning • Hail • Drought
What are the weather patterns and trends?	The CSs identified these weather patterns and trends as common: • Heavy rains result in floods that lead to the contamination of water, resulting in water-borne diseases like cholera. • Strong winds resulting in property damage, i.e., the rooftop blowing away.

	• Heatwaves due to extreme hot temperatures are often experienced, which result in health-related issues like heat rashes and nose bleeds for others.
Dissemination and Communication	
Do warnings reach all of those at risk?	The CSs agreed that the community does receive warnings. According to the citizen scientists, warnings are received on different platforms, including radio, WhatsApp groups, word of mouth, smartwatches, phones, social media, and TV. However, citizen scientists indicated that the elderly do not have access to technological devices.
Are the risks and warnings understood?	The CSs agreed that the risks and warnings are understood.
Is the warning information clear and usable?	The CSs shared that the warning information received is clear and usable. However, the warnings are not always accurate. With one volunteer describing his personal experience below; “Sometimes you see it is going to rain, but it does not rain. One day, I checked the weather, and it told me it was going to be hot, so I wore shorts with no jersey. After hours, the cold started to form, and the colour of the sky changed, and it started to rain heavily, but in most cases, the warning signs are accurate.”
Challenges and recommendations for integration of IKS-based tools in early warning systems.	The CSs indicated that indigenous knowledge system (IKS)-based tools may be less accurate than scientific warning systems, as they may lack accuracy and create unreliable warnings. Furthermore, they indicated that the language used to communicate the scientific warnings should consider the needs of most of the people in that community, as some have limited understanding of English.

Table 13: Summary of hazards and early warning tools identified for Cofimvaba Science Centre: focus group discussions and responses.

Risk Knowledge	
Are the hazards and the vulnerabilities well known?	Hazards and vulnerabilities are well known by the citizen scientists (local farmers and community members). Hazards identified were: • Drought • Heatwaves • Thunderstorms/ lightning • Strong winds • Floods
What are the patterns and trends?	The CSs identified these weather patterns and trends as common in Cofimvaba and its surrounds: • Floods are experienced in the summer season (i.e., in December, January, and February). • Strong winds are experienced at night (i.e., in kuHange and kuTsakane); however, less rain has been observed with frequent cold spells in the summer season. • Weather changes are experienced with noticeable changes in November 2024 (i.e., extremely cold in Cofimvaba due to it snowing).

Dissemination and Communication	
Do warnings reach all of those at risk?	Citizen scientists agreed that warnings are received; however, they can be ignored. In addition to this, citizen scientists in Cofimvaba noted that in some areas, there are network and signal issues, which make it more challenging for people to receive the warning information. Other barriers identified by the citizen scientists to receiving warning information include: • The lack of mobile data. • The short time frame between receiving the warning and reaction time. • The poverty and lack of infrastructure for evacuation purposes.
Are the risks and warnings understood?	The CSs indicated that the language used to communicate the warning (i.e., in the WhatsApp group) can be too advanced and complicated for those who do not understand English.
Is the warning information clear and usable?	Citizen scientists agreed that the warning information is clear; however, it can be too general, making it challenging to respond.
Challenges and recommendations for integration of IKS-based tools in early warning systems.	Citizen scientists in Cofimvaba indicated that some of the traditional cultural beliefs about the weather are changing because the weather patterns and trends are changing, which makes it a challenge to integrate them into early warning systems, as they are not accurate and reliable. The CSs identified these traditional and cultural beliefs and challenges about the weather: • Heat was believed to result in precipitation, like rain or thunderstorms, in a given area. However, nowadays the presence of heat does not always result in precipitation as was experienced in the past. • Wind was believed to result in precipitation. However, now, wind does not necessarily result in precipitation. The CSs in Cofimvaba suggested the following to improve the integration of IKS-based tools in early warning systems: • Incorporating traditional leaders into decision-making based on IKS tools • Raise awareness of rural and local community members on climate change • Consider alternative ways to communicate warnings, such as through the following platforms: ○ social media (e.g., Facebook) ○ community meetings (*imbizo*) ○ traditional media (radio/TV) ○ posters ○ coordinators to pass information ○ schools • Members of WhatsApp groups where warning information is shared can disseminate the warning to others who are not part of the group.

Table 14: Summary of hazards and early warning tools identified for Pietermaritzburg – Swayimane High School: focus group discussions and responses.

Risk Knowledge	
Are the hazards and the vulnerabilities well known?	The CSs at Swayimane High School (Grade 11 students) identified the following hazards in their area: • Mist, • Floods, • Heatwaves, • Fog, • Heavy winds, • Thunderstorms or lightning.
Dissemination and Communication	
Do warnings reach all of those at risk?	• The CSs reported that warnings reach people at risk, but delays occur due to loadshedding and communication networks. • However, some warnings are not received because of limited data or a weak signal, but when they are, they come through TVs, radios, and word of mouth.
Are the risks and warnings understood?	• Participants shared that they understand the warnings from TV. • They also indicated that they don’t understand unprocessed station data, but it is easy for them to understand warnings (information) that are issued on TV, as they are simpler.
Is the warning information clear and usable?	• The CSs indicated that warnings are clear and usable, but not always accurate and reliable. For instance, to be prepared for thunderstorms, floods, and extreme warm weather.

Table 15: Summary of hazards and early warning tools identified for Cape Town – TLC Leadership College: focus group discussions and responses

Risk Knowledge	
Are the hazards and the vulnerabilities well known?	The hazards and vulnerabilities are well known by the citizen scientists (High School level students) in Cape Town, in Manenberg. Hazards identified were: • Cold fronts • Heatwaves • Heavy rains and floods • Strong winds
What are the weather patterns and trends?	• The CSs identified heavy rains as a common weather event in Manenberg. The citizen scientists indicated that the heavy rains result in floods and, therefore, block roads and drains, making getting to workplaces, homes, and schools difficult. • Heavy rains also damage people’s property, as people are unprepared for the extreme weather events. • People experience heat strokes due to high temperatures.
Dissemination and Communication	
Do warnings reach all of those at risk?	• Warnings do not reach all those at risk because not everyone has access to the platforms on which the warnings are shared.

	- The community receives warnings on the radio, TV stations (i.e., watch the news to know what the weather is for the next day or the rest of the week), WhatsApp groups, SMSs, and smartphones (i.e., the weather app).
Are the risks and warnings understood?	- The CSs in Manenberg agreed that the risks and warnings are understood, however, to a limited extent.
Is the warning information clear and usable?	- Participants indicated that the lack of comprehension of the warnings is complicated by the use of complex language and jargon (i.e., level 5 weather warning) that they do not understand. However, they indicated that great caution is taken despite the barrier to comprehending the warning information.
Challenges and recommendations for integration of IKS-based tools in early warning systems.	The CSs suggested the following for the integration of IKS-based tools in early warning systems: - Including and sharing warnings with various community stakeholders, such as teachers and religious institutes, for greater outreach. - Host workshops aimed at transferring warning information interpretation skills and citizen science projects. - Ensuring that warnings reach people of all backgrounds in the form of posters showing visual representations in languages appropriate to the population's linguistic needs. - Promote sharing of knowledge amongst community members, extending to include those who were not involved in the citizen science project(s). - Make use of communal spaces like places of worship in addition to technological devices and programmes. - Increase the presence of weather stations in communal spaces like schools and transfer weather observation skills.

7.4 CHALLENGES AND RECOMMENDATIONS FOR INTEGRATION OF IKS-BASED TOOLS IN EARLY WARNING SYSTEMS

Indigenous Knowledge Systems remain embedded in community memory and cultural practice, but their reliability has been challenged by shifting climate patterns. Citizen scientists at the different study sites expressed varying levels of trust in IKS-based indicators. Some communities noticed a decrease in the reliability of traditional indicators like heat or wind as signals of rainfall. While IKS continues to play a role in community cohesion and local understanding of the environment, participants emphasized the need to complement it with scientific early warning tools. Table 16 presents the community perspective on the IKS tool.

Table 16: Community perspectives on IKS tools

Study Site	Existing IKS Beliefs/Indicators	Perception of Reliability
Cullinan	General awareness of traditional weather indicators	Seen as less accurate due to rapid weather changes
Cofimvaba	Heat and wind are believed to bring rain	Indicators are no longer consistent; climate shifts reduce reliability

Malamulele	Birds called "*tibewulam*" and insects	Indicators are no longer consistent; climate shifts reduce reliability
Swayimane	Birds – swallows bring heavy rains.	Hardly see the birds, and when they see them, the rain may not come as it would do in the past.
Cape Town (Manenberg)	Broader cultural knowledge-sharing practices	Openness to integrating IKS through workshops and education

Integrating IKS-based tools is essential for developing effective EWSs that are relevant and trusted within local communities. Although the IKS-based forecasting system has some significant shortcomings, it also has some important strengths. One major advantage of IKS -based tools is that the indicators are embedded within, owned, and comprehended by local communities. As a result, they are highly trusted, having been utilised for generations and are relevant as they can be understood from the local environment well in advance of making important decisions (Dube et al., 2024). According to Dube et al. (2024), the integration or parallel use of IKS-based forecasting has enabled local communities to improve decision-making regarding anticipatory actions, particularly in agricultural decision-making issues.

However, the integration of IKS-based tools faces significant challenges such as technical, cultural, and structural barriers. Some of the common key challenges include, for example, the qualitative nature of IKS indicators such as animal behaviour and tree flowering, which makes calibration, quantification, and standardization against scientific metrics like rainfall probabilities difficult. The erosion of traditional environmental signals due to rapidly shifting climate patterns is diminishing the reliability of IKS. Scientific institutions often overlook local knowledge in favour of scientific knowledge, leading to a preference for scientific knowledge over indigenous knowledge. The oral transmission of IKS, combined with a lack of formal documentation, poses a threat to the preservation of this knowledge. The contextual nature of IKS, specific to geographic locations, limits its scalability to regional or national EWS levels. Cultural differences and colonial legacies may result in distrust and misinterpretation between scientific experts and indigenous knowledge holders (Ijatuyi et al., 2025).

Recommendations for Successful Integration (Ijatuyi et al., 2025)

- ✓ *Co-Design and Equitable Partnerships*: Promotion of equitable collaborations, co-design, and co-production of EWSs with indigenous populations, the protection of intellectual property, and the creation of culturally appropriate frameworks.
- ✓ *Establish Hybrid EWS Models*: Combine scientific knowledge with cultural legitimacy by using local observations to validate meteorological forecasts.
- ✓ *Systematic Documentation and Validation*: Support community-led documentation and validate and archive indigenous indicators.

- ✓ *Diversify Communication Platforms*: Utilise technology like WhatsApp, Telegram radio, social media, posters, and community coordinators to bridge local observation with technical alerts.
- ✓ *Invest in Capacity Building*: Build capacity for both scientists to appreciate IKS and for local communities to understand scientific data, fostering mutual respect. Introducing IKS from grassroots learning, such as the classroom, can reflect the diverse cultural backgrounds of learners and enhance their understanding and interpretation of information.
- ✓ *Establish legal and policy frameworks*: Formally incorporate IKS into national disaster management frameworks and policies, and create frameworks that acknowledge the social and spiritual aspects of indigenous knowledge.

7.5 SUMMARY

This chapter demonstrates that South African communities possess strong knowledge of local hazards and existing early warning tools. Although scientific systems are widely regarded for their precision and reliability, Indigenous Knowledge Systems (IKS) remain essential for fostering community engagement and providing context-specific insights. Integrating scientific and indigenous approaches offers a significant opportunity to enhance and strengthen early warning systems. To achieve this, improved communication, community participation, and capacity building are essential. Integrating these systems will enhance climate resilience and support more inclusive and culturally grounded disaster preparedness. The key to successful integration of IKS-based tools is not simply using local knowledge to enhance scientific data but rather developing a more "person-centred" and comprehensive approach to community-based EWS and disaster resilience. For early warning systems to be successful, they must engage the communities at risk, provide public education on risks, effectively disseminate messages and warnings and ensure there is a constant state of preparedness.

Citizen scientists from the different study sites identified WhatsApp as a suitable platform for sharing the early warnings issued by the SAWS. WhatsApp has become a widely used tool for disseminating urgent weather information in South Africa. It has been identified as a key platform for sharing and receiving early warnings issued by the SAWS, especially in the context of community-based alerts.

CHAPTER 8: CONCLUSIONS & RECOMMENDATIONS

8.1 CONCLUDING REMARKS

Weather and climate risks are undoubtedly increasing in frequency, intensity, duration, and scale, directly impacting wider communities and exacerbating existing global socio-economic and environmental vulnerabilities. There is a strong scientific evidence-based consensus among the scientific community, international organisations, and researchers that climate change will continue to increase in the future, leading to more extreme weather events, rising temperatures, and sea-level rise, among others. The consensus highlights key aspects of the impacts of climate risks, ranging, for example, from climate-related disasters, extensive community health and safety risks (e.g., displacement, disease spread, food and water scarcity, increased mortality and morbidity), as well as damages to property and infrastructure. The need to develop effective adaptation measures, interventions, and coordinated efforts from different stakeholders, including various levels of government, the private sector, and the community level, to mitigate inherent impacts of weather and climate, particularly in the most vulnerable communities, cannot be overemphasized.

In this regard, the current project aimed at conducting weather and climate risk awareness and developing early warning tools for monitoring and early detection of natural disasters to support early warnings and responses. Vulnerable communities from five different provinces, including Cullinan (Gauteng), Swayimane (KwaZulu-Natal), Manenberg (Western Cape), Cofimvaba (Eastern Cape), Malamulele (Limpopo), were selected as pilot study sites. These study sites are all located in areas that have, in recent years, experienced extreme weather events resulting in significant damage, including loss of human lives, livestock, agricultural fields, homes, and other infrastructure. The project consisted of seven deliverables in total, which aimed to achieve five objectives. The project outcomes included community knowledge-sharing activities (to increase local knowledge on current and future climate-related extreme weather events), assessment of the impacts and adaptation options, provision of reliable low-cost CWSs, and empowering the local communities to prepare, communicate, and respond to weather-related hazards.

One of the objectives of this project was to implement simple, low-cost, and robust AWSs or CWSs that can be easily used by citizen scientists for data collection. However, there are concerns about the data accuracy of some CWS stations, so it is important to compare them with professional weather stations to determine which CWSs perform the best. Therefore, intercomparison analysis was conducted between the average and total measured values of weather parameters and derived variables obtained from the CWSs and those from standard AWSs at 5-minute, hourly, and daily intervals at the SAWS Irene Office and the UKZN site in Pietermaritzburg. Results of air temperature and relative humidity measured using CWSs depicted very good agreement with the standard AWS measurements. Wind speed comparisons illustrated relatively poor agreement, with most of the CWSs recording consistently higher values, except for the Acurite Atlas station. Overall, the solar radiation measurements from most of the CWSs were in good agreement with the standard AWS measurements. Rainfall measurements across all CWSs exhibited significant variations compared to the standard rain gauge readings. The observed variations could be attributed to poor calibration leading to bias in some of the CWSs right from the start, as well as differences in the measurement heights between the

CWSs and the standard AWSs at which the rain gauges are placed, which may be influenced by increased wind speeds. Intercomparison between variables derived from CWSs (heat index and wind chill) and those from the standard AWSs showed fairly good agreement. However, daily reference evapotranspiration estimates from CWSs were consistently lower than those from standard AWS stations. The HP2551, HP2000, and Decagon reference evapotranspiration estimates showed better correlation with the standard AWS estimates. The data collected by the CWSs provide sufficient information on hourly and daily values for most weather parameters and derived indices. It is important to note a possible concern regarding the accuracy of CWS's daily rainfall measurements. It is recommended to calibrate the CWS rain gauges and implement instrument bias correction to ensure accurate rainfall data. Overall, there was good agreement between the standard AWS and the CWS measurements. The Professional Wireless Weather Station HP2551, HP2000, and the Decagon Complete Weather Station demonstrated superior performance compared to the other CWSs.

Several training workshops were organised with the CSs to build their capacity to understand early warning information and develop a shared vision to support their communities' resilience to extreme weather events. Activities during the workshops included: knowledge sharing discussions to understand participants' experiences with weather, extreme weather events, climate change, and indigenous knowledge systems related to weather and climate. Additionally, training sessions were provided to enhance participants' ability to access and interpret weather forecasts, seasonal outlooks, and climate change projections. Participants emphasised the lack of an EWS for farmers to use and prepare for extreme weather events, highlighting the need for support in improving readiness and response to these events.

The use of IKS is considered a valuable tool that can be applied to support broader societal objectives, and its use contributes to inclusive EWSs. The findings of this study highlight that indigenous communities in South Africa employ a combination of meteorological, ecological, and astronomical IKS indicators to monitor local weather patterns, extreme events, and seasonal climate variations. These traditional knowledge systems are valuable for predicting and interpreting climate phenomena in areas where formal forecasts are either not easily accessible or non-existent. Despite its significance, IKS-based forecasting faces significant challenges, including inadequate knowledge transfer mechanisms, limited documentation, loss of experienced knowledge holders, and the pressures of modernization. Additional threats include the disappearance of key plants and animals, land-use changes, urbanization, population growth, and the impacts of climate change. Workshop participants emphasised the importance of accessible, localised early warning systems for agricultural planning. Integrating indigenous and scientific knowledge offers a practical pathway for enhancing climate resilience, providing more precise, context-specific forecasts that can guide local decision-making and policy. Engagements with communities during workshops demonstrated that South African communities possess strong knowledge of local hazards and existing early warning tools. While scientific systems are generally trusted for their accuracy, IKS remains valuable for community engagement and contextual understanding. The convergence of scientific and indigenous approaches presents a powerful opportunity to strengthen early warning systems. To achieve this, improved communication, community participation, and capacity building are essential. Integrating these systems will enhance climate resilience and support more inclusive and culturally grounded disaster preparedness.

Early Warning Systems involve the systematic collection of data and assessment of disaster risks to analyse and predict potential hazards, which are then transformed into warnings, timely dissemination, and used for early action. An effective EWS consists of four key components: risk knowledge, technical monitoring and warning service, communication and dissemination of warnings, and community response capability. The goal of this project is to co-design disaster early warning monitoring tools and to test the effectiveness of the proposed tools in enhancing community-based early warning systems and response procedures at the selected study sites. Citizen scientists identified WhatsApp as a suitable platform for sharing the early warnings issued by SAWS. WhatsApp has become a widely used tool for disseminating urgent weather information in South Africa and a key platform for sharing and receiving early warnings issued by SAWS. For early warning systems to be successful, it is crucial to engage the communities at risk, provide public education on risks, effectively share messages and alerts, and maintain a state of readiness. The integration of scientific and indigenous approaches presents a powerful opportunity to strengthen early warning systems. Integrating these systems will enhance climate resilience and support more inclusive and culturally grounded disaster preparedness. The EWS developed in collaboration with the citizen scientists and local communities in this project involved identifying weather hazards at their specific locations through training and workshops. Citizen Weather Stations (CWSs) were utilised to collect and monitor local weather data, while WhatsApp was used for sharing and receiving early warnings issued by the SAWS to respond to alerts and warnings. The information gathered by citizen scientists at the five selected study sites in this project was validated by SAWS and its partners. This information is important for disaster monitoring and response, scientific research, policy and decision-making, and raising awareness in the selected vulnerable communities.

8.2 RECOMMENDATIONS

Citizen science contributes to people-centred EWSs by enhancing weather and climate risk awareness in vulnerable communities through participatory monitoring that integrates scientific and local knowledge. Effective EWSs require affordable and accessible monitoring tools, community-based mechanisms that strengthen preparedness and response capacities, and the timely dissemination of clear and actionable warnings. Persistent challenges remain in reaching remote and marginalised populations due to limitations in communication infrastructure.

Aligned with the Early Warnings for All (EW4All) initiative, which emphasises inclusive, people-centred, and end-to-end early warning systems, the following recommendations are proposed to strengthen community-based EWSs and support the scaling of citizen science approaches in vulnerable contexts.

Recommendations for Action

- Scale inclusive disaster education: Implement community-based disaster education programmes in local languages using multiple platforms to ensure effective reach to vulnerable groups, including women, older persons, and people with disabilities. Emphasis should be placed on trust-building through clear, consistent, and actionable warning messages.

- Strengthen multi-channel communication: Invest in and assess complementary communication channels to support the timely and accurate dissemination of early warnings, particularly in socio-economically marginalised communities.

- Integrate indigenous and scientific knowledge: Systematically document, validate, and integrate indigenous risk knowledge in collaboration with IKS custodians to enhance locally relevant risk understanding and early warning practices.

- Sustain community-based EWSs: Ensure long-term funding, technical support, and institutional commitment for citizen science and community-led EWS initiatives to promote sustainability, scalability, and alignment with EW4All objectives.

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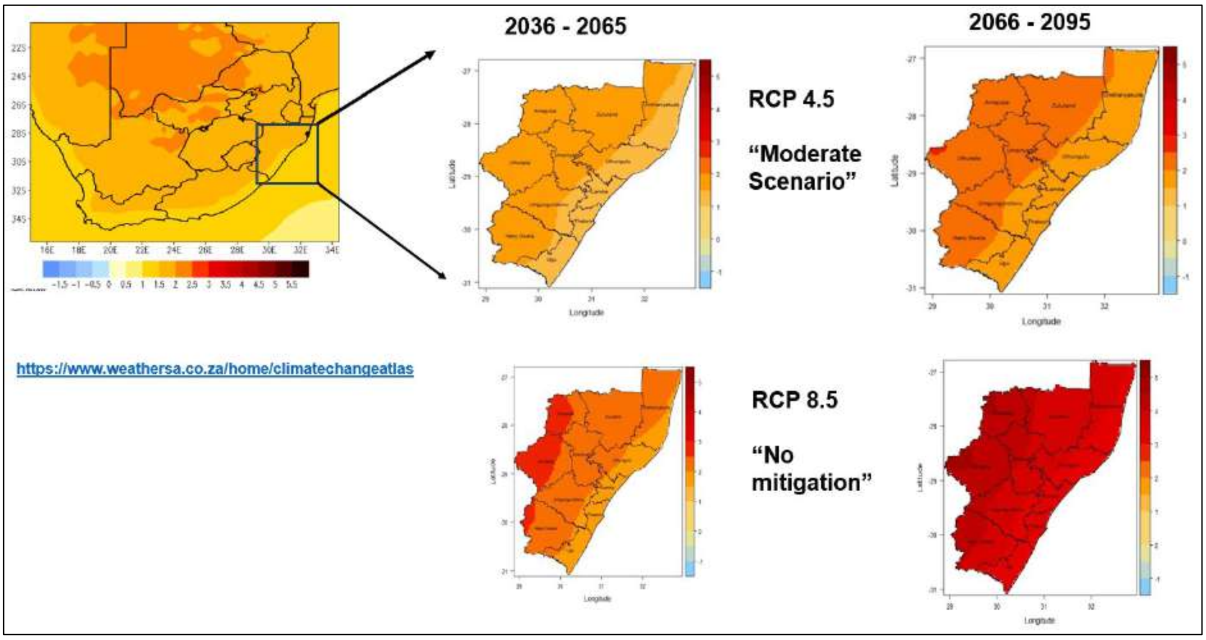
APPENDIX A: CLIMATE CHANGE AND VARIABILITY

The annual surface temperature projections for the five study site provinces, KwaZulu-Natal (KZN), Eastern Cape (EC), Western Cape (WC), Gauteng (G), and Limpopo (L) provinces are presented in Figure 57 to Figure 61, respectively. The two common climate change scenarios are shown (in Figure 57 to Figure 61) for the near future period (2036 -2065) and far future period (2066 – 2095) relative to the historical period (1975 – 2005). The temperature projections for the moderate scenario, near-future period, indicate an increase in temperature between 1 – 1.5 ºC for the five study sites. However, for the far future period, temperatures will increase in the magnitude of 2 – 2.5 ºC. The no mitigation scenario in all provinces shows a very high warming in the near future, 2 – 2.5 ºC compared to the moderate scenario, and an extreme increase in temperatures is observed (+4ºC) for the far future period. Under both RCP4.5 and RCP8.5 scenarios, temperatures are expected to increase in the near and far future periods.



https://www.weathersa.co.za/home/climatechangeatlas

Figure 57. Annual mean (2m) temperature (˚C) change projected for 2036-2065 (left) and 2066-2095 (right), relative to present (1976-2005), under conditions of the RCP4.5 (top row) and RCP85 (bottom row) for the KwaZulu-Natal province.

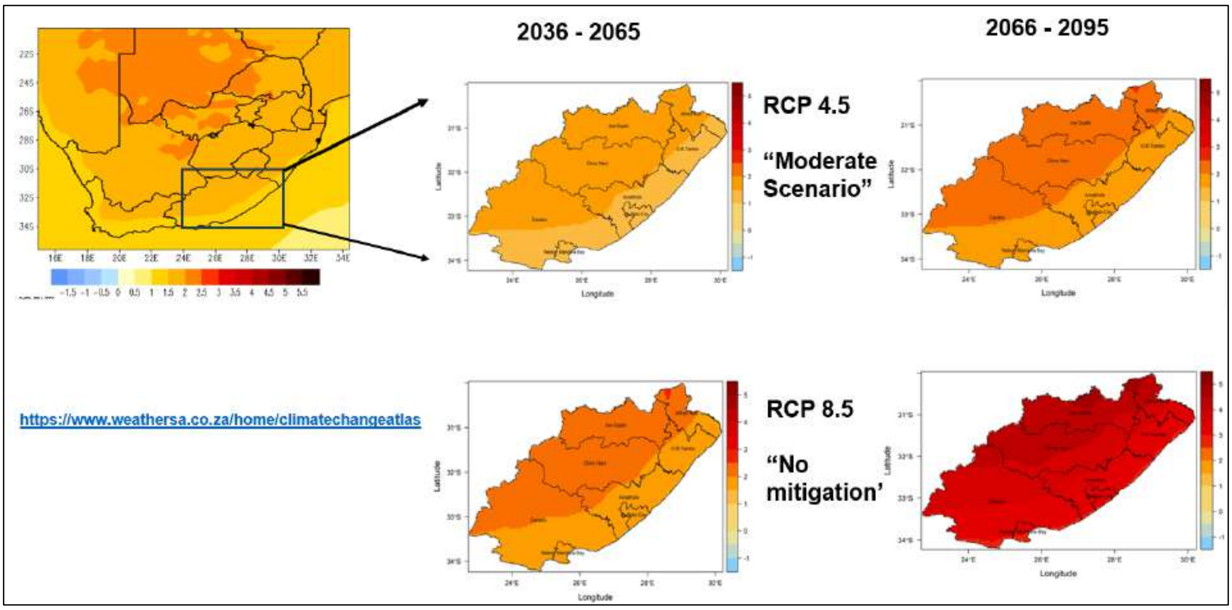


Figure 58. Annual mean (2m) temperature (˚C) change projected for 2036-2065 (left) and 2066-2095 (right), relative to present (1976-2005), under conditions of the RCP4.5 (top row) and RCP85 (bottom row) for the Eastern Cape province.

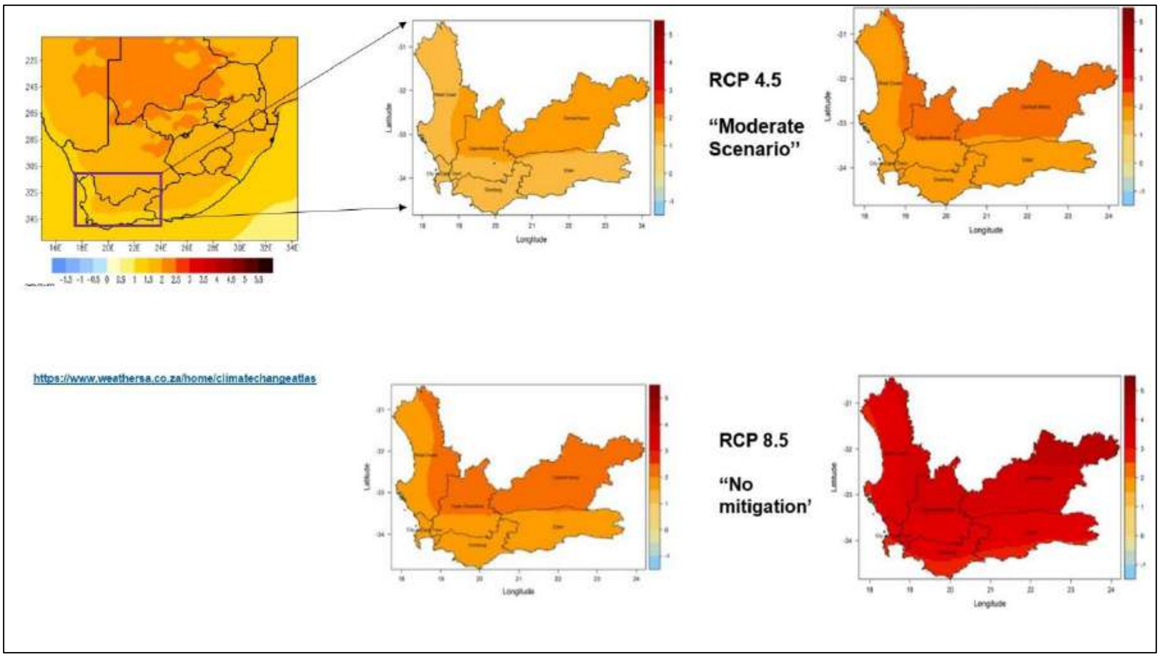


Figure 59. Annual mean (2m) temperature (˚C) change projected for 2036-2065 (left) and 2066-2095 (right), relative to present (1976-2005), under conditions of the RCP4.5 (top row) and RCP85 (bottom row) for the Western Cape province.

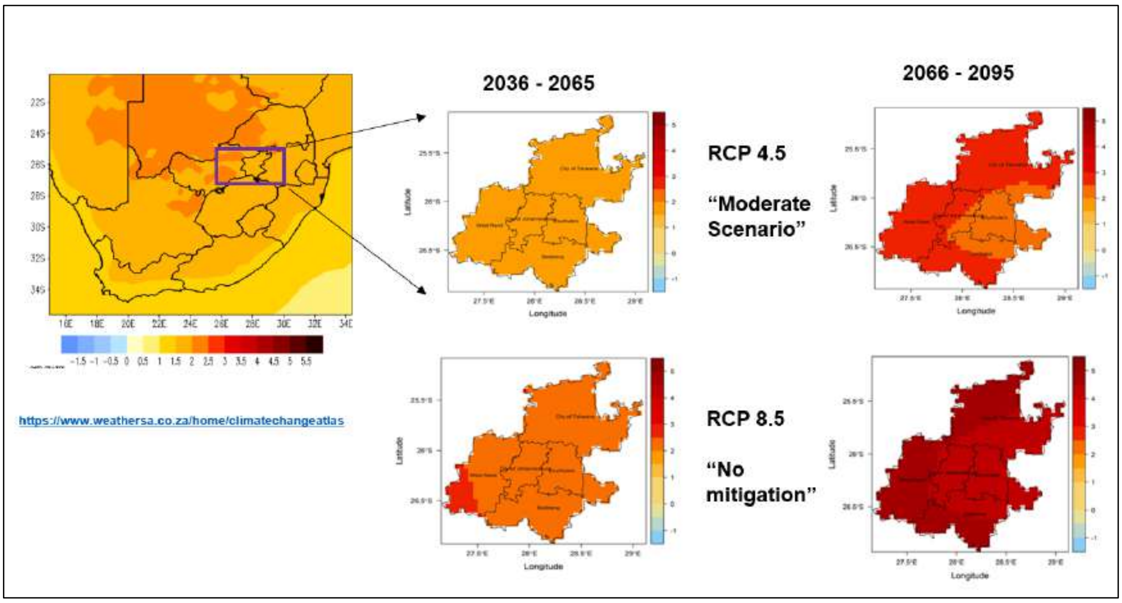


Figure 60. Annual mean (2m) temperature (˚C) change projected for 2036-2065 (left) and 2066-2095 (right), relative to present (1976-2005), under conditions of the RCP4.5 (top row) and RCP85 (bottom row) for the Gauteng province.

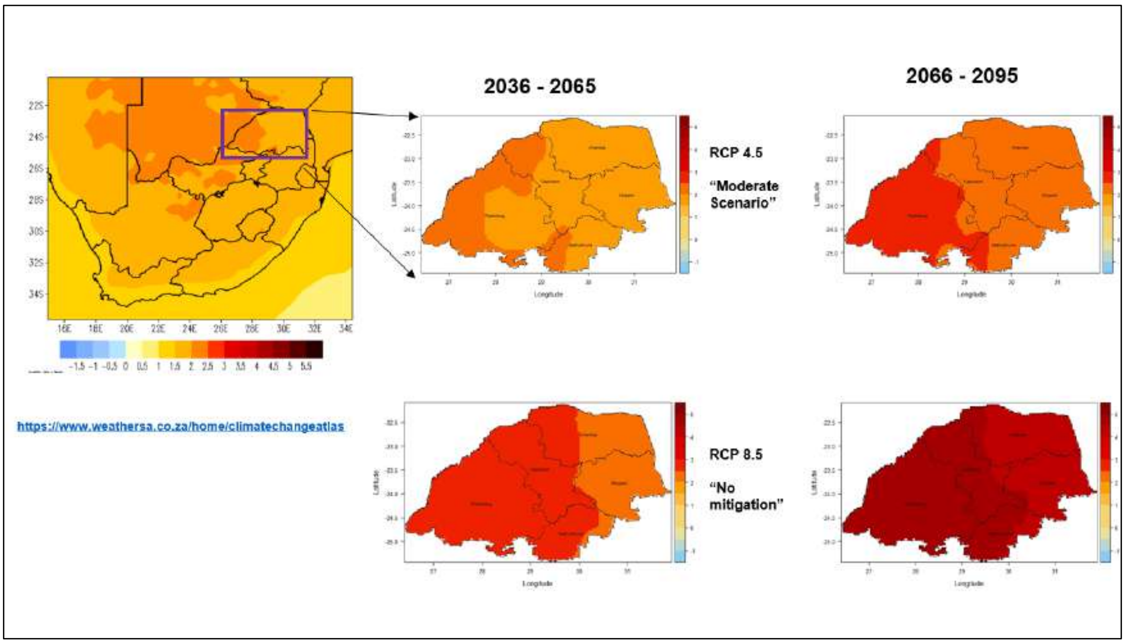


Figure 61. Annual mean (2m) temperature (˚C) change projected for 2036-2065 (left) and 2066-2095 (right), relative to present (1976-2005), under conditions of the RCP4.5 (top row) and RCP85 (bottom row) for the Limpopo province.

The annual change in rainfall projections for the five study site provinces of KZN, EC, WC, G, and L is presented in Figure 62 to Figure 66, respectively. Rainfall is a very variable parameter with more uncertainty in comparison to the projected changes in temperature. For the KZN province, a decrease in rainfall of approximately 0 – 10% is projected under the moderate scenario for the near-future period. Under the no mitigation scenario, near future, a decrease in rainfall of 5 – 10% is projected. The rainfall in KZN is projected to have both extremes of drying (a proxy for drought) as well as above-average rainfall in certain regions (a proxy for floods). The projected changes in rainfall for the EC province under the moderate scenario (near future) also indicate a decrease in rainfall of between 0 – 10% for most parts of the province. A similar signal is observed for the no mitigation scenario near future, where a decrease in rainfall between 10 – 20% for most parts of the province (Figure 63).

Rainfall change for the Western Cape province under the moderate scenario for the near future indicates a decrease in rainfall between 0 – 10% across much of the province. Under the far-future period in the moderate scenario, most of the Western Cape is projected to have a further decline in rainfall, with percentage changes ranging from 10 – 20%. A similar pattern is observed under the no mitigation scenario for the near future, where a decrease in rainfall between 10 – 20% is anticipated for most parts of the province, particularly in the City of Cape Town, Cape Winelands, and Overberg districts (Figure 64).

Rainfall projections for the Gauteng Province under the moderate scenario indicate a general decrease (0 – 5 %) in rainfall across the province in the near future, with more rainfall declines expected for the far-future period. Furthermore, rainfall projections under the no mitigation scenario indicate that Gauteng will have a greater decline in rainfall compared to the moderate scenario, with a magnitude of 5 – 10% (Figure 65). For the Limpopo Province, rainfall projections indicate a general decline across the province under both the moderate and no mitigation scenarios. The near-future projections indicate declines in rainfall of 5 – 10%. Moreover, for the far-future period, these declining trends are expected to intensify, with the most pronounced to be over 10 – 20% (Figure 66).

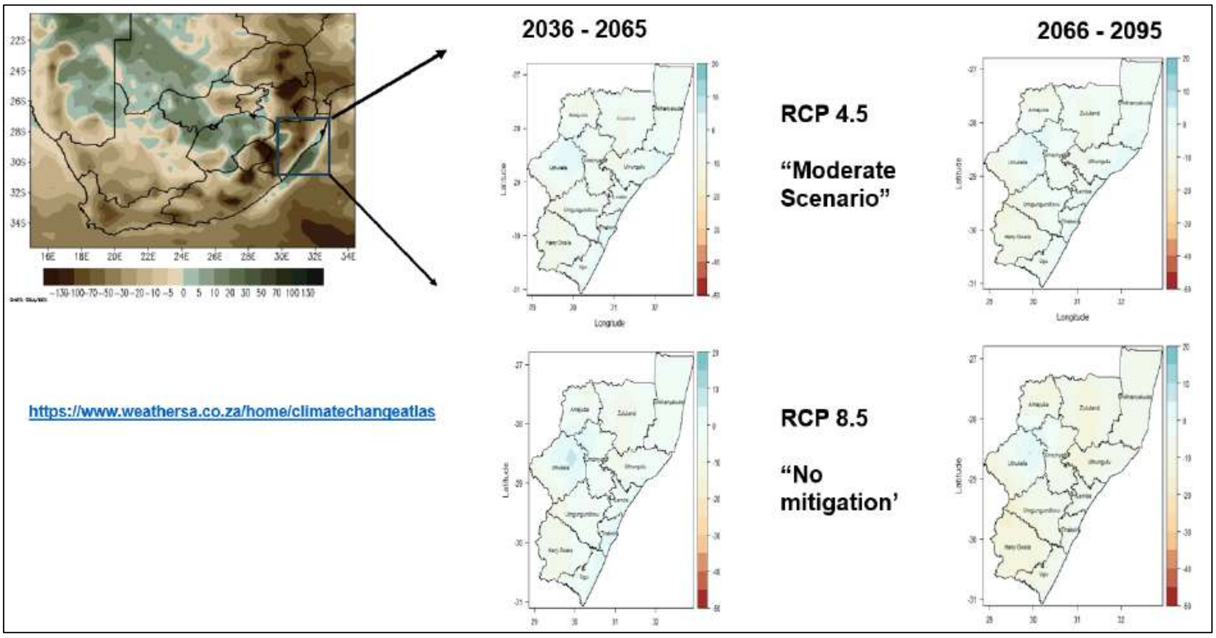


Figure 62. Percentage change in projected rainfall for 2036-2065 (left) and 2066-2095 (right), relative to the reference period (1976-2005), under conditions of the RCP4.5 (top row) and RCP85 (bottom row) for the KwaZulu-Natal province.

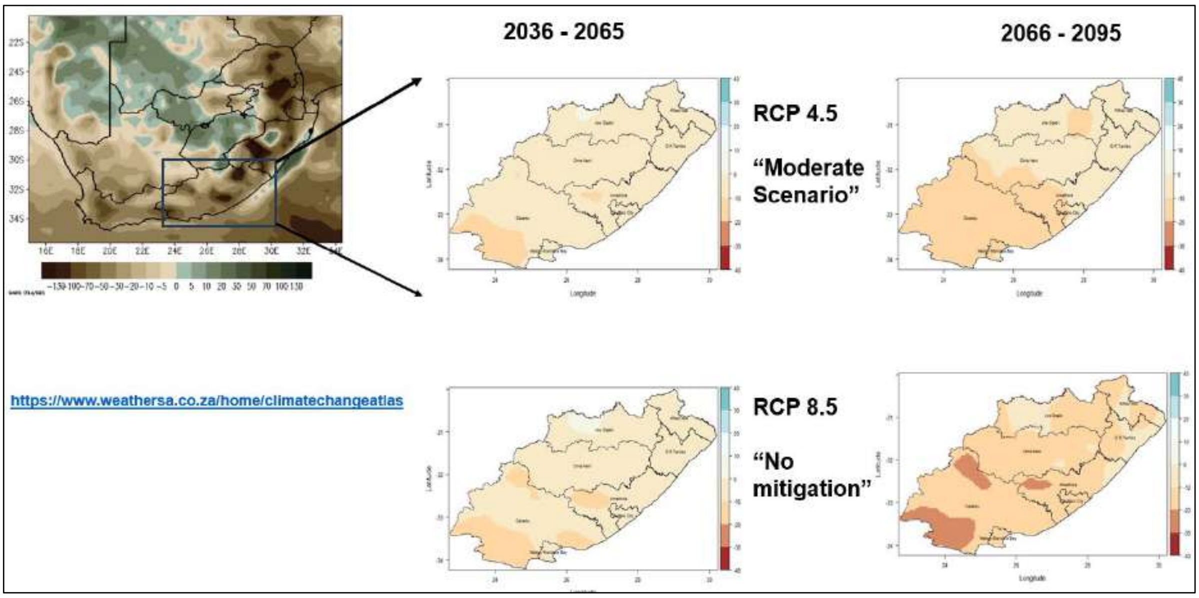


Figure 63. Percentage change in projected rainfall for 2036-2065 (left) and 2066-2095 (right), relative to the reference period (1976-2005), under conditions of the RCP4.5 (top row) and RCP85 (bottom row) for the Eastern Cape province.

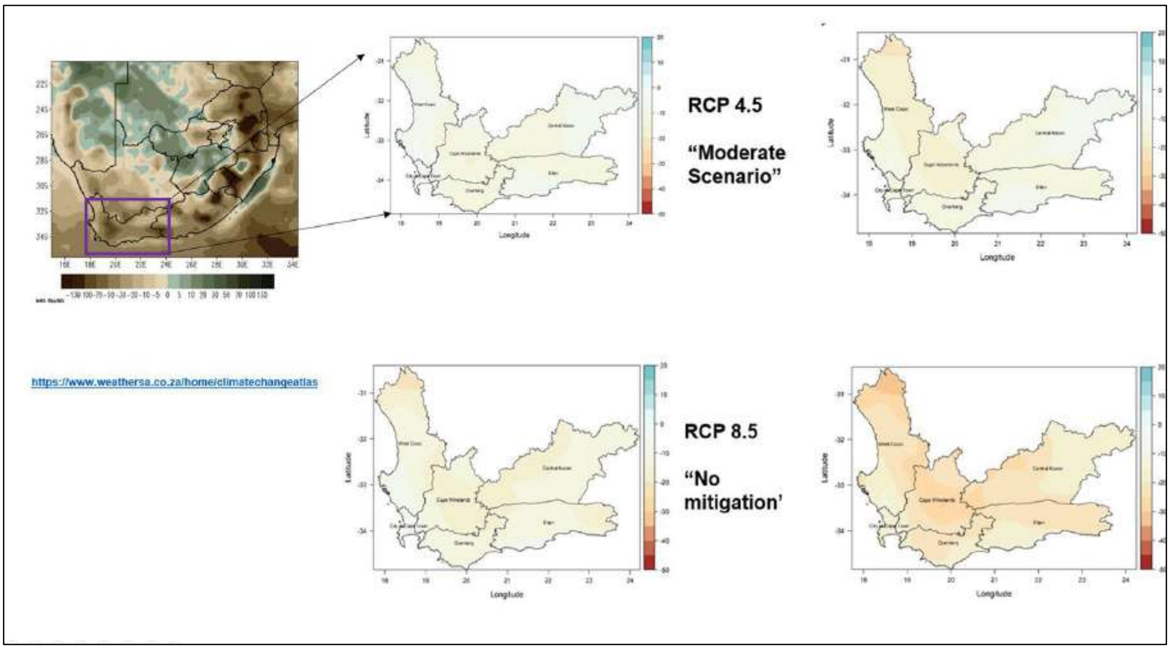


Figure 64. Percentage change in projected rainfall for 2036-2065 (left) and 2066-2095 (right), relative to the reference period (1976-2005), under conditions of the RCP4.5 (top row) and RCP85 (bottom row) for the Western Cape province.

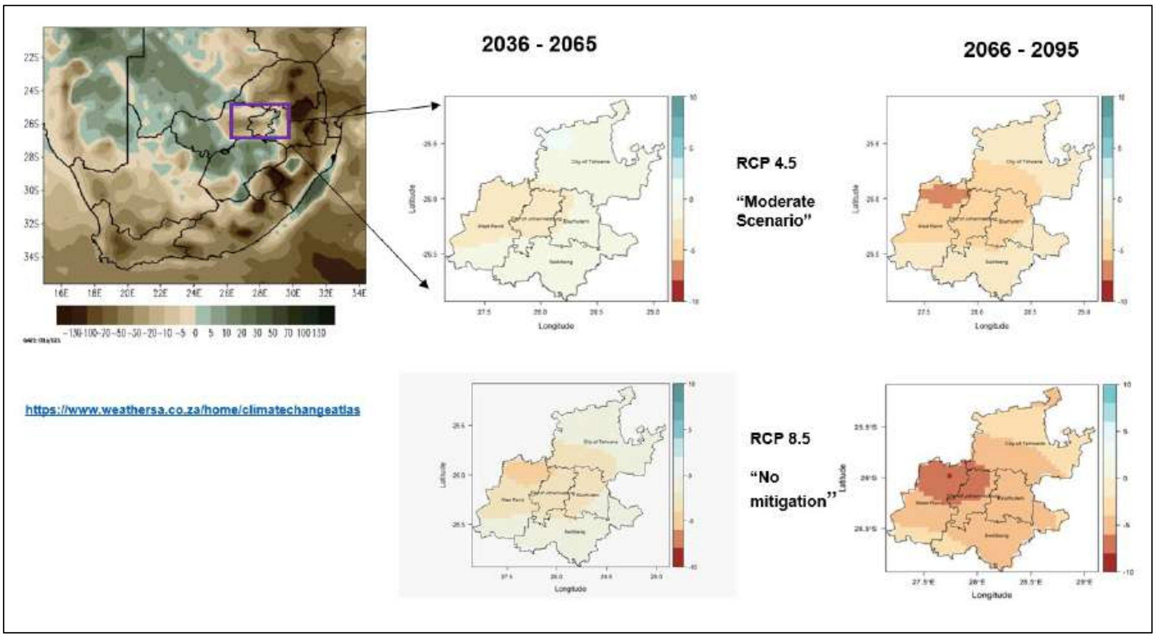


Figure 65. Percentage change in projected rainfall for 2036-2065 (left) and 2066-2095 (right), relative to the reference period (1976-2005), under conditions of the RCP4.5 (top row) and RCP85 (bottom row) for the Gauteng province.

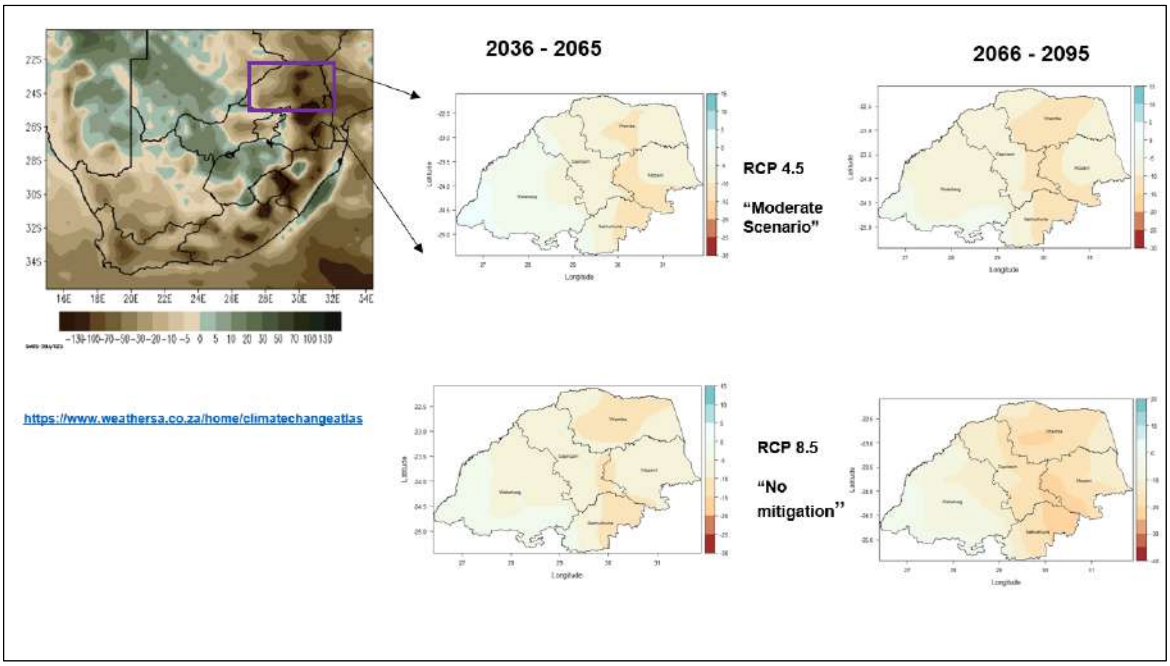


Figure 66. Percentage change in projected rainfall for 2036-2065 (left) and 2066-2095 (right), relative to the reference period (1976-2005), under conditions of the RCP4.5 (top row) and RCP85 (bottom row) for the Limpopo province.