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Long term trends in extreme daily temperature and precipitation on sub-Antarctic Marion Island from 1950 to 2020

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A Masters Dissertation submitted in partial fulfilment
of the requirements for the Master of Science
degree in Geography in the Faculty of Science and
Agriculture of the University of Fort Hare

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Declaration

I hereby declare that this dissertation represents my own work. Other sources outside my original work have been duly acknowledged. This dissertation has not been submitted for degree or examination at any other institution or university.

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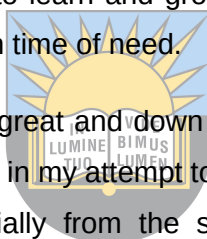
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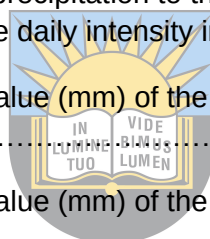


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Abstract

Sub-Antarctic Marion Island (46° 54' S, 37° 53' E) has experienced notable changes due to global climate change in recent decades. Records indicate a gradual increase in mean annual air temperature, with a rise of 2.4°C per century. Both maximum and minimum temperatures have increased by over 1°C, while annual rainfall has decreased to less than 2000 mm over the past seventy-one years. The onset of extreme events in the Antarctic Peninsula and sub-Antarctic region was observed in the early 2000s, and forecasts suggest these events will become more frequent, intense, and prolonged in the future. The objective of this study was to analyse the trends and patterns of daily extreme climatic parameters, specifically air temperature and precipitation, on Marion Island from 1950 to 2020. This analysis aimed to contextualize these changes within the observed alterations in the island's synoptic weather, providing insight into the underlying drivers. Daily temperature and precipitation data were obtained from the South African Weather Service (SAWS) and analysed. Linear regression statistics were employed to evaluate trends and patterns in the daily extremes, utilizing 25 extreme indices developed by the Expert Team on Climate Change Detection Indices (ETCCDI). The results spanning 71 years revealed a consistent climate shift on Marion Island. Mean annual air temperatures and daily maximum temperatures increased by 1.2°C ($p < 0.01$), while daily minimum temperatures rose by 0.9°C ($p < 0.01$). There was a significant rise in warm spells ($p < 0.05$) and warm nights ($p < 0.01$), accompanied by a notable decrease in cold spells ($p < 0.01$), cold nights, and annual frost days. The annual precipitation trend indicated a decline, with a significant reduction of 1042.3 mm ($p < 0.01$) in mean annual rainfall, along with a decrease in heavy precipitation events over the study period. Additionally, the occurrence of consecutive dry days increased by an average of 5 to 7 days between 1950 and 2020. Anthropogenic forcing, particularly the positive phase of the Southern Antarctic Mode, is identified as the primary cause of ocean and atmospheric warming in the sub-Antarctic region. The positive shift of the Southern Antarctic Mode due to anthropogenic forcing is a significant impact of how climate change is affecting the region and surrounding areas, and how frequent the phase could be due to an intensification of climate change conditions in the region. This phenomenon leads to the intensification and poleward migration of the Southern Hemisphere westerly winds. Changes in wind patterns, such as prolonged exposure to warm north-westerly winds and reduced exposure to post-cold front sectors associated with passing cyclones, likely contribute to the observed trends in temperature extremes and precipitation on Marion Island. Continued elevation of daily air temperature extremes and reduction in daily precipitation extremes may result in abnormal warming, further deglaciation, further retreat of the permanent snowline, disruption of soil frost and needle ice processes, and prolonged drying of the mires on this periglacial sub-Antarctic island.

Keywords: Sub-Antarctic; Marion Island; daily climate extremes; temperature; precipitation; long-term change

Chapter 1 - Introduction

Climatological and Meteorological Extremes

One of the main consequences associated with the effects of climate change has been the rise in the frequency and intensity of climate extremes or extreme weather events. An extreme exists on the far ends or tails of a distribution, the furthest end of the spectrum or threshold where the likelihood of such an event taking place is not common (Zhang et al., 2011). An event is defined as an occurrence, a noteworthy happening of some importance, and frequently one having antecedent cause (Merriam-Webster, 2022). Climate extremes, also known as extreme weather events, occur when a weather or climate variable surpasses (or falls below) a threshold value near the upper (or lower) bounds of the observed range for that variable (such as temperature or precipitation). These occurrences, which include heatwaves, droughts, floods, storms, and the melting of snow lines or ice loss, markedly diverge from the typical or average conditions expected for a specific region, season, place, or period (IPCC, 2022; Le Roux & McGeoch, 2008). Extreme events are defined differently. Some use it to refer to initial meteorological phenomena and some include in its definition the consequences that come with the impacts on humans, societies, and ecosystems. The IPCC (2022) defines it based on both the initial and physical consequences of meteorological phenomena and other weather and climate phenomena. The definition also reflects the interactions of dynamic and thermodynamic activities or processes that are highly variable or abnormally high (or lower) than the usual climate and weather phenomena occurring in a certain area. Similarly, the spatial scale of extreme climate or weather varies from the local to the continental scales (Alexander et al., 2006; IPCC, 2022).

There are two types of extreme events that depend on their cause and duration: weather-related and climate-related (Rosane, 2022). Weather-related extreme events are short term incidents such as tornadoes, heat waves, or blizzards while climate-related events are long-term and result from accumulated weather-related events over time such as droughts caused by long dry spells, wildfires that result due to prolonged drought, and sea level rise (Rosane, 2022). Extreme events may have natural-induced causes, such as ocean current variations or atmospheric pressure systems (Rosane, 2022). Changes in climate extremes and extreme weather events are among the most serious societal challenges when it comes to coping with a changing climate (Tank, 2010). According to the IPCC (2022) summary for policymakers, widespread and pervasive impacts to ecosystems, people, settlements, and infrastructure were all resultants of these noticeable rises in the frequency and intensity of climate and

weather extremes, including hot extremes on land and in the ocean, heavy precipitation events, droughts and fire weather (Mahecha et al., 2022; Turek-Hankins et al., 2021).

The cause of these impacts and the increased frequency and magnitude of these extreme events is said to be the result of human-induced climate change along with impacts in natural and human systems from slow-onset processes such as ocean acidification, sea level rise or regional decreases in precipitation (IPCC, 2022; Heim, 2015). Extremes sometimes result from the interactions between two unrelated geophysical phenomena such as a modern storm surge coinciding with an extreme tide. The summarised analyses of the sixth Intergovernmental Panel on Climate Change assessment report (IPCC, 2022) states that, globally, since the 1950s there has been an increasing trend in fewer cold days and nights and more warm days and nights, more heavy precipitation events and both increasing and decreasing regional trends in droughts and extreme arid conditions in several parts of the world (IPCC, 2022; Heim, 2015). Island systems, in particular, are stated to be among the most vulnerable to climate change because changes in temperature, rainfall and sea levels are predicted to have significant impacts on these systems in the future (Veron et al., 2019). Moreover, it has been noted that changes across the Antarctic Peninsula, sub-Antarctic islands and Southern Ocean have been rapid, with dramatic impacts expected in the 21st century and in the near future (IPCC, 2007). Thus, the Prince Edward Islands are ideal for studying the effects of climate change as global warming is intensifying in the sub-Antarctic region (Smith, 2004). Referred to as 'ecological laboratories' these islands have relatively simple ecosystems that are extremely sensitive to change (Smith, 2004).

There is increasing evidence that fossil fuel burning and consequential global heating of 1.1°C to date has led to the increased occurrence and intensity of extreme environmental events in Antarctica and the Southern Ocean (Siegert et al., 2023). These events can have significant impacts on the natural systems and biodiversity of a region, as well as on the human activities and governance (Le Roux & McGeoch, 2008). Studies over the past few decades have indicated that changes are taking place in the climate of the sub-Antarctic region and on Marion Island (Smith & Steenkamp, 1990; Smith, 2002; Smith, 2004), the larger of the two islands making up the Prince Edwards Islands. Marion Island experiences almost continuous cloud cover which is associated with low sunshine hours but a rise in temperatures has led to a decrease in cloud cover, an increase in sunshine hours and an increase in air pressure with a reduction of rainfall has also been reported (Le Roux, 2008; Le Roux & McGeoch, 2008;

Nel, 2012). These changes are thought to have resulted in the loss of Marion Island's permanent snowline which was noted to be declining by Sumner et al., (2004). Other geomorphological responses to increase (and decrease) in extreme climatic events include, for example, the increased possibility of mass wasting and reduced soil frost days. Marion Island is a periglacial environment, with evidence of glacial history between the Quaternary and Holocene periods (Nel et al., 2021). Soil frost is the process where the soil freezes and thaws repeatedly; and diurnal soil frost is said to be the most important process occurring on the island (Nel, 2012). A form of diurnal soil frost is needle-ice that forms in Polar Regions. It is formed when the air temperatures drop and the moisture contained in the soil grows into spikes of ice crystals that stick out from the ground. It is one process that results in interesting features and patterns forming on bare soil (Hagar, 2021) and is involved in erosion processes taking place on Marion Island. Needle ice grows and decays in on diurnal time scales; earlier research stated the initiation temperature of needle ice to be -2°C but more recent studies showed it to be at -0.2°C on Marion Island (Outcalt, 1971; Haussmann et al., 2009; Nel & Boelhouwers, 2014). With the warming temperatures and changing precipitation patterns, along with changes of the maxima and minima on the island that have exhibited variability over time these soil frost processes that are unique to the island's environment are under threat.



Research conducted on Marion Island between 1949 and 2003 has demonstrated that climate extremes, variability, and signatures have significant ecological implications for the island's fauna and flora. Parameters such as precipitation, wind chill, and growing degree days, which are biologically relevant, have been identified as influential factors affecting the island's ecosystems (Le Roux, 2008; Le Roux & McGeoch, 2008). Increased possibilities of extreme weather events, such as higher air temperature maxima and prolonged dry spells, are associated with climate variability, presenting organisms with unfamiliar conditions and threatening the abundance, distribution, and evolution of species, especially when occurring concurrently with other weather conditions. The sixth Assessment Report of the IPCC highlights the high likelihood of increased length, frequency, and intensity of warm spells or heat waves over most land areas, particularly by the end of the 21st century. Some scenarios suggest a significant shift in extreme event occurrences from a 1-in-20 years event to a 1-in-2 years event in certain regions. Without significant action to limit global warming to the Paris Agreement target of 1.5°C , Antarctic extreme events are expected to become more common and severe. Given the observed changes in climate and extreme events in the sub-Antarctic region, it is crucial to investigate the trends in daily extreme precipitation and temperature on

Marion Island and assess any emerging patterns. While studies on climate extremes in the Antarctic and sub-Antarctic region are limited, their importance is growing as the impacts of global warming become more evident in these areas. Therefore, there is a pressing need for more comprehensive climate analyses to enhance our understanding of extreme events in the sub-Antarctic region and improve predictions of their nature and impacts.

Environmental Setting and Study Area

Marion Island (46° 54' S, 37° 53' E), where this study is based, is the peak of a shield volcano that has an area of approximately 293 km² (Rudolph, 2020) with a cliff-faced coastline of approximately 72 km (Fig. 1.1). It is the larger of the two Prince Edward Islands approximately 2900 km south-east from Cape Town, South Africa. Situated in the sub-Antarctic, the island unlike the Arctic and sub-Arctic regions that support substantial human populations, does not support any indigenous human populations (besides researchers) (Venter, 2009); but consists mostly of marine life such as seals, penguins and seabirds (Ryan & Bester, 2008). The terrestrial ecosystem of the island is poorly developed with respects to biological diversity with an absence of most invertebrate orders and only a few species of vascular plant species.



Positioned between South Africa and Antarctica in the southern Indian Ocean, Marion Island boasts a distinct hyper-oceanic maritime climate characterized by extensive cloud cover, plentiful precipitation in various forms including rain, snow, and graupel, high relative humidity, and regular encounters with mid-latitude depressions, frontal systems, and migratory anti-cyclones. The island experiences frequent cyclones passing nearby, contributing to its persistent cloudiness, high humidity levels, and precipitation. Rainfall events exceeding or equal to 5 mm occur approximately 45% of the days, while those less than 5 mm occur about 35% of the time. Marion Island receives limited solar radiation due to the rarity of bright sunshine, with less than 50% reaching the soil surface. Situated near the Antarctic Polar Frontal Zone, the island experiences cold climates that are not as extreme as Antarctica but cooler than more temperate regions (Barendse et al., 2002). The Antarctic Circumpolar Current plays a crucial role in shaping Southern Ocean ecosystems. Despite similarities in diurnal frost cycles with mid-latitude marine environments, such as those found on sub-Antarctic islands, Marion Island's frost environments differ significantly from tropical alpine mountain systems.

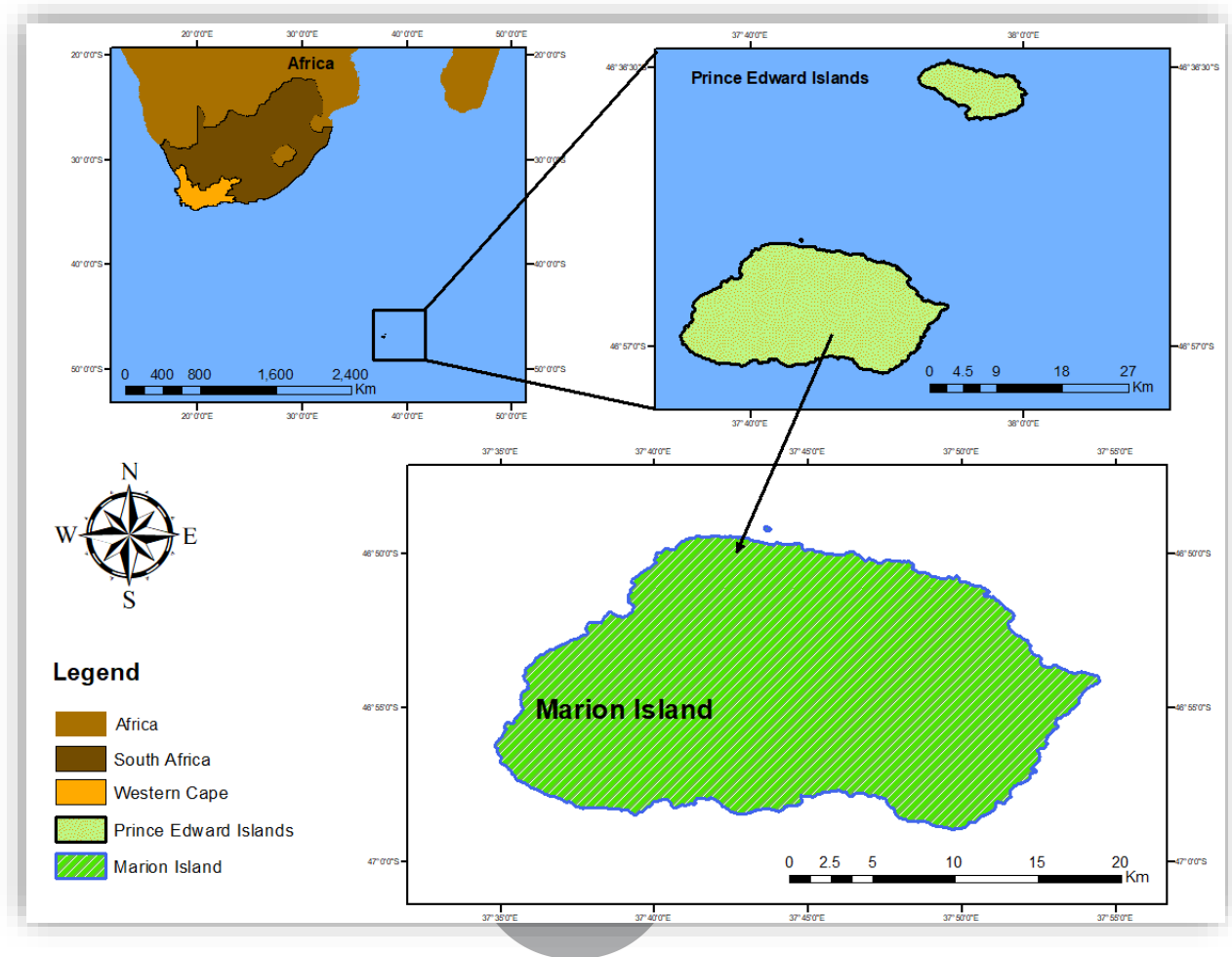


Figure 1.1: Map showing the location of Marion Island in the Southern Ocean.

The mean annual air temperature on Marion Island increased from 5.4°C in the 1950s to 6.4°C since the 1990s (Le Roux & McGeoch, 2008). Sub-zero temperatures are common throughout the year (Smith, 2002) and the mean annual soil temperature is 4.7°C measured at a depth of 5 cm and elevation of 300 m above sea level (measured at a study site at Tafelberg) (Hausmann et al., 2009). The average summer maximum and minimum temperatures on the east coast of Marion Island are between 10.5 to 10.9°C and 5.0°C, and the winter mean maxima and minima are 6.08 and 1.0°C, respectively, with the mean air temperature in winter reaching approximately 6.6°C (Hedding et al., 2007; Boelhouwers et al., 2000). The island experiences low annual and diurnal temperature ranges which are 3.6°C and 1.9°C respectively that give rise to diurnal frost cycles and frequent needle ice formation (Smith, 2002; Boelhouwers et al., 2003; Holness, 2004; Hausmann et al., 2009). Precipitation occurs mostly as rainfall, snow and hail and is measured on a daily basis at the research station with

snow records of approximately 30 to 50 days per year at sea level and frequent snow at higher altitudes (Holness, 2001; Hedding, 2007). Average yearly precipitation (at sea level) was measured at 2576 mm up to the late 1960s (Schulze, 1971) but had decreased significantly to approximately 2000 mm per annum in the late 1990s (Smith, 2002) and had continued to decrease to levels below 2000 mm since the year 2000 (Le Roux & McGeoch, 2008; Hedding & Greve, 2018; Mapuka, 2020). The maritime characteristics of this climate, combined with the significant impact of passing frontal systems, give rise to a unique weather pattern where freezing temperatures are possible in any month, gale force winds are common most weeks, and daily temperature peaks can occur during the night (Le Roux, 2008). Schulze (1971) attributes this climate to the interaction between subtropical and sub-Antarctic air masses facilitated by low-pressure systems.

Initially believed to be twin peaks of a single extinct shield volcano (Verwoerd & Langenegger, 1967), subsequent studies revealed that the Prince Edward Islands are actually twin peaks of distinct shield volcanoes situated 300 km south of the South-West Indian Ocean Ridge. These formations are thought to have originated from an oceanic inter-plate hotspot divergence zone (Verwoerd, 1971; McDougall et al., 2001; Rudolph, 2020). Marion Island, the older of the two, has experienced periods of dormant volcanic activity, with documented eruptions occurring in 1980 (McDougall et al., 2001) and 2004 (Meiklejohn & Hedding, 2005). Marion Island features two distinct lava successions: an older sequence of grey lava underlying a younger sequence of black lava (Verwoerd, 1971; Häussmann et al., 2009). The presence of striated, grooved, and smoothed features on the older grey lava rocks suggests a glaciation event occurred between the deposition of the two lava successions (Verwoerd, 1971; Hall, 2004). Evidence indicates that Marion Island underwent at least five, possibly more, glaciations during the Quaternary period, significantly influencing its vegetation (Chown & Froneman, 2008), whereas no evidence of glaciation has been found on the smaller Prince Edward Island. Geologically, Marion Island is of volcanic origin and has been dated to approximately 450,000 years ago (McDougall et al., 2001).

Situated in the “Roaring Forties” at just less than 47° South, Marion Island is characterised by strong winds of an average velocity of 32 km h⁻¹ mainly recorded (according to records at the research station) from the northwest direction and relatively low temperatures (Boelhouwers et al., 2000; Hedding et al., 2007; Nel et al., 2009). Gale force winds (moving at 15 m.s⁻¹ or more) are experienced on more than a hundred days per year, with extended periods of

exceeding 12 hours of gale force winds and rarely any periods of calm or no wind (Le Roux, 2008). The steadiness of this circumpolar wind is constantly interrupted by cyclones which pass the islands in a south-east direction. In the mid-latitudes over the Atlantic Ocean west of Africa, subtropical humid air masses penetrate the cold Antarctic air front to the south (Schultz, 1971). A low pressure centre is thus formed as a wedge in the cold air. The forward or warm front of the wedge produces much rain when it passes over the islands while it can be dry for a while before the cold rear front brings rain or snow (Schultz, 1971). Anticyclones on the other hand, which mostly move eastward north of the islands, are accompanied by dry spells, just as in the case of winds which come from a southerly direction. This wind system and especially its force are of great importance for the understanding of the ecology of the islands and for the dispersal of flora and fauna elements over the Southern Ocean (Schultz, 1971).

Marion Island's western region is notably more exposed, encountering elevated levels of relative humidity, cloud cover, and rainfall compared to its eastern counterpart, where the South African weather station is situated (Rouault et al., 2005). Since only one full automatic weather station exists on the island, it prevents an intra-island comparison of climatic variables. The islands (Marion and Prince Edward) were annexed by South Africa in 1947 and 1948 and Marion Island became a hub for meteorological research by the South African Weather Bureau— today known as the South African Weather Service— from 1949 and later other scientific research (Venter, 2009; Smith, 2002). The meteorological activities taking place on the island remain the reason why the base is significant to South Africa (and the globe) today, as they play an important role in weather forecasting and the understanding of the global climate (Venter, 2009). With this rich data set from a very important region as well as the evident shifts in climate and extreme occurrences within the sub-Antarctic, it becomes imperative to examine the trends in daily extreme precipitation and temperature and to identify any emerging patterns. Research on climate extremes is important as the effects of global warming become increasingly apparent in this region. Consequently, there is an urgent requirement for more extensive climate analyses to deepen our comprehension of extreme events in the sub-Antarctic and enhance our ability to predict their nature and consequences.

Aim

The aim of this research is to determine and assess the trends and patterns of daily extreme climatic parameters of air temperature and precipitation of Marion Island between 1950 and

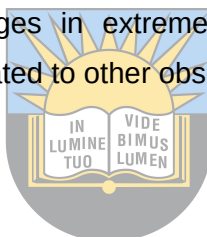
2020 and to investigate and contextualize the climatic drivers of changes to these climatic parameters.

Objectives

1. Identify and analyse the long-term trends and changes from the data for daily climatic parameters (i.e. air temperature and precipitation) on Marion Island from 1950 to 2020.
2. Identify and analyse over time the recorded extremes in daily air temperature and precipitation on the island.
3. Contextualize the discovered temperature and precipitation trends to possible climatic drivers recorded in the literature so as to understand possible drivers of change and impact on the geomorphology and ecology.

Study Questions

1. What are the long-term trends and patterns in extreme temperature and precipitation indices on Marion Island and what are the extent and rates of these changes?
2. When have significant changes in extreme daily temperature and precipitation occurred and are these correlated to other observed meteorological parameters?



Significance

The significance of the study is an improved understanding of the changes in extreme daily temperature and precipitation on sub-Antarctic Marion Island and how these changes are linked with recent observed climate changes on the island and in the sub-Antarctic region. This will also be useful in determining the current and future effects of these marked climatic changes on the geomorphology and ecology of Marion Island.

Chapter 2 - Literature Review

Climate Change in the sub-Antarctic

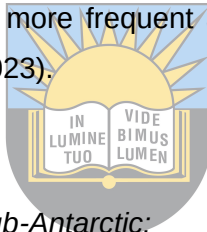
Climate change across the sub-Antarctic region has been a noticeable occurrence over the past few decades and the rate of warming is said to be increasing in the 21st century (Smith & Steenkamp, 1990; Smith, 2002; Smith, 2004; Nel et al., 2023). The sub-Antarctic region has six island groups that fall between the 45° and 55° South (Smith, 2004). The archipelagos of Crozet and Kerguelen, Heard and McDonald Islands, South Georgia, Macquarie Island as well as Marion and Prince Edward Islands comprise the 'core' of the sub-Antarctic region, since they are geographically positioned close to the Antarctic Polar Front. The area surrounding the front is where air temperatures are consistent and where annual and seasonal variability are buffered by the surrounding cold ocean (Nel et al., 2023).

The sub-Antarctic islands serve as important indicators for understanding the nature and timing of Quaternary glaciations in the Southern Hemisphere (Schaefer et al., 2015). These islands are safeguards for valuable glacial geomorphological records that shed light on the earth's response to climate change (Schaefer et al., 2015; Rudolph, 2021). They also play a crucial role in understanding the ecological succession, landscape evolution and the impact of past glaciations on their local environments (Rudolph et al., 2021). Among these islands is Marion Island that stands out as a sentinel for not only the study of glacial oscillations (Rudolph et al., 2021) but also to investigate contemporary climate change in the southern Indian Ocean Region.

Climatic records from the sub-Antarctic islands have shown a warming trend in air temperature all throughout the middle to late 20th Century with a number of reports on the landscape and ecological impacts of the warming of the climate during this period (Nel et al., 2023). There was a significant increase in air temperatures of the sub-Antarctic islands in the 1960s that was correlated with the rise of sea surface temperatures (Rouault et al., 2005). The sub-Antarctic islands (Marion, Kerguelen, and Heard Islands) and the cold temperature island (Amsterdam) in the Indian Ocean appeared to have experienced more warming in the middle of the 1960s than their Pacific Ocean counterparts (Macquarie and Campbell Islands) (Smith & Steenkamp, 1990). Signy Island in the South Atlantic Ocean had a significant mean temperature increase since the 1960s (Smith, 1990). The increasing mean annual air temperature trend established in the 20th Century was observed to be continuing into the 21st

century (Nel et al., 2023). Moreover, the air temperature from the year 2000 onwards was noticed to be the highest trend when looking at the temperature over the past 100 years (Nel et al., 2023).

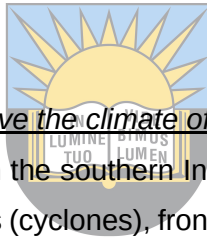
A rise in sea surface temperatures were well noted in the beginning of the 21st century (Smith & Steenkamp, 1990; Smith, 2002; Melice et al., 2003; Rouault et al., 2005) and was noticed to be correlated to the rising air temperatures of Marion Island (Smith, 2002). Extreme events are also taking place globally within the oceans. There have also been recent reports on the rise in the frequency of marine heat waves in the South Atlantic and South Indian Oceans where it was discovered that marine heat waves last for approximately 30 days and 25 days in each ocean, respectively, making these extreme oceanic events more prominent and longer-lasting in the South Atlantic than in the South Indian Ocean (Sneddon, 2023). Marine heat waves are extreme oceanic heatwaves that result from a complex interaction between the atmosphere and ocean (Sneddon, 2023). These have recently become common over the last century and are projected to be more frequent and increase in intensity under future anthropogenic warnings (Sneddon, 2023).



The synoptic weather drivers of the sub-Antarctic:

The Antarctic Circumpolar Current (ACC) stands as a pivotal element in the Southern Ocean, profoundly influencing its ecosystems (Allan et al., 2013). Recent studies employing coupled ocean-atmosphere climate models indicate that the westerly wind belt propelling the ACC is strengthening and shifting towards the poles due to global climate change (Allan et al., 2013). Correspondingly, there's a gradual southward migration of the ACC (Allan et al., 2013). Positioned between the sub-Antarctic Front to the north and the Antarctic Polar Front to the south, the Prince Edward Islands inhabit the transition zone known as the Polar Frontal Zone, delimited by these two major oceanic frontal systems. The latitude of the sub-Antarctic Front significantly influences the oceanographic conditions surrounding the islands (Allan et al., 2013). When the sub-Antarctic Front extends far north of the Prince Edward Islands, the flow velocity of the ACC around the islands decreases, leading to the generation of anti-cyclonic eddies trapped in the shallow region between the islands and in their lee due to frictional forces between the current and the islands (Allan et al., 2013).

The Southern Ocean influences most of the climate and weather conditions that occur on Marion Island. With one of the most hyper-oceanic climates in the world, the daily and annual temperature fluctuations on the island (as on other sub-Antarctic islands as well) are moderated by the high thermal inertia of the Southern Ocean (Le Roux, 2008; Schulze 1971). As a consequence, Marion Island has low daily and seasonal thermal variability, with the mean difference between the maximum and minimum temperature typically being less than 2°C in summer and less than 3°C in winter; and the mean difference between the average winter and summer temperatures being approximately 4.1°C (Schulze, 1971; Smith & Steenkamp, 1990). The regular cyclones which pass near the islands are the cause of much of the observed cloudiness, a high relative humidity and currently a precipitation of about 1696.2 mm per annum (Mapuka, 2020). In summer, the air temperature on the island is higher than that of the ocean water (sea surface temperature), but in winter the opposite is found, so that during periods of the northward displacement of the Polar Front the air temperature will in winter have decreased by more than 2°C. Besides this, the minimum temperatures at the soil surface are between 1.5 and 2°C (Schulze, 1971).



The synoptic weather patterns that drive the climate of Marion Island:

Marion Island, as stated, is situated in the southern Indian Ocean and experiences a climate influenced by mid-latitude depressions (cyclones), frontal systems, and anticyclones (Le Roux 2008; Nel, 2012). Cyclones are constantly formed in the South Atlantic on the boundary between cold and warm air masses. On Marion Island, an approaching cyclone is associated with strengthening north-westerly winds, an influx of warm sub-tropical air, and increased cloudiness (pre-cyclonic) (Nel, 2012). Once the cold front of the mid-latitude cyclone passes, cold and dry Antarctic air with south-westerly winds and clearer skies follows (post-cyclonic). Thus, with each passing cyclone, Marion Island experiences repeated exchanges from wet, warm pre-cyclonic conditions to cold, clear, and dry post-cyclonic conditions (Smith & Steenkamp 1990). In the sub-Antarctic, low annual temperature ranges with high cloudiness and precipitation result in frequent short-duration freeze-thaw events with shallow soil penetration (Boelhouwers et al. 2003; Nel, 2012). The ocean causes the island's hyper-oceanic climate (Le Roux, 2008; Nel, 2012). Rising sea surface temperatures correlate with rising air temperatures in the early 21st century on Marion Island (Smith & Steenkamp, 1990; Smith, 2002; Melice et al., 2003; Rouault et al., 2005). Studies from 1949 to 2003 showed sea surface and air temperatures increased by 1.4°C and 1.2°C respectively (Smith, 2002; Melice et al., 2003; Le Roux & McGeoch, 2008). A recent study by Shangheta (2021) focused on data up to 2018 and displayed a rise in sea surface and air temperature, though at a gentler

rate than noted by Melice et al. (2003). A recent study on sea surface temperatures around the Prince Edward Islands shows temperatures higher towards the northern side, with a summer high of 8°C and winter low of 2°C, with a delay between maximum incoming solar radiation in December to January and peak sea temperatures in February (Toolsee et al., 2021).

Climate Change on Marion Island

Conditions of drying and warming are evident on Marion Island, with a continuous trend of gradually rising temperatures and decreasing total annual rainfall (Le Roux, 2008; Mapuka, 2020; Nel et al., 2023). The first indications of rapid warming and drying emerged from the analysis of daily mean surface air temperatures between 1951 and 1988 by Smith & Steenkamp (1990), indicating that annual mean surface air temperatures began increasing by 0.93°C or 0.025°C per year after 1968, more than double the mean global rate. Smith (2002) and Le Roux (2008) also observed rapid climate changes on Marion Island between the 1950s and 2000s. Surface air and sea temperatures at mid-latitudes of the Southern Ocean warmed significantly during this period, albeit at spatially and temporally variable rates (Le Roux, 2008). Smith (2002) demonstrated a temperature increase of 1.2°C between 1969 and 1999, with the overall temperature rise related to an increase in sea surface temperature as noted by Smith and Steenkamp (1990). The rise in mean surface air temperature was associated with corresponding increases in sea surface temperatures (Rouault et al., 2005), as well as changes in radiation and precipitation (Smith & Steenkamp, 1990). A relationship between the rise of annual sea surface and air temperatures in both time and direction was established. Additionally, annual sunshine hours increased significantly by 11 hours per year over the 37-year study period, although inter-annual variability was noted to have declined (Smith & Steenkamp, 1990).

The reason suggested for the rise in annual air and sea surface temperatures are changes in the atmospheric and oceanic sea level air circulation patterns in the region which resulted from an increase in thermal energy in the Southern Ocean (Smith & Steenkamp, 1990; Smith, 2002). Rouault et al. (2005) in their analysis of sea surface temperature and daily rainfall at Marion Island argued that regional atmospheric circulation patterns have changed on inter-annual and longer timescales thus leading to the observed changes in precipitation, non-rainy days, sunshine hours, air temperature and coastal sea surface temperature, and wind speed and direction.

Recorded daily and annual air temperature maxima and minima have risen at a similar rate to mean temperatures, resulting in a roughly constant daily temperature range, which was said to be an unusual pattern because globally, thermal minima are increasing faster than maxima, leading to a narrowing of the daily temperature range and the five warmest years was recorded to be 1996-2000 (Le Roux, 2008; Le Roux & McGeoch, 2008). The mean temperature and annual daily maxima and minima were reported to have increased at a significant level with a 1°C increase from the 1950s to the 1990 and decadal trends show that there was also a 1°C rise for the mean daily maximum and minimum from the 1950s to 1990s (Le Roux & McGeoch, 2008). Annual sunshine hours have risen by 3.3 hours since the 1950s and has been linked with the rising sea temperatures and synoptic weather system trends that have changed over time (Le Roux & McGeoch, 2008; Mapuka, 2020; Smith, 2002; Smith & Steenkamp, 1990).

In terms of recorded precipitation on Marion Island, remarkable changes have been observed since the 1960s. Approximately during the same period that surface and sea surface temperatures were increasing (late 1960s to 1980s) and then decreasing (mid 1980s to 1988), opposite changes were occurring in the annual precipitation (Smith & Steenkamp, 1990). However, prior to 1967, the marked increase in the recorded precipitation on the island was not accompanied by any significant or constant change in neither sea nor surface temperature (Smith & Steenkamp, 1990). Records have shown high amounts of rainfall in the early years with a peak in the decadal average total of 2726.9 mm in 1960s which decreased to 1876 mm in the 2000s due to global climate change (Ndwayamato, 2015; Mapuka, 2020).

The 5-year running mean in total annual rainfall decreased in the 1960s and 1970s but began decreasing significantly from the 1980s with trends showing a decrease of 1.5 mm in the average rainfall event size (Chown & Smith, 1993; Smith & Steenkamp, 1990; Smith, 2002; Le Roux & McGeoch, 2008). Between 1951 and 1967 a significant average increase of 46 mm per year or 831 mm was noted. It went on to decrease by 43 mm per year and to rise again by 65 mm per year from 1983 (Smith & Steenkamp, 1990). From 1980 to 1988, annual rainfall reached notably high levels, exceeding 2000 mm per annum. However, a decline in rainfall commenced from 1989 to 1996, with the majority of years observing annual precipitation below the 2000 mm mark (Mapuka, 2020). This was said to be about 25% lower than the total for the period of the 1960s (Smith, 2002). A significant rise in no rainfall hours during the summer months was observed from 1995 to 2009, confirming the decreasing trends observed in previous years (Ndwayamato, 2015). Linear regression analyses show that the annual

precipitation decreased, on average, between 1965 and 1999 by 25 mm per year (Smith, 2002). All the months were said to be dry during this period (with the exception of October) and the greatest decline was seen for November to January and April or May (Smith, 2002). Over this period, there was an observed increase in the recorded number of rainless days, as well as in the mean and maximum duration of consecutive days without rainfall. Specifically, the frequency of dry days surged from an average of 49.1 days during the 1960s to over 89.1 days throughout the 1990s (Le Roux & McGeoch, 2008).

The annual average rainfall event size and the maximum daily rainfall event were reported to have decreased from 1949 to 2003, with variability in the daily rainfall events increasing (Le Roux & McGeoch, 2008). The rainfall dropped significantly by 1000mm in three decades (between the 1960s and the 1990s) with a rainfall event size decrease of 1.5 (Le Roux & McGeoch, 2008). Days without rainfall and consecutive dry days conversely increase during this period from an average of 49.1 to more than 89.1 days from 1960 to 1990. Duration of days between rainfall events increased from 4 to 6 days and this is accompanied by a decline of more than 5 mm in rainfall event size from 1960 to 1990 (Le Roux & McGeoch, 2008).



The most recent observations from Marion Island confirm the declining decadal trend with a recorded annual average of 1889.2 mm of rainfall for the decade of 2000-2009 and a mean annual total of 1739.3 mm for the decade of 2010-2018 (Hedding & Greve, 2018; Mapuka, 2020). The most recent decade spanning from 2010 to 2018 emerges as the driest period on record, as evidenced by monthly rainfall data. Notably, 2017 stands out as the driest year on record (Hedding & Greve, 2018; Mapuka, 2020). Extending the analysis back to the early and late 2000s, a recent study highlights a consistent decline in monthly precipitation, particularly in the months of April, May, July, August, and October. This downward trend persists across all seasons, with autumn experiencing the most pronounced reduction in seasonal rainfall, amounting to a 35% decrease over the past four decades (Mapuka, 2020). Moreover, recent data indicates a significant increase in the number of rainless days, rising from 80 to 140 days between 1980 and 2018. Consecutive days without rainfall have also seen a substantial uptick, escalating from 42 to 100 consecutive days during the same period (Mapuka, 2020).

It is clear that temperature has steadily increased since the 1950s at Marion Island and in the sub-Antarctic region with studies and subsequent analyses showing a climatological rise of

more than 1°C in the air and sea surface temperature which coincides with a decrease in rainfall, an increase in extreme events, an increase in winds from the warmer sector in the northwest, and an increase in sunshine hours since the 1950s (Smith & Steenkamp, 1990; Smith 2002; Le Roux & McGeoch, 2008; Mapuka, 2020). Only a few studies (Smith & Steenkamp, 1990; Le Roux & McGeoch, 2008) have looked at the trends in daily meteorological extremes. Although there have been studies looking at the annual, monthly and daily changes in precipitation, there are few looking at the long-term patterns and trends in extreme meteorological events on Marion Island. The question to be answered now is whether the island has experienced changes in extreme temperature and precipitation and to what extent are they influencing the island?



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Chapter 3 - Methodology

Description of the study site

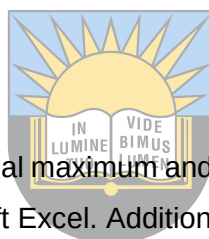
For this study, daily climate data on temperature and precipitation provided by the South African Weather Service (SAWS) were utilised. Continuous meteorological observations have been carried out on the island by the South African Weather Service since 1949 (Smith, 2002) and thus provides a reliable source of long-term data for the island. Surface air temperature was initially measured using a thermohygrograph until the year 1993, after which a thermistor connected to a data logger has been in use since then (Smith, 2002). Both instruments were placed in a Stevenson Screen, located 25 meters above sea level on the island's eastern side (Smith, 2002), where the research base and meteorological station are located. The thermistor is calibrated daily against a mercury-in-glass thermometer by the SAWS technicians available during the overwintering period (Smith, 2002). Precipitation and rainfall depth are currently measured automatically on the ground using a standard tipping bucket rain gauge with a resolution of 0.2 mm (Smith, 2002; Mapuka, 2020). Daily rainfall data for a 24-hour period is collected at 08:00 each day. Rainfall is also recorded at the Meteorological Station on the island's eastern side (Mapuka, 2020). This station, located on the lee side of the island, can occasionally be influenced by the Fohn wind, which lowers humidity (Schulze, 1971). The differences in rainfall between the island's sides are speculative (e.g., Schulze, 1971; Rouault et al., 2005). However, due to prevailing westerly winds, it is hypothesized that the climate varies most between the eastern (mainly leeward) and western (windward) sectors of the island (Smith, 2008; Mapuka, 2020). The western sector is suggested to have stronger, more consistent winds, higher humidity and rainfall, and more stable temperatures (Rouault et al., 2005). Additionally, the west is rarely affected by Fohn winds and may have a different cloud cover pattern (Schulze, 1971). Additionally, the topography can result in climatic differences between the eastern and western sides on the island, but there is no comparable rainfall data to test this (Mapuka, 2020). With no other rainfall station within a 1000 km radius, the station's data is the only long-term rainfall dataset available in the located side of the vast ocean (Mapuka, 2020).

Additional information states that a power shack was constructed in 1991 near the site where meteorological measurements had been taken since 1949 (Smith, 2002). It was found that temperatures in the Stevenson screen at this site were, on average, 0.06°C higher ($P = 0.002$) than those in an identical screen 10 meters away from the shack, based on 128 paired measurements over 10 days (Smith 2002). In April 1993, the meteorological station was

relocated to a site approximately 40 meters away and upwind of the power shack, where it still is today. This was the only known change in the station's location since 1949 (Smith, 2002).

Climate Change Detection Indices

While monthly means capture many aspects of climate, certain extremes like drought are best analysed using indices based on monthly data (Heim, 2015). However, it was highlighted in the World Meteorological Organisation Symposium that analyses and conclusions regarding weather and climate extremes are most effectively based on daily data and an internationally agreed-upon set of daily extreme indices, such as those developed by the Expert Team on Climate Change Detection Indices (ETCCDI) as presented in Zhang et al. (2011). Therefore, the decision to use daily data for this study aligns with recommendations from the WMO (1992), Heim (2015), and Zhang et al. (2011). The Expert Team on Climate Change Detection indices utilised for this study are mentioned and defined in the table below (Table 3.1). Twenty-four of the indices described by Zhang et al. (2011) were selected as they applied most to the context of Marion Island.



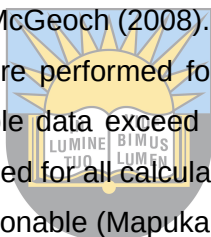
Columns for daily, seasonal, and annual maximum and minimum temperatures, along with the mean, were generated using Microsoft Excel. Additionally, a table of daily and annual rainfall was created in Excel. Following the methodology outlined by Zhang et al. (2011), this data was tabulated to identify climate extremes using the extreme temperature and precipitation indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Table 3.1). Subsequently, simple linear regression statistical analyses were performed for each index to identify extremes, patterns, and trends in the data. Table 3.1 provided the definition for each index that was used. Excel was employed to calculate each index, conduct linear regression statistics, determine significance at the 95th coefficient level, and generate graphs and tables. Once the extreme temperature and precipitation indices were determined, they were analysed over time to ascertain how extremes in temperature and precipitation were changing in the context of climate change on Marion Island. Following data analysis, graphs were generated to visualize the data over time. Finally, the generated data and indices were contextualized in relation to the climatic classification in the literature of Marion Island to identify potential drivers of changes in extreme climate variables on the island. When there exists a substantial dataset spanning several years, it becomes feasible to construct a statistical distribution of a significant weather or climate parameter. This facilitates the determination of the likelihood of encountering values exceeding or falling below various

thresholds, a crucial aspect in engineering design. However, given the geographic context, the extremity of a weather or climate extreme event depends on specific regional conditions. Consequently, certain indices need redefinition to suit the unique characteristics of the study area. This is particularly relevant for temperature indices, given Marion Island's location in the sub-Antarctic region, which exhibits a distinct climate compared to the temperature norms upon which standard indices are developed. While Marion Island is naturally a wet environment due to its oceanic nature, it is still generally a cold place when considering the average temperature. The summer days and tropical nights indices have been redefined for Marion Island. Summer days (SU12.5) are the annual count of days when the daily maximum temperature is greater than the 90th percentile (12.5°C for Marion) of the daily maximum temperature value, and tropical nights (TR6.7) are the days when the daily minimum temperature is greater than the 90th percentile of the daily minimum temperature value (6.7°C). A warm spell (or cold spell) is defined as periods characterized by several days of very warm (or cold) temperatures compared to the local or regional averages. A warm (or cold) spell duration indicator index is the representation of the count of days that contribute to warm (or cold) spells when the maximum temperature remains above its climatological 90th percentile (and 10th percentile for minimum temperature) (Met Eireann, 2019). The warm and cold spell duration indicators are normally based on at least six consecutive days but for this study area it will be based on at least 3 consecutive days of daily maximum temperature greater than the 90th percentile and daily minimum temperature less than the 10th percentile of daily maximum and minimum values. This is due to the sensitive nature of the island and how the environment quickly responds to change.

The homogenization of climate data is a crucial part in long-term data studies to ascertain the quality of the data used and study because non-climatic factors can distort the data, making it unrepresentative of actual climate variations and potentially biasing the conclusions of climatic and hydrological studies (Costa and Soares, 2009). Relying solely on data from a single station is problematic, as it is challenging to discern whether changes are due to climatic or non-climatic influences (Peterson et al., 1998). To address this issue, metadata from station history is essential for evaluating detected breaks (Costa and Soares, 2009). Some observational series lack useful reference points, such as the temperature and rainfall data from Marion Island (Mapuka, 2020), which dwells in isolation as the nearest landmass being Crozet Island (which is 1030 km away) and the closest long-term rainfall station being in Gqeberha (previously Port Elizabeth) in South Africa, which is 1750 km away from Marion Island (Mapuka, 2020). Thus, conducting homogeneity tests without a reference series is not

recommended as it is much less reliable and should not be done automatically (WMO, 2018). It is recommended to thoroughly study all available metadata to determine the final list of change points for adjustment (WMO, 2018) and such has been done for this study.

Several years in the daily climatic data were noted to have data missing. For the year 1959, precipitation data was absent from February 1st to April 1st, July 1st to 30th and October 1st to 30th. It is not certain why the data are missing, but the temperature data is available for these temporal intervals. Also data for 1966 from March 1st to June 30th (data for both temperature and precipitation) is not available because part of the base burnt down during this period. For the year 1991, precipitation data from April 1st until June 2nd and in 1992 precipitation data from March 8th to 29th is absent but temperature data is available. Data for precipitation and temperature for 2001 from October 1st to the 29th is not available and precipitation data for the month of April in 2005 is questionable. Therefore, data for the year 1966 and 2001 was excluded in all calculations and analyses for both temperature and precipitation extremes because more than 6% (more than 21 days) of the data is unavailable for both parameters for the study as was done by Le Roux & McGeoch (2008). The years 1959, 1991, 1992 and 2005 were excluded when calculations were performed for the precipitation (rainfall) parameter because the percentage of unavailable data exceed more than 6% (Le Roux & McGeoch, 2008). The year 2004 was also excluded for all calculations as well because the quality of the data for that year is noted to be questionable (Mapuka, 2020).



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Table 3.1: Extreme temperature and precipitation indices summarised by Zhang et al. (2011).

ID	Indicator Name	Indicator Definitions	Units
TXx	Max Tmax	Monthly maximum value of daily maximum temperature	°C
TNx	Max Tmin	Monthly maximum value of daily minimum temperature	°C
TXn	Min Tmax	Monthly minimum value of maximum temperature	°C
TNn	Min Tmin	Monthly minimum value of minimum temperature	°C
TN10p	Cool nights	Percentage of time when daily minimum temperature < 10 th percentile	%
TX10p	Cool days	Percentage of time when daily maximum temperature < 10 th percentile	%
TN90p	Warm nights	Percentage of time when daily minimum temperature > 90 th percentile	%
TX90p	Warm days	Percentage of time when daily maximum temperature > 90 th percentile	%
DTR	Diurnal temperature range	Monthly mean difference between daily maximum and minimum temperature	°C
FD0	Frost days	Annual count when daily minimum temperature < 0°C	Days
SU25	Summer days	Annual count when daily maximum temperature > 25°C	Days
TR20	Tropical nights	Annual count when daily minimum temperature > 20°C	Days
WSDI	Warm spell duration indicator	Annual count when at least six consecutive days of max temperature > 90 th percentile	Days
CSDI	Cold spell duration indicator	Annual count when at least six consecutive days of min temperature < 10 th percentile	Days
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
SDII	Simple daily intensity index	The ratio of annual total precipitation to the number of wet days (≥ 1 mm)	mm/day
R10	Number of heavy precipitation days	Annual count when precipitation ≥ 10 mm	Days
R20	Number of very heavy precipitation days	Annual count when precipitation ≥ 20 mm	Days
CDD	Consecutive dry days	Maximum number of consecutive days when precipitation < 1 mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days when precipitation ≥ 1 mm	Days
R95p	Very wet days	Annual total precipitation from days > 95 th percentile	mm
R99p	Extremely wet days	Annual total precipitation from days > 99 th percentile	mm
PRCPTOT	Annual total wet-dry precipitation	Annual total precipitation from days ≥ 1 mm	mm

Chapter 4 - Results

Climate Change Trends: 1950-2020

For Marion Island, the latest research indicates that the mean annual air temperature has been increasing by a rate of 2.4°C/100 years (see Nel et al., 2023). Past research has revealed that annual rainfall totals, average rainfall event size, and maximum daily rainfall from 1943 to 2003 decreased significantly (a decrease of 1000 mm of annual rainfall between the 1960s and 1990s) and the number of annual and consecutive dry days were becoming more frequent (Le Roux & McGeoch, 2008). The long-term (71-year) daily data presented here continues to show gradual changes in the climate of Marion Island with an observed rise in warming and drying conditions during the recording period (Table 4.1). From linear regression, it can be seen that all temperature and precipitation indices trends are significant at the 95th coefficient level ($p < 0.05$). Extreme indices also display significant results (with the exception of the simple daily intensity index— $p > 0.05$). The annual mean air temperatures increased by 1.2°C ($p < 0.01$) between 1950 and 2020 (Fig. 4.1). Over the same period, daily maximum air temperatures increased by 1.2°C ($p < 0.01$) (Fig. 4.2) and daily minimum air temperatures increased by 0.9°C ($p < 0.01$) (Fig. 4.3). The average annual precipitation for the study period (1950-2020) is 2170.56 mm. However, annual precipitation patterns display a declining trend, with a significant decrease of 1042.3 mm ($p < 0.01$) in the total annual rainfall between 1950 and 2020 (Fig. 4.4). For precipitation in the future, if the current declining trend continues, the rate of change over a 100-year period would be a decrease of an average of 5.8 mm per year over the next century. Annual maximum consecutive dry days display a rise from 5 days in 1950 to 7 days in 2020 (Fig 4.25). Changes in the measured variables are described in more detail below.

Table 4.1: Mean maximum and mean minimum temperatures and the mean annual precipitation for each decade of the study period.

Decade	1950-59	1960-69	1970-79	1980-89	1990-99	2000-09	2010-19
Mean Annual Air Temperature (°C)	5.4	5.3	5.7	6.1	6.4	6.0	6.6
Mean Maximum Temperature (°C)	10.3	10.3	10.5	11.2	11.4	10.9	11.2
Mean Minimum Temperature (°C)	1.1	0.6	1.3	1.4	1.8	1.5	1.7
Mean Annual Precipitation (mm)	2535*	2704.7*	2388.7	2189.3	1985.8*	1892.6*	1770

Note: Some years were excluded from the calculations (consider chapter 3), hence marked by a *

The mean annual air temperatures show a statistically significant increasing trend of 1.2°C ($p < 0.01$) between the years 1950 and 2020, with an approximate increase of 0.02°C per year (Fig. 4.1). The highest annual average for the period is 6.98°C in 1996 and the lowest average being 4.7°C in 1960. On a decadal scale, we see a significant increase of 0.2°C for all the decades and we notice that the decade of the 1990s was the warmest on record with a sharp spike in the average temperature from 1995 to 1996.

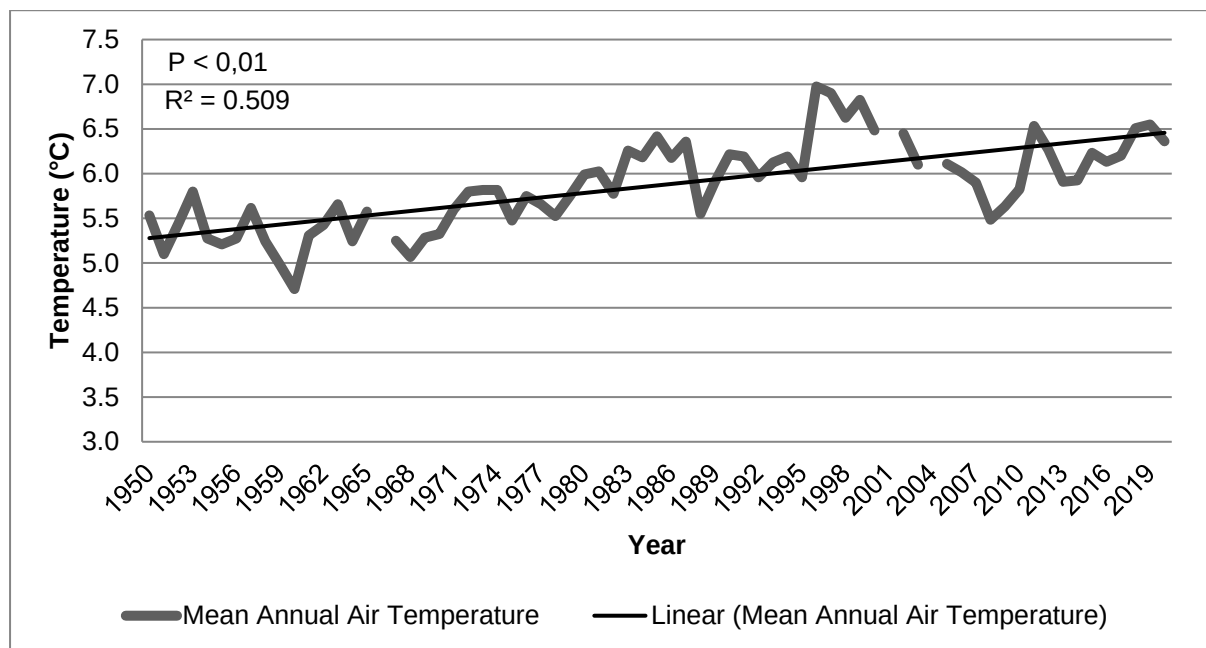


Figure 4.1: Mean annual air temperature for Marion Island (1950-2020).

Annual maximum temperatures show a significant increasing trend of 1.2°C between 1950 and 2020 ($p < 0.01$) (Fig. 4.2). The highest annual average maximum temperature for the period is 12.8°C measured in 2020 and the lowest being 9.8°C in 1957. The decadal change from linear regression is significant with a rise of 0.2°C for each decade. During the 1980s, a more than 1°C spike in the annual average is recorded for 1984 and 1985. There is also a sustained increase of more than 2°C over a period of four years from 1982 to 1985.

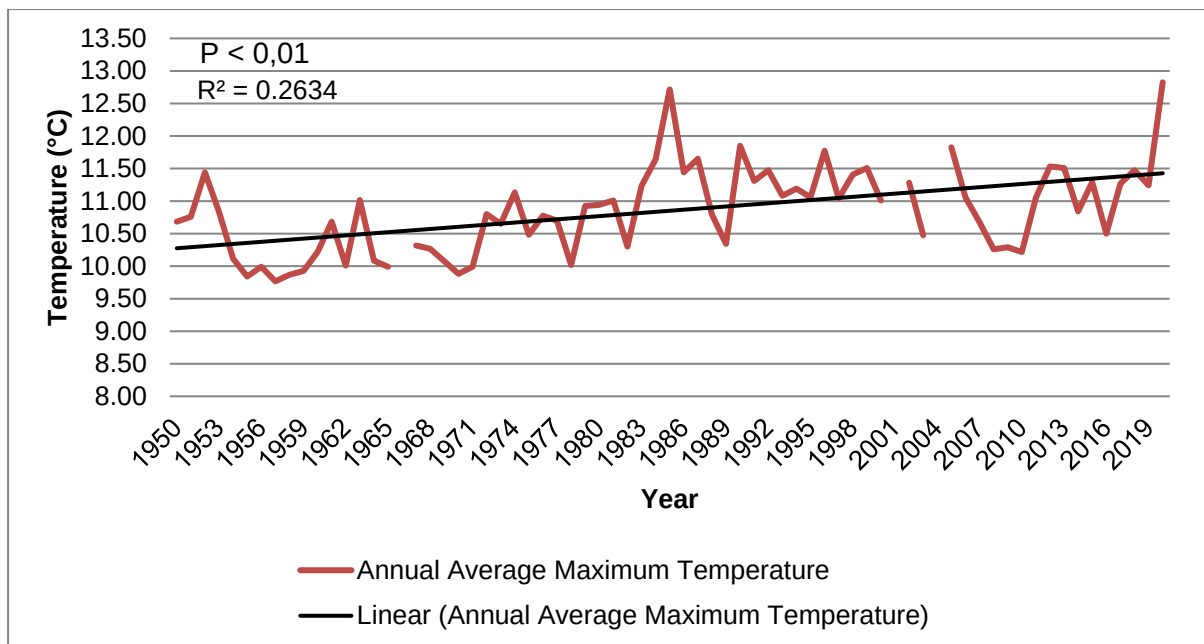


Figure 4.2: Trend in mean annual maximum air temperatures (1950 to 2020).

Annual minimum temperatures also display a rising trend with a significant increase of 0.9°C ($p < 0.01$) from 1950 to 2020 with the highest average minimum temperature being 2.8°C for the year 1996 and the lowest average minimum in the period being -0.2°C for 1989 (Fig. 4.3). The decades show a significant increasing decadal trend of 0.1°C for all the decades. The decade of the 1990s displays a more than 1°C spike in the annual average from 1995 (1.6°C) to 1996 (2.8°C) and decreases a little in 1997 (2.4°C) before dipping under the 2°C mark. There is a sustained increase from 1989 to 1996 of approximately 2°C . The temperature rises from 1989 to 1993 by 1°C and increases again from 1994 to 1996 by 1°C after decreasing slightly between 1993 and 1994.

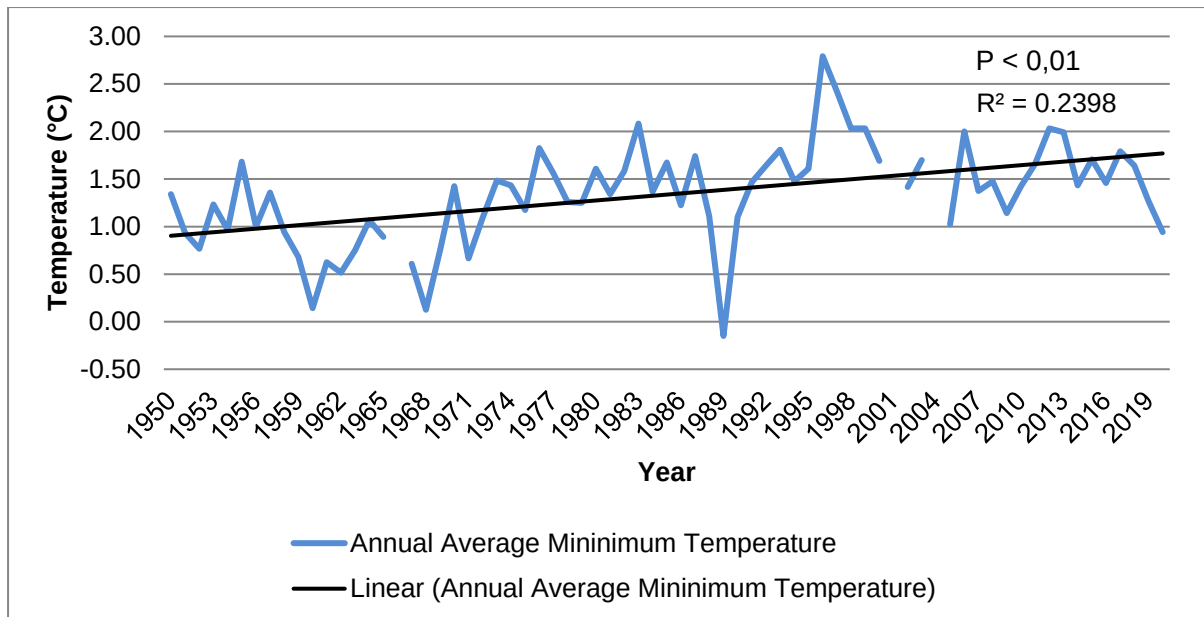


Figure 4.3: Trend in mean annual minimum air temperatures (1950 to 2020).

Annual rainfall has significantly decreased over the study period with annual totals showing a decrease of 1042.3 mm between 1950 and 2020 ($p < 0.01$) (Fig. 4.4) which is a decrease of approximately 14.89 mm annually. Most years prior to 1990 have a total rainfall that is above 2000 mm while after 1990 most total rainfall falls below the 2000 mm mark until 2020. The year 1951 has the highest annual total of 3123.7 mm whereas 2017 has the lowest total of 1437.8 mm (Fig. 4.4). Looking at the decadal change, rainfall decreases significantly by 134.0 mm from the 1960s. The decadal decline couldn't be calculated from 1950 due to data missing for 1959. The highest decadal average is the 1960s and the most recent decade (2010-2019) is the decade with the least annual rainfall average of all the decades and contains the year with the least recorded total rainfall.

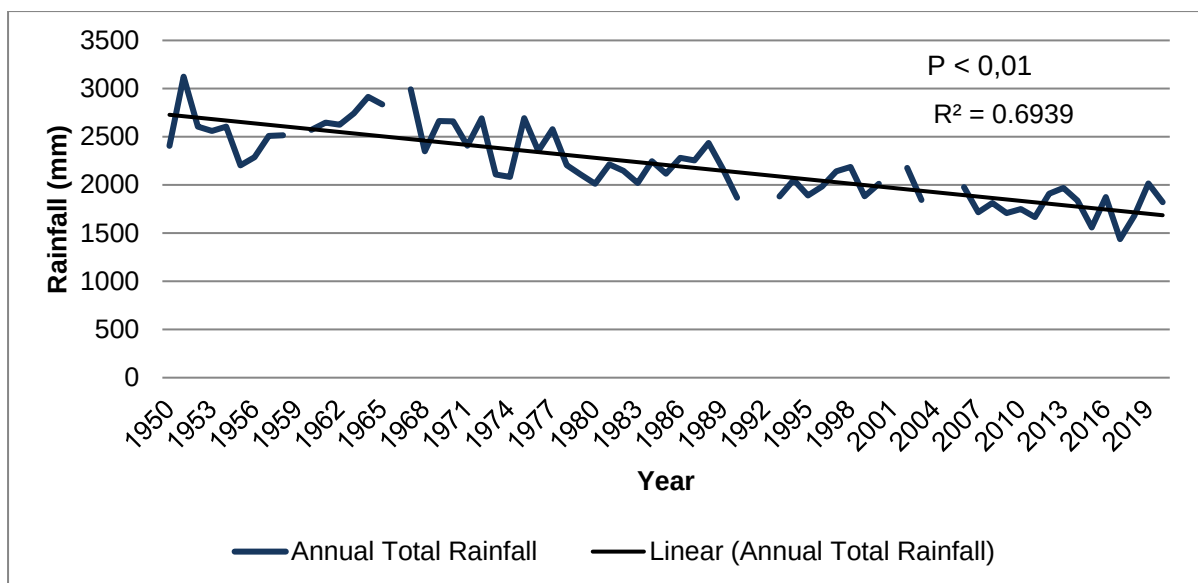


Figure 4.4: Trend in total annual rainfall for Marion Island (1950 to 2020).

Climate Change Detection Indices

The following results are based on calculations from the indices by the Expert Team on Climate Change Detection Indices (ETCCDI) used to determine extreme climatic parameters (Table 4.2). The highest daily maximum temperature recorded for this period is 23.8°C on the 8th of January 1984 and the lowest daily maximum temperature recorded for this period is -0.9°C for the 3rd of August 1956. The highest daily minimum temperature for this period is 11.8°C on the 19th of February 1976 and the lowest daily minimum temperature is -6.8°C on the 16th of September 1952. The 90th and 10th percentiles for daily maximum temperature were 12.5°C and 4.8°C; and for daily minimum temperature 6.7°C and -0.3°C. The 90th, 95th and 99th percentiles of daily precipitation (rainfall) for the study period are 18.5 mm, 26.3 mm and 46.5 mm, respectively.

Table 4:2: Results from the ETCCDI based on monthly daily data for temperature and rainfall. These are as follows: The maximum daily maximum temperature (Max Tmax); the maximum daily minimum temperature (Max Tmin); the minimum daily maximum temperature (Min Tmax); the minimum daily minimum temperature (Min Tmin); maximum 1-day precipitation amount; maximum 5-day precipitation amount; and diurnal temperature range.

Indicator Name	Max Tmax	Max Tmin	Min Tmax	Min Tmin	Max 1-day precipitation amount	Max 5-day precipitation amount	Diurnal temperature range
Units	°C	°C	°C	°C	mm	mm	°C
ID	TXx	TNx	TXn	TNn	RX1day	RX5day	DTR
January	23.8	11.3	4.4	-1.8	87.8	175.6	9.2
February	22.9	11.8	-0.9	-6.5	111.4	174.2	7.1
March	22	11.1	3.4	-1.1	69.3	147.5	6.9
April	19.4	10.9	0	-2.2	120.7	177.6	6.6
May	19.4	11.1	1.3	-3	81	159.6	6.5
June	18.6	8.9	-0.4	-6	70.4	167.4	5.8
July	18.6	9	-0.7	-6	79.2	109.6	6.0
August	16.2	9.1	-0.9	-5.5	56	99	6.5
September	39.8	9.5	-0.9	-6.8	110	143.1	8.4
October	19.2	8.8	0.1	-4.7	82.7	135.2	6.5
November	21.4	10.2	2.6	-3.1	78.8	115.8	7.5
December	21.6	10.6	2.9	-1.5	71.6	129.6	8.0

Extreme Air Temperature Indices

The percentage of annual warm days has risen significantly on Marion Island by 6.55 % ($p < 0.01$) between 1950 and 2020. Warm days are the percentage of time when the daily maximum temperature is greater than the 90th percentile (Fig. 4.5). The year with the highest percentage of warm days is 1999 with 18.36 % and the year with the lowest percentage in the study period is 1968 with 3.28 %. The decades show a significant change of 0.84 % between each decade with the highest average percentage is 1990-99 with an average percentage of 14.41 % and the decade with the lowest average percentage is 1960-69 with 5.63 %.

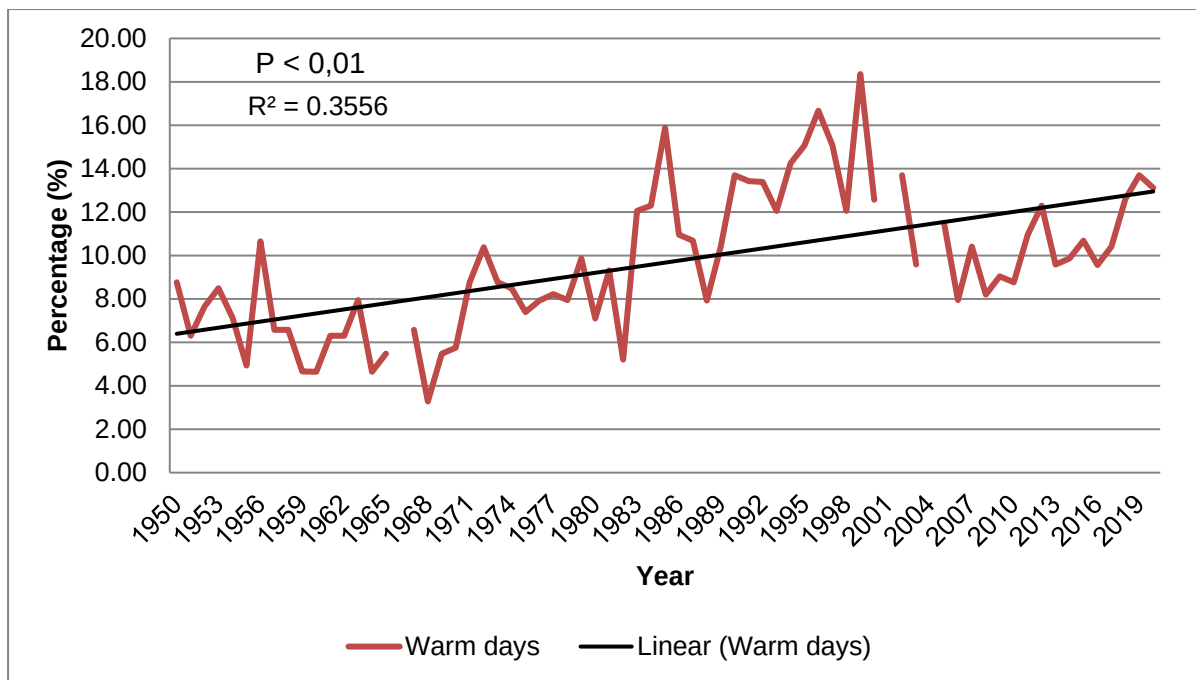
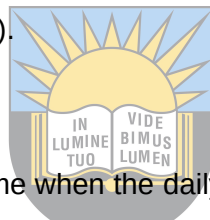


Figure 4.5: The annual percentage of time when daily maximum temperatures were greater than the 90th percentile (1950 to 2020).



Warm nights are the percentage of time when the daily minimum temperature is greater than the 90th percentile. The percentages of warm nights have also increased significantly with a percentage rise of 6.27 % between 1950 and 2020 ($p < 0.01$) (Fig. 4.6). The year with the highest percentage of warm nights is 1999 with 19.45 % and the years with the lowest percentage of 3.01 % are 1955, 1969 and 2008. Decadal change shows a significant change of 0.81 % and the decade with the highest average percentage of warm nights is 1990-99 with 15.18 % and the decade with the lowest for the 71-year period is 1960-69 with 5.02 %.

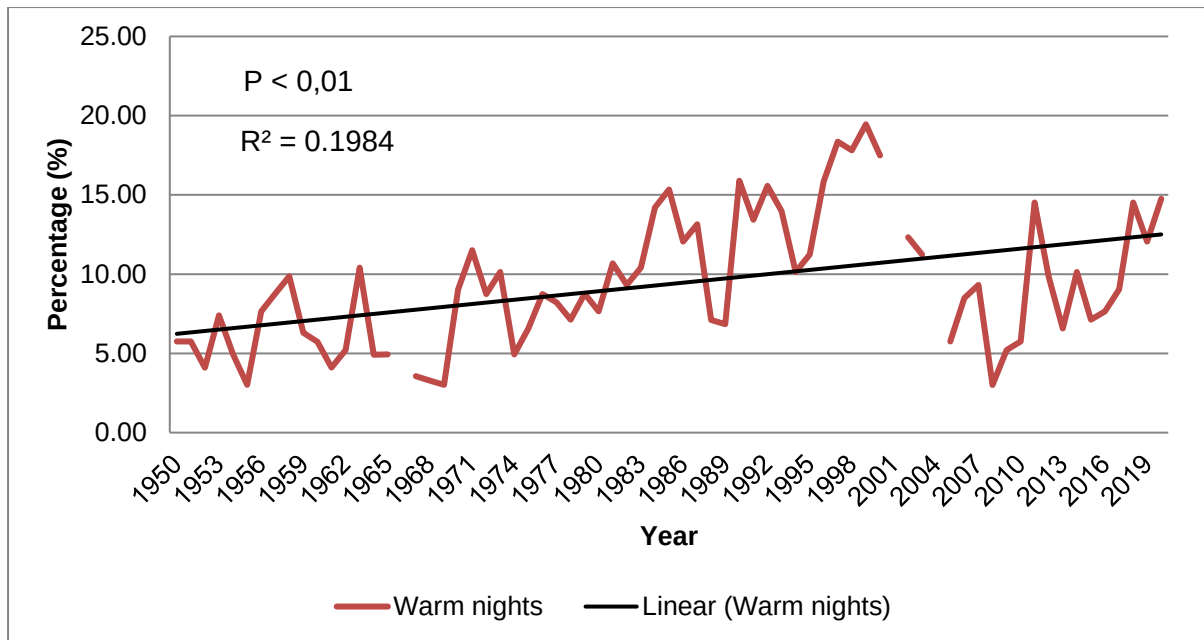


Figure 4.6: Annual percentage of time when the daily minimum temperatures were greater than the 90th percentile (1950 to 2020).



The annual percentage of cool days shows a significant decreasing trend of 4.66 % between 1950 and 2020 ($p < 0.01$) (Fig. 4.7). Cool days are the annual percentage of time when the daily maximum temperatures were less than the 10th percentile. The year with the highest percentage of cool days is 1960 with 17.21 % and the year with the lowest is 2002 with 3.84 %. The decadal change is significant with a decline of 0.6 % per decade with the highest average percentage of cool days being for 1950-59 with 12.66 % and the lowest is the 1990-99 with a percentage of 7.1 %.

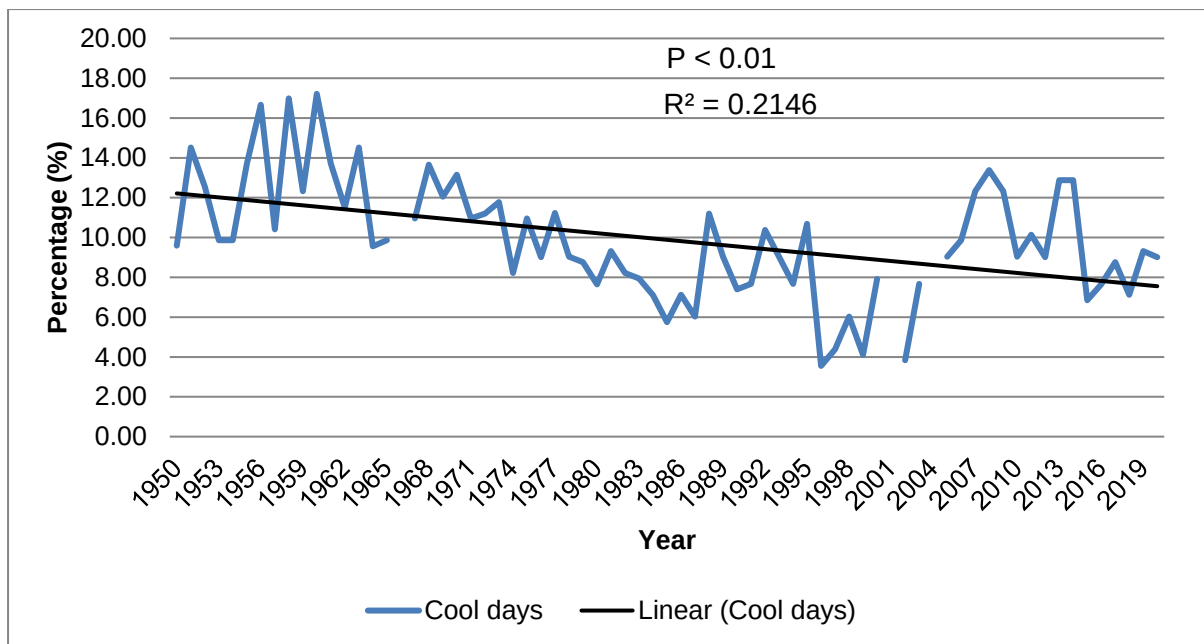
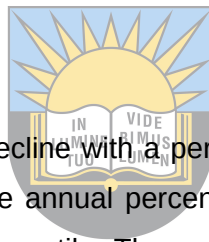


Figure 4.7: Annual percentage of time when daily maximum temperatures were less than the 10th percentile (1950 to 2020).



Cool nights also show a significant decline with a percentage of 3.58 % between 1950 and 2020 ($p < 0.01$) (Fig. 4.8). This is the annual percentage of time when the daily minimum temperatures were below the 10th percentile. The year with the highest percentage of cool nights is 1958 with 14.75 % and with the lowest is 1967 with 2.19 %. The decadal change shows that the percentage decreases significantly by 0.46 % per decade with the highest average percentage for cool nights being for 1970-79 with 11.56 % and the decade with the lowest is 2000-09 with 8.25 %.

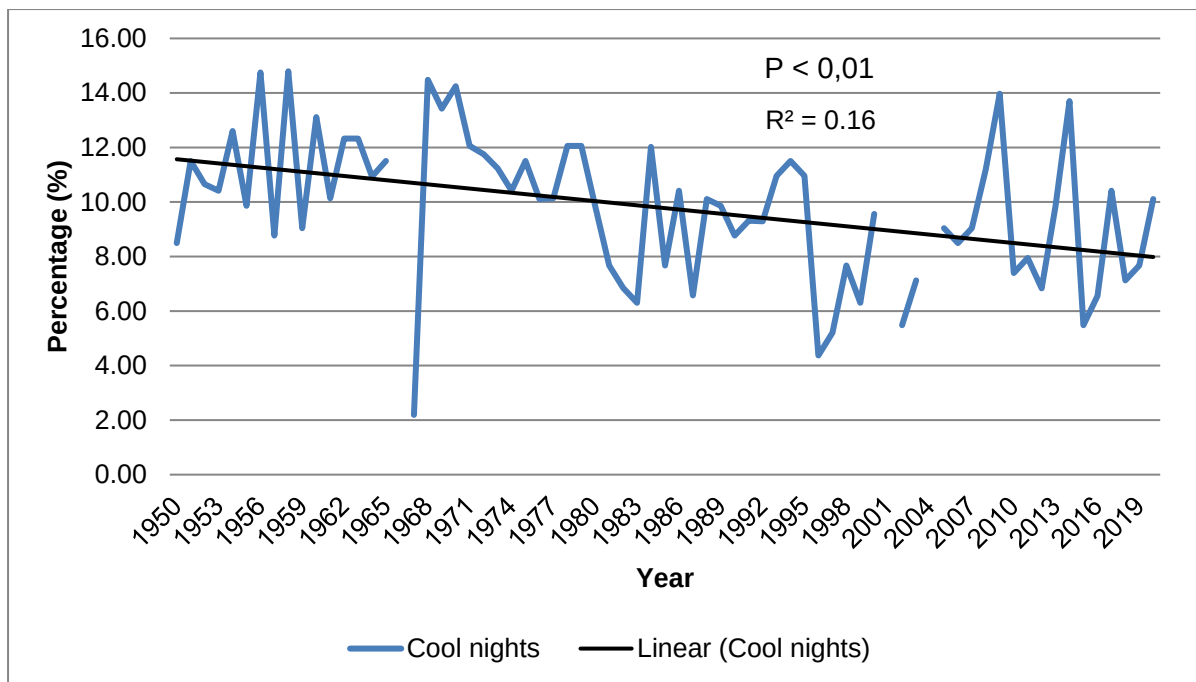
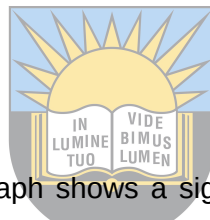


Figure 4.8: Annual percentage of time when the daily minimum temperature was less than the 10th percentile (1950 to 2020).



The warm spell duration indicator graph shows a significant increasing trend of 3.94 days between 1950 and 2020 ($p < 0.05$) (Fig. 4.9). The warm spell duration indicator is defined as the annual count when at least three consecutive days had a daily maximum temperature that was greater than the 90th percentile (12.5°C). There is an increase of warm spells from 1950—when the daily maximum temperature exceeded the 90th percentile at least once for three consecutive days, to 2020 when this took place 12 times. The year with the highest warm spell count is 1996 with 19 and the lowest years being 1965, 1968, 1969, 1978, 1982 and 2009 having a count of zero. The decade with the highest count is the 1990s and contains the most years (5 years) with a count greater than 10; the 1960s has the least count and contains no years with a count more than 10. The second greatest decade with the highest count is 2000–09, which has four separate years with a warm spell count greater than 10. The decadal change is statistically significant at 0.51 days per decade.

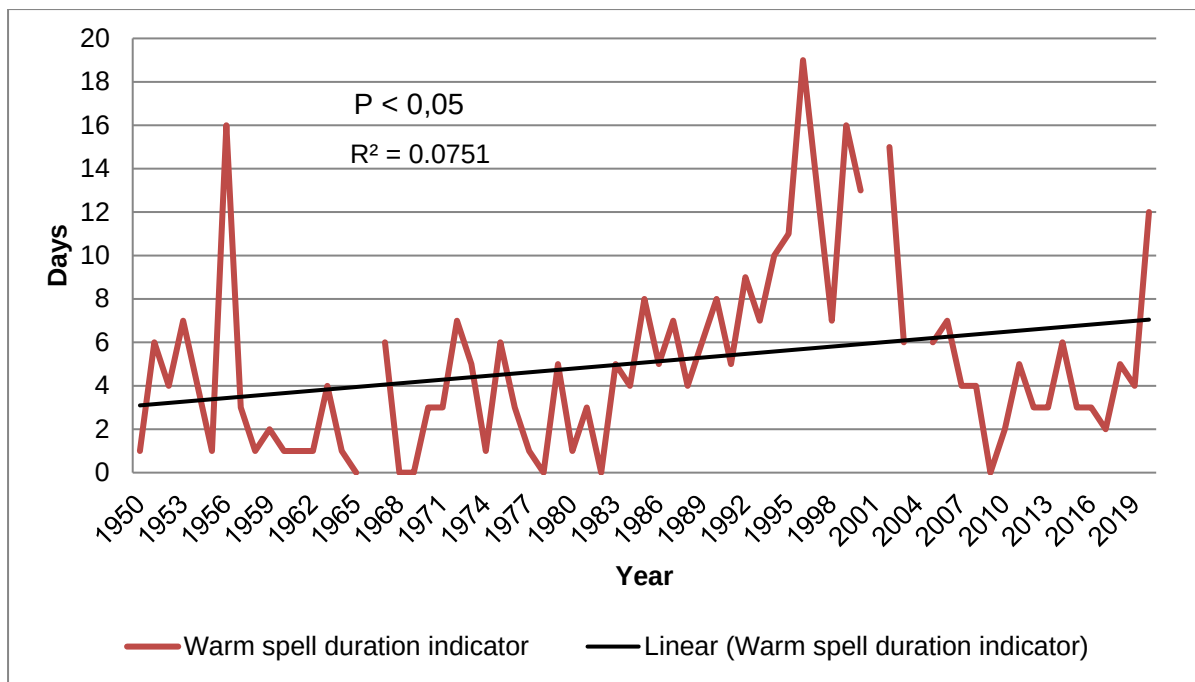


Figure 4.9: Annual count when at least three consecutive days of maximum temperature are greater than 90th percentile (12.5°C) (1950 to 2020).

The cold spell duration indicator graph demonstrates a significant decreasing trend of 3.79 days between 1950 and 2020 ($p < 0.01$) (Fig. 4.10). The cold spell duration Indicator is described as the annual count when at least three consecutive days had a daily minimum temperature value that was less than the 10th percentile. The year with the highest cold spell count is 1967 when cold spells took place 12 times followed by the years 1969, 1970, 1972 and 2014 with a count of 11 times. A few years have a count of zero (1983, 1987, 1989, 1996, 1997, 2004 and 2015). Looking at the decades during the study period, 1970-79 has the highest count with five years having a count greater than eight and the decade with the lowest count is 1990-99 with no years with a count greater than eight. The decadal change is significant with a decreasing trend of 0.49 days between each decade.

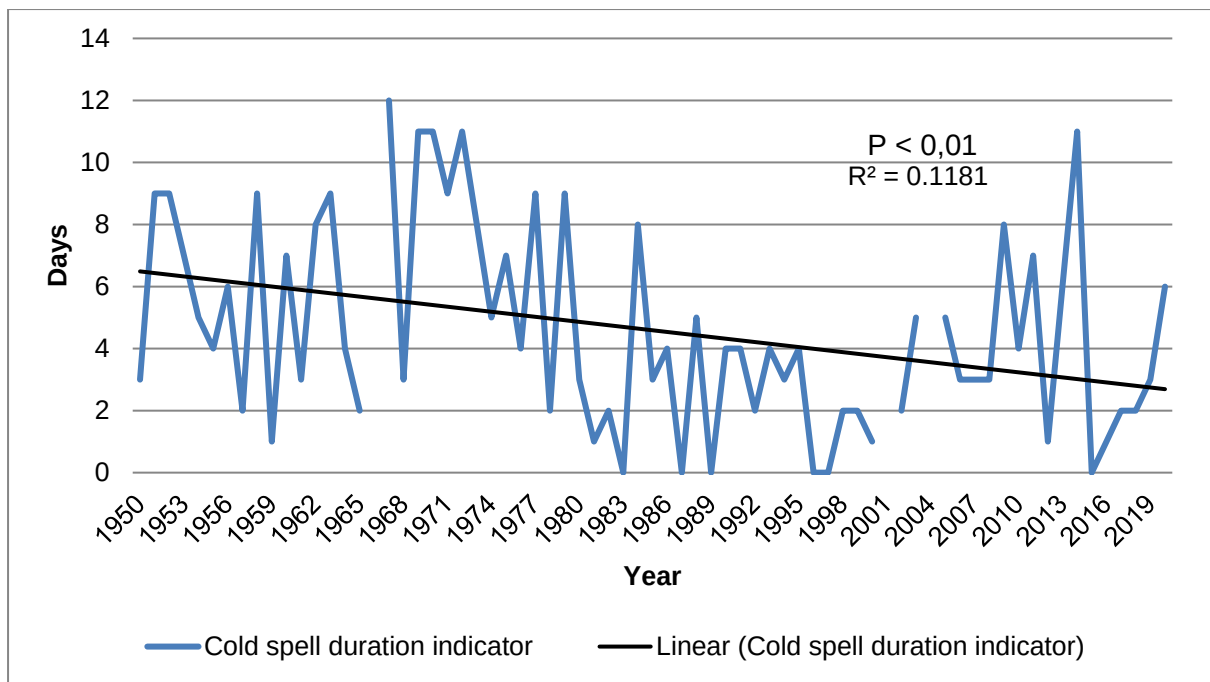


Figure 4.10: Annual count when at least three consecutive days of minimum temperature are less than the 10th percentile (1950 to 2020).



Frost days on Marion Island show a significant decreasing trend at $p < 0.01$ of 14.39 days between 1950 and 2020. The year with highest number of frost days is 1970 with 69 days and the lowest in the period is 2002, with only 26 days recorded to have a temperature lower than 0°C (Fig. 4.11). The graph displays that all years had an amount of frost days greater than 25 and even most had frost days greater than 30 days (Fig. 4.11). Observing the decades, 1960-69 has the highest frost days count with an average of approximately 53.5 days per year with second highest decade being 1970-79 with an average of approximately 50.6 days per year. The decade with the lowest frost day count is 1980-89 with an average of approximately 39.6 days per year. The decadal change is significant and shows a decrease of 1.85 days per decade.

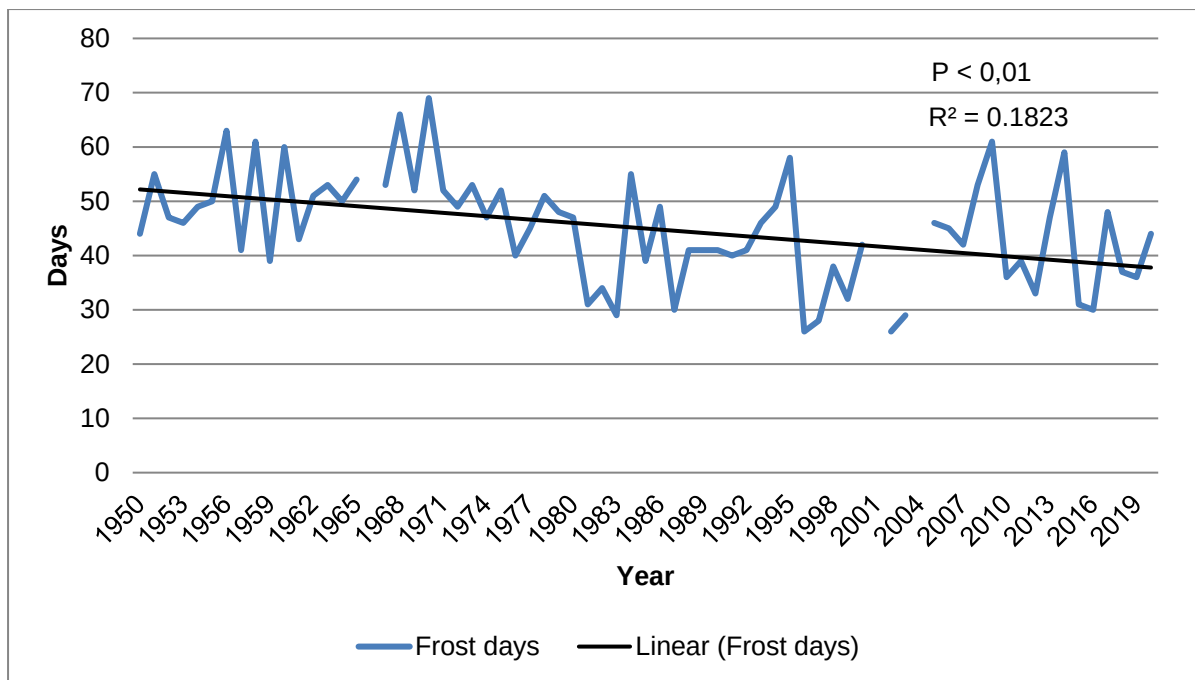


Figure 4.11: Annual count of frost days when temperature is less than 0°C (1950 to 2020).

Summer days show a significant rise of 23.94 days between 1950 with about 32 recorded days and 2020 with 48 days. The summer days index counts the days when the daily maximum temperature was greater than the 90th percentile (12.5°C). The year with the highest number of summer days is 1999 with an annual count of 67 days, followed by 1996 with 61 days; and the lowest is 1968 with a count of 12 days (Fig. 4.12). The decade with the highest summer days is 1990-99 with an average of approximately 53 days per year; and the decade with the lowest of all the decades is 1960-69 with an average of 21 days per year (Table 4.3). The period between 1984 and 2002 had the highest count of summer days especially the 1990s. Decadal change is displaying an increase of 3.08 days per decade.

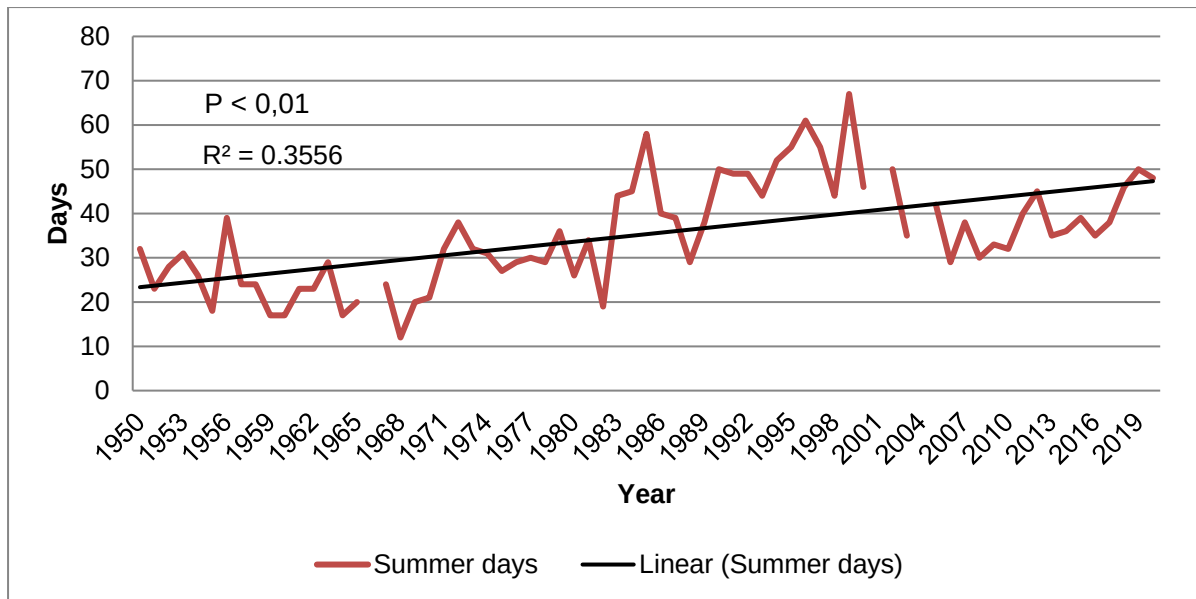


Figure 4.12: Annual count of summer days (1950 to 2020).

“Tropical” nights, as per the index, are on the rise by 22.9 days between 1950 (with 21 days) and 2020 (with 54 days) (significant at $p < 0.01$) (Fig. 4.13). The “tropical” nights index counts the number of days when the daily minimum temperature was greater than the 90th percentile (6.7°C). Much “tropical” nights can be seen between the periods of 1984 to 2000, with 1997-2000 having counts greater than 60. The year with the most “tropical” nights is 1999 with a count of 71 nights; the years with the least amount of 11 nights are 1955, 1969 and 2008. The decade with the most tropical nights is 1990-99 with an average of approximately 55 nights per year with the second highest being 1980-89 with an average of approximately 39 nights per year; the decade with the least is 1960-69 with an average of 18 nights per year (Table 4.3). The decadal change is an increase of 2.95 nights between each decade.

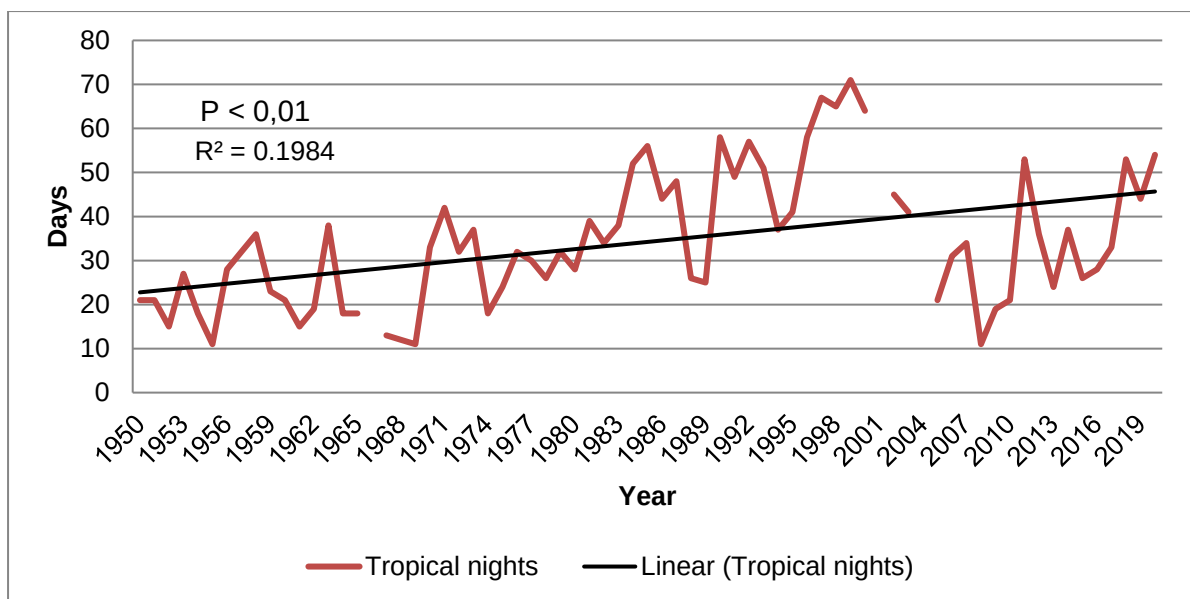


Figure 4.13: The number of annual days when the daily minimum temperature was greater than the 90th percentiles (1950 to 2020).

Table 4.3: Decadal averages for indices based on the daily temperature data. The indices are as follows: Cool Nights (TN10p), Cool Days (TX10p), Warm Nights (TN90p), Warm Days (TX90p), Frost Days (FD0), Summer Days (SU12.5), Tropical Nights (TR6.7), Warm Spell Duration Indicator (WSDI) and Cold Spell Duration Indicator (CSDI).

Decade	TN10p (%)	TX10p (%)	TN90p (%)	TX90p (%)	FD0	SU12.5	TR6.7	WSDI	CSDI
1950-59	11.10	12.66	6.36	7.18	50	26	23	5	6
1960-69	11.17	12.57	5.02	5.63	54	21	18	2	7
1970-79	11.56	10.44	8.38	8.36	51	31	31	3	8
1980-89	8.74	7.95	10.68	10.19	40	37	39	4	3
1990-99	8.44	7.10	15.18	14.41	40	53	55	11	3
2000-09	9.24	9.55	9.10	10.37	43	38	33	7	4
2010-19	8.30	9.37	9.72	10.84	40	40	35.5	3.6	3.7

Monthly Temperature Indices

The following graphs were based on the Expert Team on Climate Change Detection Indices for monthly temperature data. The graphs show the monthly maximum value of daily maximum and minimum temperatures, and the monthly minimum value of the daily maximum and minimum temperatures and the diurnal temperature range. The maximum value of the daily maximum temperature (Max Tmax) for each month displays the highest values for the summer and autumn season (Fig. 4.14). This index calculates the greatest monthly value of the daily maximum temperature for each of the twelve months of the calendar year. The highest daily minimum value is firstly determined for each month for each year and then the greatest value for that month is displayed on the graph. The month of January has a high daily maximum temperature of 23.8°C and the month with the lowest is June with 14.8°C. The seasonal average is as follows: for summer (December - February) its 22.8°C, autumn (March - May) 20.3°C, winter (June - August) 15.5°C, and spring (September - November) 19.2°C.

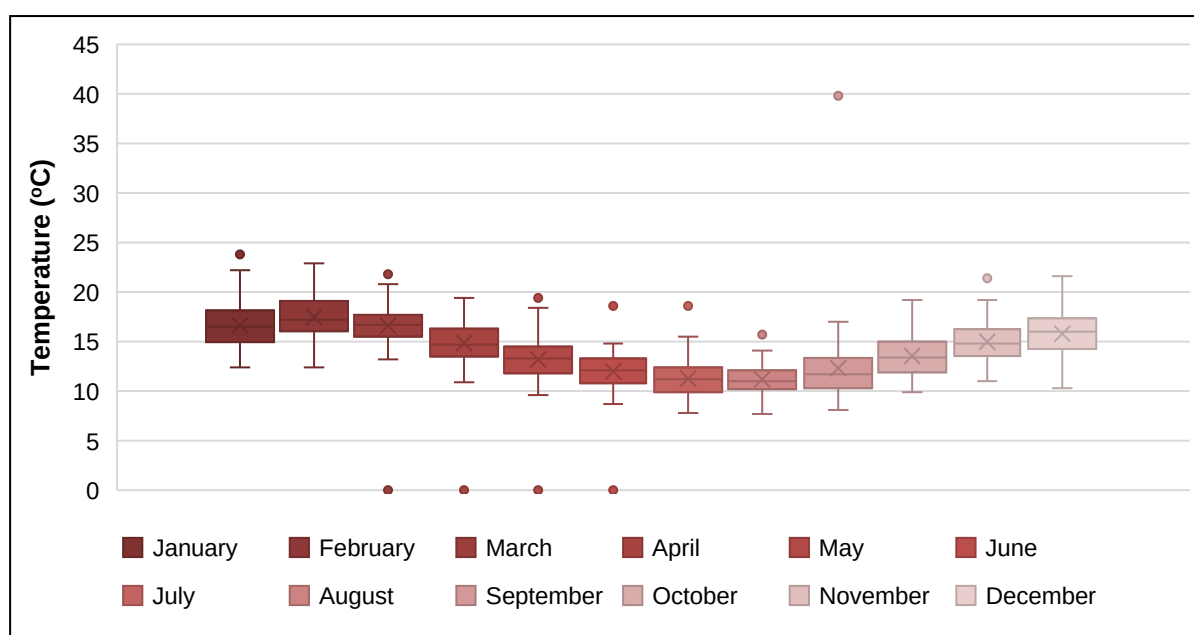


Figure 4.14: The absolute monthly maximum value recorded for each month (1950 to 2020).

The monthly maximum value of minimum temperature (Max Tmin) calculates the highest monthly value of the daily minimum temperature for the twelve months over a calendar year. The highest daily minimum value is determined for each month for each year; then the greatest value for that month is displayed on the graph. The maximum value for the daily minimum temperature displays almost equivalent values with summer and autumn months almost

displaying temperatures within the same range (Fig. 4.15). The month with the highest temperature is February with 11.8°C followed by January with 11.3°C and the lowest being October with 8.7°C. The seasonal average for summer (Dec-Feb) is 11°C, for autumn (Mar-May) 11°C, winter (Jun-Aug) 9°C and for spring (Sept-Nov) is 9.1°C.

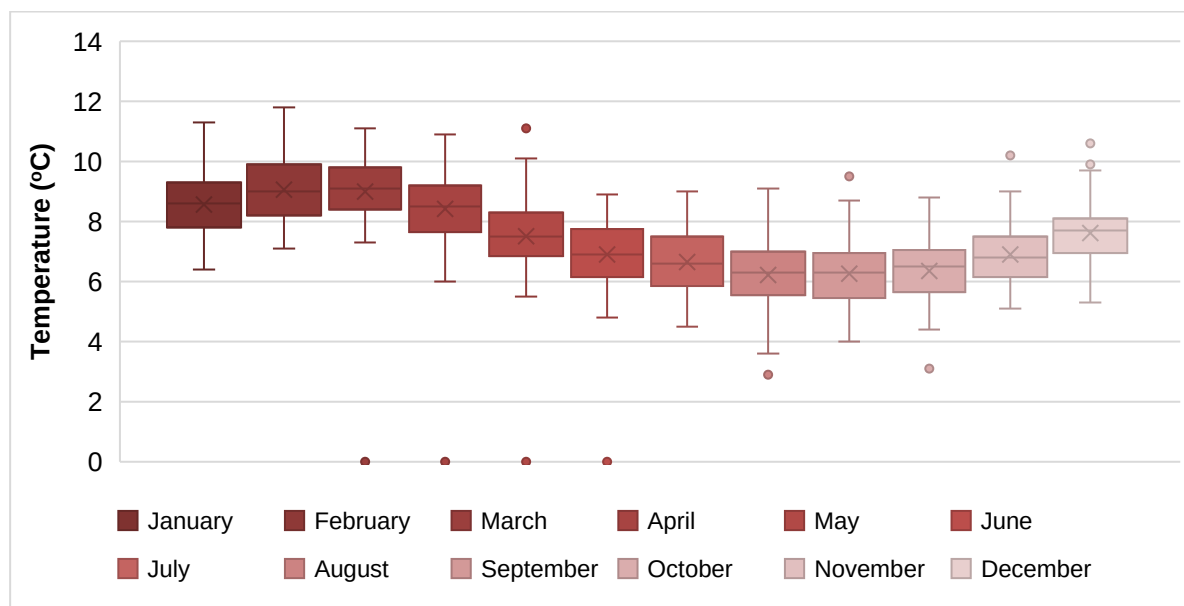


Figure 4.15: The monthly maximum value of the daily minimum temperature (1950 to 2020).

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The monthly minimum value of the daily maximum temperature (Min Tmax) displays values that are both above and below the 0°C mark (Fig. 4.16). This index calculates the lowest monthly value of the daily maximum temperature for each month. The lowest daily minimum value is first determined for each month for each year; then the smallest value for that month is displayed on the graph. January has the highest value with 4.4°C; the months with the lowest value being February, August and September with -0.9°C. February is the only summer month with a value below 0°C. The average seasonal daily minimum-maximum temperature for summer (Dec-Feb) is 2.1°C, for autumn (Mar-May) is 1.6°C, for winter (Jun-Aug) is -0.7°C and for spring (Sept-Nov) is 0.6°C.

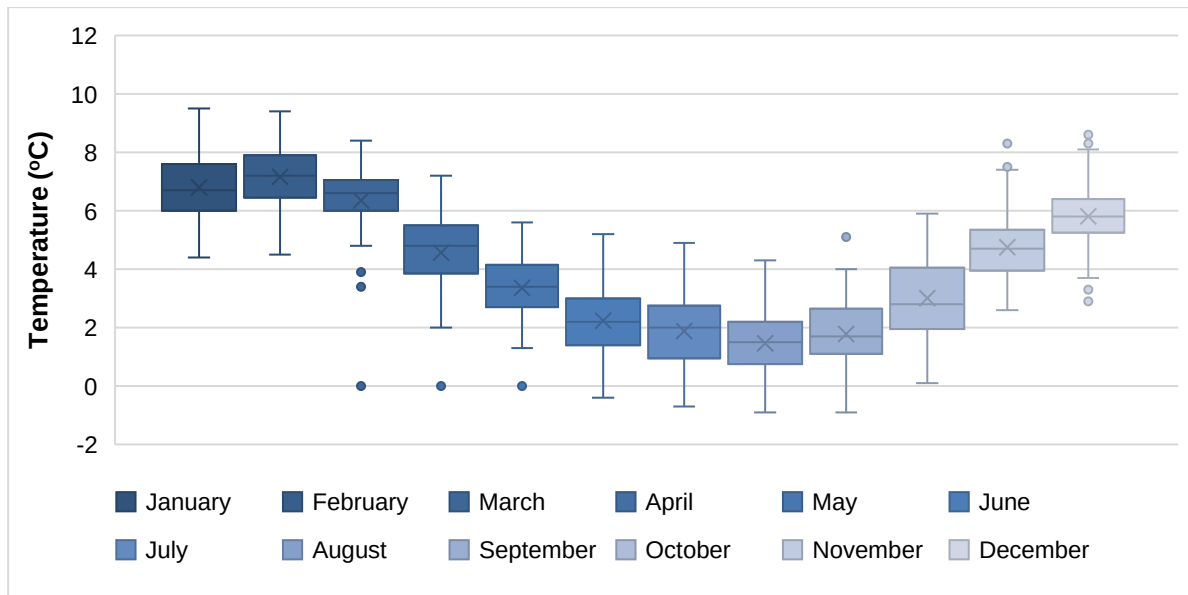


Figure 4.16: The monthly minimum value of the daily maximum temperature (1950 to 2020). The value for April is 0°C.

The minimum value of the daily minimum temperature index (Min Tmin) determines the lowest monthly value of the daily minimum temperature for the annual twelve months. The lowest daily minimum value is determined for each month for each year and then the least value for that month is displayed on the graph. The minimum value of the daily minimum temperature for each month displays values below 0°C (Fig. 4.17), with the highest value being for April with -1.1°C and the lowest being for the month of September with -6.8°C followed by February with a record of -6.5°C. The average seasonal daily minimum-minimum temperature for summer (Dec-Feb) is -3.3°C, for autumn (Mar-May) is -2.1°C, for winter (Jun-Aug) is -5.8°C and for spring (Sept-Nov) is -4.9°C.

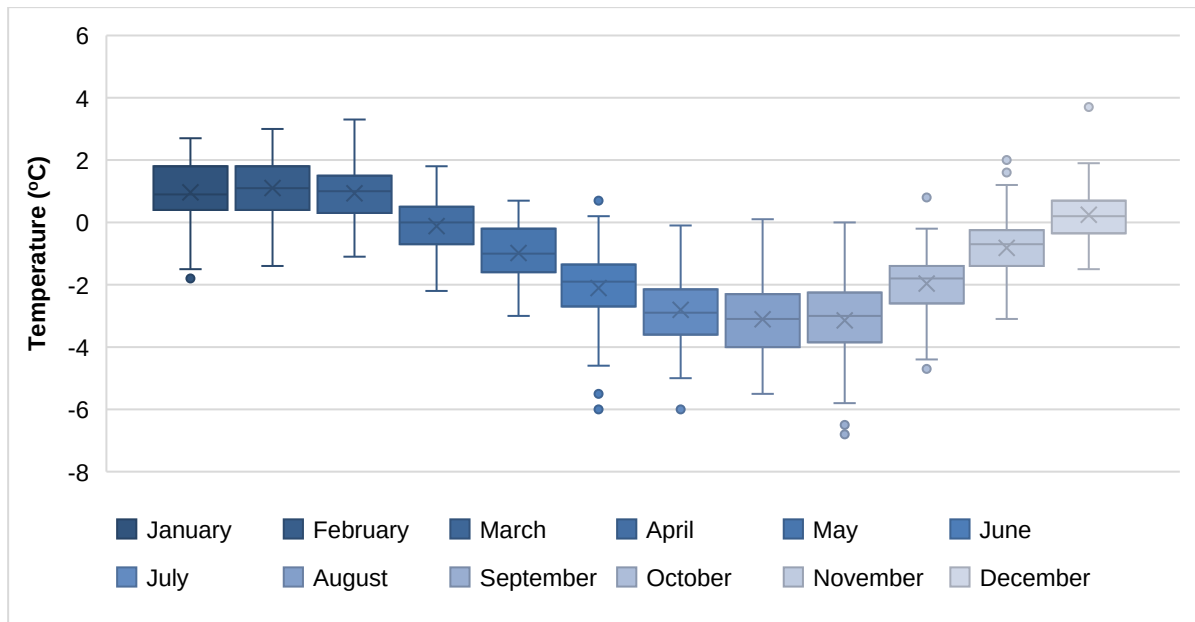


Figure 4.17: The minimum value of the daily minimum temperature (1950 to 2020).

The diurnal temperature range index calculated the monthly average difference between the daily maximum and minimum temperature for all months. The diurnal temperature range displays a high range for the summer season and low for winter, with January having the highest range of 9.2°C and June having the lowest range of 5.8°C (Fig. 4. 18). Seasonal averages for the summer (Dec-Feb) season is 8.1°C; for autumn (Mar-May) it is 6.7°C; winter (Jun-Aug) having the lowest average range of 6.1°C and the spring (Sept-Nov) season with 6.6°C.

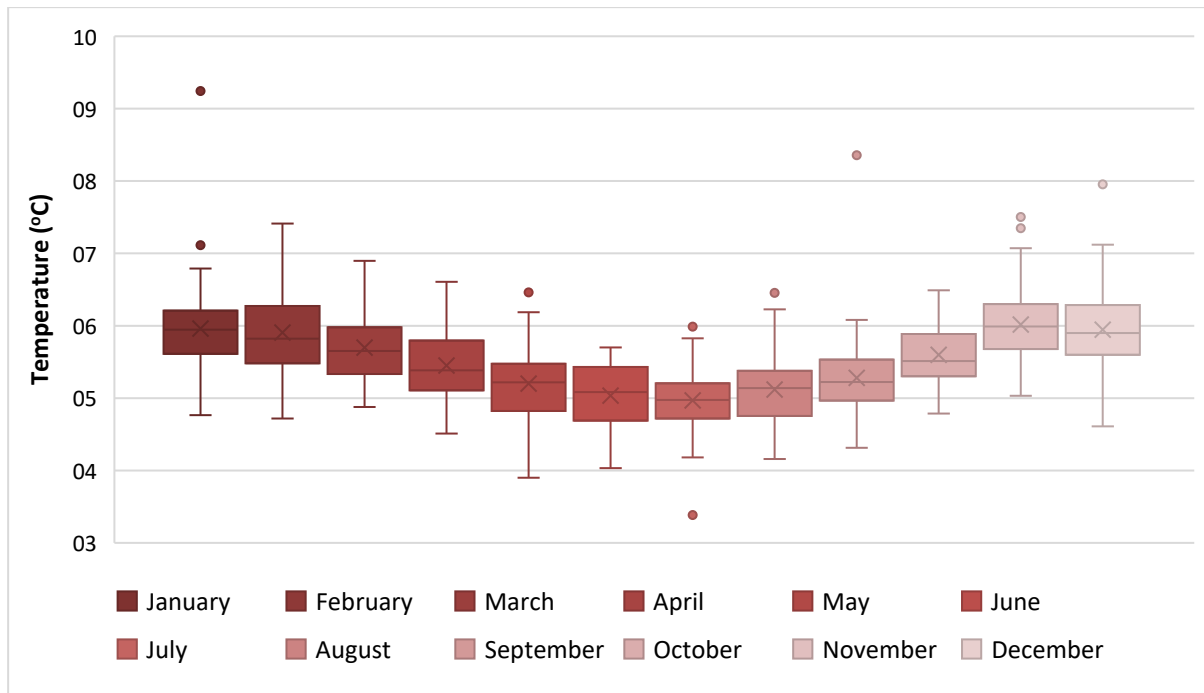


Figure 4.18: The maximum monthly difference in maximum and minimum temperature values (diurnal temperature range) (1950 to 2020).



Extreme Precipitation Indices

The annual total wet-dry precipitation index (PRCPTOT) displays an overall decreasing trend of 1036.14 mm (significant at $p < 0.01$) between 1950 and 2020 (Fig. 4.19). The annual total wet-dry precipitation index sums the total precipitation from days with rainfall greater than or equal to 1 mm. Almost all the years in the 1960s had totals above 2500 mm; most years between 1950 and 1989 had totals above 2000 mm and from the 1990s, almost all had rainfall below 2000 mm. The year with the highest total is 1951 with an annual total of 3097.2 mm and the year with the lowest is 2017 with 1410.5 mm. The decade with the highest average is 1960-69 with an average of approximately 2672.03 mm per year and the second highest being 1950-58 with approximately 2508.31 mm; the decade with the lowest is 2010-19 with approximately 1741.87 mm per year (Table 4.4). Decadal change between each decade is a significant decrease of 133.22 mm/10 years.

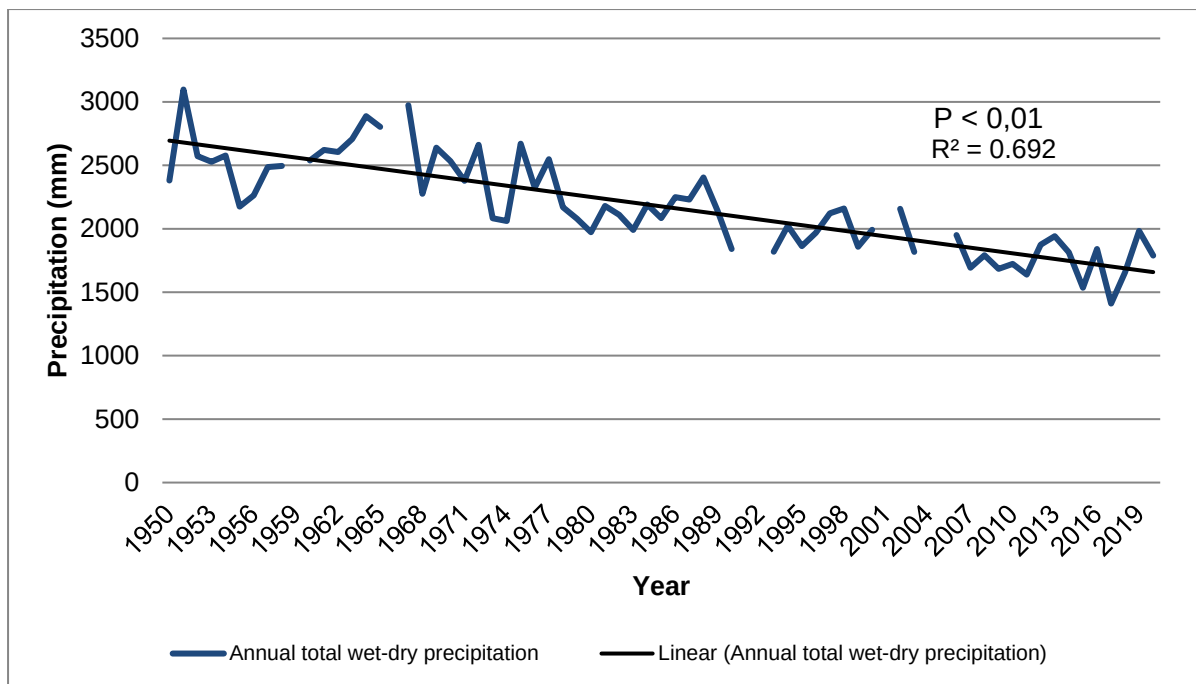
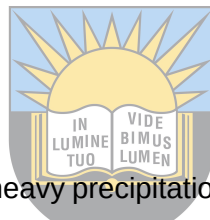


Figure 4.19: Annual total wet-dry precipitation of the total precipitation from days greater or equal to 1 mm (1950 to 2020).



There is a decrease in the number of heavy precipitation days (R10) per annum of 38.97 days/year ($p < 0.01$) between 1950 and 2020 (Fig. 4.20). The heavy precipitation days index is the annual count of the number of times daily precipitation was greater than or equal to 10 mm. The year with the heaviest precipitation days is 1962 with 102 days followed by 1951 with 101 days; the year with the least in this period is 2017 with only 36 days. Observing the decadal trend, the highest average is for the decade of 1960-69 with an average of approximately 93 days per year followed by 1950-58 with approximately 87 days per year. The lowest average is for the decade 2010-2019 with approximately 56 days per year (Table 4.4). Decadal change is significant at 5.01 days between each decade.

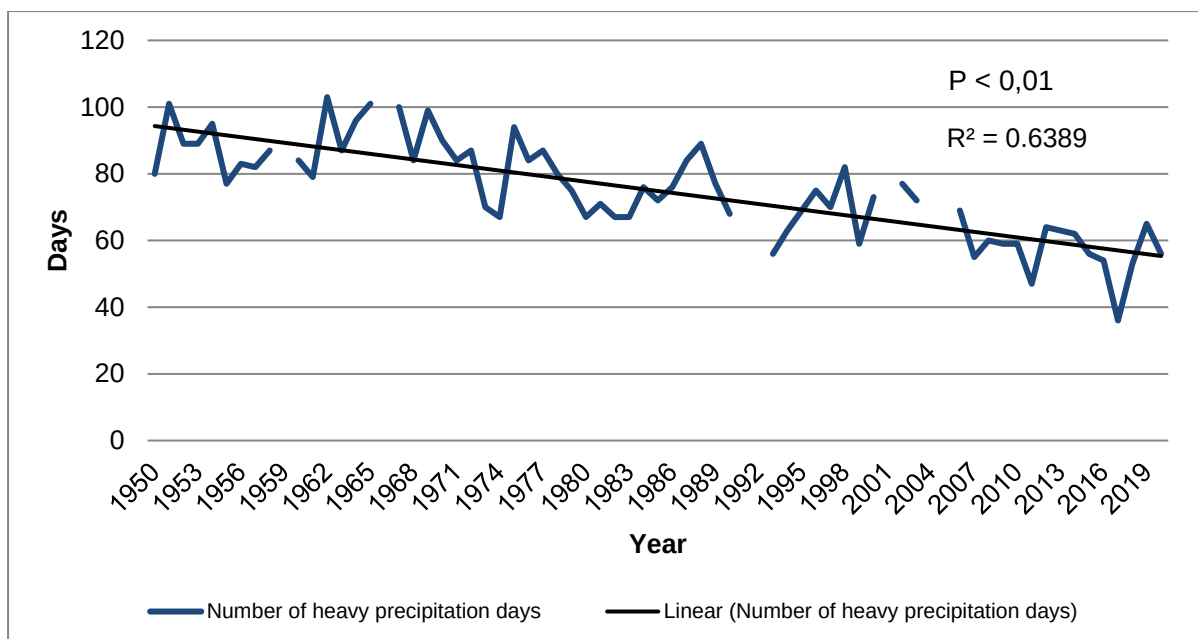
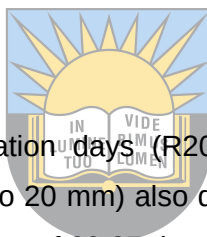


Figure 4.20: Annual count of days when precipitation is greater than or equal to 10 mm (1950 to 2020) – Heavy precipitation days.



The number of very heavy precipitation days (R20) (annual count of days when daily precipitation is greater than or equal to 20 mm) also displays a similar decreasing trend that is significant at $p < 0.01$ with a decrease of 20.87 days between 1950 and 2020. The number of heavy precipitation days with the highest value is 1964 with 52 days and with 2017 being the year with the least number of very heavy precipitation days (12 days) (Fig. 4.21). The very heavy precipitation days index is the annual count of the number of times the daily rainfall is greater than or equal to 20 mm. The decade with the highest average is 1960-69 with approximately 36 days per year followed by 1950-58 with approximately 33 days per year with very heavy rainfall. The lowest is the decade 2010-19 with an average of approximately 17.5 days per year (Table 4.4). Decadal change is a significant decrease of 2.68 days per decade.

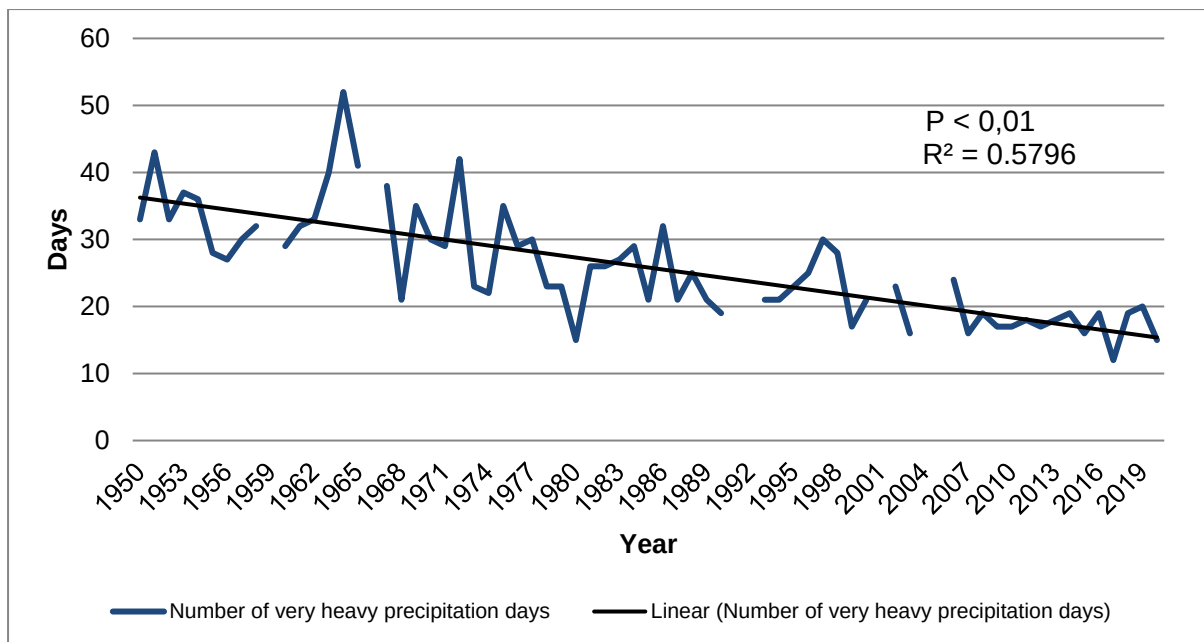


Figure 4.21: Annual count of days when daily precipitation is greater than or equal to 20 mm (1950 to 2020) – Very heavy precipitation days.



The sum of very wet days (R95p) shows a significant trend with a decline of 559.5 mm between 1950 and 2020 ($p < 0.01$) (Fig. 4.22). The very wet days index sums the annual precipitation when daily rainfall is greater than the 95th percentile (26.3 mm). The years with the highest sum of very wet days is 1951 and 1963 both having 1222.4 mm, with the second highest being 1964 with 1205.3 mm. The year with the lowest sum is 2017 with 147.3 mm. The decade with the highest average of the sum of very wet days is 1960-69 with approximately 895.8 mm per year followed by 1950-58 having approximately 709.5 mm per year; the decade with the lowest average is 2010-19 with approximately 348.0 mm per year (Table 4.4). Decadal change shows a significant decline of 71.93 mm between each decade.

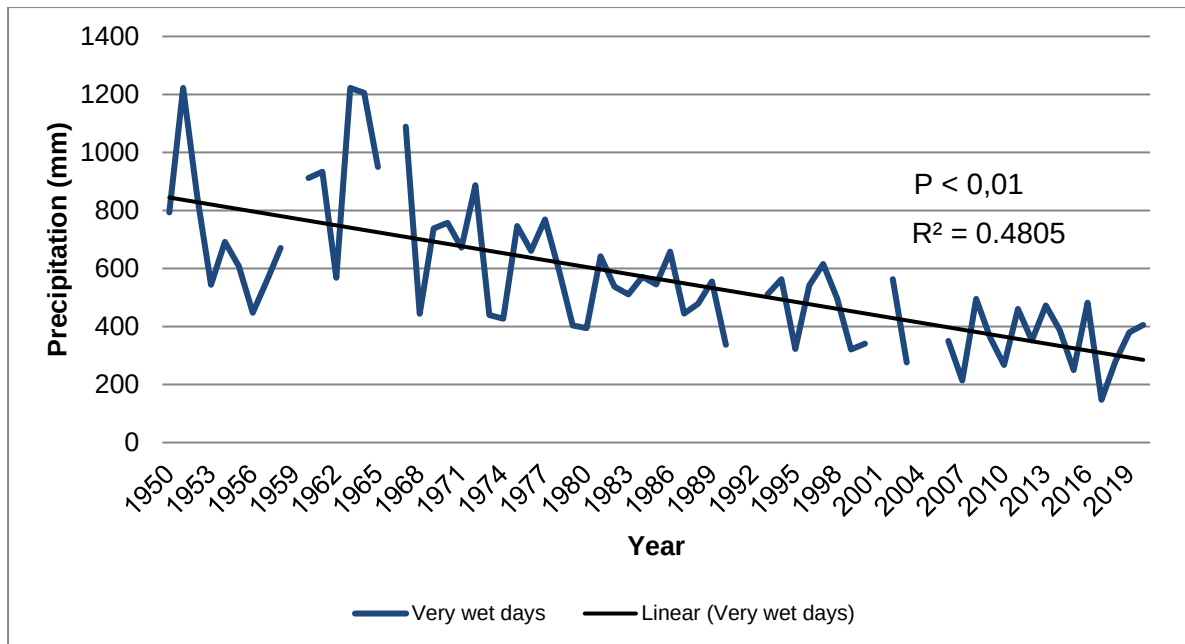


Figure 4.22: The sum of the annual precipitation when it was greater than the 95th percentile (26.3 mm) (1950 to 2020) – Very wet days.

The sum of extremely wet days (R99p) displays a similar declining trend as the very wet days, with a significant decline of 203.22 mm between 1950 and 2020 ($p < 0.01$) (Fig. 4.23). This index sums the annual precipitation for days when the daily rainfall is greater than the 99th percentile (46.5 mm). The year with the highest recorded sum is 1951 with approximately 626.5 mm and the second highest being 1961 with approximately 556.5 mm; the lowest year is 2010 and 2017 as there are no recorded extremely wet days. Considering the decadal trends, 1960-69 has the greatest average of all the decades, with approximately 315.0 mm per year, followed by 1950-58 with approximately 227.4 mm per year. The lowest average is for the last decade in the period (2010-19) with approximately 93.4 mm per year (Table 4.4). The decadal change is significant at 26.1 mm between each decade.

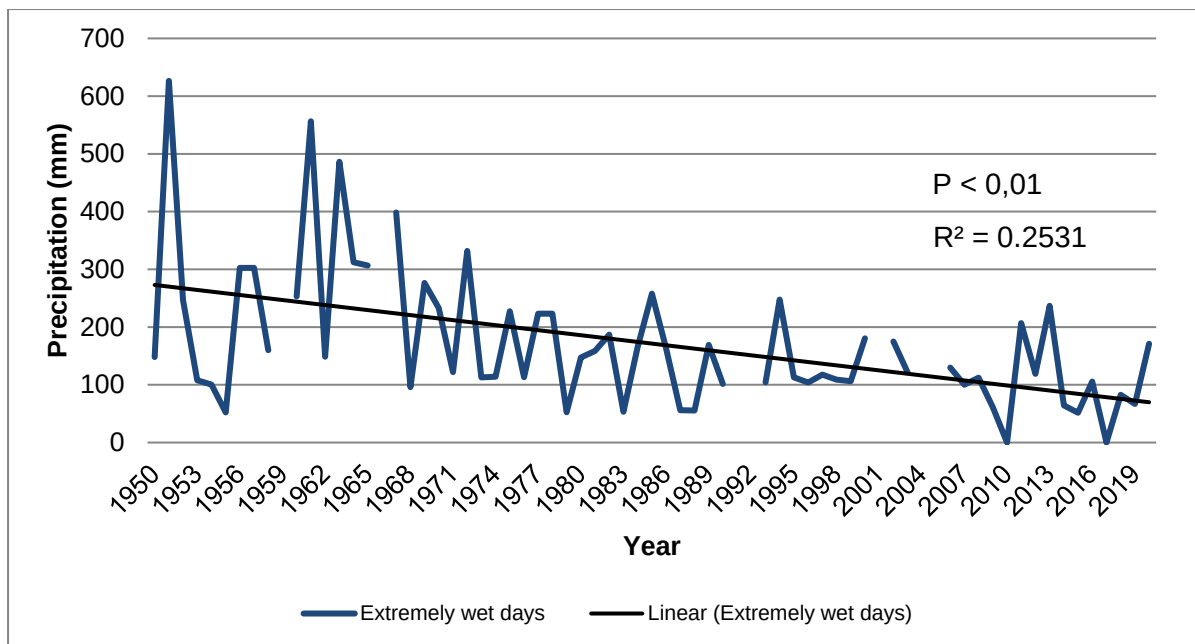


Figure 4.23: The sum of the annual daily precipitation when it was greater than the 99th percentile (46.5 mm) (1950 to 2020) – Extremely wet days.

The consecutive wet days index (CWD) shows that the number of consecutive wet days is decreasing on Marion Island by 8.05 days ($p < 0.01$) between the 71-year period (Fig. 4.24). The consecutive wet days index shows the highest number of consecutive days with precipitation greater than or equally 1 mm for that year. The threshold for this index was at least five consecutive days with rainfall and then the highest consecutive count for that year was recorded. The year with the highest number of consecutive wet days is 1975 with 27 consecutive wet days (from the 14th of May to the 9th of June); followed by 1990 which has 25 (from the 4th of June to the 28th of June) consecutive wet days. The year with the least number of consecutive days is 2008 with 8 consecutive wet days. From the decadal averages, the 1950s and 1960s are the highest with approximately 17 days of consecutive rainfall per year in each decade; and the lowest is 2000-09 with approximately 10.6 days of consecutive rainfall per year (Table 4.4). The decadal change is significant with 1.04 days for each decade.

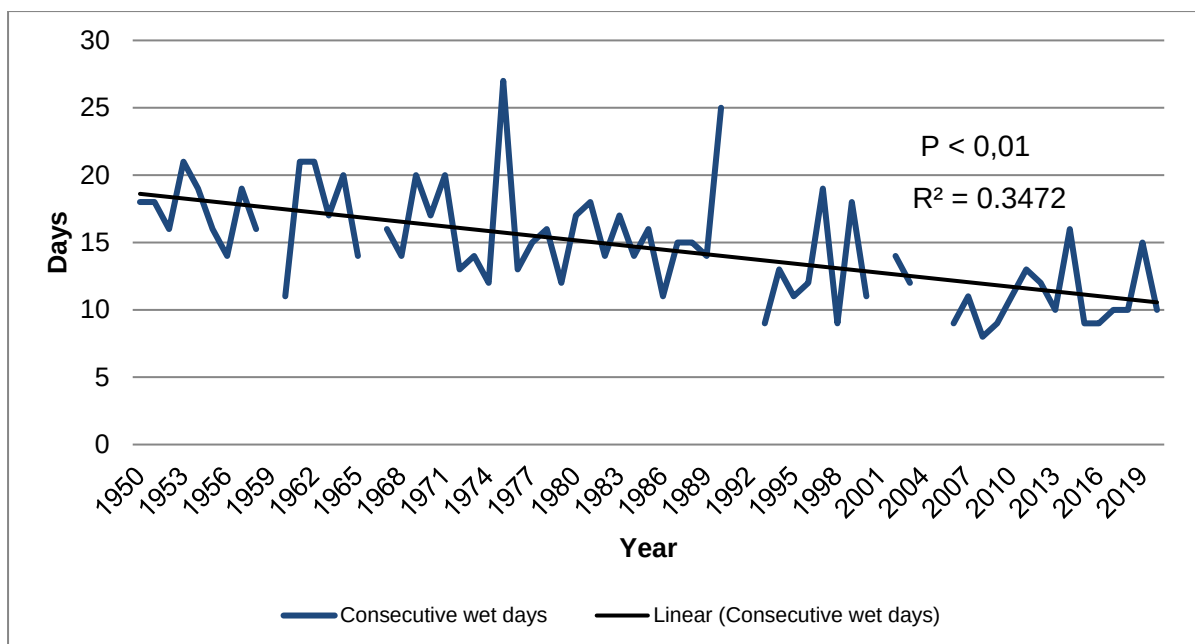


Figure 4.24: The highest number of consecutive days with precipitation greater than or equal to 1mm for the year (1950 to 2020) – Consecutive wet days.

The consecutive dry days index (CDD) indicates an increasing trend in the consecutive number of dry days on the island (3.22 days; $p < 0.01$), with the highest number being in the end of the period of this study (Fig. 4.25). The consecutive dry days index shows the highest number of consecutive days with precipitation less than 1mm for a certain year, with the threshold for this being at least three days of consecutive dry days, with the highest count being recorded. The year with the highest count of consecutive dry days is 2009 with 14 days (23rd of April to 6th of May), followed by 2012 with 13 days (13th to the 25th of October) of no rainfall (less than 1 mm). The years with the lowest values during the study period are 1952, 1954, 1957, 1962, 1969, 1987 and 1999 with the highest count being four consecutive dry days. The year 1953 has a count of 11 consecutive dry days (from 22nd of February to 4th of March), which is the highest in that decade, and the highest until it rises to 12 days in 1995 (from 17th to 28th of December). From the decadal averages, the highest is 2010-19 with approximately nine consecutive dry days per year and the 1950s, 1960s, 1970s and 1980s decades have the same average of approximately six consecutive dry days per year each (Table 4.4). Decadal change displays a significant 0.41 day increase per decade.

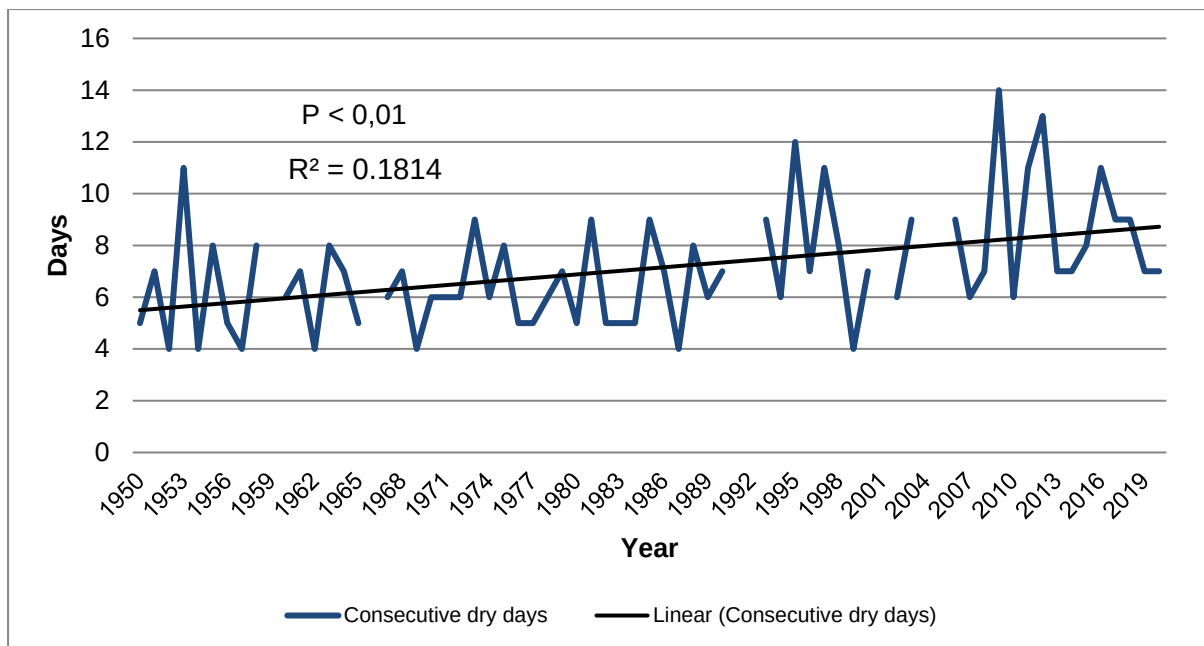
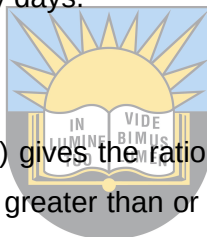


Figure 4.25: The highest number of consecutive days where rainfall was greater 1mm in the year (1950 to 2020) – Consecutive dry days.



The simple daily intensity index (SDII) gives the ratio of the annual total precipitation to the number of wet days with precipitation greater than or equal to 1 mm. The overall trend is an insignificant increase of 17.7 mm/day ($p > 0.05$) with a gentle increasing slope (Fig. 4.26). The year with the highest annual total precipitation to the number of wet days ratio is 1998 with 239.9 mm/day followed by 1960 with 230.7 mm; and the year with the lowest is 1990 with 73.6 mm/day.

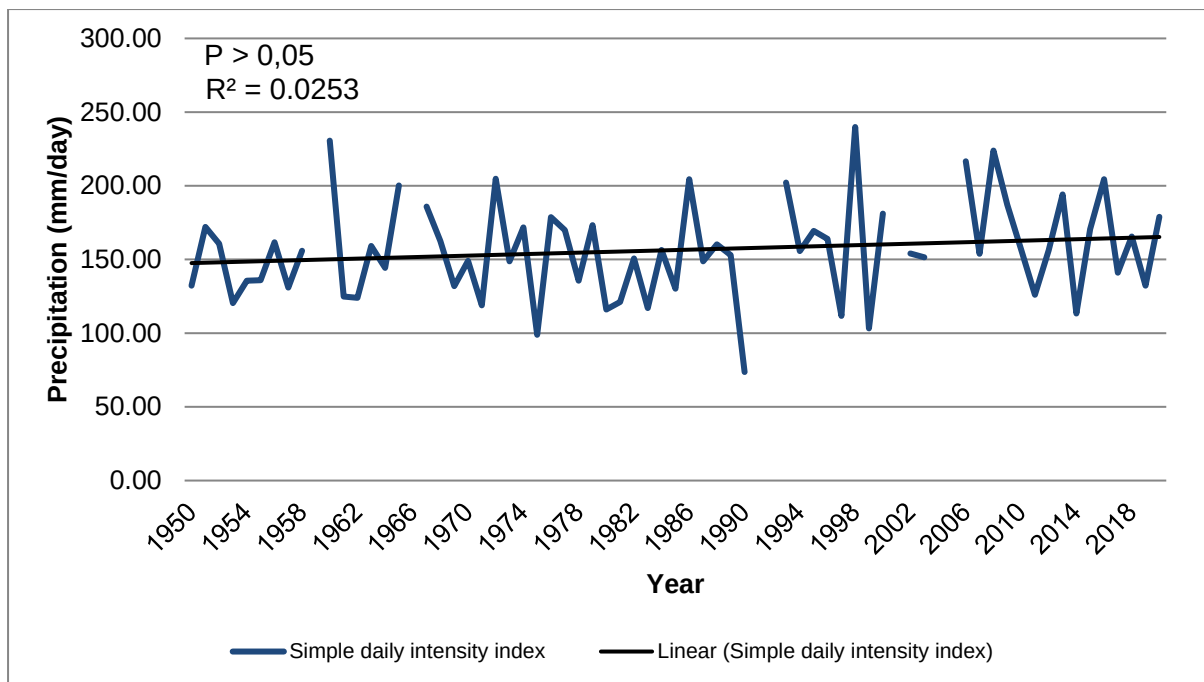


Figure 4.26: The ratio of annual total precipitation to the number of wet days greater than or equal to 1 mm (1950 to 2020) – Simple daily intensity index.



Monthly Precipitation Indices

The following graphs were based on the Expert Team on Climate Change Detection Indices for monthly rainfall data. The graphs show the monthly maximum 1-day and the maximum 5-day consecutive precipitation amount that was recorded for each month. The maximum 1-day precipitation was looking at the highest single day precipitation amount for each of the months in a year. It calculates the maximum 1-day precipitation value for each month in the year and then determines the greatest of these for that particular month. The maximum 1-day precipitation (RX1day) amount is highest for the month of April with a value of 120.7 mm followed by the month of February with 111.4 mm (Fig. 4.27). The month with the lowest rainfall amount is August with maximum 1-day amount of 56 mm for the whole period. The seasonal averages show the summer and autumn season to have averages not too far apart, with 89.3 mm for summer (Dec-Feb) and 88.2 mm for autumn (Mar-May). Winter (Jun-Aug) has an average of 65.6 mm and spring (Sept-Nov) with the highest average of all of 90.5 mm.

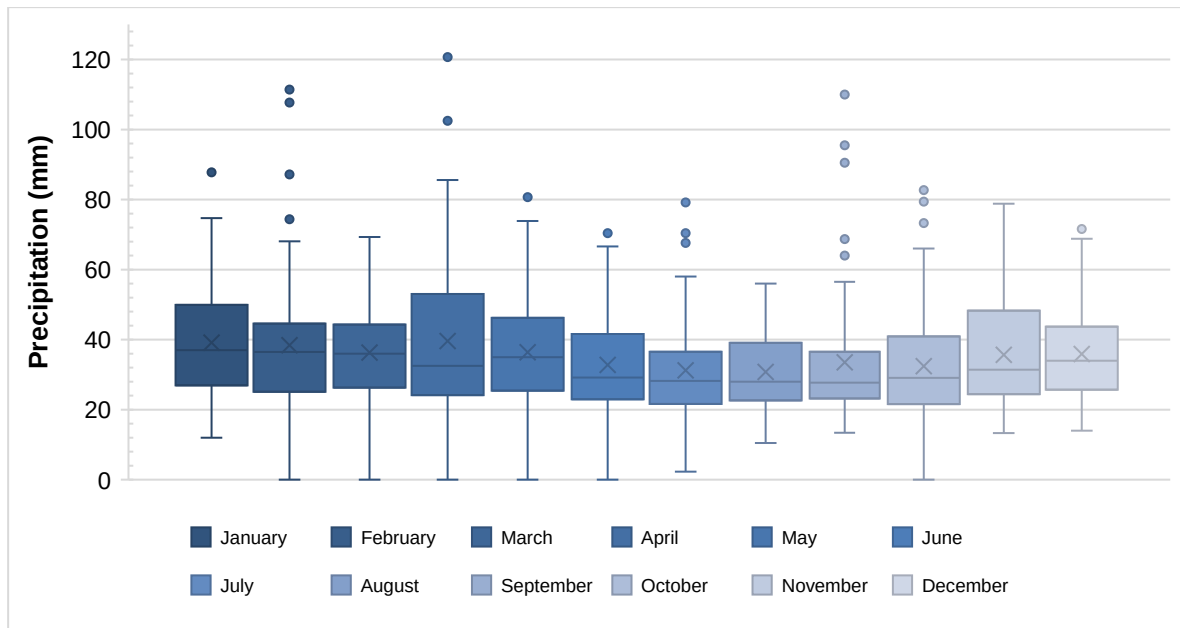
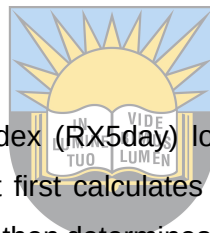


Figure 4.27: The monthly maximum value (mm) of the 1-day precipitation amount (1950 to 2020).



The maximum 5-day precipitation index (RX5day) looks at the highest 5-day consecutive precipitation value for each month. It first calculates the highest 5-day consecutive rainfall value for each month for that year and then determines the greatest value for a specific month. The maximum 5-day precipitation amount for each month displays a high amount for the months of April, January, February and June with over 160 mm for the consecutive days, with the month of April having the highest rainfall (Fig. 4.28). The lowest record total for the year is August with 99 mm. The summer season (Dec-Feb) has the highest rainfall with an average of 158.1 mm followed by autumn (Mar-May) with 151.3 mm. The winter season (Jun-Aug) is 123.6 mm and the spring season (Sep-Nov) has the lowest with 117.3 mm.

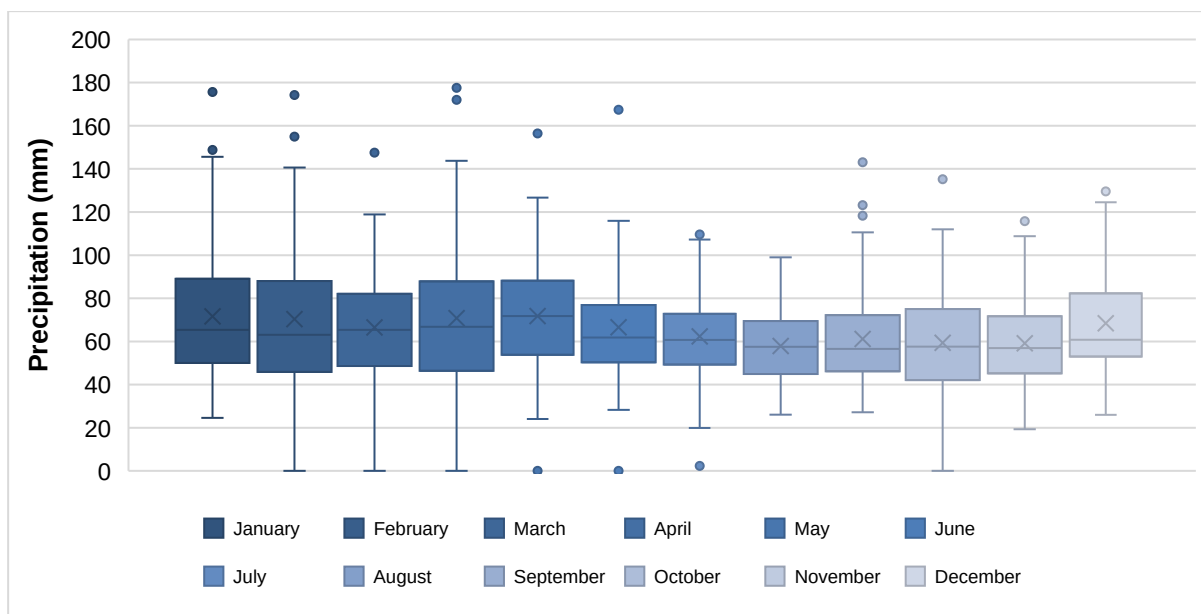


Figure 4.28: The maximum monthly value (mm) of the consecutive 5-day precipitation amount (1950 to 2020).



Table 4.4: The Decadal averages for indices based on the precipitation data. The indices are as follows: Simple Daily Intensity Index (SDII), Number of Heavy Precipitation Days (R10), Number of Very Heavy Precipitation Days (R20), Consecutive Dry Days (CDD), Consecutive Wet Days (CWD), Very Wet Days (R95p), Extremely Wet Days (R99p) and Annual Total Wet-Dry Precipitation (PRCPTOT). *University of Port Harcourt Together in Excellence*

Decade	SDII	R10	R20	CDD	CWD	R95p	R99p	PRCPTOT
1950-1959	145.1	87	33	6.2	17.4	709.5	227.4	2508.3
1960-1969	162.6	93	36	6.0	17.1	895.8	315	2672
1970-1979	155	82	29	6.4	15.9	635.7	175.3	2350.8
1980-1989	145.8	75	24	6.3	15.1	533.7	141.4	2155.5
1990-1999	152.5	68	23	8.0	14.5	463.7	125.4	1956.8
2000-2009	181.2	66	19	8.3	10.6	371.6	125.8	1869.3
2010-2019	158.3	56	17.5	8.8	11.5	348	93.4	1741.9

Table 4.5: Seasonal averages for each monthly index. The Indices are as follows: Monthly Absolute Maximum Temperature (TXx), Monthly Absolute Minimum Temperature (TXn), Monthly Least Maximum Temperature (TNx), Monthly Least Minimum Temperature (TNn), Diurnal Temperature Range (DTR), Maximum 1-day Precipitation (1-day) and Maximum 5-day Precipitation (5-day).

Season	TXx	TXn	TNx	TNn	DTR	1-Day	5-Day
DJF	22.8	11.0	2.1	-3.3	8.1	89.3	158.1
MAM	20.3	11.0	1.6	-2.1	6.7	88.2	151.3
JJA	15.5	9.0	-0.7	-5.8	6.1	65.6	123.6
SON	19.2	9.1	0.6	-4.9	6.6	90.5	117.3



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Chapter 5 - Discussion

Temperature Trends on Marion Island (1950-2020): Possible Impact on the Landscape and Ecosystem Processes

Marion Island is experiencing a warming trend in air temperatures. The mean annual air temperature on the island has increased over the years and the island is increasingly becoming warmer than it was in the 1950s and 1960s. There are noteworthy increases ($p < 0.01$) in both the annual average maximum and mean annual minimum temperatures recorded on Marion Island, currently standing at 10.9°C and 1.4°C, respectively. The previously identified upward trend in mean annual air temperature for Marion Island, as documented in earlier studies (Le Roux, 2008; Smith, 2002; Smith & Steenkamp, 1990), persists and exhibits a statistically significant rise from the early 2000s to 2020, amounting to a 1.2°C increase ($p < 0.01$). Consequently, the overall trend in warm air temperature from 1950 to 2020 displays a consistent increase. An observable temperature rise occurred between the 1950s and 1990s (Le Roux & McGeoch, 2008), consistent with climatic records from other sub-Antarctic islands during much of the latter half of the 20th century (Jacka et al., 2004; Pendlebury & Barnes-Keoghan, 2007). In the early 2000s, the annual mean temperature recorded on Marion Island was 5.6°C (Smith, 2004), which has since climbed to 5.9°C. Although the 1990s remain the warmest decade on record (see Table 4.1), the rate of warming on Marion Island has accelerated in the 21st century. Temperature data from other sub-Antarctic islands, including Crozet, Kerguelen, Macquarie, South Georgia, Campbell, and Auckland, also exhibit this increasing trend since 2000 (Nel et al., 2023). Since the beginning of the 20th century, these sub-Antarctic islands, including Marion, have experienced a warming trend ranging from 2.3 to 4.7°C per century, surpassing the 2 to 3°C warming projected for the region by 2080-2099 under the A2 emissions scenario (Meehl et al., 2007) and falling within the projected change in surface air temperature (2-3°C) for the sub-Antarctic region by the end of the 21st century (2081-2100) under the highest baseline emissions scenario RCP8.5 (IPCC, 2014) (Nel et al., 2023).

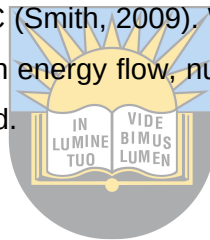
A correlation has been identified between sea surface temperature and air temperature in during the 1960s to 1990s where it was noticed that air temperature increases mirrored mirroring the rising trend in sea surface temperatures (Smith & Steenkamp, 1990; Smith, 2002). It is, therefore, worth considering whether the sea surface temperature recorded at the island also increased post early 2000s as air temperatures increased. Previous studies done on sea surface temperature and air surface temperature correlations at the Prince Edwards Islands established that the sea surface and air temperatures were rising at a significant rate

at 1.4°C and 1.2°C between 1949 and 1998 (Melice et al., 2003; Rouault et al., 2005; Le Roux & McGeoch, 2008). A recent study that from 1993 to 2016 showed that the sea surface temperatures are still rising, however not at the rate mentioned by Melice et al (2003) (see Toolsee et al., 2021; Toolsee, 2022). A meridional gradient was seen for sea surface temperature throughout the year where temperatures that were higher than 6°C were predominantly towards the north and lower than 6°C were common on the south of the Prince Edward Islands (Toolsee et al., 2021). In addition, the sea surface temperatures showed less variability (smaller standard deviations) in the northern region of the islands throughout the year, compared to the southern region where the standard deviation was significantly larger (Toolsee et al., 2021). This shows that there is still an existing correlation between sea surface and air temperature.

Daily maximum and minimum temperatures also show a continued increasing trend from the 1990s and early 2000s (Le Roux, 2008; Smith & Steenkamp, 1990). These also increased by a 1°C rise in over four decades (1950-1990) (Le Roux & McGeoch, 2008) and from the results of this study, they continue to display an increase from the early 2000s onwards (currently standing at 10.9°C and 1.4°C; $p < 0.01$). This observation shows that the overall climate of the island continues to grow significantly warmer than in previous years and from the linear extrapolation done by Nel et al. (2023), based on the current rate of warming taking place from the 2000s onwards on Marion Island, the mean annual air temperature for Marion is predicted to reach 7.2°C by 2050.

The data show that daily extremes in temperature and precipitation are common on Marion Island since the 1950s but the trends show that their intensity and frequency are gradually increasing since the late 1900s and early 2000s (especially trends of warming and drying). In terms of temperature, there is a growing trend in the number of days that are greater than the 90th percentiles of daily maximum (12.5°C) and minimum (6.7°C) temperatures. This is seen by a rising trend of warm days and nights by 6.55% and 6.27% (both $p < 0.01$), respectively. In addition, there is a decrease in days less than the 10th percentiles of daily maximum (4.8°C) and minimum (-0.3°C) temperatures as the percentages of annual cold days and nights are decreasing by 4.66% and 3.58% (both $p < 0.01$), respectively. The occurrence of warm spells has also risen throughout the study period (3.94 days trend; $p < 0.05$) and the number of cold spell occurrences indicate a decreasing trend (3.79 days; $p < 0.01$). Hot days and nights are becoming more common as well (especially since 2000) and all indications are that it will

continue into the future. The number of summer days (23.94 days; $p < 0.01$) and tropical nights (22.9 days; $p < 0.01$) have also risen. The indices indicate a significant rise in days and nights greater than the 90th percentiles in daily maximum and minimum temperatures. Ecologically, the warming temperatures will influence the soil nutrient cycle on the island (Smith, 2004). Warmer temperatures can also lead to a longer growing season, which in turn increases the primary production of the island's lowland plant communities (Smith, 2008). This will mean that more organic matter will be produced which can enhance the nutrient cycle as this plant material is broken down and the nutrients are returned to the soil. Nutrient availability is another factor where the availability and cycling of nutrients in an ecosystem are closely tied to temperature (Smith, 2004; Smith, 2008). Warmer temperatures can speed up the decomposition of organic matter, making more nutrients available for plant uptake (Smith, 2008). The spatial variability of plant nutrient concentrations on the island can be influenced by temperature where warmer areas may have different nutrient concentrations compared to cooler areas, thus affecting the overall nutrient cycling at the ecosystem level (Rossouw, 2014). Lastly, Marion Island possesses a tundra-type (polar desert) biome, where the average annual air temperature is close to 0°C (Smith, 2009). Warmer temperatures could potentially alter this biome, leading to changes in energy flow, nutrient cycling and ultimately ecological succession of this section of the island.



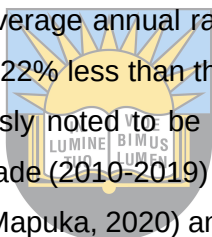
The annual number of frost days is experiencing a significant decline, with the current trend indicating a decrease of 14.39 days ($p < 0.01$). Soil frost and needle ice formation represent crucial geomorphic processes across numerous sub-Antarctic islands, including Marion Island (Nel et al., 2020). Soil frost profoundly affects various keystone species and small-scale geomorphic processes within the fellfield habitat. Moreover, rising air temperatures are likely to alter ground thermal dynamics, potentially impacting the frequency and intensity of needle ice growth, the depth of diurnal and seasonal frost, as well as sediment movement and cycling (Nel & Boelhouwers, 2014). With the continued correlation between air temperatures and surface temperatures (Nel et al., 2021), a decline in frost days in the air will certainly indicate a decline in soil frost and soil frost processes on Marion Island with consequences to important geomorphic and ecosystem processes. This will lead to a decrease in landscape complexity, resilience in sediment erosion and accumulation and associated landform development; decrease in soil aeration and drainage; however, it will lead to an increase in plant species biodiversity (Nel & Boelhouwers, 2014). For instance, needle ice helps in maintaining *Azorella selago* populations by increasing seedling mortality which reduces the competition for other plant species. The decrease of soil frost processes will lessen the seedling mortality rate

therefore leading to the expansion of the *Azorella* population. This will also lead to more species diversity in the polar biome of the island as warm temperatures will create favourable conditions for growth. The rising of temperatures on Marion Island are expected to accelerate the litter decomposition which will lead to an increased nutrient release and plant growth. Warming air temperatures in the sub-Antarctic region is posing implications on landscape and ecosystem processes (Nel et al., 2023) and with daily air temperature extremes on the rise, it means that these landscape and ecological changes will become more frequent and intense in the near future.

The existing record of warm years and daily maximum and minimum decadal averages indicates an increasing decadal trend pre-2000 (Le Roux & McGeoch, 2008). The significant increase in daily minimum and maximum temperatures measured here (1950-2020) indicate a significant change in diurnal air temperatures on the island with possible landscape process implications. As mentioned, Marion Island is a periglacial environment where diurnal landscape processes dominate (Nel et al., 2012). In a diurnal periglacial environment (like Marion Island), annual or seasonal scale measurements are ineffective in understanding climate/surface interactions (Nel et al., 2009) and diurnal scale temperature variability drives surface temperatures and dynamics (Nel, 2012). As diurnal air temperatures and warm day and night percentages increases this could limit soil frost activity and thereby alter the landscape dynamics and processes on Marion Island, especially during the summer season. Soil frost processes are linked to sediment transportation. The climate of the sub-Antarctic (low annual temperature ranges, high cloudiness and precipitation) results in high frequency short duration freeze-thaw events which superficially penetrate the soil (Boelhouwers et al., 2003). This results in needle ice induced frost creep that predominantly drive sediment transportation in scoria areas on the island (Holness, 2004). Soil frost occurrences, particularly during summer, are heavily influenced by the circulation patterns of Antarctic air masses. The duration and intensity of soil frost cycles on Marion Island are intricately linked to these post-cyclonic Antarctic air mass circulations (Nel, 2012). Consequently, as daily air temperatures rise and extreme summer conditions become more frequent, the dynamics of soil frost, including their duration and intensity, are expected to be affected on Marion Island. This, in turn, could have implications for sediment transportation processes.

Precipitation Trends on Marion Island (1950-2020)

Observations of precipitation on Marion Island show a significant decrease during the recording period, especially after the turn of the century. Average decadal rainfall measured on the island was 2535 mm in the 1950s but it decreased to 1770 mm in the 2010-2019 period. From linear regression the trend line displays a statistically significant decrease of 1042.3 mm (significant at $p < 0.01$) over the recording period. Previous studies on yearly, monthly and hourly rainfall events and totals measured on Marion Island all testified to the gradual drying conditions present at the island and in the region (Smith & Steenkamp, 1990; Smith, 2002; Hedding & Greve, 2018; Le Roux, 2008; Mapuka, 2020). Beginning from 1949 to 2003, annual rainfall, average rainfall event size and the largest rainfall event decreased while variability in daily rainfall increased (Le Roux & McGeoch, 2008). Annual rainfall was typically above the 2000 mm mark in the 1980s, however, between 1989 and 1996 it began decreasing. From 2003 to 2018 annual rainfall totals fluctuated but were all below 2000mm (Mapuka, 2020). The average precipitation on Marion Island until 2000 was established at 2326 mm (Smith, 2004) but now a more accurate average annual rainfall currently stands at 2170.6 mm for the study period (1950-2020). The post-2000 average annual rainfall sits below the 2000 mm mark at 1812.5 mm (2000-2020) and is about 22% less than the average pre-2000 (1950-1999). The driest decade on record was previously noted to be the 1990s (1975.79 mm) (Le Roux & McGeoch, 2008) however the last decade (2010-2019) is now the driest decade ever recorded (1770 mm) (Hedding & Greve, 2018; Mapuka, 2020) and as shown by the results of this study (consider Table 4.1).



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Results from the precipitation extremes show a continuous drying trend over Marion Island as the days with rainfall and heavy rain episodes are both decreasing. The annual total wet-dry precipitation index displays an increase in dry days compared to wet days (1036.1 mm decrease; $p < 0.01$). This goes along with a significant decline in heavy and very heavy precipitation days by 37.9 and 20.87 days/year, respectively (both $p < 0.01$). It makes sense then for the days greater than the 95th and 99th percentiles to be declining as well (by 559.48 mm and 203.22 mm; $p < 0.01$) because the island is more prone to long duration precipitation events rather than short period (days) with heavy precipitation. A significant precipitation extreme on Marion Island is the increase in the number of 3 or more consecutive days without rainfall. Considering the oceanic nature of its climate and that it is a wetland, the expectation is that the environment is constantly wet. However, consecutive wet days decreased by 8.05 days and consecutive dry days increased by 3.22 days ($p < 0.01$) over the study period. The latter decade of the study period (2010-2019) displays potential evidence of daily extremes in

dry spells along with the highest decline in daily extreme wet days than all the other decades. Consecutive dry days have risen to a mean of 8.6 days per year and consecutive wet days decreased to an average of 11.4 days per year (consider Table 4.3). Previous studies noted the rise in dry days and the changes in rainfall characteristics on Marion Island. The increase in dry spells on the island is reflected in the ongoing decline in precipitation, especially during the 2010-2019 decade. Mapuka (2020) discovered a significant decrease in the frequency of rainy days with 10 mm or more precipitation on Marion Island between 1980 and 2018. These intense rainy days contribute approximately 65% of the island's annual rainfall. The decline in their frequency is attributed to the increasing occurrence of anti-cyclonic air circulation and a reduction in low-pressure systems passing by the island. Anti-cyclonic air circulation tends to result in fewer rainy days, while cyclonic circulation typically brings increased rainfall and more rainy days (Mapuka, 2020). This shift in cyclonic activity may be a key factor driving the rising frequency of extreme dry spells on Marion Island. Over the same period, the number of days without rainfall increased by 53 days, and consecutive dry days rose from 49.1 days in the 1960s to 89.1 days in the 1990s (Mapuka, 2020), aligning with findings presented in this study. Additionally, the duration between rainfall events lengthened from 4 to 6 days, accompanied by a decrease in the size of rainfall events by more than 5 mm (Le Roux & McGeoch, 2008). This increase in consecutive dry days, coupled with the decrease in annual rainfall, is believed to have the most significant impact on the island's biodiversity and landscape (Mapuka, 2020). The widespread die-back of ferns, bryophytes and vascular plants as well as the drying out of mire lakes and peats on Marion Island (Hedding & Greve, 2018) are probably related to the increase of the consecutive multi-dry days in recent years (Mapuka, 2020). The decreasing precipitation and increasing consecutive days without precipitation will also affect the soil moisture content that is needed for the formation of needle ice. The further demise of glacial ice and decreasing snow cover and needle ice activity on Marion Island due to rising temperatures (Sumner et al., 2004) and extreme warming events indicate that the processes and dynamics of the cryosphere is rapidly changing (Nel et al., 2021). Snow plays a crucial role in the regulation of the ground microclimate in the island's high-altitude regions (Holness, 2004). It maintains the temperatures of the shallow soil at the freezing point of soil water and shields the soil from temperature variations (Nel et al., 2009). As a result, the longest and deepest freezing cycles are associated with snow cover, as snow presence results in deeper soil freezing while facilitating ground heat flow to the snow contact surface (Nel et al., 2009). Although a detailed analysis of the snowfall on Marion Island is not within the purview of this study, it has been anecdotally shown that snowfall depth, duration and intensity has dramatically decreased over the last 50 years.

Seasonal Extremes

The diurnal temperature range is highest in the summer months and lowest in the winter season. The highest and lowest maximum-minimum temperatures occur in the months of February and October of all the months. Most of the highest maximum-maximum temperature values take place in January and the lowest in June. January also has the highest minimum-maximum temperatures taking place while the lowest in February, August and September. The month of September is when the lowest minimum-minimum temperatures take place (followed by February) and the highest values are in March (Fig. 4.17). Previous research has investigated seasonal changes in climate on Marion Island but changes in seasonal extremes are currently relatively unknown (Smith, 2002; Le Roux & McGeoch, 2008). Much of their previous findings indicated a positive correlation in daily and annual temperature and precipitation trends and seasonal changes. It was discovered that the greatest rate of warming took place from late austral winter to midsummer (September to January) and the least took place in late summer, autumn and winter (February to August) but April was a noticeable exception as it showed more warming than all the other months (Smith, 2002). February was stated as the warmest month on Marion Island with a temperature of 7.3°C and the coldest being August with a temperature of 3.7°C; while the average difference between the daily maximum and minimum temperatures was 1.9°C (Smith, 2004). In contrast, the data presented here confirms that January is the warmest month with the highest daily maximum temperatures, and that the summer months (December, January and February) are still the hottest months of the years. Looking at how seasonal sea surface temperatures relate to seasonal temperature changes and extremes between 1993 and 2016, sea surface temperature variability was said to have peaked in the austral summer season where standard deviation surpassed 0.6°C throughout the whole area under study. However, during other seasons, such significant variability was only observed to occur in the south-western portion of the region (Toolsee et al., 2021). The period from the conclusion of the austral spring to the end of austral autumn (November to May) saw warmer surface waters (4°C – 10°C) across the entire study area. During the course of austral winter and spring (June to October) the warm waters seemed to recede northward, supplanted by cooler waters (2°C to 5°C). The sea surface temperature reached its maximum (10°C) at the summers end (February), and its minimum (2°C) at the onset of spring (September) (Toolsee et al., 2021).

Summer and autumn seasons hold the records of being the wettest and containing the months with the highest 1-day precipitation totals. The month of April is when the highest maximum 1-day precipitation amount of all the months took place, followed by February. The month with

the lowest 1-day precipitation amount of all the months took place in August. The summer season still remains the wettest containing the highest 5-day consecutive rainfall amount with the months January, February, April and June having occurrences greater than 160 mm and the month with the lowest being the month of August. Similar to the declining precipitation results recorded by Mapuka (2020), all months displayed a decrease in rainfall from 1980 to 2018, although some were not statistically significant.

Regional (sub-Antarctic) trends and implications

Seeing that the warming and drying trends are continuing on Marion Island, it, therefore, becomes important to consider whether these warming and drying trends are only experienced on Marion Island or affect other islands in the region as well. Warming was predicted to be more frequent in the Antarctic and the sub-Antarctic regions as we entered the 21st Century (IPCC, 2007; Meehl et al., 2007) as there was clear evidence of warming and drying at that time. Data from 1950 to 2008 has shown that mean maximum and minimum temperatures on New Amsterdam rose between the period, with the maximum temperature increasing from 15.8°C to 16.8°C and the minimum temperatures from 11.6°C to 11.9°C (Stern et al., 2010). The mean maximum air temperature significantly increased by 1°C in the early 21st Century for New Amsterdam (Stern et al., 2010). The Kerguelen Archipelagos also showed significant increase in average maximum and minimum air temperatures similar to New Amsterdam, with a 1°C increase in maximum temperature (7.6°C to 8.5°C) and minimum temperature from 1.2°C to 1.9°C in the period 1950-2008 (Stern et al., 2010; Lebouvier et al., 2011).

The mean annual air temperatures recorded at Kerguelen experienced cooler and more varied conditions between the years 1951 to 1975 compared to the period between 1976 and 2008 (Lebouvier et al., 2011). Both air and soil temperatures (at a depth of 20 cm) were found to be the same with a recorded decrease in annual frost days on Kerguelen (Lebouvier et al., 2011). With available data beginning from 1970, Crozet Island also shows slight but noticeable increases in its average maximum and minimum air temperatures, with the maximum temperature rising from 8.2°C to 8.4°C and minimum temperatures rising from 2.4°C to 2.7°C within the 30 year period (1970 to 2008) (Stern et al., 2010). A recent study analysing temperature data of the “core” and New Zealand sub-Antarctic islands presented an observable and significant upward trend in mean air temperatures and found that the warming trend established in the 20th Century is continuing into the 21st Century and that the 21st Century trend (2000-2021) “is in all respects higher than the long-term trend” (Nel et al., 2023).

The rate of warming observed in the sub-Antarctic islands has accelerated notably in the 21st century compared to the latter half of the 20th century (Nel et al., 2023). These measured and extrapolated trends in air temperature are expected to have significant impacts on landscape and ecosystem processes at a regional scale. As highlighted earlier, warmer air temperatures will alter ground thermal dynamics and geomorphological processes, with potential consequences for ecosystem functioning. Additionally, the increased rates of establishment and range expansion of invasive plant species due to warmer temperatures pose a significant concern for the terrestrial habitats of the sub-Antarctic (Convey, 2020). Furthermore, invasive mammals, such as mice, have been shown to disrupt ecosystem structure and functioning, as evidenced by their impact on the White Albatross population on Marion Island (Dilley et al., 2016; Greve et al., 2017). With the climate warming, the risk posed by invasive species to the ecology of the sub-Antarctic islands is anticipated to heighten (Nel et al., 2023).

The precipitation data for New Amsterdam suggested that the island was experiencing slight drying from 1950 to 2008, with annual precipitation records decreasing by about 50 mm (1130 mm to 1080 mm) (Stern et al., 2010). The annual precipitation trends for both the Kerguelen Archipelagos and Crozet Islands showed a declining outcome even though the data was considered inconclusive for that period (1950-2008 for New Amsterdam and Kerguelen; 1970-2008 for Crozet Island) due to the considerable year-to-year variability (Stern et al., 2010). Precipitation reduction was noticed to be quite significant on Kerguelen with records showing precipitation greater than 1200 mm in the early 1950s, but being below the 800 mm mark by the early 2000s (Lebouvier et al., 2011). Lebouvier et al., 2011 also noted that the lowest record of temperature being in 1965, where rainfall was below 500 mm (consider Figure 1b in Lebouvier et al., 2011).

Sub-Antarctic Islands act as ecological laboratories (Smith, 2004; Lebouvier et al., 2011) and are environments that are quite sensitive to change. Glaciers on sub-Antarctic islands (like South Georgia) are fast disappearing (see Bakke et al., 2021). The ablation of glaciers (especially on Kerguelen) was found to be due to a reduction in precipitation falling as snow (Favier et al., 2016). The decrease of glacial ice indicates that the cryosphere is fast approaching an irreversible tipping point in the sub-Antarctic (Bakke et al., 2021). A drying climate across the sub-Antarctic could result in biological communities being irreversibly altered as keystone species and groups decline (le Roux & McGeoch, 2008; Hedding & Greve, 2018). The consequences of precipitation changes across the region could lead to increased

alien invasions, elevated mineralisation rates of drier peats, altered geomorphic processes (Hedding et al., 2015), as well as the reduced transport of macronutrients by freshwater runoff affecting phytoplankton blooms and benthic productivity (Hedding & Greve, 2018).

Possible Drivers of Climate Extremes and Change on Marion Island and Across sub-Antarctic Islands

In the Southern Hemisphere, the surface climate and extreme weather events are significantly influenced by the transition of the polar stratosphere from its winter to summer state. When the stratospheric polar vortex weakens, it triggers a southward shift of the storm track and a negative phase of the Southern Annular Mode, also known as the Antarctic Oscillation. This shift leads to prolonged hot and dry periods over Australia and a reduction in wind stress at the ocean surface around Antarctica (Domeisen & Butler, 2020). The deceleration of the vortex phenomenon occurs globally, resulting in cold spells and drying over Antarctica, as well as a decline in Antarctic sea ice extent (Domeisen & Butler, 2020). Shifts in the Antarctic Oscillation has been one of the noted phenomena responsible for the warming and climate change taking place on Marion Island (Melice et al., 2003; Rouault et al., 2005). Antarctic Oscillations refers to a large-scale alternations of atmospheric air masses taking place between mid-latitudes and high latitudes of the Southern Hemisphere (Rouault et al., 2005). The Southern Annular Mode (SAM) is defined as the band of robust westerly winds or low pressure surrounding Antarctica, shifting northward and southward. It represents the dominant pattern of non-seasonal tropospheric circulation variability below the 20°S latitude, characterized by pressure anomalies in the Antarctic region and between latitudes 40-50°S (Rouault et al., 2005). Climatic records from sub-Antarctic islands have indicated a warming air temperature trend throughout much of the mid- to late 20th century (Jacka et al., 2004; Pendlebury & Barnes-Keoghan, 2007). In broad terms, the primary driver of oceanic and atmospheric warming in the sub-Antarctic region is the anthropogenic influence favoring the positive phase of the Southern Annular Mode (Pohl et al., 2021), accompanied by the strengthening and poleward migration of the Southern Hemisphere westerly winds (Perren et al., 2020). In Marion Island, the Southern Ocean plays a significant role in shaping the annual, monthly, and daily climate, with notable correlations observed between surface air temperature and sea-surface temperature (Smith & Steenkamp, 1990).

The observed warming trend at Marion Island from the 1950s to the 1980s has been attributed to changes in atmospheric and oceanic circulation patterns. A model proposed by Smith

(2002) and Smith & Steenkamp (1990) suggested that these changes in circulation patterns could explain the increase in radiation and air temperature on the island. The primary driver of this change appears to be at the synoptic scale. Marion Island experiences approximately 100 cyclones annually, and the weather conditions before and after these cyclones depend on the path they take relative to the island's position (Le Roux, 2008; Smith, 2002). Intense pre- and post-cyclonic activity occurs when cyclones pass the island, with equal durations for each phase (Le Roux, 2008). The model posits that warm temperatures result from cyclonic centers passing south of the island. As these cyclone centers shift further south, the island's weather becomes increasingly dominated by anticyclones to the north of the frontal lows, leading to longer periods of warming (Smith & Steenkamp, 1990). In warmer years, Marion Island often experiences cyclonic centers passing further south, leading to prolonged periods of warmer north-westerly winds from the cyclone's warmer sector. Conversely, it encounters fewer icy winds from the post-cold front sector (Smith, 2002). During summer, most mid-latitude cyclones track to the south of Marion Island, driven by the seasonal shift of the mean pressure field, which indicates a southward displacement of cyclonic activity compared to winter (Nel, 2012). In such instances, the duration of airflow following a cyclone depends on the position of the anticyclone trailing the cold front and the location of the cyclone's center. Conversely, when cyclones pass over or north of the island, post-cyclonic conditions tend to last longer than pre-cyclonic conditions (Le Roux, 2008), resulting in predominantly cold, clear weather (Smith & Steenkamp, 1990). This is particularly evident in the occluded zone, where cold, clear air displaces warm air to a greater vertical extent. Series of cyclones during summer are rare, with only one such event recorded during the austral summer period of November 2008 to February 2009, which led to significant soil frost (Nel, 2012). Consequently, the increasing intensity and extremes on the island may be attributed to prolonged exposure to longer periods of warm north-westerly winds and reduced exposure to the post-cold front sector.

More recently a synoptic classification system for Marion Island was developed from meteorological observations (1960 to 2009) (see Nel et al., 2021). From this, eight distinct synoptic circulation types that affect the weather on Marion Island were identified and described (Nel et al., 2021). Nel et al. (2021) highlight a discernible trend towards more frequent occurrences of specific synoptic weather systems around Marion Island, including: A cut-off low-pressure system positioned over or slightly south of Marion Island. An anticyclone situated northeast or northwest of Marion Island, accompanied by a cold front that has already passed and is now east of the island, with the mid-latitudinal depression center and polar front

located further south. Anticyclonic circulation north of Marion Island and south of 35°S. A circulation pattern wherein the island falls within the warm sector of a mid-latitudinal depression. Conversely, Nel et al. (2021) note a declining trend in the occurrence of synoptic weather systems associated with: An approaching frontal system to the west of the island, coupled with the extension of the South Indian anticyclone northward beyond 45 degrees. A low-pressure system positioned just south of the island (or just south of 50°S), resulting in reduced mean air pressure. An anticyclone with its center of high pressure situated to the west or west-southwest of Marion Island. The authors suggest that the various sequences and transitions observed in these trends may be linked to the notable warming and drying pattern observed for Marion Island (Nel et al., 2021).



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Chapter 6 - Conclusion

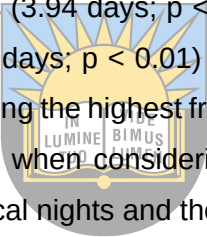
Main Findings

This research investigated the trends in extreme daily temperature and precipitation for Marion Island over a period of seven decades (1950-2020). Extreme climatic events are on the rise and were predicted to be more frequent and intense in the 21st century and near future, especially in the Antarctic and sub-Antarctic region (IPCC, 2007). Globally, the cause of the observed increase in the frequency and severity of these extreme events is recognised to be human-induced climate change and the impacts of natural and human systems from slow-onset processes like acidification, rising sea levels and regional precipitation decreases (IPCC, 2022). Fossil fuel burning and global warming of 1.1°C to date is believed as the leading cause to the rising extreme events in the Antarctic and Southern Ocean (Siegert et al., 2023). The aim of this study was to determine and assess the trends and patterns of daily air temperature and precipitation extremes and to determine their drivers of change to how they affect the region, the landscape or geomorphology processes and the ecology on Marion Island. Daily temperature and precipitation data was requested from the SAWS and was organized into tables and analysed using Microsoft Excel to evaluating trends and patterns in the daily extremes on Marion Island. Values and the significance at the 95th coefficient level were calculated and analysed for each of the 25 extreme indices as developed by the Expert Team on Climate Change Detection Indices (ETCCDI) (Zhang et al., 2011) using linear regression statistics. The results of this study can be summarized as follows:

- Observations from 1950 to 2020 of daily extremes in air temperature and precipitation on Marion Island shows that their intensity and frequency are gradually increasing on the island since the late 1900s and 2000s onwards. This rise in the frequency and intensity of daily temperature and precipitation extremes is a reflection of the reported climate change of increasing mean temperatures on the island indicated in previous studies (Le Roux, 2008; Nel et al., 2023; Smith, 2002).
- The mean annual air temperature on the island for the study period (1950-2020) stands at 5.86°C ($p < 0.05$); with the average mean maximum and minimum temperatures standing at 10.9°C and 1.3°C respectively ($p < 0.05$). Air temperature trends for mean annual air temperature (1.2°C increase; $p < 0.01$), maximum (1.2°C increase; $p < 0.01$) and minimum (0.9 increase; $p < 0.01$) temperatures rose significantly between 1950 and 2020. The 1990s are the warmest on record for air temperature, maximum and minimum temperature followed by the 2010-2020 decade. The highest mean annual air temperature recorded is in the 1996 (7.0°C); the highest mean annual maximum

temperature occurred in 2020 (12.8°C); and the highest average annual minimum temperature occurred in 1996 (2.8°C).

- The average annual precipitation for the study period 1950-2020 is 2170.6 mm, however, the annual precipitation trend has decreased by 1042.3 mm ($p < 0.01$) between 1950 and 2020. The annual precipitation for 2020 stands at 1820.9 mm with the highest precipitation recorded for the period being 3123.7 mm in 1951. The lowest amount of rainfall was recorded in 2017 (1437.8 mm) and the current driest decade is 2010-2019 followed by the 1990s. This confirms the findings of Hedding & Greve (2018) that the last decade (ending in 2019 of the study period) is the driest on record and may have serious ecological consequences.
- The day time and night time air temperatures on Marion Island are experiencing more frequent and intense daily warm extremes. Warm days (6.55%; $p < 0.01$) and nights (6.27%; $p < 0.01$), warm spells (3.94 days; $p < 0.05$), summer days (23.94 days; $p < 0.01$) and tropical nights (22.9 days; $p < 0.01$) have significantly risen between 1950 and 2020. The 1990s are showing the highest frequency of extremes in daily maximum temperatures and warm spells when considering the percentage of warm days and nights, summer days and tropical nights and the warm spell duration indicator.


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- Cold daily temperatures continue to significantly decrease on the island. Cool days (4.66%; $p < 0.01$) and nights (3.58%; $p < 0.01$), cold spells (3.79 days; $p < 0.01$) and annual frost days (14.39 days; $p < 0.01$) have significantly decreased between 1950 and 2020. Beginning from the 1990s to 2020 it is observed that cold temperatures began to significantly drop with the count of frost days being at its lowest 1980s, 1990s and the 2010-2019 decade.
- Dry days and longer dry spells continue to rise alarmingly, especially after the early 2000s. Heavy precipitation days (38.97 days; $p < 0.01$), very heavy precipitation days (20.87 days; $p < 0.01$), very wet days (559.5 mm; $p < 0.01$) and extremely wet days (203.2 mm; $p < 0.01$) and consecutive wet days (8.05 days; $p < 0.01$) have significantly decreased. Consecutive dry days have significantly increased (3.22 days; $p < 0.01$). Consecutive dry days have risen to a mean of 8.6 days per year and consecutive wet days decreased to an average of 11.4 days per year (consider table 4.3). The decade

of 2010-2020 displays a high frequency of daily extremes in dry spells and the highest decline in daily extreme wet days than all the other decades.

- Regional results based on literature from other sub-Antarctic islands show that air temperatures are also rising on other sub-Antarctic islands. Data from Kerguelen, Crozet Islands and New Amsterdam indicate warming was also taking place on these islands from 1950s to the early 2000s (Stern et al., 2010; Lebouvier et al., 2011). A recent study by Nel et al. (2023) which analysed temperature data of the “core” and New Zealand sub-Antarctic islands presents an observable and significant upward trend in mean air temperatures and found that the warming trend established in the 20th Century has continued into the 21st century and that the 21st century trend (2000-2021) “is in all respects higher than the long term trend”. This means that the rate of warming on the sub-Antarctic islands has been more intense in the 21st Century than on the latter half of the 20th Century (Nel et al., 2023).
- The Antarctic Oscillation shifts are reported to be one of the phenomena linked to the warming and climate change taking place on Marion Island (Melice et al., 2003; Rouault et al., 2005). In general terms, the main cause of ocean and atmospheric warming in the sub-Antarctic is the anthropogenic forcing of the trend towards the positive phase of the Southern Antarctic Mode (Pohl et al., 2021) and the associated intensification and poleward migration of the Southern Hemisphere westerly winds (Perren et al., 2020). The positive shift of the Southern Antarctic Mode due to anthropogenic forcing is a significant aspect of how climate change is affecting the Sub-Antarctic region and its surrounding areas, and how frequent the phase could be due to an intensification of climate change conditions in the region. An increase in prolonged exposure to longer periods of warm north-westerly winds and declining exposure to the post cold frontal sector that come with the passing cyclones could be the reason behind the increasing intensity and extremes on Marion Island.

Recommendations for Further Studies:

Further studies could investigate the correlation between daily extremes and the seasonal cycle of Marion Island. This will assist in understanding in which seasons are extremes climatic events more prevalent on Marion Island and (if they are more prevalent in summer) how does seasonal differences affect diurnal soil frost dynamics. Previous research has investigated

seasonal changes in climate on Marion Island but changes in seasonal extremes are currently relatively unknown. Much of their findings indicated a positive correlation in daily and annual temperature and precipitation trends and seasonal changes. The seasonal extremes investigated in this study discovered that the greatest rate of warming took place from spring to midsummer (September to January) and the least took place in late summer, autumn and winter (February to August) but April was a noticeable exception as it showed more warming than all the months (Smith, 2002). February was stated as the warmest month on Marion Island with a temperature of 7.3°C and the coldest being August with a temperature of 3.7°C; while the average difference between the daily maximum and minimum temperatures was 1.9°C (Smith, 2004). The data presented here confirms that February is still the month with the highest daily maximum temperatures, and that the summer months (December, January and February) are still the hottest months of the years.

Studies on climate extremes in the Antarctic and sub-Antarctic region are not common, however, as global warming and its effects become more frequent and intense, they are becoming more important as the effects of global warming are becoming more visible in the Antarctic and sub-Antarctic areas and that extremes are taking place in these regions (Siegert et al., 2023). In the sub-Antarctic region, where periglacial and glacial environments exist, extremes result in abnormal warming, deglaciation, a disturbance in the soil frost, and other geomorphologic processes and abnormal drying conditions. Furthermore, with increasing evidence that fossil fuel burning and consequential global heating of 1.1°C to date (Siegert et al., 2023), these events are having significant impacts on the natural systems and biodiversity of the region: the warming temperatures will influence the soil nutrient cycle on the island (Smith, 2004). It has been noted that warmer temperatures can also lead to a longer growing season, which in turn increases the primary production of the island's lowland plant communities (Smith, 2008) which will mean more organic matter will be produced, enhancing the nutrient cycle as this matter is broken down and the nutrients return to the soil. Warmer temperatures will speed up the decomposition of organic matter as well, making more nutrients available for plant uptake (Smith, 2008). However, more ecological research needs to be conducted to determine if shifts in the altitudinal ranges of plant species can be linked to the warming and drying currently observed on Marion Island.

Other noted implications of these climatic changes are that the spatial variability of plant nutrient concentrations on the island will be influenced by the warming temperatures as well

as warmer areas may have different nutrient concentrations compared to cooler areas, thus affecting the overall nutrient cycling at the ecosystem level (Le Roux & McGeoch, 2008; Rossouw, 2014). The widespread die-back of ferns, bryophytes and vascular plants as well as the drying out of mire lakes and peats on Marion Island are probably the results of the increased consecutive dry days in recent years and the current conditions will lead to more of these taking place in the future (Hedding & Greve, 2018; Mapuka, 2020). However, not much has been mentioned of how the observed extreme warming and drying changes may aid alien invasive species in becoming established on Marion Island, if they were to be introduced accidentally. Thus, more research should be conducted on how warming and drying climatic trends will influence ecosystem dynamics on Marion Island, particularly in the event of an accidental introduction by an alien invasive species.



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References

- Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein Tank, A.M.G., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Kumar, K.R., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D. B., Burn, J., Aguila, E., Burnet, M., Taylor, M., New, M., Zhai, P., Rasticucci, M. and Vazquez-Aguirre, J. L. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres*, 111(D5).
- Allan, E. L., Froneman P. W., Durgadoo J. V., McQuaid C. D., Ansorge I. J. and Richoux N. B. (2013). Critical indirect effects of climate change on sub-Antarctic ecosystem functioning. *Ecology and Evolution*. 3(9), 2994-3004.
- Bakke, J., Paasche, O., Schaefer, J. M. and Timmermann, A. (2021). Long-term demise of sub-Antarctic glaciers modulated by the Southern Hemisphere westerlies. *Scientific Reports*, 11, #8361.
- Barendse, J., Mercer, R. D., Marshall, D. J. and Chown, S. L. (2002). Habitat specificity of mites on sub-Antarctic Marion Island. *Environmental Entomology*, 31(4), 612-625.
- Boelhouwers, J., Holness, S. and Sumner, P. (2000). Geomorphological characteristics of small debris flows on Junior's Kop, Marion Island, maritime sub-Antarctic. *Earth Surface Processes and Landforms*, 25, 341-352.
- Boelhouwers, J., Holness, S. and Sumner, P. (2003). The maritime Subantarctic: a distinct periglacial environment. *Geomorphology*, 52, 39-55.
- Chown, S. L. and Froneman, P. W. (2008). Introduction In: Chown, S. L. and Froneman, P. W. (Eds.). *The Prince Edward Islands: Land-Sea Interactions in a Changing Ecosystem*. Published by Stellenbosch: SUN PRESS, 1-16.
- Chown, S. L. and Smith, V. R. (1993). Climate change and short-term impact of feral house-mice at sub-Antarctic Prince Edward Islands. *Oecologia*, 96, 508-516.
- Costa, A.C. and Soares, A. (2009). Homogenization of Climate Data: Review and New Perspectives Using Geostatistics. *Mathematical Geoscience*, 41, 291–305
- Convey, P. (2020). Current changes in Antarctic ecosystems. In: Goldstein, M. I. and DellaSala, D. A. (Eds.), *Encyclopaedia of the World's Biomes, Volume 2*. London: Elsevier, 666-685.

Dilley, B. J., Schoombie, S., Schoombie, J. and Ryan, P. G. (2016). 'Scalping' of albatross fledglings by introduced mice spreads rapidly on Marion Island. *Antarctic Science*, 28(2), 73-80.

Domeisen, D. I. V. and Butler, A. H. (2020). Stratospheric drivers of extreme events at the earth's surface. *Nature Communications Earth & Environment*, 1(59), 1-8.

Favier, V., Verfaillie, D., Berthier, E., Menegoz, M., Jomelli, Z., Kay, J. E., Ducret, L., Malbeteau, Y., Brunstein, D., Gallee, H., Park, Y. H. and Rinterknecht, V. (2016). Atmospheric drying as the main driver of dramatic glacier wastage in the southern Indian Ocean. *Scientific Reports*, 6(32396), 1-12.

Greve, M., Mathakutha, R., Steyn, C and Chown, S. L. (2017). Terrestrial invasions on sub-Antarctic Marion and Prince Edward Island. *Bothalia- African Biodiversity and Conservation*, 47(2), 1-21.

Hagar, J. (2021). "Ice needles" responsible for frost patterns in soils, Available at: <https://polarjournals.ch/en/2021/10/15/ice-needles-responsible-for-frost-patterns-in-soils/>

Hall, K. (2004). Quaternary glaciation on sub-Antarctic Islands. In: Ehlers, J. and Gibbard P. L. (Eds). *Quaternary Glaciations - Extent and Chronology, Part 3*. London: Elsevier, 339-345.

Hausmann, N.S., McGeoch, M.A. and Boelhouwers, J.C. (2009). Interactions between a cushion plant (*Azorella selago*) and surface sediment transport on sub-Antarctic Marion Island. *Geomorphology*, 107, 139–148.

Hedding, D. W. (2006). Geomorphology and geomorphological responses to climate change in the interior of sub-Antarctic Marion Island. MSc Dissertation. University of Pretoria, South Africa.

Hedding, D. W. and Greve, M. (2018). Decreases in precipitation on sub-Antarctic Marion Island: implications for ecological and geomorphological processes, *Weather*, 73(6), 203.

Hedding, D. W., Sumner, P. D., Holness, S. D. and Meiklejohn, K. I. (2007). Formation of a pronival rampart on sub-Antarctic Marion Island. *Antarctic Science* 19(4), 443-450.

Heim Jr, R. R. (2015). An overview of weather and climate extremes – Products and trends. *Weather and Climate Extremes*, 10(B), 1-9.

Holbrook, N. J., Sen Gupta, A., Oliver, E. C. J., Hobday, A. J., Benthuyssen, J. A., Scannell, H. A., Smale, D. A. and Wernberg, T. (2020). Keeping pace with marine heatwaves. *Nature Reviews Earth and Environment*, 1, 482–493.

Holness, S. D. (2001). Periglacial slope processes, landforms and environment at Marion Island, Maritime Subantarctic. PhD Thesis, University of the Western Cape, South Africa.

Holness, S. D. (2004). Sediment movement rates and process on cinder cones in the maritime sub-Antarctic (Marion Island). *Earth Surface Processes and Landforms*, 29, 91-103.

Intergovernmental Panel on Climate Change. (2007). IPCC fourth assessment report: climate change 2007. Retrieved from: https://archive.ipcc.ch/publications_and_data/ar4/wg2/en/tssts-4-2-7-polar-regions.html

Intergovernmental Panel on Climate Change, (2013). In: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P. M. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 1535 pp.

Intergovernmental Panel on Climate Change (2022). Summary for Policymakers. In: Pörtner, H. -O., Roberts, D. C., Poloczanska, E. S., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. and Rama, B. (Eds.), *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 3–33.

Jacka, T. H., Budd, W. F. and Holder, A. (2004). A further assessment of surface temperature changes at stations in the Antarctic and Southern Ocean, 1949-2002. *Annals of Glaciology*, 39, 331-338.

Le Roux, P. C. (2008). Climate Change. In: Chown, S. L. and Froneman, P. W. (Eds.). *The Prince Edward Islands: Land-Sea Interactions in a Changing Ecosystem*. Stellenbosch: SUN PRESS, 39-64.

Le Roux, P. C. and McGeoch, M. A. (2008). Changes in climate extremes, variability, and signature on sub-Antarctic Marion Island. *Journal of Climate Change*, 86, 309-329.

Lebouvier, M., Laparie, M., Hulle, M., Marais, A., Cozic, Y., Lalouette, L., Vernon, P., Candresse, T., Frenot, Y and Renault, D. (2011). The significance of the sub-Antarctic

Kerguelen Islands for the assessment of the vulnerability of native communities to climate change, alien insect invasions and plant viruses. *Biological Invasions*, 13, 1195-1208.

Mahecha, M. D., Bastos, A., Bohn, F. J., Eisenhauer, N., Feilhauer, H., Hartmann, H., Hickler, T., Migliavacca, M., Otto, F. E., Peng, J., Quaas, J., Tegen, I., Weigelt, A., Wendisch, M. and Wirth, C. (2022). Biodiversity loss and climate extremes — Study the feedbacks. *Nature*, 612(7938), 30-32.

Mapuka, F. N. (2020). The characteristics and trends of rainfall on sub-Antarctic Marion Island and associated air circulation patterns. MSc Dissertation, University of Fort Hare, Alice, South Africa.

McDougall, I., Verwoerd, W. and Chevallier, L. (2001). K—Ar geochronology of Marion Island, Southern Ocean. *Geological Magazine*, 138(1), 1-17.

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T. and Gregory, J. M. (2007). Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., et al. (Eds.). *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 749–844.

Melice, J. L., Lutjeharms, J. R. E., Rouault, M. and Ansorge, I. J. (2003). Sea surface temperatures at the sub-Antarctic islands Marion and Gough during the past 50 years. *South African Journal of Science*, 99, 363-366.

Meiklejohn, K. I. and Hedding, D. W. (2005). Report on Marion Island (South Africa). In: R. Wunderman (Ed.), *Bulletin of the Global Volcanism Network*, 30(2), 16.

Merriam-Webster. (2022). Event. In Merriam-Webster.com dictionary. Retrieved March 3, 2022, from <https://www.merriam-webster.com/dictionary/event>

Met Éireann (2019). Warm Spell Duration Index (WSDI). Retrieved from: <https://www.met.ie/cms/assets/uploads/2022/09/WSDI.pdf>

Ndwayamato, F. P. (2015). An assessment of hourly rainfall on sub-Antarctic Marion Island and the implications for climate change. MPhil Dissertation, University of Fort Hare, Alice, South Africa.

Nel, W. (2012). A preliminary synoptic assessment of soil frost on Marion Island and the possible consequences of climate change in a maritime sub-Antarctic environment. *Polar Research*, 31(1), #17626.

Nel, W., and Boelhouwers, J.C. (2014). First observations on needle ice formation in the sub-Antarctic. *Antarctic Science*, 26, 327–328.

Nel, W., Hedding, D. W. and Rudolph, E. M. (2023). The sub-Antarctic islands are increasingly warming in the 21st century. *Antarctic Science*, 35(2), 124-126.

Nel, W.; van de Merwe, B. J. and Meiklejohn, K. I. (2009). Rethinking climate change impacts on subsurface temperatures in a sub-Antarctic mire affected by synoptic scale processes. *Earth Surface Processes and Landforms*, 34(10), 1446-1449.

Outcalt, S. I. (1971). An algorithm for needle ice growth. *Water Resources Research*, 26, 1509-1516.

Pendlebury, S. F. and Barnes-Koeghan, I. P. (2007). Climate and climate change in the sub-Antarctic. *Papers and Proceedings of the Royal Society of Tasmania*, 141(1), 67-82.

Perren, B. B., Hodgson, D. A., Roberts, S. J., Sime, L., Van Nieuwenhuyze, W., Verleyen, E. and Vyverman, W. (2020). Southward mitigation of the Southern Hemisphere westerly winds corresponds with warming climate over centennial timescales. *Nature Communications Earth and Environment*, 1, 58.

Peterson, T.C., Easterling, D.R., Karl, T.R., Groisman, P., Nicholls, N., Plummer, N., Torok, S., Auer, I., Boehm, R., Gullett, D., Vincent, L., Heino, R., Tuomenvirta, H., Mestre, O., Szentimrey, T., Salinger, J., Forland, E.J., Hanssen-Bauer, A., Alexandersson, H., Jones, P. and Parker, D. (1998). Homogeneity adjustments of in situ atmospheric climate data: A review. *International Journal of Climatology*, 18(13):1493–1517.

Pohl, B., Saucedo, T., Favier, V., Pergaud, J., Verfaillie, D., Feral, J., Krasniqi, Y. and Richard, Y. (2021). Recent climate variability around the Kerguelen Islands (Southern Ocean) seen through weather regimes. *Journal of Applied Meteorology and Climatology*, 60(5), 711-731.

Rosane, O. (2022). Extreme weather 101: Everything you need to know. Retrieved from World Economic Forum website: <https://www.weforum.org/agenda/2022/04/extreme-weather-101-everything-you-need-to-know/>

Rossouw, M. W. (2014). Spatial variation in plant nutrient composition on Marion Island. MSc Dissertation. University of Stellenbosch, Stellenbosch, South Africa.

Rouault, M., Melice, J. L., Reason, C. J. C., and Lutjeharms J. R. E. (2005). Climate variability at Marion Island, Southern Ocean, since 1960. *Journal of Geophysical Research*, 110, #C05007.

Rudolph, E. M. (2020). Towards a reconstruction of Marion Island's glacial history. PhD Thesis, University of Fort Hare, Alice, South Africa.

Ryan, P. G. and Bester, M. N. (2008). Pelagic Predators. In: Chown, S. L. and Froneman, P. W. (Eds.). *The Prince Edward Islands: Land-Sea Interactions in a Changing Ecosystem*. Stellenbosch: SUN PRESS, 121-164.

Schaefer, J. M., Putnam, A. E., Denton, G. H., Kaplan, M. R., Birkel, S., Doughty, A. M., Kelley, S., Barrell, D. J. A., Finkel, R. C., Winckler, G., Anderson, R. F., Ninneman, U. S., Barker, S., Schwartz, R., Andersen, B. G., and Schluechter, C. (2015). The southern glacial maximum 65,000 years ago and its unfinished termination. *Quaternary Science Reviews*, 114, 52–60.

Schulze, B. R. (1971). The climate of Marion Island. In: Van Zinderen Bakker, E. M.; Winterbottom, J. M and Dyer, R. A. (Eds.). *Marion and Prince Edward Islands: Report on South African ecological and geological expedition 1965-1966*. Cape Town: AA. Balkema, 16-31.

Siegert, M. J., Bentley, M. J., Atkinson, A., Bracegirdle, T. J., Convey, P., Davies, B., Downie, R., Hogg, A. E., Holmes, C., Hughes, K. A., Meredith, M. P., Ross, N., Rumble, J. and Wilkinson, J. (2023). Antarctic extreme events. *Frontiers in Environmental Science*, 11, #3389.

Shangheta, A. L. (2021). Long term climate variability at the Prince Edward Islands in the Southern Ocean. MSc Thesis, University of Cape Town, South Africa.

Sneddon, A. (2023). Marine heatwave characteristics in the South Atlantic and South Indian Ocean. Honours Research Project, University of Cape Town, South Africa.

Smith, R. I. L. (1990). Signey Island as a paradigm of biological and environmental change in Antarctic terrestrial ecosystem. *Antarctic Ecosystems*, 32-50.

Smith, V. R. (2002). Climate change in the sub-Antarctic: An illustration from Marion Island. *Climate Change*, 52, 345-357.

Smith, V. R. (2004). Sub-Antarctic eco-labs. *Quest*, 1(2), 22-29.

Smith, V. R. (2008). Energy flow and nutrient cycling in the Marion Island terrestrial ecosystem: 30 years on. *Polar Record*, 44(3), 211-226.

Smith, V. R. (2009). A qualitative description of energy flow and nutrient cycling in the Marion Island terrestrial ecosystem. *Polar Record*, 18(115), 361-370.

Smith, V. R. and Steenkamp, M. (1990). Climate change and its ecological implications at a Subantarctic Island. *Oecologia*, 85(1), 14-24.

Stern, H., Reilly, J. C., McBride, P. and Dahni, J. (2010). Climate change illustrated by data from three India Ocean Islands in the French Southern and Antarctic Territories: New Amsterdam, Kerguelen and Crozet. 22nd Conference on Climate Variability and Change, 17 January, Atlanta, United States of America.

Sumner, P. D., Miekjohn, K. I., Boelhouwers, J. C. and Hedding, D. W. (2004). Climate change melts Marion Island's snow and ice. *South African Journal of Science*, 100, 395-398.

Tank, A. K. (2010). High resolution observations for climate change monitoring of extremes. *Terrestrial Scientific Report*, 28-33.

Toolsee, T. (2022). Interannual variability and long-term trends of surface hydrography around the Prince Edwards Island Archipelago, Southern Ocean. MSc Dissertation, University of Cape Town, Cape Town, South Africa.

Toolsee, T., Lamont, T., Rouault, M. and Anson, I. (2021). Characterising the seasonal cycle of wind forcing, surface circulation and temperature around the sub-Antarctic Prince Edward Islands. *African Journal of Marine Sciences*, 43(1), 61-76.

Treasure, A. M., le Roux, P., Mashau, M. H. and Chown, S. L. (2019). Species-energy relationships of indigenous and invasive species may arise in different ways – a demonstration using springtails. *Scientific Reports*, 9, 13799.

Turek-Hankins, L. L., de Perez, E. C., Scarpa, G., Schwerdtle, P. N., Joe, E. T., Galappaththi, E. K., French, E. M., Austin, S. E., Singh, C., Siña, M., Siders, A. R., Van Aalst, M. K., Templeman, S., Nunbogu, A. M., Agrawal, T., the Global Adaptation Mapping Initiative team and Mach, K. J. (2021). Climate change adaptation to extreme heat: A global systematic review of implemented action. *Oxford Open Climate Change*, 1(1).

Venter, I. (2009). S.A.'s new R200m high tech Marion Island science hub. Retrieved from the SEAON website on: www.saeon.ac.za/enewsletter/archives/2008/july-2008/sas-new-r200m-high-tech-marion-island-science-hub

Veron, S., Mouchet, M., Govaerts, R., Haevermans, T. and Pallens, R. (2019). Vulnerability to climate change of islands worldwide and its impacts on the tree of life. *Scientific Reports*, 9, #14471.

Verwoerd, W. J. (1971). Geology. In: van Zideren Bakker, E. M., Winterbottom, J. M., Dyer, R. A. (Eds.). *Marion and Prince Edward Islands: Report on South African ecological and geological expedition 1965-1966*. Cape Town: A. A. Balkema, 40-62.

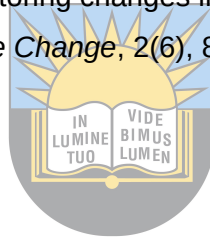
Verwoerd, W. J., and Langenegger, O. (1967). Marion and Prince Edward Islands - geological studies. *Nature*, 213, 230–232.

Verwoerd, W. J., Russell, S. and Berruti, A. (1981). 1980 volcanic eruption reported on Marion Island. *Earth and Planetary Science Letters*, 54(1), 153–156.

World Meteorological Organisation (WMO). (1992). *International Meteorological Vocabulary, 2nd Edition*. Zurich: World Meteorological Organisation, 784 pp.

World Meteorological Organisation (WMO). (2018). Guidance on the homogenization of climate station data, *EarthArXiv*.

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P. Tank, A. K., Peterson, T. C., Trewin, B. and Zwiers, F. W. (2011). Indices for monitoring changes in extremes based on daily temperature and precipitation data. *WIREs Climate Change*, 2(6), 851-870.



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*You say the emotionally immature man seeks out motivation to do something hard one time.
But an emotionally mature man uses discipline to do something hard a thousand times.*

Appendix

Table S.1: Climate change detection indices based on annual daily data for temperature (Zhang et al., 2011).

Indicator Name	Cool nights	Cool days	Warm nights	Warm days	Frost days	Summer days	Tropical nights	Warm spell duration indicator	Cold spell duration indicator
Units	%	%	%	%	Days	Days	Days	Days	Days
ID	TN10p	TX10p	TN90p	TX90p	FD0	SU12.5	TR6.7	WSDI	CSDI
1950	8,5	9,6	5,8	8,8	44,0	32,0	21,0	1,0	3,0
1951	11,5	14,5	5,8	6,3	55,0	23,0	21,0	6,0	9,0
1952	10,7	12,6	4,1	7,7	47,0	28,0	15,0	4,0	9,0
1953	10,4	9,9	7,4	8,5	46,0	31,0	27,0	7,0	7,0
1954	12,6	9,9	4,9	7,1	49,0	26,0	18,0	4,0	5,0
1955	9,9	13,7	3,0	4,9	50,0	18,0	11,0	1,0	4,0
1956	14,8	16,7	7,7	10,7	63,0	39,0	28,0	16,0	6,0
1957	8,8	10,4	8,8	6,6	41,0	24,0	32,0	3,0	2,0
1958	14,8	17,0	9,9	6,6	61,0	24,0	36,0	1,0	9,0
1959	9,0	12,3	6,3	4,7	39,0	17,0	23,0	2,0	1,0
1960	13,1	17,2	5,7	4,6	60,0	17,0	21,0	1,0	7,0
1961	10,1	13,7	4,1	6,3	43,0	23,0	15,0	1,0	3,0
1962	12,3	11,5	5,2	6,3	51,0	23,0	19,0	1,0	8,0
1963	12,3	14,5	10,4	8,0	53,0	29,0	38,0	4,0	9,0
1964	10,9	9,6	4,9	4,6	50,0	17,0	18,0	1,0	4,0
1965	11,5	9,9	4,9	5,5	54,0	20,0	18,0	0,0	2,0
1966									
1967	2,2	11,0	3,6	6,6	53,0	24,0	13,0	6,0	12,0
1968	14,5	13,7	3,3	3,3	66,0	12,0	12,0	0,0	3,0
1969	13,4	12,1	3,0	5,5	52,0	20,0	11,0	0,0	11,0
1970	14,3	13,2	9,0	5,8	69,0	21,0	33,0	3,0	11,0
1971	12,1	11,0	11,5	8,8	52,0	32,0	42,0	3,0	9,0
1972	11,8	11,2	8,7	10,4	49,0	38,0	32,0	7,0	11,0
1973	11,2	11,8	10,1	8,8	53,0	32,0	37,0	5,0	8,0
1974	10,4	8,2	4,9	8,5	47,0	31,0	18,0	1,0	5,0
1975	11,5	11,0	6,6	7,4	52,0	27,0	24,0	6,0	7,0
1976	10,1	9,0	8,7	7,9	40,0	29,0	32,0	3,0	4,0
1977	10,1	11,2	8,2	8,2	45,0	30,0	30,0	1,0	9,0
1978	12,1	9,0	7,1	8,0	51,0	29,0	26,0	0,0	2,0
1979	12,1	8,8	8,8	9,9	48,0	36,0	32,0	5,0	9,0
1980	9,8	7,7	7,7	7,1	47,0	26,0	28,0	1,0	3,0
1981	7,7	9,3	10,7	9,3	31,0	34,0	39,0	3,0	1,0
1982	6,9	8,2	9,3	5,2	34,0	19,0	34,0	0,0	2,0

1983	6,3	8,0	10,4	12,1	29,0	44,0	38,0	5,0	0,0
1984	12,0	7,1	14,2	12,3	55,0	45,0	52,0	4,0	8,0
1985	7,7	5,8	15,3	15,9	39,0	58,0	56,0	8,0	3,0
1986	10,4	7,1	12,1	11,0	49,0	40,0	44,0	5,0	4,0
1987	6,6	6,0	13,2	10,7	30,0	39,0	48,0	7,0	0,0
1988	10,1	11,2	7,1	7,9	41,0	29,0	26,0	4,0	5,0
1989	9,9	9,0	6,9	10,4	41,0	38,0	25,0	6,0	0,0
1990	8,8	7,4	15,9	13,7	41,0	50,0	58,0	8,0	4,0
1991	9,3	7,7	13,4	13,4	40,0	49,0	49,0	5,0	4,0
1992	9,3	10,4	15,6	13,4	41,0	49,0	57,0	9,0	2,0
1993	11,0	9,0	14,0	12,1	46,0	44,0	51,0	7,0	4,0
1994	11,5	7,7	10,1	14,3	49,0	52,0	37,0	10,0	3,0
1995	11,0	10,7	11,2	15,1	58,0	55,0	41,0	11,0	4,0
1996	4,4	3,6	15,9	16,7	26,0	61,0	58,0	19,0	0,0
1997	5,2	4,4	18,4	15,1	28,0	55,0	67,0	13,0	0,0
1998	7,7	6,0	17,8	12,1	38,0	44,0	65,0	7,0	2,0
1999	6,3	4,1	19,5	18,4	32,0	67,0	71,0	16,0	2,0
2000	9,6	7,9	17,5	12,6	42,0	46,0	64,0	13,0	1,0
2001									
2002	5,5	3,8	12,3	13,7	26,0	50,0	45,0	15,0	2,0
2003	7,1	7,7	11,2	9,6	29,0	35,0	41,0	6,0	5,0
2004									
2005	9,0	9,0	5,8	11,5	46,0	42,0	21,0	6,0	5,0
2006	8,5	9,9	8,5	8,0	45,0	29,0	31,0	7,0	3,0
2007	9,0	12,3	9,3	10,4	42,0	38,0	34,0	4,0	3,0
2008	11,2	13,4	3,0	8,2	53,0	30,0	11,0	4,0	3,0
2009	14,0	12,3	5,2	9,0	61,0	33,0	19,0	0,0	8,0
2010	7,4	9,0	5,8	8,8	36,0	32,0	21,0	2,0	4,0
2011	8,0	10,1	14,5	11,0	39,0	40,0	53,0	5,0	7,0
2012	6,8	9,0	9,8	12,3	33,0	45,0	36,0	3,0	1,0
2013	9,9	12,9	6,6	9,6	47,0	35,0	24,0	3,0	6,0
2014	13,7	12,9	10,1	9,9	59,0	36,0	37,0	6,0	11,0
2015	5,5	6,9	7,1	10,7	31,0	39,0	26,0	3,0	0,0
2016	6,6	7,7	7,7	9,6	30,0	35,0	28,0	3,0	1,0
2017	10,4	8,8	9,0	10,4	48,0	38,0	33,0	2,0	2,0
2018	7,1	7,1	14,5	12,6	37,0	46,0	53,0	5,0	2,0
2019	7,7	9,3	12,1	13,7	36,0	50,0	44,0	4,0	3,0
2020	10,1	9,0	14,8	13,1	44,0	48,0	54,0	12,0	6,0
R-Squared	0,1600	0,2146	0,1984	0,3556	0,1823	0,3556	0,1984	0,0751	0,1181
P-value	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01

Table S.2: Climate change detection indices based on annual daily data for rainfall (Zhang et al., 2011).

Indicator Name	Simple daily intensity index	Number of heavy precipitation on days	Number of very heavy precipitation on days	Consecutive dry days	Consecutive wet days	Very wet days	Extremely wet days	Annual total wet-dry precipitation
Units	mm/day	Days	Days	Days	Days	mm	mm	Mm
ID	SDII	10,0	20,0	CDD	CWD	R95p	R99p	PRCPTOT
1950	132,3	80,0	33,0	5,0	18,0	793,4	148,1	2380,7
1951	172,1	101,0	43,0	7,0	18,0	1222,4	626,5	3097,2
1952	160,7	89,0	33,0	4,0	16,0	852,0	247,0	2571,9
1953	120,4	89,0	37,0	11,0	21,0	543,8	107,9	2527,7
1954	135,6	95,0	36,0	4,0	19,0	691,7	100,3	2576,6
1955	136,0	77,0	28,0	8,0	16,0	607,7	52,2	2175,2
1956	161,7	83,0	27,0	5,0	14,0	447,5	302,5	2263,4
1957	130,9	82,0	30,0	4,0	19,0	556,3	302,5	2486,9
1958	156,0	87,0	32,0	8,0	16,0	670,5	160,0	2495,2
1959								
1960	230,7	84,0	29,0	6,0	11,0	911,9	253,3	2537,5
1961	124,8	79,0	32,0	7,0	21,0	933,3	556,5	2621,4
1962	124,0	103,0	33,0	4,0	21,0	568,1	148,7	2604,8
1963	159,2	87,0	40,0	8,0	17,0	1222,4	486,3	2706,9
1964	144,4	96,0	52,0	7,0	20,0	1205,3	312,3	2886,9
1965	200,2	101,0	41,0	5,0	14,0	949,8	306,8	2803,0
1966								
1967	185,9	100,0	38,0	6,0	16,0	1089,0	398,5	2973,7
1968	162,5	84,0	21,0	7,0	14,0	444,0	95,9	2275,2
1969	132,0	99,0	35,0	4,0	20,0	738,0	276,4	2638,9
1970	149,0	90,0	30,0	6,0	17,0	757,2	232,9	2533,4
1971	118,9	84,0	29,0	6,0	20,0	672,0	121,9	2377,3

1972	204,8	87,0	42,0	6,0	13,0	886,8	331,9	2662,0
1973	148,8	70,0	23,0	9,0	14,0	439,4	112,8	2082,6
1974	171,8	67,0	22,0	6,0	12,0	427,0	113,9	2061,3
1975	98,9	94,0	35,0	8,0	27,0	746,6	227,4	2671,0
1976	178,7	84,0	29,0	5,0	13,0	660,9	113,1	2323,4
1977	169,9	87,0	30,0	5,0	15,0	768,9	223,1	2548,2
1978	135,6	80,0	23,0	6,0	16,0	594,5	223,2	2169,4
1979	173,3	75,0	23,0	7,0	12,0	403,6	52,5	2079,4
1980	116,1	67,0	15,0	5,0	17,0	394,3	147,4	1973,5
1981	121,1	71,0	26,0	9,0	18,0	642,1	158,6	2180,2
1982	150,7	67,0	26,0	5,0	14,0	537,4	186,8	2110,3
1983	117,1	67,0	27,0	5,0	17,0	510,5	53,4	1990,1
1984	156,5	76,0	29,0	5,0	14,0	571,6	165,9	2190,9
1985	130,2	72,0	21,0	9,0	16,0	544,8	257,8	2083,6
1986	204,5	76,0	32,0	7,0	11,0	658,2	163,5	2249,1
1987	148,7	84,0	21,0	4,0	15,0	444,4	56,0	2230,6
1988	160,3	89,0	25,0	8,0	15,0	478,0	55,4	2404,7
1989	153,0	77,0	21,0	6,0	14,0	555,5	169,3	2142,3
1990	73,6	68,0	19,0	7,0	25,0	337,0	101,5	1841,1
1991								
1992								
1993	202,2	56,0	21,0	9,0	9,0	510,8	104,2	1819,5
1994	155,7	63,0	21,0	6,0	13,0	563,1	247,5	2023,6
1995	169,4	69,0	23,0	12,0	11,0	322,7	113,0	1863,2
1996	164,0	75,0	25,0	7,0	12,0	541,8	103,9	1968,1
1997	111,7	70,0	30,0	11,0	19,0	615,6	117,5	2122,0
1998	239,9	82,0	28,0	8,0	9,0	497,2	109,0	2159,0
1999	103,2	59,0	17,0	4,0	18,0	321,1	106,2	1857,7
2000	181,1	73,0	21,0	7,0	11,0	340,8	180,4	1992,3

2001								
2002	154,1	77,0	23,0	6,0	14,0	563,1	174,9	2156,7
2003	151,5	72,0	16,0	9,0	12,0	276,2	121,8	1817,9
2004								
2005								
2006	216,7	69,0	24,0	9,0	9,0	350,0	129,9	1950,0
2007	153,9	55,0	16,0	6,0	11,0	213,7	100,0	1693,0
2008	223,9	60,0	19,0	7,0	8,0	495,4	112,4	1790,9
2009	187,1	59,0	17,0	14,0	9,0	362,2	61,0	1684,3
2010	156,7	59,0	17,0	6,0	11,0	267,6	0,0	1723,6
2011	126,1	47,0	18,0	11,0	13,0	460,8	206,8	1638,9
2012	156,2	64,0	17,0	13,0	12,0	352,1	119,1	1874,5
2013	194,2	63,0	18,0	7,0	10,0	472,5	236,9	1941,8
2014	113,4	62,0	19,0	7,0	16,0	387,9	64,5	1814,0
2015	170,6	56,0	16,0	8,0	9,0	249,8	51,6	1535,7
2016	204,5	54,0	19,0	11,0	9,0	482,1	105,6	1840,3
2017	141,1	36,0	12,0	9,0	10,0	147,3	0,0	1410,5
2018	165,6	53,0	19,0	9,0	10,0	279,8	82,7	1656,2
2019	132,2	65,0	20,0	7,0	15,0	380,0	66,8	1983,2
2020	178,9	56,0	15,0	7,0	10,0	405,5	171,1	1788,9
R-Squared	0,0253	0,6389	0,5796	0,1814	0,3472	0,4805	0,2531	0,6920
P-value	> 0,05	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01

Table S.3: The mean, median and standard deviation of the monthly climate change detection Indices for the 71-year period (1950-2020).

	Month	January	February	March	April	May	June	July	August	September	October	November	December
Max TMax (°C)	Mean	16,6	17,5	16,6	14,8	13,2	12,0	11,3	11,2	12,3	13,5	15,0	15,8
	Median	16,5	17,2	16,7	14,7	13,3	12,1	11,2	11,0	11,7	13,4	14,8	16,0
	Standard	2,3	2,3	2,7	2,6	2,6	2,2	1,7	1,8	3,9	2,0	2,1	2,3

	Deviati on												
Max TMin (°C)	Mean	8,6	9,1	9,0	8,4	7,5	6,9	6,7	6,2	6,3	6,4	6,9	7,6
	Median	8,6	9,0	9,1	8,5	7,5	6,9	6,6	6,3	6,3	6,5	6,8	7,7
	Standa rd Deviati on	1,1	1,0	1,4	1,5	1,4	1,3	1,1	1,2	1,0	1,1	1,0	1,2
Min TMax (°C)	Mean	6,8	7,2	6,3	4,6	3,4	2,2	1,9	1,5	1,8	3,0	4,8	5,8
	Median	6,7	7,2	6,6	4,8	3,4	2,2	2,0	1,5	1,7	2,8	4,7	5,8
	Standa rd Deviati on	1,0	1,0	1,2	1,3	1,0	1,2	1,2	1,1	1,2	1,4	1,2	1,1
Min TMin (°C)	Mean	1,0	1,1	0,9	-0,1	-1,0	-2,1	-2,8	-3,1	-3,1	-2,0	-0,8	0,2
	Median	0,9	1,1	1,0	0,0	-1,0	-1,9	-2,9	-3,1	-3,0	-1,8	-0,7	0,2
	Standa rd Deviati on	1,0	1,0	0,9	0,9	0,9	1,3	1,1	1,3	1,4	1,1	1,0	0,9
Diurnal Tempe rature Range (°C)	Mean	6,0	5,9	5,7	5,5	5,2	5,0	5,0	5,1	5,3	5,6	6,0	5,9
	Median	5,9	5,8	5,7	5,4	5,2	5,1	5,0	5,1	5,2	5,5	6,0	5,9
	Standa rd Deviati on	0,6	0,6	0,5	0,5	0,5	0,4	0,5	0,5	0,5	0,4	0,5	0,6
Max 1- Day Precp. (mm)	Mean	39,1	38,4	36,3	39,6	36,4	32,8	31,2	30,8	33,5	32,4	35,7	35,9
	Median	37,0	36,5	36,0	32,5	35,0	29,2	28,2	28,0	27,7	29,1	31,4	34,0
	Standa rd Deviati on	16,3	19,0	14,9	22,6	16,8	14,5	14,2	11,5	18,7	16,2	15,2	14,0
Max 5- Day Precp. (mm)	Mean	71,6	70,4	66,5	70,8	71,8	66,6	62,4	57,9	61,2	59,4	59,1	68,4
	Median	65,4	63,1	65,4	66,8	71,8	61,8	60,7	57,5	56,6	57,6	56,9	60,8
	Standa rd Deviati on	31,2	32,4	27,4	33,7	29,3	25,5	20,0	18,0	22,3	24,0	19,7	24,7