Characterising local climates and biologically-relevant climate changes on the Southern Ocean Islands

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Abstract

The Southern Ocean climate has undergone significant changes over the last several decades, which has had consequences for conditions on the few small islands scattered across the region. Previous investigations of climate changes on the Southern Ocean Islands (SOIs) have examined single climate variables, such as temperature, and single islands or island groups. Furthermore, these studies have tended to focus on mean values without consideration of variability and extreme events. Consequently, we currently lack a comprehensive and up-to-date analysis of biologically-relevant climate changes that have occurred on these islands. Such insights are needed to determine the exposure of these unique and potentially fragile island ecosystems to climate change and the threats and challenges that their species will face. Here, we used weather station records to quantify the climate signature of SOIs and examine trends in a set of biologically-relevant climate parameters related to temperature, precipitation, and wind. We found that comprehensive warming has occurred across these islands but with important nuances, including differences in the rate of increase in minimum and maximum temperature contributing to an increase in diurnal temperature range. In contrast, precipitation changes have been highly localised, with severe drying on Marion and Crozet Islands in the Indian Ocean sector and wetting on Macquarie Island in the Pacific Ocean sector. Changes in wind speed have been idiosyncratic but have important consequences in combination with changes in other variables. Some of the implications of these changes for the SOIs are discussed.

1 Introduction

The climate of the Southern Ocean region has undergone significant changes over recent decades, including increases in sea surface temperature (Fyfe, 2006; Gille, 2002; Kostov et al., 2017) and changes in cyclonic activity (Fyfe, 2003) and precipitation (Manton et al., 2020). These trends are associated with large-scale climate drivers, chiefly the Southern Annular Mode and its variation resulting from the poleward shift and increasing intensity of westerly winds over the Southern Hemisphere, which is thought to be at least partly driven by anthropogenic influences (Fogt & Marshall, 2020; Fyfe, 2003, 2006). On the few small islands scattered across the Southern Ocean, this has materialised in changes in a range of climate variables (Hodgson, 2009; Pendlebury & Barnes-Keoghan, 2007). Temperatures are increasing on all of the islands, although at varying rates (Nel et al., 2023). Changes in precipitation have been more complex, with some islands drying and others getting wetter (Frenot et al., 1997; le Roux & McGeoch, 2008a; Manton et al., 2020; Smith, 2002). Changes in other climate variables, such as wind and cloud cover, have also been reported (Adams, 2009; le Roux & McGeoch, 2008a).

Quantifying the direction and magnitude of these changes in local climate is essential for predicting how species on the islands will respond and what consequences this will have for Southern Ocean Island (SOI) ecosystems. Species on these islands may be particularly vulnerable to climate change for several reasons. Small islands tend to host only small populations of species, which are more prone to the effects of stochastic events and inbreeding and less able to adapt to environmental change, making them more vulnerable to extinction (Matthies et al., 2004; Willi et al., 2006). The small size of the islands also limits the availability of suitable habitats for species' range shifts in response to climate change and reduces opportunities for microrefugia (Christmas et al., 2016). Many species are endemic to the region or particular islands and, therefore, have only a narrow geographic range, a factor associated with a low potential to adapt to environmental changes (Sheth & Angert, 2014; Valladares et al., 2014).

Many of these islands have weather stations that have been actively recording data for several decades, some for more than 70 years. These meteorological records represent the few long-term *in situ* climate records across the region and have been a valuable data source for quantifying climate changes. Much of this previous research has focused on single islands (e.g. Adams, 2009; le Roux & McGeoch, 2008a; Smith, 2002), making it difficult to directly compare changes across the region. Pendlebury and Barnes-Keoghan (2007) investigated the climate of the SOIs and a comparison of temperature and precipitation changes on two islands (Marion and Macquarie Island). Nearly two decades have passed since these early studies. There is now more data to investigate these trends, and further changes may have occurred over the last two decades. More recent analyses have looked at trends in individual climate variables, including temperature (Nel et al., 2023; Richard et al., 2013) and precipitation (Manton et al., 2020) on multiple islands across the Southern Ocean region.

Different climate variables interact in ways that are critically important to biodiversity, and a multivariate approach to understanding the climate niche of species and local climate changes is important (Lomolino et al., 2006). For example, wind stress plays a significant role in determining species richness, vegetation cover, and species composition on the SOIs (Momberg et al., 2021) and has been shown to be undergoing significant changes (le Roux & McGeoch, 2008a). While poleward and upslope range shifts are typically expected in response to warming, changes occurring in other climate variables, such as wind, can put constraints on this and result in unexpected species responses (Rapacciuolo et al., 2014; Srivastava et al., 2021). A decoupling of climate variables can also result in greater exposure to climate change than would be expected solely from temperature changes, as species that are adapted to survive under a particular combination of climate variables may quickly find themselves in novel climatic conditions (Vanderwal et al., 2013; Williams & Jackson, 2007).

An analysis of climate change that doesn’t consider a wide range of variables is likely to underestimate the exposure of species to climate change. The interactions between changing climate variables can also result in complex and unforeseen impacts. Concurrent changes in environmental variables can be difficult for species to adapt to, as phenotypic changes in response to one stressor may make an individual poorly adapted to other stressors (Côté et al., 2016; Valladares et al., 2007). Moreover, the effect of multiple environmental stressors can often be non-additive, resulting in significant impacts under seemingly trivial climate changes (Srivastava et al., 2021). An example from the SOIs that highlights the importance of these climatic interactions is the island-wide dieback of the Macquarie Island endemic *Azorella macquariensis*, which is believed to be the result of a pathogenic outbreak, triggered first by drought-like conditions but then exacerbated through wetter and warmer seasons (Dickson et al., 2021).

Another essential consideration when quantifying climate change impacts on biodiversity is the biological relevance of the parameters being investigated. Many studies focus on trends in monthly or yearly averages, effectively ignoring climate variability, which can often have more relevance to species' fitness and survival (Sher et al., 2004). Extreme weather events represent one such facet of climate variability and are increasingly being recognised as crucial for climate change biology (Jentsch et al., 2007; Knapp et al., 2008). Despite this, these biologically-relevant factors and their implications for biota have rarely been explored on the SOIs (but see le Roux & McGeoch, 2008a; van der Merwe et al., 2024).

Here, we provide a comprehensive overview of biologically-relevant climate parameters and their recent changes on nine SOIs using weather station data records from each site. Specifically, we (1) quantify the multivariate climate signature of each island, (2) compare the islands' climate signatures across the region, and (3) examine trends in the biologically-relevant climate parameters of each island and (4) differences in climate change trends across the region. These trends are used to consider how climate change varies across the Southern Ocean region and the consequences for SOI biodiversity.

2 Methods

2.1 Study system

The SOIs are most broadly considered to be the isolated islands between the latitudes 40-60°S, including Amsterdam and Saint Paul Islands and the Tristan da Cunha archipelago, which lie slightly north of 40°S (Fig. 1). In this group, long-term weather station records were available for Macquarie Island, the Prince Edward Islands, the Crozet Islands, the Kerguelen Islands, the Auckland Islands, the Falkland Islands, Gough Island, and Amsterdam Island (Table 1). South Georgia has hosted long-term weather stations, but available records did not cover a comprehensive range of climate variables.

The climate of the islands in this region is typically described as cold, wet, and windy, with a strong oceanic character that results in low daily and seasonal temperature variation (Convey & Biersma, 2024; Selkirk, 2007), heavily influenced by their proximity to a set of frontal systems. The most prominent of these fronts is the Antarctic Polar Front (APF) (Fig. 1), where cold waters flowing north from the Antarctic continent meet the warmer waters of the sub-Antarctic (Freeman et al., 2016), resulting in a sudden drop in sea surface temperature of about 2°C when crossing from north to south (Selkirk et al., 1990). The meeting of warmer air moving poleward and colder air from Antarctica drives strong westerly winds across the Southern Ocean (Turner & Marshall, 2011). These winds are experienced persistently on the SOIs due to the absence of obstructing land masses across the Southern Ocean (Bonan, 2015; Hall & Visbeck, 2002). The high latitude of these islands means that they also experience considerable seasonal variation in day length.

2.2 Meteorological data

Weather station records were used to investigate the climate and climate trends of the islands (Fig. 1). The data used here were supplied by the various organisations of administering countries (Table 1). These were the Australian Bureau of Meteorology (http://www.bom.gov.au/; data sublicensed by the Australian Antarctic Data Centre), the New Zealand National Institute of Water and Atmospheric Research DataHub (https://data.niwa.co.nz/; previously 'CliFlo'), the South African Weather Service (https://www.weathersa.co.za/), Météo-France (https://donneespubliques.meteofrance.fr/), and the United Kingdom Met Office Integrated Data Archive System (MIDAS) Land and Marine

Surface Stations Data (Met Office, 2012). The Falkland Islands have multiple weather stations, and the station at RAF Mount Pleasant had the longest and most complete meteorological record and was chosen as the data source.

Data records from the beginning of 1950 until the end of 2022 were extracted for daily measurements of total precipitation, maximum temperature, minimum temperature, relative humidity, wind speed, gust speed (the speed of the maximum wind gust), and total sunshine hours (Table S1). Daily minimum and maximum temperatures were used in place of daily mean temperature as they are more informative of biological responses (Braganza et al., 2004; Easterling et al., 2000) and were also more consistently available for these islands.

The measurements available include single values taken across a 24-hour period (e.g. maximum temperature, total precipitation) and spot measurements taken at a specific time every day (e.g. relative humidity at 09:00). To make the data comparable between islands, the spot data used here are the records from 09:00 local time, except for Marion Island, where records were taken from 08:00 local time instead, as this was the closest time available from these records. Temporal data coverage differed considerably between islands and across climate variables primarily due to the different histories of weather stations and recording instruments on each island (Fig. S1). The switch to an automatic weather station (AWS) on Campbell Island in the 1990s resulted in two separate data records and station identifiers, although both stations had the same coordinates (McGlone et al., 2007). The two were merged to create a single climate record, favouring the data from the newer AWS record when they overlapped.

The *homogen* function of the ‘climatol’ package (Guijarro, 2024) in RStudio v4.3.2 (RStudioTeam, 2020) was used to remove large outliers, impossible values (e.g. relative humidity > 100%), and instances of many consecutive identical values in time series resulting from issues with instruments or errors during data recording. Small gaps in the data were estimated based on the rest of the time series and concurrent data from other stations (Guijarro, 2023). This allowed for a more complete time series and the inclusion of more months and years in analyses. Sections of records with very few values and large gaps were removed. Changes in instrumentation and exposure of weather stations (e.g. due to newly constructed buildings) can result in data shifts and trends that may be incorrectly attributed to climate change (WMO, 2020). Homogenisation of the data can correct for these step changes but was not possible due to the paucity of nearby weather stations required as reference points.

2.3 Climate parameters

A set of annual climate parameters was calculated based on the daily climate variable data (Table 2). This set of parameters consists of eight indices developed by the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDI, Karl et al., 1999) and 24 parameters that are of general interest to climate change research and are not captured by the ETCCDI indices, some of which are based on those used by le Roux and McGeoch (2008a). ETCCDI indices were calculated using the 'RClimDex' package (Zhang et al., 2018) in RStudio v4.1.2.

2.4 Data analysis

The climate of each island was characterised by calculating mean values for all climate parameters based on the latest 10 years of data. Principal component analysis (PCA) was used to visualise and compare climatic differences between islands. A subset of climate parameters was used for this, as there was a high degree of correlation between parameters related to the same climate variable (Fig. S2). For example, islands with higher mean wind speeds generally had higher gust speeds, and islands with higher total precipitation generally had heavier and more frequent precipitation events. Consequently, a complementary subset of parameters was chosen to represent basic measures of each variable that reflect the main climatic differences between islands.

Bootstrapped linear regression models were used to quantify trends in annual climate parameters over time. Bootstrapping was necessary as the data for some parameters violated the assumptions of normality (Hesterberg, 2011). Generalised additive models (GAMs) were also fit to each relationship to identify non-linearity in trends.

PCA was conducted on decadal means of climate parameters for each island to visualise and compare the direction and magnitude of climate changes. This was done using a subset of parameters for temperature and precipitation as these were the most complete records across islands and represent the two most important climate variables for determining species niches (Hawkins et al., 2003; McCain, 2007; Moles et al., 2014). Mean minimum and maximum temperatures were highly positively correlated, and only mean maximum temperature was used as a result. Consecutive wet days was highly negatively correlated with consecutive dry days and so only consecutive dry days was used.

3 Results

3.1 Comparison of island climates

The vast majority of climatic variation (82.92%) between islands was captured by the first two principal components of PCA (Fig. 2b). Two key axes of climatic variation emerged from this. The first reflected variation in diurnal temperature range (DTR), sunshine hours, and parameters related to the precipitation regime (PC1 – 54.65% of variation explained), though notably not total precipitation. Islands with more dry days and longer dry periods had shorter wet periods and tended to experience a higher diurnal temperature range and more sunshine hours. The second axis reflected variation in minimum and maximum temperature, wind speed, and total precipitation to a lesser extent (PC2 – 28.27% of variation explained). Warmer islands tended to experience higher precipitation and had lower wind speeds.

Based on the climatic differences between islands illustrated in Fig. 2, these islands can be roughly characterised into four groups. The first includes the Falkland and Kerguelen Islands, which shared a very similar climate that is relatively cold, dry, and windy, with fewer sunshine hours and a greater diurnal temperature range than the other islands. The second group includes Gough and Amsterdam Island, which had much higher temperatures and generally experienced lower wind speeds than all the other islands. These two islands did, however, differ considerably in their precipitation regimes, with Gough much wetter than Amsterdam and having the highest annual total precipitation of all islands. The third group of islands consists of Macquarie and Campbell Islands, which had a cold, wet, windy climate with a relatively low diurnal temperature range and few sunshine hours. Although these islands did not have the highest annual total precipitation, they had the most frequent and intense (i.e. high precipitation during precipitation events) precipitation regimes. The fourth group of islands consists of Marion Island and the Crozet Islands, which fell somewhere between the Macquarie-Campbell and Falkland-Kerguelen groups. Their climate was colder than Macquarie-Campbell, with a greater diurnal temperature range and higher annual total precipitation but less frequent and intense precipitation regimes and more sunshine hours than Campbell-Macquarie.

3.2 Temperature trends

Trends in climate parameters for islands are summarised in Fig. 3, and details of linear regression models and GAMs, as well as plots of significant linear regression models, can be found in the supplementary material (Table S2-S3, Fig. S3-S11)

Temperature trends were the most consistent changes across islands (Fig. 3a). Maximum and minimum temperature have increased significantly on all islands except Falkland, where only maximum temperature has increased significantly. These trends have generally been linear, except for on the Auckland Islands. Rates of minimum and maximum temperature increase varied between islands by up to 4-fold in some cases. However, it should also be noted that the length of records can differ considerably between islands (Fig. S1). These trends can, therefore, be potentially more reflective of shorter-term fluctuations than rates of long-term trends. For example, Auckland had high rates of change but relatively short records. Increases in maximum and minimum temperature have been significant during summer and winter on most islands, though with some exceptions (Fig. 3a). For example, on Crozet, significant changes have occurred only in the summer. These were, again, largely linear trends except for a few cases, such as Auckland and Amsterdam.

Changes in the coefficient of variation (CV) indicate that maximum and minimum temperature have either become significantly less variable or not changed significantly (Fig. 3a). Decreases in CV have been more common for minimum (7/9 islands) than maximum temperature (3/9 islands). Diurnal temperature range (DTR) has increased significantly on Marion, Amsterdam, and Falkland, potentially due to the greater rate of increase in max temperature compared to min temperature on these islands. In contrast, DTR has decreased on Campbell and Auckland, where minimum temperature has increased at a greater rate than maximum temperature, though this has not been a linear trend on Auckland. On Macquarie, Kerguelen, and Crozet, maximum and minimum temperature have increased at similar rates, and DTR has not changed significantly. Growing season length has increased as a result of rising temperatures on Campbell, Marion, Auckland, and Kerguelen.

3.3 Precipitation trends

Trends in precipitation have varied considerably between islands (Fig. 3b). On Campbell, Auckland, and Gough, there have been significant changes in only a single climate parameter, and on Falkland, there have been none. Macquarie has experienced a significant increase in total precipitation, occurring during both the summer and winter. This increase appears to be a result of more frequent precipitation events (i.e. fewer dry days) and increasing intensity of precipitation events (i.e. more precipitation during precipitation events). In contrast, Marion, Amsterdam, Crozet, and Kerguelen have all experienced significant decreases in total precipitation, which has occurred primarily during the summer in all cases and also during the winter on Marion. This drying trend is least explicit on Kerguelen, where the primary decrease in precipitation occurred during the 1950s and 1960s, followed by shorter-term fluctuations rather than a clear negative linear trend. However, there has been a somewhat consistent and linear increase in the number of dry days on the island.

Marion and Crozet have undergone by far the most extreme changes in precipitation including the highest rates of change in total precipitation (decrease of 91.2 and 148 mm per decade, respectively) (Fig. 3b). On these islands, the decrease in total precipitation has resulted from precipitation events becoming less frequent and less intense. In addition, there has been a significant increase in the length of periods without precipitation (i.e. increasing consecutive dry days) and, on Marion, a decrease in the length of periods with precipitation (i.e. decreasing consecutive wet days). The decrease in total precipitation on Amsterdam is primarily a consequence of less intense precipitation events rather than less frequent precipitation events. There have also been significant changes in the variability of precipitation on islands, becoming less variable on islands that have become wetter and more variable on those that are now drier.

3.4 Wind trends

Trends in wind parameters were complex (Fig. 3c). Significant changes in mean wind speed include an increase on Macquarie and Falkland and a decrease on Campbell. Trends in gust speeds did not necessarily occur alongside or match those of mean wind speed. For example, maximum gust speed has decreased significantly on Macquarie despite mean wind speed increasing. On Crozet, only gust speed has increased significantly. On Amsterdam and Kerguelen, significant changes have only occurred in max gust speed, but this represents a rapid decrease early in the records rather than a consistent linear trend. Linear models indicated significant changes in wind parameters on Marion; however, these trends all show substantial fluctuations that depart substantially from a linear trend. This could be a result of instrumentation errors rather than reflecting actual trends in these parameters and is most evident in the very low values for wind speed starting in the 1960s and running until the late 1980s. Consequently, it is not possible to determine long-term trends from this data.

Significant inclining trends in wind chill (i.e. becoming less severe) is most common, largely irrespective of changes in wind, indicating that rising temperatures are primarily responsible (Fig. 3c). These changes have occurred under variable combinations of mean and minimum wind chill and the number of extreme wind chill events on each island. In some cases, these trends have not been linear but decreased early in the records and fluctuated substantially over time. On Marion, this is true of mean wind chill, which is, again, likely a result of instrumental changes for wind speed measurement on the island.

3.5 Other trends

There were few significant changes in the number of sunshine hours, with a decrease only on Campbell and an increase, and increase in variability, on Macquarie (Fig. 3d). All islands with significant changes in relative humidity have experienced a decline. On Campbell, this has not been a linear change, and the same is true for the decrease in variability of relative humidity on Marion and Gough. The number of high evaporation events has decreased on Campbell, Macquarie, and Kerguelen and increased on Marion.

3.6 Decadal shifts in climate

Shifts in the climate of islands across decades, based on a subset of key parameters, are shown in the PCA of Fig. 4. PC1 explains 51.96% of the variation between decades and is most associated with changes in precipitation regime (consecutive dry days, number of dry days). PC2 explains 26.68% of the variation between decades and is most associated with changes in temperature and total precipitation.

Multivariate changes in climate on some islands have largely been unidirectional shifts. Marion and Crozet have shifted consistently and experienced similar changes, including a large change in climate from the 1980s to the 1990s. Consequently, these islands have remained relatively climatically similar to each other. Amsterdam has also undergone climate changes in a consistent direction. The climate shifts of Macquarie and Campbell have followed similar patterns to each other, showing a change in one direction before shifting in the opposite direction. Auckland has not necessarily experienced the same pattern of climate changes as neighbouring Macquarie and Campbell, though it is difficult to make this comparison due to the shorter record for these islands. These changes do show a large change in climate from the 1990s to the 2010s and then back again in the 2020s. Kerguelen and Falkland have similar climates and have both undergone major changes, but in different directions. These island groups have largely maintained a similar climate relative to each other. Compared with the other islands, the climate of Gough appears to have shifted considerably less, and these changes do not show a clear direction of change.

4 Discussion

4.1 The climate of the Southern Ocean Islands

The climates of the SOIs are commonly described as wet, windy, cold, and oceanic (Convey & Biersma, 2024; French & Smith, 1985; Pendlebury & Barnes-Keoghan, 2007; Selkirk, 2007). Here, we show that, while this is very broadly true in comparison with other global regions, there is considerable climatic variation between the SOIs. Climatic differences are marked, even between those considered part of the 'core' group of sub-Antarctic islands (Marion Island, Macquarie Island, the Crozet Islands, the Kerguelen Islands) (Convey & Biersma, 2024).

As expected, the lower-latitude Gough and Amsterdam Islands experience much higher temperatures than the other islands, with the latter being decidedly warmer. Despite these temperature differences, these islands experience similar daily temperature variation to the colder islands due to the shared characteristics of oceanity. Gough and Amsterdam were also notably less windy than the other islands, reflecting their position further from the high wind systems of the 40-60°S region (Freeman et al., 2016; Turner & Marshall, 2011). The much higher total precipitation of Gough, despite similar precipitation regimes, likely reflects the disparate positions of these islands and the climatic manifestations of global circulation patterns and ocean currents that contribute to variable precipitation across the Southern Ocean (Adams, 2009; Manton et al., 2020).

Localised climates of the Southern Ocean are also apparent in other islands. Macquarie, Campbell, and the Auckland Islands are located in the Pacific Ocean sector of the Southern Ocean and are climatically similar relative to the other SOIs. Likewise, Marion and Crozet, in the Indian Ocean sector, share a similar climate that differs somewhat from the islands in the Pacific Ocean sector. Precipitation is the biggest difference between these groups. The Indian Ocean sector receives more rain in total, but the Pacific Ocean sector has more frequent rainfall and fewer hours of sunshine.

Although precipitation differs markedly between Pacific and Indian Ocean groups, temperature differences are less consistent. Macquarie experiences similar temperatures to Marion and Crozet, while Campbell and Auckland are notably warmer despite occupying a higher latitude than Marion and the Crozet Islands. Marion, Macquarie, and Crozet are closer to the APF than Campbell and Auckland, which could explain this temperature difference. Alternatively, this could be due to Campbell and Auckland lying closer to larger continental landmasses.

Interestingly, the islands in the Pacific Ocean sector experience less daily temperature variation than those in the Indian Ocean sector. An important consideration here is that the climate of Marion and Crozet, in the Indian sector, has shifted considerably over the last several decades and appears to have previously more closely resembled that of islands in the Pacific Ocean sector.

Kerguelen has a climate that is markedly different from Marion and Crozet, despite occupying a similar position in the Indian Ocean sector. Kerguelen more closely resembles the Falkland Islands and is considerably colder and drier than islands at similar latitudes. Notably, Kerguelen is the only island looked at here that is south of the APF. There is some evidence to suggest that climate changes in this region of the Southern Ocean have differed on either side of the APF (Freeman et al., 2016). The colder and drier climate of the Falkland Islands is likely due to their proximity to the South American continent, which lies in the path of the region's eastward-flowing oceanic and atmospheric circulations (Bonan, 2015; Hall & Visbeck, 2002). The rain shadow effect of the Andes Mountain range reduces precipitation reaching the islands (Clapperton, 1990). While this proximity could also explain the warmer temperatures of Falkland, it does not appear to result in a higher diurnal temperature range, which might be expected. On the other hand, a higher diurnal temperature range is a notable feature of Kerguelen relative to the other similarly isolated islands looked at here. This demonstrates the complexity of the factors that determine the SOIs.

The data used here to characterise the climate of these islands represents the climate at one specific location on each island (Potter et al., 2013). Topographic factors can contribute to large differences in climate, which means that conditions at one location may poorly represent the general climate of the whole island (Geiger et al., 2012). This is particularly relevant for Kerguelen. The weather station at Port-aux-Français, on the eastern side of the archipelago, has been noted to be particularly dry relative to much of the archipelago due to strong Föhn effects (Frenot et al., 1998; Frenot et al., 2001). This could contribute to the apparently different climate from nearby Marion and Crozet. However, the fact that nearby islands cluster together in the analysis (e.g. Marion and Crozet, Macquarie and Campbell) is strong evidence that the vast majority of differences in climate between islands are likely due to localised weather systems.

4.2 Comprehensive warming across the Southern Ocean

The climates of all the islands investigated here have undergone significant warming, though at different rates. The highest rates of warming have been on Auckland and the Falklands. These are short records compared to the other islands, and the high rate likely reflects the higher rates of temperature increase noted in the region in recent years (Nel et al., 2023). Amsterdam has experienced an exceptionally high rate of maximum temperature increase (+0.23°C $10y^{-1}$), while the lowest overall temperature changes have been on Crozet, Campbell, and the Falklands. The rate of temperature increases on these islands have generally been lower than the global average surface air temperature (+0.186°C $10y^{-1}$, from 1976-2005) (Bokuchava & Semenov, 2021), though they are generally warming at a greater rate than the coastal Antarctic to their south (+0.08°C $10y^{-1}$) (Jacka et al., 2004). In contrast, these rates are much lower than high latitudes of the Northern Hemisphere, such as on Svalbard (+0.6°C $10y^{-1}$) (Piskozub, 2017), though the Arctic is experiencing some of the highest rates of warming across the globe due to Arctic Amplification (Rantanen et al., 2022; Walsh, 2014). Warming rates on the SOIs are more comparable to the alpine regions of the Swiss Alps (+0.14°C $10y^{-1}$) and the Hindu Kush-Himalayas (+0.104°C $10y^{-1}$) (Körner, 2021). Interestingly, rising temperatures have generally only increased the growing season on the colder islands (Macquarie, Marion, Kerguelen, Campbell), as the warmer islands already experience very few days in which temperatures are unsuitable for growth. Trends in growing season length have been consistent and substantial, increasing by around one day per year on average.

Investigating minimum and maximum temperature in addition to mean temperature has yielded valuable insights, including different rates of increase of these parameters. On all islands, maximum temperature has increased faster than minimum temperature. This contrasts with the trend of minimum temperatures increasing faster than maximum temperatures which has occurred across much of the globe, though this seems to have decreased since the 1980s (Alexander et al., 2006; Vose et al., 2005). Under a warming scenario, maximum temperatures are a key determinant of when organisms will reach their thermal limits (Jentsch et al., 2007; Kingsolver et al., 2013; Román-Palacios & Wiens, 2020). In cold climates, however, minimum temperatures can be a more important environmental filter in determining species composition within communities (Körner, 2023). Therefore, the increase in minimum temperature may be more consequential for changes in community composition and species ranges.

The more rapid increase in maximum temperature relative to minimum temperature may be partly responsible for the increase in diurnal temperature range (DTR) on Marion, Amsterdam, and Falkland. Studies have noted a general decrease in DTR across the globe, in contrast with the increase in DTR observed here for the SOIs (Alexander et al., 2006; Vose et al., 2005). These changes importantly highlight that organisms on these islands are experiencing not only higher temperatures but also a wider range of temperatures. Furthermore, this shift represents another departure from the defining characteristics of the region's climate, as conditions on these islands become both warmer and less equable.

4.3 Localised precipitation trends

While temperatures have increased across the board on these islands, precipitation trends have varied substantially between islands in different regions of the Southern Ocean. Marion, Amsterdam, and Crozet in the Indian Ocean sector have all experienced drying trends with substantial decreases in total precipitation. This trend has been most extreme on Marion, where precipitation has decreased on average by around 1000 mm since 1950. This appears to be a consequence of decreasing precipitation during summer and winter, whereas on Amsterdam and Crozet, significant drying has only occurred in the summer. Unlike these neighbouring islands, Kerguelen has not experienced consistent drying, outside of an increase in the number of dry days. The drastic decrease in precipitation on Kerguelen during the 1950s and 1960s may represent a shift from a previously much wetter climate, or alternatively, the 1950s may have been an exceptionally wet decade. One possible reason why the Kerguelen Islands have not undergone the same drying trends seen on other nearby islands may, again, be related to the position of this island group south of the APF.

In contrast to the drying occurring on islands in the Indian Ocean sector, Macquarie has experienced an increase in precipitation since 1950. The changes responsible for this increase appear to be an increase in both the intensity and frequency of precipitation events. Despite this trend towards a wetter climate, relative humidity has declined, probably as a consequence of the island's warming. Neighbouring Campbell has seen a decrease in the number of dry days, much like Macquarie, suggesting some change in the precipitation regime. There have been no significant precipitation changes on neighbouring Auckland Island, though the precipitation record for this island is relatively short. This may be because these islands are considerably further north than Macquarie, despite being in the same Pacific Ocean sector.

The direction of trends in precipitation observed here typically agrees with those based on reanalysis data products, most notably an increase in precipitation in the Pacific Ocean sector and a decrease in precipitation in the Indian Ocean sector (Manton et al., 2020). This strong regionality in climate changes indicates that conditions on Heard and McDonald Islands may also be getting drier, which would be a valuable insight given the absence of long-term climate records for these islands. However, there is considerable disagreement between weather station records and reanalysis products on the magnitude of these precipitation trends. Siems et al. (2022) note a roughly four times greater precipitation increase observed in the Macquarie meteorological records than that estimated by reanalysis data. Weather station data are undoubtedly susceptible to orographic effects yet, even given the possibility that these records may be somewhat overstating the rate of change occurring on these islands, these trends still strongly indicate alarming changes in precipitation regimes occurring across the islands. Furthermore, satellite-based and reanalysis products for precipitation over the Southern Ocean are prone to high uncertainty for a number of reasons (Siems et al., 2022).

4.4 Wind and other parameters

Changes in wind on the islands have been complex. Most islands have experienced changes in wind or gust speed; however, trends vary substantially between islands. Despite the long record of wind and gust speed recordings on Marion Island, long-term trends on the island are indiscernible due to issues with the data record. Analysis of remotely sensed data found significant short-term variation in wind speeds around Marion Island but a long-term trend was not discernible, suggesting there have not been any significant and consistent changes (Toolsee & Lamont, 2022). This also fits with the inconsistent or absent trends in wind speeds on nearby Amsterdam, Kerguelen, and Crozet Islands, further supporting the idea that winds have not changed substantially in the Indian Ocean sector of the Southern Ocean.

The increase in sunshine hours on Macquarie is surprising given that precipitation has increased on Macquarie Island. It is also surprising that sunshine hours have not increased on Marion, Amsterdam, and the Crozet Islands, given that precipitation has decreased considerably.

4.5 Implications of climate changes in the sub-Antarctic

Differences in climate change direction (e.g. wetting vs drying), patterns (e.g. less frequent precipitation vs less intense precipitation), and combinations (e.g. changes in wind chill depend on changes in temperature and wind speed) will mean differences in climate change exposure on each island. This highlights the caution that must be taken when generalising climate change and its impacts across the region (Adams, 2009).

Some of the climate changes occurring may be particularly consequential in the context of the SOIs as they are of a higher magnitude relative to historical conditions to which species are adapted. This is the case for islands where temperature and DTR have increased. For example, on Amsterdam, the more than 1°C increase in DTR since the 1950s equates to a ~25% greater DTR experienced on the island. Similarly, high evaporation events were rare on Campbell and Macquarie around the 1960s (<10 per year) but trends indicate these events may soon disappear completely. These islands also experience very little direct sunlight daily; therefore, changes in sunshine hours may be low but still represent a substantial shift. In contrast, changes in precipitation may be less impactful initially, as annual precipitation is high on these islands. Likewise, plants on the islands are experiencing warmer temperatures for growth and have a longer growing season, yet growth may still be limited by low light availability in the winter.

Marion Island has undergone by far the most severe climate changes, largely due to the drastic drying trend that has occurred. Species on the island have much less water available, as well as being exposed to more frequent and longer periods of drought. Moreover, they are are now exposed to both higher temperatures and a wider range of temperatures. These simultaneous changes in variables are evident on all islands to an extent, and the effects of this for organisms can often be non-additive (Srivastava et al., 2021) and particularly challenging to cope with if adaptations are antagonistic to each other (Côté et al., 2016). Comparisons of historical and current vegetation have revealed substantial changes in vegetation on Marion Island which are likely, in part, a consequence of climate changes (le Roux & McGeoch, 2008b; van der Merwe et al., 2024). Macquarie Island is another island that has experienced a considerable climate shift through key changes in temperature, precipitation, wind, and sunshine hours, changes which have been implicated in the island-wide dieback of *A. macquariensis*. Other than these examples, however, evidence of climate change impacts on these islands is fairly limited. This suggests that these species and ecosystems possess some ability to cope with the environmental changes that have occurred. Alternatively, it's possible that changes have not been recognised due to a lack of long-term records on these islands and the confounding impact of invasive herbivores such as rabbits (Chapuis et al., 2004; Scott & Kirkpatrick, 2013).

An important consideration when investigating climate change exposure is that the conditions experienced by organisms are not the same as those experienced at weather stations. Microclimate conditions vary with the islands' topography and through interactions with other organisms. While the broader climate changes identified here are undoubtedly consequential, modelling these microclimates and how they are changing can provide even more valuable insight. Tools to allow for this are becoming increasingly available and ever-improving (Lembrechts et al., 2019). Coupling microclimate modelling tools with remotely sensed climate data can yield promising results (Zellweger et al., 2019). Such approaches have already been applied to the SOIs for temperature on Macquarie Island (Baker et al., 2021) and wind exposure on Marion Island (Goddard et al., 2022). Further application of these tools will help to better quantify climate change exposure at the community or individual level on the SOIs.

4.6 Conclusions

Understanding the biologically relevant climate changes that have occurred and are continuing to occur on islands in the Southern Ocean is a critical step in understanding how biodiversity on these islands will be impacted. The results presented here provide the first comparable analysis of such changes over a comprehensive range of important climate parameters. Across these islands, there have been changes in temperature, precipitation, and other important parameters, which will have various impacts on species, communities, and ecosystems. Distinct climate shifts are occurring on each island, highlighting the importance of considering these islands individually but also providing an opportunity to understand biodiversity responses to climate changes of different forms. Changes in the islands' climate signatures and individual parameters provide a valuable basis for predicting and testing the responses of the unique flora and fauna of the SOIs to climate change. These predictions can help to inform species vulnerability assessments and make effective climate-smart management decisions.

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Data availability: Data available on request.

Tables and figures

Table 1 The Southern Ocean Islands included in this analysis and details of their weather stations

Island	Latitude	Longitude	Abbreviation	Administrating country	Weather station			Data source
					Location	Elevation (m a.s.l)	Year established	
Macquarie Island	-54.63	158.86	MQ	Australia	Isthmus	6	1948	Bureau of Meteorology (Australia)
Marion Island (Prince Edward Islands)	-46.9	36.75	MA	South Africa	Transvaal Cove	24	1949	South African Weather Service
Gough Island	-40.32	-9.94	GO	United Kingdom	Transvaal Bay	54	1963	South African Weather Service
Kerguelen Islands	-49.25	69.17	KG	France	Port-aux-Français	29	1951	Météo-France
Possession Island (Crozet Islands)	-46.41	51.76	CR	France	Alfred-Faure	146	1974	Météo-France
Amsterdam Island	-37.83	77.55	NA	France	Martin-de-Viviès	27	1951	Météo-France
Campbell Island	-52.54	169.15	CA	New Zealand	Beeman Cove	16	1948	National Institute of Water and Atmospheric Research (New Zealand)
Auckland Islands	-50.7	166.1	AK	New Zealand	Enderby Island	39	1941	National Institute of Water and Atmospheric Research (New Zealand)
East Falkland (Falkland Islands)	-52	-59	FK	United Kingdom	RAF Mount Pleasant	73	1985	Met Office Integrated Data Archive System (United Kingdom)

Table 2 Climate parameters calculated for islands based on seven main climate variables. Parameters were calculated for each year of data. ETCCDI = Expert Team on Climate Change Detection, Monitoring and Indices (see methods for details)

Variable	Name	Description	Abbreviation	Unit	Raw Data	Derived from
Temperature	Mean maximum temperature	Mean maximum daily temperature	TXmn	°C	Max. temperature	None
Temperature	Maximum temperature coefficient of variation	CV of maximum daily temperature	TXcv	-	Max. temperature	None
Temperature	Mean minimum temperature	Mean minimum daily temperature	TNmn	°C	Min. temperature	None
Temperature	Maximum temperature coefficient of variation	CV of minimum daily temperature	TNcv	-	Min. temperature	None
Temperature	Mean maximum winter temperature	Mean maximum winter daily temperature	WTXmn	°C	Max. temperature	None
Temperature	Mean maximum summer temperature	Mean maximum summer daily temperature	STXmn	°C	Max. temperature	None
Temperature	Mean minimum winter temperature	Mean minimum winter daily temperature	WTNmn	°C	Min. temperature	None
Temperature	Mean minimum summer temperature	Mean minimum summer daily temperature	STNmn	°C	Min. temperature	None
Temperature	Growing season length	Annual (1st Jan to 31st Dec in NH, 1st July to 30th June in SH) count between first span of at least 6 days with TG > 5C and first span after 1st July (1st January in SH) of 6 days with TG < 5C	GSL	days	Max. temperature	ETCCDI
Temperature	Diurnal temperature range	Monthly mean difference between TX and TN	DTR	°C	Max. temperature, min. temperature	ETCCDI
Precipitation	Total precipitation	Annual total precipitation	Rt	mm	Precipitation	None
Precipitation	Total winter precipitation	Total precipitation during the period from April – September	WRt	mm	Precipitation	None
Precipitation	Total summer precipitation	Total precipitation during the period from October – March	SRt	mm	Precipitation	None
Precipitation	Precipitation coefficient of variation	CV of daily precipitation	Rcv	-	Precipitation	None
Precipitation	Number of days without rain (dry days)	Annual count of days with 0 mm of rain	Rdry	days	Precipitation	None
Precipitation	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	RX1day	mm	Precipitation	ETCCDI
Precipitation	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	RX5day	mm	Precipitation	ETCCDI

Table 2 (continued)

Variable	Name	Description	Abbreviation	Unit	Raw Data	Derived from
Precipitation	Number of heavy precipitation days	Annual count of days when PRCP >= 10mm	R10MM	days	Precipitation	ETCCDI
Precipitation	Number of very heavy precipitation days	Annual count of days when PRCP >= 20mm	R20MM	days	Precipitation	ETCCDI
Precipitation	Consecutive dry days	Maximum number of consecutive days with RR < 1mm	CDD	days	Precipitation	ETCCDI
Precipitation	Consecutive wet days	Maximum number of consecutive days with RR > 1mm	CWD	days	Precipitation	ETCCDI
Wind	Mean wind speed	Mean daily spot wind speed	WSmn	m/s	Wind speed	None
Wind	Mean gust speed	Mean speed of daily maximum wind gust	GSmn	m/s	Gust speed	None
Wind	Maximum gust speed	Annual maximum speed of daily maximum wind gust	GSX	m/s	Gust speed	None
Wind and temperature	Mean wind chill	Mean daily wind chill based on minimum daily temperature and mean daily wind speed. Calculation from National Oceanic and Atmospheric Administration (NOAA)	WCmn	Wind chill index	Wind speed, min. temperature	None
Wind and temperature	Minimum wind-chill	Lowest value of calculated wind chill.	MWC	Wind chill index	Wind speed, min. temperature	le Roux and McGeoch (2008a)
Sunshine	Mean sunshine	Mean daily sunshine hours	SNmn	hours	Sunshine	None
Sunshine	Sunshine coefficient of variation	CV of daily sunshine hours	SNcv	-	Sunshine	None
Relative humidity	Mean relative humidity	Mean daily spot relative humidity	RHmn	%	Relative humidity	None
Relative humidity	Relative humidity coefficient of variation	CV of daily spot relative humidity	RHcv	-	Relative humidity	None
Extreme events	Number of high evaporation events	Upper quartile of max temperature and wind speed. No rainfall.	HEE	days	Wind speed, Max. temperature, precipitation	le Roux and McGeoch (2008a)
Extreme events	Number of extreme wind-chill events	Lower quartile of min temperature and upper quartile of wind speed.	EWC	days	Wind speed, min. temperature	le Roux and McGeoch (2008a)

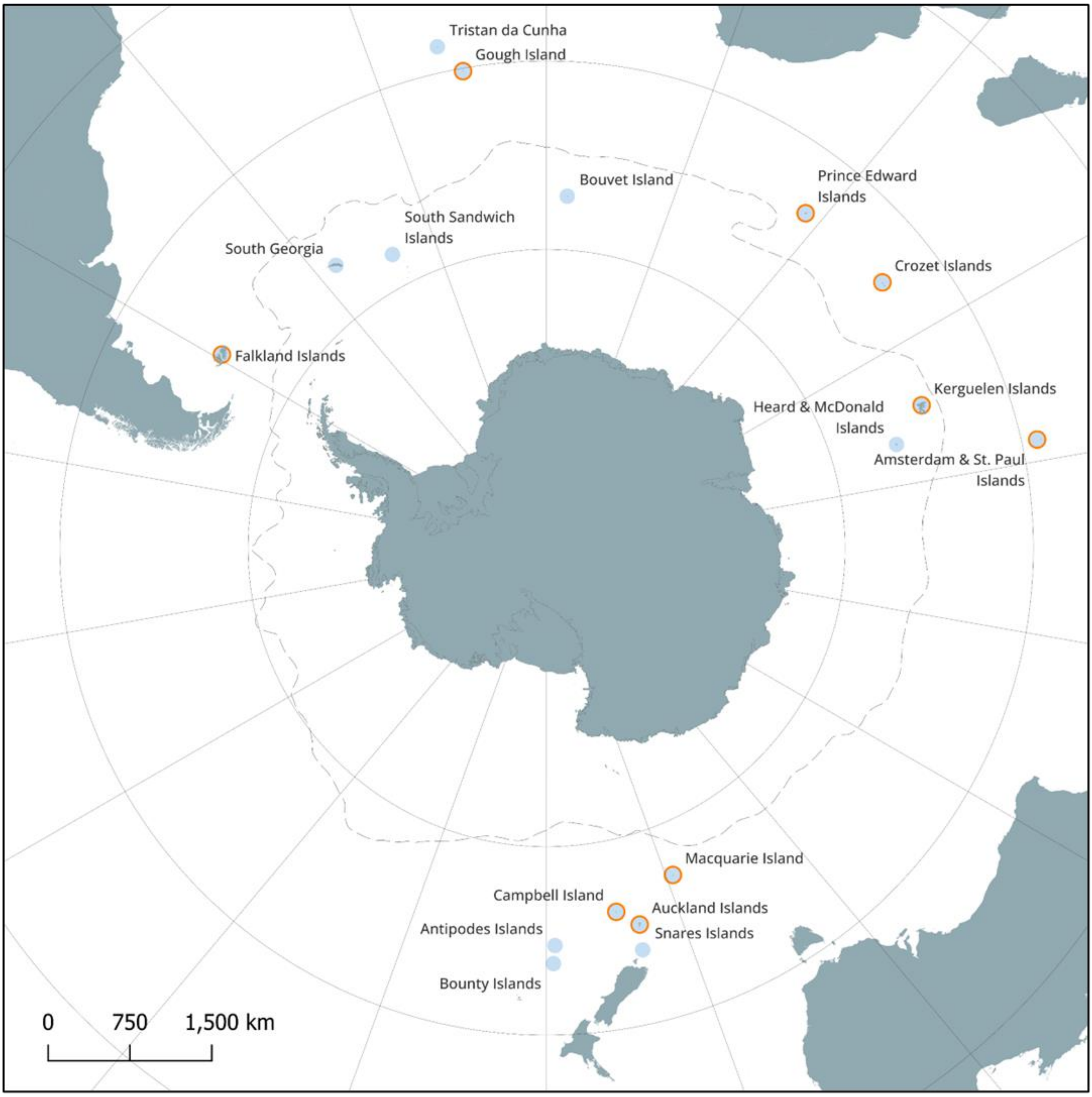

Fig. 1 The Southern Ocean with islands and island groups between ~ 40-60°S. The position of the Antarctic Polar Front (APF) is marked by a dashed line. Orange circles indicate the islands with meteorological records used in this study

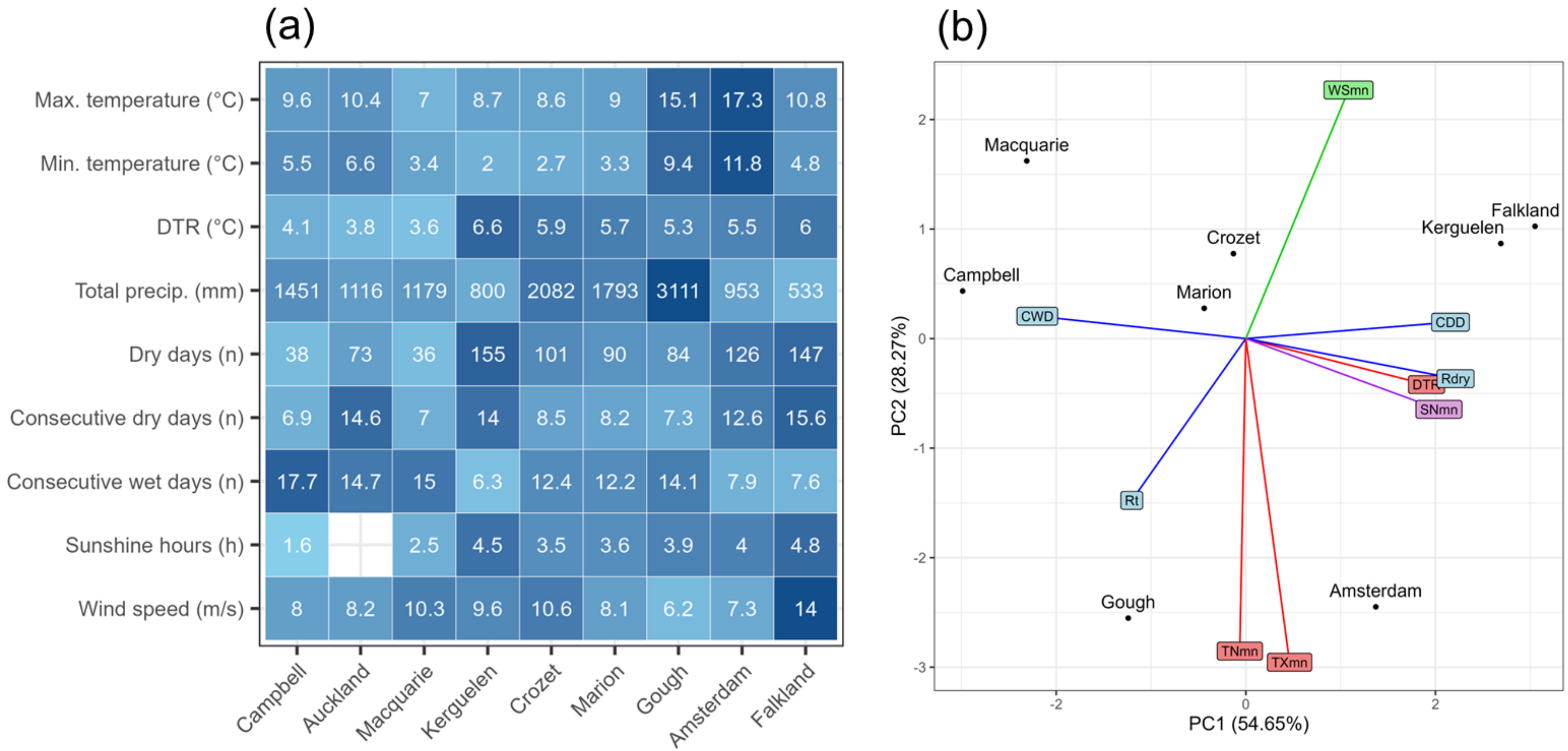

Fig. 2 Comparisons of the climate of the Southern Ocean Islands. **(a)** Mean values of key climate parameters for each island based on the most recent 10 years of available data. Darker coloured boxes indicate higher values of that parameter relative to other islands. No box indicates no data and as a result Auckland Island was excluded from the principal component analysis (PCA). **(b)** The first two PCA axes for the parameters in (a). The colour of loadings for parameters corresponds to their climate variable group: temperature (red), precipitation (blue), wind (green), and other (purple). Abbreviations for parameters are maximum temperature (TXmn), minimum temperature (TNmn), diurnal temperature range (DTR), total precipitation (Rt), number of dry days (Rdry), consecutive dry days (CDD), consecutive wet days (CWD), sunshine hours (SNmn), and wind speed (WSmn)

Temperature (a)

	CA	AU	MQ	KG	CR	MA	AM	GO	FK
Max. (°C)	0.05 0.11	0.22 0.28	0.1 0.27	0.17 0.38	0.07 0.08	0.17 0.46	0.23 0.58	0.19 0.5	0.31 0.28
CV	<0.01 0.04			0.01 0.12		<0.01 0.14			
Summer		0.18 0.17	0.11 0.26	0.22 0.51	0.11 0.11	0.18 0.4	0.27 0.6	0.24 0.54	0.34 0.19
Winter	0.07 0.16	0.26 0.29	0.08 0.18	0.12 0.15		0.17 0.39	0.19 0.39	0.13 0.21	0.26 0.16
Min. (°C)	0.13 0.39	0.33 0.51	0.08 0.21	0.14 0.52	0.07 0.09	0.1 0.3	0.08 0.14	0.13 0.18	
CV	0.02 0.21	0.03 0.28	0.02 0.07	0.19 0.33	0.03 0.09	0.02 0.27		0.01 0.17	
Summer	0.12 0.3	0.33 0.4	0.09 0.18	0.17 0.62	0.11 0.17	0.12 0.26	0.08 0.14	0.17 0.36	0.2 0.11
Winter	0.15 0.33		0.08 0.12	0.11 0.26		0.09 0.21	0.08 0.09	0.15 0.22	
DTR	0.08 0.32	0.12 0.2				0.07 0.35	0.15 0.62		0.32 0.66
GSL	7.6 0.22		9.06 0.09	9.42 0.16		11.2 0.13			
	Pacific			Indian				Atlantic	

Precipitation (b)

	CA	AU	MQ	KG	CR	MA	AM	GO	FK
Total (mm)			39.5 0.37	31.1 0.09	91.2 0.11	148 0.71	25.3 0.16		
CV			0.02 0.07	0.04 0.12	0.03 0.09	0.03 0.2			
Summer			15.7 0.18	14.5 0.09	53.1 0.12	78.3 0.6	17.3 0.14		
Winter			23.7 0.31			69.8 0.58			
Dry days	1.56 0.08		2.67 0.14	5.61 0.22	11.1 0.27	7.42 0.54	1.95 0.08	3.13 0.18	
CDD					1.13 0.06	0.54 0.1			
CWD		1.04 0.12				1.1 0.27			
Max. 1-day (mm)					2.83 0.08		2.32 0.07		
Max 5-day (mm)			1.5 0.09		4.62 0.07	4.77 0.11	4.07 0.09		
Heavy days			1.26 0.3		3.7 0.11	5.37 0.65	1.02 0.13		
V. heavy days			0.24 0.08			2.94 0.6			
	Pacific			Indian				Atlantic	

Wind (c)

	CA	AU	MQ	KG	CR	MA	AM	GO	FK
Wind speed (m/s)	0.21 0.38		0.2 0.32			0.35 0.09			0.25 0.09
Gust speed (m/s)	0.29 0.12				0.39 0.1	0.26 0.05			
Max. gust (m/s)			0.92 0.23	1.62 0.31		0.79 0.07	0.79 0.12		
Wind chill	0.13 0.17	0.48 0.43		0.22 0.19		0.37 0.2		0.28 0.31	
MWC	0.34 0.12							0.34 0.09	0.7 0.12
EWC	4.91 0.38			4.77 0.16		1.24 0.21	6.21 0.46	1.76 0.2	
	Pacific			Indian				Atlantic	

Other (d)

	CA	AU	MQ	KG	CR	MA	AM	GO	FK
Sunshine hours	0.05 0.11		0.08 0.31						
CV			0.02 0.17						
Relative humidity (%)	0.59 0.26		0.39 0.15				1.53 0.34	0.96 0.32	
CV		0.03 0.33				<0.01 0.17		<0.01 0.16	
HEE	0.27 0.1		0.63 0.28	1.85 0.16		0.5 0.19			
	Pacific			Indian				Atlantic	

Fig. 3 Local climate trends for Southern Ocean Islands. Coloured cells indicate significant trends from bootstrapped linear regression models, with green positive trends and orange negative trends. Values in the top left of cells are linear rates of change multiplied by ten, denoting the estimated change in parameter over a decade. R-squared values for models are shown in the bottom right of each cell. Lines in cells indicate the general shape of the relationship in cases that these depart substantially from a consistent linear trend. Full details of linear regression models and GAMs, as well as plots of significant linear models can be found in the supplementary material (Table S2-S3, Fig. S3-S11). Labels at the bottom of the plot are the ocean regions which islands are in. Island abbreviations are Campbell Island (CA), Auckland Island (AU), Macquarie Island (MQ), Kerguelen Islands (KG), Crozet Islands (CR), Marion Island (MA), Amsterdam Island (AM), Gough Island (GO), and Falkland Islands (FK). Parameter abbreviations are coefficient of variation (CV), diurnal temperature range (DTR), growing season length (GSL), consecutive dry days (CDD), consecutive wet days (CWD), minimum wind chill (MWC), extreme wind chill events (EWC), and high evaporation events (HEE)

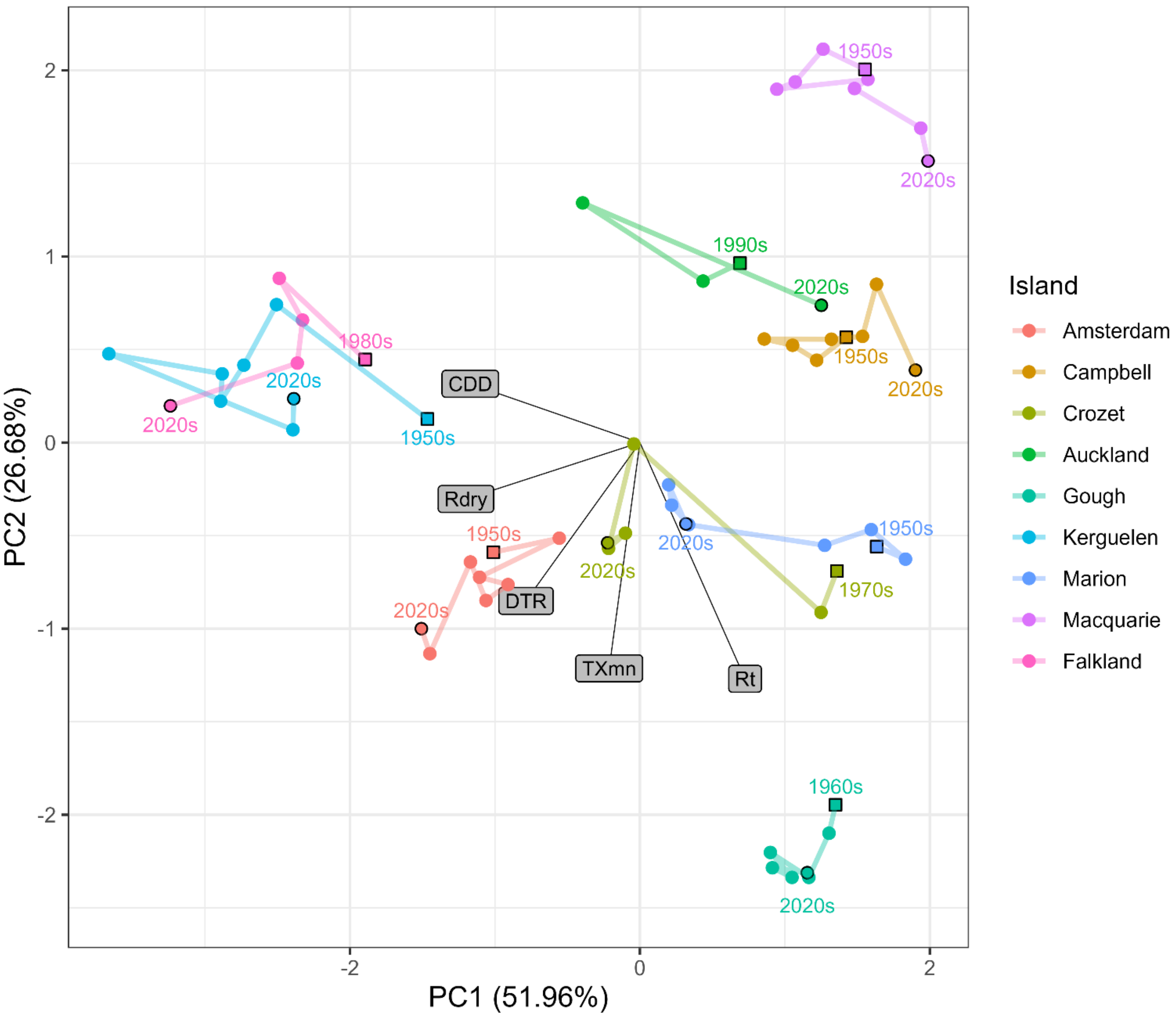

Fig. 4 Shifts in the five key temperature and precipitation parameters on the Southern Ocean Islands across decades based on the first two axes of principal component analysis (PCA). Each point corresponds to the mean values for parameters in that decade. Black outlines denote the earliest (squares) and latest (circles) decades. Abbreviations for climate parameters are consecutive dry days (CDD), number of dry days (Rdry), total precipitation (Rt), maximum temperature (TXmn), and diurnal temperature range (DTR)