A new daily observational record from Grytviken, South Georgia: exploring 20th century extremes in the South Atlantic

Zoë Thomas[1,2*], Chris Turney[1,2], Rob Allan[3], Steve Colwell[4], Gail Kelly[3], David Lister[5], Philip Jones[5,6], Mark Beswick[7], Lisa Alexander[2,8], Tanya Lippmann[9], Nicholas Herold[2,8], and Richard Jones[10]

[1]Palaeontology, Geobiology and Earth Archives Research Centre, School of Biological, Earth And Environmental Science, University of New South Wales, Sydney, Australia

[2]Climate Change Research Centre, School of Biological, Earth And Environmental Science, University of New South Wales, Sydney, Australia

[3]Met Office Hadley Centre/ACRE, Exeter, UK

[4]British Antarctic Survey, Cambridge, UK

[5]Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, UK

[6]Center of Excellence for Climate Change Research, Department of Meteorology, King Abdulaziz University, Jeddah, 21589, Saudi Arabia

[7]National Library & Archive, Met Office, Exeter, UK

[8]ARC Centre of Excellence for Climate System Science, University of New South Wales, Sydney, Australia

[9]Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, Netherlands

[10]Department of Geography, Exeter University, Devon, EX4 4RJ, UK

*z.thomas@unsw.edu.au

Abstract

Although recent work has highlighted a host of significant late 20th century environmental changes across the mid to high latitudes of the Southern Hemisphere, the sparse nature of observational records limits our ability to place these changes in the context of long-term (multi-decadal and centennial) variability. As a result, investigating the impact of anthropogenic forcing on climate modes of variability and ecosystems is particularly challenging, though historical records from sub-Antarctic islands offer the potential to develop highly resolved records of change. In 1905, a whaling and meteorological station was established at Grytviken on Sub-Antarctic South Georgia in the South Atlantic (54°S, 36°W) providing near-continuous daily observations through to present day. Here we report this new, previously unpublished, daily observational record from Grytviken for temperature and precipitation, which we compare to different datasets (including Twentieth Century Reanalysis; 20CR version 2c). We find a significant trend towards increasingly warmer daytime extremes commencing from the mid-20th century accompanied by warmer night-time temperatures, with an average rate of temperature rise of 0.13°C per decade over the period 1907-2016 (p<0.0001). Analysis of these data, and reanalysis products, suggest a realignment of synoptic conditions across the mid to high-latitudes since the mid-20th century, characterised by stronger westerly airflow linked to warm foehn winds across South Georgia. These rapid rates of warming have negative implications for biodiversity levels and the continued survival of some marine biota across the region.

1. Introduction

Climate changes in the mid to high latitudes of the Southern Hemisphere have exhibited extreme and regionally asymmetric trends in temperature and precipitation over the last half century, with warming particularly marked over the Antarctic Peninsula and South Atlantic during recent decades (Turner et al. 2005; Abram et al. 2014; Richard et al. 2013; Turney et al. 2016a; Jones et al. 2016a). However, due to the sparse distribution and temporal limitations of instrumental records, the long-term evolution of climatically sensitive high latitude regions of the Southern Hemisphere, especially prior to the 1950s, remains elusive. Sub-Antarctic islands are particularly important in this regard, straddling major ocean and atmospheric boundaries and offering the potential to develop highly resolved records of change. The ecosystems that inhabit these islands are of global importance, with high biological diversity and productivity, but appear to be increasingly vulnerable to late twentieth century change (Boyd et al. 2014; Constable et al. 2014; Trathan et al. 2012; Turney et al. 2017). Although invariably remote, numerous whaling stations were established across the Southern Ocean islands in the late 19th and early 20th century, where in some locations, daily weather observations were meticulously recorded. Although South Georgia lies in a strategic location for understanding Southern Ocean atmosphere-ocean dynamics, only a monthly resolved dataset has until now been available. These historical data provide key records for expanding the observational network, allowing a better characterisation of climate variability across southern latitudes.

South Georgia is a relatively small, mountainous and heavily glaciated Sub-Antarctic island (~3500 km^2) located approximately 1500 km northeast of the Antarctic

Peninsula (Figure 1). It has experienced substantial glacier retreat during the second half of the 20th century, with particularly dramatic losses during the first decade of the 21st century (Cook et al. 2010; Gordon et al. 2008). While the precise drivers of this glacier retreat remain unclear, due to the large potential and diverse impacts of this retreat on the terrestrial and marine biota, understanding these drivers of change is crucial (Cook et al. 2010; Murphy et al. 2007). Fortunately in this regard, (though resulting in devastating local impact on fauna) the island was home to numerous whaling stations after 1905, of which the station at Grytviken, the longest operating whaling station on the island, provides the longest and most complete meteorological records. While monthly climate statistics from Sub-Antarctic South Georgia are currently available in the public domain, disentangling changes in extremes requires daily-resolved data. A coordinated effort was therefore undertaken to locate and transcribe the records from Grytviken, to improve our understanding of South Atlantic climate change through the 20th century.

2. Data and Methods

The establishment of a whaling and meteorological station at Grytviken, South Georgia (also known as Cumberland Bay or King Edward Point), in 1905 allowed the creation of one of the longest observational records from the high latitudes of the Southern Hemisphere. Between 1905 and 1969 the occupying Norwegian-Argentine whaling station (Compania Argentina de Pesca) took meteorological readings. Following this, the British Falkland Island Dependencies Survey (and later British Antarctic Survey) took ownership of the station until the outbreak of the South Atlantic Conflict in April 1982. A small British Military garrison reoccupied the station weeks later, where they remained until March 2001. Near-continuous measurements were taken from 1905 to 1982, and although it is believed that the occupying military did take meteorological readings, uncertainty over the station layout and the location of the data has unfortunately resulted in an eighteen-year gap in the record. Monthly data from 1984-1988 are available from BAS, but so far no daily data or metadata have been identified. We therefore exclude these data from our analyses, and highlight these unverified data where shown. The British Antarctic Survey returned to the island in March 2001 and set up an automatic weather station (AWS), providing continuous measurements to the present day.

The meteorological station of Grytviken is located on the north coast of South Georgia (World Meteorological Organization station number: 88903; 54°16'59''S, 36°30'0''W). The weather station is located at an altitude of 2.2 m above mean sea level. The data from the early Norwegian-Argentine occupation from 1905 to 1962 are archived at the Met Office archives in Exeter, UK, and from 1963-1982 at the British Antarctic Survey Archives in Cambridge, UK. Data from the automated weather station present since 2001 can be accessed via https://legacy.bas.ac.uk/cgi-bin/metdb-form-2.pl?tabletouse=U_MET.GRYTVIKEN_AWS&complex=1&idmask=.....&acct=u_met&pass=weather. The data elements transcribed were daily maximum temperatures (TX), daily minimum temperatures (TN) and daily precipitation totals (PREC).

Metadata for the meteorological station are detailed, including height above ground, particulars of the instruments, and dates and details of any station/instrument location changes. Importantly, this metadata allows us to cross-check with our homogeneity tests to confirm the integrity of the record. For instance, when the station changed hands from Argentine to British control, metadata from the station reads: 'The former station closed in 1948 and was replaced by King Edward Point, the two sites should be compatible. Reliability: compared with 888900 [Stanley] and 879680 [Orcadas] for the years 1923-1980 and 1905-1980." It was also established from the metadata that temperature data from January 1905 to June 1907 should be discounted due to faulty exposure of the thermometers, which were affected by solar radiation, providing erroneously high readings. Although the thermometer screen was reported to have moved in January 1978, there is no evidence that this created a difference in the temperature readings. However, there is no known metadata available when the station was under military control, except that the thermometer screen was moved. The Milos 500 AWS was installed in March 2001, providing hourly readings, and was replaced by a Milos 530 AWS in 2006, which records one-minute observations. Both AWS used a platinum resistance thermometer probe, with an accuracy of ±0.2°C. In terms of precipitation data, up to 1982 measurements were taken with a Snowdon rain gauge, which can under-read in snow conditions as the wind can blow some of the snow over the top of the gauge (Goodison et al. 1998). The data since 2010 have been collected using a Laser Precipitation Monitor, which is thought to be more accurate. However, since there is no overlap between the two instrumentation methods, there is no way to assess how different the totals are, thus long-term trends that include data using both instruments should be interpreted with extreme caution. Homogeneity tests were undertaken to detect and adjust for sudden step changes present in the time series for reasons other than climatic changes (such as instrument change) using the software package RHTestsv4 (Wang 2008a,b; Wang and Feng 2013), and found no significant inhomogeneities in the daily precipitation, maximum or minimum temperature data.

Basic quality controls have been undertaken for all series following the procedures outlined in Alexander et al. (2006), and where necessary, unreliable data removed. Missing data criteria were adapted from Zhang et al. (2011) and applied as follows: monthly indices were calculated if no more than 3 days are missing in a month, seasonal indices were calculated if no more than 6 days missing in the three month period (and no more than four days missing per month), while annual values were calculated if no more than 15 days are missing in a year and no single month is missing. In addition to the missing data between March 1982 and March 2001, there are several other gaps in the observations associated with observer illness or instrumentation problems affecting the following periods: October 1910 to May 1911; January 1919 to April 1920; March to April 1928; and May 1946 to December 1949. After the AWS was installed in 2001, there were occasional issues with the automatic instrumentation and/or computer that could take several days to resolve (this was particularly acute during 2007). In addition, the data were removed between September 1968 and December 1969, owing to suspect diurnal temperature range and unusually high precipitation values. It is worth noting that while rarely transcribed, log books often have valuable qualitative data in addition to the quantitative data recorded. Following identification of potentially spurious value(s), we looked at the original photographs taken to help identify any transcription errors, and if there were any qualitative comments made that could help to corroborate the values. For example, in August 1939, the mean monthly temperature is one degree lower than the next lowest monthly temperature. The logbook was consulted, and determined that there were no transcription errors. Instead, comments in the 'observations' section had several phrases indicating particularly cold conditions: "*muy frio*" (very cold), "*ventisca dia y moche*" (blizzard day and night), "*viento fuerte*" (strong wind) and "*temperatura muy baja*" (temperature very low). Qualitative data such as these can be valuable sources of extra quality assurance.

The data were analysed using R-based CLIMPACT software package (Alexander and Herold 2015) to calculate selected extreme climate indices (Zhang et al. 2011). We use daily minimum (TN) and maximum (TX) temperature as well as daily precipitation in this assessment. We use percentile-based threshold levels using 1950-1980 as our baseline, including the 90th percentile of the daily minimum (TN90p) and maximum (TX90p) temperature to measure changes in moderate extremes. We used a generalized least squares approach, fit by maximizing the restricted log-likelihood (REML) with autoregressive (AR) errors, to estimate the slope term of an assumed linear trend. We utilised the Akaike information criterion (AIC) to compare different models and chose an autoregressive model of order AR(1), which was determined to successfully remove autocorrelation of the residuals. The trends are reported as °C of warming per decade or precipitation sum (mm) increase per decade calculated for each period, with the associated standard error and *p* value. To further explore the atmospheric drivers of observed climate changes we also use the ACRE-facilitated NOAA-CIRES Twentieth Century Reanalysis Project (20CR version 2c) (Compo et al. 2011; Giese et al. 2016). The data will be publically accessible via the ISTI (International Surface Temperature Initiative; http://www.surfacetemperatures.org/) and the GPCC (Global Precipitation Climatology Centre; https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html).

3. Results

A warming trend over the 20th century is observed in mean monthly temperature at Grytviken from daily data (calculated as the average of TX and TN) (Figure 2), with an average rate of temperature rise of 0.14°C per decade over the period 1907-2016 ($p<0.0001$; Table 1), calculated from the annual mean. However, more detailed analysis of this rate of increase shows a slight decrease in temperatures over the first two decades of the record at South Georgia, before the warming trend was established. When splitting the record approximately in half (1906-1950, and 1951-2016), there is no significant trend identified in the early half of the twentieth century, but a strong trend in the latter half, peaking at 0.22°C per decade ($p<0.0002$; Table 1). Importantly, however, the rate of warming is not constant year round. When seasonal trends are investigated, the largest warming trend occurs during the austral spring and summer months (Table 1).

To determine whether the AWS station is producing temperatures that would bias the trends, we compare the observations from South Georgia to the Twentieth Century Reanalysis (20CR v2c) (Figure 2B). We observe a close correspondence between the two time series (Pearson product-moment correlation of 0.648, p=3.099E-09), though it is important to note that due to South Georgia's small size, the reanalysis assigns it as an ocean grid box rather than a land box, which helps to explain the lower variability in the reanalysis time series. The decadal rates of change over different time periods for the reanalysis data are reported in Table 2. These show coherence to the observational trends, in all periods, suggesting that the data from the AWS have not biased the linear trend since 1950.

To investigate the distribution of temperatures across the seasons more fully, we explored the probability distribution functions for daily seasonal temperatures at South Georgia over each 20-year period since 1907 (Figure 3). Although the shape of the distributions remains largely unchanged (with only a slight shift to a more positively skewed distribution between the first and second half of the 20th century in all seasons), TX and TN appear to have shifted to the right through the 20th century. Most notably, the overall distribution in TX and TN appears to have remained broadly the same across the period 1907-1966 but subsequent bi-decadal averages show a mostly uniform shift to higher temperatures, most notably during the austral spring and summer. This shift implies that there was a change in the frequency of occurrence of cold and warm extremes across the mid-twentieth century, with more frequent warm extremes and less frequent cold extremes experienced over recent decades compared to the beginning of the 20th century.

Since some weather extremes are predicted to become more frequent due to anthropogenic influences on climate (Field et al. 2012), past extremes can provide a baseline for comparing modern extremes. However, since extremes are inherently rare events, we look at 'moderate' extreme indices, defined as those that occur several times per year, rather than rarer events whose statistics would be harder to robustly characterise (Sardeshmukh et al. 2015; Zhang et al. 2011). To further explore the changes of warm and cool extremes during the summer and winter, we therefore analysed the change in the frequency of occurrence of temperatures exceeding the 90th percentile (TX90p and TN10p) using the period 1950-1980 as a baseline. Here we observe an increase in the frequency of moderate warm extremes during the austral summer (December-February) and a decrease in the occurrence of moderate cool extremes during winter (June-August) (Figure 4). The mean minimum temperature in DJF increased from 1.05°C in 1907-1926 to 1.61°C in 1947-1966 and to 2.47°C in 2001-2016, with their standard deviations at 2.14, 1.96 and 2.30 respectively. A similar pattern was found for the mean maximum temperature in DJF, increasing by a total of 1.5°C over the same period.

Analysis of the annual precipitation total (using totals with <6 missing observations per year) shows a strong increasing trend through the 20th century (Figure 5), representing an average increase of approximately 40 mm per year (though this is superimposed on a highly variable time series). A marked shift in the amount of precipitation is observed from the most recent period (2010-2016), but due to possible inhomogeneities caused by instrument changes from 2010 (though none were detected in our tests, there is a 28 year gap between the two types of instrument), it remains unclear how significant this is. It is possible that the increasing precipitation trend described above may have resulted in more precipitation falling as rain, rather than snow, which is better recorded (Forland and Hanssen-bauer 2000; Hanssen-Bauer 2002; Førland and Hanssen-Bauer 2001). It is noted, however, that even omitting the 2010-2016 precipitation totals still results in a significant increasing trend in annual precipitation sum (Figure 5 and Table 2). To understand the seasonal variation in rainfall, we divided the data into seasons (December-February (DJF), March-May (MAM), June-August (JJA) and September-November (SON); Figure 6), where there is a clear bias towards higher precipitation in autumn and winter. In addition, the trajectory of the locally weighted scatterplot smoothing lines indicates a greater rate of increase in precipitation in these seasons (and with lower totals, but similar rates of increase in SON), suggesting that whatever mechanism is driving the increase in precipitation, it dominates in autumn and winter.

4. Discussion

The warming trends observed at Grytviken, South Georgia, are comparable to the trends from nearby Orcadas station on Laurie Island on the eastern side of the Antarctic Peninsula (Zazulie et al. 2010). The total amount of annual mean warming at Grytviken between 1907 and 2016 is 1.52°C (□□□2.32E-06; Table 1□□□equivalent to an average rate of 0.14°C per decade, comparable to the 0.2°C per decade observed at Laurie Island (1903-2008) (Zazulie et al. 2010). A strong seasonal component is identified in the South Georgia dataset, however, with the austral summer months contributing most to the annual trend, particularly during the second half of the 20th century (Table 1) (1951-2017; 0.21°C per decade, p=0.0002). Similar seasonal differences in trends are also observed at Orcadas, with the rate of summer warming in the latter half of the 21st century double that of the early 21st century (Zazulie et al. 2010). Compared to the Falkland Islands, the linear trend of the temperature series from 1920-2010 is 0.05°C per decade (p=0.002) (Lister and Jones 2014; Jones et al. 2016b), which is substantially lower than South Georgia.

It is important to note here that many warm extremes on South Georgia relate to foehn winds, which are defined as strong, warm, dry winds that descend from mountains (Skansi et al. 2017). Much of South Georgia's climate is strongly modified by the steep orography, with a high mountain chain >2000 metres above sea level down the spine of the island. Located within the belt of the westerly winds, the island acts as a natural barrier to the prevailing airflow. Strong prevailing airflow over a topographic obstacle results in an adiabatic cooling of the rising air at the moist adiabatic lapse rate, causing latent heat to be released and precipitation to occur, decreasing the humidity of the advected air. As the parcel then starts to descend down the leeward slope, it warms at the faster dry adiabatic lapse rate, resulting in a temperature and humidity gradient between the windward and leeward side of the topographic barrier at the same elevation (Elvidge and Renfrew 2016; Skansi et al. 2017). Foehn warming can also take place without precipitation, where warming on the leeside of a topographic barrier can be generated by the descent of warmer air sources above it caused by blocked flow (Elvidge and Renfrew 2016). These foehn winds have been shown to be frequent; occurring approximately every 4 days, and capable of warming the daily mean temperature by up to 20°C, with a mean increase in temperature across all events of ~10°C (as measured between 2003-2013) (Bannister 2015). While wind speed and direction was recorded at South Georgia since 1905, this has not yet been transcribed (in part due to the notorious unreliability of historical observational wind data), limiting our understanding of foehn winds during the 20th century. However, wind speed and direction have been measured with the AWS on South Georgia since installation in 2001, though unfortunately, due to local topographic modification (e.g. wind channelling), the recorded wind direction at King Edward Point is not indicative of the synoptic wind pattern. Instead, in Bannister et al. (2015), ERA-Interim reanalysis was used to illustrate synoptic conditions during foehn events, and showed a well-defined ridge of high pressure, roughly centred just north of South Georgia, during strong foehn conditions, a feature that is absent in the climatological mean.

There are several important modes of variability that affect climate and weather in the high latitudes of the South Atlantic. One mode of variability is the Pacific-South

American (PSA) teleconnection pattern, through which the El Niño-Southern Oscillation (ENSO) signal propagates into high southern latitudes during the austral spring/summer (Mo and Higgins 1998; Ding et al. 2012), causing strong northerlies to advect warm maritime air from the South Pacific towards South Georgia. Related to this, an increase in Rossby wave penetration thought to be linked to tropical Pacific temperatures has been suggested to play a potential role in the evolution of Antarctic climate since the mid 20th century (Fogt et al. 2011; Ding et al. 2012; Turney et al. 2017, 2016a).

The major mode of variability in atmospheric circulation in the high southern latitudes, however, is the Southern Annular Mode (SAM); a circumpolar pattern of pressure gradients defined as the zonal mean atmospheric pressure difference between 40°S and 65°S (Marshall 2003; Thompson et al. 2011). The multi-decadal trend to a more positive SAM since the mid-20th century (Abram et al. 2014) is manifested by a strengthening and southward shift of westerly airflow over the Southern Ocean (Visbeck 2009; Marshall 2003; Thompson et al. 2011). Although the increase in the SAM index has occurred in all seasons, the most pronounced trend is observed over the summer-autumn (Marshall 2003). The impact of SAM may have been amplified as a result of the spring Antarctic ozone hole which established in the late 1970s and exerts its greatest effect on climate and circulation patterns during the summer (Thompson and Solomon 2002; Zazulie et al. 2010). However, the warming trends observed from South Georgia start before this time, suggesting that ozone cannot be the sole driver of the warming trends observed. Indeed, although of a smaller magnitude, warming is also observed in the winter months.

The precipitation trends observed from South Georgia differ in two main aspects to the temperature trends: firstly, that increasing precipitation appears to commence from the beginning of the 20th century, and secondly, the increases appear to occur mainly over the autumn and winter months. The difference in temperature and precipitation trends (both the timing of the changes and the seasonality) suggests different climate drivers. Several other records from nearby meteorological stations also observe a long term increase in precipitation, including the annual precipitation recorded on the Falklands Islands (Lister and Jones 2014; Jones et al. 2016b) and greatly increased snow accumulation on the Antarctic Peninsula (Thomas et al. 2008). To elucidate the dominant atmospheric circulation that might explain the observed climate and weather extremes over South Georgia, we utilised the Twentieth Century Reanalysis, 20CR version 2c (Compo et al. 2011) (Figure 7 and 8).

We investigate the total precipitation sum in autumn and winter (March-August) and correlate to the 850hPa geopotential height and the 850hPa meridional wind over the period 1905-1983 (the data gap between 1983 and 2010 unfortunately prevents analysis in recent decades). We observe a correlation between low pressure over South America and precipitation at South Georgia, allowing the delivery of moisture via northerly and easterly airflow over South Georgia (Figure 7). Although the Amundsen Sea Low is generally associated with quasi-stationary low pressure systems (Clem and Fogt 2015), when large seasonal variability across the region allows a low pressure system to develop over South America, our analysis shows more rainfall is delivered via meridional airflow over South Georgia. The increasing trends in rainfall from the South Georgia climate records are in general agreement with Turney et al. (2016a) who reported higher rainfall over the Falkland Islands from the 1940s (as reported in Lister and Jones (2014)), consistent with a lower mean sea level pressure in the South Atlantic and higher pressure in the Amundsen Sea Low, leading to an unprecedented increase in growth of peat sequences relative to the last 6000 years.

However, while the above mechanisms dominate in winter, causing enhanced precipitation over South Georgia, there is a seasonal change in the configuration of the synoptic conditions, consistent with the summer impact of SAM. We therefore investigate the summer months (December-February) in mean monthly temperature, correlating with the 850hPa geopotential height, and the 850hPa zonal wind to understand the mechanisms of synoptic change. We split our data into an 'early' period (1905-1950) and a 'late' period (1950-2016). Our analysis finds a strengthening correlation between temperature and high-latitude zonal airflow over the 20th century, resulting from a southwards shift in the circumpolar trough during the summer (Figure 8). Based on these results, we investigate the time series from the 20th Century Reanalysis of the 850 hPa zonal wind over South Georgia, averaged over December-February (Figure 9). We find a significant ($p<0.036$) increasing trend in the zonal wind. While there is no doubt that further work is needed to increase the density of early observations in reanalysis products (such as the data reported in this paper), the changing synoptic conditions that are produced are generally consistent with both independent climate proxy data (Turney et al. 2016b; Amesbury et al. 2017) and observations. These changes in the synoptic weather regimes give rise to surface warming over South Georgia, through the relationship with the foehn effect. Although the link between increasing westerly winds and warming over South Georgia may at first seem counterintuitive, there is a demonstrated link between the strength of the westerly winds and the occurrence and magnitude of foehn winds (Bannister and King

2015; Bannister 2015). If the strength of the winds is sufficiently high, downslope winds develop on the (north-eastern) leeside of the island, causing substantial temperature increases as the descending air warms adiabatically. Regardless of the precise mechanism of the generation of the foehn winds, the relationship between the positive trend in SAM from the 1960s (Jones et al. 2009), enhancing westerly airflow over the island, and the increased frequency and magnitude of foehn winds, helps to explain the tendency for the high rate of summer warming and increasing frequency of warm extremes that we observe in South Georgia over the past century.

5. Wider Implications

Changes to the climatic and environmental constraints that shape the current biological diversity constitute the dominant threat to the island of South Georgia. Contemporary glacier retreat resulted in the increased threat of invasive rat species from areas that were previously isolated due to ice barriers (Cook et al. 2010). However, while a recent program to eradicate rats was successfully implemented (Martin and Richardson 2017), further biological invasions and colonisation of alien species will likely continue with the current rate and direction of regional climate change. The South Georgian shelf is the most speciose region of the Southern Ocean reported to date (Hogg et al. 2011), with a cumulative dominance of endemic and range-edge species, many of which, such as Antarctic krill *Euphausia superba*, show declining habitat suitability with warming temperatures (Whitehouse et al. 2008). This in turn has negative impacts on the breeding success of krill-dependent penguins and seals (Murphy et al. 2007). Critical to this is the link between synoptic-scale and mesoscale meteorological processes. The data presented here underscore the importance of the rescue of historical, daily-resolved data from these remote islands to disentangle seasonal and extreme changes and demonstrate a link between increasing temperature trends and atmospheric circulation dominated by stronger westerly airflow, resulting in significant foehn-related warming.

Acknowledgments

This work was supported by the Australian Research Council (FL100100195). This work is part of the Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative, and Prof. Rob Allan is supported by funding from the Joint BEIS/Defra Met Office Hadley Centre Climate Programme (GA01101). He also acknowledges the University of Southern Queensland, Toowoomba, Australia, where he is an Adjunct Professor. Support for the Twentieth Century Reanalysis Project version 2c dataset is provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER), and by the National Oceanic and Atmospheric Administration Climate Program Office. We thank Gil Compo for valuable comments on the manuscript.

References

Abram, N. J., R. Mulvaney, F. Vimeux, S. J. Phipps, J. Turner, and M. H. England, 2014: Evolution of the Southern Annular Mode during the past millennium. *Nat. Clim. Chang.*, **4**, 1–6, doi:10.1038/NCLIMATE2235.

Alexander, L., and N. Herold, 2015: ClimPACTv2: indices and software. Technical report of the World Meteorological Organisation Commission for climatology expert team on sector-specific climate indices. World Meteorological Organisation. https://github.com/ARCCSS-extremes/climpact2/blob/mas.

Alexander, L. V., and Coauthors, 2006: Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res. Atmos.*, **111**, 1–22, doi:10.1029/2005JD006290.

Amesbury, M. J., T. P. Roland, J. Royles, D. A. Hodgson, P. Convey, H. Griffiths, and D. J. Charman, 2017: Widespread Biological Response to Rapid Warming on the Antarctic Peninsula. *Curr. Biol.*, **27**, 1616–1622.e2, doi:10.1016/j.cub.2017.04.034. http://dx.doi.org/10.1016/j.cub.2017.04.034.

Bannister, D., 2015: Fohn winds on South Georgia and their impact on regional climate. University of East Anglia, .

——, and J. King, 2015: Föhn winds on South Georgia and their impact on regional climate. *Weather*, **70**, 324–329, doi:10.1002/wea.2587.

Boyd, P. W., S. T. Lennartz, D. M. Glover, and S. C. Doney, 2014: Biological ramifications of climate-change-mediated oceanic multi-stressors. *Nat. Clim. Chang.*, **5**, 71–79, doi:10.1038/nclimate2441.

Clem, K. R., and R. L. Fogt, 2015: South Pacific circulation changes and their connection to the tropics and regional Antarctic warming in austral spring, 1979–2012. *J. Geophys. Res. Atmos.*, **120**, 2773–2792, doi:10.1002/2014JD022940.Received.

Compo, G. P., and Coauthors, 2011: The Twentieth Century Reanalysis Project. *Q. J. R. Meteorol. Soc.*, **137**, 1–28, doi:10.1002/qj.776.

Constable, A. J., and Coauthors, 2014: Climate change and Southern Ocean ecosystems I: How changes in physical habitats directly affect marine biota. *Glob. Chang. Biol.*, **20**, 3004–3025, doi:10.1111/gcb.12623.

Cook, a J., S. Poncet, a P. R. Cooper, D. J. Herbert, and D. Christie, 2010: Glacier retreat on

South Georgia and implications for the spread of rats. *Antarct. Sci.*, **22**, 255–263, doi:10.1017/s0954102010000064.

Ding, Q., E. J. Steig, D. S. Battisti, and J. M. Wallace, 2012: Influence of the tropics on the southern annular mode. *J. Clim.*, **25**, 6330–6348, doi:10.1175/JCLI-D-11-00523.1.

Elvidge, A. D., and I. A. Renfrew, 2016: The causes of foehn warming in the lee of mountains. *Bull. Am. Meteorol. Soc.*, **97**, 455–466, doi:10.1175/BAMS-D-14-00194.1.

Field, C. B., and Coauthors, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 582 pp.

Fogt, R. L., D. H. Bromwich, and K. M. Hines, 2011: Understanding the SAM influence on the South Pacific ENSO teleconnection. *Clim. Dyn.*, **36**, 1555–1576, doi:10.1007/s00382-010-0905-0.

Forland, E. J., and I. Hanssen-bauer, 2000: Increased precipitation in the Norwegian Arctic:True or false? *Clim. Change*, **46**, 485–509, doi:10.1023/A:1005613304674.

Førland, E. J., and I. Hanssen-Bauer, 2001: Changes in Temperature and Precipitation in the Norwegian Arctic during the 20th Century. *Detecting and Modelling Regional Climate Change*, M.B. India and D.L. Bonillo, Eds., Springer Berlin Heidelberg, Berlin, Heidelberg, 153–161 http://dx.doi.org/10.1007/978-3-662-04313-4_14.

Giese, B. S., H. F. Seidel, G. P. Compo, and P. D. Sardeshmukh, 2016: An ensemble of ocean reanalyses for 1815-2013 with sparse observational input. *J. Geophys. Res. Ocean.*, **121**, 6891–6910, doi:10.1002/2016JC012079.

Goodison, B. E., P. Y. T. Louie, and D. Yang, 1998: *WMO Solid Precipitation Measurement Intercomparison*.

Gordon, J. E., V. M. Haynes, and A. Hubbard, 2008: Recent glacier changes and climate trends on South Georgia. *Glob. Planet. Change*, **60**, 72–84, doi:10.1016/j.gloplacha.2006.07.037.

Hanssen-Bauer, I., 2002: Temperature and precipitation in Svalbard 1912 – 2050: measurement and scenarios. *Polar Rec. (Gr. Brit).*, **38**, 225–232.

Hogg, O. T., D. K. A. Barnes, and H. J. Griffiths, 2011: Highly diverse, poorly studied and uniquely threatened by climate change: An assessment of marine biodiversity on South Georgia's continental shelf. *PLoS One*, **6**, doi:10.1371/journal.pone.0019795.

Jones, J. M., R. L. Fogt, M. Widmann, G. J. Marshall, P. D. Jones, and M. Visbeck, 2009: Historical SAM variability. Part I: Century-length seasonal reconstructions. *J. Clim.*, **22**, 5319–5345, doi:10.1175/2009JCLI2785.1.

——, and Coauthors, 2016a: Assessing recent trends in high-latitude Southern Hemisphere surface climate. *Nat. Clim. Chang.*, **6**, In press, doi:10.1038/nclimate3103. http://dx.doi.org/10.1038/nclimate3103.

Jones, P. D., C. Harpham, and D. Lister, 2016b: Long-term trends in gale days and storminess for the Falkland Islands. *Int. J. Climatol.*, **36**, 1413–1427, doi:10.1002/joc.4434. http://doi.wiley.com/10.1002/joc.4434.

Lister, D. H., and P. D. Jones, 2014: Long-term temperature and precipitation records from the Falkland Islands. *Int. J. Climatol.*, **1850**, n/a-n/a, doi:10.1002/joc.4049. http://doi.wiley.com/10.1002/joc.4049.

Marshall, G. J., 2003: Trends in the Southern Annular Mode from observations and reanalyses. *J. Clim.*, **16**, 4134–4143, doi:10.1175/1520-0442(2003)016<4134:TITSAM>2.0.CO;2.

Martin, A. R., and M. G. Richardson, 2017: Rodent eradication scaled up: clearing rats and mice from South Georgia. *Oryx*, 1–9, doi:10.1017/S003060531700028X. https://www.cambridge.org/core/product/identifier/S003060531700028X/type/

journal_article.

Mo, K. C., and R. W. Higgins, 1998: The Pacific–South American Modes and Tropical Convection during the Southern Hemisphere Winter. *Mon. Weather Rev.*, **126**, 1581–1596, doi:10.1175/1520-0493(1998)126<1581:TPSAMA>2.0.CO;2.

Murphy, E. J., and Coauthors, 2007: Climatically driven fluctuations in Southern Ocean ecosystems. *Proc. R. Soc. B Biol. Sci.*, **274**, 3057–3067, doi:10.1098/rspb.2007.1180. http://rspb.royalsocietypublishing.org/cgi/doi/10.1098/rspb.2007.1180.

van Oldenborgh, G. J., and G. Burgers, 2005: Searching for decadal variations in ENSO precipitation teleconnections. *Geophys. Res. Lett.*, **32**, 1–5, doi:10.1029/2005GL023110.

Richard, Y., and Coauthors, 2013: Temperature changes in the mid- and high- latitudes of the Southern Hemisphere. *Int. J. Climatol.*, **33**, 1948–1963, doi:10.1002/joc.3563. http://doi.wiley.com/10.1002/joc.3563.

Sardeshmukh, P. D., G. P. Compo, and C. Penland, 2015: Need for caution in interpreting extreme weather statistics. *J. Clim.*, **28**, 9166–9187, doi:10.1175/JCLI-D-15-0020.1.

Skansi, M., and Coauthors, 2017: Evaluating Highest-Temperature Extremes in the Antarctic. *Eos (Washington. DC).*, 1–6, doi:10.1029/2017EO068325. https://eos.org/features/evaluating-highest-temperature-extremes-in-the-antarctic.

Thomas, E. R., G. J. Marshall, and J. R. McConnell, 2008: A doubling in snow accumulation in the western Antarctic Peninsula since 1850. *Geophys. Res. Lett.*, **35**, 1–5, doi:10.1029/2007GL032529.

Thompson, D. W. J., and S. Solomon, 2002: Interpretation of Recent Southern Hemisphere Climate Change. *Science (80-.).*, **296**, 895–899, doi:10.1126/science.1087440.

http://www.sciencemag.org/cgi/content/abstract/302/5643/273.

Thompson, D. W. J., S. Solomon, P. J. Kushner, M. H. England, K. M. Grise, and D. J. Karoly, 2011: Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nat. Geosci.*, **4**, 741–749, doi:10.1038/ngeo1296. http://dx.doi.org/10.1038/ngeo1296.

Trathan, P. N., J. Forcada, and E. J. Murphy, 2012: Environmental Forcing and Southern Ocean Marine Predator Populations: Effects of Climate Change and Variability. *Antarctic Ecosystems: An Extreme Environment in a Changing World*, John Wiley & Sons, Ltd, Chichester, UK.

Turner, J., and Coauthors, 2005: Antarctic climate change during the last 50 years. *Int. J. Climatol.*, **25**, 279–294, doi:10.1002/joc.1130.

Turney, C. S. M., and Coauthors, 2016a: Anomalous mid-twentieth century atmospheric circulation change over the South Atlantic compared to the last 6000 years. *Environ. Res. Lett.*, **11**, 64009, doi:10.1088/1748-9326/11/6/064009. http://dx.doi.org/10.1088/1748-9326/11/6/064009.

Turney, C. S. M., and Coauthors, 2016b: Anomalous mid-twentieth century atmospheric circulation change over the South Atlantic compared to the last 6000 years. *Environ. Res. Lett.*, doi:10.1088/1748-9326/11/6/064009. http://www.scopus.com/inward/record.url?eid=2-s2.0-84977547766&partnerID=MN8TOARS.

Turney, C. S. M., and Coauthors, 2017: Tropical forcing of increased Southern Ocean climate variability revealed by a 140-year subantarctic temperature reconstruction. *Clim. Past*, doi:10.5194/cp-13-231-2017.

Visbeck, M., 2009: A station-based southern annular mode index from 1884 to 2005. *J. Clim.*, **22**, 940–950, doi:10.1175/2008JCLI2260.1.

Wang, X. L., 2008a: Accounting for autocorrelation in detecting mean shifts in climate data series using the penalized maximal t or F test. *J. Appl. Meteorol. Climatol.*, **47**, 2423–2444, doi:10.1175/2008JAMC1741.1.

——, 2008b: Penalized maximal F test for detecting undocumented mean shift without trend change. *J. Atmos. Ocean. Technol.*, **25**, 368–384, doi:10.1175/2007JTECHA982.1.

Wang, X. L., and Y. Feng, 2013: RHtestsV4 User Manual.

Whitehouse, M. J., M. P. Meredith, P. Rothery, A. Atkinson, P. Ward, and R. E. Korb, 2008: Rapid warming of the ocean around South Georgia, Southern Ocean, during the 20th century: Forcings, characteristics and implications for lower trophic levels. *Deep. Res. Part I Oceanogr. Res. Pap.*, **55**, 1218–1228, doi:10.1016/j.dsr.2008.06.002.

Zazulie, N., M. Rusticucci, and S. Solomon, 2010: Changes in climate at high southern latitudes: A unique daily record at Orcadas spanning 1903-2008. *J. Clim.*, **23**, 189–196, doi:10.1175/2009JCLI3074.1.

Zhang, X., L. Alexander, G. C. Hegerl, P. Jones, A. K. Tank, T. C. Peterson, B. Trewin, and F. W. Zwiers, 2011: Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Wiley Interdiscip. Rev. Clim. Chang.*, **2**, 851–870, doi:10.1002/wcc.147.

Tables

	1907-1950	**1950-2016**	**1950-1983**	**1907-2016**
South Georgia Observations				
TM Annual	**-0.097**	**0.11*****	**0.14**	**0.13*****
Std. err.	0.0107	0.0037	0.0090	0.0026
***p* value**	0.370	0.0043	0.143	8.36E-06
TM SON	**-0.14**	**0.14****	**0.19**	**0.14*****
Std. err.	0.0134	0.005	0.015	0.0034

***p* value**	0.291	0.012	0.221	9.32E-05
TM DJF	**-0.01**	**0.22*****	**0.31****	**0.16*****
Std. err.	0.014	0.006	0.014	0.003
***p* value**	0.970	0.001	0.030	1.14E-05
TM MAM	**-0.09**	**0.03**	**-0.07**	**0.08****
Std. err.	0.0133	0.0063	0.0165	0.0032
***p* value**	0.506	0.703	0.684	0.0159
TM JJA	**0.13**	**0.09***	**0.06**	**0.16*****
Std. err.	0.014	0.005	0.014	0.003
***p* value**	0.370	0.068	0.660	1.85E-06
Twentieth Century Reanalysis:20CR v2c				
TM Annual	**0.01*****	**0.04****	**0.21*****	**0.08*****
Std. err.	0.952	0.123	0.0001	0.0017
***p* value**	0.009	0.003	0.004	1.31E-05

Table 1: *Trends (°C per decade) for mean monthly mean temperature and seasons, with standard error, and p-values for selected periods of time (*** where p<0.01; ** where p<0.05; * where p<0.1) for observations at South Georgia, and the Twentieth Century Reanalysis.*

	1907-1950	**1907-1983**	**1950-1983**	**1907-2016**
TM Annual	**18.8**	**43.8*****	**94.4***	**45.1*****
Std. err.	4.144	1.583	5.316	1.426
***p* value**	0.654	0.008	0.089	0.003
TM SON	**9.14**	**16.8*****	**30.3**	**15.7*****
Std. err.	1.247	0.542	2.215	0.422
***p* value**	0.468	0.002	0.183	0.0004
TM DJF	**12.3**	**13.0****	**-7.80**	**10.3****
Std. err.	1.648	0.590	1.948	0.494
***p* value**	0.459	0.031	0.692	0.041
TM MAM	**-9.11**	**10.9***	**15.6**	**15.2*****
Std. err.	1.460	0.621	2.497	0.487
***p* value**	0.537	0.082	0.538	0.003
TM JJA	**17.8**	**9.60**	**48.3****	**15.3****

Std. err.	2.119	0.745	1.824	0.611
***p* value**	0.406	0.202	0.014	0.014

Table 2: *Trends (precipitation sum (mm) per decade) for mean monthly precipitation sum, with standard error, and p-values for selected periods of time (*** where p<0.01; ** where p<0.05; * where p<0.1).*

Figures

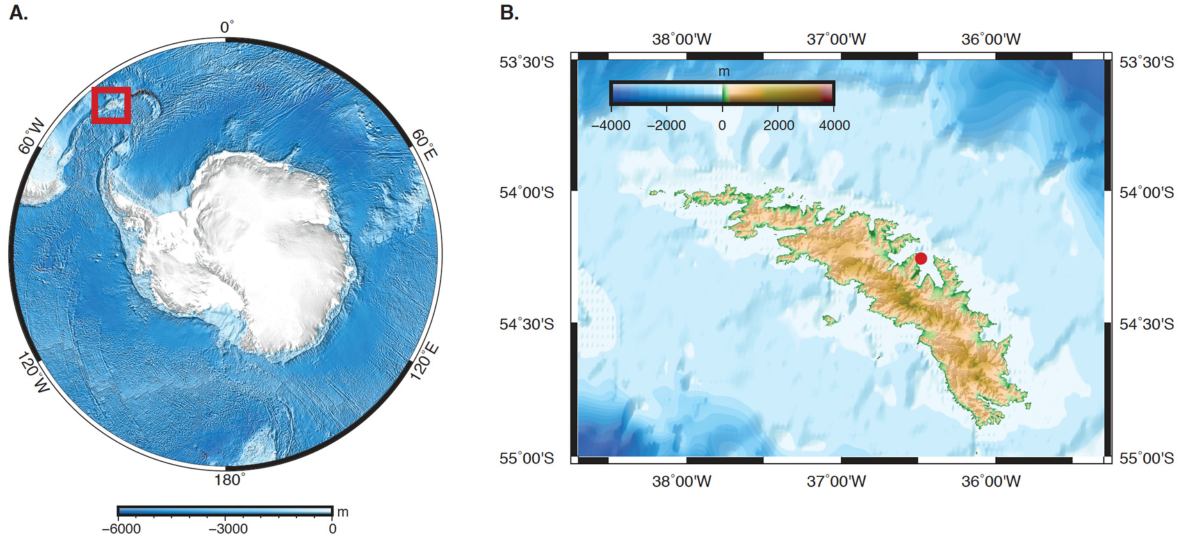
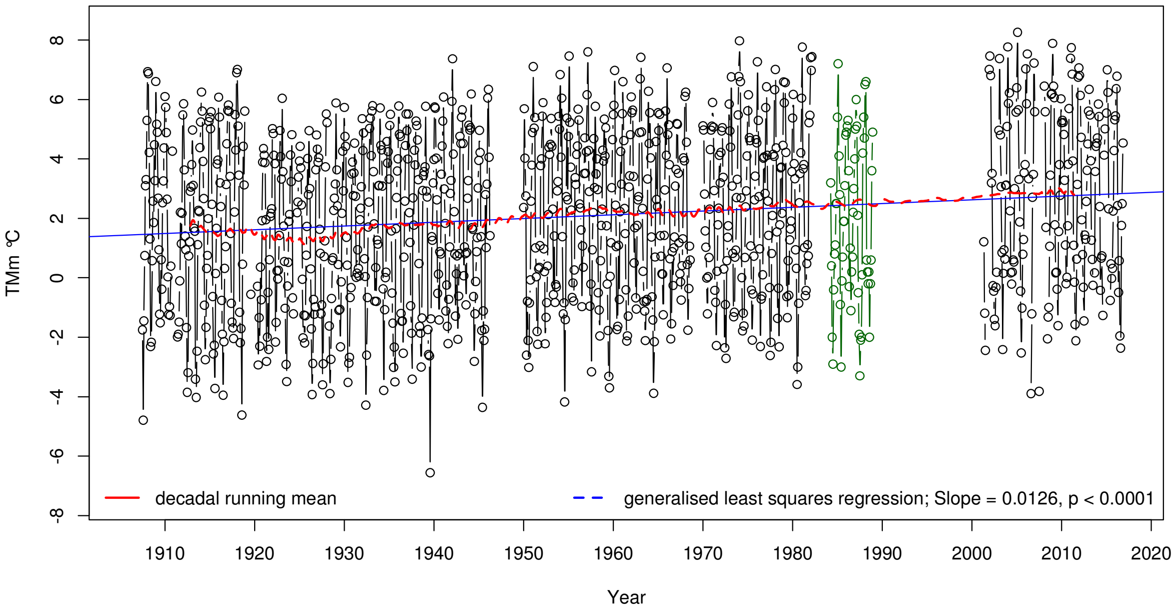


Figure 1 *Location of South Georgia (red square, Panel A), and the meteorological station at Grytviken in Cumberland Bay (red dot, Panel B).*



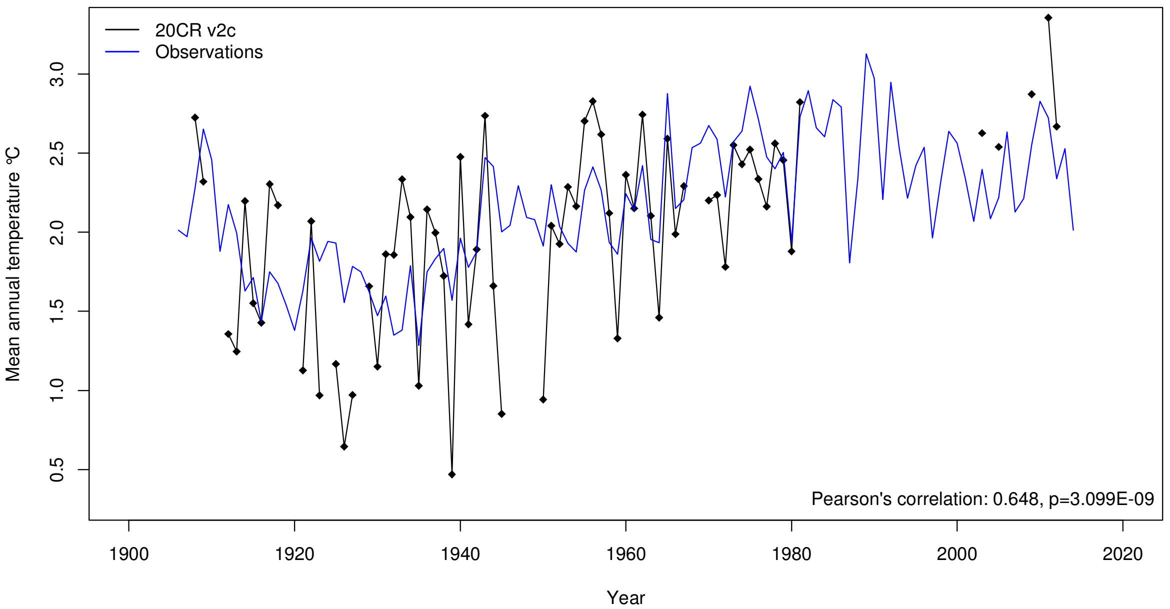


Figure* 2 *A. *Average mean monthly temperature from South Georgia, with generalised least squares regression (blue) and decadal running mean (red) lines shown. Dark green data (1984-1988) from military station is unverified and not included in the linear regression or decadal running mean.* ***B.*** *Mean annual air temperature from the Twentieth*

Century Reanalysis (20CR v2c) plotted against South Georgia mean annual temperature from observations.

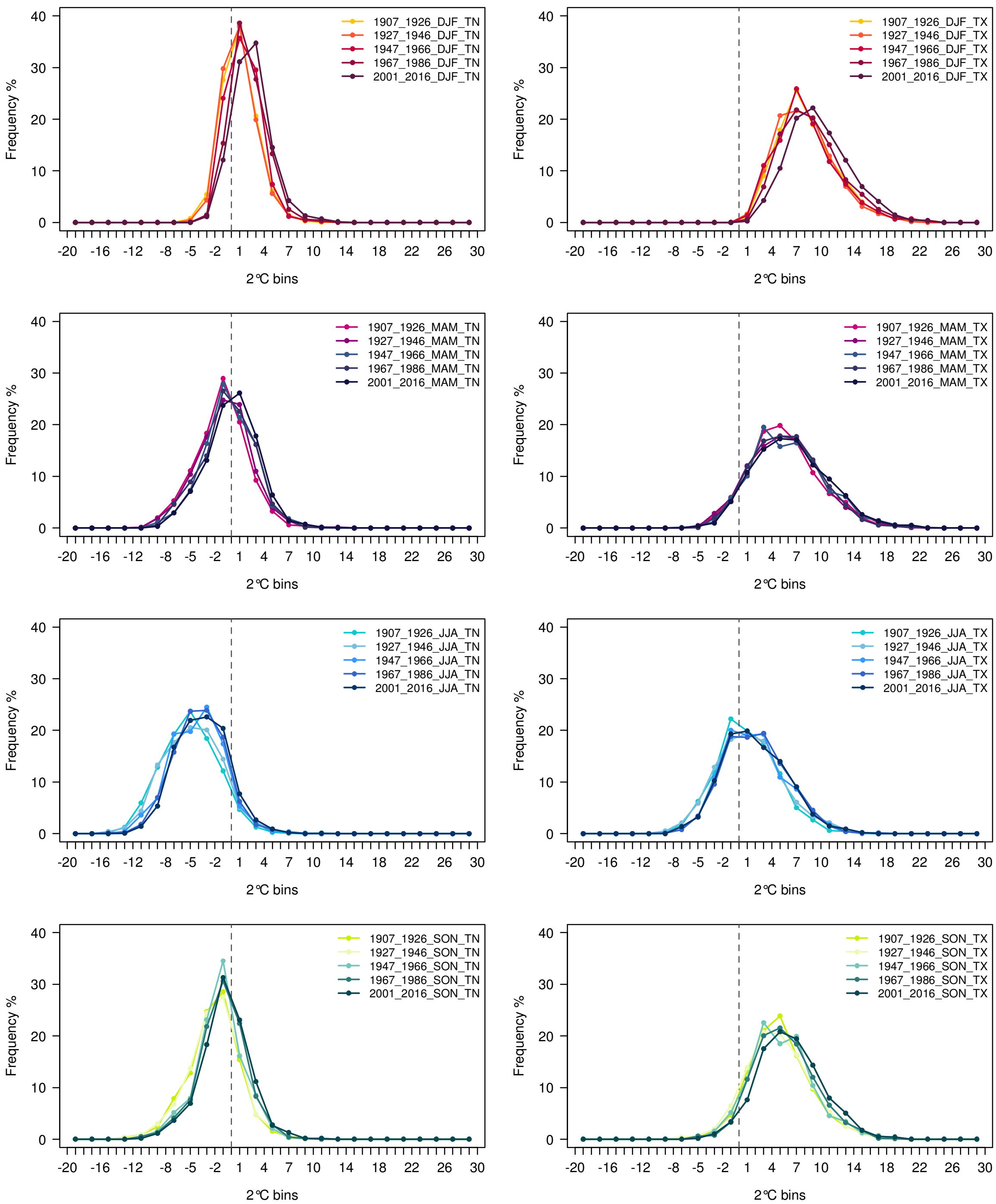


Figure 3 *Distribution of frequencies of daily minimum (TN; left column) and maximum (TX; right column) temperatures during December-February (DJF), March-May (MAM),*

June-August (JJA) and September-November (SON) for 20-year periods since 1907. Note data gap between 1983-2001. Dashed line at 0°C. Two degree bins have been used.

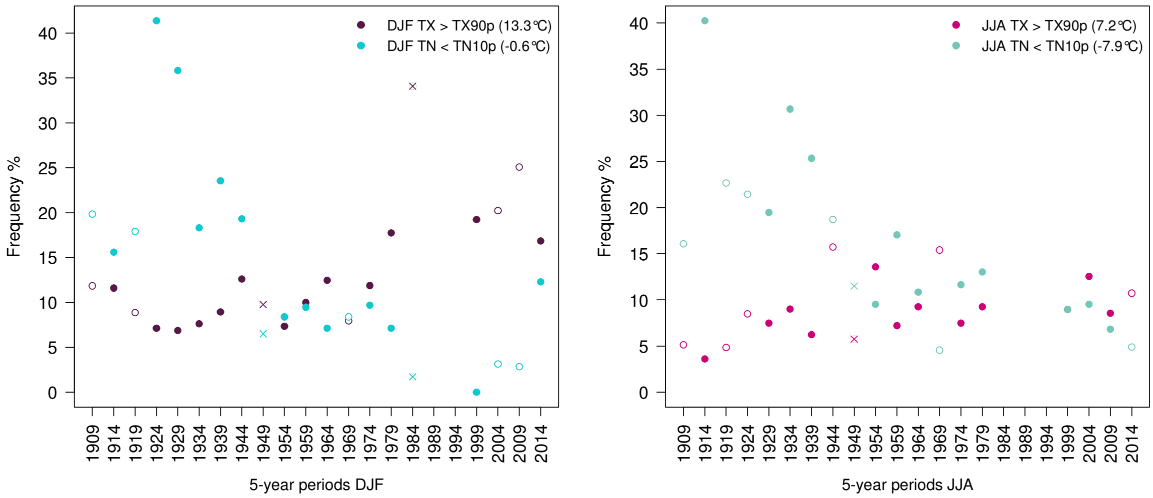


***Figure 4** Changes in the percentages of relatively warm days (TX90p; purple) and cold days (TN10p; blue) for 5-year periods for December-February (DJF), and for relatively warm days (TX90p; pink) and cold days (TN10p; green) for 5-year periods for June-August (JJA). Open circles indicate periods where only 3 or 4 years of data were available; crosses where 1 or 2 years of data were available.*

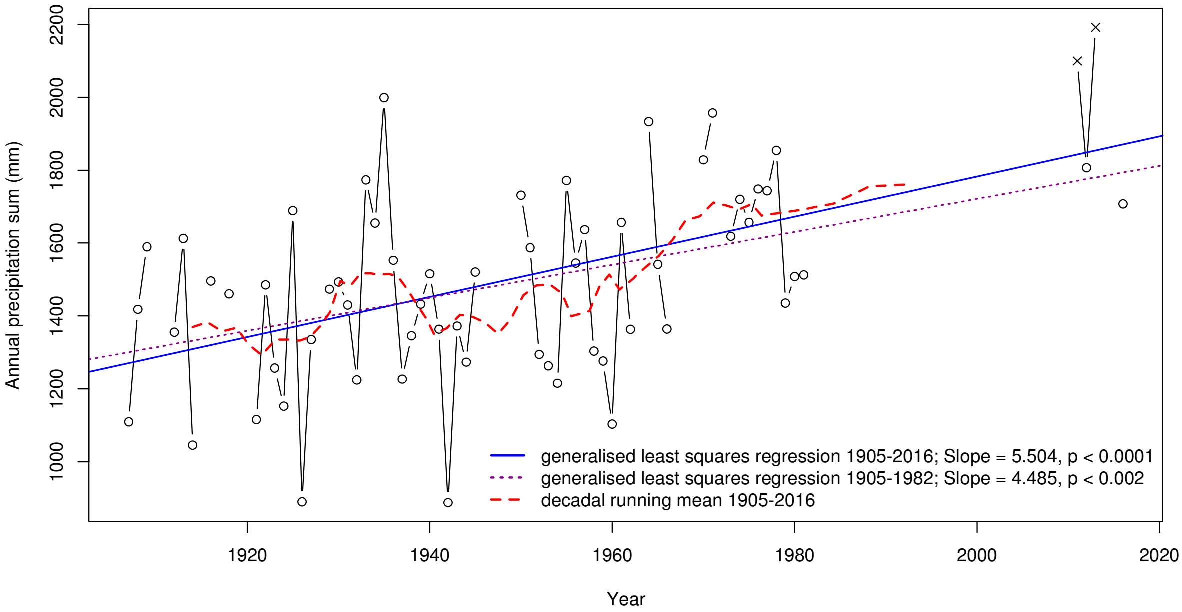


Figure 5 *Annual precipitation totals (in mm), including only years with no missing observations (open circles), and years with <6 missing days per year (crosses), with linear regressions for the years 1905-1982 and 1905-2016, and a decadal running mean (1905-2016).*

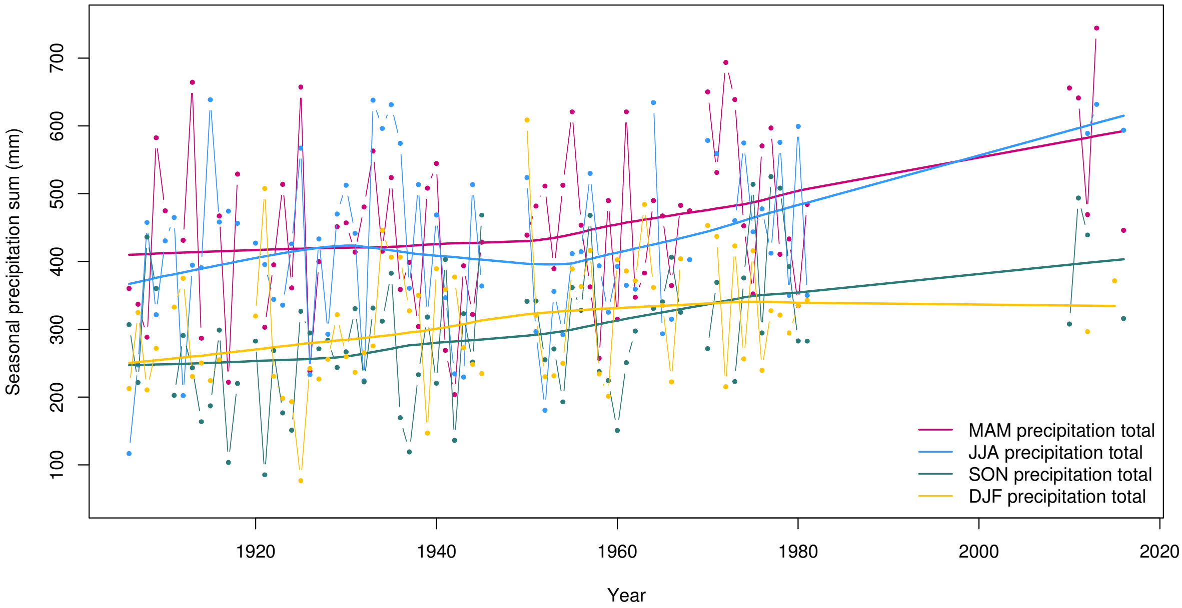


__Figure 6__ Seasonal precipitation totals, including only years with <3 missing days per season, each with a locally weighted scatterplot smoothing (1905-2016).

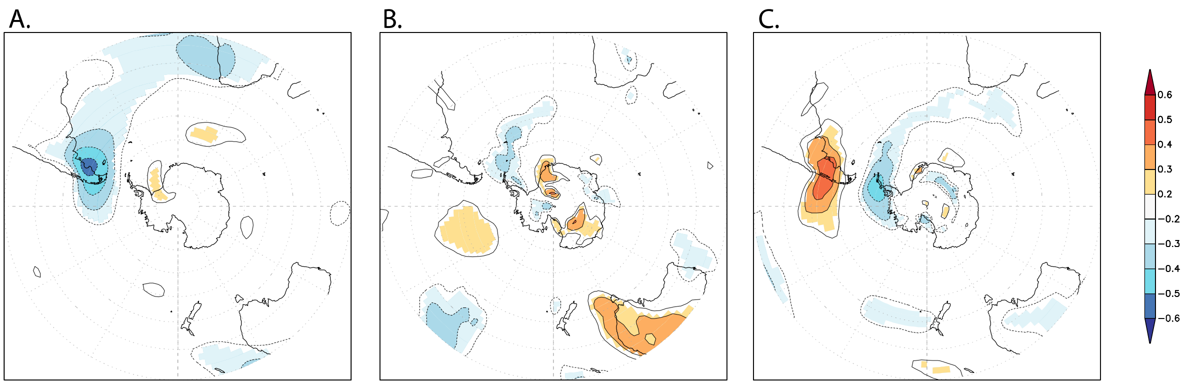


***Figure 7** Correlations between the detrended and deseasonalised monthly precipitation sum from South Georgia (marked with an 'X') and A. 850 hPa geopotential height, B. 850 hPa meridional, C. 850 hPa zonal, averaged over March to August over the period 1905-1983 using the Twentieth Century Reanalysis (20CR) version 2c. Significance p_{field}<0.1. Analyses were made with KNMI Climate Explorer* (van Oldenborgh and Burgers 2005).

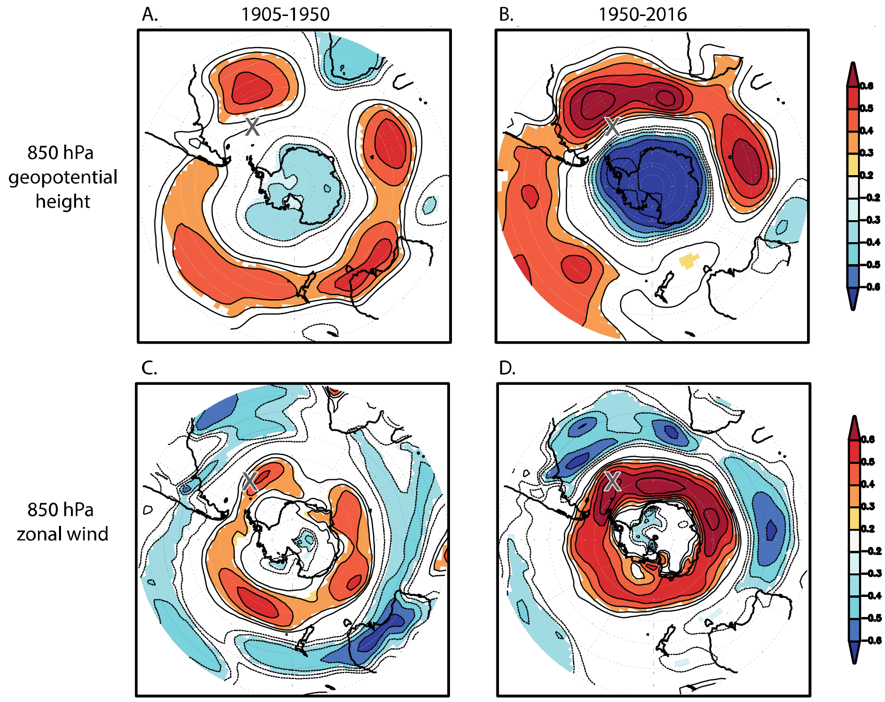


Figure 8 *Correlations between the detrended and deseasonalised mean monthly temperature from South Georgia (marked with an 'X') and A. 850 hPa geopotential height (1905-1950), B. 850 hPa geopotential height (1950-2016), C. 850 hPa zonal wind (1905-1950), and D. 850 hPa zonal wind (1950-2016), averaged over December to February using the Twentieth Century Reanalysis (20CR) version 2c. Significance* p_{field}*<0.1. Analyses were made with KNMI Climate Explorer* (van Oldenborgh and Burgers 2005).

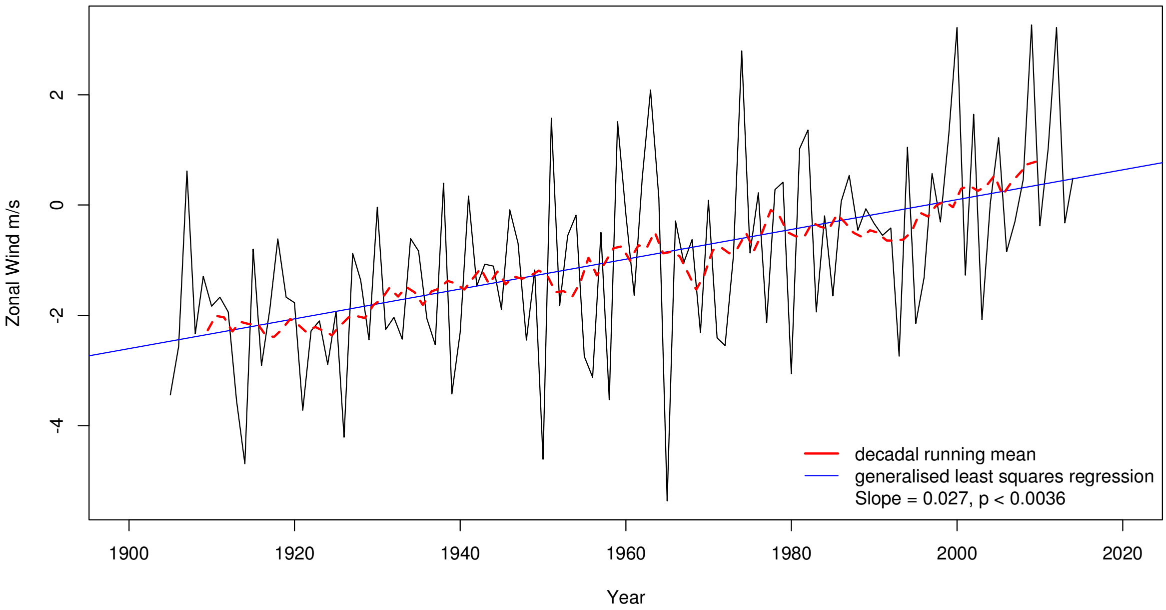


__Figure 9__ Zonal wind speed at 850 hPa from the 20th Century Reanalysis (20CR v2c) averaged over December-February at South Georgia, with generalised least squares regression (blue) and decadal running mean (red) lines shown.