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LETTER

Anomalous mid-twentieth century atmospheric circulation change over the South Atlantic compared to the last 6000 years

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Abstract

Determining the timing and impact of anthropogenic climate change in data-sparse regions is a considerable challenge. Arguably, nowhere is this more difficult than the Antarctic Peninsula and the subantarctic South Atlantic where observational records are relatively short but where high rates of warming have been experienced since records began. Here we interrogate recently developed monthly-resolved observational datasets from the Falkland Islands and South Georgia, and extend the records back using climate-sensitive peat growth over the past 6000 years. Investigating the subantarctic climate data with ERA-Interim and Twentieth Century Reanalysis, we find that a stepped increase in precipitation across the 1940s is related to a change in synoptic atmospheric circulation: a westward migration of quasi-permanent positive pressure anomalies in the South Atlantic has brought the subantarctic islands under the increased influence of meridional airflow associated with the Amundsen Sea Low. Analysis of three comprehensively multi-dated (using ^{14}C and ^{137}Cs) peat sequences across the two islands demonstrates unprecedented growth rates since the mid-twentieth century relative to the last 6000 years. Comparison to observational and reconstructed sea surface temperatures suggests this change is linked to a warming tropical Pacific Ocean. Our results imply 'modern' South Atlantic atmospheric circulation has not been under this configuration for millennia.

1. Introduction

Identifying the impact of anthropogenic forcing of climate modes in observation-poor regions is extremely challenging. The situation is particularly acute over the mid to high latitudes of the Southern Hemisphere. The southern annular mode (SAM), defined as the pressure difference between 40 °S and 65 °S, is the leading mode of climate variability in the southern mid-latitudes (Marshall 2003). The widely reported positive shift in SAM during the mid-1970s is evidenced by the intensification and southward shift of westerly airflow over the Southern Ocean (Marshall 2003, Visbeck 2009) and has been linked to hemispheric-wide changes in the atmosphere-ocean-ice domains (Hall and Visbeck 2002, Le Quéré *et al* 2009, Marshall and Speer 2012, Lenton *et al* 2013), including extensive warming, glacier retreat, sea-ice retreat, and ecological change (Domack *et al* 2005, Gordon *et al* 2008, Cook *et al* 2010, Mulvaney *et al* 2012). Model projections suggest a trend towards increasingly positive SAM into the 21st century as a result of a persisting Antarctic ozone hole and increasing atmospheric greenhouse gas concentrations (Thompson and Solomon 2002 , Thompson *et al* 2011, Lee and Feldstein 2013, Previdi and Polvani 2014, Thomas *et al* 2015) with ozone hole recovery complicating this projection (Perlwitz *et al* 2008). Unfortunately, continuous meteorological observations across the Southern Ocean only capture intra-annual to decadal climate variability over the 20th century (Zazulie *et al* 2010, Richard *et al* 2013), limiting our ability to place recent changes in the context of long-term (i.e. multi-decadal and longer) natural variability (Zhang *et al* 2007).

Climate proxies allow the extension of the observational record into the Holocene at sub-annual (e.g. ice cores, tree rings and corals) to multi-decadal (e.g. sediments, pollen, shells, boreholes) resolution (Jones *et al* 2002, Jones *et al* 2009, Mulvaney *et al* 2012, Masson-Delmotte *et al* 2013, PAGES 2k Consortium 2013, Lough *et al* 2014, Palmer *et al* 2015). Using annually-resolved proxies across the Southern Hemisphere and the Antarctica Peninsula (Villalba *et al* 2012, Abram *et al* 2014), the 1970s shift in SAM has been shown to be part of an increasingly positive trend since the 1940s, consistent with anthropogenic forcing (Thompson *et al* 2011, Thomas *et al* 2015). Divergence from modeled natural trends, however, suggest a relatively late anthropogenic climate impact (post-1980s) across the south Atlantic region (King *et al* 2015), implying the 1940s shift in SAM and associated climate impacts may not in fact be anthropogenic, but rather part of a longer natural cycle. Comparison to a long-term proxy climate baseline is therefore essential for understanding the late 20th century trend.

The last 6000 years is a particularly useful period against which to compare recent climate trends. The Antarctic ice sheets and sea level had achieved close to their modern configurations at the start of this period (Wanner *et al* 2008). Importantly, postglacial conditions in the Southern Ocean appear to have become established around 6.5 ka (Rosqvist *et al* 1999), with surface water cooling and sea ice expansion from 5000 years ago (Hodell *et al* 2001, Wanner *et al* 2008, Renssen *et al* 2012) and stable ice shelves on the Peninsula (Domack *et al* 2005). These changes are coincident with the end of the so-called Hypsithermal and the African humid period (deMenocal *et al* 2000, Haug *et al* 2001, Tierney *et al* 2015), all implying the establishment of 'pre-industrial' (CE 1850) global atmospheric and oceanic circulation. Options for the development of a network of annually resolved climate proxies spanning 6000 years has been limited across the south Atlantic region.

Fortunately, peat growth can be promoted by temperature and precipitation increases on multi-decadal to centennial timescales (MacDonald *et al* 2006, Dise 2009, Loisel and Yu 2013). On the Antarctic Peninsula, for instance, studies have highlighted exceptionally high peat growth during the latter part of the 20th century in the context of the last 350 years (Convey *et al* 2011, Royles *et al* 2012, Royles and Griffiths 2015), consistent with significant and rapid regional warming (Vaughan *et al* 2003) and a decrease in seasonality (Franzke 2012), linked to the positive recent trend in SAM (Thompson and Solomon 2002). A more extensive network of sites across the region is therefore required to place recent climate changes in the context of variability as experienced over the last 6000 years (Van der Putten *et al* 2012).

Whilst the South Atlantic Falkland Islands and South Georgia lie outside the 'hotspot' of late 20th century warming observed over the Antarctic Peninsula (Vaughan *et al* 2003) and the wider West Antarctic (Steig *et al* 2009), they are highly sensitive to changes in the strength of regional and hemispheric-wide Southern Hemisphere atmospheric circulation (figure 2) (Turney *et al* 2016a). Importantly, the south Atlantic region has some of the longest observational records in the Southern Ocean, of which a monthly resolved dataset back to CE 1895 has recently been reported for the Falkland Islands (Lister and Jones 2015). This area also has considerable scope for developing peat sequences that capture environmental and climate changes over the last 6000 years. Here we explore the atmospheric drivers of observed climate changes using the ERA-Interim (Dee *et al* 2011) and ACRE-facilitated NOAA-CIRES Twentieth Century Reanalysis Project (20CR version 2c) (Compo *et al* 2011) products. We extend the observational record by investigating climate-sensitive peat growth on the Falkland Islands and South Georgia over the last 6000 years, thereby placing recent observed warming in the South Atlantic in a multi-millennial context.

2. Data and methods

2.1. Observational record

Meteorological observations on the Falkland Islands commenced at Cape Pembroke Lighthouse around CE 1850 and ended in 1947, with parallel (but discontinuous) measurements made at Stanley from 1923 until 1986 (Lister and Jones 2015). During the Falkland Islands Conflict (1982) observations were disrupted and the meteorological station relocated to the airport at Mount Pleasant, where measurements were first made in 1986. Recent work by Lister and Jones report an updated climate dataset from the Falkland Islands, combining the above series into one continuous record, commencing from CE 1895 (Brooks 1920, Lister and Jones 2015). In parallel to the Falkland Islands record, South Georgia temperature observation started with whaling operations on the island from 1905 but experienced significant disruption as a result of the 1982 conflict, with continuous observations not resuming until 2001. Both datasets are available at http://hadobs.metoffice.com/crutem4/data/download.html. Mean monthly sea level pressure data from Stanley were obtained from sub-daily values (Cram *et al* 2015, Jones *et al* 2016), available online at http://cru.uea.ac.uk/cru/data/tpi/ and from the International Surface Pressure Databank on request (https://reanalyses.org/observations/international-surface-pressure-databank), the latter hosted by the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI). The surface pressure data has been gathered through international cooperation facilitated by the international Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative and other contributing organisations, assembled under the auspices of the Global Climate Observing System (GCOS) Working Group on Surface Pressure and the World Climate Research Programme/GCOS Working Group on Observational Data Sets for Reanalysis by NOAA Earth System Research Laboratory (ESRL), NCEI, and the University of Colorado's Cooperative Institute for Research in Environmental Sciences (CIRES). The sub-daily pressure series was checked for gross errors by looking at pressure differences between adjacent readings. If pressure differences were large, they were compared to adjacent readings and any other available weather information. Individual readings were removed where the indications pointed towards an error.

2.2. Proxy data

Three peat sequences were cored on two South Atlantic islands: an Ericaceous-grass dominated peatland on Canopus Hill, above Port Stanley Airport, Falkland Islands (a 1.6 m sequence at 51.691°S, 57.785°W, approximately 30 m above sea level), and moss species *Polytrichum strictum* and *Chorisodontium aciphyllum*-dominated peat in both King Edward Cove, Cumberland Bay, South Georgia (a 0.8 m sequence at 54.293°S, 36.494°W, approximately 5 m above sea level) and Junction Valley, South Georgia (a 0.70 m sequence at 54.298°S, 36.524°W, approximately 80 m above sea level) (figure 1). The two South Georgian sites are particularly susceptible to föhn winds that can exaggerate surface warming (Bannister and King 2015). Each sequence was contiguously sampled (every centimetre) for total organic carbon (%TOC) and nitrogen, determined using a LECO TruSpec CN analyser at the University of New South Wales Analytical Centre following standard techniques (Harris *et al* 2001). Comprehensive dating of the sequences (see details below) allowed us to reconstruct changes in the carbon flux (the amount of carbon sequestered) in each of the peat sequences using a method that takes into account the bulk density through each profile (Cannell *et al* 1993).

To provide a robust geochronological framework we undertook a multidating programme, using a combination of radiocarbon dating of terrestrial plant macrofossils and ^{137}Cs in the peat. Terrestrial plant macrofossils (seeds and leaves) were extracted from the peat sequences and given an acid-base-acid pretreatment and then combusted and graphitized in the University of Waikato AMS laboratory, with $^{14}C/^{12}C$ measurement by the University of California at Irvine (UCI) on a NEC compact (1.5SDH) AMS system. The pretreated samples were converted to CO_2 by combustion in sealed pre-baked quartz tubes, containing Cu and Ag wire. The CO_2 was then converted to graphite using H_2 and a Fe catalyst, and loaded into aluminum target holders for measurement at UCI. This was supplemented by ^{137}Cs measurements down the profile to detect the onset of nuclear tests. ^{137}Cs analysis was undertaken following standard techniques with measurements made using an ORTEC high-resolution, low-background coaxial germanium detector at the University of Exeter (Mitchell *et al* 1992, MacKenzie *et al* 1997). Detectable measurements of ^{137}Cs were used for further age control (Leslie and Hancock 2008).

The radiocarbon and ^{137}Cs ages were used to develop an age model using a P_sequence deposition model in OxCal 4.2 (Bronk Ramsey 2008); with variable atmospheric ^{14}C over the Southern Ocean (Turney *et al* 2016b) we undertook RScaled Outlier analysis detection (probability = 0.05) (Bronk Ramsey 2009). The ^{14}C ages were calibrated against the Southern Hemisphere (SHCal13) and Bomb04SH calibration datasets (Hua and Barbetti 2004, Hogg *et al* 2013) with the prior U(1952, 2011) used to capture the range of dates for the onset of ^{137}Cs deposition in each sequence (Hancock *et al* 2011). Using Bayes' theorem, the algorithms employed sample possible solutions with a probability that is the product of the prior and likelihood probabilities. Taking into account the deposition model and the actual age measurements, the posterior probability densities quantify the most likely age distributions; the outlier option was used to detect ages that fall outside the calibration model for each group, and if necessary, down-weight their contribution to the final age estimates. Modelled ages reported in the text are described as thousands of calendar years BP or cal BP (table 1).

To investigate whether the changes in peat growth may reflect some natural long-term forcing we undertook tipping point analysis. This technique is based on the fact that abrupt climate changes, if characterised by long-term forcing prior to reaching a tipping point in the system dynamics, can be mathematically detected by looking at the pattern of fluctuations in the short-term trends of the data before

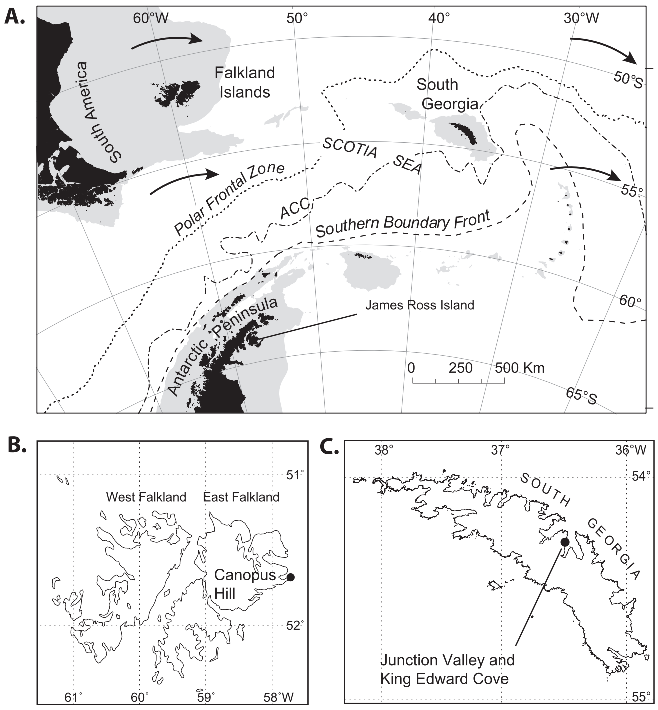

Figure 1. Location of the Falkland Islands and South Georgia in the South Atlantic Ocean with mean locations of the Polar and Southern boundary fronts (dashed lines), the continental shelf (grey areas) and prevailing westerly airflow (solid arrows) (panel A); modified from Strother *et al* (2015). Reprinted by permission of SAGE Publications, Ltd. Canopus Hill, Port Stanley Airport, in the east Falkland Islands (panel B). Junction Valley and King Edward Cove, in South Georgia (panel C).

the shift takes place (Dakos *et al* 2008). This is based on the concept of 'critical slowing down', where on the approach to such an abrupt shift, the equilibrium state of the system takes increasingly longer to recover from small perturbations (Held and Kleinen 2004, Dakos *et al* 2012). This increased recovery time is detected as a short-term increase in the lag-1 autocorrelation or 'memory' of the time series (Ives 1995). An increasing trend in variance is also often found due to the ability of the system to travel farther from its equilibrium point as the basin of attraction (which describes the stability of the system) shallows and widens (Lenton *et al* 2012). Some data pre-processing can be undertaken, including detrending to remove non-stationarities, and interpolation to make the data equidistant. The analysis was carried out with and without this pre-processing, as when there is a relative sparseness of data points, and/or if there is no obvious long-term trend, interpolation and detrending can bias the analysis (Dakos *et al* 2012). Autocorrelation at lag-1 and variance were then measured over a sliding window of 50% of the length of the dataset, using the R functions ar.ols () and var() respectively. The Kendall tau rank correlation coefficient is used to provide a quantitative measure of the trend (Kendall 1948) by assessing the predominance of concordant pairs, providing an objective evaluation of the statistical evidence for the trend.

3. Results and discussion

3.1. Observational period

The South Atlantic climate series from South Georgia and the Falklands provides a valuable record of climate change in the mid-latitudes of the Southern Hemisphere (figure 2). While spring–summer (September–February) temperature trend records a relatively modest long-term increase on both islands (figure 3), the complete annual Falklands record captures a highly statistically significant warming of 0.5 °C/century from CE 1910–2010 ($p = 0.002$) (Lister and Jones 2015). Where there is overlapping observational data (1905–2011), the deseasonalised and detrended temperature trends on the Falkland Islands and South Georgia are statistically similar ($r = 0.506$, $p < 0.0001$), demonstrating a coherent change across the region. Importantly, while there does appear to be a long-term warming trend, climate regime analysis of the precipitation dataset (Rodionov 2004) identifies a significant (90% confidence) and substantial step-change to sustained wetter conditions in the mid-1940s (representing a 23% increase). The observed change to wetter conditions followed a short-lived period of higher temperatures observed across South America and the Antarctic Peninsula (Turner *et al* 2005, Schneider and Steig 2008) (figure 3).

The increases in South Atlantic temperature and precipitation do not appear to have been accompanied by any long-term change in local mean sea

Table 1. Radiocarbon and modelled calibrated age ranges for peat sequences on the Falkland Islands (FI) and South Georgia (SG) using SHCal13 (Hogg *et al* 2013) and Bomb04SH (Hua and Barbetti 2004) using the P_sequence and Outlier analysis option in OxCal 4.2 (Bronk Ramsey 2008, Bronk Ramsey and Lee 2013).

Depth, cm	Wk lab number	Material	% Modern/^{14}C BP ± 1 σ	Mean cal. years BP ± 1σ
Canopus Hill, FI				
8–9	34 598	Fruits and leaves	117.0 ± 0.4%M	−30 ± 19
9		^{137}Cs		−28 ± 19
11–12	32 994	Fruits and leaves	107.8 ± 0.4%M	−17 ± 20
18–19	37 007	Fruits and leaves	107.3 ± 0.3%M	12 ± 53
25–26	35 146	Fruits and leaves	95 ± 25	105 ± 76
35–36	37 008	Fruits and leaves	647 ± 25	603 ± 29
39–40	33 445	Fruits and leaves	761 ± 25	663 ± 32
57–58	32 996	Fruits and leaves	1818 ± 25	1681 ± 57
70–71	32 350	Fruits and leaves	2235 ± 25	2212 ± 63
97–98	32 997	Fruits and leaves	2749 ± 25	2810 ± 35
107–108	32 998	Fruits and leaves	2914 ± 26	2998 ± 57
120–121	41 767	Fruits and leaves	3238 ± 20	3420 ± 57
141–142	32 351	Fruits and leaves	3955 ± 32	4325 ± 64
148–149	41 768	Fruits and leaves	4390 ± 20	4412 ± 59
153.5–154.5	42 144	Fruits and leaves	4039 ± 21	4472 ± 31
156.5–157.5	42 145	Fruits and leaves	4075 ± 22	4496 ± 39
King Edward Cove, SG				
8–9	34 599	Fruits and leaves	115.2 ± 0.4%M	−38 ± 10
15		^{137}Cs		−12 ± 9
16–17	34 600	Fruits and leaves	103.9 ± 0.3%M	−5 ± 7
27–28	33 000	Fruits and leaves	100.3 ± 0.3%M	79 ± 62
35–36	33 446	Fruits and leaves	103 ± 25	159 ± 70
40–41	34 601	Fruits and leaves	251 ± 25	251 ± 58
45–46	32 358	Fruits and leaves	446 ± 26	439 ± 64
57–58	37 009	Fruits and leaves	729 ± 25	631 ± 37
64–65	34 602	Fruits and leaves	1193 ± 25	774 ± 68
70–71	32 359	Fruits and leaves	983 ± 25	853 ± 46
75–76	37 010	Fruits and leaves	1015 ± 25	897 ± 51
81–82	35 149	Fruits and leaves	1373 ± 30	1223 ± 48
Junction Valley, SG				
7–7.5	35 147	Fruits and leaves	>47 600	
9		^{137}Cs		−25 ± 14
10–11	37 011	Fruits and leaves	121.7 ± 0.4M	−19 ± 12
12–13	37 012	Fruits and leaves	107.2 ± 0.2%M	−1 ± 28
14–15	35 148	Fruits and leaves	144 ± 25	71 ± 72
20–21	32 356	Fruits and leaves	737 ± 25	561 ± 108
22–23	37 013	Fruits and leaves	545 ± 25	653 ± 134
33–34	37 014	Fruits and leaves	1821 ± 25	1714 ± 163
36–37	34 607	Fruits and leaves	3714 ± 25	3996 ± 71
58–59	34 608	Fruits and leaves	4858 ± 25	5535 ± 63
64–65	32 357	Fruits and leaves	5071 ± 30	5783 ± 69

Note: calibrated ages are relative to before present (BP) i.e. CE 1950.

level pressure in spite of the regional (Visbeck 2009) and hemispheric-wide (Marshall 2003) atmospheric circulation changes represented by the recent positive SAM index values (figure 3). Crucially, although the multi-decadal trend to more positive SAM and the deepening of the Amundsen Sea Low (ASL) has taken place since the mid-20th century (Fogt *et al* 2012, Hosking *et al* 2013), increasing northerly airflow (and temperature) over the region (Abram *et al* 2014, Lister and Jones 2015) and reanalysis of late 20th century atmospheric circulation in both the ERA-Interim (Dee *et al* 2011) and the 20CR 2c (Compo *et al* 2011) suggests wetter conditions have the opposite relationship (figures 4(A)–(F)). Here we find high rainfall over the subantarctic islands is associated with conditions that comprise both relatively low pressure in the South Atlantic and high pressure over the Bellingshausen and Amundsen seas (rather than a weakening); a configuration that enhances meridional airflow across the region, delivering moist southerly air masses over the islands, with westerly winds displaced to the north.

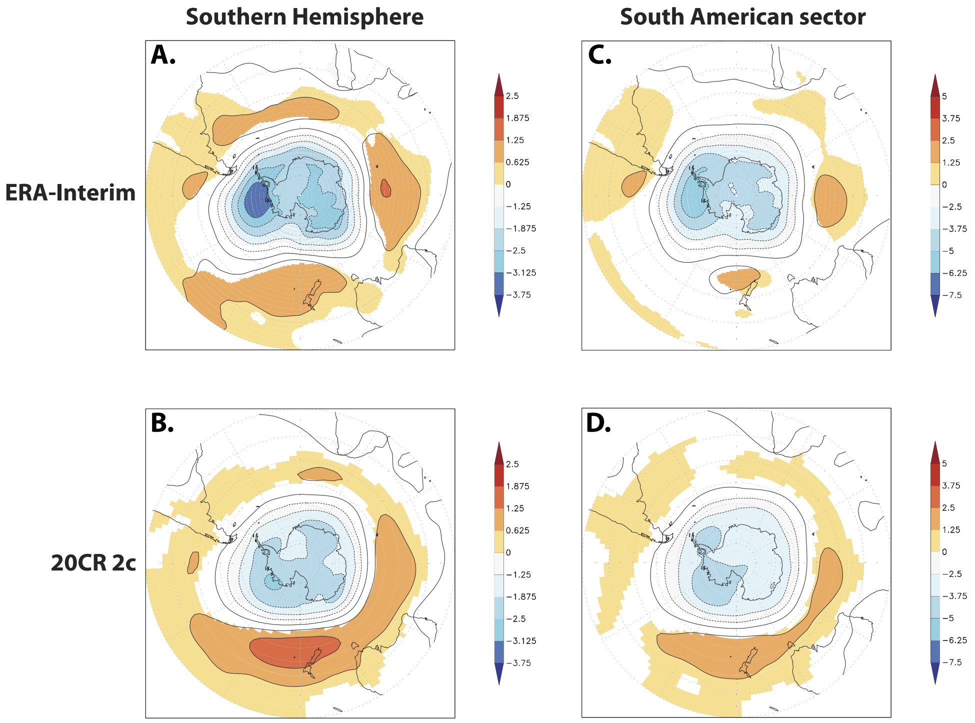

Figure 2. Regressions of deseasonalised and detrended mean sea level pressure (MSLP) on hemispheric-wide (Marshall 2003) (panels A and B) and South American (Visbeck 2009) (panels C and D) annual (July–June) southern annular mode (SAM) using ERA-Interim (post-1979; panels A and C) (Dee *et al* 2011) and 20CR 2c (post-1957; panels B and D) (Compo *et al* 2011). Scale on right hand side in each panel: hPa per unit of SAM. Significance $p_{\text{field}} < 0.1\%$. Analyses were made with KNMI Climate Explorer (van Oldenborgh and Burgers 2005).

Whilst the ASL is generally considered quasi-stationary because of the large number of low pressure systems in this sector of the circumpolar trough, they are by no means permanent (Hosking *et al* 2013). With large variability in pressure systems across the region on daily to seasonal timescales, our analysis suggests that when both low pressure is present over the South Atlantic and high pressure is found west of the Peninsula, more rainfall is delivered to the subantarctic islands and across the wider southern South America (figures 4(A)–(F)).

Reconciling the 1940s stepped increase in Falkland Islands' precipitation with the above association of pressure systems across the South Atlantic and Peninsula is not immediately apparent. To investigate the synoptic conditions for the first half of the Port Stanley record (CE 1904–1940) we interrogated the 20CR 2c (figures 4(G)–(I)) (Compo *et al* 2011, Cram *et al* 2015). Whilst the observational record that contributes to the high-latitudes of the Southern Hemisphere is relatively sparse during the early 20th century (Jones *et al* 2016), we find Falkland Islands precipitation was similarly driven by southerly airflow (figure 4(I)). In marked contrast to the last seventy years, however, the synoptic configuration appears to have been different. Crucially, during the first half of the 20th century there appears to have been no dynamic link with pressure over the Amundsen and Bellingshausen Seas. Instead, high precipitation before the mid-1940s was solely influenced by the South Atlantic pressure system centred over South Georgia (figure 4(G)) with return northerly airflow strengthened out to the east (figure 4(I)). The ASL is a semi-permanent feature, a consequence of the Antarctic Peninsula and regional topography that dynamically influences atmospheric flow in the southeast Pacific sector of the Southern Ocean (Fogt *et al* 2012), suggesting a fundamental change in atmospheric circulation took place across the 1940s that brought the South Atlantic into the sphere of influence of this dynamic feature. The 'absence' of a role for pressure changes over the Amundsen and Bellingshausen Seas prior to the 1940s appears to have limited precipitation over the islands.

Several physical mechanisms need to be considered to understand the circulation changes. One possible cause may be related to the release of CFCs that started in the 1920s, though measurable ozone depletion was not observed until the 1980s (Thompson *et al* 2011). Alternatively, the changes may be linked to expansion of the tropical belt and Hadley circulation (Seidel *et al* 2008) which have recently been reported to have shifted south since the 1940s (Brönnimann *et al* 2015, Nguyen *et al* 2015), potentially affecting circulation across the mid-latitudes. Additionally, during at least the last four decades the Antarctic Peninsula region is known to be sensitive to tropical Pacific temperatures that generate an atmospheric Rossby wave response (Yuan 2004, Compo

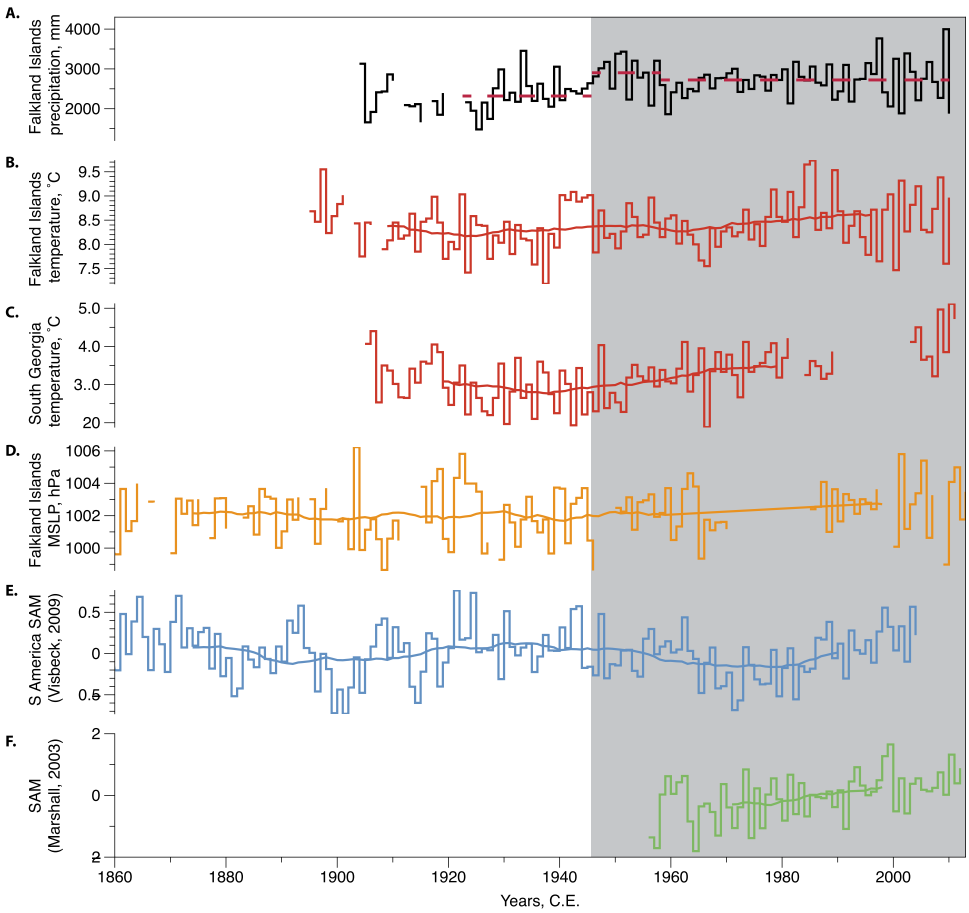

Figure 3. Late 19th and 20th century climate trends in the South Atlantic. Port Stanley (Falkland Islands) Spring/Summer (September–February) precipitation (black line) and temperature (red line) (Lister and Jones 2015) (panels A and B). Grytviken (South Georgia) Spring/Summer (September–February) temperature (panel C). Combined Cape Pembroke–Stanley Spring/Summer (September–February) mean sea level pressure (panel D). Annual (July–June) South American (Visbeck 2009) and hemispheric-wide (Marshall 2003) reconstructions of the southern annular mode index (panels E and F, respectively). 30 year running means shown in bold (note: due to data gaps, not all running means extend across the full period). Climate regime analysis of the Port Stanley Spring/Summer precipitation record identifies a shift during the mid-1940s (dashed lines) (Rodionov 2004). Grey column denotes the period since the shift to higher precipitation.

and Sardeshmukh 2010, Gordon *et al* 2010, Steig *et al* 2013, Turney *et al* 2015), causing anomalously high pressure over the Amundsen and Bellingshausen Seas, and enhancing southerly (colder) airflow across the Weddell Sea and South Atlantic (Abram *et al* 2014). To investigate a possible role for the tropical Pacific in atmospheric circulation changes over the South Atlantic, we regressed the Port Stanley precipitation record against the post-1950 HadISST sea surface temperature dataset (Rayner *et al* 2003) and find a highly significant relationship with the tropical Pacific (figure 5). Specifically, high precipitation is associated with warmer temperatures in the central and eastern Pacific (Nino 3.4 and 3 regions), with zero lag. Our results imply the step change to wetter conditions across the 1940s marked a threshold after which low-latitude climate variability was more strongly projected on the South Atlantic, consistent with previous studies suggesting disproportionate remote impacts of tropical Pacific temperature changes (Sardeshmukh *et al* 2000).

Although further work is needed to increase the density of early observations in reanalysis products, our results are consistent with the stepped change to wetter conditions from the mid-1940s (figure 3) and suggests this came about from a change in circulation across the mid-latitudes of the Southern Hemisphere (possibly linked to increasing sea surface temperatures in the tropical Pacific) that allowed the influence of synoptic conditions in the Amundsen and Bellingshausen seas to align with those over the South Atlantic.

3.2. Proxy records of past change

Comprehensive radiocarbon and ^{137}Cs dating of the subantarctic sequences (table 1) provides a robust geochronological framework for reconstructing change across the region. The Junction Valley sequence preserves a record of more than 6000 years, with Canopus Hill extending over 4000 years (figure 6). The youngest record is the relatively low-lying King Edward Cove that captures changes in peat growth

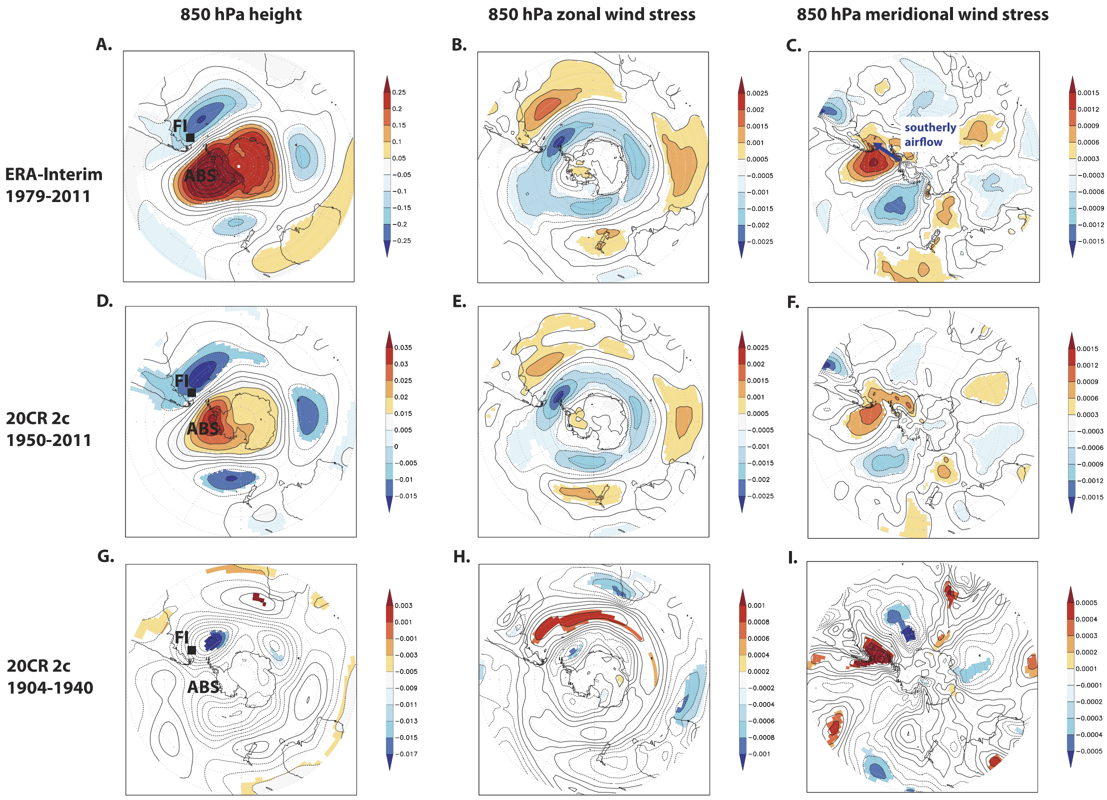

Figure 4. Changing atmospheric circulation during the mid-20th century. Regressions of deseasonalised and detrended 850 hPa pressure (panel A), zonal (panel B) and meridional (panel C) wind stress (ms^{-1}) on summed Falkland Islands (FI; Port Stanley) Spring/Summer (September–February) precipitation (ERA-Interim 1979–2011). Scale on right hand side of each panel: hPa mm^{-1} (left column) and ms^{-1} mm^{-1} (middle and right columns). 'ABS' denotes the Amundsen and Bellingshausen Seas. A comparable relationship is also observed across 1950–2011 using 20th Century Reanalysis 2c (panels D, E and F, respectively). Note, the change in relationship between Spring/Summer precipitation and deseasonalised and detrended 850 hPa pressure (panel G), zonal (panel H) and meridional wind stress (panel I) (20CR 2c) across the 1940s. Significance $p_{\text{field}} < 0.1\%$. Analyses were made with KNMI Climate Explorer (van Oldenborgh and Burgers 2005).

during the past 1200 years. Fortunately, the rapid and dramatic increase in atmospheric ^{14}C as a consequence of nuclear tests (the so-called 'bomb' spike) (Hua and Barbetti 2004) and the associated increase in ^{137}Cs (with a half-life of 30 years) (Leslie and Hancock 2008) provide two independent time-parallel marker horizons in each sequence (figure 6). The %TOC values for the three sites fluctuate around 40%–50%, which is typical of cold climate Holocene peats (Vitt *et al* 2000, Beilman *et al* 2009, Nakatsubo *et al* 2015). The carbon: nitrogen (C:N) profiles are also broadly comparable across the three sites with values ranging from ~30 to 40. Subtle down core fluctuations in the TOC% and C: N records most likely reflect past hydrological change impacting humification rates (Kuhry and Vitt 1996, Anderson 2002). The relative complacency of both the TOC% and C:N records down profile across the three sites highlights the long-term geomorphic stability of each bog catchment, with no evidence for significant periods of inwash.

To investigate the role of temperature and precipitation on peat growth (MacDonald *et al* 2006, Dise 2009, Loisel and Yu 2013), we interrogated the highest resolution record with the most complete climate dataset (figure 7). The carbon accumulation rate from Canopus Hill (Falkland Islands) was binned at decadal resolution across the 20th century and log transformed. Whilst higher mean spring–summer (September–February) temperatures are associated with increased accumulation ($r^2 = 0.26$), the strongest relationship is observed with cumulative spring–summer precipitation ($r^2 = 0.66$), suggesting the delivery of moisture across the growing season is the primary driver of growth. The implication is following recharge of water table levels by moisture-laden southerly airmasses, warmer spring/summer conditions encourages further growth.

Crucially, all three sequences record a dramatic increase in peat growth and carbon sequestration that commenced immediately prior to the 1950s onset of nuclear tests (figure 8). The same trend is observed in all three sequences using the method reported by (Yu *et al* 2003) (data not shown). The Canopus Hill sequence on the Falklands records the greatest increase with a tenfold increase in accumulation across the 20th century, with a pronounced peak commencing in the 1940s. Similar increases in accumulation are also recorded in the South Georgia sequences, with a threefold increase in King Edward Cove and a sixfold increase in Junction Valley. The increase in

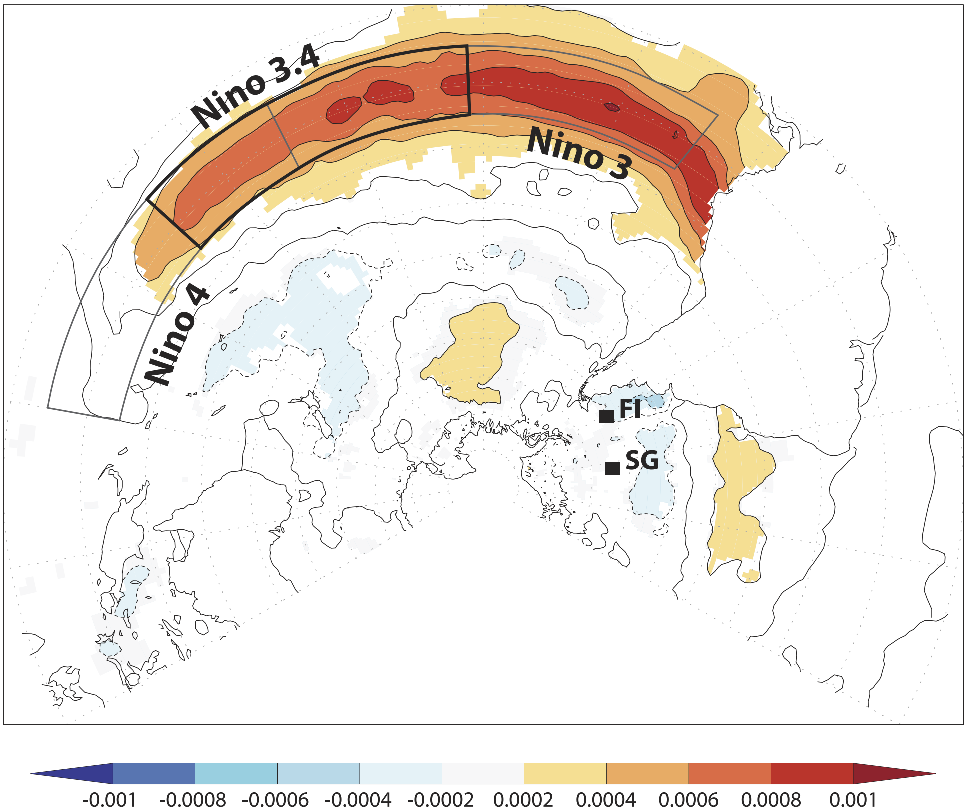

Figure 5. Tropical teleconnection with the South Atlantic in the second half of the 20th Century. Regression of deseasonalised and detrended sea surface temperatures (°C; HadISST) on summed Falkland Islands (FI; Port Stanley) Spring/Summer (September–February) precipitation (mm) since 1950 (Rayner *et al* 2003). Scale: °C mm^{-1}. Location of South Georgia (SG) and El Niño regions 3, 3.4 and 4 also shown. Significance $p_{\text{field}} < 0.1\%$. Analyses were made with KNMI Climate Explorer (van Oldenborgh and Burgers 2005).

peat growth is consistent with the observational record showing a stepped increase to sustained higher precipitation during the 1940s (figure 3). The greatest accumulation of peat at this time supports precipitation as a key driver of growth on the islands, supported by warmer temperatures (figure 7). At no other time over the past 6000 years do we observe a comparable rate of peat growth as the mid- to late-20th century (figure 8).

To investigate whether changes in the peat accumulation might reflect long-term forcing we undertook tipping point analysis (figure 9). In a long-term forcing scenario, the leading early warning indicators of critical slowing down (autocorrelation and variance) would be expected to increase, as the basin of attraction of the system widens and shallows. If, on the other hand, there is no underlying long-term forcing, these indicators would show no trend. Our tipping point analysis on the three peat sequences from the Falklands and South Georgia show no consistent parallel increase in autocorrelation or variance, under all pre-processing scenarios (figure 9), arguing against a long-term forcing that led to a shift in the climate system. These results are consistent regardless of the sampling resolution of the record; the Canopus Hill sequence, with the highest resolution averaging 30 years, shows negative trends for autocorrelation and variance. The abrupt acceleration in peat growth is therefore more likely to be the result of a short-term or noise-induced change, consistent with the observed relatively abrupt nature of wetter conditions across this region.

Our results identify a shift in atmospheric circulation across the mid latitudes of the Southern Hemisphere in the 1940s that appears anomalous in the context of the last six millennia. This finding is consistent with other records spanning the mid to late Holocene. Recent work using proxy data has argued that the trend to positive SAM since the 1940s is unprecedented over the past millennia (figure 8(B)) (Villalba *et al* 2012, Abram *et al* 2014), providing warmer air masses over the South Atlantic subantarctic islands that would have helped drive peat growth (figure 7). Curiously, whilst the James Ross Island ice core record on the Antarctic Peninsula suggests an exceptional rate of warming in the 20th century (Mulvaney *et al* 2012) it does not preserve the highest absolute temperatures across this period (figure 8(F)) suggesting absolute temperatures may have been offset by enhanced southerly airflow as implied by the South Atlantic subantarctic islands (figures 8(C)–(E)). This interpretation is supported by a multi-proxy reconstruction of Nino 3.4 temperatures for the last millennium (Emile-Geay *et al* 2013) which shows

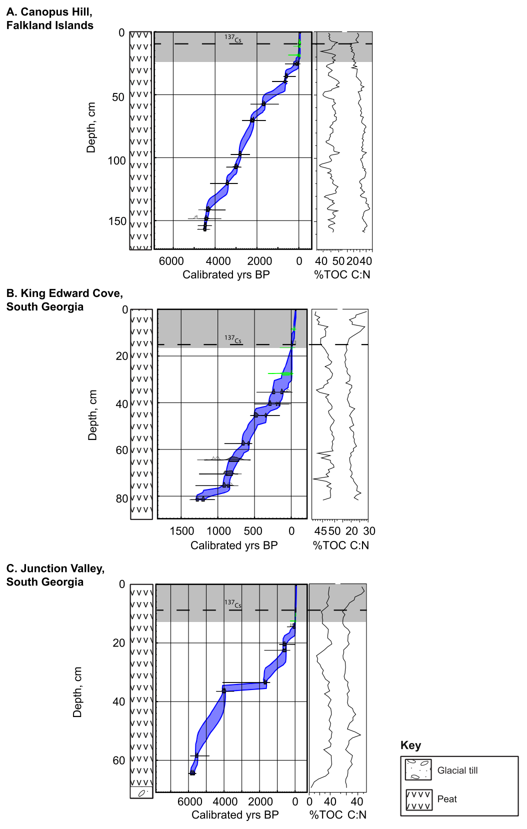

Figure 6. Lithostratigraphy, age-depth model (blue envelope denotes 1σ range), % total organic carbon (%TOC) and C:N content of peat sequences from Canopus Hill (Falkland Islands), King Edward Cove and Junction Valley (South Georgia). Dash lines denote stratigraphic location of measurable ^{137}Cs in each sequence. The blue envelope captures the 95% confidence interval for each age model. Grey column denote the increase in peat (and carbon) accumulation.

unprecedented warming in the central tropical Pacific since the mid-20th century (figures 8(A)), consistent with higher pressure in the Amundsen and Bellingshausen seas and enhanced southerly airflow over the region (Yuan 2004, Gordon *et al* 2010, Abram *et al* 2014). The dramatic increase in precipitation and associated peat growth therefore implies a threshold in the global climate system was passed during the 1940s that is without parallel in the last 6000 years. If correct, the south Atlantic region may indeed be one of the first to have experienced the effects of anthropogenic climate change (King *et al* 2015).

4. Conclusions

Historic observations suggest unusual climate changes in the South Atlantic during the latter half of the 20th century. Whilst not of the magnitude of warming observed over the Antarctic Peninsula, historic observations and well-dated proxy sequences provide the opportunity to test whether the climate changes across the region are exceptional. Focusing on the last 6000 years, during which near-contemporary climate conditions were established, we investigated monthly observational records from the Falklands and South Georgia to derive an understanding of the physical processes driving modern climate. We explored these changes in the context of the last 6000 years using three highly-resolved and multi-dated peat sequences that are sensitive to precipitation and temperature changes. We find an order of magnitude increase in peat growth coincided with a stepped shift to sustained wetter conditions in the 1940s. However, the changes

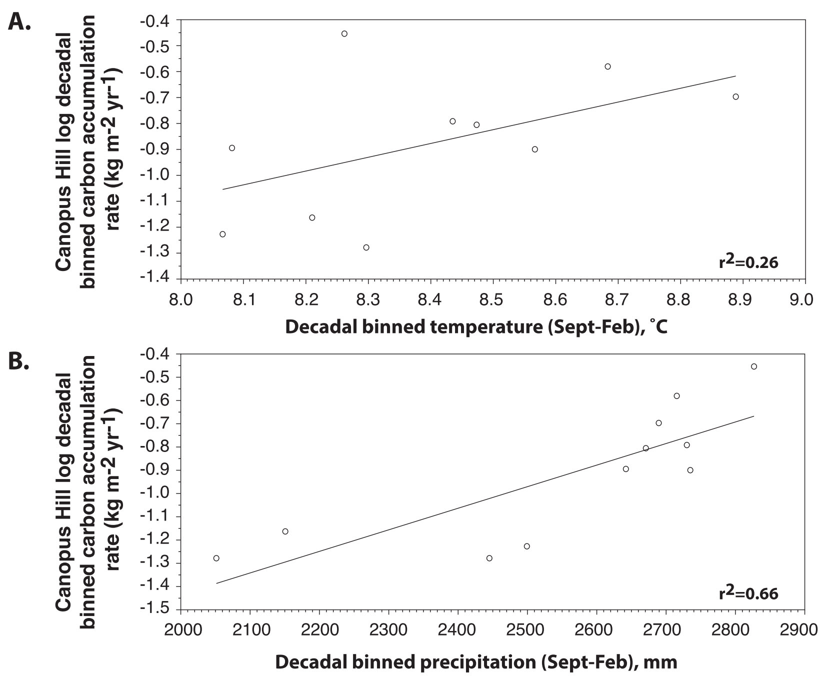

Figure 7. Relationship between 20th century decadally-binned carbon accumulation rate (logged) and Spring/Summer temperature (panel A) and total precipitation (panel B) at Canopus Hill (Falkland Islands).

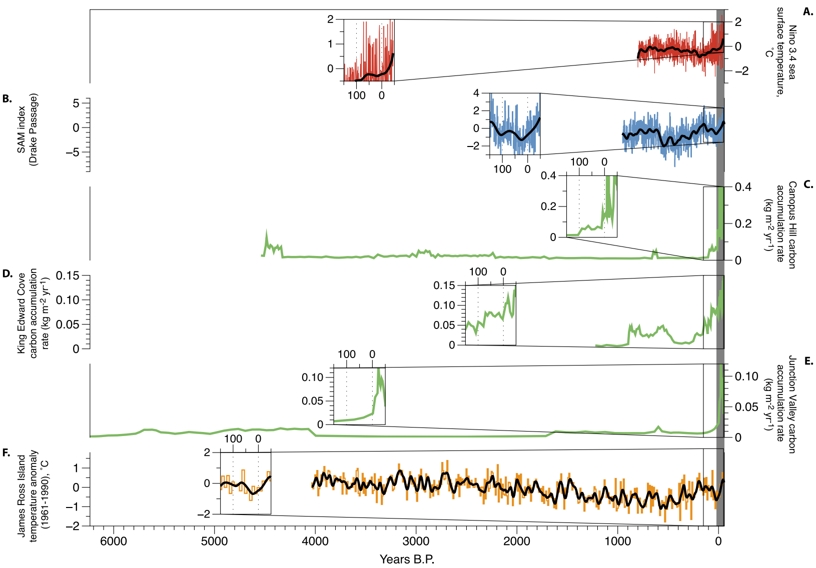

Figure 8. Comparison between Nino 3.4 sea surface temperature (SSTs) over the last millennium (panel A) (Emile-Geay *et al* 2013), southern annular mode (SAM) for the Drake Passage (panel B) (Abram *et al* 2014), carbon flux on the Falkland Islands (Canopus Hill; panel C) and South Georgia (King Edward Cove, panel D and Junction Valley, panel E), and James Ross Island (JRI) temperature anomalies (panel F) (Mulvaney *et al* 2012). A 50 year locally weighted smoothing (LOESS) curve was fitted to the Nino 3.4, SAM and JRI datasets (black lines). Grey column defines anomalously growth rate in peat post-1940s relative to 6000 year record. Inset panels show climate changes and acceleration in carbon sequestration since the mid-20th century.

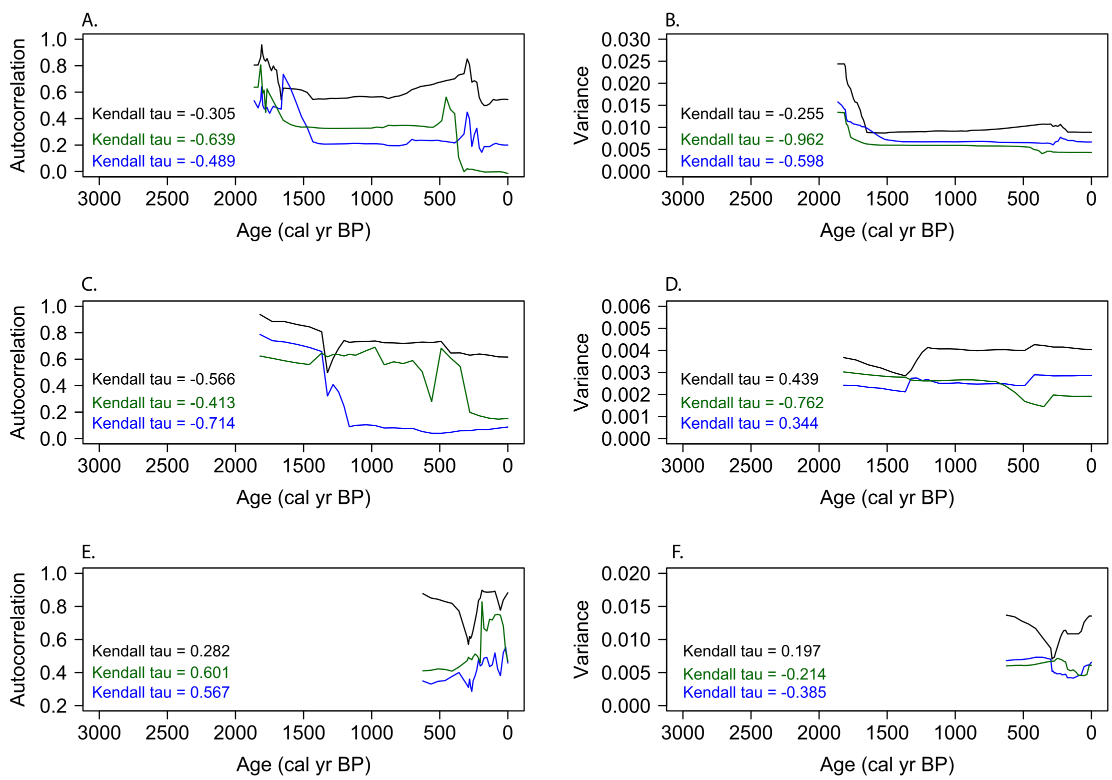

Figure 9. Tipping point analysis for carbon flux (left panels) autocorrelation and (right panels) variance and corresponding Kendall tau values of the Falkland Islands (Canopus Hill, panels A and B) and South Georgia (King Edward Cove, panels C and D, and Junction Valley, panels E and F). Black lines show results from no detrending or interpolation, blue lines show detrending only, and green lines show both detrending and interpolation.

preserved on the subantarctic islands cannot be explained by a simple latitudinal shift in zonal airflow, rather a realignment of synoptic conditions across the mid-latitudes that appears linked to tropical Pacific temperature changes. The changes observed on the South Atlantic subantarctic islands are unprecedented in the context of the last 6000 years and suggest the regional circulation changes being experienced today are anthropogenic in origin. If the trends reported here persist, it seems probable that exceptionally high growth rates of peat sequences will continue in the region accompanied by continuing widespread glacier and sea ice retreat across the Antarctic Peninsula. Importantly, our results also note a word of caution in the use of post-1950 proxy-climate relationships for the reconstruction of modes of variability, suggesting teleconnections were not stable across the 20th century.

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