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

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2016 Environ. Res. Lett. 11 064009
(http://iopscience.iop.org/1748-9326/11/6/064009)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 160.5.164.96
This content was downloaded on 24/08/2017 at 11:23

Please note that terms and conditions apply.

You may also be interested in:

- Tropical circulation and precipitation response to ozone depletion and recovery
  Stefan Brönnimann, Martin Jacques-Coper, Eugene Rozanov et al.

- Observed connections of Arctic stratospheric ozone extremes to Northern Hemisphere surface climate
  Diane J Ivy, Susan Solomon, Natalia Calvo et al.

- Possible causes of the Central Equatorial African long-term drought
  Wenjian Hua, Liming Zhou, Haishan Chen et al.

- The dependence of wintertime Mediterranean precipitation on the atmospheric circulation response to climate change
  Giuseppe Zappa, Brian J Hoskins and Theodore G Shepherd

- Anthropogenic effects on the subtropical jet in the Southern Hemisphere: aerosols versus long-lived greenhouse gases
  L D Rotstayn, M A Collier, S J Jeffrey et al.

- Is anthropogenic sea level fingerprint already detectable in the Pacific Ocean?
  H Palanisamy, B Meyssignac, A Cazenave et al.

- A connection from Arctic stratospheric ozone to El Niño-southern oscillation
  Fei Xie, Jianping Li, Wenshou Tian et al.

- Decelerating Atlantic meridional overturning circulation main cause of future west European summer atmospheric circulation changes
  Reindert J Haarsma, Frank M Selten and Sybren S Drijfhout
Anomalous mid-twentieth century atmospheric circulation change over the South Atlantic compared to the last 6000 years

Chris S M Turney¹, Richard T Jones², David Lister³, Phil Jones¹⁴, Alan N Williams¹⁵, Alan Hogg⁶, Zoë A Thomas¹, Gilbert P Compo²⁸, Xungang Yin⁹, Christopher J Fogwill¹, Jonathan Palmer¹, Steve Colwell¹⁰, Rob Allan¹¹ and Martin Visbeck¹²

¹ Climate Change Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, New South Wales, Australia
² Department of Geography, Exeter University, Devon, EX4 4RJ, UK
³ Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, UK
⁴ Center of Excellence for Climate Change Research / Department of Meteorology, King Abdulaziz University, Jeddah, Saudi Arabia
⁵ Extent Heritage, 2/729 Elizabeth Street, Waterloo, NSW 2017, Australia
⁶ Waikato Radiocarbon Laboratory, University of Waikato, Private Bag 3105, Hamilton, New Zealand
⁷ Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309, USA
⁸ Physical Sciences Division, Earth System Research Laboratory, NOAA, Boulder, CO 80305, USA
⁹ ERT, Inc., Asheville, NC 28801-5001, USA
¹⁰ British Antarctic Survey, Cambridge, CB3 0ET, UK
¹¹ Met Office Hadley Centre, Exeter, UK
¹² GEOMAR Helmholtz Centre for Ocean Research Kiel and Kiel University, Germany

E-mail: c.turney@unsw.edu.au

Keywords: southern annular mode (SAM), Southern Hemisphere westerlies, subantarctic climate extremes, temperature, climate reanalysis, anthropogenic climate change, El Niño-Southern Oscillation (ENSO)

Abstract
Determining the timing and impact of anthropogenic climate change in data-poor 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 air flow associated with the Amundsen Sea Low. Analysis of three comprehensively multi-dated (using ¹⁴C and ¹³⁷Cs) 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...
established around 6.5 ka. 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. 

Antarctic ice sheets and sea level had achieved close to pre-industrial levels by 4 ka (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 longer-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-anual (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, Mason-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, Royle 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/cruem4/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://reanalysis.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 Ericaceae–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
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 ± 1σ | 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 | 107.3 ± 0.3%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                   | 103 ± 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    | 37 099        | 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                   | −25 ± 14                 |
| 9        |                | $^{137}$Cs       |                           | −19 ± 12                 |
| 10–11    | 37 011        | Fruits and leaves | 121.7 ± 0.4%M              | −1 ± 28                  |
| 12–13    | 37 012        | Fruits and leaves | 107.2 ± 0.2%M              | 71 ± 72                  |
| 14–15    | 35 148        | Fruits and leaves | 144 ± 25                  | 561 ± 108                |
| 20–21    | 32 356        | Fruits and leaves | 737 ± 25                  | 653 ± 134                |
| 22–23    | 37 013        | Fruits and leaves | 545 ± 25                  | 1714 ± 163               |
| 33–34    | 37 014        | Fruits and leaves | 1821 ± 25                 | 3996 ± 71                |
| 36–37    | 34 607        | Fruits and leaves | 3714 ± 25                 | 5535 ± 63                |
| 58–59    | 34 608        | Fruits and leaves | 4858 ± 25                 | 5783 ± 69                |
| 64–65    | 32 357        | Fruits and leaves | 5071 ± 30                 |                         |

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.
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 (Compo 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 $p_{\text{ideal}} < 0.1\%$. Analyses were made with KNMI Climate Explorer (van Oldenborgh and Burgers 2003).

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 $p_{\text{ideal}} < 0.1\%$. Analyses were made with KNMI Climate Explorer (van Oldenborgh and Burgers 2003).

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 (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 2013, 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...
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 137Cs 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
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 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 $\alpha_{100} < 0.1\%$. 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 subtantarctic 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 subtantarctic 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 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 (Fl; 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<0.1%. Analyses were made with KNMI Climate Explorer (van Oldenborgh and Burgers 2005).
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 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 137Cs 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.

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).
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.

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.
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 understanding proxy-climate relationships for the reconstruction of modes of variability, suggesting teleconnections were not stable across the 20th century.

Acknowledgments

CSMT and CF acknowledge the support of the Australian Research Council (FL100100195, FT120100004 and DP130104156). A big thanks to the captain and crew of the Fishery Patrol Vessel The Pharos for travel to and from South Georgia. We thank the Government of South Georgia and the South Sandwich Islands, and the Falkland Islands Government for permission to undertake sampling on the island (permit numbers SGEP0110/11 and R07/2011 respectively) and Darren Christie for assisting with the fieldwork on the Falkland Islands. Sarah Kelloway and Charlotte Cook (UNSW) helped process the samples for TOC analysis; Christopher Bronk Ramsey (Oxford University) kindly provided guidance on OxCal modelling. Rob Allan is supported by a combination of funding from the Joint DECC/Defra Met Office Hadley Centre Climate Programme (GA011011), the European Union’s Seventh Framework Programme (FP7) European Reanalysis of Global Climate Observations 2 (ERA-CLIM2) project and the Climate Science for Service Partnership (CSSP) China under the Newton Fund. Gail Kelly kindly digitised the Cape Pembroke surface pressure data. The NOAA-CIRES Twentieth Century Reanalysis Project version 2c used resources of the National Energy Research Scientific Computing Center managed by Lawrence Berkeley National Laboratory which is supported by the Office of Science of the US Department of Energy under Contract No. DE-AC02-05CH11231. Support for the Twentieth Century Reanalysis Project version 2c dataset is provided by the US Department of Energy, Office of Science Biological and Environmental Research (BER), and by the National Oceanic and Atmospheric Administration Climate Program Office. Two anonymous reviewers kindly improved an earlier draft of this manuscript.

References

Abram N J, Mulvaney R, Vimeux F, Phipps S J, Turner J and England M H 2014 Evolution of the Southern annular mode during the past millennium Nat. Clim. Change 4 564–9
Anderson D E 2002 Carbon accumulation and C/N ratios of peat bogs in North-West Scotland Scottish Geogr. Mag. 118 523–41
Bannister D and King J 2015 Fohn winds on South Georgia and their impact on regional climate Weather 70 324–9
Beilman D W, MacDonald G M, Smith L C and Reimer PJ 2009 Carbon accumulation in peatlands of West Siberia over the last 2000 years Glob. Biogeochem. Cycles 23 GB1012
Bronk Ramsey C 2008 Radiocarbon dating: revolutions in understanding Archaeometry 50 249–75
Bronk Ramsey C 2009 Dealing with outliers and offsets in radiocarbon dating Radiocarbon 51 1023–45
Bronk Ramsey C and Lee S 2013 Recent and planned developments of the program OxCal Radiocarbon 55 720–30
Brönnimann S, Fischer A M, Rozanov E, Poli P, Compo G P and Sardeshmukh P D 2015 Southward shift of the northern tropical belt from 1945 to 1980 Nat. Geosci. 8 969–74
Brooks C E P 1920 Geophysical Memoirs (London: Meteorological Office) pp 97–146
Cannell M G R, Dewar R C and Pyatt D G 1993 Conifer plantations on drained peatlands in Britain: a net gain or loss of carbon? Forestry 66 355–69
Compo G P and Sardeshmukh P D 2010 Removing ENSO-related variations from the climate record J. Clim. 23 1957–78
Compo G P et al 2011 The twentieth century reanalysis project Q. J. R. Meteorol. Soc. 137 1–28
Convey P, Hopkins D W, Roberts J S and Tyler A N 2011 Global southern limit of flowering plants and moss peat accumulation Polar Res. 30 8929
Cook A J, Poncet S, Cooper A P R, Herbert D J and Christie D 2010 Glacier retreat on South Georgia and implications for the spread of rats Antarctic Sci. 22 255–63
Cram T, Compo G P, Yin X, Allan R J, McColl C, Vose R S, Whitaker J S, Matsui N, Ashcroft L and Auchmann R 2015 The international surface pressure databank version 2 Geosci. Data J. 2 31–46
Dakos V, Carpenter S R, Brock W A, Ellison A M, Guttl V, Ives A R, Keft S, Livina V, Seekell D A and van Nes E H 2012 Methods for detecting early warnings of critical transitions in time series illustrated using simulated ecological data PLoS One 7 e41010
Dakos V, Scheffer M, van Nes E H, Brockvkin V, Petoukhov V and Held H 2008 Slowdown as down an early warning signal for abrupt climate change Proc. Natl Acad. Sci. USA 105 14308–12
Dee D P et al 2011 The ERA-Interim reanalysis: configuration and performance of the data assimilation system Q. J. R. Meteorol. Soc. 137 553–97
deMenocal P, Ortiz J, Guilderson T and Sarthrein M 2000 Coherent high- and low-latitude climate variability during the Holocene warm period Science 288 2198–202
Dise N B 2009PEATland response to global climate change Science 326 810–1
Domack E, Duren D, Leventer A, Ishman S, Doane S, McCallum S, Amblans D, Ring J, Gilbert R and Prestigne M 2003 Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch Nature 436 681–5
Emile-Geay J, Cobb K M, Mann M E and Wittenberg A T 2013 Estimating central equatorial Pacific SST variability over the past millennium: II. Reconstructions and implications J. Clim. 26 2329–52
Fogt R L, Wovrosh A J, Langen R A and Simmonds I 2012 The characteristic variability and connection to the underlying synoptic activity of the Amundsen–Bellingshausen Seas Low J. Geophys. Res.: Atmos. 117 D07111
Franzke C 2012 Significant reduction of cold temperature extremes at Faraday/Vernadsky station in the Antarctic Peninsula Int. J. Climatol. 33 1070–8
Gordon A L, Huber B, McKee D and Visbeck M 2010 A seasonal cycle in the export of bottom water from the Weddell Sea Nat. Geosci. 3 551–6
Gordon E, Haynes V M and Hubbard A 2008 Recent glacier changes and climate trends on South Georgia Glob. Planet. Change 60 72–84
Hall A and Visbeck M 2002 Synchronous variability in the Southern Hemisphere atmosphere, sea ice, and ocean resulting from the annular mode J. Clim. 15 3043–57
Hancock G J, Leslie C, Everett S E, Timms S G, Brunskill G J and Haese R 2011 Plutonium as a chronomarker in Australian
and New Zealand sediments: a comparison with 137Cs J. Environ. Radioact. 102 919–29
Harris D, Horwáth W R and van Kessel C 2001 Acid fumigation of soils to remove carbonates prior to total organic carbon or CARBON-13 isotopic analysis Soil Sci. Soc. Am. J. 65 1853–6
Haug G H, Hughen K A, Sigman D M, Peterson L C and Rohl U 2001 Southward migration of the intertropical convergence zone Science 293 1304–8
Held H and Klein T 2004 Detection of climate system bifurcations by degenerate fingerprinting Geophys. Res. Lett. 31 L23207
Hodell D A, Kanfoush S L, Shemesh A, Crosta X, Charles C D and Guilderson T P 2001 Abrupt cooling of Antarctic surface waters and sea ice expansion in the South Atlantic sector of the Southern Ocean at 5000 cal yr B.P. Quat. Res. 56 191–8
Hogg A G et al 2013 SHCal13 Southern Hemisphere calibration, 0–30 000 years cal BP Radiocarbon 55 1889–903
Hosking J S, Orr A, Marshall G J, Turner J and Phillips T 2013 The influence of the Amundsen–Bellingshausen Seas low on the climate of West Antarctica and its representation in coupled climate model simulations J. Clim. 26 6633–48
Hua Q and Barbetti M 2004 Review of tropospheric bomb 14C data for carbon cycle modeling and age calibration purposes Radiocarbon 46 1273–98
Ives A R 1995 Measuring resilience in stochastic systems Ecological Monogr. 65 217–33
Jones M, Leng M, Eastwood W J, Keen D H and Turney C S M 2002 Interpreting stable-isotope records from freshwater snail-shell carbonate: a Holocene case study from Golhisar Gölü, south-west Turkey Holocene 12 543–58
Jones P D, Harpham C and Lister D 2016 Long-term trends in gale days and storminess for the Falkland Islands Int. J. Climatol. 36 1413–27
Jones P D et al 2009 High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects Holocene 19 3–49
Kendall M G 1948 Rank Correlation Methods (Oxford: Griffin)
King A D, Donat M G, Hawkins E, Alexander L V, Kendall M G 1948 Kendall’s Rank Correlation Methods (Oxford: Griffin)
Kuhl Y and Vitt D H 1996 Fossil carbon/nitrogen ratios as a measure of peat decomposition Ecology 77 271–51
Le Quéré C et al 2009 Trends in the sources and sinks of carbon dioxide Nat. Geosci. 2 831–8
Lee S and Feldstein S B 2013 Detecting ozone- and greenhouse gas-driven wind trends with observational data Science 339 563–7
Lenton T M, Livina V N, Dakos V, van Nes E H and Scheffer M 2012 Early warning of climate tipping points from critical slowing down: comparing methods to improve robustness Phil. Trans. R. Soc. A 370 1185–204
Leclair C and Hancock G 2008 Estimating the date corresponding to the horizon of the first detection of 137Cs and 210Pb in sediment cores J. Environ. Radioact. 99 683–90
Lister D H and Jones P D 2015 Long-term temperature and precipitation records from the Falkland Islands Int. J. Climatol. 35 1224–31
Loisel J and Yu Z 2013 Recent acceleration of carbon accumulation in a boreal peatland, south central Alaska J. Geophys. Res.: Biogeosci. 118 41–53
Lough J M, Llewellyn L E, Lewis S E, Turney C S M, Palmer J G, Cook C G and Hogg A G 2014 Evidence for suppressed mid-Holocene northeastern Australian monsoon variability from coral luminescence Paleoclimoogy 29 581–94
MacDonald G M, Beltran D M, Kremenetski V, K, Sheng Y S, Smith L C and Velicchio A A 2006 Rapid early development of circumboreal peatlands and atmospheric CH4 and CO2 variations Science 314 285–8
MacKenzie A B, Farmer J G and Sugden C L 1997 Isotopic evidence of the relative retention and mobility of lead and radiocesium in Scottish ombrotrophic peats Sci. Total Environ. 203 115–27
Marshall G 2003 Trends in the Southern Annular Mode from observations and reanalyses J. Clim. 16 4134–43
Marshall J and Speer K 2012 Closure of the meridional overturning circulation through Southern Ocean upwelling Nat. Geosci. 5 171–80
Masson-Delmotte V et al 2013 Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed T F Stocker et al (Cambridge: Cambridge University Press) pp 383–464
Mitchell P, Schell W, McGarry A, Ryan T, Sanchez-Cabeza J and Vidal-Quadrás A 1992 Studies of the vertical distribution of 14C, 13C, 239, 240Pu, 241Pu, 241Am and 239Pu in ombrogenous mires at mid-latitudes J. Radioanal. Nucl. Chem. 156 361–67
Mulvaney R, Abram N, Hindmarsh R C A, Arrowsmith C, Fleet L, Trisst J, Sime I, Almeyen O and Foord S 2012 Recent Antarctic Peninsula warming relative to Holocene climate and ice-shelf history Nature 489 141–4
Nakatubo T, Uchida M, Sasaki A, Kondo M, Yoshitake S and Kanda H 2015 Carbon accumulation rate of peatland in the High Arctic, Svalbard: implications for carbon sequestration Polar Sci. 9 267–75
Ngc R H, Lueas C, Evans A, TIMBL B and Hanson L 2015 Expansion of the Southern Hemisphere Hadley Cell in response to greenhouse gas forcing J. Clim. 28 8067–77
PAGES 2k Consortium 2013 Continental-scale temperature variability during the past two millennia Nat. Geosci. 6 339–46
Palmer J G, Cook E R, Turney C S M, Allen K, Fenwick P, Cook B I, O’Donnell A, Lough J M, Grierson P and Baker P 2013 Drought variability in the eastern Australia and New Zealand summer drought atlas (ANZDAD, CE 1500–2012) modulated by the Intergreded Pacific Oscillation Environ. Res. Lett. 10 124002
Perlwitz J, Pawson S, Fogt R L, Nielsens J E and Neff W F 2008 Impact of stratopheric ozone hole recovery on Antarctic climate Geophys. Res. Lett. 35 L08714
Previdi M and Polvani L M 2014 Climate system response to stratospheric ozone depletion and recovery J. R. Meteorol. Soc. 140 2401–19
Rayner N A, Parker D E, Horton E B, Folland C K, Alexander L V, Rowell D P, Kent E C and Kaplan A 2003 Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century J. Geophys. Res.: Atmos. 108 4607
Renssen H, Seppä H, Crosta X, Goosse H and Roche D M 2012 Global characterization of the Holocene thermal maximum in the Southern Hemisphere Int. J. Climatol. 32 487–97
Richard Y, Rouault M, Pohl B, Crétat J, Duclot I, Taboulot S, Perlwitz J, Pawson S, Fogt R L, Nielsen J E and Neff W D 2008 Detection of climate system bifurcations by degenerate fingerprinting Geophys. Res. Lett. 31 L23207
Rodionov S N 2004 A sequential algorithm for testing climate regime shifts Geophys. Res. Lett. 31 L9204
Royles J and Griffiths H 2015 Climate change impacts in polar regions: lessons from Antarctic moss bank archives Glob. Change Biol. 21 1041–57
Royles J, Ogée J, Wingate L, Hodson D A, Convey P and Griffiths H 2012 210Pb isotope evidence for recent climate-related enhancement of CO2 assimilation and peat accumulation rates in Antarctica Glob. Change Biol. 18 3112–24
Sardeshmukh P D, Compo G P and Penland C 2000 Changes of the Southern Hemisphere Hadley Cell in response to greenhouse gas forcing J. Clim. 13 4307–15
Schneider D P and Steig E J 2008 Ice cores record significant 1940s Antarctic warmth related to tropical climate variability Proc. Natl Acad. Sci. USA 105 12154–8
Seidel D J, Fu Q, Randel W J and Rechichler J T 2008 Widening of the tropical belt in a changing climate Nat. Geosci. 1 21–4
Steig E J, Schneider D P, Rutherford S D, Mann M E, Comiso J C and
Shindell D T 2009 Warming of the Antarctic ice-sheet surface
since the 1957 international geophysical year Nature 457
459–62
Steig E J et al 2013 Recent climate and ice-sheet changes in West
Antarctica compared with the past 2000 years Nat. Geosci. 6
372–5
Strother S L, Salzmann U, Roberts S J, Hodgson D A, Woodward J,
Van Nieuwenhuyze W, Ver leyen E, Vyverman W and
Moreton S G 2015 Changes in Holocene climate and the
intensity of Southern Hemisphere westerly winds based on a
high-resolution palynological record from sub-Antarctic
South Georgia Holocene 25 263–79
Thomas J L, Waugh D W and Gnanadesikan A 2013 Recent climate and ice-sheet changes in West
Antarctica compared with the past 2000 years Nat. Geosci. 6
372–5
Strother S L, Salzmann U, Roberts S J, Hodgson D A, Woodward J,
Van Nieuwenhuyze W, Verleyen E, Vyverman W and
Moreton S G 2015 Changes in Holocene climate and the
intensity of Southern Hemisphere westerly winds based on a
high-resolution palynological record from sub-Antarctic
South Georgia Holocene 25 263–79
Thomas J L, Waugh D W and Gnanadesikan A 2013 Recent climate and ice-sheet changes in West
Antarctica compared with the past 2000 years Nat. Geosci. 6
372–5
Strother S L, Salzmann U, Roberts S J, Hodgson D A, Woodward J,
Van Nieuwenhuyze W, Verleyen E, Vyverman W and
Moreton S G 2015 Changes in Holocene climate and the
intensity of Southern Hemisphere westerly winds based on a
high-resolution palynological record from sub-Antarctic
South Georgia Holocene 25 263–79
Vallalba R et al 2012 Unusual Southern Hemisphere tree growth
patterns induced by changes in the Southern Annular Mode
Nat. Geosci. 5 793–8
Visbeck M 2009 A station-based Southern Annular Mode Index
from 1884 to 2005 J. Clim. 22 940–50
Vitt D H, Halsey L A, Bauer I E and Campbell C 2000 Spatial and
temporal trends in carbon storage of peatlands of continental
western Canada through the Holocene Can. J. Earth Sci. 37
683–93
Wanner H et al 2008 Mid- to late Holocene climate change: an
overview Quart. Sci. Rev. 27 1791–828
Yu Z, Campbell I D, Campbell C, Vitt D H, Bond G C and Apps M J
2003 Carbon sequestration in western Canadian peat highly
sensitive to Holocene wet-dry climate cycles at millennial
timescales Holocene 13 801–8
Zhang X, Zwiers F W, Hegerl G C, Lambert F H, Gillett N P,
Solomon S, Stott P A and Nozawa T 2007 Detection of human
influence on twentieth-century precipitation trends Nature
448 461–5