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A 250 year periodicity in Southern Hemisphere westerly winds over the last 2600 years

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Abstract

Southern Hemisphere westerly airflow has a significant influence on the ocean–atmosphere system of the mid- to high-latitudes with potentially global climate implications. Unfortunately historic observations only extend back to the late nineteenth century, limiting our understanding of multi-decadal to centennial change. Here we present a highly resolved (30 yr) record of past westerly air strength from a Falkland Islands peat sequence spanning the last 2600 years. Situated under the core latitude of Southern Hemisphere westerly airflow, we identify highly variable changes in exotic pollen derived from South America which can be used to inform on past westerly air strength and location. The results indicate enhanced airflow over the Falklands between 2000 and 1000 cal. yr BP, and associated with increased burning, most probably as a result of higher temperatures and/or reduced precipitation, comparable to records in South America. Spectral analysis of the charcoal record identifies a 250 year periodicity within the data, suggesting solar variability has a modulating influence on Southern Hemisphere westerly airflow with potentially important implications for understanding global climate change through the late Holocene.

1 Introduction

A major limitation for quantifying the magnitude and impact of change across the Southern Ocean is the relatively short duration or low resolution of ocean–atmosphere records. This is particularly significant with regards the Southern Hemisphere westerly storm belt, which since the mid-1970s, has undergone a significant intensification and southward shift (Gillett et al., 2008; Messié and Chavez, 2011). One measure of this change in atmospheric circulation is the Southern Annular Mode (SAM), described as the pressure difference between Antarctica (65° S) and the latitude band at around 40° S (Karpechko et al., 2009; Marshall, 2003). Since the mid-1970s SAM appears to have undergone a positive shift in the troposphere, which has been associated with

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hemispheric-wide changes in the atmosphere–ocean-ice domains, including the delivery of precipitation and significant surface and subsurface warming (Cook et al., 2010; Delworth and Zeng, 2014; Domack et al., 2005; Gille, 2008, 2014; Thompson et al., 2011). This trend is projected to continue during the 21st century as a result of both ongoing greenhouse gas emissions and a persistence of the Antarctic ozone hole (Liu and Curry, 2010; Thompson et al., 2011; Yin, 2005), potentially resulting in reduced Southern Ocean uptake of anthropogenic CO_2 (Ito et al., 2010; Le Quére et al., 2009; Lenton et al., 2013; Marshall, 2003; Marshall and Speer, 2012).

While no observational records for SAM extend beyond the late nineteenth century (Fogt et al., 2009; Marshall, 2003; Visbeck, 2009), proxy records of past westerly airflow have been generated on annual to centennial timescales through the Holocene (Abram et al., 2014; Björck et al., 2012; Lamy et al., 2010; Strother et al., 2015; Villalba et al., 2012). Crucially the association between proxies and changes in westerly wind strength and/or latitude is often implied but few provide a direct measure of past airflow or directly test their interpretation through time. One possibility is the identification of exotic airborne pollen preserved in sedimentary sequences. Ideally, the peat or lake record should be close enough to the source vegetation to have a relatively high input of pollen but not so close that the influx is constant over time. Whilst numerous studies have been undertaken in the Arctic (Fredskild, 1984; Jessen et al., 2011) and the high-latitudes of the Indian and Pacific oceans (McGlone et al., 2000; Scott and van Zinderen Barker, 1985), few have been reported from the south Atlantic. Recent work on a lake core taken from Annekov Island, South Georgia (Strother et al., 2015) demonstrates the considerable potential of this approach but the relatively large distance from the nearest source in South America (Fig. 1) (approximately 2100 km) limits the delivery of pollen.

Here we report a new high-resolution record of westerly airflow over the past 2600 years from the Falkland Islands. The Falkland Islands (52° S) lie west of Annekov Island and 500 to 730 km east of Argentina within the main latitudinal belt of Southern Hemisphere westerly airflow. The close proximity to South America means that these

islands receive a relatively high input of exotic pollen (Barrow, 1978), making them an ideal location to investigate past changes in westerly airflow.

2 Methods

The Falkland Islands are a low-lying archipelago in the South Atlantic Ocean, situated in the furious fifties wind belt on the southeast South American continental shelf at 51–52° S, 58–61° W (Fig. 1). The Falkland Islands experience a cool temperate but relatively dry oceanic climate, dominated by westerly winds (Otley et al., 2008). Across the year, the temperature ranges from 2.2 °C (July) to 9 °C (February), with the islands experiencing a relatively low but variable precipitation (typically ranging between 500 and 800 mm year^{-1}) lying in the lee of the Andes to the west (Lister and Jones, 2014). In the modern climate the prevailing wind direction across the Falkland Islands is predominantly from the west with strong winds throughout the year and no significant seasonal variation (Upton and Shaw, 2002).

To investigate past westerly airflow an exposed Ericaceous-grass peatland was cored above Port Stanley Airport (51.691° S, 57.785° W, approximately 30 m a.s.l.) (Fig. 1). The one metre sequence reported here comprises a uniform dark-brown peat sequence from which the uppermost 90 cm was contiguously sampled for pollen, charcoal and comprehensive dating.

Pollen samples were prepared using standard palynological techniques (Faegri and Iverson, 1975). Volumetric samples were taken every 1 cm along the core and *Lycopodium* spores were added as a “spike”. The samples were deflocculated with hot 10 % NaOH and then sieved through a 150 µm mesh. The samples then underwent acetolysis, to remove extraneous organic matter before the samples were mounted in silicon oil. Pollen types/palynomorphs were counted at 400 × magnification until a minimum of 300 target grains were identified. The pollen counts were expressed as percentages, with only terrestrial land pollen (TLP) contributing to the final pollen sum. Pollen/Palynomorphs were identified using standard pollen keys (Barrow, 1978;

Macphail and Cantrill, 2006) and the pollen type slide collection at Exeter University. Past fire activity was assessed using micro-charcoal counts of fragments identified on the pollen slides e.g. (Whitlock and Larsen, 2001). Counts were undertaken at each level until a fixed total of 50 lycopodium spores was counted and the total expressed as a concentration (fragments per cm^3). The results were sub-divided into two size classes: < 50 and 50–150 µm.

Terrestrial plant macrofossils (fruits and leaves) were extracted from the peat sequence and given an acid-base-acid (ABA) 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 an 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 (Appleby, 2001) with measurements made using an ORTEC high-resolution, low-background coaxial germanium detectors. The first detectable measurements were obtained between 8.5 and 9.5 cm and assigned an age of CE 1963, the time of peak radionuclide fallout (Hancock et al., 2011).

The radiocarbon and ^{137}Cs ages were used to develop an age model using a P_sequence deposition model in OxCal 4.2 (Ramsey, 2008). The ^{14}C ages were calibrated against the Southern Hemisphere calibration (SHCal13) dataset (Hogg et al., 2013). 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 likeliest age distributions. All ages returned an *agreement index* of > 60 % indicating they had a large overlap with the likelihood probability distribution (A_{model} = 67.2; $A_{overall}$ = 66.0). Calibrated ages are reported here as thousands

of calendar years BP or cal. BP (Table 1 and Fig. 2). The pollen sequence reported here spans the last 2600 yr with an average 30 yr resolution.

To investigate the periodicities preserved in the palaeoenvironmental proxies utilised herein, we undertook Multi-Taper Method (MTM) analysis using a narrowband signal and red noise significance (with a resolution of 2 and number of tapers, 3) (Thomson, 1982). To test the robustness of the obtained periodicities, we also undertook single spectrum analysis (SSA) which applies an empirical orthogonal function (EOF) analysis to the autovariance matrix on the chronologies (Burg, 1978). Both analyses were undertaken using the software *kspectra* version 3.4.3 (3.4.5). Wavelet analysis was undertaken on the 30 year averaged charcoal data using the R package "biwavelet" (Gouhier, 2013). The Morlet continuous wavelet transform was applied, and the data were padded with zeros at each end to reduce wraparound effects (Torrence and Webster, 1999).

3 Results and discussion

Only a limited number of Holocene pollen records come from the Falkland Islands (Barrow, 1978). The pollen record in the uppermost 90 cm at Port Stanley Airport is dominated by *Poaceae* and *Empetrum,* consistent with previous work and today's vegetation (Barrow, 1978; Broughton and McAdam, 2003; Clark et al., 1998). The most significant change in the pollen taxa is a pronounced shift to increased representation of *Asteroideae* (accompanied by a relative decline in *Poaceae*) centered on 47 cm (equivalent to 1250 cal. BP) (Fig. 2). Although undifferentiated in the counts, the *Asteroideae* are most likely *Chilliotrichum diffusum*, common on the island across a range of habitats including *Empetrum* heath e.g. (Broughton and McAdam, 2003). The shift in the pollen diagram therefore most likely reflects the replacement of upland grasslands by *Empetrum* heath. Highly variable charcoal counts were obtained through the sequence, with the same peaks identified in both the < 50 and > 50 µm fractions (Fig. 2), suggesting sustained periods of fire across the island and possibly as far afield as South

America. Importantly, the sequence preserves a record of continuous exotic pollen delivery into the site, with *Nothofagus*, *Podocarp*, *Ephedra fragilis* and *Anacardium*-type, all originating from South America. Crucially all samples contain measurable quantities of *Nothofagus*, a taxa not known to have grown on the Falkland Islands since the Middle Miocene/Early Pliocene (Macphail and Cantrill, 2006) but detected as pollen in Lateglacial (Clark et al., 1998) and Holocene (Barrow, 1978) sequences. The youngest arboreal macrofossils of the other exotic taxa is dated to late Tertiary deposits on West Point Island, West Falkland (Birnie and Roberts, 1986).

The above taxa were converted to frequency and concentration values to explore changing input into the site over the last 2600 yr (Fig. 3). Crucially, the *Nothofagus* demonstrate a comparable trend to charcoal preserved in the sequence. While the *Nothofagus* pollen concentration is relatively variable, consistent with more distal studies (Strother et al., 2015), the counts are sufficiently high to recognize identical features in the charcoal record, with several periods of low fire frequency associated with implied weaker westerly airflow. Periods with prominent peaks in *Nothofagus* and charcoal are recognized at approximately 2450, 2100, 1800, 1500, 1200, 600 and 150 cal. years BP (Fig. 3).

In contrast to previous work at Annenkov Island, which suggested enhanced westerly airflow is associated with wetter conditions (Strother et al., 2015), we appear to observe the reverse, with stronger westerly airflow linked to warmer/drier conditions, leading to greater fire frequency. However, modern comparisons between the SAM (as a measure of westerly airflow) and air temperature suggest a positive correlation (Abram et al., 2014). Comparing historic observations of SAM (Marshall, 2003) with ERA79 Interim reanalysis (Dee et al., 2011), we observe a highly significant relationship between enhanced westerly airflow and 2 m air temperature across much of South America, the Antarctic Peninsula and the Falkland Islands (Fig. 4), supporting our observations. The contrasting moisture interpretation is most probably a result of the rain shadow effect of the Andes on the Falklands with the South Atlantic playing a more significant role on South Georgia.

The MTM analysis identifies two different periodicities in the charcoal (< 50 µm) record from Port Stanley Airport significant above 95 %: 146 and 244 yr (Fig. 5a) with the latter exhibiting a broad multi-decadal peak. To test whether the MTM spectral peaks are robust, we undertook SSA on the sequence chronologies. A Monte Carlo significance test identified two significant periodicities (above 95 %) at 233 and 361 yr (Fig. 5b). The 233–244 yr signal is significant in both analyses, suggesting this periodicity is pervasive through the record and the more robust.

The existence of a 200–250 yr periodicity has been identified in numerous Holocene records globally (Galloway et al., 2013; Poore et al., 2004), including Southern Ocean productivity as recorded in Palmer Deep (Domack et al., 2001; Leventer et al., 1996) and dust deposition over Antarctica (Delmonte et al., 2005). Importantly, a similar periodicity has been observed in records of atmospheric ^{14}C (Stuiver and Braziunas, 1993; Turney et al., 2005), suggesting solar variability may play a role (Leventer et al., 1996).

The role changing solar output may have on westerly airflow is not immediately apparent. One possibility is that the 200–250 yr periodicity may change salinity in the North Atlantic (Stuiver and Braziunas, 1993), driving changes in the Meridional Overturning Circulation that are transmitted globally. However, the existence of the same periodicity in the delivery of dust on to the East Antarctic Ice Sheet (Delmonte et al., 2005) does imply a direct atmospheric link, either through changing sea ice extent or sea surface temperatures, or via the westerlies themselves. A recent modeling study suggested centennial-duration periods of lower solar activity may lead to an equatorward shift in the mean westerly latitude (Varma et al., 2011). Future work in this area is required to understand the driving mechanism(s) behind the 200–250 yr periodicity on global climate.

Importantly, the 250 yr periodicity identified here varies in amplitude over the last 2600 yr (Fig. 6). A Gaussian filtered curve and wavelet plot shows this periodicity is most strongly expressed between 2000 and 1000 cal. BP (Fig. 6b and c). Our results imply that the central Southern Hemisphere westerlies were particularly strong during this period and/or lay close to the latitude of the Falkland Islands, at least within the

South American sector. A record of comparable latitude and age from the Chilean coast is the Palm2 record (Lamy et al., 2010) (Fig. 6d), which used accumulation rates of biogenic carbonate as a proxy for salinity changes in surface fjord waters. Here, lower salinities were associated with strong winds and relatively high precipitation, which decreased the salinity of fjord waters, and limited the influence of the open ocean water, reducing biogenic carbonate production. While the dataset from Palm2 does not have the resolution of our record, a similar trend in westerly winds is recorded between 2000 and 1000 cal. yr BP, with an implied reduction in the expression of this periodicity over the last millennium. While the change in the trend may be interpreted as reflecting either a change in the latitude and/or strength of the winds, given the current association between the Falkland Islands and the core latitude of westerly winds, we interpret the high amplitude periodicity between 2000 and 1000 cal. yr BP to be a period of stronger winds. This is supported by a study on Patagonian *Fitzroya cupressoides* from 40–42° S (Roig et al., 2001). Whilst a living series spanning 1229 yr did not identify a 200–250 yr periodicity, a 245 yr cycle was identified in a floating 50 000 yr-old tree ring series of comparable length, consistent with our record suggesting a suppression of this periodicity across a large latitudinal range over the last 1000 years.

4 Conclusions

Southern Hemisphere westerly airflow is believed to play a significant role in precipitation, sea ice extent, sea surface temperatures and the carbon cycle across the mid to high latitudes. Unfortunately, the observational record only extends back to the late nineteenth century, limiting our understanding of what drives past changes in westerly winds. Although proxies of westerly airflow can provide long-term perspectives on past change, few provide a direct (passive) measure of westerly winds. Exotic pollen sourced from vegetation upwind of sedimentary sequences potentially provide a valuable insight into past variability. Here we report a new, comprehensively-dated high-resolution pollen record from a peat sequence on the Falkland Islands which lies un-

der the present core of Southern Hemisphere westerly airflow (the so-called "furious fifties") and spanning the last 2600 years. We observe peaks in taxa from South America (particularly *Nothofagus*) that appear to be linked to warm, dry conditions, leading to fire across the island. Spectral analysis identifies a robust 250 yr periodicity, with evidence of stronger westerly airflow between 2000 and 1000 calendar yrs. Along with other records, this periodicity strongly suggests solar forcing plays a significant role in modulating the strength of the Southern Hemisphere westerlies, something hitherto not recognised, and will form the focus of future research.

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The authors declare no competing financial interests.

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Table 1. Radiocarbon ages and modelled calibrated age ranges using SHCal13 (Hogg et al., 2013) and Bomb04SH (Hua and Barbetti, 2004) using the P_sequence option in OxCal (Ramsey, 2008).

Depth, cm	Wk lab number	Material	^{14}C $\pm 1\sigma$	Cal. yr BP $\pm 1\sigma$
8–9	34 598	Fruits and leaves	117.0 ± 0.4 %M	−22 ± 13
11–12	32 994	Fruits and leaves	107.8 ± 0.4 %M	Failed age model
18–19	37 007	Fruits and leaves	107.3 ± 0.3 %M	−7 ± 2
25–26	35 146	Fruits and leaves	95 ± 25	85 ± 61
35–36	37 008	Fruits and leaves	647 ± 25	603 ± 29
39–40	33 445	Fruits and leaves	761 ± 25	660 ± 27
57–58	32 996	Fruits and leaves	1818 ± 25	1672 ± 50
70–71	32 350	Fruits and leaves	2235 ± 25	2204 ± 66
97–98	32 997	Fruits and leaves	2749 ± 25	2802 ± 31

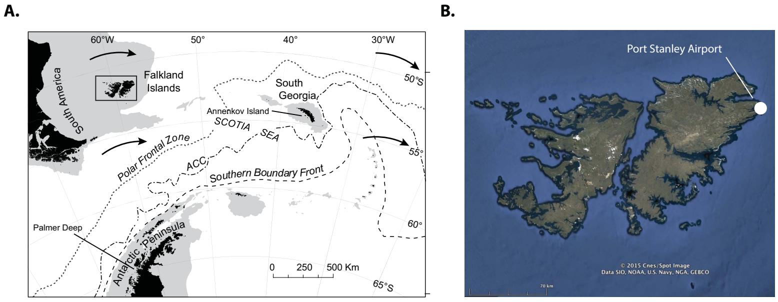

Figure 1. Location of the Falkland Islands in the South Atlantic Ocean with mean locations of the Polar and Southern Boundary fronts (dashed lines), the continental shelf (grey areas) and prevailing westerly airflow (solid arrows) **(a)**; and Port Stanley Airport site in the east Falkland Islands **(b)**. **(a)** was modified from (Strother et al., 2015) and **(b)** was obtained from Google Earth.

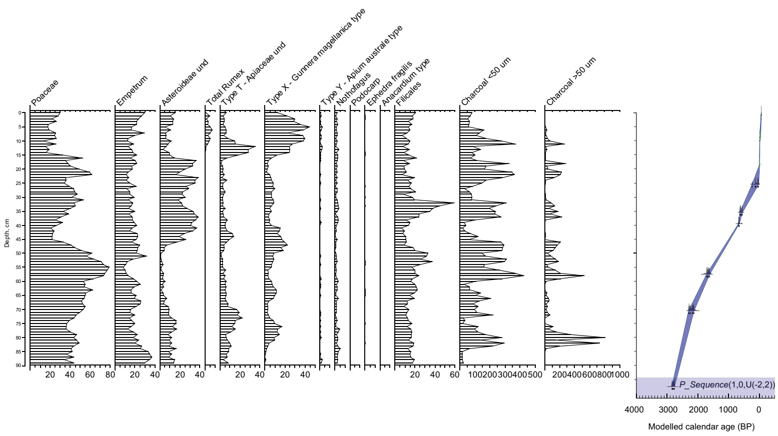

Figure 2. Pollen concentration diagram (%TLP) and charcoal counts plotted with age–depth relationship for the Port Stanley Airport peat sequence (blue envelope denotes 68 % confidence limits).

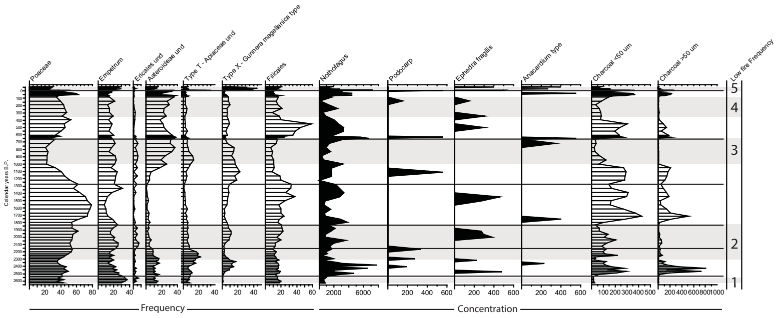

Figure 3. Pollen frequency and concentration diagram from Port Stanley Airport site plotted against calendar age.

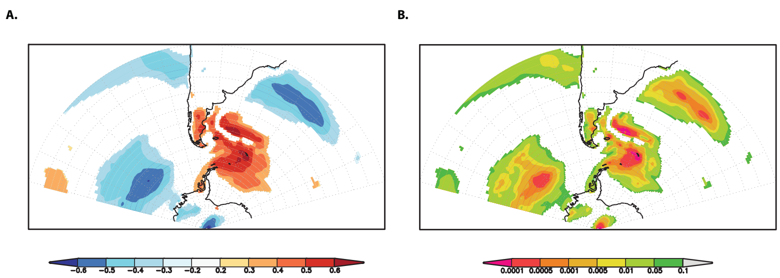

Figure 4. Correlation **(a)** and significance **(b)** of relationship between the hemispherically-averaged Southern Annular Mode (SAM) index (Marshall, 2003) with 2 m air temperature in the ERA-79 Interim reanalysis (Dee et al., 2011) (July–June 1979–2013). Analyses were made with KNMI Climate Explorer (van Oldenborgh and Burgers, 2005).

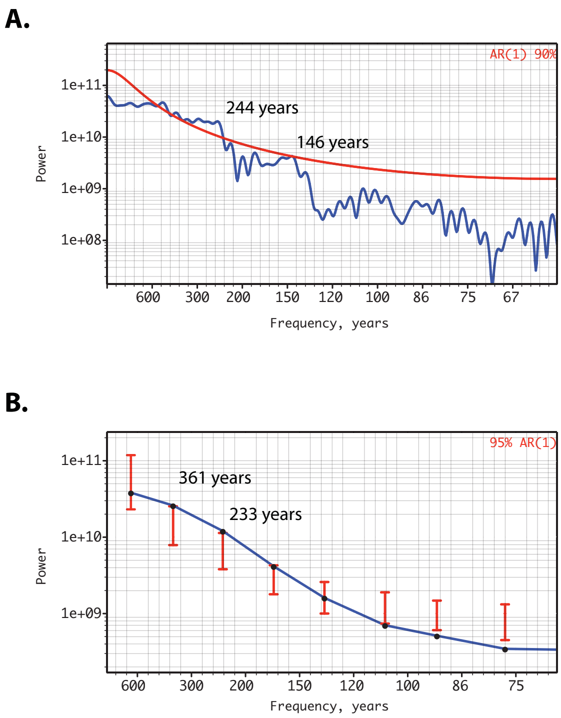

Figure 5. Multi-Taper Method (MTM) **(a)** and Monte-Carlo Single Spectrum Analysis (SSA) analyses **(b)** of charcoal from the Port Stanley Airport sequence. Error bars denote 95 % confidence.

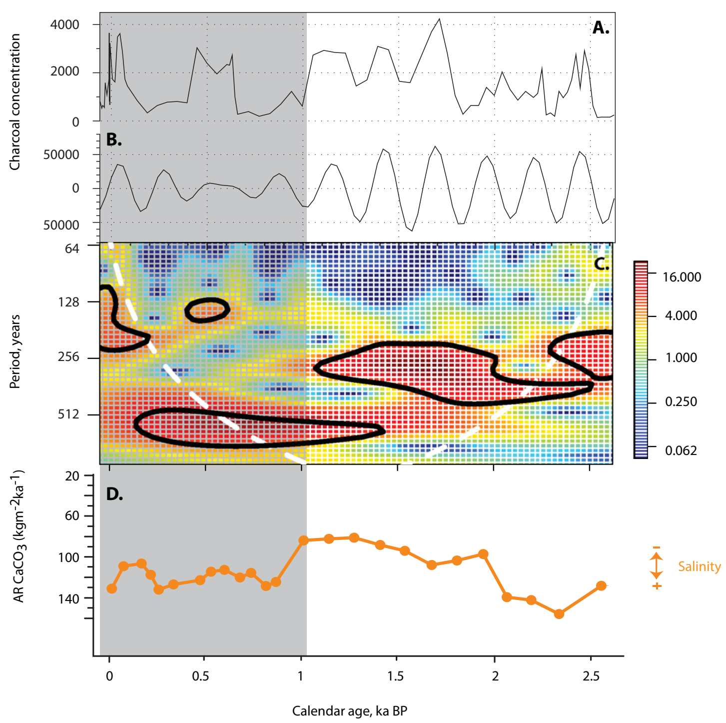

Figure 6. Charcoal concentration (< 50 µm) **(a)**, charcoal Gaussian filtered for the periodicity 244 ± 49 years **(b)** and wavelet analysis of charcoal concentration **(c)** from Port Stanley Airport (52° S). Solid black line in wavelet denotes 95 % confidence in periodicity; white dashed line denotes cone of influence. **(d)** shows biogenic carbonate accumulation rate (AR) from Palm2, Chile (53° S) (Lamy et al., 2010).

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