THE UNIVERSITY OF NEW SOUTH WALES
SYDNEY • AUSTRALIA

Professor Chris Turney
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15 October 2015

Dear Ed,

Many thanks for the very helpful comments and suggestions on our manuscript entitled 'A 250-year periodicity in Southern Hemisphere westerly winds over the last 2600 years.' Please find attached a revised version of the manuscript with 7 eps figure files and a manuscript showing tracked changes.

As you will read in the attached we have undertaken further analysis on the dataset and referenced further key studies, building on the points made by the reviewers.

Specifically, we have drilled down into the solar irradiance reconstructions and made more detailed comparisons to our study. Crucially, we find the 5-yr resolved tree ring-derived ^{14}C -production rate is identical in structure to the Total Solar Irradiance (TSI) reported by Steinhilber et al. (using ice core-derived ^{10}Be records). However, the expression of the de Vries cycle is quite different in the lower-resolved (20-30 yr resolved) ^{10}Be dataset (202 yrs) when compared to the tree ring ^{14}C (225 yrs); a similar difference is observed when the ^{14}C production rate is downscaled to the same resolution of the Canopus Hill record (30 years). Whilst we cannot test for coherence between the two different resolved records, our results strongly suggest the Southern Hemisphere westerly winds are highly sensitive to relatively small changes in amplitude of solar irradiance. Comparison between the records suggests a 20-40 year lag.

We discuss this in several places in the manuscript but include a description of the key findings in lines 268-287: 'The detection of solar forcing in palaeo records is highly sensitive to the chronological framework being investigated (Gray et al., 2010). To explore the possible role of solar variability on Southern Hemisphere westerly airflow we first analyzed the modelled production rate of ^{14}C derived from 5-yr resolved tree-ring data (Reimer et al., 2013), a cosmogenic radionuclide that is produced in the upper atmosphere (with ^{14}C increasing with reduced solar activity) (Bond et al., 2001; Turney et al., 2005). We resampled the ^{14}C dataset at 30-yr resolution to mimic the resolution of the Canopus Hill sequence and compared these to the Total Solar Irradiance (TSI) generated from the polar ice core ^{10}Be which is reported at a 20-30 yr resolution (Steinhilber et al., 2009) (Figure 6). Regardless of the dataset used, the same pattern is observed with large amplitude changes in solar irradiance between 2600 and 2300 years ago and from 1300 cal. years BP to present day, but with sustained high irradiance between 2300 and 1300 cal. years BP (Figure 6A, C and E). We find the 5-year resolved IntCal13 dataset produces a periodicity comparable to the Falkland Islands record (225 yrs at 99% confidence; Figure 6A and B). Importantly, when we look at the downscaled records of solar irradiance, the statistical significance decreases in the lower-resolved ^{14}C dataset (230 yrs at 90%; Figure 6C and D) or shifts to a

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lower frequency in the ^{10}Be record (202 yrs at 99%; Figure 6E and F).' In support of this work, we have also generated a new figure (Figure 6).

Further to the above, we have elaborated on the mechanism of charcoal transportation from Patagonia and cited several key studies (lines 43-46): 'The close proximity to South America means that these islands receive a relatively high input of particles from the continental mainland (Barrow, 1978; Rose et al., 2012), making them an ideal location to investigate past changes in westerly airflow.'

and lines 211-218: 'Although charcoal fragments <106μm might reflect fire in the local environment, charcoal of this size can be transported long distances (Clark, 1988). The vast majority of the charcoal fragments <50 μm, comparable in size to exotic *Nothofagus* (20-40μm) and *Podocarpus* (40-50μm in diameter) pollen (Wang et al., 2000; Wilson and Owens, 1999). The close correspondence between the *Nothofagus* pollen record and charcoal fragments in the Canopus Hill sequence on the Falkland Islands strongly suggests similar sources, indicating the higher charcoal counts provides a more robust measure of the westerly airflow.'

We have also provided further information for why we have not used charcoal flux (rather than concentration) for analysis of the profile (line 168-178) and included a dedicated figure (Figure 3) showing the age-depth profile. The suggested revised text is the following: 'The exotic pollen taxa were expressed as concentration values to explore their changing input onto the site over the last 2600 yrs (Figure 2). Although this data could be re-expressed as a pollen influx, the interpretation of flux data in non-annually laminated sequences can be strongly influenced by the choice of age model and the density of dated points down the core (Davis, 1969; Hicks and Hyvärinen, 1999). Consideration of the radiocarbon and ^{137}Cs ages (Table 1) suggests that the depth-age relationship can be described by a linear relationship ($r^2 = 0.98$) below a depth of 18 cm (Figure 3). This means that the pollen (and charcoal) concentration data below this depth are equivalent to influx. In the uppermost section of the core (above 18 cm) a faster rate of sediment accumulation (or less compaction) means that the deposition time is reduced.'

We trust you find the revised manuscript satisfactory. The manuscript is much improved and we thank you and the reviewers for their thoughtful and helpful comments.

With very best wishes,

Chris

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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-year) record of past westerly wind strength from a Falkland Islands peat sequence spanning the last 2600 years. Situated within the core latitude of Southern Hemisphere westerly airflow, we identify highly variable changes in exotic pollen and charcoal derived from South America which can be used to inform on past westerly air strength. We find a period of high charcoal content between 2000 and 1000 cal. yrs BP, associated with increased burning in Patagonia, most probably as a result of higher temperatures and stronger westerly airflow. Spectral analysis of the charcoal record identifies a pervasive c.250-year periodicity that is coherent with radiocarbon production rates suggesting solar variability has a modulating influence on Southern Hemisphere westerly airflow with important implications for understanding global climate change through the late Holocene.

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Keywords: Falkland Islands; exotic pollen; radiocarbon (^{14}C) dating; solar forcing; Southern Annular Mode (SAM); Southern Hemisphere Westerlies

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 to 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 hemispheric-wide changes in the atmosphere-ocean-ice domains, including precipitation patterns and significant surface and subsurface ocean 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).

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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; Lisé-Pronovost et al., 2015; McGlone 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 particles preserved in sedimentary sequences. Ideally, the peat or lake record should be close enough to the source to have a relatively high input of material (e.g. pollen, charcoal) 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 (Figure 1) (approximately 2100 km) limits the delivery of pollen with no charcoal reported.

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 within the main latitudinal belt of Southern Hemisphere westerly airflow, 500 to 730 km east of Argentina and 1410 km west of Annekov Island. The close proximity to South America means that these islands receive a relatively high input of particles from the continental mainland (Barrow, 1978; Rose et al., 2012), 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

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continental shelf at 51-52°S, 58-61°W (Figure 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) lying in the lee of the Andes. Modern climate records show 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).

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Climate amelioration following the Last Glacial Maximum led to the establishment of blanket peat across large parts of the islands from 16,500 cal. years BP (Wilson et al., 2002). To investigate past westerly airflow in the late Holocene, an exposed Ericaceous-grass peatland was cored on Canopus Hill, above Port Stanley Airport (51.691°S, 57.785°W, approximately 30 m above sea level) (Figure 1). The one metre sequence reported here comprises a uniform dark-brown peat from which the uppermost 90 cm was contiguously sampled for pollen, charcoal and comprehensive dating.

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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 106 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 X

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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 (<106μm) identified on the pollen slides (Whitlock and Larsen, 2001). Counts were undertaken at each level until a fixed total of 50 lycopodium spores were counted and the total expressed as a concentration (fragments per cm^3). More than 99% of charcoal fragments were less than 50μm in size, with negligible amounts identified in the 50-106μm and >106μm fractions.

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 with measurements made using an ORTEC high- resolution, low-background coaxial germanium detectors. Detectable measurements were obtained between 8.5 and 9.5 cm and

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assigned an age of CE 1963, the time of early radionuclide fallout at these latitudes (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) with `General Outlier` analysis detection (probability=0.05) (Ramsey, 2011). The ^{14}C ages were calibrated against the Southern Hemisphere calibration (SHCal13) dataset . 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 are reported here as thousands of calendar years BP or cal. BP (Table 1 and Figure 2). The pollen sequence reported here spans the last 2600 yrs with an average 30-year resolution (Figure 3).

To investigate the periodicities preserved in the palaeoenvironmental proxies utilised herein, we undertook Multi-Taper Method (MTM) analysis using a narrowband signal, red noise significance and robust noise background estimation (with a resolution of 2 and 3 tapers) (Thomson, 1982). We also applied single spectrum analysis (SSA), which applies an empirical orthogonal function (EOF) analysis to the autovariance matrix on the chronologies. Here we undertook a Monte Carlo significance test (95% significance), using a window of 9, a Burg covariance, and 8 components. Both analyses used the software

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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). To test the robustness of the obtained periodicities, the Lomb-Scargle algorithm was employed, a spectral decomposition method that computes the spectral properties of time series with irregular sampling intervals (Ruf, 1999), in this instance, the ‘raw’ charcoal values. This method minimises bias and induced periodicities that may arise from interpolating missing or unevenly spaced data. The technique was undertaken using the `lsp()` function within the `'lomb'` package in R (v.3.0.2). Periodicities were extracted from data sets using Analyseries (Paillard et al., 1996).

A measure of solar variability was derived by calculating the ^{14}C production rate using the IntCal13 atmospheric radiocarbon dataset (Reimer et al., 2013) and an ocean–atmosphere box diffusion model (Oeschger et al., 1975); the same as that reported in previous studies (Bond et al., 2001; Turney et al., 2005). The model consists of one box for the atmosphere, one for the ocean mixed layer, 37 boxes for the thermocline, five boxes for the deep ocean and two for the biosphere (short and long residence time) (Stuiver and Braziunas, 1993a). The climate-influenced mixing parameters (air-gas sea exchange, eddy diffusivity, and biospheric uptake and release) were held constant through the run using the same setup as Marine04 (Table 2) (Hughen et al., 2004). The model was parameterized to produce a pre-industrial marine mixed layer ^{14}C of -46.5 ‰

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and a deep ocean value of -190‰ at CE 1830 for the 2013 marine calibration dataset Marine13 (Reimer et al., 2013).

3. Results and Discussion

Only a limited number of Holocene pollen records have been reported from the Falkland Islands (Barrow, 1978). The pollen record in the uppermost 90 cm at Canopus Hill 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 1100 cal. BP) (Figure 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 (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 (<106 μm) (Figure 2), with negligible macrocharcoal fragments (>106μm) identified, suggesting there was little or no fire on the site.

The exotic pollen taxa were expressed as concentration values to explore their changing input onto the site over the last 2600 yrs (Figure 2). Although this data could be re-expressed as a pollen influx, the interpretation of flux data in non-annually laminated sequences can be strongly influenced by the choice of age model and the density of dated points down the core (Davis, 1969; Hicks and Hyvärinen, 1999). Consideration of the radiocarbon and ^{137}Cs ages (Table 1)

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suggests that the depth-age relationship can be described by a linear relationship (r^2 = 0.98) below a depth of 18 cm (Figure 3). This means that the pollen (and charcoal) concentration data below this depth are equivalent to influx. In the uppermost section of the core (above 18 cm) a faster rate of sediment accumulation (or less compaction) means that the deposition time is reduced.

Importantly, the sequence preserves a record of exotic pollen delivery into the site, with *Nothofagus* dominating the input but with trace amounts of *Podocarp*, *Ephedra fragilis* and *Anacardium*-type record (<0.5% total land pollen), all originating from South America. Whilst the low levels of most exotic pollen precludes meaningful interpretation, all samples contain *Nothofagus* (<5% total land pollen), a taxa not known to have grown on the Falkland Islands since the Middle Miocene/Early Pliocene (Macphail and Cantrill, 2006) but has been detected in Lateglacial (Clark et al., 1998) and Holocene (Barrow, 1978) sequences. Producing relatively small pollen grains (20-40μm in diameter) (Wang et al., 2000), the nearest source of contemporary *Nothofagus* is South America which extends from 33° in central Chile to 56°S on Tierra del Fuego (Veblen et al., 1996). The youngest arboreal macrofossils of the other exotic taxa are dated to late Tertiary deposits on West Point Island, West Falkland (Birnie and Roberts, 1986).

Whilst exotic pollen values are relatively low, peaks in *Nothofagus* coincide with increased amounts of charcoal in the Canopus Hill sequence. Importantly, negligible amounts of macro-charcoal (>106μm) were identified, suggesting the charcoal has been blown to the site from Patagonia. The aerial delivery of the

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charcoal to the Falkland Islands is supported by the close correspondence with charcoal in Laguna Guanaco in southwest Patagonia (51°S) (Moreno et al., 2009). Importantly, *Nothofagus* dominates lowland Patagonian vegetation and, in areas away from human activity, was established by 5000 cal. years BP (Iglesias et al., 2014; Kilian and Lamy, 2012), with a stepped expansion in *Nothofagus* at Laguna Guanaco centred on 570 BP (Moreno et al., 2009) and evidence for temporary forest fragmentation during periods of stronger westerly airflow (Moreno et al., 2014). In marked contrast to Patagonia, the Falklands *Nothofagus* pollen record is highly variable and of sufficient concentration to recognize similar changes to those in the charcoal record, with periods of high fire frequency associated with high input of exotic pollen.

Although charcoal fragments <106µm might reflect fire in the local environment, charcoal of this size can be transported long distances (Clark, 1988). The vast majority of the charcoal fragments <50 µm, comparable in size to exotic *Nothofagus* (20-40µm) and *Podocarpus* (40-50µm in diameter) pollen (Wang et al., 2000; Wilson and Owens, 1999). The close correspondence between the *Nothofagus* pollen record and charcoal fragments in the Canopus Hill sequence on the Falkland Islands strongly suggests similar sources, indicating the higher charcoal counts provides a more robust measure of the westerly airflow. A sustained period of charcoal delivery to the Falkland Islands is observed between 2000 and 1000 cal. BP, with prominent peaks in *Nothofagus* and charcoal recognized at approximately 2400, 2100, 1800-1300, 1000, 550 and 250 cal. BP (Figure 2) which we interpret here as stronger westerly wind flow.. Our results suggest reports of pre-European human activity on the Falkland

Islands as inferred by the presence of charcoal in peat sequences (Buckland and Edwards, 1998) may be premature.

In contrast to previous work at Annenkov Island which suggested enhanced westerly airflow is associated with wetter conditions (Strother et al., 2015), we observe the reverse. Modern comparisons between the SAM (as a measure of westerly airflow) (Marshall, 2003) and air temperature suggest a positive correlation (Abram et al., 2014). Comparing historic observations of SAM with ERA79 Interim reanalysis (Dee et al., 2011), we observe a highly significant relationship with more positive phases of SAM associated with warmer 2-10 metre height air temperatures and wind speeds across much of South America, the Antarctic Peninsula and the Falkland Islands (Figure 4), supporting our interpretation. The contrasting moisture interpretation to that in South Georgia may be a result of the rain shadow effect of the Andes on the Falklands. It should be noted, however, that the reanalysis product used here is only for the period commencing CE 1979 (the satellite era) and that different atmospheric dynamics may have been involved in the delivery of exotic pollen and charcoal to the Falkland Islands on centennial timescales.

The MTM analysis identifies two different periodicities in the charcoal record (<106μm) from Canopus Hill significant above 95%: 242 and 95 yrs, with the former exhibiting a broad multi-decadal peak (Figure 5A). To test whether the MTM spectral peak is robust, we undertook SSA on the sequence chronologies. A Monte Carlo significance test identified a significant periodicity (above 95%) at 231 yrs (Figure 5B). Furthermore, the Lomb-Scargle algorithm identified a 268-

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yr peak (Figure 5C), indicating this periodicity is pervasive through the record regardless of the sampling method, and therefore 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). Furthermore, whilst no spectral analysis was undertaken, a series of recurring 200-yr long dry/warm periods have recently been reported from Patagonia over the last three millennia and linked to positive SAM-like conditions (Moreno et al., 2014). The origin of the ~250 yr periodicity may be linked to postulated centennial-scale changes in climate modes of variability including the El Niño-Southern Oscillation (ENSO) (Ault et al., 2013) or Southern Ocean convection (Martin et al., 2013). Importantly, a 200-250 yr periodicity has also been observed in records of atmospheric ^{14}C and ^{10}Be (Adolphi et al., 2014; Steinhilber et al., 2012; Stuiver and Braziunas, 1993b; Turney et al., 2005), suggesting the so-called de Vries solar cycle may play a role (Leventer et al., 1996).

The detection of solar forcing in palaeo records is highly sensitive to the chronological framework being investigated (Gray et al., 2010). To explore the possible role of solar variability on Southern Hemisphere westerly airflow we first analyzed the modelled production rate of ^{14}C derived from 5-yr resolved tree-ring data (Reimer et al., 2013), a cosmogenic radionuclide that is produced in the upper atmosphere (with ^{14}C increasing with reduced solar activity) (Bond

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et al., 2001; Turney et al., 2005). We resampled the ^{14}C dataset at 30-yr resolution to mimic the resolution of the Canopus Hill sequence and compared these to the Total Solar Irradiance (TSI) generated from the polar ice core ^{10}Be which is reported at a 20-30 yr resolution (Steinhilber et al., 2009) (Figure 6). Regardless of the dataset used, the same pattern is observed with large amplitude changes in solar irradiance between 2600 and 2300 years ago and from 1300 cal. years BP to present day, but with sustained high irradiance between 2300 and 1300 cal. years BP (Figure 6A, C and E). We find the 5-year resolved IntCal13 dataset produces a periodicity comparable to the Falkland Islands record (225 yrs at 99% confidence; Figure 6A and B). Importantly, when we look at the downscaled records of solar irradiance, the statistical significance decreases in the lower-resolved ^{14}C dataset (230 yrs at 90%; Figure 6C and D) or shifts to a lower frequency in the ^{10}Be record (202 yrs at 99%; Figure 6E and F).

Our results imply that the central Southern Hemisphere westerlies were particularly strong during 2000 and 1000 cal. BP and/or lay close to the latitude of the Falkland Islands, at least within the South American sector (Figure 7). Records of comparable latitude and age from South America are Laguna Guanaco (51˚S) (Moreno et al., 2014) and Palm2 (53˚S) (Lamy et al., 2010). The Laguna Guanaco record captures a remarkably similar fire history as preserved in the Canopus Hill with a pronounced peak in charcoal over the same period (Figure 7D). In Palm2, accumulation rates of biogenic carbonate provide a proxy for salinity changes in surface fjord waters off the west coast of Chile with lower salinities associated with strong winds and relatively high precipitation, limiting the influence of the open ocean water and reducing biogenic carbonate production. While the dataset from Palm2 does not have the resolution of the other records, a similar trend with pervasive lower salinities (stronger westerly winds) is recorded between 2000 and 1000 cal. yrs BP (Figure 7E). Whilst the change in the trend may be interpreted as reflecting either a change in the latitude and/or strength of the winds, the parallel peaks and troughs in *Nothofagus* and charcoal from Canopus Hill (in contrast to constant *Nothofagus* levels at Laguna Guanaco – (Moreno et al., 2009)) imply the core latitude of the westerly winds has not changed and instead was particularly strong between 2000 and 1000 cal. yrs BP, resulting in increased fire frequency in Patagonia (Holz and Veblen, 2012). This is supported by a study on Patagonian *Fitzroya cupressoides* from 40-42°S (Roig et al., 2001). Whilst a living series spanning 1,229-yrs 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. Importantly, the ~250-yr periodicity identified in the charcoal record varies in amplitude over the last 2600 yrs (Figures 7A-C). A Gaussian filtered curve and wavelet plot shows the ~250 year periodicity is most strongly expressed between 2600 and 1000 cal. BP, and spans the prominent (sustained) peak in charcoal, with an implied reduction in the expression of the ~250 year periodicity over the last millennium.

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The role changing solar output may have on westerly airflow is not immediately apparent. The period of strongest inferred winds falls within a millennial-duration period of high solar irradiance (Figure 7F) but with a relatively muted

250-yr periodicity in the 5-yr resolved ^{14}C production rate data (Figure 7G). We do, however, observe a consistent relationship, with peaks in solar irradiance leading charcoal on the order of 20-40 years, suggesting Southern Hemisphere westerly winds may be particularly sensitive to the de Vries cycle during periods of high solar irradiance and less sensitive with reduced solar output. How solar periodicity may influence the strength of Southern Hemisphere westerly airflow is not precisely known. One possibility is that the ~250 yr periodicity may change salinity in the North Atlantic (Stuiver and Braziunas, 1993b), 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 (Shindell et al., 1999). Recent work has highlight the role of high solar irradiance in increasing troposphere-stratosphere coupling, extending the seasonal length during which stronger Southern Hemisphere westerly winds are experienced at the surface (Kuroda and Yamazaki, 2010), similar to that observed in the Northern Hemisphere (Ineson et al., 2011). Alternatively, recent modelling work suggests insolation changes can lead to increased 'baroclinicity' (Fogwill et al., 2015) or a 'Split Jet' (Chiang et al., 2014), strengthening westerly winds. Further work is required to understand the driving mechanism(s) behind the ~250 yr periodicity on global climate.

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

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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 and charcoal fragments sourced upwind of sedimentary sequences can 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 under 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*) and charcoal fragments (<106μm) that appear to be linked to warm and windy conditions. Spectral analysis identifies a robust ~250-yr periodicity, with evidence of stronger westerly airflow between 2000 and 1000 cal. yrs BP. In comparison with other Southern Hemisphere records, the 250-yr periodicity suggests solar forcing plays a 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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Competing financial interests

The authors declare no competing financial interests.

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Table and Figure Captions

Depth, cm	Wk lab number	Material	%M/^{14}C BP ± 1 σ	Modelled years BP ± 1σ
8-9	34598	Fruits and leaves	117.0±0.4%M	-16±11
11-12	32994	Fruits and leaves	107.8±0.4%M	-8±2
18-19	37007	Fruits and leaves	107.3±0.3%M	3±31
25-26	35146	Fruits and leaves	95±25	94±66
35-36	37008	Fruits and leaves	647±25	603±29
39-40	33445	Fruits and leaves	761±25	661±28
57-58	32996	Fruits and leaves	1818±25	1672±51
70-71	32350	Fruits and leaves	2235±25	2201±67
97-98	32997	Fruits and leaves	2749±25	2802±32

Table 1: Radiocarbon and modelled calibrated age ranges 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 and Lee, 2013; Ramsey, 2008).

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Parameter	Marine98	Marine04
Air-gas sea exchange	19 moles/m²/yr	18.8 moles/m²/yr
Eddy diffusivity	4000 m²/yr	4220 m²/yr
Pre-industrial atmospheric [CO_2]	280 ppm	270 ppm
Initial atmospheric $\Delta^{14}C$	90‰	100‰

Table 2: Box diffusion model parameters for Marine98 (Bond et al., 2001; Turney et al., 2005) versus Marine04 (Hughen et al., 2004).

A. **B.**

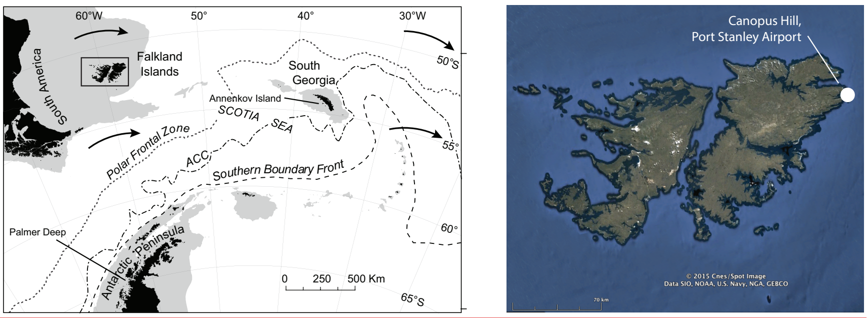

Figure 1: Location of the Falkland Islands in the South Atlantic Ocean with mean locations of the Polar and Southern Boundary fronts (dashed lines), the continental shelf (grey areas) and prevailing westerly airflow (solid arrows) (Panel A); and Canopus Hill, Port Stanley Airport, in the east Falkland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

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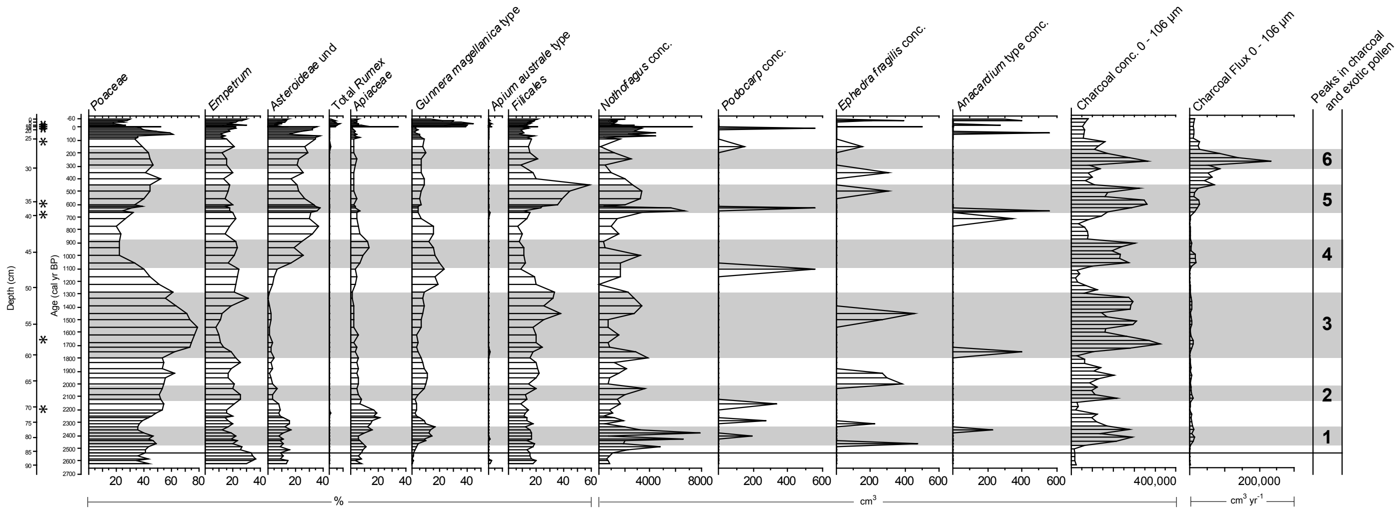

Figure 2: Pollen diagram from Canopus Hill, Port Stanley Airport, plotted against depth and calendar age. The location of ^{137}Cs and ^{14}C ages are marked by asterisk.

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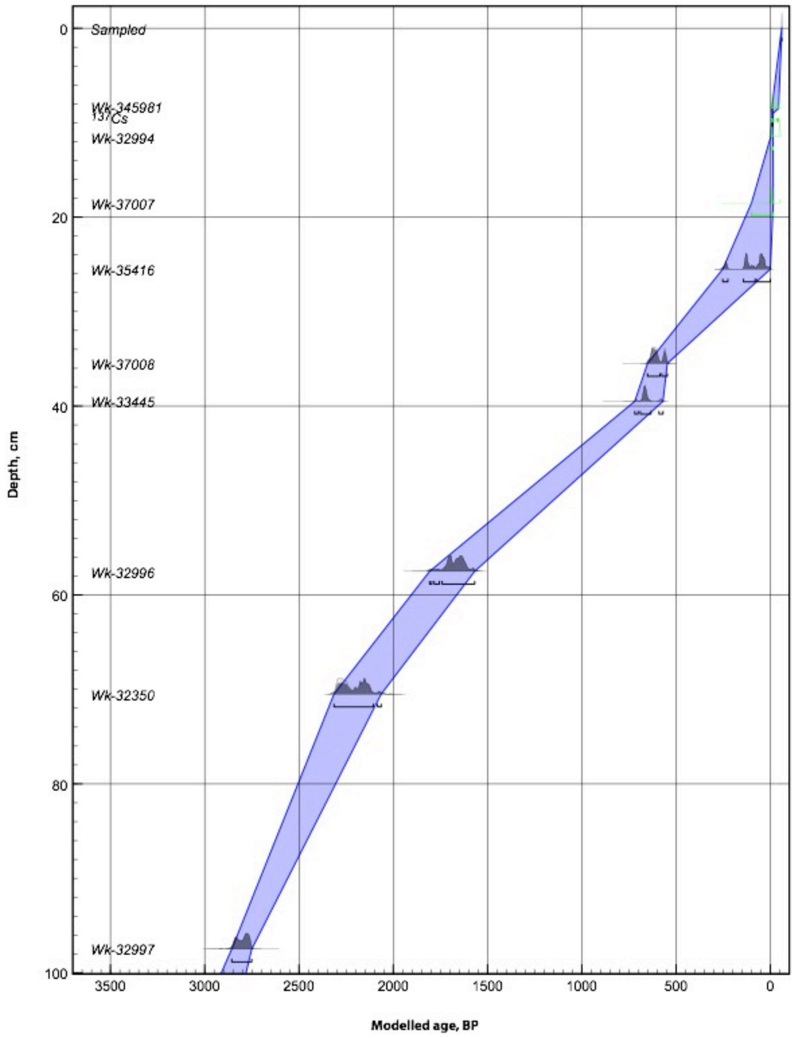

Figure 3: Age-depth plot for Canopus Hill, Port Stanley Airport, with 1σ age range (blue envelope) and probability distributions.

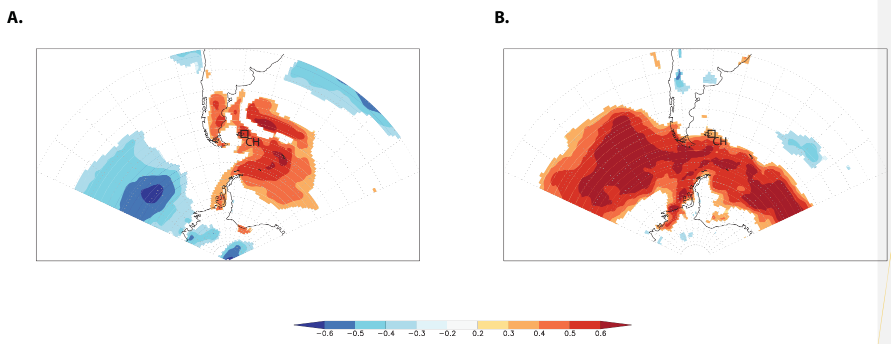

Figure 4: Correlation of relationship between the hemispherically-averaged Southern Annular Mode (SAM) index (Marshall, 2003) with 2-10 metre air temperature (Panel A.) and wind strength (Panel B.) in the ERA-79 Interim reanalysis (Dee et al., 2011) (July-June, 1979-2013). Location of Canopus Hill, (CH), Falkland Islands, shown. Analyses were made with KNMI Climate Explorer (van Oldenborgh and Burgers, 2005).

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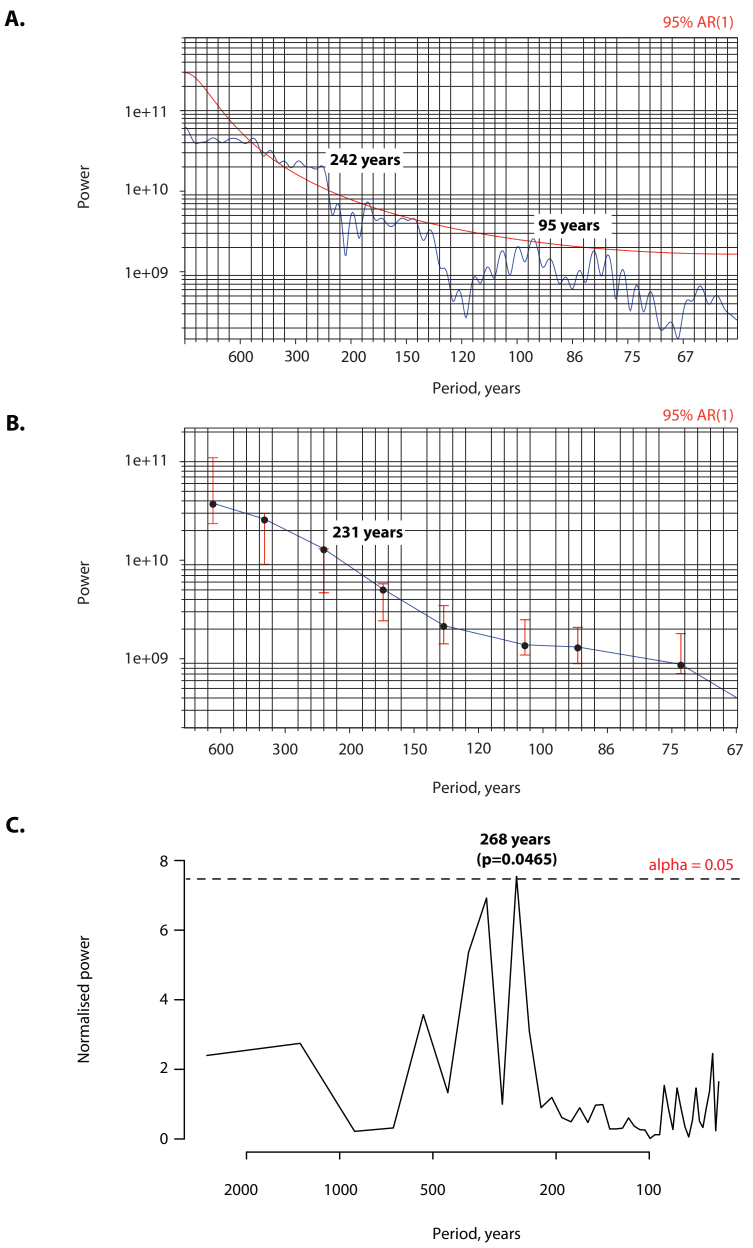

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Figure 5: Multi-Taper Method (MTM) (Panel A.), Monte-Carlo Single Spectrum Analysis (SSA) analyses (Panel B.) and Lomb-Scargle analysis (Panel C.) of charcoal from the Canopus Hill sequence. Error bars denote 95% confidence.

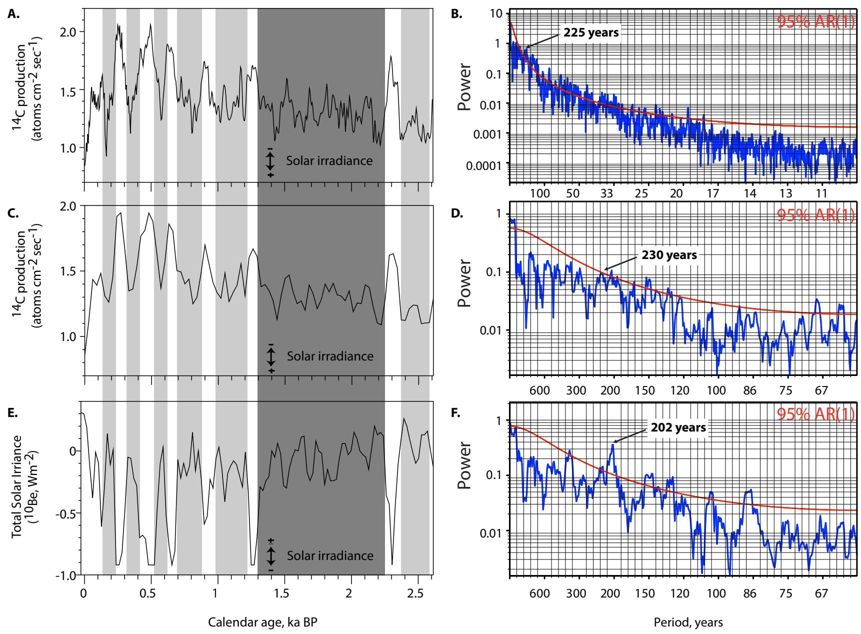

Figure 6: Changes in solar output and Multi-Taper Method (MTM) analysis of reconstructed radiocarbon (^{14}C) production rate (5-yr resolution; this study) (Bond et al., 2001; Turney et al., 2005) (Panels A. and B), ^{14}C production rate (resampled at 30 years) (Panels C. and D.) and Total Solar Irradiance (based on polar ice ^{10}Be) (resampled at 30-yrs) (Panels E. and F.) (Steinhilber et al., 2009) for the full length of each record. The dark gray column defines a millennial-duration period of sustained high solar irradiance in all records; the light gray columns define temporary (centennial-duration) periods of high irradiance. The periodicities that fall within the reported range of the de Vries cycle are identified in the MTM panels (200-230-yrs).

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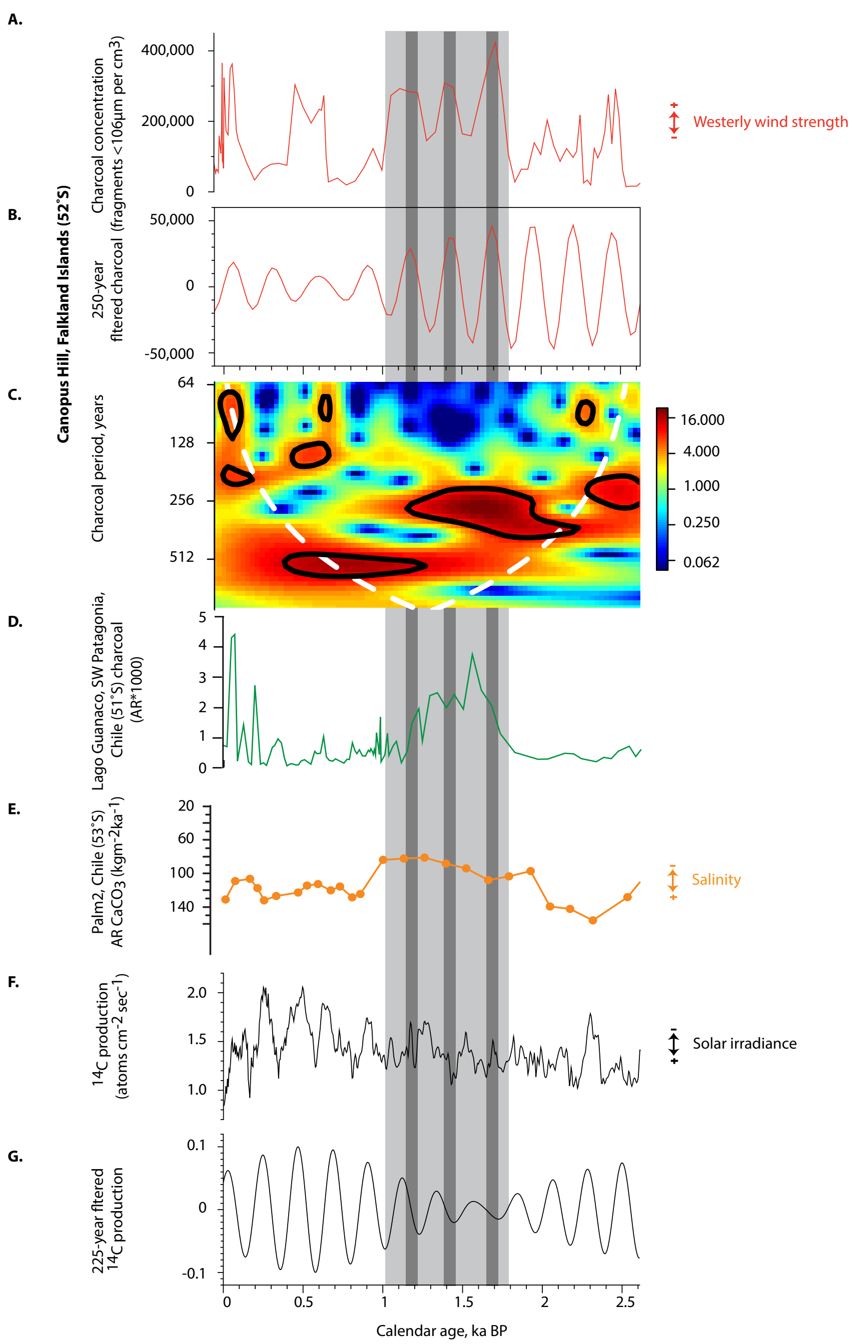

A.
B.
C.
D.
E.
F.
G.
Canopus Hill, Falkland Islands (52°S)
Charcoal concentration (fragments <106µm per cm3)
400,000
200,000
0
Westerly wind strength
250-year fltered charcoal
50,000
0
-50,000
Charcoal period, years
64
128
256
512
16.000
4.000
1.000
0.250
0.062
Lago Guanaco, SW Patagonia, Chile (51°S) charcoal (AR*1000)
5
4
3
2
1
0
Palm2, Chile (53°S) AR CaCO3 (kgm-2ka-1)
20
60
100
140
Salinity
14C production (atoms cm-2 sec-1)
2.0
1.5
1.0
Solar irradiance
225-year fltered 14C production
0.1
0
-0.1
0
0.5
1
1.5
2
2.5
Calendar age, ka BP

Figure 7: Charcoal concentration (<106μm) (Panel A.), Gaussian-filtered charcoal in the 250-year band (250±25 yr^{-1}) (Panel B.) and wavelet analysis of charcoal concentration (Panel C.) from Canopus Hill, Port Stanley Airport (52˚S). Solid black line in wavelet denotes 95% confidence in periodicity; white dashed line denotes cone of influence. Panel D. shows charcoal concentration data from Laguna Guanaco, Chile (51˚S) (Moreno et al., 2009) and Panel E. the biogenic carbonate accumulation rate (AR) from Palm2, Chile (53˚S) . Reconstructed ^{14}C production and Gaussian-filtered ^{14}C in the 225-year band (225±22.5 yr^{-1}) are plotted in Panels F and G. The light grey column defines the period of strong inferred westerly winds across the South Atlantic 2000 to 1000 cal. BP; the dark grey columns, peaks in charcoal 250-yr periodicity lagging minima in ^{14}C production rate (high solar irradiance) by 20-40 yrs.