Evidence for increased expression of the Amundsen Sea Low over the South Atlantic during the late Holocene

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Abstract:

The Amundsen Sea Low (ASL) plays a major role in the climate and environment of Antarctica and the Southern Ocean, including surface air temperature and sea ice concentration changes. Unfortunately, a relative dearth of observational data across the Amundsen and Bellingshausen Seas prior to the satellite era (post-1979) limits our understanding of past behaviour and impact of the ASL. The limited proxy evidence for changes in the ASL are primarily limited to the Antarctic where ice core evidence suggests a deepening of the atmospheric pressure system during the late Holocene. However, no data has previously been reported from the northern side of the ASL. Here we report a high-resolution, multi-proxy study of a 5000 year-long peat record from the Falkland Islands, a location sensitive to contemporary ASL dynamics which modulates northerly and westerly airflow across the southwestern South Atlantic sector of the Southern Ocean. In combination with climate reanalysis, we find a marked period of wetter, colder conditions most likely the result of enhanced southerly airflow between 5000 and 2500 years ago, suggesting limited ASL influence over the region. After 2500 years ago, drier and warmer conditions were established, implying more westerly airflow and the increased projection of the ASL onto the South Atlantic. The possible role of the equatorial Pacific via atmospheric teleconnections in driving this change is discussed. Our results are in agreement with Antarctic ice core records and fjord sediments from the southern South American coast, and suggest the Falkland Islands provide a valuable location for reconstructing high southern latitude atmospheric circulation changes on multi-decadal to millennial timescales.

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1. Introduction

The leading mode of variability in atmospheric circulation across the southern mid-high latitudes is the Southern Annular Mode (SAM), manifested as the pressure difference between 65˚S and 40˚S (Marshall, 2003; Thompson et al., 2011). The multi-decadal trend to a more positive SAM since the mid-20th century (Fogt et al., 2012; Hosking et al., 2013) is expressed by a strengthening and poleward shift of mid-latitude westerly airflow and storm tracks over the Southern Ocean (Marshall, 2003; Thompson et al., 2011; Visbeck, 2009), and has been linked to changes in climate, ocean ventilation, air-sea carbon flux, sea ice trends, and ice sheet dynamics on interannual to multi-decadal timescales (Jones et al., 2016a; Landschützer et al., 2015; Pritchard et al., 2012; Le Quéré et al., 2007; Thomas et al., 2018). Whilst the SAM may dominate contemporary climate across the mid latitudes, other climate modes and atmospheric patterns also play important roles both spatially and temporally. Arguably the most important in this regard is the Amundsen Sea Low (ASL), a quasi-stationary low-pressure system located in the Amundsen and Bellingshausen Seas (45-75˚S, 180-60˚W) - a consequence of the Antarctic Peninsula and regional topography that dynamically influences atmospheric flow across this sector of the Southern Ocean (Fogt et al., 2012; Hosking et al., 2013; Turner et al., 2013). Proxy reconstructions of SAM and/or associated westerly winds have been generated for the Holocene (Abram et al., 2014; Dixon et al., 2012; Fletcher and Moreno, 2012; Mayewski et al., 2017; Moreno et al., 2012; Sime et al., 2010; Turney et al., 2017b) but there is a relative dearth of records for the past behaviour of the ASL (Mayewski et al., 2013).

Seasonally, the ASL migrates across the Bellingshausen Sea into the Ross Sea: during the austral summer, the pressure minimum extends east to the Antarctic Peninsula (reaching its lowest geopotential height off coastal West Antarctica in the Amundsen Sea), while in winter, the ASL migrates to the west into the eastern Ross Sea (Fogt et al., 2012). As a result, the ASL plays a dominant role in climate and environmental variability across the wider south Pacific and southwestern South Atlantic sectors of the Southern Ocean (Kreutz et al., 2000; Turner et al.,

2016). In particular, both the geopotential height and location of the ASL affects regional synoptic conditions that extend into the interior of West Antarctica and southern South America (Clem et al., 2017; Ding et al., 2011; Schneider et al., 2012). Across the period 1979-2008 (satellite era) the ASL appears to have deepened, with associated changes in the strength and location of the mid-latitude jet as described by the zonally-averaged SAM index (Jones et al., 2016a). This deepening has been linked to stratospheric ozone depletion (Clem et al., 2017; Jones et al., 2016a; Raphael et al., 2016) as well as reduced sea ice along the western Antarctic Peninsula and climate changes across a broader sector of the Southern Ocean (Jones et al., 2016a; Turner et al., 2013; Turney et al., 2016b). Other possible drivers of ASL dynamics operating on a range of timescales are changes in the equatorial Pacific (Abram et al., 2014; Ding et al., 2011; Lachlan-Cope and Connolley, 2006; Turney et al., 2017a) and the Interdecadal Pacific Oscillation (IPO) (Meehl et al., 2016); though these are not necessarily exclusive to one another.

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The lack of long-term surface-based (*in situ*) observations in the Amundsen, Bellingshausen, and Ross Seas severely limits our understanding of the properties and impact of the ASL on multi-decadal to millennial timescales; an important consideration given uncertainties over the response of the ASL to future anthropogenic forcing (IPCC AR5, 2013). Fortunately, palaeoclimate proxy data from the region integrated with reanalysis data offers an opportunity to identify processes and mechanisms on timescales beyond those of satellite-era observations (since 1979). A major challenge for reconstructing changes in the ASL, however, is disentangling the role of mid-latitude westerly airflow associated with SAM. The location of the palaeo records and the proxies used are crucial in this regard. For instance, recent work from Siple Dome in West Antarctic recognised increased delivery of sea salt sodium ($ssNa^+$) interpreted as representing a deepening of the ASL, with a particularly marked trend since 2900 years ago (hereafter 2.9 ka) (Mayewski et al., 2013). Although Siple Dome provides an important southern 'observation' point, information is needed on the northern side of the ASL to provide a more

complete reconstruction of its location and/or depth during the Holocene, as well a more thorough understanding tropical Pacific-high latitude teleconnections. Here we report a new high-resolution record of local vegetation change and 'exotic' macrofossils – the latter a proxy for westerly airflow - extending the record over the past 5 ka and demonstrate a marked change in synoptic conditions around 2.5 ka, providing important new insights into the long-term behaviour of the ASL and the role of the tropic Pacific.

1.1 Study site

The Falkland Islands lie at 52°S, 540 km east of the coast of South America and 1500 km west of subantarctic South Georgia. The present climate of the Falkland Islands is highly influenced by the surrounding cool South Atlantic waters resulting in a cool temperate, maritime climate, with corresponding low seasonality. Weather station data from the east Falkland Islands (Mount Pleasant Airport) reveal a mean annual temperature of 5.5°C, high mean monthly and annual wind speeds of ca. 8.5 m s^{-1} (with prevailing westerly winds), and relatively low annual precipitation of ca. 600 mm, distributed uniformly throughout the year (Lister and Jones, 2014).

The Falkland Islands are dominated by extensive undulating lowlands, but several upland areas in excess of 500 m above sea level (asl) occur within the archipelago. The islands are not glaciated today and record only two periods of restricted glaciation in the Late Pleistocene (Clapperton, 1971, 1990, 1993; Clapperton and Sugden, 1976; Roberts, 1984). Blanket peat was established across large parts of the archipelago from 16.5 ka (Wilson et al., 2002). The islands are situated within the main latitudinal belt of Southern Hemisphere westerly airflow (Barrow, 1978), and are therefore ideally placed to monitor changing Holocene wind strength across the South Atlantic. The need to understand the climate impacts is an urgent one; recent studies have suggested that with the projected increase in temperatures on the Falkland Islands, upland species are highly vulnerable to climate change (Upson et al., 2016).

To investigate past airflow, a 1.5 m sequence was taken with a D-section corer from an exposed Ericaceous-grass peatland on Canopus Hill (51.691°S, 57.785°W, approximately 30 m asl), outside Port Stanley (35 km from Mount Pleasant Airport). The uniform dark-brown peat was contiguously sampled for pollen, charcoal and comprehensive radiocarbon dating. Work at this site has previously recognised the input of exotic pollen and charcoal derived from South America but was limited to the last 2.5 kyr (Turney et al., 2016a).

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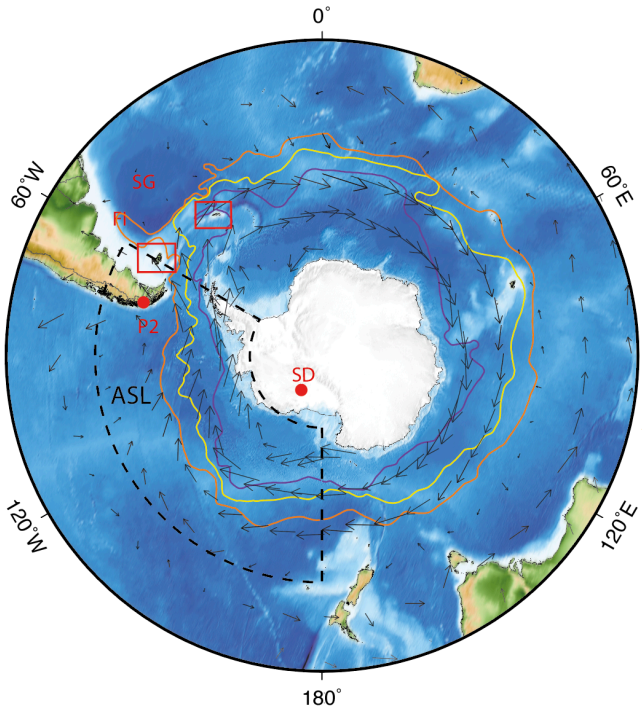

Figure 1. Location of the Falkland Islands (FI), South Georgia [SG], Siple Dome [SD] and Palm2 [P2]. Dashed line denotes contemporary limits of the ASL domain defined across the 1979–2001 average (Fogt et al., 2012). Mean locations of the southern limb of the Antarctic Circumpolar Current (purple), the polar front (red) and the subantarctic front (green) are shown, following Orsi et al. (1995), based on analyses of hydrographic station data available up to 1990. The grey arrows denote the 925 hPa winds (vectors) trends since 1979 from ERA-Interim (Dee et al.,

2011), depicting the location and increase in westerly winds over the satellite era. Map made using Generic Mapping Tools (GMT) (Wessel et al., 2013).

2. Methods

2.1 Pollen and charcoal analysis

The pollen samples were prepared using standard palynological techniques (Faegri and Iverson, 1975). Volumetric samples were taken every 1 cm along the core, with *Lycopodium* spores added as a 'spike'. The samples were deflocculated with hot 10% NaOH and then sieved through a 106 µm mesh, before acetolysis, to remove extraneous organic matter. The samples were mounted in silicon oil and pollen types/palynomorphs were counted at 400× magnification until a minimum of 300 target grains were identified. Pollen/palynomorphs were identified using standard pollen keys (Barrow, 1978; Macphail and Cantrill, 2006) and the pollen type slide collection at the University of Exeter, UK. The pollen counts were expressed as percentages, with only total land pollen (TLP) contributing to the final pollen sum. The *Lycopodium* 'spike' was also used to calculate total and individual pollen concentrations (grains cm^{-3}) (Stockmarr 1971), and these values were divided by the deposition time (year cm^{-1}) to calculate pollen accumulation rates (PAR; grains cm^{-2} $year^{-1}$). Major pollen zone boundaries were determined using CONISS (stratigraphically constrained cluster analysis) (Grimm, 1987) using the rioja package in R (Juggins, 2017). Past fire activity was investigated using counts of micro-charcoal fragments (< 106 µm) identified on the pollen slides (Whitlock and Larsen, 2001). Counts were undertaken at each level until a fixed total of 20 *Lycopodium* spores were counted and the total expressed as a concentration (fragments per cm^3). Charcoal accumulation rate (CHAR) was calculated by dividing the total charcoal concentration by the deposition time estimated from the age-depth relationship.

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2.2 Radiocarbon and ^{137}Cs dating

To derive a chronological framework for the Canopus Hill peat sequence, terrestrial plant macrofossils (fruits and leaves) were extracted. These macrofossils were given an acid–base–acid (ABA) pre-treatment and then combusted and graphitised 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 pre-treated 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 aluminium target holders for measurement at UCI. The ^{14}C measurements were supplemented by ^{137}Cs measurements near the top of the profile to detect the onset of nuclear tests in the mid-20th century. The anthropogenic radionuclide ^{137}Cs (with a half time of 30 years) is derived from atmospheric nuclear weapons testing and can provide an important "first appearance" horizon of known age (1954–1955) i.e. an independent marker horizon to assist with age model validation (Hancock et al., 2011). ^{137}Cs analysis was undertaken following standard techniques with measurements made using an ORTEC high-resolution, low-background coaxial germanium detector. Specifically, we analysed contiguous peat samples for the first presence of ^{137}CS; detectable measurements were obtained down to 8.5-9.5 cm.

2.3 Age modelling

The ^{14}C and ^{137}Cs ages were used to develop an age model using a P_sequence deposition model in OxCal 4.2 (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013); with the General Outlier analysis detection method (probability=0.05) (Bronk Ramsey, 2009). The ^{14}C ages were calibrated against the Southern Hemisphere calibration (SHCal13) data set (Hogg et al., 2013). The model was based on 1000 iterations, with the surface (depth zero) and year of sampling (2010) as the uppermost chronological control point. Using Bayes' theorem, the algorithms employed sample possible solutions with a probability that is the product of the prior and likelihood probabilities (Bronk Ramsey, 2008). Taking into account the deposition model and

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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. The first presence of ^{137}Cs was assigned the prior U(1952, 2011) in the OxCal age model to capture the possible range of calendar years (CE) for the onset of ^{137}Cs deposition in the sequence (Hancock et al., 2011). Modelled ages are reported here as thousands of calendar years before present (CE 1950) or ka (Table 1). We used the mean of the modelled age solutions to estimate the age of a fraction at each sample depth. The radiocarbon ages follow a stratigraphic order except for the two basal ages. We suspect these basal ages may comprise intruded younger root material; a scenario not unusual in relatively slowly accumulating sedimentary sequences e.g. (Brock et al., 2011). The sedimentation rate is internally more consistent when excluding these two basal ages; without them the sedimentation rate from the entire metre of sediment above does not change significantly (with a sedimentation rate for 141.5-156 cm of 38 yrs/cm compared to an average of 27 yrs/cm for the preceding metre of sediment), whereas including them increases the sedimentation rate over this depth range abruptly to 11.6 yrs/cm. The calibrated 2σ age range for both the age model including and excluding these two basal ages are found in Table 1; the calibrated age ranges are almost identical for both age models until 142 cm, from where it diverges. Importantly, our conclusions are not at all affected by the choice of age model.

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Depth, cm	Wk lab number	Material	% Modern /^{14}C BP ± 1 σ	2σ cal. age range (years BP)	2σ cal. age range (years BP)	Mean cal. age (years BP)
				With 2 basal ages	Excluding 2 basal ages	
8-9	34598	Fruits and leaves	117.0±0.4%M	-4 to -43	-4 to -44	-21
9		^{137}Cs		-6 to -42	-6 to -42	-19
11-12	32994	Fruits and leaves	107.8±0.4%M	-2 to -14	-1 to -14	-8
18-19	37007	Fruits and leaves	107.3±0.3%M	0 to -13	26 to -15	-3
25-26	35146	Fruits and leaves	95±25	250 to -1	250 to -1	86
35-36	37008	Fruits and leaves	650±25	650 to 550	650 to 550	600
39-40	33445	Fruits and leaves	760±25	720 to 570	720-570	660
57-58	32996	Fruits and leaves	1820±25	1800 to 1600	1800 to 1600	1680
70-71	32350	Fruits and leaves	2240±25	2320 to 2100	2310 to 2100	2220

97-98	32997	Fruits and leaves	2750±25	2870 to 2760	2870 to 2760	2810
107-108	32998	Fruits and leaves	2910±26	3140 to 2880	3140 to 2880	3000
120-121	41767	Fruits and leaves	3240±20	3480 to 3360	3470 to 3360	3420
141-142	32351	Fruits and leaves	3960±32	4430 to 4180	4510 to 4240	4350
148-149	41768	Fruits and leaves	4390±20	4520 to 4300	5030 to 4850	4910
153.5-154.5	42144	Fruits and leaves	4040±21	4520 to 4420		
156.5-157.5	42145	Fruits and leaves	4080±22	4570 to 4430		

Table 1. Radiocarbon and modelled calibrated age ranges for the Canopus Hill peat sequences using the P_sequence and Outlier analysis option in OxCal 4.2 (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013). The SHCal13 (Hogg et al., 2013) and Bomb04SH (Hua and Barbetti, 2004) calibration curves were used. Note: calibrated ages are relative to Before Present (BP) i.e. CE 1950.

3. Results and Discussion

3.1 Contemporary Climate

Regional climate dynamics were explored using the ERA Interim reanalysis (Dee et al., 2011), and the instrumental observations from Mount Pleasant Airport weather station on the Falkland Islands (Jones et al., 2016b; Lister and Jones, 2014). Given the seasonal nature of vegetation growth (including peat accumulation), spatial correlations using deseasonalised and detrended (to remove potential bias as a result of similar seasonal and long-term trends) spring-summer precipitation and temperature were investigated. These analyses show important links with atmospheric synoptic conditions (Figure 2) including a clear link between precipitation and zonal and meridional circulation (Figure 2c). Spatial correlations suggest limited ocean influence on these climate variables on the Falkland Islands. Crucially, wetter conditions are associated with a weakening of the ASL and the delivery of more southerly and easterly airflow across the South Atlantic (Jones et al., 2016b). Conversely, more northerly airflow is associated with less precipitation over the Falklands. A similar picture emerges with

variations in temperature (Figure 2a and d) with a deeper (i.e. more intense low pressure) ASL associated with warmer temperatures over the Falkland Islands, and a weaker ASL with cooler conditions.

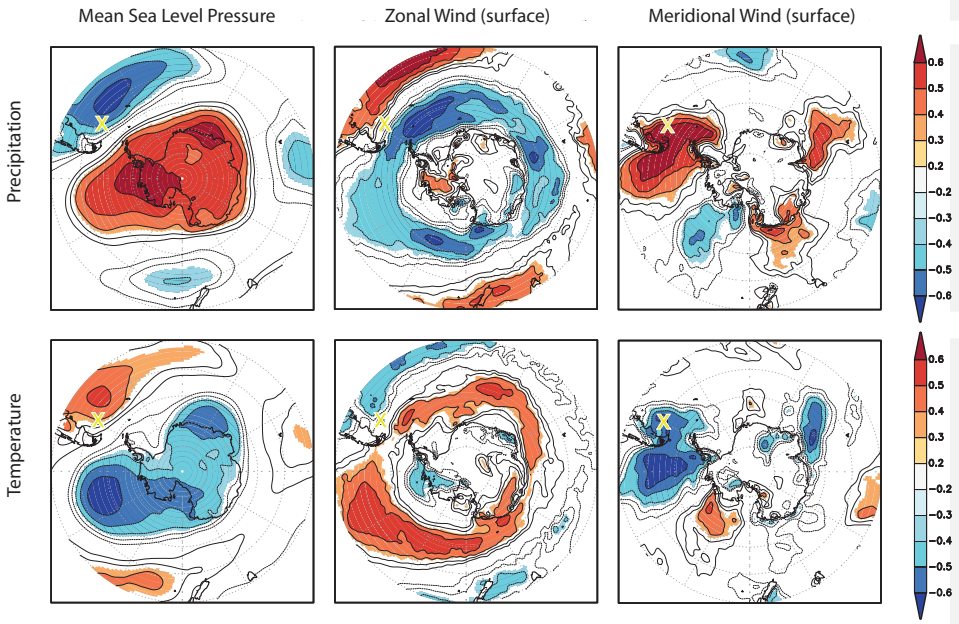

Figure 2. Spatial correlation of relationships between precipitation, temperature and synoptic conditions from Mount Pleasant Airport (October to March), Falkland Islands ('X'). Mean Sea Level Pressure (MSLP), surface zonal wind and surface meridional wind correlated with October to March precipitation (upper row) and temperature (lower row) using ERA-79 Interim reanalysis (Dee et al., 2011) (1979–2013). Significance $p_{field} < 0.05$. Analyses were made with KNMI Climate Explorer (van Oldenborgh and Burgers, 2005).

3.2 Holocene Climate and Environmental Change

The Canopus Hill peat sequence reported here from the Falkland Islands represents one of the longest pollen records from the South Atlantic, with the only published early Holocene record from Barrow et al. (1978), which has limited age control and resolution. Our reconstruction appears to represent changing environmental conditions through the mid to late Holocene (Figure 3). The pollen record is dominated by Poaceae and *Empetrum*, consistent with both previous studies and current vegetation on the islands (Barrow, 1978; Broughton and Mcadam, 2003; Clark et al., 1998; Turney et al., 2016a). However, in contrast to these previous studies, we observe a major shift in the representation of Cyperaceae and the total accumulation of pollen centred on ~2.5 ka (Figure 4).

Similar changes to the above are also observed in the aeolian transportation of exotic pollen and charcoal derived from long-distance transport. These 'exotic' pollen in the Canopus Hill sequence represent South American flora delivered to the site by westerly airflow. While only representing between 0.3% and 4.6% of the pollen sum, we recorded *Nothofagus*, *Podocarpus*, *Ephedra fragilis*, and *Anacardium*-type (arboreal) pollen grains. *Nothofagus* was the most frequently recorded exotic taxon in the samples, due to its high representation on Tierra del Fuego and the Islas de los Estados (upstream of the Falkland Islands), and high production of wind-dispersed pollen that can be carried over long distances (Moreno et al., 2009). In extreme situations, *Nothofagus* pollen has been recovered as far from South America as Marion Island and Tristan da Cunha (Hafsten, 1960; Mildenhall, 1976; Wace and Dickson, 1965).

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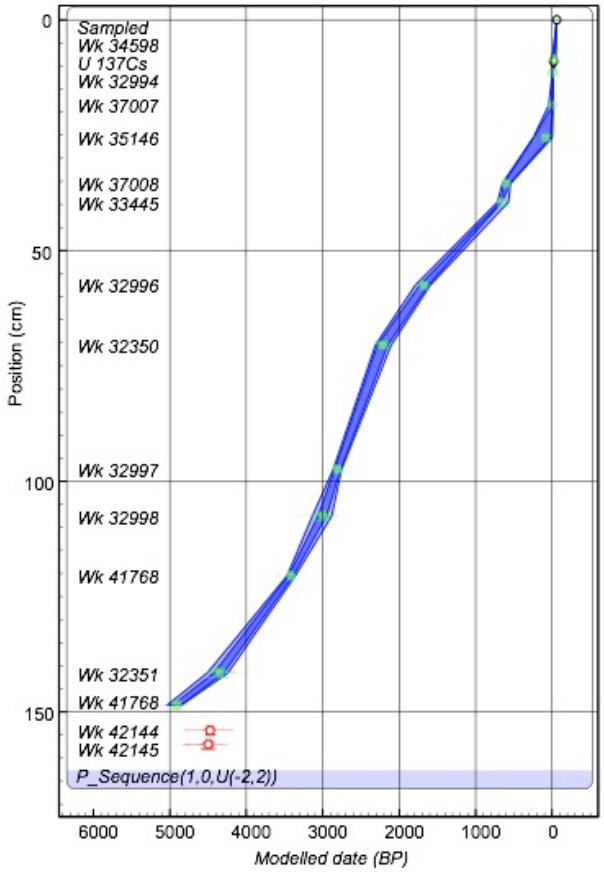

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332 Figure 3. The age-depth relationship from Canopus Hill, with 1σ and 2σ age range (dark and
333 light blue envelopes respectively) and probability distributions generated from the Bayesian
334 age model. Red symbols indicate radiocarbon ages not incorporated into the age model.
335 Calibrated using SHCal13 atmospheric curve (Hogg et al., 2013) and 'Post-bomb' atmospheric
336 SH curve (Hua and Barbetti, 2004). Plot made with OxCal v4.3.2 (Bronk Ramsey, 2017).

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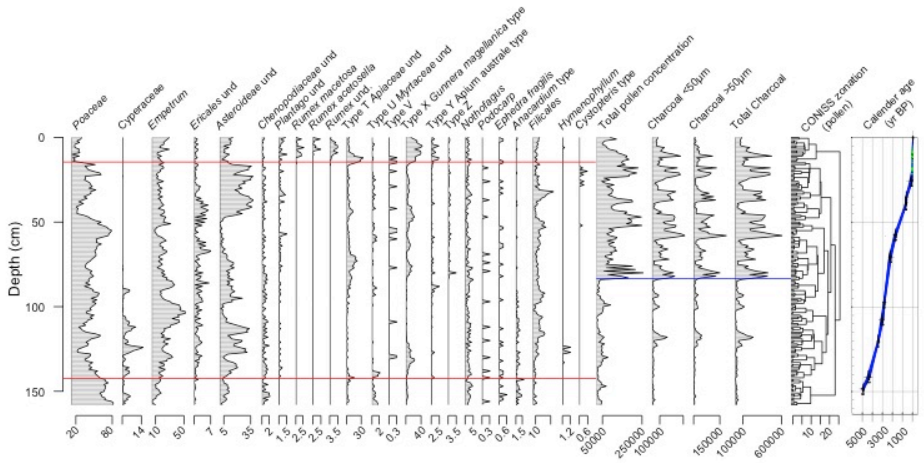

Figure 4: Summary pollen diagram from Canopus Hill, Port Stanley, with the left hand panels describing palynomorphs as percentages of the total land pollen plotted against depth. The middle panels show total pollen, charcoal of different size fractions and total charcoal expressed as a concentration (number cm^{-3}). Parallel lines denote major pollen (red) and charcoal/pollen concentration (blue) zone boundaries were determined using CONISS (Grimm, 1987).

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Differences in the exotic pollen assemblages can reflect either changes in the transport pathway (i.e. direction and wind strength) or regional vegetation change in the source area(s). Today, *Nothofagus* dominates lowland Patagonian vegetation and is found throughout Patagonian Late Glacial sequences. This taxa is thought to have been most widely established by 5 ka (Iglesias et al., 2014; Kilian and Lamy, 2012), with a reasonably constant representation until stepped expansion at Lago Guanaco, almost directly west of the Falklands (51.03°S, 72.83°W, 185m asl), centred on 570 cal. years (Moreno et al., 2009; Villa-martínez et al., 2012). Fire activity and the introduction of exotic weeds introduced by European settlers is thought to have resulted in the rapid decline of *Nothofagus* at the end of the 19th century (Moreno et al., 2009). The fact that *Nothofagus* is consistently represented throughout the Canopus Hill record indicates pervasive westerly winds throughout the mid to late-Holocene, but does not have sufficiently high concentrations to robustly identify long-term changes.

Recent syntheses of charcoal stratigraphies across Patagonia have detected regional trends in biomass burning during the Holocene with a moderate increase occurring over the last 3000 years (Huber et al., 2004; Whitlock et al., 2007; Power et al., 2008). Highly variable counts of charcoal were obtained through the Canopus Hill sequence, however, more than 99% of charcoal fragments were less than 50 µm in size, with negligible amounts identified in the 50–106 µm and >106 µm fractions (Figure 4). As charcoal of this size can be transported long distances (Clark, 1988) it is likely that this influx of charcoal predominantly represent South American sources and westerly (and south-westerly) airflow, and that there was little or no fire in the local environment throughout the mid- to late-Holocene. The presence of fire in the Patagonian landscape during the late Holocene thus provides a ready source of exotic material for aerial transport to the Falkland Islands delivered via westerly airflow. The aeolian delivery of the charcoal to the Falkland Islands is supported by a correspondence between the Canopus Hill and Lago Guanaco, Southwest Patagonia (Moreno et al., 2009) charcoal records. There is

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also a weak correlation between charcoal and *Nothofagus*, particularly in the younger half of the record, probably reflecting the similar transport modes.

Centennial-scale variability in the Canopus Hill charcoal record over the last 2.5 kyr has previously been identified, apparently coherent with radiocarbon production rates (Turney et al., 2016a), suggesting that solar variability has a modulating influence on Southern Hemisphere westerly airflow. Similar cyclical variations in West Antarctic Peninsula glacier discharge as observed from the $\delta^{18}O_{diatom}$ record from Site 1099 in the Palmer Deep, has also been reported (Pike et al., 2013) which shows an underlying decrease towards lower values, reported from ~2.5 kyr. Specifically, this increased glacial ice discharge is considered to have been driven by atmospheric warming (as a result of peak local summer insolation; Figure 5), supporting the findings from Canopus Hill.

3.3 Holocene changes in the Amundsen Sea Low (ASL)

Our results support the notion of pervasive westerly winds throughout the mid- to late-Holocene, as shown by the consistent representation of *Nothofagus* pollen, as well as the pollen of other rare exotic taxa including *Podocarp*, *Ephedra fragilis* and *Anacardium*-type found throughout the Canopus Hill peat sequence. Whilst the presence of *Nothofagus* implies westerly airflow has been maintained across the South Atlantic, the relatively high expression of Cyperaceae between 5 and ~2.5 ka (Figure 5) suggests enhanced delivery of cooler and moister air to the Falklands. Our analyses exploring contemporary drivers of synoptic conditions imply these conditions could have been brought about by more southerly airflow across the South Atlantic (Figure 2), synoptic conditions inconsistent with today's expression of the ASL. The marked decline in Cyperaceae and increase in charcoal at ~2.5 ka indicates a shift to drier and potentially warmer conditions, most probably a result of reduced southerly airflow and the northward movement and/or expansion of the ASL. The inferred increase in primary

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Moved up [1]: Recent syntheses of charcoal stratigraphies across Patagonia have detected regional trends in biomass burning during the Holocene with a moderate increase occurring over the last 3000 years (Huber et al., 2004; Whitlock et al., 2007; Power et al., 2008).

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productivity and pollen accumulation on the islands supports this interpretation (Turney et al., 2016b).

These results complement other studies from the broader South Atlantic region (Figure 5). Ice core-derived proxies from Siple Dome, located in a key region for understanding ASL dynamics, imply distinct changes in atmospheric circulation. Here, $ssNa^+$ provides a measure of sea-salt species, the transport of which is significantly influenced by the ASL (Kreutz et al., 2000), with higher values associated with a deeper ASL. The long-term increase of $ssNa^+$ over the mid- to late Holocene thus implies a deepening of the ASL (Mayewski et al., 2013) consistent with our data. The slight difference in the timing between these records may be a consequence of chronological uncertainties or a lag in the projection of the ASL onto the South Atlantic (possibly reflecting an eastward migration/extension of the ASL to where it is more commonly located today). Farther north, the marine sequence from the Palm2 within the Skyring fjord system west of the Andean crest of South America shows strong fluctuations of biogenic carbonate accumulation rates in superficial fjord waters (Lamy et al., 2010). This record represents marine carbonate production and its subsequent accumulation on the sea bed in response to salinity changes in the upper water column of the fjord; prevailing westerly winds keep the low-salinity waters inside the fjord, therefore, lower salinity anomalies suggest stronger westerly winds. Intriguingly, the Palm2 record shows a pronounced sustained decrease in salinity anomalies from ~2/2.5 ka (Figure 5), interpreted to be a result of a strengthening of mid-latitude westerly winds and possible influence of the ASL, consistent with our reconstruction. The differences in the timing within the records that we compare may be an artefact of the uncertainties in the individual age models, or represent real dynamic changes operating on multi-decadal to centennial timescales. The changes at Palm2 do appear to be more abrupt than those observed from Siple Dome, but we do not interpret this as a regime shift (Thomas, 2016). The last age control point for the Palm2 record is from a marine shell at the start of the inflection, dating to 2570±30 ^{14}C BP, calibrated to 2410 cal yr BP (no 2σ age range given),

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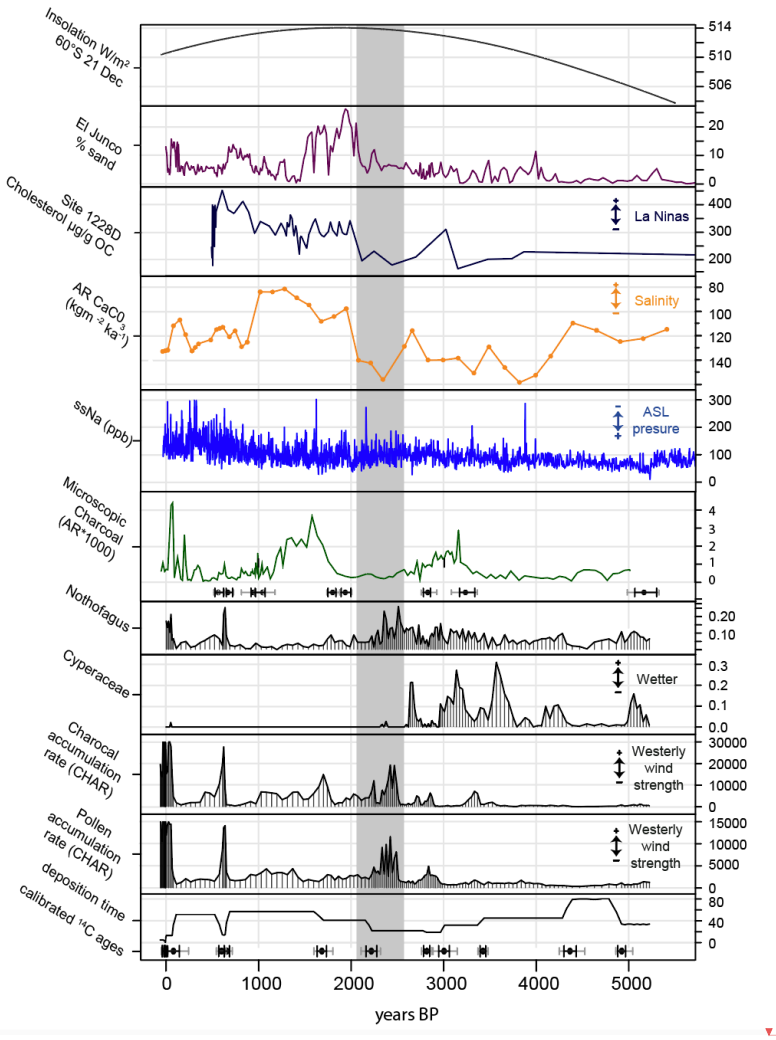
suggesting the age uncertainties between the changes observed in the Canopus Hill record and the Palm2 record may possibly overlap.

Taken together the above results imply that there was a long-term change in the behaviour of the ASL with the establishment of contemporary synoptic conditions around 2.5 ka. The reason for a change at ~2.5 ka is not immediately apparent but one possibility is the tropical Pacific. Today, equatorial Pacific ocean-atmospheric linkages are known to modulate the ASL with associated impacts across the broader region including climate, sea ice and ice sheet dynamics (Abram et al., 2014; Ding et al., 2011; Lachlan-Cope and Connolley, 2006; Turney et al., 2017a). Reconstructions of sea surface temperatures and precipitation suggest the establishment of more pervasive El Niño-Southern Oscillation (ENSO) activity from 3 to 2.5 ka (Carre et al., 2014; Makou et al., 2010; Rein et al., 2005), that may have been projected onto the southeast Pacific sector of the Southern Ocean (Abram et al., 2014). The ENSO circulation pattern is teleconnected to Southern Ocean and Antarctic climate, in particular the Amundsen Sea low-pressure region, possibly via movements of the South Pacific Convergence Zone (Russell and McGregor, 2010). Contemporary La Niña events are accompanied by a northerly shift in the South Pacific Convergence Zone and the production of cyclones in the region of the Amundsen Sea low, enhancing warm northerly airflow over Patagonia, the Western Antarctic Peninsula and the Falkland Islands. In addition, Fogt et al. (2011) found that when a La Niña event occurs during a positive phase of the SAM, the ASL deepens, suggesting that the SAM and the ASL may modulate one another. Whilst a shift to more negative IPO has been linked to a deepening of the ASL (Meehl et al., 2016), the long-term changes in this climate mode are currently uncertain. Given the projected increase in extreme ENSO events under future anthropogenic forcing (Cai et al., 2015) further work is needed to determine the mechanisms, timing and impacts of these low to high latitude teleconnections through the Holocene.



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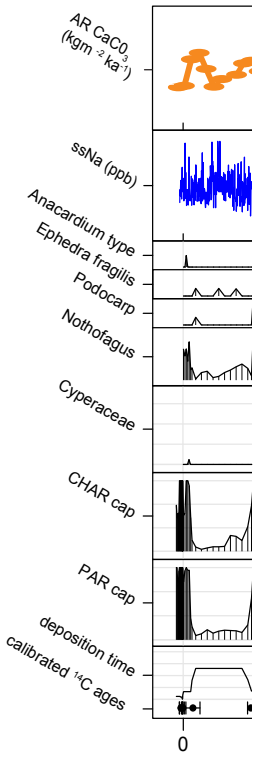

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Figure 5: Key data from the Canopus Hill sequence (Falkland Islands) and other South Atlantic records. From bottom to top: deposition time, total pollen accumulation rate (PAR), total charcoal accumulation rate (CHAR), Cyperaceae and Nothofagus re-expressed as accumulation rates, microscopic charcoal from Lago Guanaco (Moreno et al. 2009), ssNa⁺ from Siple Dome (Mayewski et al., 2013), salinity anomalies from Palm2 (Lamy et al., 2010), cholestrol abundance, ODP Site 1228, Peru margin (Makou et al., 2010), percentage of sand, El Junco Crater Lake, Galápogos (Conroy et al., 2008) and summer (21 Dec) insolation (W/m²) at 60°S

(Laskar et al., 2004). Calibrated radiocarbon ages and 1σ (black) and 2σ (grey) age ranges for Canopus Hill and Lago Guanaco are plotted at the base of the respective panel. Note that PAR and CHAR have both been truncated at the modern end due to high accumulation rate. The grey boxed area marks the transition period during which the ASL strengthened over the South Atlantic.

4. Conclusion

The Amundsen Sea Low (ASL) has been recognized as an important driver of Southern Ocean climate and environmental changes during the late twentieth century. Unfortunately, however, there are limited observational and proxy datasets capturing the long-term behaviour and impact of the ASL. Here we report a comprehensively dated peat record from Canopus Hill (Falkland Islands) in the southwestern South Atlantic Ocean, a region highly sensitive to the ASL. Our multi-proxy study including local vegetation change and exotic pollen and charcoal (wind-blown macrofossils originating from South America) allows us to reconstruct climate changes over the last 5000 years. We observe a marked shift from pervasive wet and cool to drier and warmer conditions around 2500 years ago. ERA Interim reanalysis suggests this change was a consequence of the establishment of contemporary westerly airflow associated with the ASL projecting onto the South Atlantic. The timing of this change is consistent with increased surface warming and expression of the El Niño-Southern Oscillation (ENSO) in the region, suggesting a strengthening of equatorial-high latitude atmospheric teleconnections. Our study demonstrates the value of the Falkland Islands for reconstructing atmospheric circulation changes across the southwestern South Atlantic on multi-decadal to millennial timescales.

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Deleted: Figure 4: Key data from the Canopus Hill sequence (Falkland Islands) and other South Atlantic records. From bottom to top: deposition time, total pollen accumulation rate (PAR), total charcoal accumulation rate (CHAR), *Cyperaceae, Nothofagus, Podocarp, Ephedra, Anacardium*-type re-expressed as accumulation rates, $ssNa^{+}$ from Siple Dome (Mayewski et al., 2013) and salinity anomalies from PALM2 (Lamy et al., 2010). Calibrated radiocarbon ages and 1σ range are plotted at the base of the figure. Note that PAR and CHAR have both been capped at the modern end due to high accumulation rate. The grey boxed area marks the period during which there was limited expression of the ASL over the South Atlantic.

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Anonymous Referee #1 Received and published: 20 April 2018

Thomas et al. present new high-resolution pollen data on a radiocarbon dated peat record from the Falkland Islands for the last about 5000 years. They relate major changes in the vegetation dynamics on the island and in the far-distant Patagonia pollen transport to major reorganizations of the high latitude Antarctic atmospheric circulation pattern in the Southeastern Pacific sector, namely the intensity and position of the Amundsen Sea Low (ASL).

Main observation of this study is a significant change in the vegetation and enhanced charcoal input around 2.5 kyrs indicating a shift to warmer/drier conditions over the island likely associated with a strengthening and northward expansion of the ASL. Simple Dome ice core data and a marine carbonate record from the Chilean fjord region are used for comparison and in support of their interpretation. This peat record is one of the few very valuable paleoenvironmental data available from this part of the world. However, this cannot be the only reason to assume, that it is representative for the whole South Atlantic ("across the South Atlantic"), as it is stated several time in the manuscript. Rather it responds to SE Pacific/Southern Ocean climate variability, which is restricted more or less to the southeastern South Atlantic (as it is shown also in the correlation maps, Fig. 2). Altogether, the manuscript is well organized and concise, referencing is adequate, and the layout and total number of figures are very reasonable.

We thank the reviewer for their kind remarks and constructive suggestions, which have been extremely helpful to for improving our manuscript. We have addressed all the comments in the revised manuscript and detail these below. (Our responses in blue, reviewer comments in black).

General remarks:

1. Please provide evidence for the representativeness of this location for the South Atlantic, if not please correct the respective statements in the whole manuscript

We understand the reviewers concern here and stated more explicitly the importance of the location and our interpretation of the results. Crucially, the Falkland Islands lie at a strategic location sensitive to changes in the Amundsen Sea Low, through the influence of the latter on atmospheric circulation over the southeastern South Atlantic region (e.g. Fogt et al. 2012, Russell and McGregor 2010, Hosking et al. 2013 and Turner et al. 2013).

2. The indicated wind pattern in figure 1 is too simplistic and this map would benefit from adding major surface current patterns and the frontal zones in this region.

This is a good suggestion. We have added the 925 hPa winds (vectors) trends since 1979 from ERA-Interim (Dee et al., 2011). This shows both the location and increase in westerly winds over the satellite era. We have also added the mean locations of the southern limb of the Antarctic Circumpolar Current (purple), the polar front (red) and the subantarctic front (green), following Orsi et al. (1995). (See the revised Figure 1 below).

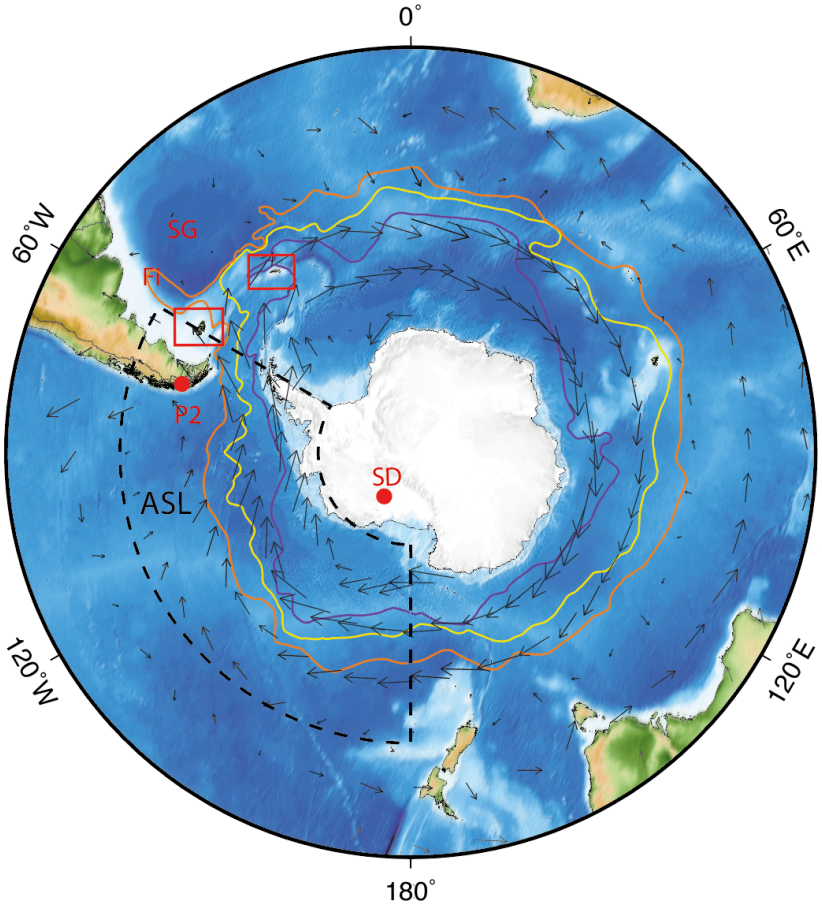

Figure 1. *Location of the Falkland Islands (FI), South Georgia [SG], Siple Dome [SD] and Palm2 [P2]. Dashed line denotes contemporary defined limits of the ASL domain (Fogt et al., 2012). Mean locations of the southern limb of the Antarctic Circumpolar Current (purple), the polar front (red) and the subantarctic front (green) are shown, following Orsi et al. (1995). The grey arrows denote the 925 hPa winds (vectors) trends since 1979 from ERA-Interim (Dee et al., 2011), depicting the location and increase in westerly winds over the satellite era. Map made using Generic Mapping Tools (GMT) (Wessel et al., 2013).*

3. The interpretation of the own data is very much restricted to the atmospheric part. Changes in ACC strength, Drake Passage through flow, and the surface current dynamics in the southwestern South Atlantic (Malvinas confluence dynamics e.g. Voigt et al. 2015) are important as well and not discussed.

We appreciate the reviewers concern. Our analysis demonstrates the dominant control on temperature and precipitation at Canopus Hill is via atmospheric processes. Spatial correlation maps suggest limited ocean influence on these climate variables on the Falkland Islands; something we have now stated explicitly. As part of this we have added a discussion of ocean currents, and have also added the mean locations of the southern limb of the Antarctic Circumpolar Current (purple), the polar front (red) and the subantarctic front (green), following Orsi et al. (1995), to Figure 1. We feel a figure showing this does not add to the narrative but if the editor would like us to include we are happy to do so.

4. Regarding the age model I have two comments/remarks. One is regarding the 137Cs record. It is mentioned in the text as age marker for the earlie sixties nuclear weapon testing fallout. Normally, the manuscript should contain the graphic display of the whole measured activity profile, just the mentioning in the text is not enough. Second, if fruits and leaves werde 14C dated (as indicated in the table), there is not much reason to exclude two dated at the base but include only the one date above (this could have been a outlier as well). Sedimentation rates would make sense with the two basal xsages as well. So I suggest to include them into the bayesian age modelling.

We thank the reviewer for their suggestions to improve the description of the age modelling. As commented in Hancock et al. (2011), the anthropogenic radionuclide, ^{137}Cs (with a half time of 30 years) is derived from atmospheric nuclear weapons testing and can provide an important "first appearance" horizon of known age (1954–1955) i.e. an independent marker horizon to assist with age model validation. Specifically, we analysed contiguous peat samples for the first presence of ^{137}CS and in the age model used the prior U(1952, 2011) to capture the possible range of calendar years (CE) for the onset of ^{137}Cs deposition in the sequence (Hancock et al 2011). We have however, included more detail on the measurement and application of ^{137}Cs for constructing our age model.

We agree that we should have explained in more details why the two basal ages were removed. The sedimentation rate is internally more consistent when excluding these two basal ages; without them the sedimentation rate from the entire metre of sediment above does not change significantly (with a sedimentation rate for 141.5-156 cm of 38 yrs/cm compared to an average of 27 yrs/cm for the preceding metre of sediment), whereas including them increases the sedimentation rate over this depth range abruptly to 11.6 yrs/cm. We suspect these basal ages may comprise some intruded younger root material; a scenario not unusual in relatively slowly accumulating sedimentary sequences e.g. Brock et al. (2011, *Quaternary Geochronology*). However, we have run the age model again to include these basal ages, and have added a column in Table 1 include the mean calibrated 2 sigma age range. The calibrated age ranges are almost identical for both age models until 142 cm, from where it diverges. Importantly, our conclusions based on the changes observed in the Canopus Hill Record at ~2.5 ka BP are not at all affected by the choice of age model. The modified Table 1 is pasted below:

Depth, cm	Wk lab number	Material	% Modern /^{14}C BP ± 1 σ	2σ cal. age range (years BP)	2σ cal. age range (years BP)	Mean cal. age (years BP)
				With 2 basal ages	Excluding 2 basal ages	
8-9	34598	Fruits and leaves	117.0±0.4%M	-4 to -43	-4 to -44	-21
9		^{137}Cs		-6 to -42	-6 to -42	-19
11-12	32994	Fruits and leaves	107.8±0.4%M	-2 to -14	-1 to -14	-8
18-19	37007	Fruits and leaves	107.3±0.3%M	0 to -13	26 to -15	-3
25-26	35146	Fruits and leaves	95±25	250 to -1	249 to -1	86
35-36	37008	Fruits and leaves	647±25	652 to 547	652 to 547	603
39-40	33445	Fruits and leaves	761±25	719 to 570	719-570	661
57-58	32996	Fruits and leaves	1818±25	1804 to 1595	1801 to 1597	1682
70-71	32350	Fruits and leaves	2235±25	2315 to 2102	2314 to 2104	2215
97-98	32997	Fruits and leaves	2749±25	2866 to 2755	2865 to 2755	2810
107-108	32998	Fruits and leaves	2914±26	3140 to 2877	3139 to 2878	2997
120-121	41767	Fruits and leaves	3238±20	3476 to 3361	3471 to 3362	3416
141-142	32351	Fruits and leaves	3955±32	4430 to 4184	4511 to 4236	4352
148-149	41768	Fruits and leaves	4390±20	4515 to 4300	5027 to 4845	4908
153.5-154.5	42144	Fruits and leaves	4039±21	4521 to 4421		
156.5-157.5	42145	Fruits and leaves	4075±22	4567 to 4429		

Table 1. *Radiocarbon and modelled calibrated age ranges for the Canopus Hill peat sequences using the P_sequence and Outlier analysis option in OxCal 4.2 (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013). The SHCal13 (Hogg et al., 2013) and Bomb04SH (Hua and Barbetti, 2004) calibration curves were used. Note: calibrated ages are relative to Before Present (BP) i.e. CE 1950.*

5. In the "contemporary climate" chapter the author use deseasonalised/detrended seasonal data? As a paleoclimatologist, I's difficult for me to understand this preprocessing step and perhaps some additional explanation could make things clearer here.

This is a fair point. Using deseasonalised and detrended data means that the correlations between two records are not based on them having similar seasonal differences, or similar trends, which would bias the correlation. We have included a more detailed explanation in the main manuscript to explain this. Thank you for the suggestion to make this clearer.

6. In the data comparison chapter the Siple Dome and PALM2 data are assumed to be consistent with the Falkland data. There are, however, rather large offsets in the timing of the proposed "regime shift". Majewski et al. e.g. suggest the Siple Dome ssNa+ shift to start aroud 1000-1500 years BP - that is more than 1000 years later that the quite abrupt shift described in the in the Canopus Hill record. There is also a 500 year offset to the carbonate accumulation record from the Chilean Fjords, which, by the way, is not an accumulation of carbonate in the surficial fjord waters, neither a carbonate preservation issue. If I understood these authors well, it represents marine carbonate production in the surficial fjord waters and its subsequent accumulation on the sea bed in response to salinity changes in the upper water column of the fjord. Of course all these records have theirs own stratigraphic issues, but one perhaps should discuss the potential meaning of these offsets more thoroughly.

We acknowledge are there are differences in the timing within the records that we compare. These may be an artefact of the uncertainties in the individual age models, or represent real dynamic changes operating on multi-decadal to centennial timescales. Importantly, we now make clear we are not specifically suggesting that there is a 'regime shift' that affects the entire region concurrently. Indeed, the Siple Dome ssNA+ record shows a more long-term trend to a deepening of the ASL that may suggest an early expression in this part of the Antarctic (as shown in Figure 4). Identifying a particularly time for a shift may be misleading, and we have removed any reference to a specific age.

In terms of the PALM2 record (and other records that we have since added from the Peruvian margin), there changes do appear to be more abrupt, and several centuries after the observed shift in the Canopus Hill record. We have included a significantly more detailed discussion on the timing of these changes. We have also reworded the description of the PALM2 record to be clearer, thank you.

7. The Late Holocene changes described in Lamy et al. address the latitudinal northward displacement of the westerly wind strength from its southern core (Early Holocene) towards its northern margin (Late Holocene). Conceptually, they suggest a weakening of the core westerlies in the Magellan Strait region, which is somehow in contradiction to what the authors assume in this manuscript.

In terms of comparisons to other reconstructions of westerly airflow, there is a substantial incongruity between different proxy records over the Holocene. It must also be pointed out that while the Lamy et al. reconstruction covers the full Holocene, the new extended record from Canopus Hill only covers the last 5000 years; thus comparisons between the early and late Holocene are not possible. The Lamy et al. (2010) paper does seem to indicate stronger westerly airflow from ~2 ka BP, which may have been influenced by the ASL, however, the last age control point for this record is the start of the inflection, which is dated to 2570 ^{14}C BP, calibrated to 2410 cal yr BP (note however that no uncertainty or calibrated age range is given, nor is there a reported uncertainty for the marine reservoir correction of 200 years). This indicates that the age uncertainties between the changes observed in the Canopus Hill record and the PALM2 record may possibly overlap.

8. Beside the millenial-scale trend there is much more centennial-scale fluctuation in the pollen/charcoal data from Falkland Island that unfortunately are not discussed.

While there is discussion in Turney et al. (2016) with regards to the centennial-scale variability identified in Canopus Hill, we agree that this should be briefly discussed. In addition, similar cyclical variations in West Antarctic Peninsula glacier discharge in Pike et al. (2013, *Nature Geoscience*) have also been reported; something not discussed in the previous draft of the manuscript but is now included.

Minor comments:
Line 30: please explain why ASL is of global significance.

A fair point, we did not explain this well. We have reworded the beginning of the abstract to introduce the ASL better.

Line 98: More precisely it is a vegetation record. "record of airflow" is for my feeling to imprecise here

We do understand the reviewers point here, however, we strongly believe it is more appropriate to call it a record of airflow. In particular, the *Nothofagus* and charcoal is emphatically not a record of vegetation change on the Falkland Islands (being wind-blown from South America), and it would be incorrect to discuss it in this way. It is true however that the local pollen does represent vegetation on the Falkland Islands. We will be more explicit about the interpretation of the proxies depending on whether they represent local or 'exotic' sources.

Line 133: If mentioned, please provide the exact information for the two periods

We are unsure what the reviewer means here, though we infer that it is the period defining the contemporary limits of the ASL and oceanic fronts. Assuming this is correct, we have added this information: The contemporary limits of the ASL (45-75°S, 180-60°W) are defined across the 1979–2001 average (Fogt et al., 2012), while the Orsi et al. (1995) oceanic front data is based on analyses of hydrographic station data available up to 1990 (see Table 1 of Orsi et al. 1995 for more details). We hope this satisfactory.

Line 125: "contiguously" should be "continuously"

In fact we do mean 'contiguously' here (differing from 'continuously' to mean having discrete boundaries between each sample, i.e. every cm).

Line 283-283: This cannot be, except the authors assume an full inversion of the westerly winds? Across the South Atlantic would mean easterly winds?

We think there may be some confusion here. From a climate/meteorological context, west to east airflow is described as 'westerly winds', i.e. from the west.

Line 291: "compliment" should be "complement"

We have changed this, thank you.

Anonymous Referee #2 Received and published: 26 September 2018

The authors present a new blanket peat record from Canopus Hill, Falkland Islands, to reconstruct changes in the in the Amundson Sea Low (ASL) and the Southern Annual Mode. The new record from Canopus Hill extend previously published results (Turney et al., 2016) to the mid-Holocene. The new record suggests a major shift of the ASL at around 2.5 kyr BP, as previously stated by Turney et al (2016). The main results presented in this study are therefore not really original and are therefore not a major advancement. The comparison of the Canopus Hill record with other records show some differences in the timing of this major change, which however are not really discussed in the manuscript. Overall, the manuscript require major revisions (see detailed comments below).

We thank the reviewer for their comments, which have helped clarify our manuscript. (Our responses in blue, reviewer comments in black). We suspect there may be some confusion regarding the Turney et al. (2016) paper, which presents a record only 2.5 kyr long, and therefore does not (and could not!) report a shift at 2.5 ka BP. We think this confusion may be a result of the sentence at line 125-127: "*Work at this site has previously recognised the input of exotic pollen and charcoal derived from South America (Turney et al., 2016a), with changes to westerly airflow over the past ~2.5 ka.*" We appreciate that this sentence is confusing, and we sincerely apologise for this oversight. The sentence was only intended to convey the fact that exotic pollen has been previously identified at this site over the length of the Turney et al. (2016) record, which had only been analysed back to 2.5 kyr ago. It is an unfortunate and confusing coincidence that the changes we see in this manuscript occur at the limit of the Turney et al. (2016) study. We have changed this sentence to ensure that it does not promote confusion to "*Work at this site has previously recognised the input of exotic pollen and charcoal derived from South America but was limited to the last 2.5 kyr (Turney et al., 2016a).*"

Importantly, in terms of the originality of the manuscript, the South Atlantic is traditionally interpreted in terms of westerly wind strength changes. Here we report the first Atlantic record that recognises changes in the Amundsen Sea Low through the mid to late Holocene. We have ensured this finding is highlighted more clearly. Viewing the CPD metrics, the discussion paper has been viewed more than 377 times, demonstrating the interest in this topic. Both reviews have made excellent suggestions to improve the clarity and we believe the manuscript has been significantly improved.

1) The current age model and its uncertainties are not very well presented and it remains unclear why two radiocarbon ages at the base of the sequence were omitted. These ages are clearly not in stratigraphic order and the authors should provide plausible explanations for this mismatch. The 2-sigma age range should be also given in table 1 to allow readers to evaluate the chronological age uncertainties.

We have added more detail on the construction of the age model, and included the 2-sigma age range. However, the only radiocarbon ages that are not in stratigraphic order are the two basal ages that were excluded, though we agree that we should have explained in more detail why the two basal ages were removed. The sedimentation rate is internally more consistent when excluding these two basal ages; without them the sedimentation rate from the entire metre of sediment above does not change significantly (with a sedimentation rate for 141.5-156 cm of 38 yrs/cm compared to an average of 27 yrs/cm for the preceding metre of sediment), whereas including them increases the sedimentation rate over this depth range abruptly to 11.6 yrs/cm. We suspect these basal ages may comprise some intruded younger root material; a scenario not unusual in relatively slowly accumulating sedimentary sequences e.g. Brock et al. (2011, *Quaternary Geochronology*). However, we have run the age model again to include these basal ages, and have added a column in Table 1 include the mean calibrated 2 sigma age range. The calibrated age ranges are almost identical for both age models until 142 cm, from where it diverges. Importantly, our conclusions based on the changes observed in the Canopus Hill Record at ~2.5 ka BP are not at all affected by the choice of age model. The modified Table 1 is pasted below:

Depth, cm	Wk lab number	Material	% Modern /^{14}C BP ± 1 σ	2σ cal. age range (years BP)	2σ cal. age range (years BP)	Mean cal. age (years BP)
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9		^{137}Cs		-6 to -42	-6 to -42	-19
11-12	32994	Fruits and leaves	107.8±0.4%M	-2 to -14	-1 to -14	-8
18-19	37007	Fruits and leaves	107.3±0.3%M	0 to -13	26 to -15	-3
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Table 1. *Radiocarbon and modelled calibrated age ranges for the Canopus Hill peat sequences using the P_sequence and Outlier analysis option in OxCal 4.2 (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013). The SHCal13 (Hogg et al., 2013) and Bomb04SH (Hua and Barbetti, 2004) calibration curves were used. Note: calibrated ages are relative to Before Present (BP) i.e. CE 1950.*

2) It I s not entirely clear how the SAL and the Southern Annual Mode (SAM) are dynamically linked! The authors should discuss this in greater detail in their manuscript.

We apologise that this was not clear in the manuscript. In fact the dynamical links between these two modes of variability are not well understood. While there have been suggested links between strong cyclone events in the Amundsen-Bellinghausen Sea region and the Southern Annular Mode e.g. Fogt et al. (2012), the main modulator is not clear. We have added some more information to the introduction about this, but also go into more detail in the discussion about the links between the SAM, ASL and ENSO (see response to comments 5 and 6).

3) Lines: 230-232: Explain the difference to previous publications (e.g., Turney et al., 2016a), in particular in the representation of Cyperaceae and the total accumulation of pollen centred at 2.5 ka BP. The core presented in Turney et al., 2016 was also collected from Canopus Hill.

We apologise that this was not clear in the manuscript. The data presented in Turney et al. (2016a) was indeed collected from the same site (Canopus Hill). However, this record was only 2.5 kyr long. We have removed the Turney et al. (2016) reference from line 230 as this does add confusion since the sentence does say through the mid- to late-Holocene, which the Turney et al. (2016) record does not infer.

4) Line 267-269: It would be interesting to see a detailed comparison between the charcoal records from Canopus Hill and Patagonia to support the statement that "The aeolian delivery of the charcoal to the Falkland Islands is supported by the close correspondence between the Canopus Hill and Lago Guanaco, Southwest Patagonia (Moreno et al., 2009) charcoal records". Such a comparison would strengthen the manuscript, and in particular the statement " Our results support the notion of pervasive westerly winds throughout the mid- to late-Holocene".

We apologise for the confusion. As intimated in the previous sentence, this observation was intended to convey that Lago Guanaco shows a consistent pattern of pervasive fire in the immediate area in Patagonia over the last 3000 years, with limited expression prior to this time. We have included the Moreno et al. charcoal record in Figure 4 to aid comparison. More importantly the presence of fire in the Patagonian landscape during the late Holocene provides a ready source of exotic material for aerial transport to the Falkland Islands as a result of westerly airflow. We have amended this sentence, and broadened the discussion of *Nothofagus*; the fact that *Nothofagus* is consistently represented throughout the Canopus Hill record indicates pervasive westerly winds throughout the mid to late-Holocene, but does not have sufficiently high concentrations to robustly assess changes.

5) The authors state that "These results compliment other studies from the broader South Atlantic region (Figure 4). " However, the change is ssNA in Simple Dome are rather smooth, especially when compared to the pollen record. This difference should be explained in more detail, e.g. are the Falkland Islands more sensitive to these changes than Simple Dome. A marked increase in ssNA at around 2.9 ka is hardly visible in the Simple Dome record and pre-dates the vegetation changes at 2.5 ka. What is the reason for the 400 year time lag. Adding the uncertainties of the age estimate of 2.5 kyr in the Canopus Hill record. Furthermore, the increase in the PALM2 record starts even later at around 2kyr BP. The authors should discuss the offsets more carefully and not simply state that a major change in the westerlies occurred at 2.5 kyr as this estimate is not supported by the current evidences. This discrepancy could be either related to dating uncertainties or may hold important information on the spatial-temporal impacts of the ASL/westerlies.

We acknowledge are there are differences in the timing within the records that we compare. These may be an artefact of the uncertainties in the individual age models, or represent real dynamic changes operating on multi-decadal to centennial timescales. Importantly, we now make clear we are not specifically suggesting that there is a 'regime shift' that affects the entire region concurrently. Indeed, the Siple Dome ssNA+ record shows a more long-term trend to a deepening of the ASL that may suggest an early expression in this part of the Antarctic (as shown in Figure 4). Identifying a particular time for a shift may be misleading, and we have removed any reference to a specific age. The uncertainties of the age estimates for the Canopus Hill record are already plotted in Figure 4, and show that there are relatively large uncertainties of between 100 and 300 years (though the calibrated 2-sigma age range is now clearer to see in Table 1).

However, there does seem to be some confusion regarding the changes at ~2.5 ka BP. We do not state that there is a change in westerlies at 2.5 ka BP, but rather that the changes in vegetation and westerly airflow at Canopus Hill are consistent with the deepening of the ASL. As suggested in point 2, we have added more detail on the dynamical link between the westerlies and the ASL, which provides more context to the discussion. In terms of comparisons to reconstructions of westerly airflow in published literature, there is a substantial incongruity between different proxy records over the Holocene. The Lamy et al. (2010) paper does seem to indicate stronger westerly airflow from ~2 ka BP, which may have been influenced by the ASL, however, the last age control point for this record is the start of the inflection, which is dated to 2570 ^{14}C BP, calibrated to 2410 cal yr BP (note however that no uncertainty or calibrated age range is given, nor is there a reported uncertainty for the marine reservoir correction of 200 years). This indicates that the age uncertainties between the changes observed in the Canopus Hill record and the PALM2 record may possibly overlap. We will include a significantly more detailed discussion on the timing of these changes.

Interestingly, the $\delta^{18}O_{diatom}$ record from Site 1099 in the Palmer Deep representing multi-centennial fluctuations in glacial discharge presented by Pike et al. (2013, *Nature Geoscience*), also shows an underlying decrease towards lower values, "particularly from ~2.5 kyr". Specifically, this increased glacial ice discharge is thought to have been driven by atmospheric warming (as a result of peak local summer insolation; now added to Figure 4), in addition to the maximum Holocene ENSO frequency from circa 2.2 kyr (suggested by Makou et al. (2010, Geology), likely representing increased La Niña intensity (Site 1228 Peru Margin core displays an increase in La Nina events, now plotted in Figure 4). We have added these important details to the discussion.

6) I would also suggest to include ENSO reconstructions (e.g., Moy et al., 2002 or Carre et al., 2014) in a separate figure

This is an excellent idea to include an ENSO reconstruction, although we think it is best to add to Figure 4 to enable better comparisons. Unfortunately, since this paper was submitted, the record of Moy et al. 2002 has been questioned as an El Nino record (Schneider, T., Hampel, H., Mosquera, P. V., Tylmann, W. and Grosjean, M.: Paleo-ENSO revisited: Ecuadorian Lake Pallcacocha does not reveal a conclusive El Niño signal, Glob. Planet. Change, 168(June), 54–66, doi:10.1016/j.gloplacha.2018.06.004, 2018.). This study states that ENSO may not be the major driver of precipitation at Lake Pallcacocha, and therefore may not be appropriate to cite in an ENSO context. While Carre et al. (2014) establish that modern ENSO conditions were established between 3 and 4.5 ka BP, this is based on discontinuous records; the record published by Makou et al. (2010 *Geology*) appears to present a more continuous record of ENSO over the time period of interest for this study, and we have included this record in Figure 4. We also significantly broaden our discussion of the potential influence of ENSO on the ASL: The El Nino Southern Oscillation circulation pattern is teleconnected to Southern Ocean and Antarctic climate, in particular the Amundsen Sea low-pressure region, via movements of the South Pacific Convergence Zone (Russel and McGregor et al. 2010, Climatic Change). Specifically, La Niña events are accompanied by a northerly shift in the South Pacific Convergence Zone and the production of cyclones in the region of the Amundsen Sea low. This then produces a warm, northerly airflow over Patagonia, the Western Antarctic Peninsula and the Falkland Islands. In addition, Fogt et al. (2011) found that when a La Niña event occurs with the positive phase of the SAM, ASL exhibits deeper pressure anomalies, suggesting that the SAM and the ASL may indeed modulate one another. Please see revised Figure 4 below:

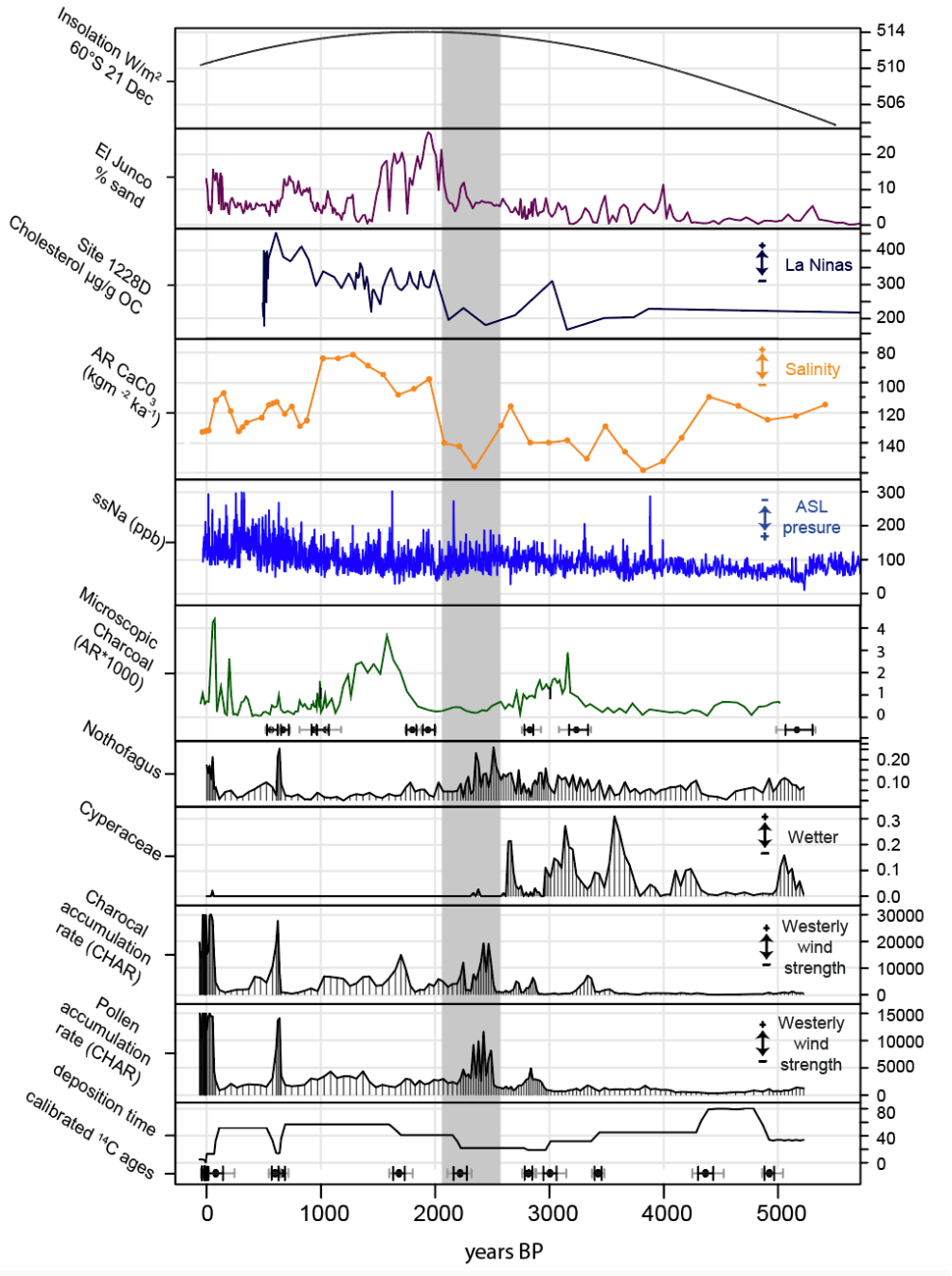

Figure 4: *Key data from the Canopus Hill sequence (Falkland Islands) and other South Atlantic records. From bottom to top: deposition time, total pollen accumulation rate (PAR), total charcoal accumulation rate (CHAR), Cyperaceae and Nothofagus re-expressed as accumulation rates, microscopic charcoal from Lago Guanaco (Moreno et al. 2009), $ssNa^{+}$ from Siple Dome (Mayewski et al., 2013), salinity anomalies from PALM2 (Lamy et al., 2010), cholestrol abundance, ODP Site 1228, Peru margin (Makou et al. 2010), percentage of sand, El Junco Crater Lake, Galápogos (Convey et al. 2010) and summer (21 Dec) insolation (W/m^2) at 60°S (Laskar et al. 2004). Calibrated radiocarbon ages and 1σ (black) and 2σ (grey) age ranges for Canopus Hill and Lago Guanaco are plotted at the base of the respective panel. Note that PAR and CHAR have both been capped at the modern end due to high accumulation rate. The grey boxed area marks the transition period during which the ASL strengthened over the South Atlantic.*