

Northward shift of the southern westerlies during the Antarctic Cold Reversal

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Highlights:

We present empirical palaeoclimate data that demonstrate a northward shift of the southern westerly wind during the Antarctic Cold Reversal (ACR) that drove antiphase west-east environmental responses across the island of Tasmania.

Stronger westerly wind flow over Tasmania during the ACR drove wetter conditions on the western (windward) slopes of the Tasmanian mountains that dampened regional fire activity and drove regional vegetation change toward more cold tolerant plant communities.

Stronger westerly wind flow over Tasmania during the ACR drove increased evaporation on the eastern (leeward) side of the Tasmanian mountains.

Our results support that millennial scale climate variability involves global reorganisation of ocean and atmospheric circulation and heat transport.

Graphical Abstract

Graphical Abstract for Northward shift of the southern westerlies during the Antarctic Cold Reversal

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Figure. S6.

Schematic illustrating (a) the approximate latitudinal positions of major components of Southern Hemisphere atmospheric system prenorthward shift of the ITCZ, and (b) atmospheric processes involved in the northward shift of the ITCZ and southern westerlies (SWW). Schematic shows a northward intensification of the Southern Hemisphere winter Hadley circulation, which delivers increased heat and eddy-momentum flux into the Southern Hemisphere subtropics. The increased momentum flux strengthens the subtropical jet and pulls the eddy driven polar jet (of which the surface expression is the southern westerlies) northward.

1 Article Type: Short Communication

2 Northward shift of the southern westerlies during the Antarctic Cold Reversal

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- 21 Abstract: Inter-hemispheric asynchrony of climate change through the last deglaciation has been
- 22 theoretically linked to latitudinal shifts in the southern westerlies via their influence over CO₂ out-

gassing from the Southern Ocean. Proxy-based reconstructions disagree on the behaviour of the westerlies through this interval. The last deglaciation was interrupted in the Southern Hemisphere by the Antarctic Cold Reversal (ACR; 14.7 to 13.0 ka BP (thousand years Before Present)), a millennialscale cooling event that coincided with the Bølling–Allerød warm phase in the North Atlantic (BA; 14.7 to 12.7 ka BP). We present terrestrial proxy palaeoclimate data that demonstrate a migration of the westerlies during the last deglaciation. We support the hypothesis that wind-driven out-gassing of old CO₂ from the Southern Ocean drove the deglacial rise in atmospheric CO₂.

32 1.0 Introduction

33 The southern westerlies are part of a zonally-symmetric system that dominates the climate of the mid-34 to high-latitudes of the Southern Hemisphere (Garreaud, 2007). Changes in the strength and 35 latitudinal position of the southern westerlies are believed to modulate global atmospheric CO_2 36 concentration via changes in wind stress over the Southern Ocean. Wind stress influences the 37 upwelling of CO₂ saturated deep waters and the capacity of the surface ocean to absorb, or release, CO₂ (Siani et al., 2013). In the ocean, the latitudinal position of the southern westerlies is linked to the 38 39 position of the Subpolar Oceanic Front and the Antarctic Circumpolar Current (Toggweiler et al., 2006), 40 while on land changes in the southern westerlies govern mid- to high-latitude terrestrial climate, 41 principally hydroclimate (Garreaud, 2007), which has a profound influence over a range of terrestrial 42 processes (Fletcher and Moreno, 2012; Mariani and Fletcher, 2017). Parallel latitudinal shifts of the 43 southern westerlies and Intertropical Convergence Zone (ITCZ) have also been proposed for the last 44 deglaciation as part of the atmospheric response to changes in ocean heat transport by the Atlantic 45 Meridional Overturning Circulation (AMOC) (Buizert et al., 2018; Denton et al., 2010; Markle et al., 46 2017; Pedro et al., 2016; Sigman et al., 2020). However, while paleoclimate proxy data confirm a 47 cooling in the mid- to high latitudes of the Southern Hemisphere (poleward of ca. 40°S) during the 48 ACR, the available data provide no clear constraint on the latitudinal behaviour of the southern 49 westerlies through this interval.

We reconstruct westerly wind behaviour in the mid-latitudes of the Australian sector of the Southern Hemisphere from multiproxy data from six radiocarbon-dated lake sediment sequences from Tasmania (40-44°S; Figure 1a). Tasmania is uniquely situated to investigate the behaviour of the southern westerlies during the ACR due to its location at the northern margins of the westerly wind belt and an exceptionally strong correlation between southern westerly wind speed and its rainfall anomalies (Figure 1b) (Gillett et al., 2006). This means that rainfall proxies can be applied to reconstruct past changes in wind regimes. Tasmania's mountainous west coast and contrasting 57 lowland east coast create an orographic effect that splits the island into clear zones of positive 58 (western sites) and negative (eastern sites) correlation between southern westerly wind speed and 59 rainfall (Figure 1b). This allows us to target sites where there is an unambiguous southern westerly 60 influence over rainfall.

61 We compile new lake sediment rainfall proxies including charcoal, pollen and geochemistry from six 62 lakes located in zones of both significant positive and significant negative correlation between 63 southern westerly wind speed and rainfall (Figure 1b). While the charcoal proxy is influenced by 64 human-caused fire ignitions (Bowman and Brown, 1986), the occurrence and spread of fires is 65 moisture-limited in the high-rainfall west of Tasmania (McWethy et al., 2013; Styger and Kirkpatrick, 66 2015). Sedimentary charcoal analyses have previously revealed a coherence between changes in 67 regional charcoal (biomass burning) and changes in moisture delivery by the southern westerlies 68 through the Holocene: increased southern westerly flow over Tasmania results in reduced 69 sedimentary charcoal content (and vice-versa), reflecting the primacy of southern westerly-derived 70 orographic rainfall over regional fire regimes (Mariani and Fletcher, 2017; Mariani and Fletcher, 2016).

71

72 2.0 Material and methods

73 2.1 Construction of age models

¹⁴C analysis using accelerator mass spectrometry (AMS) was used to date each sediment record utilised in this analysis. Results for each sample submitted for analysis, along with their calibrated age ranges, are provided in Table 1. All radiocarbon ages were calibrated using SHCal20 (Hogg et al., 2020) and age-depth models for each core (Figure 3) were constructed using the *rbacon* v2.3.9.1 (Blaauw and Christen, 2011) package in R. Modelling was restricted to ~9 to 18 ka. Modelled age outputs were then used to compare regional proxy data records.

80 2.2 Palaeofire compilation

81 Palaeofire analysis was carried out using the paleofire package in R (Blarquez et al., 2014) and follows 82 the methodology outlined in Mariani & Fletcher (2016). Three charcoal records from the precipitation-83 dominant western Tasmania were considered for this analysis (Lake Selina, Basin Lake and Lake Vera). 84 Firstly, a transformation of the data was performed using the function pfTransform with MinMax, Box-85 Cox and Z-score methods. Transformation and standardization of different charcoal records is a highly 86 recommended step in generating a synthesis (Blarquez et al., 2014). Here, we used the methodology 87 proposed by Power et al. (2008) and involved a three-step data transformation including a min-max 88 data-rescaling, variance homogenization using Box-Cox data transformation (Box and Cox, 1964), and 89 final rescaling to Z-scores. The palaeofire composite was calculated using the function pfCompositeLF, 90 consisting in a modified version of existing methods (Daniau et al., 2012; Marlon et al., 2008), involving 91 a two-stage smoothing method (including LOWESS; Cleveland, 1979) of the selected bins interval. In 92 this case, 100 years-bins were used, since it represents the best achievable resolution in order to 93 include the majority of charcoal records for the entire reconstruction period. Confidence intervals were obtained using the function circboot with 1000 repetitions, which applies a "moving" or 94 95 "circular" block bootstrap method (Kunsch, 1989) to test significance of changes in stationary time 96 series.

97 2.3 Geochemical proxy analysis

98 Micro-X-Ray fluorescence spectrometry (µXRF) elemental profiles were obtained for three western 99 Tasmanian records (Lake Tiberias, Lake Selina and Hazards Lagoon from the Australian Nuclear Science 100 and Technology Organisation (ANSTO)). Cores were scanned at 0.5 mm resolution using Cox Analytical 101 Systems ITRAX µXRF core scanner with a Mo tube (55mA current; 20s count time; 30kV voltage). Raw 102 data were normalised to kpcs (Croudace and Rothwell, 2015). Ca/Ti ratios for each record were 103 extracted from the full dataset as a proxy for relative evaporation levels across western Tasmania 104 (Croudace and Rothwell, 2015). 105 The geochemistry of lake sediments is also influenced by changes to in-lake processes such as 106 evaporative conditions and lake levels. The deposition of evaporative carbonate minerals into lake 107 sediments is influenced by authigenic (within-lake) and allogenic (external catchment) processes, 108 making it necessary to isolate the signal of authigenic deposition in order to infer changes to in-lake 109 conditions (Cohen, 2003). For example, by normalising µXRF carbonate proxy elements (calcium and 110 strontium) against stable detrital elements in the record, it is possible to isolate the authigenic carbonate signal (Croudace & Rothwell, 2015). This method has been widely used in paleolimnology, 111 112 including in western Tasmania (Fletcher et al., 2014), and forms the basis for interpretations of in-lake 113 conditions at Lake Rolleston. Precipitation of evaporative carbonate minerals in fresh-water lakes 114 varies with changes to evaporative conditions and lake levels (Cohen, 2003; Haberzettl et al., 2007; 115 Kelts and Hsü, 1978). The type of evaporative minerals that are precipitated in the water column are 116 dependent on initial water chemistry, which is related to the underlying catchment geology (Eugster 117 and Hardie, 1978).

118 2.4 Palynology

Pollen samples were prepared and analysed for the four western Tasmanian sites (Basin Lake, Lake 119 Vera, Paddy's Lake and Lake Selina) according to standard protocols (Faegri and Iversen, 1989). 120 121 Percentages of Phyllocladus aspleniifolius and Poaceae taxa were isolated from the full pollen 122 datasets, focusing on the last 18 kyrs. Raw percentage data for these taxa were calculated from the 123 terrestrial pollen sum and are presented in Figures S4 (P. aspleniifolius) and S5 (Poaceae). Data from 124 all six sites were then collated into one time series to construct a regional time-series for each taxon. 125 Prior to collation, data were standardised (transformed into z-scores) to account for differences in the 126 mean abundances of the original datasets.

127

128 3.0 Results

129 All graphed results are in the Supplementary Information (Figs. S1-5) and this section only briefly 130 describes the results here. All selected cores span the ACR interval with sufficient dating to resolve 131 environmental changes through this interval (Figure S1). Synthesis of the charcoal records from the western Tasmanian sites (n=4) demonstrates a sharp increase in CHAR across the west commencing 132 133 at ca. 17.8 ka BP and continuing until ca. 15 ka BP, before declining between ca. 13.5 ka BP. CHAR 134 values rise again toward peak regional values at ca. 12.2 ka BP and decline thereafter (Figs 2, S3). Calculation of the Ca/Ti ratio for the evaporation-dominant sites in eastern Tasmania show a discrete 135 136 peak in overall values during the ACR interval (ca. 14.7 to 13.0 ka BP) indicating a peak in calcite 137 precipitation under evaporative conditions during this interval (Figure 2). The synthesised pollen 138 records from the precipitation-dominant western Tasmanian sites show increased values in the 139 hygrophilous conifer P. aspleniifolius between ca. 16-12 ka BP, with a discrete dip centred on the ACR 140 interval (Figure S4). High Poaceae values, associated with cool temperatures in western Tasmania 141 (Fletcher and Thomas, 2007), occur discretely during the ACR interval, embedded in a long-term 142 decrease commencing at ca. 18 ka BP (Figure S5).

143

144 4.0 Discussion

Charcoal influx to the western Tasmanian lakes decreases during the ACR (Figs. 2d, S2-3), consistent 145 146 with enhanced westerly winds and rainfall, reducing biomass burning. This change is synchronous with 147 a marked increase in carbonate precipitation and subsequent deposition (sedimentary Ca/Ti ratio) 148 (Kylander et al., 2011) at two sites in eastern Tasmania (Figs. 2a,b) and a concomitant decrease in 149 carbonate deposition in the west (Figure 2c). Carbonate precipitation occurs under increased 150 evaporative conditions in freshwater lakes (Kelts and Hsü, 1978) and the east-west anti-phasing of 151 carbonate deposition displayed in our data during the ACR mirrors the modern rainfall-southern westerly relationship (Figure 1), suggesting an increase in wind speed over Tasmania at this time. The 152 153 increasing sedimentary charcoal in the west of Tasmania immediately prior to (ca. 17-15 ka BP) and

154 following (>13 ka BP) the ACR (Figure 2d) is consistent with a drier climate under a weaker southern 155 westerly flow. These trends in proxy-inferred hydroclimate across Tasmania indicate either a 156 strengthening of the westerly flow at their northern edge or a northward displacement of the westerlies during the ACR. The modern zone of maximum westerly winds speed lies between 50-60°S 157 158 (Garreaud et al., 2009). A reduction in westerly wind-driven upwelling at marine core site TN057-13PC 159 (located at 53.2°S, 5.1°E; Figure1a) on the southern edge of the southern westerlies during the ACR 160 (Anderson et al., 2009) (Figure 3g) is synchronous with our inference of an increase in westerly flow 161 at their northern edge in Tasmania (see Supplementary Information Table S1). This synchronicity of 162 the ACR signal across the Southern Hemisphere suggests that a northward shift in the Australian sector 163 is more likely than a stationary strengthening.

164

165 Our composite pollen data (see Figs. S4-5) from across western Tasmania indicate a regional expansion 166 of Poaceae pollen (indicative of grassland; Figure 2f) during the ACR at the expense of Phyllocladus 167 aspleniifolius (Figure 2e), a lowland temperate rainforest tree. Forests replaced grasslands during the 168 last deglaciation in Tasmania in response to increasing temperature (Colhoun, 2000; Fletcher and Thomas, 2010), and our pollen data reflect a short-lived reversal of this trend in response to a 169 170 temperature decrease during the ACR. Cooling over Tasmania is supported by proxy and model-based 171 reconstructions of the ACR across the mid- to high-latitudes of the Southern Hemisphere (Koffman et 172 al., 2017; Pedro et al., 2016; Putnam et al., 2010; Vandergoes et al., 2008). Collectively, our data 173 indicate reduced temperature and increased southern westerly flow over Tasmania during the ACR 174 that resulted in a cool and wet climate on the mountainous west coast sites, and a cool and dry climate 175 on the lowland east coast sites.

176

We observe a synchronous and in-phase relationship between southern westerly changes over
Tasmania and changes in the strength of the Leeuwin Current (De Deckker et al., 2012) (inferred from

179 core MD03-2611 in the Great Australian Bight; Figure1a), a surface ocean current that delivers warm 180 tropical water from the Indo-Pacific Warm Pool to southern Australia (carrying tropical foraminifera 181 such as Globigerinoides ruber) (Figure 3d) (Weaver and Middleton, 1989). The Leeuwin current is strongest in the Austral winter, when the northerly displaced southern westerlies accelerate the 182 183 current along Australia's southern coast (Cirano and Middleton, 2004). We suggest the increased 184 proportion of tropical foraminifera observed in MD03-2611 during the ACR can be explained by a 185 northward-shifted southern westerly wind flow over the Australian sector. This shift would strengthen 186 the Leeuwin Current along the south coast of Australia, in a similar way as seasonal migrations of the 187 southern westerlies do today (Figure 3d).

188

Northward migration of the southern westerlies during the ACR is consistent, from an atmospheric 189 190 dynamics perspective, with the documented northward shift of the ITCZ over northern Australia 191 (Ayliffe et al., 2013; Ceppi et al., 2013; Denniston et al., 2013). The tendency for the ITCZ and southern 192 westerlies to shift in the same direction is explained in detail elsewhere (Ceppi et al., 2013; Lee et al., 193 2011) and is documented by empirical data in the Australian sector during the Holocene (Mariani et al., 2018). In brief, a northward shift of the ITCZ is associated with strengthening of the Southern 194 195 Hemisphere Hadley circulation delivering increased heat and eddy-momentum flux into the Southern 196 Hemisphere subtropics. The increased momentum flux strengthens the subtropical jet and pulls the 197 eddy driven jet (of which the surface expression is the southern westerlies) northward (Ayliffe et al., 198 2013; Denniston et al., 2013; Ceppi et al., 2013; Chiang et al., 2014) (Figure 6).

199

200 Importantly, our interpretation reconciles southern westerly proxy data spanning the ACR in the 201 Australian region (De Deckker et al., 2012) with southern westerly behaviour elsewhere in the 202 Southern Hemisphere. Rainforest declines in northeastern Brazil and the expansion of Magellanic 203 moorland in western Patagonia indicate a northward shift in both the ITCZ and southern westerlies between 15-13 ka BP (Montade et al., 2015). Recent Antarctic ice core based evidence show zonal
shifts in moisture sources that similarly indicate northward movement of the westerlies during the
ACR as well as earlier abrupt glacial climate changes (Buizert et al., 2018; Markle et al., 2017).

207 Our results provide further empirical evidence for the dynamics-based view that millennial scale 208 climate variability involves major global reorganisation of ocean and atmospheric circulation and heat 209 transport (Buizert et al., 2018; Markle et al., 2017; Pedro et al., 2016). The much-cited thermal ocean 210 seesaw mechanism (Stocker and Johnson, 2003) is only one component of this larger coupled ocean-211 atmosphere reorganisation. Enhanced northward ocean heat transport is the primary energy source 212 sustaining the Northern Hemisphere warming of the Bølling-Allerød and the South Atlantic and Southern Ocean cooling of the ACR (Pedro et al., 2018). The northern warming is abrupt (decadal 213 214 scale) because it is associated with breakdown of stratification, release of accumulated sub-surface 215 heat and rapid sea ice retreat in the North Atlantic and Nordic seas (Dokken et al., 2016; Sadatzki et 216 al., 2018, Capron et al., 2021). The large-scale atmospheric counterpart to these changes stems from 217 the effective northward shift of the thermal equator, which sets the position of the Hadley circulation 218 and ITCZ. In shifting north, the cross equatorial Hadley cell gathers more energy from the warmer 219 (northern) hemisphere for redistribution to the cooler (southern) hemisphere (Hartman et al., 2016), 220 i.e. the dynamic atmospheric response acts to reduce the thermal imbalance between the 221 hemispheres (see e.g. Fig 4 of Pedro et al. 2018). As detailed by Ceppi et al., (2013), and noted earlier, 222 the northward shift of the westerlies occurs because a stronger cross-equatorial Hadley circulation 223 also fluxes more momentum into the southern hemisphere subtropics, causing northward 224 intensification of the eddy-driven jet and its surface expression in the southern westerlies.

An alternative hypothesis to the above 'extended thermal seesaw' was recently proposed by Denton et al, (2021). In their 'Zealandia Switch', orbitally-forced changes in southern hemisphere insolation drive millennial-scale variability in the position of the southern westerlies. When combined with the physical constraints of the Australian/Zealandia bathymetric footprint, these wind changes are 229 proposed to affect the global heat budget through the regulation of heat transport from the Tropical 230 Pacific into the northern and southern hemisphere. We cannot exclude that this mechanism 231 contributes to SH cooling during the ACR. However, the extended thermal seesaw framework has the 232 advantages of satisfying the north-south timing, amplitude and spatial pattern of observed for 233 millennial scale climate variations in multiple data compilations and data-model comparisons [e.g. 234 Menviel et al., 2011; Pedro et al., 2016; Buizert et al., 2018, Corrick et al., 2020; Anderson et al., 2021, 235 Capron et al., 2021]. Whether the 'Zealandia Switch' hypothesis satisfies such tests remains to be 236 elucidated.

237 The northward shift of the southern westerlies during the ACR is synchronous with a reduction in 238 Southern Ocean upwelling inferred from opal burial rates at TN057-13-4PC situated at 53°S, 5°E and 239 with a CO₂ plateau in Antarctic ice cores (Figure 3i). Similarly, our evidence for southward shifted 240 westerlies during the periods of deglacial warming that bracket the ACR aligns with increases in 241 inferred Southern Ocean upwelling and intervals of CO₂ rise (Figure 3g,h). These results are consistent 242 with the hypothesis that the position of the southern westerlies contributed to the observed deglacial 243 CO_2 trends (Anderson et al., 2009; Toggweiler et al., 2006, Rae et al., 2018, Allen et al., 2019): i.e. 244 enhanced Southern Ocean upwelling contributing to CO₂ outgassing when the winds were shifted 245 southward toward Drake Passage and reduced outgassing when the winds shifted back northward, 246 intensifying over Tasmania, during the ACR.

247

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Figure 1 (a) A map of zonal (southern westerly) wind speed showing the location of proxy sites
mentioned in the text and (b) a correlation map of southern westerly wind speed and rainfall in
Tasmania with sites analysed in this study: LV – Lake Vera; BL – Basin Lake; LS – Lake Selina; PL –
Paddy's Lake; LT – Lake Tiberias and HL – Hazards Lagoon.

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Figure 2 Proxy data spanning the period between 18-11 ka BP showing (a) Lake Tiberias and (b) Hazards Lagoon and (c) Lake Selina Ca/Ti ratio, indicating changes in evaporite deposition. Black curves indicate the weighted average (5-year window) for (a), (b) and weighted average (43-year window) for (c); (d) western Tasmania charcoal influx composite (n=3) showing upper and lower confidence intervals (dashed grey lines) indicating moisture-driven changes in fire activity; (e)

426 composite pollen (n=6) of the hygrophilous rainforest tree *Phyllocladus aspleniifolius*; and (f) 427 composite Poaceae pollen curve (n=6) indicating changes in the grassland component of western 428 Tasmanian pollen records. Black curves for both (e) and (f) indicate the weighted average (7-year 429 window). Chronologies and associated uncertainties for all records used to create composite curves 430 are presented in Supplementary Table 1 and Supplementary Figure 3.



433 Figure 3 Global proxy data spanning the period between 18-11 ka showing (a) Proxy NGRIP surfaceair temperature (¹⁵N and diffusion-based reconstruction) (Buizert et al., 2018); (b) Proxy AMOC 434 strength (²³¹Pa/²³⁰Th) from the Bermuda Rise (McManus et al., 2004); (c) Normalized index 435 436 summarizing common latitudinal shifts of both the ITCZ and the southern westerlies (Montade et 437 al., 2015); (d) Globigerinoides ruber % from ocean core MD03-2611 at 37°S (De Deckker et al., 2012) 438 a tropical foraminifera indicating changes in the strength of the Leeuwin Current; (e) Lake Tiberias Ca/Ti ratio showing changes in evaporation (this study); (f) western Tasmania charcoal influx 439 440 composite (n=3) indicating moisture-driven changes in fire activity (this study); (g) radiocarbon surface reservoir age determined off the coast of Chile at 46°S (Siani et al., 2013) showing changes 441 in wind-driven upwelling (De Deckker et al., 2012); (h) Southern Ocean Opal flux, a proxy for 442 443 upwelling south of the Antarctic polar front from core TN057-13-4PC at 53°S showing changes in 444 wind-driven upwelling (Anderson et al., 2009); and West Antarctic Ice Sheet Divide ice core (WDC) 445 (i) CO₂ and (j) δ^{18} O (Buizert et al., 2018).

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- 464 **Data and materials availability:**
- 465 All data will be made available upon request
- 466
- 467







Declaration of interests

 \boxtimes The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Conceptualization: MSF Methodology: MSF, MM, JAA, KB, PSG, HH Investigation: MSF, MM, JAA, KB Visualization: MSF, MM, KB, TH Funding acquisition: MSF, ALP

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