Supplementary material to accompany the manuscript entitled:

Hydrographic shifts south of Australia over the last deglaciation and possible interhemispheric linkages

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Previous work in the region of interest

Gingele et al. (2004) and Gingele and De Deckker (2005) made the first attempt at describing two deep-sea cores (MD03-2607 and 2611 that are separated by some 600 km) obtained by the RV *Marion Dufresne* in 2003 during the AUSCAN campaign (Hill and De Deckker, 2003). These preliminary studies identified the nature and extent in time of the cores, based on broad sampling for oxygen isotopes, and a few radiocarbon dates presented in the second paper. These studies were the basis for further and more extensive studies using a multitude of proxies that followed on over the next one and a half decades. Calvo et al. (2007) produced a sea-surface temperature record (based on alkenometry) spanning the last 30 ka from core 2611. This record also identified SST progressively dropped by 2°C from 6.5 ka until 600 years ago, also seen west of New Zealand (Barrows et al., 2007). In addition, these authors clearly identified the presence of the Antarctic Cold Reversal in core 2611. Schmidt et al. (2010) studied many of the (short) multicores taken during the AUSCAN cruise and produced a sound chronology and sedimentation rates based on ^{210}Pb accumulation rates and therefore confirmed the suitability of one of the multicores for covering the missed interval in the two long cores mentioned above. The same year, Gingele et al. (2007) examined in detail the last 17 ka record of core 2611 using a varieties of proxies (clay mineralogy, trace and rare-earth elements, as well as Sr and Nd isotopes) and showed several key features: (1) that the period of SST drop identified by Calvo et al. (2007) for the latter part of the Holocene coincided with an increase of aeolian activity on the Australian mainland; and (2) that two important phases of fluvial activity generated in the

Murray Darling Basin [core 2611 is in fact located opposite the mouth of the River Murray] during the 13.5 to 11.5 ka and 9.5-7.5 ka periods represented significant hydrological shifts in this large basin. Three additional papers of relevance to the study here were published on core 2611 and these are: (1) by Moros et al. (2009) which examined in detail the Holocene climatic evolution based on a variety of proxies, including detailed analysis of planktonic foraminiferal assemblages; (2) by De Deckker et al.(2012) which followed by the examination of the same core spanning the period from 30 to 10 ka BP that provided good evidence of the bi-polar seesaw, with warm water reaching the core site originating from the tropics via the Leeuwin Current coinciding with cold "Heinrich Stadials" (=HS) in the northern hemisphere; (3) by Perner et al. (2018) which looked in great detail the last 8 ka of the marine record offshore Kangaroo Island and provided valuable information on the start of ENSO, thus identifying obvious teleconnections in this region of the globe.

An earlier study by Ikehara et al. (1997) that also examined $U^{K'}_{37}$ -reconstructed SST from a core south of Tasmania and located further south (48° 08'S) than core RS147-GC07 studied by Sikes et al. (2009; 45°09'S), determined a drop of 4.4°C at the LGM compared to the Holocene (sic) but the data are of very low resolution and no precise dates were given. We note that for the interval of 30 ka to ~17 ka in their core, Ikehara et al. (1997) only analysed 8 levels. Once again, this is insufficient for comparison with our data. Overall, Sikes et al. (2009) studied three cores located in a NS transect South of Tasmania and their findings are of interest here, but unfortunately too few samples were taken from those cores.. Nevertheless, Sikes et al. (2009) indicated that the STF was pinned to the southern tip of Tasmania during the last glacial (sic) but, unfortunately, no definite age was in fact provided. These authors also stated that the warming of the Southern Ocean South of the Tasmania commenced at 21 ka. Examination of the original data identifies that only one sample with a $U^{K'}_{37}$ -reconstructed SST of 14.1°C was obtained for dated horizon 21.18 ka and the previous (older one) was dated at 29.72 ka with a

SST of 17.4°C, whereas at 20.08 ka, the reconstructed SST was 13.8°C. Those data are insufficient to make such a claim and will not be discussed any further.

Calvo et al. (2004)'s and Pelejero et al. (2006)'s studies of the short core Fr1/94-GC3 located on the East Tasman Plateau cannot be compared with cores 2611 and GC15 because too few samples (8) were used for determining SST by alkenometry for the time interval of interest here. Equally, De Deckker et al. (2019) who also examined the same core (Fr1/94-GC3 analysed by the 2 previous authors), using many proxies, including three different ones to reconstruct SSTs (one being Calvo et al. (2004)'s method), once again used too few samples for their palaeoenvironmental reconstructions, and therefore are not discussed any further here. Finally, the study by Nürnberg and Groeneveld (2006) of ODP core 1172A, for a core adjacent to site Fr1/94-GC3 on the East Tasman Plateau, which included SST reconstructions based on the Mg/Ca of foraminifers, only analysed too few samples for the interval of interest here.

Previous work done on the two cores

Several investigations have already been done on the two cores, but none at high resolution in comparison with the present study. The Holocene sequence of core MD03-2611 was first studied by Moros et al. (2009), followed by De Deckker et al. (2012) who discussed the link of its glacial record with general circulation in the SH. After that, Perner et al. (2018) concentrated on the last 8 ka of the core so as to determine the onset of ENSO in the Australian region by also examining possible teleconnections across the Pacific Ocean, and finally De Deckker et al. (2020) concentrated on the entire record of the core spanning the last 94 ka and compared this record against proxies of environmental changes inland Australia. In this paper, these authors produced maps showing changes both at sea and on land, spanning the 34 to 14 ka BP period on 2 ka time slices. Never in these papers were the record of the last deglaciation examined at high resolution.

Concerning the other core SS02-GC15, Perner et al. (2018) examined the last mid to late Holocene record for comparison with the first core. De Deckker et al. (2020) studied the entire core record which spans the last 25 ka, with the same low resolution approach taken for core MD03-2611 for supplying additional information to be placed on the 2 ka maps from 25 to 14 ka.

Additional notes on the properties of the modern Leeuwin Current

The LC can at times flow along the entire coast of southern Australia, even reaching at times the west coast of Tasmania (Legeckis and Cresswell, 1981; Cresswell and Peterson, 1993). Despite the fact that the LC, when pre-eminent mostly in winter during La Niña years offshore Kangaroo Island (Fig. 1), SSTs are lower than summer ones, but under exceptional circumstances such as during La Niña years during the 2007–2008 and 2008–2009 summer seasons (Richardson et al. 2020). During those events, above average wind stress caused by southeasterly winds would have been the dominant factor that caused upwelling as a tongue of cold water extending from Cape Bonney (refer to maps a-f in Fig. 26 in Wijffels et al. 2018 where ephemeral and very local upwelling usually occurs) to just south and west of Kangaroo Island (Richardson et al., 2020). During those two seasons, summer SSTs were locally reduced, almost equivalent to winter ones. For more information on the modern oceanography offshore southern Australia, refer to the review of (Middleton and Bye, 2007) and, on water masses, the recent studies of Richardson et al. (2019, 2020).

Marine reservoir age used for sediment depth / age relationships

The samples used here were analyzed at the Poznan Radiocarbon Laboratory (prefix Poz) and at the Swiss Federal Institute of Technology Zürich (prefix ETH), the Australian Nuclear Science and Technology Organization (prefix OZH) and the Australian National University (prefix S-ANU) Radiocarbon Laboratories. Conventional radiocarbon analyses, for instance performed at the Poznan Radiocarbon Laboratory, were carried out on regular size samples (≥4 mg carbonate). Samples were leached with 0.5 M HCL to remove any potential surface contamination prior decomposition with phosphoric acid and converted to graphite for the measurements. A more recently developed analysis at the ETH Zürich allows measurements of small-size samples that contain only 0.3 to 1 mg carbonate. Based on a novel procedure, samples were at first leached with 100 µl of 0.02 M HCl for cleaning (Bard et al., 2015), before being dissolved with 85% phosphoric acid in septa-sealed vials. Subsequently, samples were measured directly as CO_2 with an Atomic Mass Spectrometer (AMS), equipped with a gas ion source (Wacker et al., 2013a,b). Dates published in previous papers (Gingele et al., 2007; Moros et al., 2009; De Deckker et al., 2012; Perner et al., 2018) are indicated in Supplementary Table 1.

For the radiocarbon date calibration we assume a constant reservoir age of 440 years over the time period investigated. However, we need to take into account recent studies (Skinner et al., 2017; Butzin et al., 2017, 2020) that indicate that the marine reservoir age requires better constricting, especially for the glacial ocean, in comparison with today, for a time when its carbon reservoir was substantially different. For the Last Glacial Maximum (LGM), high reservoir ages of > 1500 years for polar surface water masses (Skinner et al., 2010; Butzin et al., 2017, 2020) and lower reservoir ages of 600-800 years for tropical waters (Butzin et al., 2020) are suggested. Prior to these studies, Sikes and Guilderson (2016), examined marine reservoir ages for cores located north and east of New Zealand in the southwestern Pacific Ocean by comparing with tephra ages on land (with radiocarbon dates for organic deposits associated with those layers) also found in marine sediment cores. Their findings relate to six distinct periods of tephra deposition with calibrated years of ~25.6 ka, ~17. 9 ka, ~14.0 ka, ~9.3 ka, ~8.0 ka and ~5.5 ka. Sikes and Guilderson (2016) concluded that the reservoir age for subtropical waters (the Leeuwin Current originates from the tropics) was ~700 years during the last glaciation, and was much older in subantarctic waters. By 20 ka, the reservoir age difference between subtropical and subantarctic surface waters was nearly leveled out north and east of New Zealand. For the early deglaciation (~18-14 ka), Sikes and Guilderson (2016) report a marine reservoir age of ~600-700 years, and for the Holocene it was similar to today's range. The Sikes and Guilderson (2016) reservoir ages for the LGM of the western Pacific Ocean appear lower than the modeled marine reservoir age discussed in Skinner et al. (2017) whose map (Fig. 3) for ventilation ages display values > 1250 reservoir ages south of Australia. In addition, the dot located in that figure 3 (op. cit.) near the site of core MD03-2611 was incorrectly placed and instead should refer to a site from the northwest Pacific Ocean (L. Skinner, pers. comm.). Butzin et al. (2017, fig. 3A; 2020, fig 2) reproduced this erroneous location, plus the values obtained by Sikes and Guilderson (2016) for around New Zealand appear correctly as an 'enclave' of lower values (some <1000 ^{14}C years) within modelled the broad latitudinal band of much older (~1,000 years) waters in that region. Furthermore, the dot located south of Tasmania in Butzin et al. (2020, Fig 2) does not provide information on surface waters (see Hines et al. (2015) as they relate to deep-sea corals).

As our study area is affected by different water masses, stratification changes, as well as by varying oceanic frontal influences marked age reversals should therefore be found in age depth relationships according to Butzin et al. (2020) and Skinner et al. (2017) when applying a constant reservoir age. This is not the case (Supplementary Figure 1). There are no age reversals at times / core depths when subtropical water and oceanic frontal influences changed markedly offshore South Australia.

Since there is so little information on LGM reservoir age for the Australian region, we take into account the work of Sikes and Guilderson (2016) from the western Pacific. Following Sikes and Guilderson (2016), we calibrated the AMS^{14}C dates using a reservoir age of 700 years for samples ranging from 21 to 18 ^{14}C ka BP, and then decrease this value down to 600 years for the period spaning 18 to 14 ^{14}C ka BP, and with 440 years for younger samples. The calibrated results are shown in Supplementary Table 1 and Supplementary Figure 1. We note that the range of (1 σ) errors obtained during calibration is overall lower than the values to be added which provides confidence in our age model.

In addition, with the used reservoir age of 440 years the timing of deglacial SST changes matches quite closely (Figure 4) with Antarctic ice core temperature reconstructions (although here there is a range of timings/structures as well)—offering some (indirect) confirmation of the simple approach. A higher reservoir age would actually shift the age e.g. of the marked *N. incompta* spike closer to 14.7 ka (Figure 4J) and the northward STF displacement occurred exactly at the same time of the discussed changes seen in NH and SH ice cores. In addition, millennial fluctuations seen in the frontal retreat (Figure 4J) would perfectly match fluctuations in the sea-ice extent recorded in Antarctic ice cores (Figure 4I sea-salt records). Thus a more detailed matching to Antarctica is possible but this itself makes large assumptions about the relative timing between these locations and that local influences are minor. There is strong support for a common SH climate evolution supporting such an approach in general. However, with frontal and water mass changes indicated by the faunal composition changes, there are clear local/regional influences present in the records which complicate any effort to do detailed correlations between our sites and Antarctica temperature histories (which themselves vary from region to region). In the end, the detailed correlation would change the age model by very little and which is within the current error bars of the existing age model (Supplementary Figure 1) supporting the chosen approach and suggesting the more extreme reservoir ages found in some locations likely do not apply to our dates/ages/locations.

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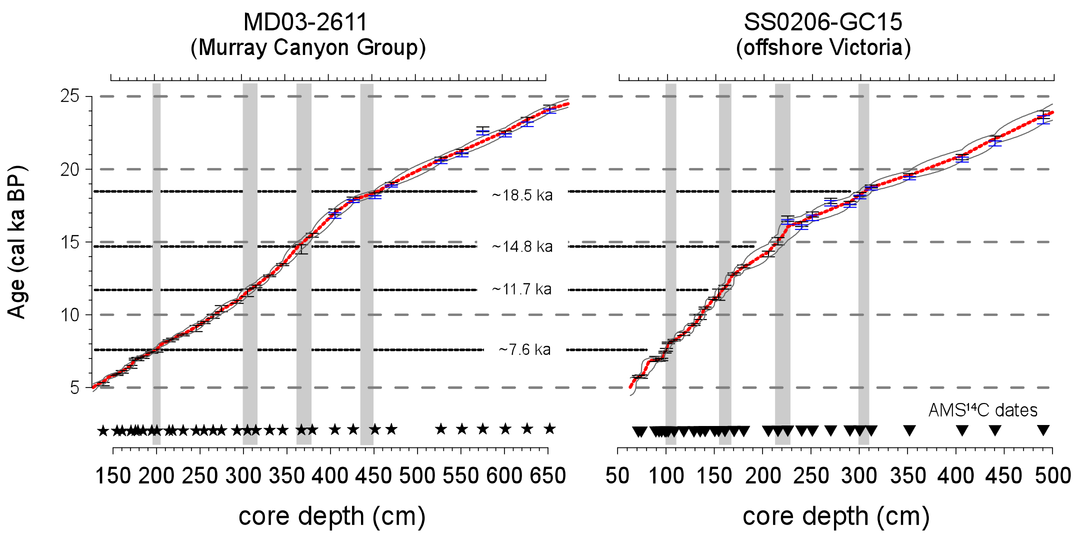
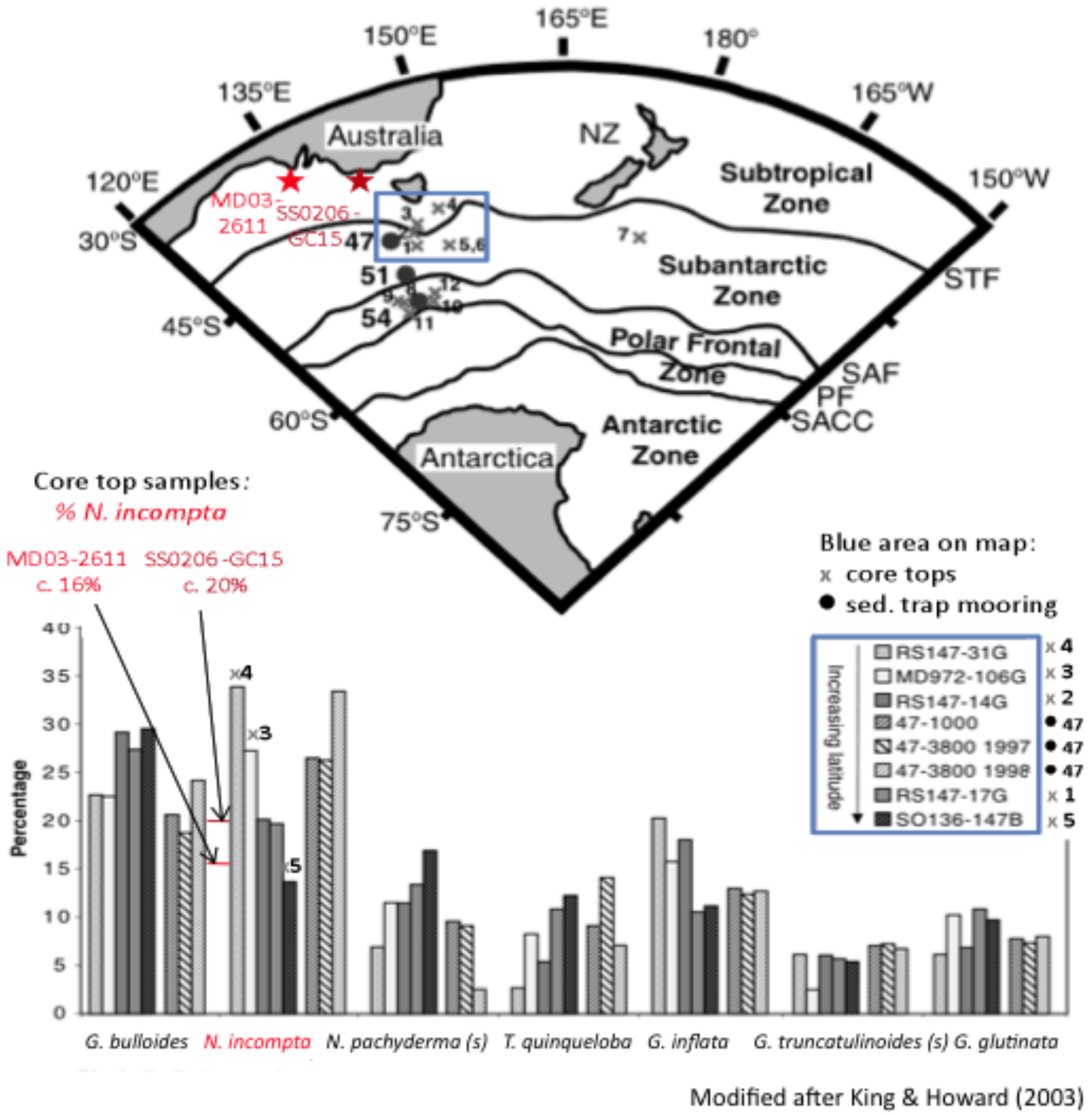


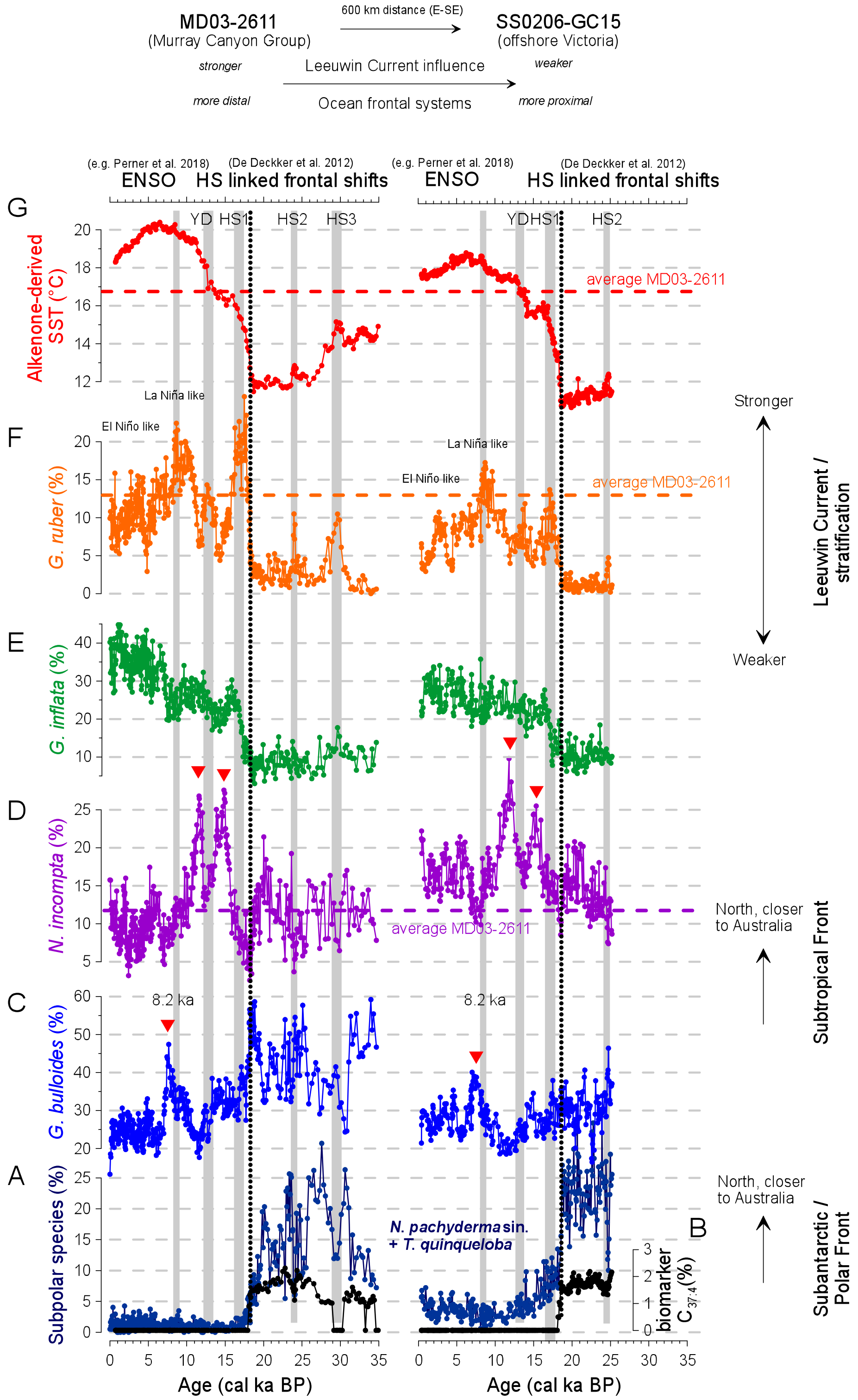
Supplementary Figure 1 Age versus depth of the calibrated AMS^{14}C dates from cores MD03-2611 (left) and SS0206-GC15 (right), with 95.4% error bars. The dashed red lines illustrate the age-depth models used, and the grey lines mark the uncertainty range (95.4% minimum and maximum uncertainty range) of the respective age-depth models. Depth positions of AMS^{14}C dates in MD03-2611 (stars) and SS0206-GC15 (triangles) are shown close to the respective x-depth-axis. Vertical grey bars and horizontal black dashed lines mark the depth positions and the timing, respectively, of marked proxy data changes (see Figs. 2 and 3) in the respective cores.

N. incompta % in sediment trap and core top samples South of Australia



Supplementary Figure 2 Core top showing *N. incompta* percentages at our sites MD03-2611 and SS0206-GC15 compared with the data published in King and Howard (2003). The latter were obtained from sediment trap moorings (black dot on map) and core tops (grey "x") taken from a transect passing over the STF (blue box area) south of Tasmania. Note the high *N. incompta* percentages at the STF.

Biomarker and key faunal changes on a long-term perspective (35 ka BP to the present)

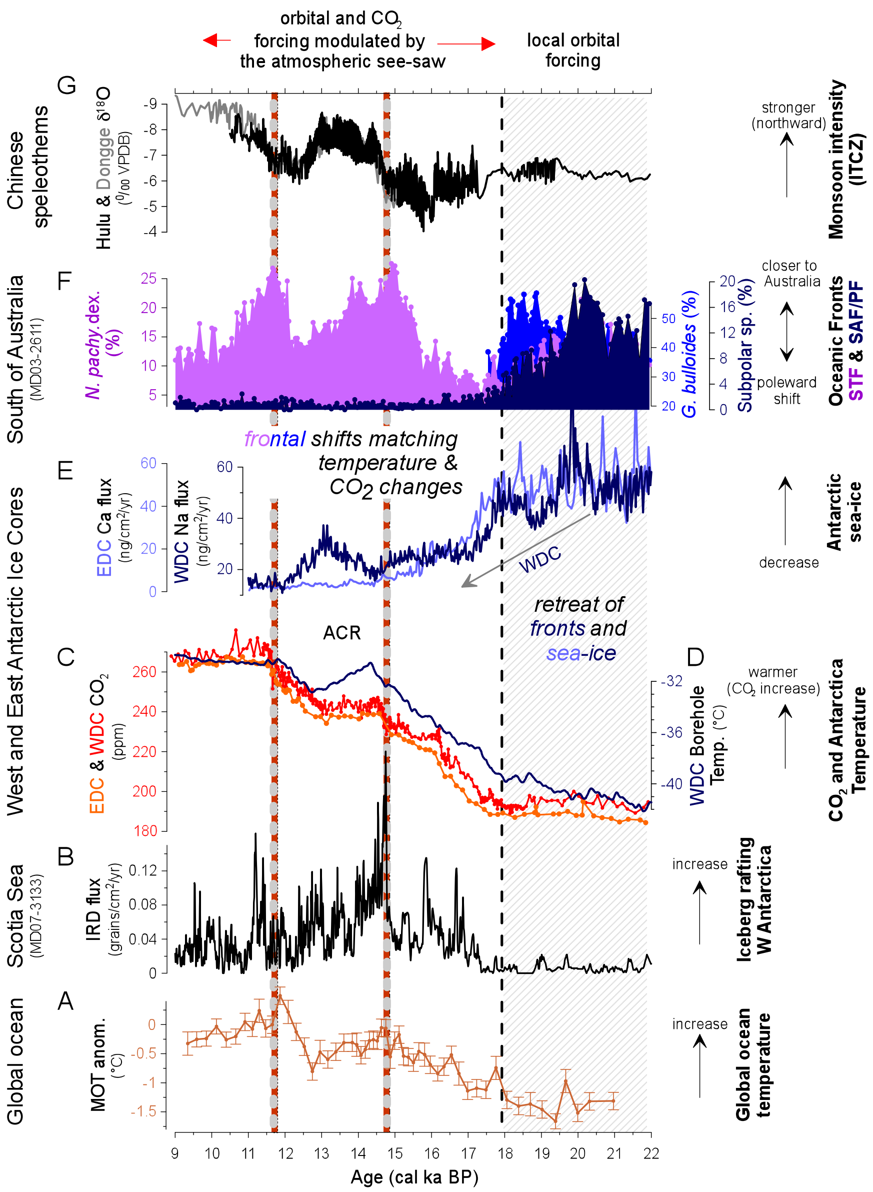


Supplementary Figure 3 Long-term trends (35 ka BP towards the present day) in foraminiferal assemblages (**A**, **C-F**) and alkenone-derived SSTs (**G**) and % $C_{37:4}$ (**B**) in cores MD03-2611 and SS0206-GC15. The foraminiferal 'subpolar species' group (*N. pachyderma* sin. plus *T. quinqueloba*) (**A**) and freshwater-related alkenone % $C_{37:4}$ (**B**) indicate proximity to the SAF/PF. Subtropical Front taxa are *G. bulloides* and *N. incompta* (**C**) and (**D**), respectively. *G. ruber* (**F**) is indicative of the presence of the warm Leeuwin Current with also the thermocline-dweller *G. inflata* (**E**). During the pre-Holocene, the LC presence offshore South Australia is controlled by

HS linked frontal shifts (grey vertical bars; De Deckker et al., 2012). From 18.5 ka (vertical dotted black line) onward, the LC prevails but with varying strength as indicated by fluctuating but relatively high % levels of *G. ruber* (**F**) and *G. inflata* (**E**). Mid- to late Holocene changes in the LC strength are linked to ENSO (Perner et al., 2018). Two marked northward displacements of the STF occur at 14.8, and 11.7 ka are clearly evident by the *N. incompta* % (**D**, red triangles) and a further event sticks out at 7.6 ka (**C**, red triangle). The warmest biomarker SSTs (**G**) are recorded c. 6 ka BP during a La Niña-like phase (Perner et al., 2018). Vertical grey bars indicate NH cold (HS) events.

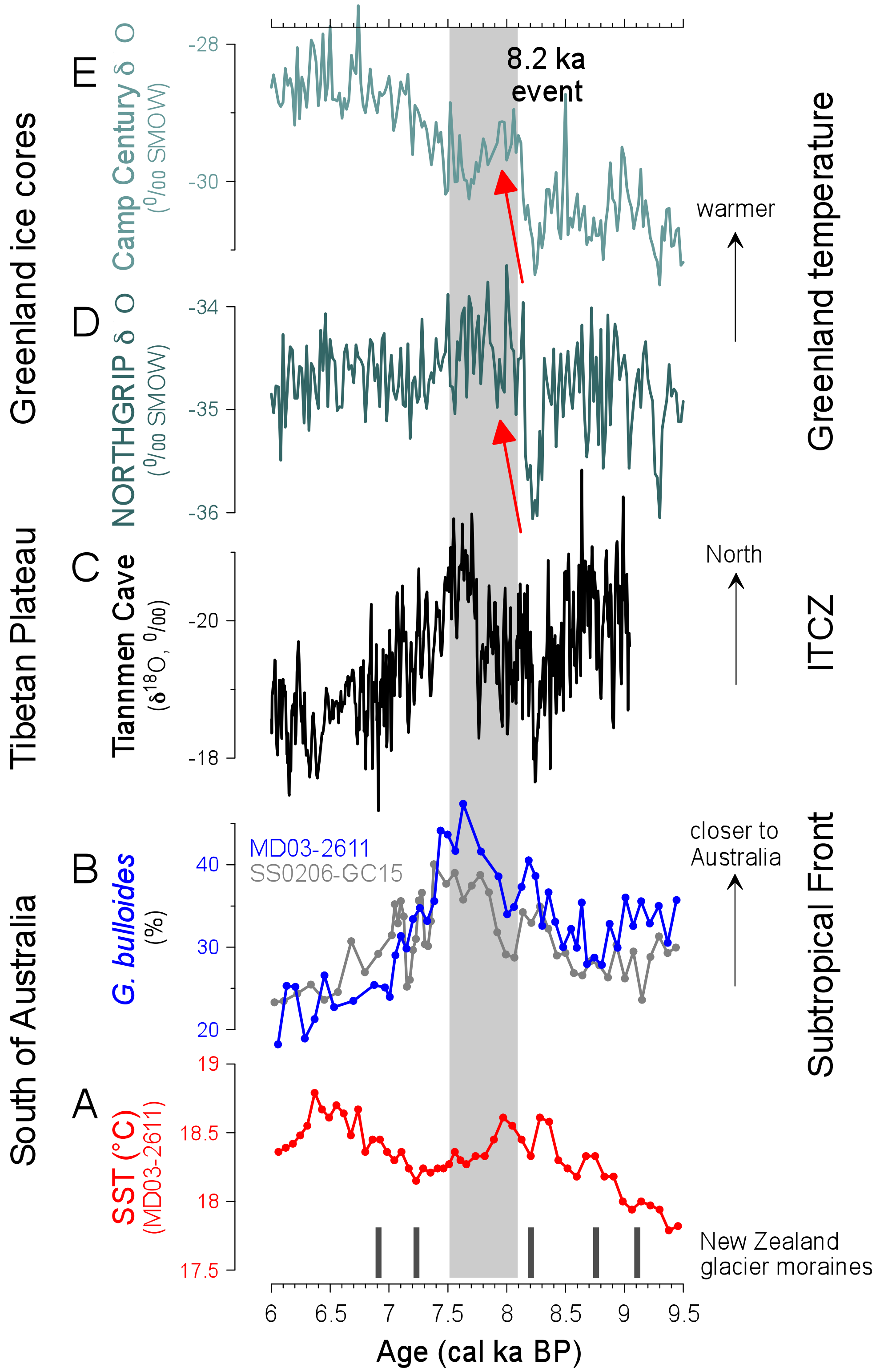
Comparison of additional Northern and Southern Hemispheric records

The following two Supplementary Figures present comparisons of additional key-records from the Northern and Southern Hemisphere mentioned but not shown in the main text. Supplementary Figure 4 focuses on the time interval 22 to 9 ka BP and Supplementary Figure 5 presents a zoom-in of the so-called "8.2 ka event"



Supplementary Figure 4. **(A),** Global ocean temperature (Bereiter et al., 2018) is compared with **(B)** Southern Hemisphere ice rafting (Weber et al., 2018); **(C)** EPICA Dome C (EDC; Lourantou et al., 2016) and West Antarctic

Ice Sheet Divide ice core (WDC; WAIS, 2013) ice core CO_2; (**D**) WDC borehole temperature (Cuffey et al., 2016); **(E)** sea-ice WDC Na flux (WAIS, 2013) and EDC Ca flux (Röthlisberger et al., 2002), and **(G)** Northern Hemisphere speleothem $\delta^{18}O$ data (Wang et al., 2001; Yuan et al., 2004).



Supplementary Figure 5. Comparison of proxy data from the m arine core MD03-2611 SST record (**A**) and estimates of Subtropical Front location with respect to Australia (**B**) with **(C)** Tibetan Plateau Tiannmen Cave speleothem $\delta^{18}O$ data (Cai et al., 2012) indicative of the latitudinal ITCZ shifts, and with **(D)** Northern Hemisphere Greenland ice core $\delta^{18}O$ data from NORTHGRIP, and (**E**) from Camp Century (Vinther et al., 2009) records. Note the parallel changes after the so-called "8.2 ka event" reflecting a temperature rise in the Northern Hemisphere (**D**, **E**), a northward displaced ITCZ (**C**) against Subtropical Front (shift **B**) and a slight SST decline (**A**).

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