

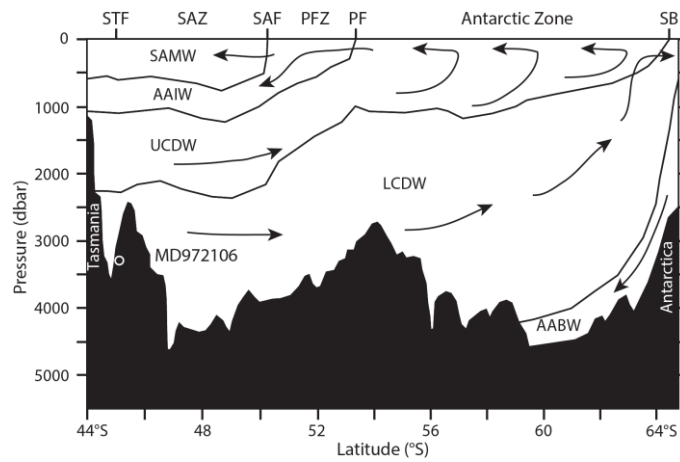
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Varied contribution of the Southern Ocean to deglacial atmospheric CO₂ rise

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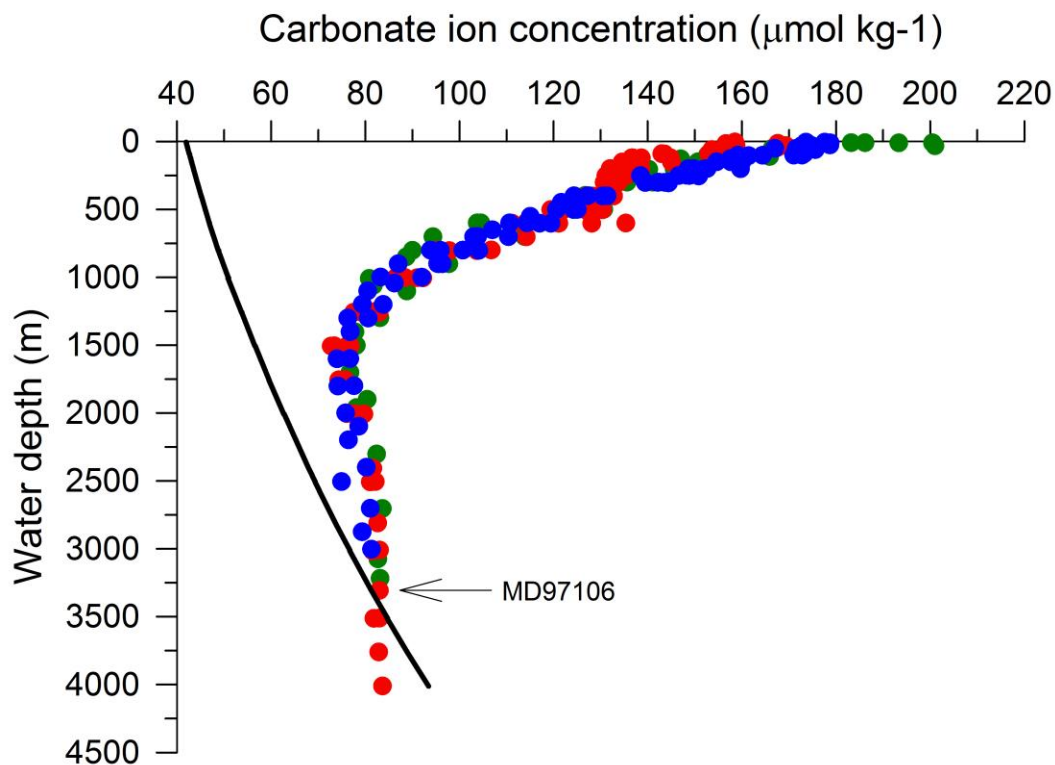
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Supplementary Information for “Varied contribution of the Southern Ocean to deglacial atmospheric CO₂ rise”.

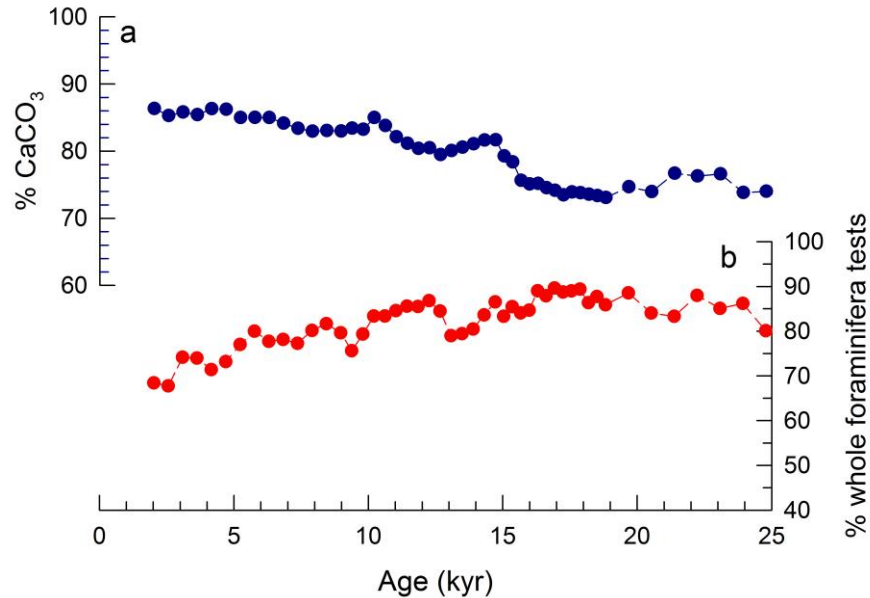


Supplementary Figure 1. Circulation and water masses along WOCE SR3 repeat hydrographic transect between Tasmania and Antarctica along ~140° E. MD972106

(45°09'S, 146°17'E, water depth 3310 m) is located at the southern edge of the Sub-Tropical front and bathed in Lower Circumpolar Deep Water. STF = Sub-Tropical Front, SAZ = Sub-Antarctic Zone, SAF = Sub-Antarctic Front, PFZ = Polar Frontal Zone, PF = Polar Front, SB = southern boundary of the ACC, SAMW = Sub-Antarctic Mode Water, AAIW = Antarctic Intermediate Water, UCDW = Upper Circumpolar Deep Water, LCDW = Lower Circumpolar Deep Water and AABW = Antarctic Bottom Water. Southern Ocean frontal locations and water masses are well defined through the WOCE SR3 repeat hydrographic section between Tasmania and Antarctica¹⁻⁴. Climatological data from the World Ocean Atlas 2013 (WOA13; 0.25°)⁵, shows modern summer and winter sea surface temperatures (SST) of 14.0°C and 11.0°C at MD972106, respectively, indicating that the core site is located at the southern edge of the STF. Southern Ocean frontal locations and water mass profiles compiled from Rintoul and Bullister (ref. ¹) and Sokolov and Rintoul (ref. ⁴).

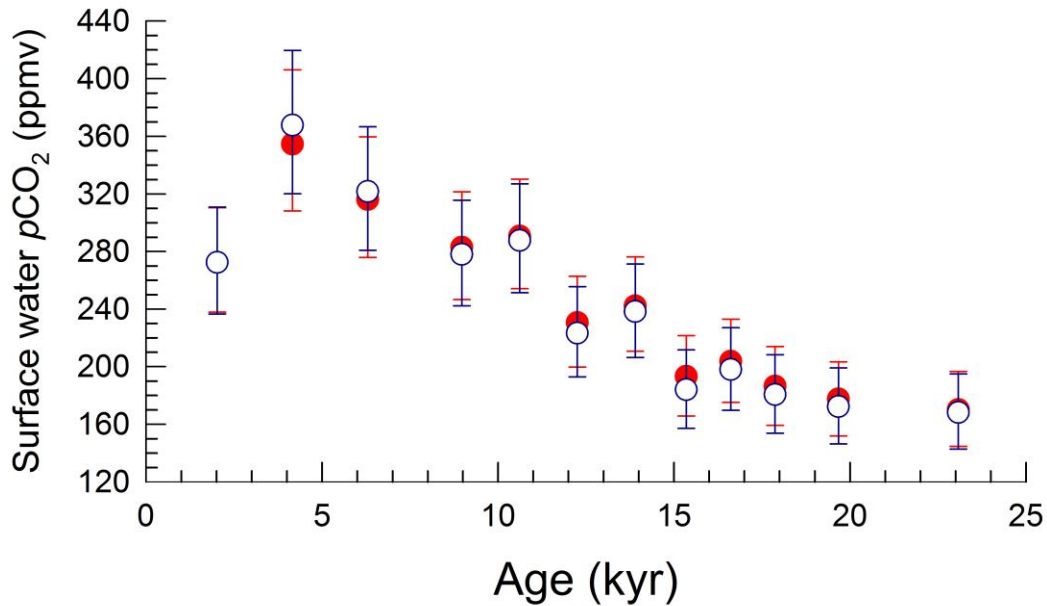


Supplementary Figure 2. WOCE SR3 repeat hydrographic vertical profiles of carbonate ion concentration ($[\text{CO}_3^{2-}]$) between 44°S and 46°S , and calcite solubility (solid line). The seawater calcite saturation horizon occurs at $\sim 3,500$ m water depth. MD972106 ($45^\circ 09'\text{S}$, $146^\circ 17'\text{E}$, water depth 3310 m) is located above the modern calcite saturation horizon and above the foraminiferal lysocline that occurs at $\sim 3,600$ m water depth⁶. $[\text{CO}_3^{2-}]$ are from WOCE SR3 repeat hydrographic transect from voyage AA9404 (green), AA0301 (blue) and AA9706 (red). $[\text{CO}_3^{2-}]$ was calculated from TA, DIC, temperature, pressure, salinity, $[\text{PO}_4^{3-}]$ and $[\text{SiO}_4^{4-}]$ from the WOCE line SR3 section between 44°S and 46°S (refs. ⁷⁻⁹) using the CO2Sys Excel macro (version 2.1) (ref. ¹⁰) and constants from Mehrbach *et al.* (ref. ¹¹) refitted by Dickson and Millero (ref. ¹²). Calcite solubility was calculated from the equation of Mucci (ref. ¹³) that includes pressure adjustments in K_{sp} following Ingle (ref. ¹⁴).



Supplementary Figure 3. Indicators of post-depositional calcite dissolution.

Carbonate preservation indices (%CaCO₃ and % whole foraminiferal tests) for MD972106, **a**, %CaCO₃ (blue) and **b**, % whole foraminiferal (%WF) (red) as a function of age (kyr). The timescale for MD972106 is based on radiocarbon dates (see Methods). %CaCO₃ is highest during the Holocene (~85%) and decreases to ~75% during the Last Glacial Maximum (LGM). Similarly, %WF is lowest during Holocene (~76%) and increases during to ~86 % during the LGM. At MD972106 (and other South Tasman Rise sites¹⁵), the pattern of decreasing %CaCO₃ during the LGM likely results in part from the dilution of carbonate by terrigenous sediment¹⁵. MD972106 is located above the modern calcite saturation horizon (at ~3,500m water depth; Supplementary Fig. 2). Holocene core-top *G. bulloides* (300-355 μm) shell weights indicate the foraminiferal lysocline at the South Tasman Rise occurs at ~3,600m water depth⁶. These indicators of post-depositional dissolution suggest that seafloor calcite dissolution did not play an important role over the past 25 kyr at MD972106. %CaCO₃ are from Moy *et al.*, (ref. ¹⁶) and %WF were determined using similar methods to those described by Howard and Prell (ref. ¹⁷).



Supplementary Figure 4. Reconstructed surface water $p\text{CO}_2$ from pH, alkenone SST and DIC (Method 2) at the MD972106 site over the past 25,000 years. For Method 2, adjustments for temperature and $[\text{CO}_3^{2-}]$ on *G. bulloides* $\delta^{13}\text{C}$ used to estimate DIC do not significantly change the $p\text{CO}_2$ estimates for this method. The average difference in $p\text{CO}_2$ calculated from (a) boron isotope-based pH estimates and DIC (where $\delta^{13}\text{C}$ for *G. bulloides* is not temperature and $[\text{CO}_3^{2-}]$ -adjusted; blue open circles) and (b) boron isotope-based pH estimates and DIC (where $\delta^{13}\text{C}$ for *G. bulloides* is temperature- and $[\text{CO}_3^{2-}]$ -adjusted; solid red circles) is ~ 2 ppm. The small average $p\text{CO}_2$ difference of ~ 2 ppm indicates that the temperature and $[\text{CO}_3^{2-}]$ adjustments on *G. bulloides* $\delta^{13}\text{C}$ used to estimate DIC do not play a significant role in $p\text{CO}_2$ estimates for Method 2. $\delta^{13}\text{C}$ for *G. bulloides* were adjusted for temperature and for $[\text{CO}_3^{2-}]$ (see Methods). Error bars represent 95% confidence intervals around the Monte Carlo mean, where 2σ uncertainties on the individual input variables and other carbonate system parameters are propagated via the Monte Carlo simulation ($n = 10,000$) in the program R (Methods).

Supplementary Note 1 Anthropogenic-influenced surface water pH, $p\text{CO}_2$ and $[\text{CO}_3^{2-}]$ at the MD972106 site calculated using WOCE SR3 repeat hydrographic data from voyage AA0301 (ref. ⁸; Fig. 1 in main text) and the CO2Sys Excel macro (version 2.1) (ref. ¹⁰) and constants from Mehrbach *et al.* (ref. ¹¹) refitted by Dickson and Millero (ref. ¹²).

Supplementary Note 2 Anthropogenic CO_2 value for surface waters from the WOCE SR3 repeat hydrographic section close to MD972106 site are $\sim 45 \mu\text{mol kg}^{-1}$ (GLODAP v1.1 database¹⁸), which corresponds to a $[\text{CO}_3^{2-}]$ decrease of $\sim 29 \mu\text{mol kg}^{-1}$ with respect to estimated pre-industrial values. Present-day surface $[\text{CO}_3^{2-}]$ is $\sim 183 \mu\text{mol kg}^{-1}$; thus pre-industrial $[\text{CO}_3^{2-}]$ is estimated to be $\sim 212 \mu\text{mol kg}^{-1}$. Calculated $[\text{CO}_3^{2-}]$ for surface waters are from WOCE line SR3 TA, DIC, temperature, pressure, salinity, $[\text{PO}_4^{3-}]$ and $[\text{SiO}_4^{4-}]$ from the GLODAP v1.1 database¹⁸ using the CO2Sys Excel macro (version 2.1) (ref. ¹⁰) and constants from Mehrbach *et al.* (ref. ¹¹) refitted by Dickson and Millero (ref. ¹²).

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