Middle Holocene expansion of Pacific Deep Water into the Southern Ocean

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The Southern Ocean is a key region for the overturning and mixing of water masses within the global ocean circulation system. Because Southern Ocean dynamics are influenced by the Southern Hemisphere westerly winds (SWW), changes in the westerly wind forcing could significantly affect the circulation and mixing of water masses in this important location. While changes in SWW forcing during the Holocene (i.e., the last ~11,700 y) have been documented, evidence of the oceanic response to these changes is equivocal. Here we use the neodymium (Nd) isotopic composition of absolute-dated cold-water coral skeletons to show that there have been distinct changes in the chemistry of the Southern Ocean water column during the Holocene. Our results reveal a pronounced Middle Holocene excursion (peaking ~7,000–6,000 y before present), at the depth level presently occupied by Upper Circumpolar Deep Water (UCDW), toward Nd isotope values more typical of Pacific waters. We suggest that poleward-reduced SWW forcing during the Middle Holocene led to both reduced Southern Ocean deep mixing and enhanced influx of Pacific Deep Water into UCDW, inducing a water mass structure that was significantly different from today. Poleward SWW intensification during the Late Holocene could then have reinforced deep mixing along and across density surfaces, thus enhancing the release of accumulated CO₂ to the atmosphere.

Southern Ocean | cold-water corals | neodymium isotopes | Holocene | water mass mixing

The mixing of water masses in the Southern Ocean plays a central role in the distribution of physical and chemical properties in the global ocean, thereby influencing the exchange of heat and carbon with the atmosphere (1, 2). Under modern boundary conditions, buoyancy loss of surface waters in the North Atlantic leads to the formation of North Atlantic Deep Water (NADW), whereas diapycnal mixing in the Pacific Basin interior drives the upwelling of bottom waters and fuels the southward flow of oxygen-poor and nutrient-rich Pacific Deep Water (PDW). Both water masses are exported into the Antarctic Circumpolar Current (ACC), where the denser NADW becomes Lower Circumpolar Deep Water (LCDW), whereas PDW becomes Upper Circumpolar Deep Water (UCDW). Surface buoyancy fluxes and a strong wind-induced Ekman divergence cause upwelling of these circumpolar water masses along steepened isopycnals. While UCDW supplies the formation regions of Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water, the denser LCDW feeds primarily into the formation of Antarctic Bottom Water (AABW), thus separating the meridional overturning circulation into an upper and a lower cell, respectively (Fig. 1) (1–3).

Although water masses are predominantly mixed along isopycnals, mixing across isopycnals is an important driver of the deep overturning circulation, and is particularly enhanced in the Southern Ocean where the zonal flow of the ACC is forced over rough topography such as in the Drake Passage (7, 8). Recent observations suggest that changes in atmospheric forcing imposed by the Southern Hemisphere westerly winds (SWW) can

alter momentum and buoyancy fluxes and hence the eddy circulation in the Southern Ocean water column (8). Furthermore, changes in SWW forcing have a direct effect on Southern Ocean upwelling rates and hence the oceanic degassing of CO₂, expressed in enhanced upwelling of CO₂-rich deep waters through a deepened mixed layer during phases of poleward SWW intensification (9–11). Consequently, the interaction between SWW forcing, sea-ice extent, deep-water circulation, and the structure of the Southern Ocean water column is proposed to have played an important role in controlling atmospheric CO₂ concentrations during the last glacial–interglacial transition (12–14).

During the Holocene, the position and/or intensity of the SWW are thought to have shown pronounced changes, as reflected in regional air and sea-surface temperature (SST) distributions, changes of the hydrological cycle, and Antarctic sea-ice extent (15–20). In particular, intervals of poleward SWW intensification were associated with Southern Hemisphere warming, poleward increases in precipitation (16, 18), and enhanced upwelling of deep waters (19, 20), together leading to reduced sea-ice coverage on the Antarctic shelves (19, 20) and altering the mass balance of Antarctic glaciers (21). However, Southern Ocean water mass mixing and water column structure are largely unconstrained for the Holocene epoch.

Here, to address this critical data gap, we use neodymium (Nd) isotopes extracted from the aragonitic skeletons of cold-water

Significance

Southern Ocean circulation is a central aspect of the climate system influenced by the overlying Southern Hemisphere westerly winds (SWW) and surface buoyancy forcing. Yet, the response of Southern Ocean water mass mixing to SWW changes is largely unconstrained for the Holocene (the last ~11,700 y). We extracted the fingerprint of ocean chemistry from Drake Passage cold-water corals to trace past water mass mixing. Our data suggest that poleward weakening of the SWW in the Middle Holocene led to increased admixture of CO₂-rich Pacific-derived water masses into the Southern Ocean. These results indicate that the Holocene circulation reacts more sensitively to atmospheric forcing than previously appreciated, thus providing insight into the Southern Ocean's possible role during future climate change.

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Fig. 1. Sample locations of Southern Ocean cold-water corals. (A) Map of Drake Passage coral sampling locations at Sars Seamount (red), Cape Horn, and Burdwood Bank (blue). White line demarks section shown in B. Thin gray and black lines indicate the mean positions of the Subantarctic Front (SAF), the Polar Front (PF), and the Southern ACC front (SACC) (3). (B) Oxygen concentration section across the Drake Passage (4). Pacific Southern Ocean (blue-filled circle and red-filled square) and Cape Horn (blue-filled square) sampling locations were transferred into the Drake Passage section density structure relative to the mean frontal positions. All other symbols indicate Sars Seamount and Burdwood Bank sampling locations (SI Appendix, Table S1). Symbol color coding according to the modern water mass structure in red (UCDW), green (LCDW), and blue (AAIW). Thin black lines indicate surfaces of neutral density anomaly γ^n (in kg/m^3) (5). Black arrows indicate the Southern Ocean overturning circulation, i.e., the direction of upwelling deep waters and downwelling intermediate and bottom waters north and south of the PF, respectively. Note the PDW-derived O_2 minimum at UCDW depths. Base map and oxygen section were generated with ODV software (6).

corals as a tracer for past water mass mixing in the Drake Passage of the Southern Ocean (22, 23). The Drake Passage is an area of intense mixing in the Southern Ocean which has recently attracted increasing attention (7, 8, 13, 22). Intense mixing may play a part in the observed homogeneity of the modern Nd isotope distribution in the Drake Passage (24, 25) (SI Appendix, Fig. S3), as does the reduced Nd isotope gradient between NADW and PDW in the South Atlantic/Pacific (25, 26) (SI Appendix, section 4). Consequently, any variation in Drake Passage seawater Nd isotopic compositions would suggest pronounced changes in chemical and/or physical water column structure.

Results

The Neodymium Isotopic Composition of Holocene Drake Passage Cold-Water Corals. Twenty-five specimens of fossil cold-water corals *Desmophyllum dianthus*, *Caryophyllia*, and *Flabellum curvatum* from 3 locations in the Drake Passage (Burdwood Bank, Cape Horn, and Sars Seamount; Fig. 1), and 3 specimens from 2 locations in the Pacific sector of the Southern Ocean (SI Appendix, Fig. S1), were analyzed for their Nd isotopic composition (Methods). The Drake Passage corals cover a depth range from 695 to 1,750 m and their ages range from 11.6 ka BP (i.e., thousand years before present, where present is 1950) to modern. The specimens collected from 816-m water depth at Burdwood Bank and the specimen from 1,012-m water depth at Cape Horn are today bathed by AAIW ($\gamma^n = 27.35\text{--}27.6 \text{ kg/m}^3$, O_2 of $\sim 6.5 \text{ mL/L}$) (3, 4, 27) (Fig. 1B). The corals collected from 695–1,323-m water depth at Sars Seamount are bathed by UCDW ($\gamma^n = 27.6\text{--}28.0 \text{ kg/m}^3$, O_2 of $\sim 4.2 \text{ mL/L}$) (3, 4, 27) (Fig. 1B), while 2 deeper corals from Sars Seamount (1,701- and 1,750-m water depth) correspond to the modern density level of LCDW ($\gamma^n = 28.0\text{--}28.2 \text{ kg/m}^3$, O_2 of $\sim 4.6 \text{ mL/L}$) (3, 4, 27) (Fig. 1B). While recognizing that the water mass structure of the Drake Passage may have changed in the past, we grouped the fossil corals into records of AAIW (Cape Horn, Burdwood Bank), UCDW (695–1,323 m at Sars Seamount), and LCDW (1,701–1,750 m at Sars Seamount) (Figs. 1 and 2). The South Pacific corals were included in the AAIW and UCDW records according to the water mass structure at their sampling locations (Figs. 1B and 2). Since

most corals representing UCDW depths were collected from a narrow depth range of 695–981 m at Sars Seamount, any potential bias from combining data from multiple locations or depths is minimized. All our Nd isotope analyses were performed on corals with robust U-Th age constraints (Methods) and the majority of our coral samples were previously analyzed for their radiocarbon content (13). Neodymium isotopes are expressed as $\epsilon_{\text{Nd}} = ((^{143}\text{Nd}/^{144}\text{Nd}_{\text{sample}})/(^{143}\text{Nd}/^{144}\text{Nd}_{\text{CHUR}}) - 1) \times 10,000$, where CHUR is the chondritic uniform reservoir (SI Appendix, Table S1).

Neodymium isotopic compositions of Holocene corals range from $\epsilon_{\text{Nd}} = -5.8 \pm 0.2$ to $\epsilon_{\text{Nd}} = -8.2 \pm 0.2$ over the past 11.6 ka (SI Appendix, Table S1). At UCDW depth levels, a pronounced maximum of $\epsilon_{\text{Nd}} = -5.8 \pm 0.2$ was recorded at 6.8 ka BP, which is highly radiogenic in comparison to ϵ_{Nd} of ~ -7.4 to -8.2 during the Early and Late Holocene (Fig. 2). The 2 corals collected from deeper depths (1,701–1,750 m), where LCDW is currently the prevailing water mass (Fig. 1B), show ϵ_{Nd} of ~ -8.2 at both 5.8 and 10.2 ka BP (Fig. 2), indicating no change from modern seawater values at these depths (ϵ_{Nd} of ~ -8.2) (24) during the Early or Middle Holocene. At sites in AAIW depths, Nd isotopes evolve from $\epsilon_{\text{Nd}} = -6.5 \pm 0.2$ during the Middle Holocene toward a modern ϵ_{Nd} value of -7.6 ± 0.2 (Fig. 2), thus following a similar evolution to UCDW.

The radiogenic Nd isotopic composition of the upper-cell water masses AAIW and UCDW during the Middle Holocene is a distinct feature of our dataset. These upper-cell data differ from a Middle Holocene coral from LCDW depths in the Drake Passage and from concurrent LCDW Nd isotopic compositions in the deep South Atlantic and South Pacific (28–30) (Fig. 2). Furthermore, the pronounced Nd isotope change recorded in these corals is distinct from the Nd isotopic composition of modern corals and seawater data from the Drake Passage (24, 25) (Fig. 2 and SI Appendix, section 4).

Discussion

The Origin of the Drake Passage Neodymium Isotope Signal. The skeletons of aragonitic cold-water coral specimens in the Drake Passage were shown to record an ambient Nd isotope seawater signal (24). Nevertheless, the observed Holocene Nd isotope variability in the Drake Passage could potentially reflect a number

Fig. 2. Results from Holocene Southern Ocean cold-water corals. Cold-water coral Nd isotope results from the Drake Passage (including <0.5 ka BP coral data from ref. 24) and the South Pacific. Also shown for comparison are previously published Nd isotope records from South Atlantic LCDW/AABW (gray shading) cores TNO57-21 (4,981-m water depth; site 8) (gray triangles) (28) and MD07-3076 (3770 m water depth; site 7) (gray circles) (29), South Pacific LCDW core PS75/073-2 (3,234-m water depth; site 3) (green shading; not including measurements with analytical uncertainty $>1 \text{ } \epsilon_{\text{Nd}}$) (30), and South Atlantic AAIW core Geob2107-3 (1,048-m water depth; site 6) (light-blue shading) (31). Site numbers refer to locations shown in *SI Appendix, Fig. S1*. The gray bar at the y axis represents the 2 SD range of Burdwood Bank and Sars Seamount seawater Nd isotopic compositions ($\gamma^{\text{N}} = 26.93\text{--}28.23 \text{ kg/m}^3$, $\epsilon_{\text{Nd}} = -8.1 \pm 0.5$, 2 SD, $n = 18$; see also *SI Appendix, Fig. S3*) (24). The green bar indicates the Early Holocene phase of major grounding line retreat of ice sheets in the Pacific sector of Antarctica (32, 33).

of different processes, since seawater Nd isotopic compositions can be altered through lithogenic input from dust (34), rivers (35), boundary exchange (36), or glacial erosion (37). The effect of dust input is typically restricted to the uppermost levels of the water column (34) and is negligible in this region of the Southern Ocean (37), while modern seawater Nd isotope data indicate that there is no influence of boundary exchange on CDW within the fast-flowing ACC in the Drake Passage (24, 25). In particular, there is no observable release of Nd at the sampling locations in the modern day (24), and there is no reason to envisage more pronounced exchange during the Middle Holocene. Furthermore, a Sars Seamount coral from 1,701-m water depth dating to $5.69 \pm 0.27 \text{ ka BP}$ shows ϵ_{Nd} of -8.2 ± 0.3 compared to $\epsilon_{\text{Nd}} = -6.3 \pm 0.2$ in a coral from 869-m water depth at the same time ($5.76 \pm 0.06 \text{ ka BP}$; *SI Appendix, Table S1*). This 2- ϵ_{Nd} offset is difficult to reconcile with a local benthic source of radiogenic Nd from the seamount. Although regional input fluxes could have differed in the past, the timing of major ice-sheet retreat in Antarctica (Fig. 2) (32, 33) and changes in terrestrial input from nearby potential source areas show no correspondence to the Middle Holocene Nd isotope maximum (see also *SI Appendix, section 3 and Fig. S2*).

We emphasize that any local imprint of radiogenic terrestrial surface input could only have been preserved if it was exported directly to the Drake Passage (i.e., a scenario in which the inputs were sufficient to alter the mass balance of UCDW in the entire Southern Ocean is unlikely). Therefore, we may consider AAIW,

which is formed from Southern Ocean surface waters, as a potential candidate for delivering a local radiogenic meltwater-sourced signal to middepths of the Drake Passage. Indeed, the Nd isotopic compositions of UCDW and AAIW are similar during the Middle Holocene (Fig. 2). However, interpreting such values as a shuttle transferring radiogenic surface waters to middepth (i.e., both AAIW and UCDW layers) would also require 1) a significant deepening of the mixed layer down to the coral collection depth near 900-m water depth at Sars Seamount, or 2) a dramatic steepening of the isopycnals, or 3) a southward oceanic frontal shift of $\sim 3\text{--}5^\circ$ latitude in the Drake Passage to align AAIW isopycnals with the coral sampling locations within modern-day UCDW (3, 4) (Fig. 1). Critically, all of the above scenarios are difficult to reconcile with radiocarbon evidence from the same Drake Passage corals (13). Radiocarbon in the ocean is a function of surface ocean exchange with the atmosphere and water mass mixing and aging at depth (38), thereby providing an independent and complementary tracer to Nd isotopes (22, 39). The Middle Holocene Nd isotope excursion is associated with poorly ventilated water masses at UCDW depths, expressed as a relatively high radiocarbon age offset between the coral and the contemporaneous atmosphere (B-atm) of $\sim 1,200 \text{ y}$ (Fig. 3). Therefore, the UCDW coral data are inconsistent with enhanced admixture of well-ventilated AAIW to UCDW depths. Instead, the Middle Holocene tracer distribution at these depth levels is consistent with the general pattern of the modern Southern Ocean overturning circulation (Fig. 1B), explaining both the similar Nd isotopic compositions of UCDW and AAIW and the offset in ventilation between these two waters masses (Fig. 3). As such, the Middle Holocene radiogenic Nd isotope

Fig. 3. Drake Passage cold-water coral data in radiocarbon–Nd isotope space. The benthic-atmosphere (B-atm) radiocarbon age offsets were calculated using $^{14}\text{C}_{\text{atmosphere}}$ age of 0 y (1950 AD) for the modern seawater values (40, 41). For past B-atm ages, we used coral ^{14}C ages (13) and IntCal13 atmospheric ^{14}C ages at the calendar age of each coral (41). (Inset) The dashed line shows a hypothetical conservative mixing calculation between modern NADW and PDW, with white dots indicating 10% intervals. Endmembers in the mixing calculation are modern NADW ($\epsilon_{\text{Nd}} = -13.2$, $[\text{Nd}] = 17.6 \text{ pmol/kg}$, B-atm = 500 y, DIC [dissolved inorganic carbon] = $2,160 \text{ } \mu\text{mol/kg}$) (40, 42) and PDW ($\epsilon_{\text{Nd}} = -3.5$, $[\text{Nd}] = 44.4 \text{ pmol/kg}$, B-atm = 2,100 y, DIC = $2,350 \text{ } \mu\text{mol/kg}$) (40, 43). The dashed gray rectangle indicates the modern Drake Passage seawater properties (24, 40).

excursion was recorded in 2 independent settings (Sars Seamount and Burdwood Bank) and its origin must lie with a radiocarbon-depleted water mass source.

Radiocarbon-depleted water masses are typically found in the deep ocean (38, 40) and hence we consider the possibility of mixing radiogenic Nd and radiocarbon-depleted waters into UCDW from below. A record from LCDW depths in the South Pacific shows invariable Nd isotopic compositions during the Holocene (ϵ_{Nd} of ~ -8) (30) (Fig. 2), in excellent agreement with the Nd isotopic compositions recorded by our Drake Passage corals from 1,701 and 1,750-m water depth at Sars Seamount, and inconsistent with an LCDW origin for the radiogenic signal in the UCDW layer. We therefore conclude that the Holocene Nd isotope evolution of UCDW in the Drake Passage was primarily controlled by the lateral admixture of radiogenic Nd at UCDW depths, and that this signal was propagated along isopycnal surfaces into shallower depths during UCDW upwelling and subsequently incorporated during AAIW formation.

Expansion of Pacific-Derived Waters into the Southern Ocean. Compared to the modern day, the Middle Holocene UCDW properties show greater geochemical similarity to waters found in the middepth Pacific Ocean, for both Nd isotopes and radiocarbon (Fig. 3). Simple endmember changes in NADW or PDW are unable to explain the Nd isotope shift in UCDW, since the Middle Holocene Nd isotopic composition of PDW was largely invariable (44), while the Nd isotope signature of NADW would need to have changed to ~ -8 , which is not supported by North Atlantic Nd isotope data (45). Consequently, we propose that the Middle Holocene Nd isotope shift to -5.8 in the Drake Passage records a significantly increased fraction of Nd from radiogenic PDW at UCDW depths.

Given the homogeneity of Nd isotopes in the modern Drake Passage water column (Fig. 4A; see also *SI Appendix, section 4*), one possibility to explain our data is to invoke wholesale changes of the entire Drake Passage water column during the Middle Holocene. Although the radiogenic Nd isotope signal recorded in our corals from UCDW and AAIW depths is not seen in any LCDW records from this time (Fig. 2), the lack of high-resolution LCDW data (and the age uncertainty of our Middle Holocene LCDW coral sample; *SI Appendix, Table S1*) means that we cannot rule out that short-lived changes may have occurred in LCDW, too. However, this scenario would require an abrupt invasion of Pacific-derived water masses at all depths and/or a substantial reduction of NADW input on centennial timescales in order to explain the large difference in ϵ_{Nd} values recorded almost concurrently at ~ 5.7 ka BP in UCDW (-6.3) and LCDW (-8.2) depths (Fig. 2 and *SI Appendix, Table S1*). Such large hydrographic changes are inconsistent with strong NADW export and the resulting unradiogenic Nd isotopic composition of LCDW in the Holocene Southern Ocean (28–30) (Fig. 2). Moreover, considering that skeletal subsamples for Nd isotope analyses typically integrate the seawater signal of several decades (24), our observation of radiogenic values in 4 coral specimens retrieved from 2 different locations during the Middle Holocene suggests that this signal may have been a relatively persistent feature rather than a transient short-lived excursion. We therefore suggest that our data reflect changes restricted to UCDW and AAIW depths and indicate a vertical Nd isotope gradient in the Drake Passage during the Middle Holocene (Fig. 4B), which is remarkably different from the homogeneous Nd isotope distribution in the modern water column (24, 25).

The increased presence of PDW in the Drake Passage seems to have been closely preceded by large-scale equatorward SWW intensification during the Early to Middle Holocene (15–20, 46–48), as reflected in increased sea spray on Macquarie Island north of the Polar Front in the southwest Pacific ($54^{\circ}\text{S}/158^{\circ}\text{E}$) (47) (Fig. 5E), enhanced moisture supply to southeast Australia (48) (Fig. 5F), and decreasing SST off New Zealand (15). Concurrent

Fig. 4. Vertical distribution of Nd isotopes in the modern and past Drake Passage. (A) Late Holocene coral data for AAIW (blue triangles) and UCDW (red circle) (<1.1 ka BP) (24) and foraminifera-derived data for South Pacific LCDW (green circle) (30) compared to modern seawater profiles from Sars Seamount (gray-filled circles) and Burdwood Bank (gray-filled triangles) framed by light-gray bar ($\epsilon_{\text{Nd}} = -8.1 \pm 0.5$, 2 SD, $n = 18$, see also Fig. 2) (24). (B) Older Holocene coral data (filled colored symbols) compared to light-gray bar integrating modern seawater and coral data from A ($\epsilon_{\text{Nd}} = -8.0 \pm 0.6$, 2 SD, $n = 23$) (24). Dark-gray polygon frames the Middle Holocene coral results (thick black outline; 6.8–5.8 ka BP) and concurrent LCDW data from the South Pacific (30).

poleward weakening of the SWW is evident from decreasing fluvial runoff in southern Patagonia (53°S) (16) (Fig. 5D), reduced upwelling of CDW on the West Antarctic shelves (19, 20), and decreasing West Antarctic air temperatures (17) (Fig. 5C). Together, these changes suggest a more northerly position of the SWW in the South Pacific during the Middle Holocene (Fig. 5G). The northward SWW migration is part of large-scale climate reorganizations expressed in a concurrent positive Northern Hemispheric extratropical temperature anomaly (Fig. 5A), which has been ascribed to orbital forcing modulated by snow, ice, vegetation, and ocean circulation feedbacks (49). Here we postulate that SWW forcing played an important role in setting the Drake Passage water column structure, and hence the Nd isotope fingerprint, during the Holocene.

Poleward SWW weakening can reduce the wind forcing over the ACC, in particular where the zonal ACC flow is constrained by topography (1, 3, 51). Such a reduction is dynamically coupled to diapycnal mixing in the Southern Ocean water column, including between UCDW and LCDW (8). Recent model results highlight the role of Southern Ocean diapycnal mixing for the structure of the Atlantic overturning circulation (52), while other simulations indicate a pronounced reorganization of the overturning circulation in the Pacific in connection with SWW changes (51, 53). Reduced SWW forcing was shown to decrease upwelling of NADW in the Southern Ocean and enhance upwelling of NADW-influenced deep waters (via diapycnal mixing) in the Indo-Pacific (51). Deep-water upwelling rates in the Pacific are slow, but these waters are funneled via the PDW outflow into the Southern Ocean, where they join the circumpolar flow predominantly at UCDW depth levels (1, 2, 27) (Fig. 1B). We therefore propose that poleward SWW weakening caused a decrease of diapycnal mixing in the deep Southern Ocean, which was offset by increased upwelling in the Pacific Basin, thereby fueling enhanced PDW export to the Drake Passage. The combination of these

Fig. 5. Drake Passage water mass mixing compared to Holocene climate parameters. All site numbers refer to locations shown in *SI Appendix, Fig. S1*. (A) Interhemispheric extratropical temperature anomaly, where positive values represent Northern Hemisphere positive anomalies and vice versa (49). (B) Excess rhenium (ϵ_{Re}) from 1,015-m water depth off Chile, located at hinge depth between high O_2 (AAIW) and low O_2 (PDW) (site 5) (50). (C) Antarctic Peninsula deuterium isotope-based temperature record from James Ross Island (note reversed axis) (site 10) (17). (D) Accumulation rate of terrestrial organic carbon in a Patagonian fjord, recording SWW-induced fluvial input (site 4) (16). (E) Diatom-inferred conductivity as a tracer for SWW-controlled sea spray on Macquarie Island north of the PF (site

2) (47). (F) Depth of southeast Australian Lake Gnotuk, indicative of SWW-driven precipitation–evaporation (P–E) balance (site 1) (48). (G) Summary panel of the latitudinal SWW trends, with peak northward intensity between ~7.5 and 5.5 ka BP highlighted by the yellow shading (15–20, 46–48). (H) EPICA Dome C (EDC) ice core CO_2 record (11-point running mean) (site 13) (55, 56). (I) Drake Passage Nd isotope data from UCDW (red), LCDW (green), and AAIW depths (blue) (this study and <0.5 ka BP coral data from ref. 5). Gray bar at the y axis represents the range of modern local seawater Nd isotopic compositions (see legend of Fig. 2 for details) (24). Thick colored lines in C, E, and F are 3-point running means of the respective datasets.

processes resulted in the observed vertical Nd isotope gradient in the Drake Passage water column between ~7 and 6 ka BP (Fig. 4B). This hypothesis is supported by reduced oxygenation at intermediate water depths off Chile (50) (Fig. 5B) and the presence of depleted radiocarbon within PDW off New Zealand (B-atm ~ 2,100 y at 7 ka BP) (54), which are both consistent with a southward expansion of poorly ventilated PDW during the Middle Holocene and an enhanced influence of PDW in the Drake Passage. While there are few well-resolved Nd isotope records from intermediate waters during the Holocene, a reconstruction from AAIW depths in the southwest Atlantic shows a small Middle Holocene excursion toward more radiogenic Nd isotope values (31) (Fig. 2), consistent with our observations from the Drake Passage. Given the more pronounced changes recorded by the UCDW corals in the Drake Passage, and their more Pacific-like Nd isotopic compositions, we suggest that changes in the Nd isotopic composition of UCDW originated through increased PDW influence in the Pacific sector of the Southern Ocean and were advected downstream to exert a control on the Holocene evolution of Nd isotopes in South Atlantic AAIW (Fig. 1B).

Interestingly, many proxy data including the interhemispheric temperature distribution (49) (Fig. 5A), expansion of PDW in the southeast Pacific (50) (Fig. 5B), and the poleward SWW weakening in Patagonia (16) (Fig. 5D) show rather gradual changes over the Early to Middle Holocene, whereas the change in Nd isotopic composition of UCDW seems relatively abrupt and delayed in comparison (Fig. 5I). The abrupt nature of the Nd isotope pattern is more similar to SWW strength in the southwest Pacific (47) (Fig. 5E) and precipitation changes in southeast Australia (48) (Fig. 5F). Rapid Nd isotope shifts in the Drake Passage suggest that diapycnal mixing in the Southern Ocean and PDW export into UCDW can change on relatively short timescales, possibly in response to latitudinal SWW changes across a critical threshold. Furthermore, they also relate to the unique ability of the cold-water coral archive to record abrupt oceanographic changes (39).

During the Late Holocene, the Nd isotope values of UCDW corals are within error of modern seawater values at the coral sampling locations (24) (Fig. 5I). These similar-to-modern values coincide with reduced activity of the SWW at their equatorward flank and intermediate intensity near their modern core latitudes in the southwest Pacific (18, 46–48) (Fig. 5E and F). However, invariable organic carbon fluxes suggest that the SWW did not reach their Early Holocene maximum intensity in southernmost Chile (16) (Fig. 5D). Hence, the intermediate position/intensity of the SWW during the Late Holocene (Fig. 5G) may indicate a characteristic boundary condition required for the modern state of circulation and mixing in the deep Southern Ocean. Such atmospheric forcing could have played an important role in reinforcing Southern Ocean deep mixing and CO_2 degassing, which is indicated by the coincidence of SWW changes, the presence of CO_2 -rich PDW in the Southern Ocean, and the Middle Holocene turning point in the evolution of atmospheric CO_2 (55, 56) (Fig. 5H). Poleward intensification of the SWW under projected future global-warming scenarios (57) would be expected to play a role in further release of accumulated CO_2 to the atmosphere (9–11), thus acting as an amplifier of the anthropogenic increase of atmospheric CO_2 .

Methods

All cold-water coral samples presented in this study were subjected to rigorous physical and chemical cleaning to remove any contaminant trace metal rich phases from the aragonitic coral skeletons. Samples were then processed for U-series dating and Nd isotope analyses following previously established procedures (see [SI Appendix, section 2](#) for full details). Mass spectrometric analyses of Nd isotopes were carried out in the MAGIC laboratories at Imperial College London and at the Institute for Chemistry and Biology of the Marine Environment (ICBM) in Oldenburg, Germany (see [SI Appendix, section 2](#) for full details of analytical protocols and data processing). Inter-calibration between the different mass spectrometers was achieved using internal and external reference materials. All data are reported with the long-term 2 SD uncertainties calculated from repeat analyses of reference materials. Where the internal 2 SE exceeded the 2 SD external uncertainty,

the propagated uncertainty is reported. All data are available in [SI Appendix, Table S1](#).

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