Key Points:
- A high-resolution record of benthic seawater cadmium was generated from a core at intermediate water depth in the Florida Straits
- Atlantic Meridional Overturning Circulation was significantly reduced during the Younger Dryas and early Heinrich Stadial 1
- A mid-Heinrich Stadial 1 upper branch Atlantic Meridional Overturning Circulation recovery could imply decoupling of overturning branches

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Timing of Deglacial AMOC Variability From a High-Resolution Seawater Cadmium Reconstruction

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Abstract A new, high-resolution record of benthic seawater Cd (Cd_w) was generated from a Florida Straits sediment core at 546 m water depth. The record provides additional evidence for Cd_w below modern values in this channel during the Younger Dryas and Heinrich Stadial 1—climatological periods associated with ice sheet melt. Lower Cd_w values are interpreted as a weakening of the Atlantic Meridional Overturning Circulation (AMOC), reflecting a decreased northward transport of southern sourced higher-nutrient intermediate waters by the surface return flow of AMOC. Comparison of this new Cd_w record with previously published neodymium isotope and $\delta^{18}O$ records from the same core shows synchronous transitions, further illustrating the connection between Cd_w levels and AMOC strength in the Florida Straits. An increase in Cd_w near 16 ka bolsters existing evidence for a resumption of upper branch AMOC strength approximately midway through Heinrich Stadial 1.

1. Introduction

Atlantic Meridional Overturning Circulation (AMOC) in the modern ocean transports heat from the Southern to the Northern Hemisphere because the formation and southward flow of cold deep water in the North Atlantic is compensated by the northward flow of warmer water in the upper ocean. Because it transports heat, the AMOC may cause and/or play a role in the global expression of abrupt climate changes over the last glacial cycle. Reconstructions of both conservative and nonconservative water mass properties have revealed a more stratified north Atlantic during the Last Glacial Maximum (LGM) around 20 ka, with shallow overturning limited to about the top 2 km, and during certain periods of the deglaciation, little or no overturning at all (Adkins, 2013; Boyle & Keigwin, 1987; Lynch-Stieglitz et al., 2007; McManus et al., 2004; Rahmstorf, 2002). Evidence for AMOC reduction has coincided with abrupt and short-lived (millennial scale) cold periods observed in the Northern Hemisphere. These cold periods are thought to be induced by large influxes of freshwater during glacial melt and ice sheet calving (Boyle & Keigwin, 1987; Broecker, 1994; Rooth, 1982). The connection between freshwater fluxes and AMOC changes has been validated by data from circulation tracers and nutrient proxies and is supported by modeling studies, for example, Gregory et al. (2006), Kageyama et al. (2010), and Rahmstorf (1995). However, uncertainty remains around the precise triggers, timing, and sequence of changes in AMOC.

Intermediate waters in the modern Florida Straits are composed of a mixture of waters originating in the Southern Hemisphere entering the Caribbean from the south and waters originating in the Northern Hemisphere flowing into the Caribbean as the western limb of the North Atlantic gyre (Figure 1, left). The two water mass inputs into the Straits differ in their nutrient content. Waters coming from the south, which form part of the upper branch of the AMOC, have high nutrient concentrations and those from the north have relatively lower nutrient concentrations.

Florida Straits reconstructed seawater cadmium (Cd_w) has been used to infer changes in the upper branch of AMOC over the Younger Dryas North Atlantic cold period (YD, 12.7–11.5 ka) (Came et al., 2008). Cadmium has a nutrient-like profile that closely resembles phosphate in the modern ocean (Boyle et al., 1976). Higher Cd_w is expected in the Florida Straits when AMOC is strong, as the enhanced circulation increases the northward influx of higher-nutrient intermediate water from farther south in the Atlantic. This study provides a higher-resolution benthic Cd_w record than previously available for the region, complete for both Heinrich Stadial 1 (HS1, 17.5–14.5 ka) and much of the YD. The new Cd_w record allows for direct comparison against other measures of circulation and nutrient changes from other proxies in the same core.
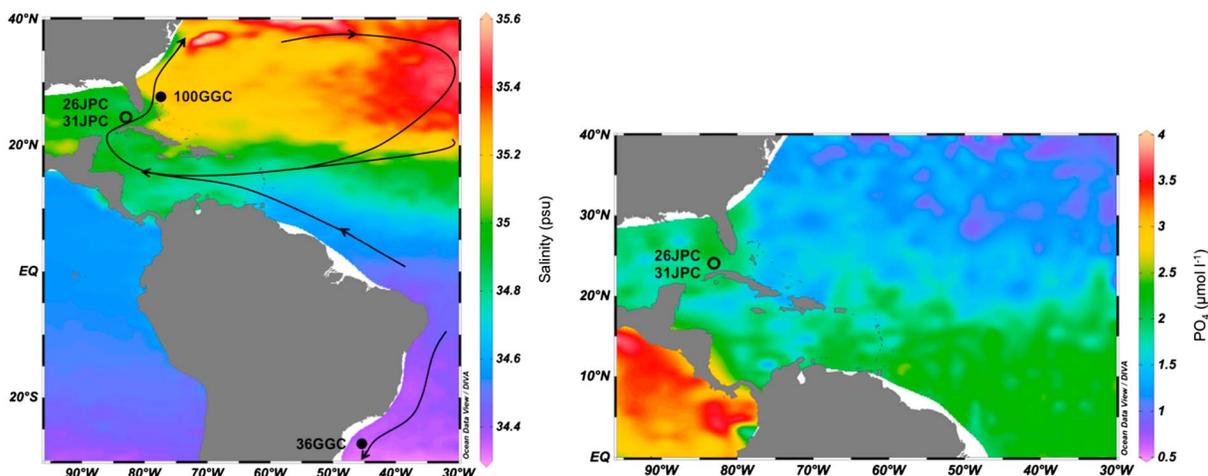
Figure 1. Core locations. (left) Approximate location of Florida Straits cores KNR166-2-26JPC (24°19.61′N, 83°15.14′W, 546 m (this study)) and KNR166-2-31JPC (24°13′N, 83°18′W, 751 m (Came et al., 2008)) (open circle). Colors show salinity (psu) at potential density 27.3 kg m^{-3} (Garcia et al., 2014; Zweng et al., 2013), the isopycnal calculated for benthic waters at KNR166 2–26JPC. As waters circulate along constant density surfaces, salinity traces flow of different water masses through the straits as indicated by arrows. OCE205-2-100GGC (26°04′N, 78°02′W, 1057 m) and KNR159-5-36GGC (27°31′S, 46°28′W, 1268 m) (closed circles) measure northern subtropical gyre and South Atlantic waters, respectively (Came et al., 2008). (right) Modern PO$_4$ (μmol L^{-1}) at potential density 27.3 kg m^{-3} (Garcia et al., 2014), with KNR166-2-26JPC and KNR166-2-31JPC approximate locations indicated (open circle).

2. Methods

We analyzed core KNR166-2-26JPC, recovered from 24°19.61′N, 83°15.14′W in the Florida Straits at 546 m water depth (Figure 1). The core is located on the landward side of the Florida current, where isopycnals are tilted to a shallower depth relative to the open North Atlantic due to the presence of Florida current. Today, this core location is situated in waters at potential density 27.3 kg m^{-3}, an isopycnal that also characterizes Antarctic Intermediate Water.

Radiocarbon measurements on the planktonic foraminifera *Globigerinoides ruber* and *Globigerinoides sacculifer* were converted to calendar ages with the CALIB 7.1 calibration program and Marine13 marine reservoir calibration curve (Reimer et al., 2009) (Table 1). Calendar ages were then linearly interpolated for the depths between radiocarbon dates. Dates from between 344 and 408 cm were excluded from the age model as that interval of the core includes nonsequential ages and anomalously coarse sediments resembling laterally transported contourite deposits; see Lynch-Stieglitz et al. (2011). Sedimentation rates ranged from ~14 to 300 cm kyr^{-1}, with an average of ~70 cm kyr^{-1} from LGM to present.

Cd/Ca ratios were measured in tests of the aragonitic benthic foraminifer *Hoeglundina elegans*, excluding the 344–408 cm interval (~11.5–11.9 ka). Samples for analysis included 1–11 foraminifera tests each, picked from the >250 μm sieve fraction. Crushed tests were reductively and oxidatively cleaned using the methods of Boyle and Keigwin (1985) as modified by Boyle and Rosenthal (1996). Cd/Ca was measured using a Thermo Finnigan Element2 magnetic sector inductively coupled plasma–mass spectrometer following the methods delineated by Marchitto (2006). Analytical precision on Cd/Ca is ~ 2% (1σ) for samples >10 μg post-cleaning mass. Of 300 measurements, 13 were smaller than 1 μg after cleaning (based on Ca measurement) and are considered lost (not reported). One additional sample is omitted from plots due to high Al/Ca (>1,000 μmol mol^{-1}), and another is omitted because it is a Cd/Ca outlier, being >0.02 μmol mol^{-1} higher than both of its neighboring samples, suggesting contamination. Contamination indicators on the remaining samples were generally low: all but three Al/Ca <200 μmol mol^{-1}, all Fe/Ca <100 μmol mol^{-1}, and all Mn/Ca <20 μmol mol^{-1}. *Hoeglundina's* aragonitic tests do not allow for manganese-calcium carbonate overgrowths that can alter trace metal content (Boyle et al., 1995).

Cd/Ca ratios were converted to seawater Cd concentration (Cd$_w$) using the relationship

$$D_p = \frac{\left(\frac{Cd}{Ca}\right)\text{foram}}{\left(\frac{Cd}{Ca}\right)\text{water}}$$

Table 1
Radiocarbon Dates, KNR166-2-26JPC

Core depth	Species	^{14}C age	Error	Calendar age	Source
0.75	*G. Sacculifer*	1,070	70	640	Lynch-Stieglitz et al. (2011)
48.25	*G. Sacculifer*	2,990	30	2,760	Lynch-Stieglitz et al. (2011)
112.25	*G. Sacculifer*	6,720	40	7,250	Lynch-Stieglitz et al. (2011)
144.25	*G. Sacculifer*	8,100	80	8,570	Lynch-Stieglitz et al. (2011)
216.25	*G. Sacculifer*	9,550	40	10,416	Lynch-Stieglitz et al. (2011)
280.25	*G. Sacculifer* and *G. ruber*	10,100	45	11,110	Lynch-Stieglitz et al. (2011)
344.25	*G. Sacculifer*	10,000	110	10,970	Lynch-Stieglitz et al. (2011)
356.25	*G. Sacculifer*	11,750	95	13,230[a]	Lynch-Stieglitz et al. (2011)
364.25	*G. Sacculifer* and *G. Ruber*	10,600	70	11,900[a]	Lynch-Stieglitz et al. (2011)
374.25	*G. Sacculifer*	10,500	50	11,688[a]	Lynch-Stieglitz et al. (2011)
392.25	*G. Ruber*	10,850	65	12,350[a]	Lynch-Stieglitz et al. (2011)
408.25	*G. Sacculifer* and *G. Ruber*	10,300	60	11,300[a]	Lynch-Stieglitz et al. (2011)
442.25	*G. Sacculifer* and *G. Ruber*	10,700	65	12,100	Lynch-Stieglitz et al. (2011)
464.25	*G. Sacculifer* and *G. Ruber*	10,800	55	12,280	Lynch-Stieglitz et al. (2011)
544.25	*G. Sacculifer* and *G. Ruber*	11,000	65	12,550	Lynch-Stieglitz et al. (2011)
592.25	*G. Ruber*	11,400	65	12,860	Lynch-Stieglitz et al. (2011)
606.25	*G. Sacculifer*	11,600	35	13,090	Lynch-Stieglitz et al. (2011)
648.25	*G. Sacculifer*	12,350	200	13,830	Lynch-Stieglitz et al. (2011)
704.25	*G. Ruber*	13,500	55	15,710	Lynch-Stieglitz et al. (2011)
732.25	*G. Ruber*	15,000	60	17,780	This study
752.25	*G. Ruber*	15,550	70	18,410	Lynch-Stieglitz et al. (2011)
802.25	*G. Ruber*	17,750	80	20,920	This study
848.25	*G. Ruber*	20,300	120	23,940	Lynch-Stieglitz et al. (2011)
878.25	*G. Sacculifer* and *G. Ruber*	21,300	95	25,230	Lynch-Stieglitz et al. (2014)
952.25	*G. Ruber*	26,300	130	30,140	Lynch-Stieglitz et al. (2011)
1014.25	*G. Ruber*	28,200	180	31,520	Lynch-Stieglitz et al. (2011)
1032.25	*G. Ruber*	28,200	590	31,830[a]	Lynch-Stieglitz et al. (2011)
1074.25	*G. Ruber*	29,300	380	32,990	Lynch-Stieglitz et al. (2011)
1088.25	*G. Sacculifer* and *G. Ruber*	31,300	200	34,800[a]	Lynch-Stieglitz et al. (2014)
1104.25	*G. Sacculifer* and *G. Ruber*	30,600	170	34,220	Lynch-Stieglitz et al. (2014)
1118.25	*G. Sacculifer*	30,900	220	34,460	Lynch-Stieglitz et al. (2011)

Note. Calibrated using Calib 7.1 and Marine13 curve. Calendar ages are rounded to nearest 10 years for radiocarbon ages with standard deviation >50 years, per Reimer et al. (2009).
[a]Not used in age model.

where the average partition coefficient D_p between the foraminifera and seawater in *Hoeglundina* is 1 for all water depths (Boyle et al., 1995). For the Cd_w calculation, the seawater Ca concentration is assumed to be the global mean value of 0.01 mol kg^{-1} (Boyle, 1992).

3. Results

H. elegans Cd/Ca values range from 0.012 to 0.063 μmol mol^{-1} over the past 22 ka. The late Holocene (past 2 ka) Cd_w average is 0.37 nmol kg^{-1}, in good agreement with the phosphate-based prediction of 0.42 ± 0.10 nmol kg^{-1} for this core location (Bryan & Marchitto, 2010). Florida Straits seawater cadmium shows clearly lower values during the Last Glacial Maximum compared to the Holocene (Figure 2). A transition from lower LGM Cd_w levels to increased Cd_w occurs near 16 ka—about midway through the HS1. Cd_w reaches a maximum during the Bølling-Allerød North Atlantic warm period, near 14 ka. Cd_w then drops abruptly near the onset of the YD, remaining low before increasing to modern levels between 12 and 11.5 ka. The transition out of the YD appears to be abrupt, but this is obscured by the previously noted gap in the sediment record. Cd_w climbs slightly above modern levels during the early-middle Holocene (~9–6 ka) before declining toward the present.

4. Discussion

### 4.1. Florida Straits Seawater Cadmium and AMOC

The results presented in this study are consistent with a lower resolution Cd_w record generated from KNR166-2-31JPC, located nearby in the Florida Straits at 24.22 N, 83.30 W, 751 m (Came et al., 2008). Cd_w variations in
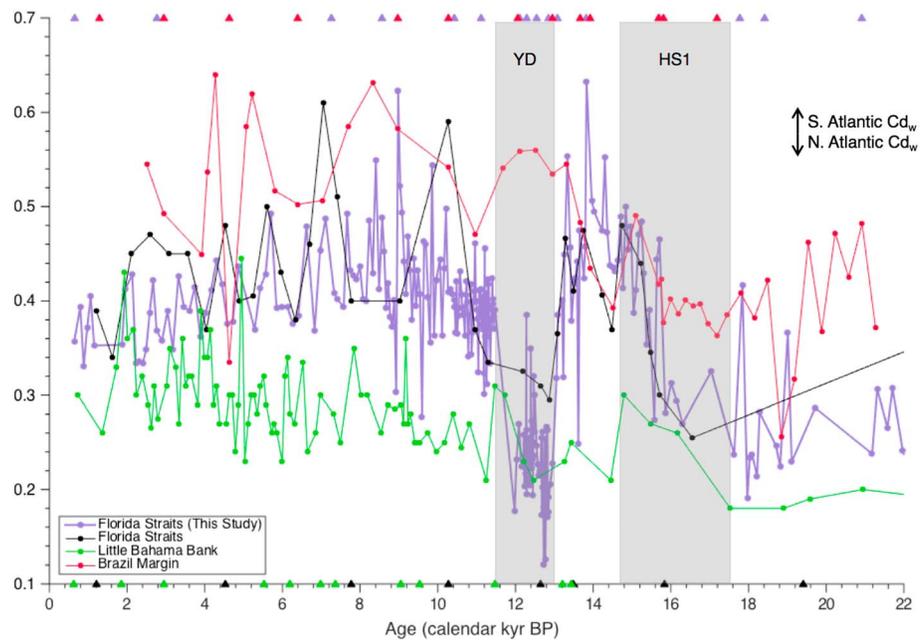
Figure 2. Benthic Cd_w of the Atlantic cores versus age. Violet: Florida Straits, this study, 546 m depth. Red: Brazil Margin 1,268 m. Black: Florida Straits, 751 m. Green: Little Bahama Bank, 1,057 m, all from Came et al. (2008). Radiocarbon age control dates of the cores are indicated with triangles of corresponding colors. Gray bars indicate boundaries of the Younger Dryas and Heinrich Stadial 1.

this record were interpreted to indicate AMOC strength, based on a comparison between the Florida Straits record and records from two other cores (Figure 2). Cd_w in a core from the Little Bahama Bank (26°04 N, 78°02 W, 1,057 m) reflects lower nutrient content in waters sourced in the North Atlantic and recirculated in the subtropical gyre. A core from the Brazil Margin (27°31 S, 46°28 W, 1,268 m) has higher Cd_w values representative of the higher-nutrient intermediate waters at the site. Recently, published Cd_w records from the Tobago Basin (11°36′N, 60°57′W, 852 m and 12°05′N, 61°14′W, 1,330 m) reinforce the view that AAIW Cd_w was higher than Cd_w in North Atlantic sourced waters throughout this time period (Poggemann et al., 2017). In the Florida Straits, lower Cd_w values imply a weaker AMOC, with reduced northward intrusion of high-nutrient waters from the south. The high nutrient levels of the southern sourced waters reflect the higher-nutrient Antarctic Intermediate Water (AAIW) and added nutrients from organic matter remineralization in the tropics. Higher Cd_w in the Florida Straits implies a greater presence of southern sourced water when overturning circulation, and North Atlantic Deep Water (NADW) production is strong. A section of phosphate measured in the region reveals greater nutrient gradient above 550 m (Roemmich & Wunsch, 1985), such that for a relaxation of tilt of the isopycnals (expected when AMOC is reduced), a greater change in nutrient levels would be expected for the KNR166-2-26JPC site at 546 m than the KNR166-2-31JPC site at 751 m analyzed by Came et al. (2008). This is consistent with the lower Cd_w values in the KNR166-2-26JPC record relative to that of KNR166-2-31JPC during the YD, even as both sites record lower nutrients in that period relative to the Bølling-Allerød, indicating reduced AMOC surface return flow.

The Brazilian Margin record cannot be considered a true end-member for determining the relative northern and southern water contributions at the Florida Straits. The waters entering the Caribbean from the south on this density surface have higher salinity relative to the Brazil Margin site (Figure 1, left), implying significant dilution of AAIW. On the other hand, the nutrient values of waters entering the Caribbean from the south are similar to those at the Brazil Margin, as the dilution of AAIW by lower-nutrient northern sourced waters is compensated by the ingrowth of nutrients by the remineralization of organic matter (Figure 1, right). Despite these complications, we expect that in the past, the nutrient content of waters entering the Caribbean from the tropics was higher relative to that of North Atlantic gyre water, as it is today. We will thus interpret high Cd_w in the Florida Straits as reflecting a strong inflow of water from the south as in (Came et al., 2008).
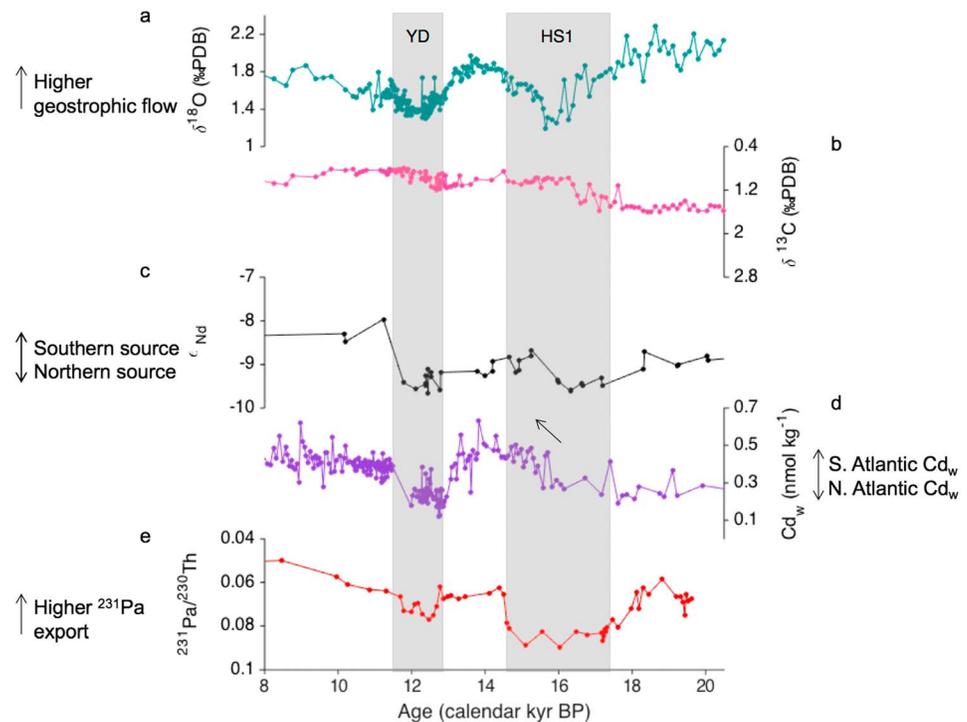
Figure 3. Tracers of North Atlantic circulation over deglaciation. From Florida Straits (KNR166-2-26JPC): (a) Ice volume-corrected benthic $\delta^{18}O$ (Lynch-Stieglitz et al., 2014). (b) Benthic $\delta^{13}C$ (Lynch-Stieglitz et al., 2014) scaled to phosphate per (Broecker & Maier Reimer, 1992). (c) Authigenic ε_{Nd} (Xie et al., 2012). (d) Benthic Cd_w (this study). (e) $^{231}Pa/^{230}Th$ from the Bermuda Rise (McManus et al., 2004). All proxies are plotted so that arrows up indicate stronger AMOC.

For both the KNR166-2-26JPC and KNR166-2-31JPC records, Florida Straits intermediate waters appeared dominated by northern sources during the LGM and YD and by southern influxes during the Bølling-Allerød and Holocene (Figure 2). The KNR166-2-26JPC record also shows lower Cd_w during only the first half of HS1, suggesting AMOC strengthened midway through that interval.

4.2. Colocated Proxy Comparisons

A Florida Straits neodymium isotope record indicates similar timing of local water mass changes as interpreted from the high-resolution Cd_w record. Nd isotope ratios trace water masses independently of biological processes. Today, the ratio for the water masses sourced in the North Atlantic is near $\varepsilon_{Nd} = -13.5$ (Piepgras & Wasserburg, 1980, 1987) and higher, -6 to -9, for waters sourced in the Southern Ocean (Jeandel, 1993). The difference is due to the input of older weathered continental material (low ε_{Nd}) into the Atlantic and newer volcanic weathered material (high ε_{Nd}) in the Pacific, a mixture of which contributes to the Southern Ocean water ε_{Nd} ratio. Comparing the KNR166-2-26 JPC Cd_w record with ε_{Nd} from the same core (Xie et al., 2012), the timing of transitions into and out of the deglacial cold periods is in overall agreement (Figure 3c). As with the Cd_w record, authigenic ε_{Nd} transitions from more northern like to more southern like values between ~16 ka into the Bølling-Allerød and declines again into more northern values at the start of the YD. This suggests that AMOC weakened such that AAIW intrusion declined during early HS1 and the YD and that AMOC recovered during late HS1 and the Bølling-Allerød.

A record of benthic foraminifera $\delta^{18}O$ in the Florida Straits is interpreted to reflect changes in AMOC strength, which change the density gradient across the Straits, and also suggests weakened AMOC associated with meltwater events (Lynch-Stieglitz et al., 2011, 2014). The density gradient increases with increased vertical shear in the Gulf Stream as it travels through the Florida Straits. When flow weakens, isopycnal tilt between the Florida side and the Bahamas side of the Straits flattens (Lynch-Stieglitz et al., 1999). For KNR166-2-26JPC on the Florida side, this is apparent as a decrease in $\delta^{18}O$ (reduced density) during mid-HS1 and the YD. That the $\delta^{18}O$ transitions are concurrent with those of Cd_w (Figure 3a) provides further validation for the link between AMOC strength and local water mass changes. Flattening of isopycnals places the core depth in

lower-nutrient water as density surfaces that were shallower in a stronger AMOC regime reach the 546 m depth of the core location when AMOC is weaker. However, Florida Straits nutrient changes cannot be explained entirely by this effect. By comparing modern phosphate (Roemmich & Wunsch, 1985) and inferred isopycnal tilt based on Younger Dryas oxygen isotope data from the Florida Straits (Lynch-Stieglitz et al., 2011), we find that isopycnal tilt flattening can explain some, but not all, changes in Cd_w during the Younger Dryas.

These colocated proxy records bolster our conclusion that AMOC strength determines the proportions of water masses that dominate the Florida Straits, and that those water mass changes control Cd_w changes in the region. In contrast, a model study (Schmittner & Lund, 2015) shows that carbon from respired organic matter in the upper North Atlantic accumulates during periods of weakened AMOC, which would eventually counteract the reduced import of high-nutrient southern source waters. While Cd_w in the Florida Straits does rise somewhat gradually over HS1, contemporary changes in same-core ε_{Nd} and $\delta^{18}O$, which are not nutrient proxies, support interpreting the rising Cd_w as an increase of southern sourced water transport and not a localized accumulation of remineralized nutrients.

In the Florida Straits, changes in $\delta^{13}C$ do not directly reflect AMOC variability: changes in $\delta^{13}C$ over deglaciation do not correlate with water mass changes as indicated by Cd_w and ε_{Nd} in the core record (Figure 3). While Cd_w reflects large changes in nutrient levels, the $\delta^{13}C$ signal is more muted when placed on an equivalent scale. The distinction between high $\delta^{13}C$ in lower-nutrient northern sourced waters and low $\delta^{13}C$ in higher-nutrient southern sourced waters is dampened by opposing effects of air-sea exchange on the carbon isotope fractionation at the sites of water mass formation (Lynch-Stieglitz & Fairbanks, 1994).

4.3. Comparison With Other Atlantic Records

The McManus et al., 2004 study employed the $^{231}Pa/^{230}Th$ circulation tracer at the Bermuda Rise to show evidence of AMOC decline during HS1 and the YD. While the transitions into and out of the YD cold period are similarly timed in $^{231}Pa/^{230}Th$ and the Florida Straits Cd_w record, the period of high $^{231}Pa/^{230}Th$ during HS1 spans 17.5–14.7 ka. In that record, AMOC recovery at the end of HS1 appears to occur rapidly, over about 200 years from 14.7 to 14.5 ka (Figure 3e). By contrast, the Florida Straits Cd_w record implies a more gradual recovery beginning near 15.7 ka (Figure 3d).

Given the distance between the two core sites, it is logical to question whether any local effects on the radiocarbon dates used to establish the age models applied to the records could explain the difference in timing and rate of AMOC changes out of HS1. Both KNR166-2-26JPC, from the Florida Straits, and OCE326-GGC5, from the Bermuda rise, are located in regions with well-equilibrated surface waters. Surface waters with the oldest apparent radiocarbon ages are found in upwelling zones, where older, ^{14}C depleted waters are brought to the surface. Butzin, Prange, and Lohmann (2012) and Franke, Paul, and Schulz (2008) employed model simulations of ocean ^{14}C with variable climate conditions over the deglaciation. In these studies, ventilation changes between the LGM and modern oceans do imply large radiocarbon age differences between the periods in some regions. Yet for our sites of comparison, no offsets between the two locations are indicated. For these reasons, we reject reservoir age as an explanation for the discrepancy.

It is plausible that the upper branch of AMOC, as recorded by multiple tracers in the Florida Straits, strengthens near 16 ka, while changes in the abyssal Atlantic occurred later. Bradtmiller, McManus, and Robinson (2014) synthesize data from multiple cores at various depths across the Atlantic. These $^{231}Pa/^{230}Th$ records show that AMOC was likely diminished but not entirely shut off during HS1 and LGM. Their interpretation indicates greater transport in intermediate waters than in deep waters during those periods, unlike the Holocene, when the North Atlantic is well ventilated at all depths. It is therefore possible that the Florida Straits Cd_w recorded an earlier strengthening of the shallower cell during mid-HS1, whereas $^{231}Pa/^{230}Th$ from 4.55 km depth on Bermuda rise captured a later reinvigoration of deep AMOC, indicating enhanced NADW production.

Data from other Atlantic records could support this interpretation. Huang, Oppo, and Curry (2014) found that their three ε_{Nd} records from intermediate depths near Demerara Rise off the Brazilian coast show a two-phase AMOC strength trend within HS1. In the first phase, ~18–16 ka, ε_{Nd} values indicate a reduced AAIW component of the local water mass; in the second phase, ~15.5–14.7 ka, the AAIW fraction has increased, which is interpreted as a partial AMOC recovery. Near the South Iceland Rise, an abrupt, localized decrease

in the ^{14}C age of waters ~1–2 km depth at 16 ka has been attributed to enhanced ventilation via rerouting of freshwater overflow from the northwest to the northeast Atlantic, enhancing sea ice and brine production (Thornalley et al., 2011). This change contrasts with the NGRIP ice core $\delta^{18}O$ record showing polar warming not evident until the start of the Bølling-Allerød (Andersen et al., 2004; Rasmussen et al., 2006). These findings also suggest a decoupling of shallow overturning, which may have strengthened earlier coming out of HS1, from deeper circulation which may have lagged. However, even if full overturning did not restart until the start of the Bølling-Allerød, it is important to note that changes in shallow overturning could also force atmospheric change.

The interpretation of low Cd_w values as weakened AMOC during the late last glacial period (~18–20 ka) is difficult to reconcile with other records of deglacial circulation (e.g., Gherardi et al., 2009; Huang et al., 2014; McManus et al., 2004), which imply stronger AMOC during the late glacial period relative to the early HS1. It is possible that at this location, nutrient changes associated with the weakening of upper AMOC return flow at the start of HS1 are not distinguishable in an already stratified glacial North Atlantic. As the nutrient structure and overturning regime of the Atlantic at LGM remains uncertain, it is unclear whether extending this type of Cd_w analysis through the glacial is appropriate at this site. Because of these complications, we decline to interpret the lack of significant change in Cd_w the late glacial to early HS1 period in terms of circulation.

4.4. Climate Implications of a Mid-Heinrich Stadial 1 AMOC Recovery

The increase of Cd_w in the Florida Straits record near 16 ka implies a mid-HS1 AMOC recovery. If AMOC resumed before the end of HS1, it should also be apparent in climate records. An obvious indication of the resumption of upper AMOC and its associated northward heat transport would be a temperature increase in North Atlantic surface waters. Indeed, this is indicated near 16 ka in several sea surface temperature proxy records from the subpolar North Atlantic (Bond et al., 1993; Hodell et al., 2017; Naafs et al., 2013).

Increased AMOC leads to warming in the Northern Hemisphere (and potentially cooling in the Southern Hemisphere), which fuels Northern Hemisphere monsoon systems (Parsons et al., 2014). Furthermore, increases in AMOC northward heat transport have been linked to northward shifts of the Intertropical Convergence Zone (ITCZ) (Cheng et al., 2012; Chiang et al., 2003; Deplazes et al., 2013). An abrupt weakening of the East Asian Summer Monsoon (EASM), thought to correlate with maximum southern ITCZ displacement at 16.1 ka, is inferred from Chinese speleothem records (Wang et al., 2001; Zhang et al., 2014). The Hulu Cave record shows evidence of EASM weakening during six Heinrich Stadials, which Zhang et al. (2014) link to AMOC variability and southern ITCZ displacement. If EASM strength is tied to AMOC, as AMOC weakens, so should EASM (indicated by higher $\delta^{18}O$, interpreted as lower summer precipitation), via atmospheric and oceanic teleconnections. Hulu and Qingtan Cave records are consistent with AMOC changes over the middle-to-late HS1, as evident in the Florida Straits Cd_w record. The trend of reduced to gradually increasing precipitation coincides with upper branch AMOC recovery during the later HS1, as expected.

A record from the San Làzaro Basin on the California Margin shows that the YD and HS1 are locally marked by high surface water $\delta^{18}O$ (Rodríguez Sanz et al., 2013). Saltier conditions observed in those periods are ascribed to a weakening California current, which prevented the advection of colder fresher water as observed in the Holocene. The authors link the weakening current to the southward shift of the ITCZ and the North Pacific High. Also observed is a distinct two-phase structure to the local expression of HS1. A sharp transition from saltier to fresher conditions in the San Làzaro Basin starting at 16.2 ± 0.8 ka is consistent with the timing and trends of ITCZ maximum southern displacement recorded in the Chinese speleothems and with the mid-HS1 recovery of AMOC recorded in the Florida Straits.

Questions remain regarding the timing of ice rafting events within the Heinrich Stadial period (Hemming, 2004). This uncertainty further complicates understanding the sequence between ice sheet collapse, AMOC change, and climate variability (Marshall & Koutnik, 2006), and it reinforces the question of why weakened AMOC persisted throughout HS1 at depth as indicated by Gherardi et al. (2009), Hall et al. (2011), and McManus et al. (2004) and other records. Nevertheless, the Florida Straits Cd_w record supports evidence of a recovery of AMOC strength beginning near 15.7 ka and before the HS1 period terminates, as expressed in ice core $\delta^{18}O$ (Andersen et al., 2004), North Atlantic [231]Pa/[230]Th (McManus et al., 2004), and other records.

5. Conclusions

The new benthic seawater cadmium record provides a high-resolution record of circulation changes over the last deglaciation in the Florida Straits. Multiple proxy records from the same core support the interpretation of periods of diminished Cd_w during Heinrich Stadial 1 and the Younger Dryas as indicative of reduced overturning circulation in the North Atlantic. The record builds on existing evidence of a resumption of AMOC strength near 16 ka, which is coherent with evidence for mid-HS1 ITCZ migration. Further investigation into the timing and locations of deglacial freshwater input, AMOC variability, and related climate impacts is warranted. To that end, this Cd_w record provides compelling evidence from the upper ocean for a mid-HS1 AMOC recovery against which other proxy measurements over HS1 can be compared.

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