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Key Points:

- We reconstructed seawater cadmium in the Florida Straits over the Holocene
- Cd gradually declined in the last 8,000 years, economically explained by weakening AMOC but inconsistent with geostrophic transport estimates
- More intense sampling over last 2,000 years suggests little Cd variability on centennial timescales, consistent with weak AMOC variability

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

S. G. Valley,
shannon.valley@whoi.edu

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Seawater Cadmium in the Florida Straits Over the Holocene and Implications for Upper AMOC Variability

Shannon G. Valley[1], Jean Lynch-Stieglitz[2], Thomas M. Marchitto[3], and Delia W. Oppo[1]

[1]Woods Hole Oceanographic Institution, Woods Hole, MA, USA, [2]Georgia Institute of Technology, School of Earth and Atmospheric Sciences, Atlanta, GA, USA, [3]University of Colorado Boulder, Department of Geological Sciences & INSTAAR, Boulder, CO, USA

Abstract Atlantic Meridional Overturning Circulation (AMOC) plays a central role in the global redistribution of heat and precipitation during both abrupt and longer-term climate shifts. Over the next century, AMOC is projected to weaken due to greenhouse gas warming, though projecting its future behavior is dependent on a better understanding of how AMOC changes are forced. Seeking to resolve an apparent contradiction of AMOC trends from paleorecords of the more recent past, we reconstruct seawater cadmium, a nutrient-like tracer, in the Florida Straits over the last ~8,000 years, with emphasis on the last millennium. The gradual reduction in seawater Cd over the last 8,000 years could be due to a reduction in AMOC, consistent with cooling Northern Hemisphere temperatures and a southward shift of the Intertropical Convergence Zone. However, it is difficult to reconcile this finding with evidence for an increase in geostrophic flow through the Florida Straits over the same time period. We combine data from intermediate water depth sediment cores to extend this record into the Common Era at sufficient resolution to address the broad scale changes of this time period. There is a small decline in the Cd concentration in the Late Little Ice Age relative to the Medieval Climate Anomaly, but this change was much smaller than the changes observed over the Holocene and on the deglaciation. This suggests that any trend in the strength of AMOC over the last millennium must have been very subtle.

1. Introduction

Atlantic meridional overturning circulation (AMOC) is a key component of the climate system, as it transfers heat from the Southern Hemisphere to the Northern Hemisphere. It has been implicated in the global expression of climate change, by forcing a "bipolar seesaw" of hemispheric temperatures (Broecker, 1998; Rahmstorf, 2002) and via processes that force shifts in the mean position of the intertropical convergence zone (ITCZ) and monsoons (Chiang & Bitz, 2005; Vellinga & Wood, 2002; Zhang & Delworth, 2005). Additionally, AMOC transports heat and carbon from the surface to the interior ocean (Kostov et al., 2014; Marshall et al., 2014), and may help determine the pace and patterns of warming due to the release of anthropogenic carbon. Regionally variable wind-driven processes dominate AMOC variability on intra-annual to interannual timescales (Xu et al., 2014; Zhao & Johns, 2014), while buoyancy-driven processes that are more coherent across latitudes play a larger role in forcing AMOC variability on decadal and longer timescales (Buckley et al., 2012; Tulloch & Marshall, 2012). Accordingly, modeling and observational studies have found that AMOC is not coherent between the North Atlantic subpolar and subtropical gyres on interannual to decadal timescales (Bingham et al., 2007; Lozier et al., 2010; Mielke et al., 2013; Williams et al., 2014). However, a model study finds coherent AMOC variability between the subtropics and subpolar regions on decadal or longer timescales and we should therefore expect studies of AMOC variability from different regions to yield similar results on these longer timescales (Gu et al., 2020).

A decline in AMOC over the industrial era (nineteenth and twentieth centuries) has been inferred from many paleoclimate proxy records (Caesar et al., 2021), but the timing of the weakening differs among records (Caesar et al., 2018; Lower-Spies et al., 2020; Thornalley et al., 2018), and there are even some records that do not suggest a weakening (Lund et al., 2006; Wanamaker et al., 2012). AMOC decline over the late twentieth century has been inferred from North Atlantic sea surface temperature data (Rahmstorf et al., 2015), sea-level variations across the Florida Current (Piecuch, 2020), and from partial records of circulation and sea surface height (Mercier et al., 2015). However, other studies suggest that the sea-surface temperature patterns and sea-level may respond to factors other than AMOC (Menary et al., 2020; Piecuch et al., 2016). For recent decades, observational arrays that capture continuous measurements of northward and southward flow across the Atlantic basin have come online (Lozier et al., 2019; Srokosz & Bryden, 2015). A decade of measurements from the RAPID array at 26.5 N confirmed an AMOC decline since 2008, though the extent to which this trend is related to Atlantic Multidecadal Variability/Atlantic Multidecadal Oscillation (AMV/AMO), decadal variability, and anthropogenic warming is undiscernible from the abbreviated record (Smeed et al., 2018). Models also project continued AMOC decline through 2100, but rates and magnitudes of weakening vary depending on ocean resolution and how the model constructs deep convection (IPCC, 2021). In light of the uncertainty around multidecadal AMOC variability and projections of future AMOC, paleoceanographic reconstructions seek to place AMOC variability over the last decades within the context of past variability.

1.1. Holocene AMOC Variability

In the Northern Hemisphere, Holocene climate has been largely stable relative to the preceding deglacial period. The most notable temperature features over the last ∼11,700 years are an abrupt and transient cooling near 8.2 ka (Rohling & Pälike, 2005) and gradual cooling from the climate optimum around 6–8 ka until the modern period (Kaufman et al., 2020). Both features are much smaller in magnitude than abrupt changes observed during the last deglaciation. It is thought that the transient cooling at 8.2 ka is due to a weakening of AMOC (Barber et al., 1999). It is still debated whether the cooling trend over the Holocene is global in extent, and the magnitude of cooling in the Northern Hemisphere varies considerably among reconstructions (e.g., Bader et al., 2020; Kaufman et al., 2020; Liu et al., 2014; Marcott et al., 2013; Marsicek et al., 2018). It is also unclear how AMOC changed along with the apparent Northern Hemisphere cooling over the Holocene. While records suggest a weakening of the Iceland-Scotland Overflow, one component of North Atlantic Deepwater (NADW), over the last ∼8 ka (Hoogakker et al., 2011; Kissel et al., 2009; Thornalley et al., 2013), several other records based on Pa and Th measurements are interpreted to represent no trend in overall AMOC strength for example, (Hoffmann et al., 2018; Lippold et al., 2019).

Attempts to characterize AMOC variability in the pre-modern Common Era have also yielded mixed findings. While the warm Medieval Climate Anomaly (MCA; ∼950–1300 CE) and the cool Little Ice Age (LIA, ∼1300–1850 CE) were first identified in Europe, much of the North Atlantic cools from the MCA to the LIA (Moffa-Sánchez et al., 2019), suggesting the possibility that this represented a transition from strong to weak AMOC. Lund et al. (2006) applied the geostrophic method using benthic $\delta^{18}O$ measurements to estimate Gulf Stream transport in the Florida Straits, a component of upper branch AMOC. They estimated that this transport was 10% weaker during the LIA than during the MCA. The interpretation that the lower LIA Florida Straits transport was due to a weaker AMOC was supported by a reconstruction of surface ocean radiocarbon north of Iceland (Wanamaker et al., 2012). However sortable silt records, which record the strength of key deep-sea AMOC components, show considerable regional variability, and do not show a coherent trend from the MCA to the LIA (Moffa-Sánchez et al., 2019).

1.2. Florida Straits Nutrients and AMOC

The 32 Sv of western boundary flow carried by the Florida Current transports both the surface branch of the AMOC (17 Sv), and the western limb of the subtropical gyre (15 Sv; Szuts & Meinen, 2017). The densest waters ($\sigma_\theta > \sim27$ kg m^{-3}) that transit through the Florida Straits constitute part (4–5 Sv) of the upper branch of the AMOC (Schmitz & Richardson, 1991) and are composed of fresh, higher nutrient Antarctic Intermediate Waters from the South Atlantic (Palter & Lozier, 2008) significantly diluted by saltier, lower nutrient waters by the time they reach the Florida Straits. The high nutrient content of the southern sourced waters reflects both high initial nutrient content of Antarctic Intermediate Water (AAIW) and additional nutrients gained from remineralization of organic matter as these waters pass through the tropics. Because of the strong tilt of isopycnals associated with the Florida Current, these densest high-nutrient waters are concentrated on the landward side of the Straits (Figure 1). This nutrient transport into the North Atlantic associated with the upper branch of the AMOC has been termed “the nutrient stream” and feeds marine productivity in the North Atlantic (Williams et al., 2006).

We would expect a decrease in nutrient content in the denser levels of the Florida Straits with a weakening of AMOC, as the contribution of northern-sourced gyre waters increases relative to southern-sourced water, and conversely an increase in nutrients with a stronger AMOC. Models show that projected future decreases in AMOC are accompanied by a decrease of nutrient transport into the North Atlantic, with a reduction of both

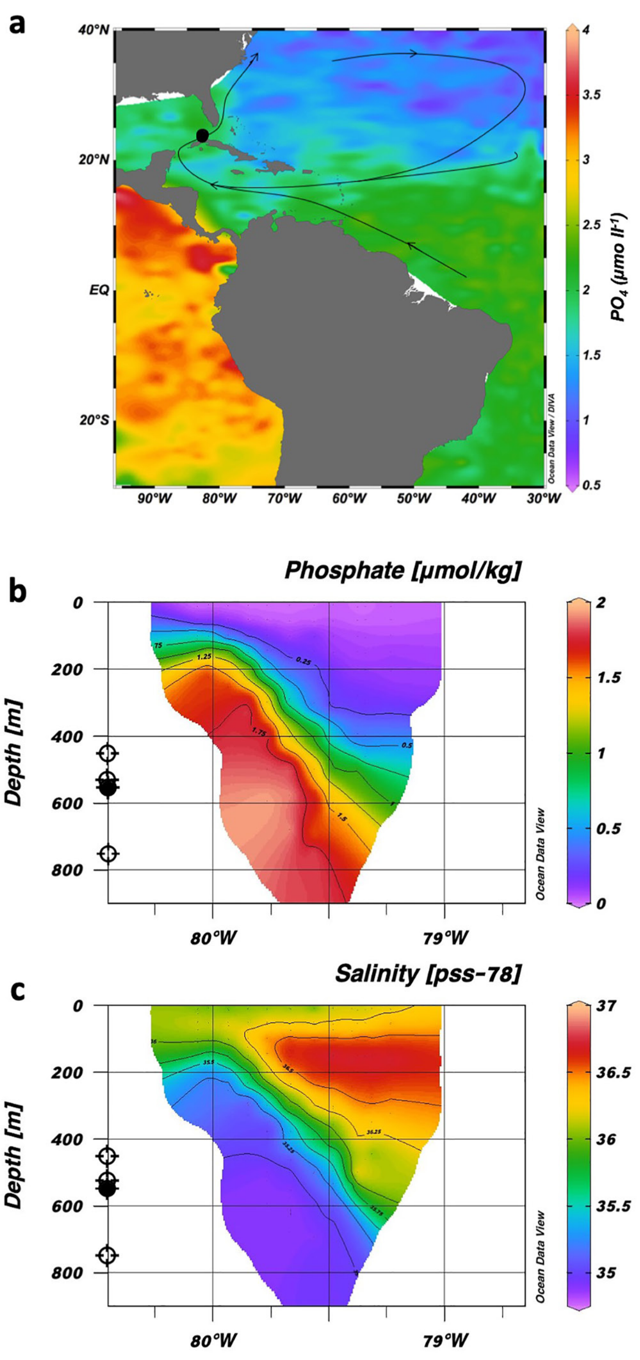

Figure 1. (a) Phosphate at potential density of 27.3 kg m^{-3} (Garcia et al., 2014) with approximate location (solid circle) of core KNR166-2 26JPC and large-scale upper Atlantic circulation patterns (black arrows). (b) Phosphate and (c) salinity in the Florida Straits at 27°N (Garcia et al., 2014; Schlitzer, 2000), downstream of our study area in the southern Florida Straits. Water depths of cores used in this study are indicated: KNR166-2 26JPC (solid circle) and other cores listed in Table 1 (open circles).

the nutrient concentration and volumetric flux in the densest levels of the Florida Straits (Tagklis et al., 2020; Whitt, 2019). We can get a sense of the scaling between nutrient changes in the Florida Straits and the strength of AMOC on a century timescale from a modeling study examining the changes in the nutrient stream projected to 2080 under the RCP8.5 global warming scenario (Whitt, 2019). In this study there was a reduction of norward volume transport by the Gulf Stream at 30.5 N (just north of the Florida Straits) of 22% (8 Sv) and a 35% reduction in nitrate transport. This corresponds to a 17% reduction in nitrate concentration. Because the import of nutrients along the western boundary currents is a dominantly advective phenomenon, the response in the nutrients to an increase in flow should be very rapid. Indeed, Carracedo et al. (2021) find that on interannual timescales the nutrient content and flow in the densest layers of the Florida Current are positively correlated. However, because the Florida Straits transport will only be coherent with AMOC variability on decadal or longer timescales (Gu et al., 2020), it would be unwise to interpret nutrient variability on shorter timescales in terms of AMOC changes.

Given the link between nutrient transport into the North Atlantic and AMOC, Cd/Ca measurements in benthic foraminifera have been used to reconstruct the nutrient tracer seawater Cd (Cd_w) in order to qualitatively infer past variability in AMOC (as in Came et al., 2008; Poggemann et al., 2017; Valley et al., 2017, 2019). Other tracers, such as Nd isotopes, which distinguish AAIW from northern sourced intermediate water, have also been used for qualitative reconstructions of AMOC variability (Huang et al., 2014; Xie et al., 2012). In a transient model study, Gu et al. (2017) show that the northward penetration of AAIW varies coherently with AMOC over the deglaciation. In this study, we investigate how Cd_w has changed along the Florida Margin over the mid to late Holocene, with particular focus on the last ~1,000 years, and discuss the implications for changes in AMOC over this time period.

2. Methods

Four of the Florida Straits cores included in the Lund et al., 2006 study were analyzed for trace and minor metal content (Table 1; Figure 2). The selected cores were retrieved from 447 to 751 m water depth on the Florida margin and the core sites are today bathed with the high nutrient AAIW. Radiocarbon measurements indicate that each core has a modern core top; age models are applied as in previous studies (Lund et al., 2006; Lund & Curry, 2004, 2006), but raw ^{14}C values are converted to calendar ages using CALIB 8.2 and the Marine20 calibration curve (Heaton et al., 2020). The cores had sedimentation rates ranging from 10 to 40 cm kyr^{-1}, and were sampled at 1 cm increments (30–90 years nominal time resolution), however the actual resolution of our composite record is diminished by bioturbation and age model uncertainty.

Cd/Ca, Mg/Ca, and Li/Ca were measured in the tests of the benthic foraminifer *Hoeglundina elegans*, after cleaning using the reductive and oxidative procedures outlined by Boyle and Keigwin (Boyle & Keigwin, 1985) and modified by Boyle and Rosenthal (1996). We analyzed 1–20 > 250 μm foraminifera per sample (samples containing more than 10 foraminifera were homogenized and split before cleaning, then analyzed separately as replicates) on a Thermo Element2 sector field inductively coupled plasma mass spectrometer (ICP-MS) using the methods of Rosenthal et al. (1999) and T. M.

Table 1
Florida Straits Core Locations

Water depth (m)	Core	Latitude (N)	Longitude (W)
447	KNR166-2 3MC-H	24 23.04	83 20.33
530	W167-79GGC	24 21.50	83 20.90
546	KNR166-2 26JPC[a]	24 19.61	83 15.14
547	KNR166-2 62MC-A	24 19.60	83 15.40
751	KNR166-2 11MC-D	24 13.18	83 17.75

[a] Core KNR166-2 26JPC as analyzed in Valley et al. (2019).

Marchitto (2006). Analytical precision (1σ) is 2% for Cd/Ca, 0.5% for Mg/Ca, and 0.9% for Li/Ca (Bryan & Marchitto, 2008).

As the partitioning of Cd in *H. elegans* is not strongly depth dependent, Cd_w was calculated from Cd/Ca using a partition coefficient of 1 (Boyle et al., 1995) and an assumed global mean seawater Ca concentration 0.01 mol kg^{-1} (Boyle, 1992).

Because of the scarcity of Common Era samples, Cd_w data from the four cores are combined to create a composite record. Over the depth range that includes the cores in this study, modern phosphate varies by approximately 0.20 μmol kg^{-1} (J. Zhang et al., 2017), equivalent to an estimated range of 0.08 nmol kg^{-1} of Cd_w. There are no systematic offsets in the Cd_w records by depth (Figure S1 in Supporting Information S1). Measurements from the individual cores are binned and averaged at 50-year intervals (Figure 4).

Of 180 samples analyzed (including replicates), 11 Mg/Li ratios are discarded due to Li contamination in the acid used to dissolve the foraminifera. In addition, 13 Cd_w and 13 Mg/Li temperature data points are excluded

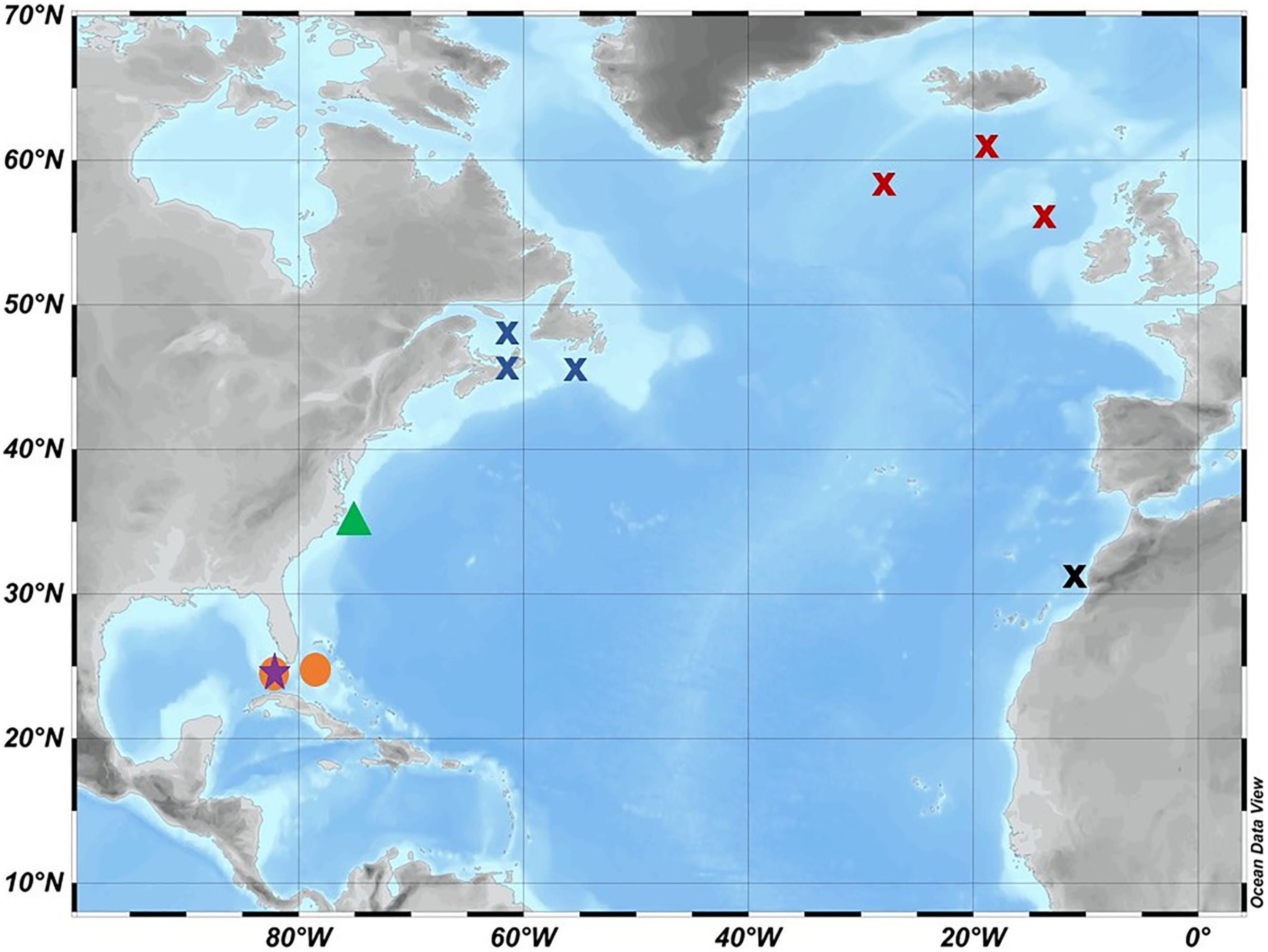

Figure 2. Common Era AMOC reconstruction approximate source locations. Star: Florida Straits cores used for Cd_w reconstruction; see Table 1 for location detail. Circles: cores used in the Lund et al., 2006 density gradient-based reconstruction of Gulf Stream transport. Triangle: cores used in Thornalley et al. (2018) sortable silt reconstruction of deep western boundary current flow. "X" symbols show the subsurface temperature proxy sites applied in Thornalley et al. (2018), where red and blue symbols indicate areas in a dipole where the subsurface ocean warms and cools, respectively, with strengthened AMOC.

as outliers, identified using the function smooth.m (Matlab version R2017b) with a robust Lowess smoothing method and 10% data smoothing window. Data beyond 2σ of the smoothed time series were marked as outliers.

Temperatures were reconstructed from Mg/Li ratios using the empirically derived polynomial calibration equation for *H. elegans*:

$$\mathrm{Mg/Li} = 0.150 \pm 0.012 + 0.0209 \pm 0.0027T - 0.0002 \pm 0.0001T^2$$

(T. M. Marchitto et al., 2018). The equation's fit corresponds to $r^2 = 0.95$, and the 1σ standard error of estimate for Mg/Li is 0.022 mol $\mathrm{mmol^{-1}}$, equivalent to ±1.0°C at 0°C and ±1.7°C at 20°C.

Published Cd/Ca and Mg/Li records from the same region (Valley et al., 2017, 2019; Figure S2 in Supporting Information S1) provide a longer-term framework for our new Common Era records. Previous work focused on deglacial changes; here we discuss Holocene trends and variability to contextualize our new records.

3. Results and Discussion

3.1. Mid-late Holocene

$\mathrm{Cd_w}$ derived from the Florida Straits KNR166-2 26JPC core (547 m) peaks around 8 ka (Figure 3). Thereafter, the decay of the North American and European ice sheets plays a lesser role in climate variability relative to the last deglaciation, and this portion of the Holocene is the focus of our analysis. One of the most noted events in Northern Hemisphere Holocene climate is an abrupt and brief (~200 years) incidence of Greenland cooling around 8.2 ka (Alley et al., 1997; Thomas et al., 2007). There is no indication of lower $\mathrm{Cd_w}$ that would be expected for a brief period of substantially weakened AMOC. Instead, the amplitude of variability near 8.2 ka is not distinct from the general variability of $\mathrm{Cd_w}$ in our record. However, given our record's ~80-year time resolution at this core section and the presence of bioturbation, it is not clear that such a brief decrease in $\mathrm{Cd_w}$ would have been recorded. However, the lack of an 8.2 ka signal is in line with Lippold et al. (2019) and Hoffmann et al. (2018) who also failed to see evidence in Bermuda Rise and Carolina Slope sedimentary records for an AMOC weakening at 8.2 ka.

The most evident trend in mid-late Holocene $\mathrm{Cd_w}$ is a gradual decline from a 300-year average of 0.47 ± 0.03 nmol $\mathrm{kg^{-1}}$ (reported errors are 2σ standard error on the mean, unless otherwise indicated) near 8.2 ka to an average of 0.36 ± 0.05 mol $\mathrm{kg^{-1}}$ around 510 BP, the most recent 300-year period in the record. Such a gradual change in nutrient content of the deep Florida Straits could reflect changes in the nutrient content of the northern and/or southern sourced intermediate waters, as well as the mixture between the two. A southern hemisphere record of AAIW does suggest a small (<0.05 nmol $\mathrm{kg^{-1}}$) decline in $\mathrm{Cd_w}$ over the last 8 ka (Umling et al., 2019), which is not enough to account for the decline we see in the Florida Straits. However, since the AAIW gains considerable amount of nutrients in the tropics, probably a more relevant record is from the Tobago Basin off Venezuela, which also shows a slight decline in intermediate water $\mathrm{Cd_w}$ (Poggemann et al., 2017). There are two records from the Bahamas on the seaward (subtropical gyre) side of the Florida Current (Came et al., 2008; T. Marchitto et al., 1998) that are today near the AAIW density level, but are not in the core of AAIW which travels up the western boundary and have a much stronger imprint of the Northern Hemisphere end member. The first shows no discernible trend over the last 8 ka, and the second shows a slight increase in $\mathrm{Cd_w}$ over this time period. These records suggest that the larger decline in $\mathrm{Cd_w}$ we observe on the Florida margin reflects, in large part, a decrease in the proportion of southern versus northern sourced intermediate waters rather than end member changes.

The simplest explanation for the decline in $\mathrm{Cd_w}$ at AAIW levels in the Florida Straits is that the contribution of Southern sourced intermediate waters has declined with time, and that this reflects a decrease in the import of these intermediate waters into the northern hemisphere as part of the upper branch of AMOC. This explanation would seem in conflict with geostrophic transport estimates through the Florida Straits which suggest an increase in upper-level Florida Current flow over the Holocene (Lynch-Stieglitz et al., 2009). However, this increase has been interpreted as likely reflecting an increase in the wind driven gyre flow through the straits. The wind driven gyre flow is primarily carried above AAIW density layer (e.g., Szuts & Meinen, 2017), and the change in geostrophic transport is found in the upper layers, driven by the changes in density on the gyre side of the Florida Current. Given the scaling between nutrient concentration and AMOC flow from the climate models, we would suggest a substantial AMOC reduction on the basis of the magnitude in the reduction in $\mathrm{Cd_w}$. To reconcile the

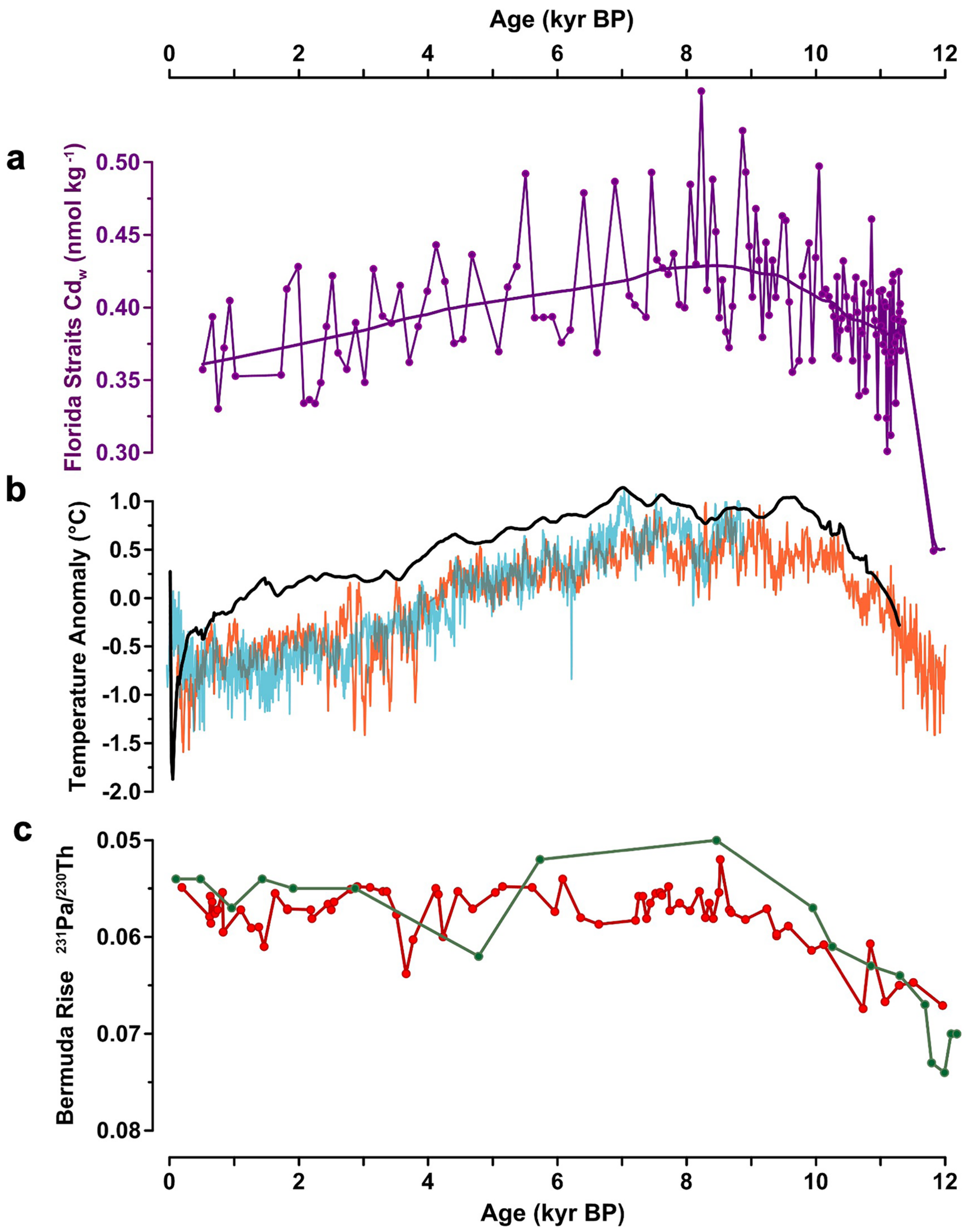

Figure 3. Holocene climate reconstructions. (a) Florida Straits Cd$_w$ with 10% robust Lowess smoothing line from core KNR166-2 26JPC at 547 m; (b) modified from (Marcott et al., 2013), mean temperature reconstruction for 90° to 30°N; Dongge Cave speleothem δ^{18}O (blue, Wang et al., 2005) and Cariaco Basin Ti% (orange, Haug et al., 2001), both indicators of regional precipitation change influenced by ITCZ positioning, where up implies a more northerly ITCZ; (c) Bermuda Rise ^{2s31}Pa/^{230}Th AMOC reconstruction from ODP Site 1063 (red, Lippold et al., 2019) and OCE-326-GGC5 (green, McManus et al., 2004), both at 4.6 km.

geostrophic transport estimate with the inference of a weakening AMOC from the Cd$_w$, the increase in wind driven flow would have to more than compensate to result in a strengthening of total flow of the Florida Current over the Holocene. It is also possible that since only 4.5 of the 17 Sv passing through the Florida Straits that constitutes the upper branch of the AMOC is represented in the AAIW density layer, the Holocene decrease in this denser component of the upper branch of the return flow implied by the decline in nutrient concentrations

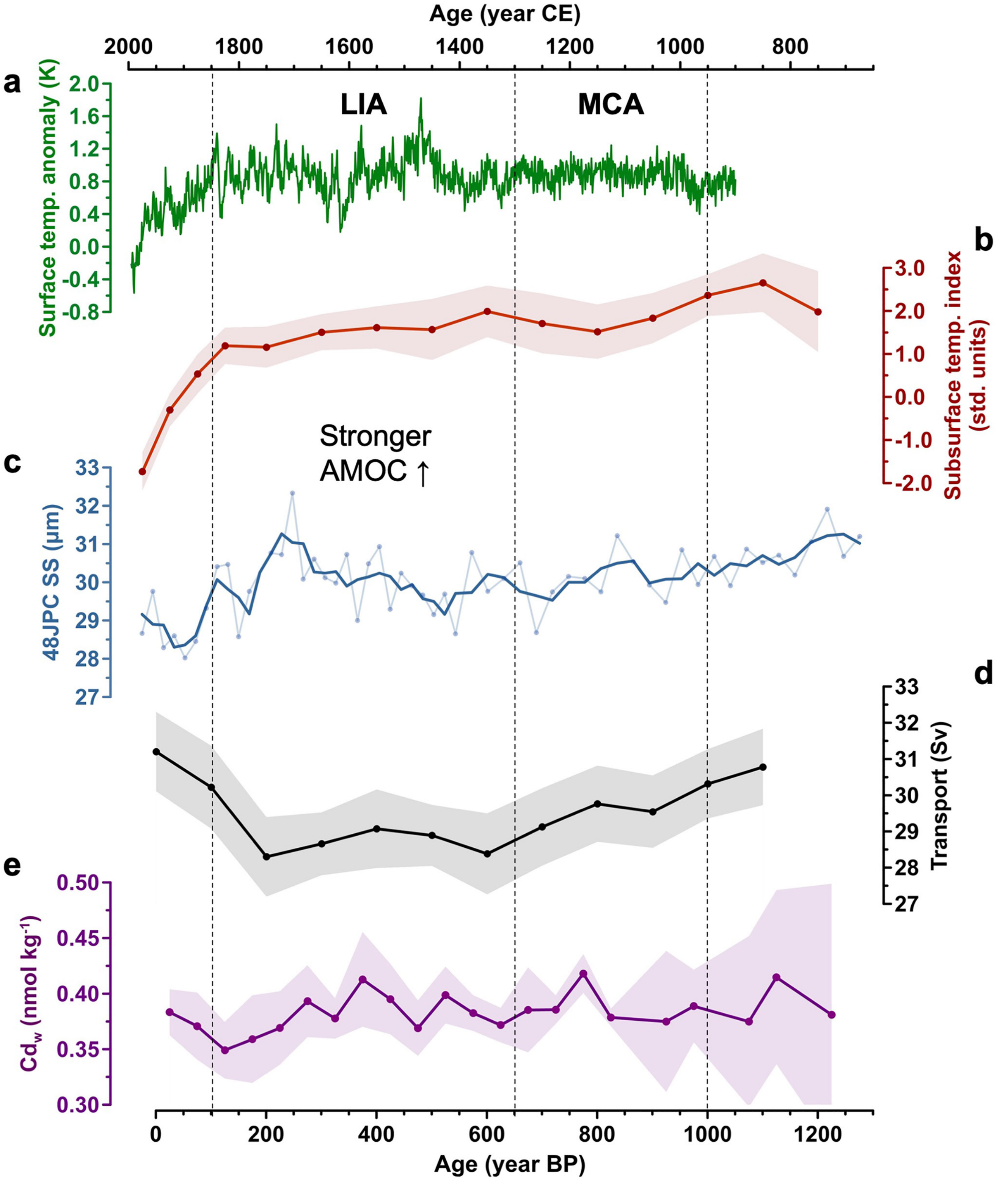

Figure 4. Indicators of Common Era AMOC variability. (a) North Atlantic surface temperature AMOC index (Rahmstorf et al., 2015), (b) Subsurface temperature AMOC index (Thornalley et al., 2018), (c) Mean grain size sortable silt (SS) with three-point means (bold curve) (Thornalley et al., 2018), (d) Transport (Sv) estimate from Florida Straits density-gradient analysis (Lund et al., 2006), and (e) this study: 50-year average Florida Straits seawater cadmium data shown with 95% confidence interval and using the Marine20 age calibration.

was compensated by an increase in less dense AMOC return flow. It has recently been suggested that a large fraction of the surface return flow bypasses the Florida Straits today (Drouin et al., 2022), so perhaps an even larger fraction of these surface waters bypassed the Straits in the mid-Holocene. Another possible explanation for the discrepancy is that the assumption in the geostrophic transport estimate that the bottom velocity was as weak as today over the entire 8 kyr time period is incorrect. Since we do not have enough evidence to provide a unique, consistent explanation of both data sets, the interpretation of a gradual decline in AMOC over the Holocene based on the Cd_w record should be viewed as provisional.

The inferred gradual AMOC decline from the Florida Straits Cd_w record is consistent with several records of a ~7 kyr progressive decline in Iceland Scotland overflow (Hoogakker et al., 2011; Kissel et al., 2009; Kissel et al., 2013; Thornalley et al., 2013), one component of NADW. However, other studies from the high latitude North Atlantic and the Bermuda Rise instead find centennial variability but no large-scale trends in AMOC or NADW components (Figure 3c: Hoffmann et al., 2018; Keigwin & Boyle, 2000; Lippold et al., 2019; McManus et al., 2004; Mjell et al., 2015), and a study from the South Atlantic finds evidence of enhanced AAIW in the late Holocene relative to the mid Holocene (Voigt et al., 2016).

The implied long-term reduction in the incursion of AAIW into the North Atlantic as part of the upper branch of the AMOC took place as temperatures in the extratropical Northern hemisphere appear to have declined, with an average temperature decrease of 2°C between 7 ka and 100 years BP (Marcott et al., 2013). Large-scale change in Florida Straits Cd_w over the last 8,000 years also parallels evidence of ITCZ migration over the same period. The ITCZ shifted progressively southward after the Holocene Thermal Maximum around 7–9 ka, as inferred from precipitation change near the Cariaco Basin in South America and the Dongge Cave in China (Haug et al., 2001; Wang et al., 2005, Figure 3). Cooling temperatures in the mid to late Holocene and the southward ITCZ migration have been attributed to declining Northern Hemisphere summer insolation (Wanner et al., 2008) and corresponding snow-ice albedo and vegetation feedbacks (Marcott et al., 2013). However, changes in mean annual ITCZ position can also reflect changes in AMOC's transport of heat north of the equator (Zhang & Delworth, 2005). The temporally coherent Florida Straits Cd_w decline suggests that a weakening AMOC and the resulting decrease of heat transport into the Northern Hemisphere could have provided an additional mechanism for the southward ITCZ shift.

3.2. Common Era

Florida Straits Cd_w is stable through the Medieval Climate Anomaly (MCA; ~950–1300 CE) and the early LIA, with possible lower values in the later LIA (Figure 4). The measurements of Cd_w from all four cores averaged 0.383 ± 0.005 nmol kg^{-1} over the last 2,000 years. During the MCA Cd_w averaged 0.392 ± 0.011 nmol kg^{-1} and it averaged 0.380 ± 0.007 nmol kg^{-1} over the LIA. The difference between these periods is not statistically significant (2σ) under a Student's *t*-test. However, there is a suggestion of lower Cd_w during the latter half of the LIA (1675–1850 CE), which featured Cd_w 0.025 ± 0.020 nmol kg^{-1} lower than the MCA average, consistent with the proxies applied in Thornalley et al. (2018) that indicate the late LIA as a transition period to a weakened industrial era AMOC. Further, the trend of Cd_w estimates over the entire period of both the MCA and LIA (950–1850) is significant at the 95% level. The idea that this slight trend in Cd_w over this time period is due to a weakening AMOC is supported by Lund et al. (2006). The surface temperature AMOC index of Rahmstorf et al. (2015), instead, does not support a weakening of AMOC over this time period (Figure 4).

As was the case for the longer Holocene records, we have to consider the possibility that changes in the end member composition of the southern or northern source waters rather than AMOC changes could have produced the late LIA reduction, but in this case we have no other record at similar resolution to help us assess this possibility. However, even if we ascribed all of the observed Cd_w variability to changes in AMOC, the magnitude of these changes was likely modest. Following the results from the Whitt (2019) modeling study and assuming that the reduction in nutrient is proportional to nutrient concentration across the section, one would then expect the 3% reduction in Cd_w concentration for the LIA relative to the MCA to be associated with a decline in Florida Straits Transport of around 4% or 1.4 Sv. This is only slightly smaller than the reduction in transport observed by Lund et al. (2006) over the same time period.

During periods of reduced AMOC, intermediate waters along the Florida Margin are expected to warm due to the relaxation of the tilted isotherms in this location, or by other mechanisms of subsurface western tropical

Atlantic warming (Valley et al., 2019 and references therein). There is a small but significant (95% confidence, students *t*-test) increase in Mg/Li temperature during the LIA (6.5°C, std. err. 0.06) relative to the MCA (6.2°C, std. err. 0.08; Figure S1 in Supporting Information S1). While a 2°C warming was associated with weakened Florida Straits transport during the earlier Younger Dryas glacial period, the small change in temperatures in the combined Florida Straits Common Era core records underscores the subtlety of any changes in AMOC that may have occurred over the last 2,000 years.

4. Conclusions

If the gradual reduction in Florida Straits Cd_w from the mid to late Holocene represents a decline in AMOC, this would suggest that the cooling temperatures in the Northern Hemisphere may have, like the dramatic climate changes of the deglaciation, been driven at least in part by changes in AMOC-driven oceanic heat transport even without the influence meltwater from large ice sheets. It is worth noting that there is still considerable disagreement among proxy records as to the sign and magnitude of trends in AMOC over the Holocene. However, there are now multiple lines of evidence suggesting that cooler temperatures in the late Little Ice Age were accompanied by a weakening AMOC, even though the timing of transitions into and out of the LIA weakening are inconsistent across records. The records presented here from the Florida Straits highlight the subtlety of AMOC changes over the LIA and MCA. However, the observations in the paleorecord of a slight reduction in AMOC during the transition from the MCA to the LIA in the North Atlantic stand in contrast to the apparent dramatic slowdown associated with warming over the Industrial Era (e.g., Caesar et al., 2021). These findings underscore the need for greater understanding of AMOC's stability and under what conditions AMOC changes may lead or lag shifts in climate. These questions are highly relevant in the current period of warming temperatures and changes in buoyancy forcings at high latitudes.

Data Availability Statement

Data generated in this study is available at the NOAA National Centers for Environmental Information Database (Valley et al., 2022).

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