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1. Supplementary Information:

A. Flat Files

Item	Present?	Filename This should be the name the file is saved as when it is uploaded to our system, and should include the file extension. The extension must be .pdf	A brief, numerical description of file contents. i.e.: *Supplementary Figures 1-4, Supplementary Discussion, and Supplementary Tables 1-4.*
Supplementary Information	Yes	SupplementalTable1.pdf	Figure 1 credits and table of data in the figure.
Reporting Summary	No		

Atlantic circulation change still uncertain

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Deep oceanic overturning circulation in the Atlantic (Atlantic Meridional Overturning Circulation, AMOC) is projected to decrease in the future in response to anthropogenic warming. Caesar et al.[1] argue that an AMOC slowdown started in the 19th century and intensified during the mid-20th century. Although the argument and selected evidence proposed have some merits, we find that their conclusions might be different if a more complete array of data available in the North Atlantic region had been considered. We argue that the strength of AMOC over recent centuries is still poorly constrained and the expected slowdown may not have started yet.

Recently, Moffa-Sanchez et al.[2] compiled a comprehensive set of paleoclimate proxy data from the North Atlantic and Arctic regions using objective criteria for identifying high-quality datasets of ocean conditions spanning the last two millennia (Figure 1). Although no direct (singular) proxy for AMOC exists, the paleoceanographic proxy data compiled by Moffa-Sanchez et al.[2] highlight the spatial and temporal complexities of ocean state in modern times and the recent past. When all the available proxy records potentially related to AMOC variability and 20th century observational datasets are considered, the time history of the AMOC system becomes less certain. In contrast, selecting only a subset of proxy records that share similar trends, as performed by Caesar et al.[1], provides an incomplete perspective on AMOC changes through time.

Increased data availability in recent decades has enabled a shift in the fields of paleoceanography and paleoclimatology toward more objective and transparent data selection in studies aimed at quantitatively reconstructing past variability. Such screening methods tend to minimize the impact of spurious or less reliable records on analyses and work to enhance the common signal in proxy records. Additionally, analyzing networks of suitable and carefully selected data enables robust uncertainty estimates on the resulting reconstructions, which is essential in providing confidence in the results and the ability to compare information across disciplines. Key to such work is identifying robust criteria and weighting schemes that objectively identify and utilize the most reliable data. Caesar et al.[1] use a variety of proxy records in their analysis, but do not identify the reasoning or criteria for selecting those records over many others that are likely related to aspects of AMOC dynamics (see the recent review[2]).

Objective and inclusive data selection standards are especially important when addressing AMOC, which is a system composed of many different components that can behave differently at different latitudes, depths, and timescales[3] and looking at any singular index of AMOC inherently oversimplifies the system. The complex signals in the available AMOC-related proxy variables over recent centuries support this notion[2], though many of these studies were not considered by Caesar et al.[1]

In addition to the need for objective standards, we argue that most of the records compiled in the Caesar et al. paper have substantial caveats that were not discussed. Reconstructing the strength of AMOC more than a few decades ago relies upon paleoclimate and paleoceanographic proxies because direct measurements are unavailable. Some proxies are more directly related to components of AMOC variability than others, and some sites are better situated to record specific oceanographic and atmospheric processes than others. The limited scope of data utilized combined with the inherent uncertainties in the proxies and conflicting evidence from other sources, leaves the question open whether the available evidence supports the conclusion that AMOC is currently undergoing an unprecedented shift/weakening.

Key information and rationale about the records included are lacking in Caesar et al.[1]. For example, the Rahmstorf et al.[4] AMOC reconstruction used by Caesar et al.[1] is based on the subpolar North Atlantic temperature minus the Northern Hemisphere mean temperature, each constructed from tree ring and ice core records, and a scaling coefficient derived from one climate model. These data are land-based estimates influenced by atmospheric conditions, not necessarily robust indicators of marine temperatures, and the resulting index is strongly impacted by the global warming signal[5]. Furthermore, subpolar gyre sea surface temperatures (SSTs) are an unreliable indicator of AMOC variability[5,6] because SST can have multiple drivers and the spatial AMOC/SST fingerprints used for such reconstructions are temporally non-stationary[2,5]. Variables related to marine biological processes used as evidence by Caesar et al.[1] are potentially problematic as they are not directly responding to the AMOC and their signal may be compromised by other non-physical factors. For instance, the Sherwood et al.[7] study provides nitrogen isotopic evidence of a shift in nutrient dynamics since the 19th century in the northwestern Atlantic which they attribute to local changes in water masses, and others[4] have linked to AMOC. The interpretation of this proxy is predicated on stable nitrogen utilization and nitrogen isotope signatures in the system despite massive anthropogenic perturbation of the global N cycle over the study period[8]. Additional evidence used to infer an AMOC slowdown by Caesar et al.[1] come from sortable silt records off Cape Hatteras[9], which are arguably one of the most direct proxies available for near-bottom water current speed[10]. However, this proxy assumes that the position of the bottom current is stationary through time and that these deep flow changes are representative of AMOC strength. Similar methods have been used to examine the other parts of the deep AMOC limb, including the Nordic Overflows with results that are not consistent with conclusions reached by Caesar et al.[1] (for example, see[11, 12, 13]), yet these records were not considered.

Finally, the proxy data presented by Caesar et al.[1] need to be reconciled with observations of AMOC and AMOC-related variables in the 20th and 21st centuries. Caesar et al.[1] plot a trend derived from Smeed et al.[14] to support their supposition that AMOC has significantly decreased in recent decades. However, the decreasing trend measured in RAPID data between 2004 and 2012 is really more of a stepwise shift[14] and is likely a part of decadal-scale variability with increases in AMOC from 1960 to the early 2000s[15, 16]. To date, the RAPID array observations are too short to resolve multidecadal and longer-scale variability. Some indirect or partial AMOC measures over the instrumental era permit investigation into decadal-to-multidecadal variability and suggest a modest decline in transport[17], others show no trend[18, 19], and one record[20] shows a recent strengthening of the AMOC at subpolar latitudes. While diverse regional responses are plausible amidst a large-scale AMOC decline, work remains to understand the origin of such discrepancies.

These apparently contradictory results may be reconciled with more information regarding the spatial and temporal scales of variability involved in each dataset as well as the sensitivity and fidelity of the proxies to record aspects of AMOC during a large global climate perturbation. Real and interesting subtleties and discrepancies in the data still exist, and any impression that the historical AMOC evolution is confidently known from a subset of the available data is misleading until the conflicts are resolved. Instead, highlighting apparent contradictions will help us with the work of reconciling the data and answering the important question of whether the AMOC and/or its components have indeed slowed down in recent centuries. The authors declare no competing interests.

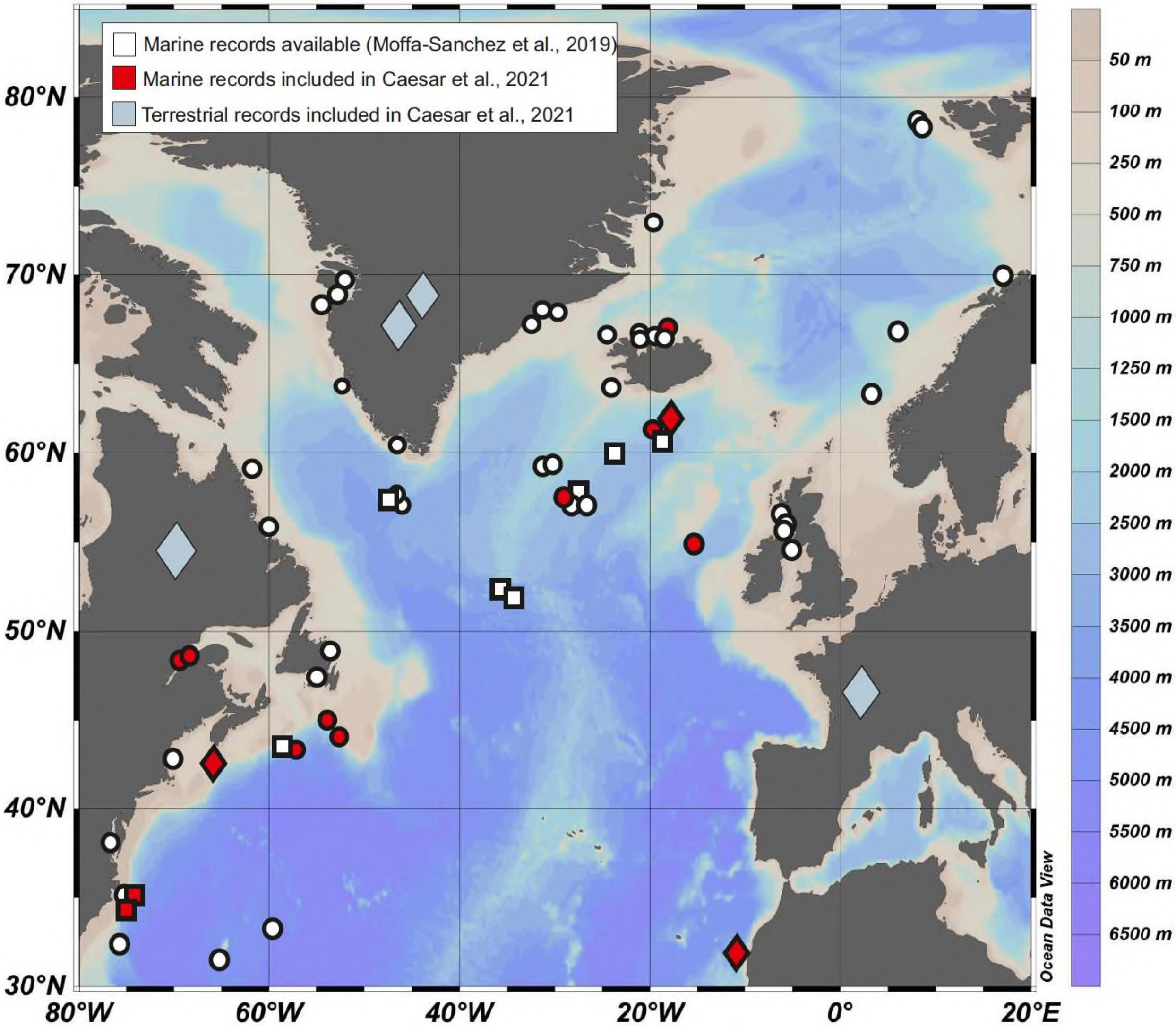

Figure 1. Available well-dated northern North Atlantic paleoceanographic records include proxies for temperature, salinity, sea ice, and ocean circulation. A full list is in Supplementary Information Table 1. Surface (circles) and deep ocean records (squares) screened by Moffa-Sanchez et al.[2] (white) are compared with the subset of data (red) used by Caesar et al.[1] The red diamonds are only presented in Caesar et al.[1] and include: biological productivity, nutrient records, and intermediate water temperatures. Multiple cores/archives in the same location are offset for visibility. Source locations, original studies, and figure-making software credits are in Supplementary Information Table 1.

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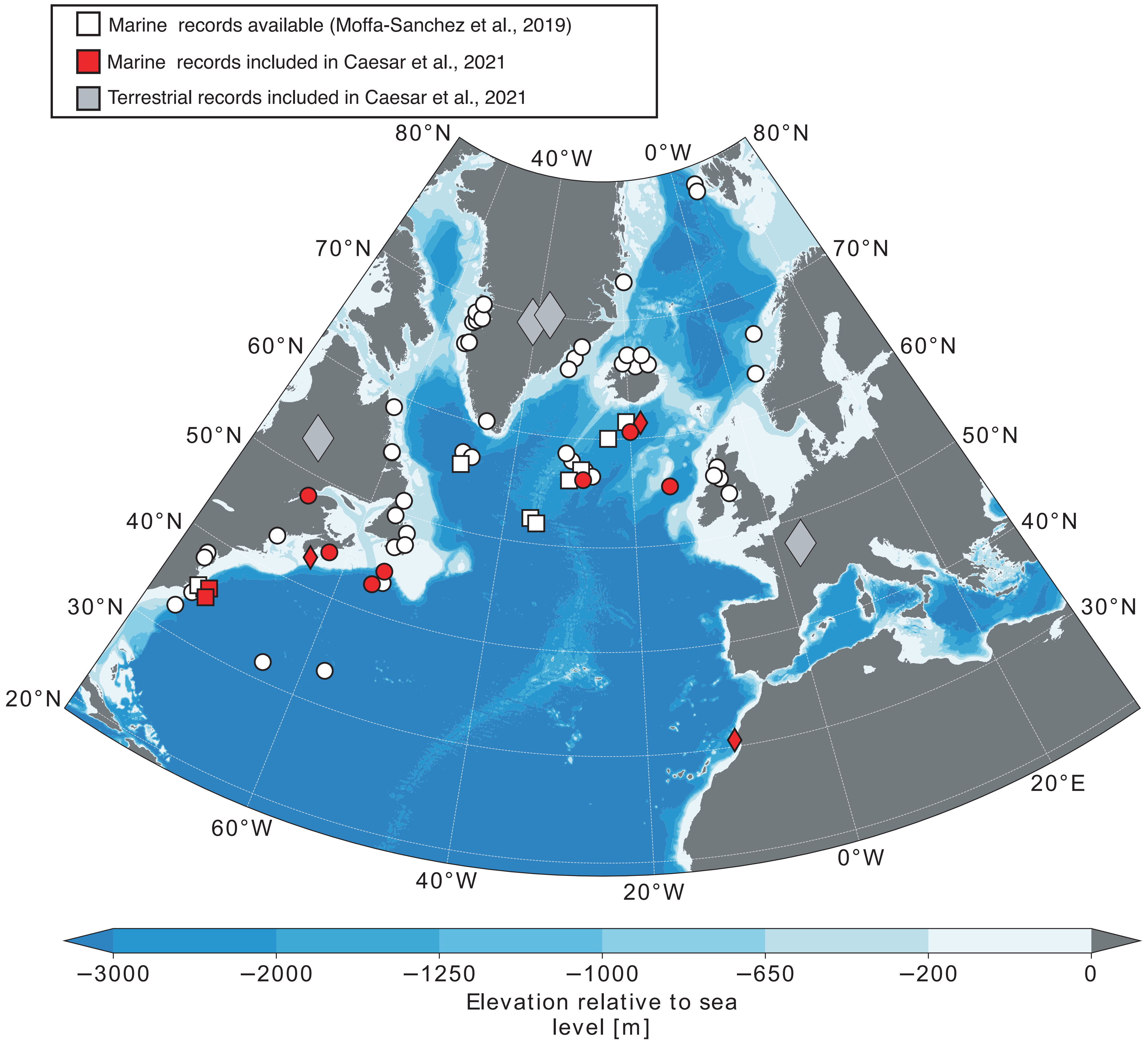
☐ Marine records available (Moffa-Sanchez et al., 2019)
🟥 Marine records included in Caesar et al., 2021
▨ Terrestrial records included in Caesar et al., 2021
80°N
40°W
0°W
80°N
70°N
70°N
60°N
60°N
50°N
50°N
40°N
40°N
30°N
30°N
20°N
20°E
60°W
0°W
40°W
20°W
−3000
−2000
−1250
−1000
−650
−200
0
Elevation relative to sea level [m]

Supplemental Table 1: These are the locations and citations to the available highly-time-constrained paleoceanographic data in the northern North Atlantic in Figure 1. The figure was made with open-source projects matplotlib[1] (https://matplotlib.org/), cartopy (https://scitools.org.uk/cartopy) and xarray[2] (http://xarray.pydata.org/en/stable/). The bathymetry contours are from GEBCO bathymetry (http://www.gebco.net/) .

Core name	**Latitude Decimal Degrees**	**Longitude Decimal Degrees**	**Proxy***	**References**
SUBPOLAR N ATLANTIC				
SURFACE				
MD99-2322	67.1363	-30.8278	diatom assemblage	3
RAPiD-35-COM	57.5042	-48.7223	SS, foraminifera assemblages and $\delta^{18}O$	4,5
RAPiD-35-25B	57.5078	-48.7233	Mg/Ca temperatures, foraminiferal assemblages and $\delta^{18}O$	6,7
RAPID-21-12B	57.4515	-27.9088	foraminiferal $\delta^{18}O$ and Mg/Ca, SS	8,9
RAPiD-21-12B and 3K	57.2715	-27.5488	diatom assemblages, alkenones and SS	5,10,11
RAPiD-17-5P	61.4817	-19.5360	foraminiferal $\delta^{18}O$ and Mg/Ca and SS	4,6
LO09-14 and D37-2P	58.2605	-30.2075	diatom assemblages	12
GS06-144-04	58.9122	-31.2542	foraminifera, alkenones, $\delta^{18}O$	13
ENAM9606/MD200309	55.6503	-13.9850	foraminiferal $\delta^{18}O$ and Mg/Ca	14
AI07-04BC/3G	48.7333	-53.4833	Alkenones	15
AI07-11BC/12G	47.1333	-54.5500	Alkenones	15
AI07-06G	47.8500	-53.5800	benthic foraminifera and dynoflagellate assemablages	16
CR02-23&MD99-2220	48.6387	-68.6322	foraminiferal $\delta^{18}O$	17
GS06-144-03	57.2900	-48.3700	$\delta^{18}O$ foraminifera and Ice rafted debris	18
PO175GKC	66.2040	-31.9850	IRD and biomarkers	19
MD04-2832 & PM06-MC01C	56.6698	-5.8687	foraminiferal $\delta^{18}O$	20
KNR140_2_59GGC	32.9770	-76.3160	foraminiferal Mg/Ca	21
MD99-2209 and RD-98	38.8863	-76.3947	$\delta^{18}O$ and Mg/Ca ostracod and foraminiferal	22
MD03-2661	38.8868	-76.3982	$\delta^{18}O$ and Mg/Ca ostracod and foraminiferal	22
PTXT-2	38.3263	-76.3925	$\delta^{18}O$ and Mg/Ca ostracod and foraminiferal	22
MD99-2203	34.9772	-75.2017	foraminiferal Mg/Ca and $\delta^{18}O$	23
MC13A	43.0833	-55.8000	%Nps	24
MC25A	43.4500	-54.8167	%Nps	24

KNR158-10MC/09GGC	44.8333	-54.9000	%Nps	[25]
OCE-326-MC-29D	45.8850	-62.7950	Mg/Ca and δ^{18}O benthic foraminifera, %Nps, alkenone, planktonic foraminiferal δ^{18}O	[26]
HU89-038-BC-004A and HU89-038-BC-004D	33.6933	-57.6117	carbonate content, sediment magnetic variables, foraminifera, stable isotopes	[27]
Red Algae	56.0332	-5.6022	red algae Mg/Ca	[28]
Long-lived bivalve	56.6292	-6.4000	bivalve growth increments	[29]
Long-lived bivalve	54.0917	-4.8333	bivalve growth increments	[30,31]
Long-lived bivalve	43.6870	-69.7990	δ^{18}O, *Arctica islandica*	[32]
BB 001	32.1667	-64.5000	coral Sr/Ca and d18O	[33]
Ki1, Ki2 Moore et al., 2017	55.3983	-59.8467	Mg/Ca, growth coralline algae	[34]
Gamboa et al., 2010/Halfar et al., 2011	47.3083	-52.7892	Mg/Ca coralline algae	[35,36]
Gamboa et al., 2010/Halfar et al., 2012	51.5856	-55.4248	Mg/Ca coralline algae	[35,36]
Gamboa et al., 2010/Halfar et al., 2013	50.0250	-55.8833	Mg/Ca coralline algae	[35,36]
Halfar et al., 2013	55.4352	-59.8654	Mg/Ca, growth coralline algae	[37,38]
Hu2006-40	59.2640	-62.4478	SS	[39]
DEEP				
CH77-02	52.7000	-36.0830	magnetism	[40,41]
MD08-3182Cq	52.6990	-35.9360	magnetism	[40]
RAPiD-35-COM	57.5042	-48.7223	SS, foraminifera assemblages and δ^{18}O	[4,5]
RAPiD-21-12B and 3K	57.4515	-27.9080	Diatom assemblages, alkenones and SS	[5,10,11]
RAPiD-17-5P	61.4817	-19.5360	foraminiferal δ^{18}O and Mg/Ca and SS	[4,6]
GS06-144-09MC-D&GS06-144 08GC	60.3167	-23.9667	SS	[42,43]
MD99-2251	57.4478	-27.9078	magnetism and SS	[40,44,45]
KNR-178-48JPC	35.7667	-74.4500	mean sortable silt	[25]
KNR-178-56JPC	35.4667	-74.7167	mean sortable silt	[25]
KNR158-10MC/09GGC	44.8333	-54.9000	benthic foraminiferal Mg/Ca and δ^{18}O	[46]
NORDIC SEAS				

JM97-948 2A&MD95-2011	66.9697	7.6393	diatom and foraminiferal assemblages, $\delta^{18}O$ and Mg/Ca foraminifera, current speed, alkenones	47–52
P1_003MC, P1_003SC	63.7622	5.2553	foraminiferal $\delta^{18}O$	53
MD99-2275	66.5517	-17.6998	alkenones, diatom assemblages, IP25, radiocarbon	11,54–62
Long-lived bivalve	66.5265	-18.1957	bivalve $\delta^{18}O$ and radiocarbon	63,64
MD99-2269	66.6314	-20.8544	diatom assemblage, IRD, coccolith counts, IP25	65–69
HM107-03	66.5025	-19.0722	foraminifera, stable isotopes, diatoms and ice rafted debris	70
MSM5/5-712-1	78.9157	6.7672	foraminiferal assemblages, Mg/Ca, SS, $\delta^{18}O$ benthic and planktic	71,72
MD99-2273	66.7630	-18.7503	foraminifera $\delta^{18}O$, ^{14}C	57,60
JM-06-WP-04-MCB	78.9155	6.7668	Dinocyst assemblage	73
PS2641 BC/GC	73.1550	-19.4817	Org Geochem (IP25), foraminifera assemblages, IRD	74,75
JM96-1206/2GC	68.1002	-29.4433	planktic and benthic foraminifera assemblages	76
W GREENLAND				
M343300	68.4719	-54.0017	diatom, benthic foraminifera, dynoflagellate assemblages, alkenone UK37	77–80
M343310	68.6477	-53.8248	diatom, benthic foraminifera, dynoflagellate assemblages, IP25, alkenones	78,79,81–85
DA00-03P	69.0000	-53.1333	diatom and dinoflagellate assemblages	66,86
DA00-02P	68.8647	-53.3287	diatom and dinoflagellate assemblages	86,87
DA06-139G	70.0913	-52.8930	benthic foraminifera, dinoflagellates, diatom assemblage	88,89
GA306-BC/GC3	66.6247	-54.2097	diatom benthic foraminiferal assemblages, foraminiferal $\delta^{18}O$	90–92
GA306-BC/GC4	66.7447	-53.9403	diatom benthic foraminiferal assemblages, foraminiferal $\delta^{18}O$	90–92
PO243-451	60.6993	-46.0333	benthic foraminifera and diatom assemblages	93,94
MARINE RECORDS USED IN[95]				
MC13A	43.0833	-55.8000	%Nps	24
COR05-37	48.3333	-61.5000	$\delta^{18}O$	96

OCE-326-MC-29D	45.8850	-62.7950	foraminiferal δ^{18}O, %Nps, Benthic δ^{18}O, and Mg/Ca	26
RAPID-21-12B	57.4515	-27.9088	foraminiferal Mg/Ca	8
RAPiD-17-5P spliced with RAPiD-12K	61.4817	-19.5360	foraminiferal Mg/Ca	6,97
ENAM9606	55.6503	-13.9850	foraminiferal Mg/Ca	14
GeoB6007-2&OC437-7 24GGC	30.8500	-10.2700	foraminiferal Mg/Ca	98,99
KNR-178-48JPC	35.7667	-74.4500	mean sortable silt	25
KNR-178-56JPC	35.4667	-74.7167	mean sortable silt	25
16MC/RAPID-17-5P	61.4820	-19.5360	% T. quinqueloba	100
CR02-23&MD99-2220	48.6387	-68.6322	foraminifera δ^{18}O	17
δ^{15}N Sherwood 2011	42.0	-65.6	δ^{15}N from deep corals	101

*%Nps represents percent *Neogloboquadrina pachyderm*a sinistral coiling, and SS represents percent sortable silt

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