Last century warming over the Canadian Atlantic shelves linked to weak Atlantic Meridional Overturning Circulation

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Abstract

The Atlantic meridional overturning circulation (AMOC) is a key component of the global climate system. Many models predict a weakening or even a collapse of the AMOC under future climate change. Recent studies suggested a 20th century weakening of the AMOC of unprecedented amplitude (~ 15%) over the last millennium. Here, we present a record of $\delta^{18}O$ in benthic foraminifera from sediment cores retrieved from the Laurentian Channel and demonstrate that the $\delta^{18}O$ trend is linked to the strength of the AMOC. In this 100-year record, the AMOC signal decreased steadily to reach its minimum value in the late 1970's, where the weakest AMOC signal then remains constant until 2000. We present a longer $\delta^{18}O$ record of 1,500 years and highlight the uniqueness of these high $\delta^{18}O$ values over that period. Moreover, the long record is also characterized by statistically heavier $\delta^{18}O$ during the Little Ice age, suggesting a relatively weak AMOC.

1. Introduction

The Atlantic meridional overturning circulation (AMOC) encompasses the advection of warm and saline waters in the upper ocean to the northern parts of the Atlantic, where it cools, becomes denser and sinks, ultimately creating North Atlantic deep water. Both observational and modeling studies have suggested that the strength of this oceanic circulation cell is not constant through time (Bohm et al., 2015; Rahmstorf et al., 2015), and that these changes drive many other climatic events across wide ranges of spatial and temporal scales (Delworth et al., 2008). Weakening of the AMOC as a response to warming and/or high latitude freshwater release is a common feature of many climate models (Bakker et al., 2016; Jungclaus et al., 2006; Krebs & Timmermann, 2007; Stouffer et al., 2006; Yang et al., 2016; Yu et al., 2016). However, a recent study suggested that current models are not sensitive enough in their AMOC response (Liu et al., 2017), which implies that previous model projections of collapse probabilities are underestimated. The possibility of an AMOC collapse under global warming is a major concern due to its potentially dramatic impacts on oceanic circulation and global climate. The consequences of freshwater input near sites of deep water formation are a contemporary concern as the total freshwater storage of the North Atlantic increased by 19 000 km^3 between 1961 and 1995 (~0.02 Sv on average; Curry, 2005). This freshwater is transported to the Labrador Sea and creates salinity anomalies (Luo et al., 2016). It is therefore increasingly critical that we understand the impacts of climate change and freshwater release on convection in the Labrador Sea and its corresponding impact on AMOC intensity (Gregory et al., 2005). This is especially true if we are to identify the forcing(s) responsible for the ongoing AMOC weakening (Bakker et al., 2016; Thornalley et al., 2018).

High-resolution modeling (~10 km ocean, ~50 km atmosphere) suggests a robust relationship between a weakening AMOC and the decrease in the proportion of Labrador-derived water (Labrador Subarctic Slope Water : LSSW) entering the Northwest Atlantic shelf compared to Atlantic-derived water (Atlantic Temperate Slope Water : ATSW) under climate change (Saba et al., 2016; Fig 1a). Interestingly, historical instrumental temperature data suggest a significant reorganisation of the Northwest Atlantic slope currents from the bottom water of the St. Lawrence Estuary (Gilbert et al., 2005). The significant bottom water warming (+1.7°C) during the twentieth-century was attributed to a decrease in the proportion (72 to 53%) of cool LSSW entering the Laurentian Channel (Gilbert et al., 2005). This warming was suggested to be unique over the last millennium (Thibodeau et al., 2010a) and the last ~6,000 years (Thibodeau et al., 2013). This major change in the regional oceanography has severe

environmental consequence, as the ATSW is characterized by lower dissolved oxygen content than the LSSW which, in conjunction with localized eutrophication, is thought to be responsible for the development of the permanent hypoxic zone in the St. Lawrence Estuary (Benoit et al., 2006; Gilbert et al., 2005; Lefort et al., 2012; Thibodeau et al., 2006; Thibodeau et al., 2010b). As detailed in figure 1, the recirculation gyre is considered to be controlled by the strength of the formation of deep water in the Labrador Sea and thus by the strength of the deep western boundary current (DWBC) (Zhang et al., 2007). A strong recirculation gyre keeps the Gulf Stream path well separated from the coast (Fig 1a) and allows for southern penetration of the LSSW. In episodes of weak convection characteristic of modern conditions (Rahmstorf et al., 2015), a larger proportion of the warm water from the Gulf Stream and ATSW is expected to be found in the Laurentian Channel bottom water (Fig 1b). It was further suggested that the westward transport of Labrador current water along the continental shelf edge to the south of the Grand Banks of Newfoundland is the most important factor driving temperature and salinity variability in the Laurentian Channel (Petrie & Drinkwater, 1993; Fig 1c). Thus, the observed warming in the Laurentian Channel and the western North Atlantic could be linked to the weakened state of the AMOC (Caesar et al., 2018; Rahmstorf et al., 2015; Thornalley et al., 2018).

Here, we present two high-resolution records of oxygen isotope ($\delta^{18}O$) measurements of the benthic foraminiferan *Globobulimina auriculata* covering the last century and the last 1,500 years respectively. We demonstrate how these records can be used to track sub-surface temperature of the western North Atlantic. We then tested this paleotemperature record against instrumental measurements, new model simulations, AMOC index and other AMOC-related proxies to link our record to the AMOC intensity. As such, we provide here a new paleoreconstruction of the AMOC intensity and highlight that the AMOC is probably at its weakest state since the last 1,500 years. While the uncertainties are larger when we investigate older periods, we further report statistically heavier $\delta^{18}O$ during the Little Ice Age (LIA), which could be related to weaker AMOC conditions during that time. Thus, our record is significant for the investigation of the potential mechanisms responsible for the last century AMOC weakening.

2. Methods

We investigated the effects of an AMOC reduction on the western North Atlantic slope water temperature via freshwater perturbation experiments using two climate models: the University of Victoria climate model (UVic v2.9) and the water isotope-enabled Community Earth System Model (iCESM1.3). The UVic model is a climate model of intermediate complexity including an ocean general circulation model at coarse resolution (3.6 × 1.8°, 19 vertical levels), a single-layer atmospheric energy-moisture balance model, a dynamic-thermodynamic sea ice model, and biogeochemical components. The freshwater perturbation experiment analyzed here has 0.05 Sv freshwater discharged into the North Atlantic between 45–65°N and 60–0°W for 100 years. Readers are referred to previous publications for a detailed description of the experimental setup (Schmittner & Lund, 2015).

The water isotope-enabled Community Earth System Model version 1.3 (iCESM) is a state-of-the-art fully coupled Earth system model with the capability to simulate the oxygen isotopes in the hydrological cycle (Nusbaumer et al., 2017; Wong et al., 2017; Zhang et al., 2017; Zhu et al., 2017a). The numerical experiments analyzed here are from a recent study (Zhu et al., 2017b). The simulations were conducted with a horizontal resolution of 1.9 × 2.5° (latitude × longitude) for the atmosphere and land, and a nominal 1° for the ocean and sea ice. The ocean model consists of 60 uneven levels with an interval of ~10 m for the upper 200 m. The preindustrial control simulation was run for 500 years, with forcing fixed at the values from 1850 A.D., and water isotopes in the ocean initialized from the Goddard Institute for Space Studies interpolated observational dataset (LeGrande & Schmidt, 2006). In the freshwater perturbation experiment, 0.10 Sv of isotopically depleted fresh water was discharged into the northern North Atlantic (50–70ºN) for 100 years. The $\delta^{18}O$ signature of the freshwater forcing was set as –30 ‰ SMOW (Hillaire-Marcel & Causse, 1989). The simulation of $\delta^{18}O$ in the model helps to test our interpretation of the benthic $\delta^{18}O$ records in the Laurentian channel. The response of carbonate $\delta^{18}O$ (‰ PDB) to freshwater forcing is calculated in the model with the simulated ocean temperature and $\delta^{18}O$ (‰ SMOW) of seawater, using the paleotemperature equation of Shackleton (1974).

We then compiled $\delta^{18}O$ data (‰ VPDB) measured on the benthic foraminifera *Globobulimina auriculata* in two sediment cores (CR02-23 and MD99-2220; core details in S1-2) from the Laurentian Channel (Fig 1a). The calcareous shells were picked under binocular and roasted at ~ 200 ºC for about 2 hours in order to eliminate organic matter. Samples were analyzed with a Micromass Isoprime™ isotope ratio mass spectrometer in dual inlet mode coupled to a MultiCarb™ preparation system. The CO_2 was extracted at 90ºC by acidification

with concentrated H_3PO_4. The analytical reproducibility determined by replicate measurements of internal standard carbonate material was routinely better than 0.05 ‰, which is equivalent to a precision of about 0.15-0.20°C in temperature.

3. Results and Discussion

3.1. Modelled effect of reduced AMOC on subsurface temperature

To test the link between AMOC strength and subsurface warming, the AMOC strength was reduced in two models (iCESM and UVic) (see detailed results in S3). Both models used here produced a large-scale subsurface warming in the northwest Atlantic at 45°N (Fig S1) with a maximum of 1–3°C around 50°W. The AMOC reduction obtained with the UVic model (~ 17 %) is consistent with the most recent estimate of weakening (Caesar et al., 2018; Rahmstorf et al., 2015; Thornalley et al., 2018). This subsurface warming of the western North Atlantic under weak AMOC conditions is expected from field data (Dima & Lohmann, 2010), theory (Petrie & Drinkwater, 1993; Zhang, 2008; Zhang et al., 2007), coarse (this study) as well as high-resolution and eddy-permitting models (Brickman et al., 2018; Caesar et al., 2018; Saba et al., 2016; Thornalley et al., 2018). Thus, the warming can be considered a robust fingerprint of the weakened AMOC.

3.2. Influence of temperature and water mass contribution on the $\delta^{18}O$ record

The isotopic signature of oxygen in *Globobulimina auriculata* tests is a good proxy of temperature change in the Laurentian Channel during the last century (Thibodeau, et al., 2010a). The warming instrumentally observed in the Laurentian Channel bottom water seems well captured by *Globobulimina auriculata* $\delta^{18}O$ in the high sedimentation box-core CR02-23 samples (Fig 2), as the $\delta^{18}O$ decreases from 1940 to 2000 by about 0.4 ‰ synchronously with the 2°C increase in temperature from the bottom water of the St. Lawrence Estuary. However, the $\delta^{18}O$ of benthic foraminifera also records the change in the proportion of water masses entering the Laurentian channel, as these water masses are characterized by different isotopic conditions. Using the isotopic signature of both water mass (ATSW = 0.5 ‰ and LSSW = -0.5 ‰), it was estimated that the proportion of these water masses is currently about 50-50% (Thibodeau et al., 2010a). Based on dissolved oxygen and temperature, it was hypothesized that the proportion of ATSW entering the Laurentian channel was much lower in 1940 at about 30% (Gilbert et al., 2005), which imply an increase of $\delta^{18}O$ by about 0.2 ‰ between 1940 and

2000. We observed that the $\delta^{18}O$ of seawater exhibits an enrichment of 0.2 to 0.3 ‰ in the subsurface western North Atlantic in the freshwater perturbation experiment using iCESM (Fig S3), which is coherent with the magnitude of the increase in the proportion of ATSW entering the Laurentian Channel inferred from temperature and dissolved oxygen changes (Gilbert et al., 2005; Thibodeau et al., 2010a)). Considering a relationship of about -0.3 ‰/°C, one would expect a decrease of -0.6 ‰ in the $\delta^{18}O$ of *Globobulimina auriculata* considering the instrumentally-measured 2°C warming in the bottom water between 1940 and 2000. However, we only observed a depletion of about 0.4 ‰, which is coherent with the modelled enrichment due to the change in water masses. We therefore suggest that the Laurentian Channel benthic $\delta^{18}O$ record is strongly influenced by AMOC intensity via the advection of the western North Atlantic subsurface temperature and water mass dynamics.

3.3. Comparison with other AMOC-related proxies over the last century

An annually-resolved $\delta^{15}N$ record retrieved from soft corals over the Canadian shelf shows a high degree of similarity with both the $\delta^{18}O$ record and the instrumental record of temperature (Fig 2). This record was interpreted as an increase in the proportion of ATSW reaching the Canadian shelf, a unique event of the last 1800 years (Sherwood et al., 2011) and is consistent with the AMOC index (Caesar et al., 2018; Rahmstorf et al., 2015). The CR02-23 $\delta^{18}O$ record presented here is also in agreement with the AMOC index over the 1940-2000 period despite some leads and lags that can be attributed to either the different resolution and time integration of the respective proxies. The leads and lags could also be caused by the fact that the AMOC-index and our record integrate different signals; the AMOC-index estimates the difference in the temperature anomalies between the sub-polar gyre and the Northern hemisphere while the $\delta^{18}O$ captures the temperature and water mass distribution of the slope water. Despite the potential caveats, the similarity between our $\delta^{18}O$ record, the temperature-based AMOC index, and instrumental data adds to the evidence linking the strength of the AMOC with the western North Atlantic subsurface temperature (Marcott et al., 2011; Petrie & Drinkwater, 1993; Saba et al., 2016), which implies that temperature can been used to diagnose the state of AMOC, as done previously (Caesar et al., 2018; Rahmstorf et al., 2015; Thornalley et al., 2018; Zhang, 2008). The $\delta^{18}O$ of benthic foraminifera in the Laurentian Channel can thus provide crucial information to reconstruct AMOC variability during the last century despite the fact that it incorporates both the temperature and the water mass signal.

The trend of $\delta^{18}O$ derived from the benthic foraminifera in long piston core MD99-2220 (hereafter MD) during the 20th century is unique in its magnitude for the last 1,500 years. While the current global warming trend could be invoked to explain this warming, we stress that neither of the parent water masses warmed significantly during the same period (Gilbert et al., 2005). Moreover, the absolute value of 1.5-2.0°C is much larger than the ~0.4°C attributed to the global trend (IPCC, 2013). Potential control from the North Atlantic Oscillation can also be discarded as no correlation with the temperature time series was observed (Gilbert et al., 2005). While still controversial, the reduction of the AMOC since the late 1930s and the drastic shift in North Atlantic overturning cell at the beginning of the 70's was already identified using field data (Dima & Lohmann, 2010). The agreement between the instrumental data, various climate archives, the two models, and the AMOC index lead us to conclude that the weakening of the AMOC is a major factor causing the sub-surface warming recorded in the sediment cores and corals compiled here. The evidence presented here thus reinforces previous findings and provides complementary geological evidence for the 20th century AMOC slowdown.

While our record and modeling results strengthens the previous hypothesis regarding the recent weakening of the AMOC and its consequences in the western North Atlantic, it also highlights some discrepancies such as the 100-year difference in the beginning of the weakening of the convection in the Labrador Sea (Thornalley et al., 2018) and the AMOC (Caesar et al., 2018; Rahmstorf et al., 2015). Interestingly, our $\delta^{18}O$ record, interpreted as being controlled by DWBC strength, mimics the AMOC index with a weakening starting within the last century as opposed to the 19th century decline in the Labrador Sea convection (Thornalley et al., 2018). While it is conceivable to invoke a potential lag between a reduced convection in the Labrador Sea and its expression on surface waters, the pre-AD 1200 paleorecord does not seem to exhibit such lag, as the $\delta^{18}O$ matches the proxy for convection in the Labrador Sea (Fig 3; see section 3.5). However, the amplitude of the recent weakening is unique over this period and so caution should be exercised when directly using the paleorecord to find the cause of this apparent mismatch. Moreover, the potential absence of decline in Labrador Sea convection during the last part of 20th century (Böning et al., 2016) and the last couple of decades (Yashayaev & Loder, 2016) also highlight the need to reconcile estimation of convection in the Labrador Sea and the integrative AMOC proxies.

While it is possible to use our $\delta^{18}O$ proxy in longer reconstruction, it is not possible to constrain $\delta^{18}O$ change solely to a change in the proportion of water masses as we did for the

last century since it is not known if the parent water masses temperature varied. As such, potential temperature changes of the Gulf Stream (and ATSW) and Labrador Current (and LSSW) should also be considered as a potential driver of $\delta^{18}O$ when analysing the pre-20th century record.

3.4. The 1600-1900 period

While we observe a step-wise decrease in the AMOC starting in the late 15th century, these variations are within the natural range of variability of our $\delta^{18}O$ record (Fig S6). However, the 1600-1899 $\delta^{18}O$ values in core MD are significantly heavier compared to the pre-1600 record, suggesting a statistically weaker AMOC during the LIA. Alternative explanations for the low $\delta^{18}O$ during this period include a warming of either parent water mass, which would be counterintuitive for this time period (Keigwin, 1996). While the $\delta^{18}O$ of the Gulf Stream increased by about 0.1 ‰ between 1600 and 1900 (Saenger et al., 2011), it would account only for half of the increase observed in the MD core. Thus, a change in the proportion of the water masses entering the Laurentian Channel due to a weaker AMOC cannot be excluded at this point. At about AD 1850-1875, the sharp depletion in $\delta^{18}O$ is synchronous with the sudden decrease in DWBC intensity and Labrador Sea convection, which might be due to the beginning of the post-LIA ice cap melt and the consequent freshening of the Labrador Sea surface water (Koerner, 1977; Koerner & Fisher, 1990). While the MD core might record a weakened AMOC state during most of the LIA (1625-1850), its step-wise nature, rather than a continual weakening trend observed in the sortable silt record, suggests that the signal reflects DWBC intensity (Fig 3c). This highlights a potential discrepancy between how the AMOC signal is expressed in the $\delta^{18}O$ record and how it is translated in current velocity at 2,000 m depth, where the 48JPC and 56JPC cores were retrieved (Thornalley et al., 2018). Here, the potential interference from temperature and salinity changes in the parent water masses should be investigated in greater detail.

3.5. The pre-1600 period

The comparison of the MD core with the AMOC index highlights the absence of any trend within these two records throughout this period (Fig 3a). However, the MD record is characterized by more variability pre-AD 1500. This may be caused by the construction of the AMOC index based on multiple different proxies of SST in both the western North Atlantic

and the subpolar North Atlantic, whereas the MD core records the subsurface signal at a single location, implying that the AMOC index integrates a much larger oceanic area and reduces the variability (Rahmstorf et al., 2015). This might alternatively be explained by subsurface temperature being slightly more sensitive to convection relative to the surface temperature. This is supported by the agreement pre-AD 1500 between the MD core and temperature and salinity reconstructions from the Labrador Sea (Fig 3b), which are considered effective proxies for Labrador Sea convection (Moffa-Sánchez et al., 2014). Thus, the $\delta^{18}O$ seems to record most of the natural variability of the Labrador Sea convection over that period.

4. Implications

Our record adds to the existing paleoreconstructions of AMOC for the last millennium and highlights the statistically weaker state of the AMOC during the 20th century. The data provided here are important to disentangle the potential causes of the 20th century weakening, as they record sub-surface processes, which is different from the previously-published surface AMOC index (Rahmstorf et al., 2015) and reconstruction of the DWBC (Thornalley et al., 2018). Moreover, the heavy $\delta^{18}O$ recorded during the LIA suggests a potential weakening of the AMOC during that period. These data could be used with temperature reconstructions of the Labrador current and Gulf Stream in order to further constrain the implication of the heavy $\delta^{18}O$ values in the Laurentian Channel. Our $\delta^{18}O$ record thus captures crucial information that will contribute to a better understanding of AMOC variability throughout the last 1,500 years and its drivers.

5. Acknowledgments

Author contributions: BT and CN designed the study, BT performed isotopic analyses on CR02-23 and MD99-2220, AS performed the modeling with UVic2.9 and JZhu performed the modeling with iCESM1.3. BT and CN wrote the manuscript with the contribution of JZhu, AS, DN, CT, JZhang and ZL.

Data and materials availability: All data used in this paper are available in the online material. The iCESM model codes are available through the National Center for Atmospheric Research software development repository. Data for the iCESM model are available by reasonable request to JZ (jiazhu@umich.edu). The UVic model cores are available at http://climate.uvic.ca/model/. Data for the UVic experiment are available at http://www.clim-past.net/11/135/2015/cp-11-135-2015-supplement.zip or by reasonable request to AS (aschmitt@coas.oregonstate.edu).

Figures and Tables

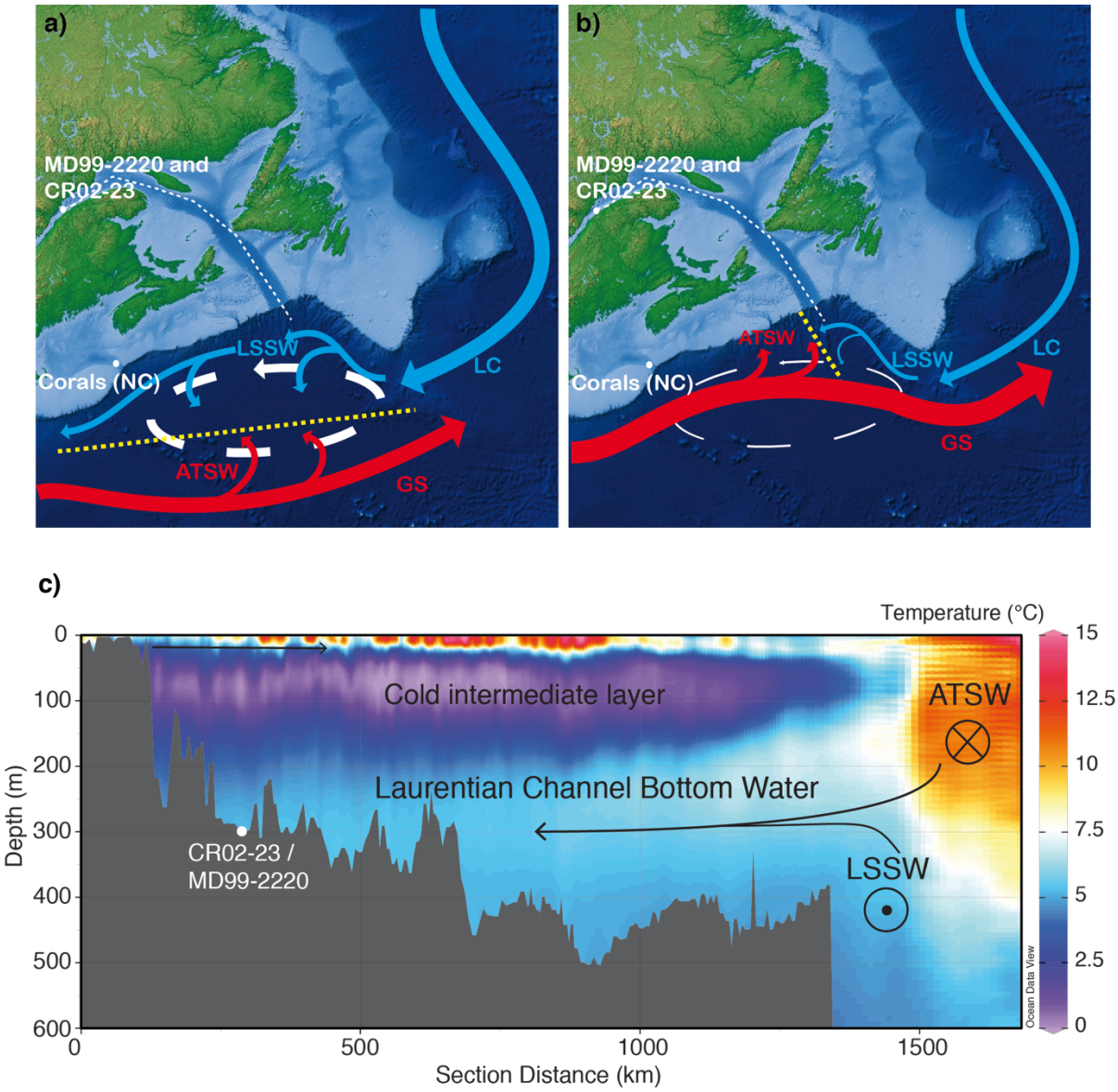

Figure 1. Link between the strength of convection in the Labrador Sea, the westward transport of Labrador current and the temperature across the Laurentian Channel. Schematic diagram of oceanic circulation near the entrance of the Laurentian Channel in episodes of **a)** strong westward transport of Labrador current and **b)** weak westward transport of Labrador current and **c)** the 2000-2010 averaged temperature (Levitus et al., 2013) profile along the Laurentian Channel. The oceanography of the Northwest Atlantic is characterized by the interaction between water masses formed in the Labrador Sea (Labrador current: LC) moving southward and the northward flowing Gulf Stream (GS). The exact location where these two water mass systems meet (yellow dashed lines) is determined by the

strength of the northern recirculation gyre (white arrows) (Hogg et al., 1986). The width of the arrows represents the relative strength of the current. White dots indicate the position of core MD99-2220 and CR02-23, which were cored close to each other (respectively at; 48°38.32'N, 68°37.93'W; 320m and 48°42.01'N, 68°38.89'W; 345m). The position of corals raised from the Northeast Channel where a $\delta^{15}N$ time series was recorded is also marked (42°00'N, 65°36'W, between 275 and 450 m) (Sherwood et al., 2011). The temperature profile depicts the annually averaged position of the slope waters and how they fill the bottom of the Laurentian Channel.

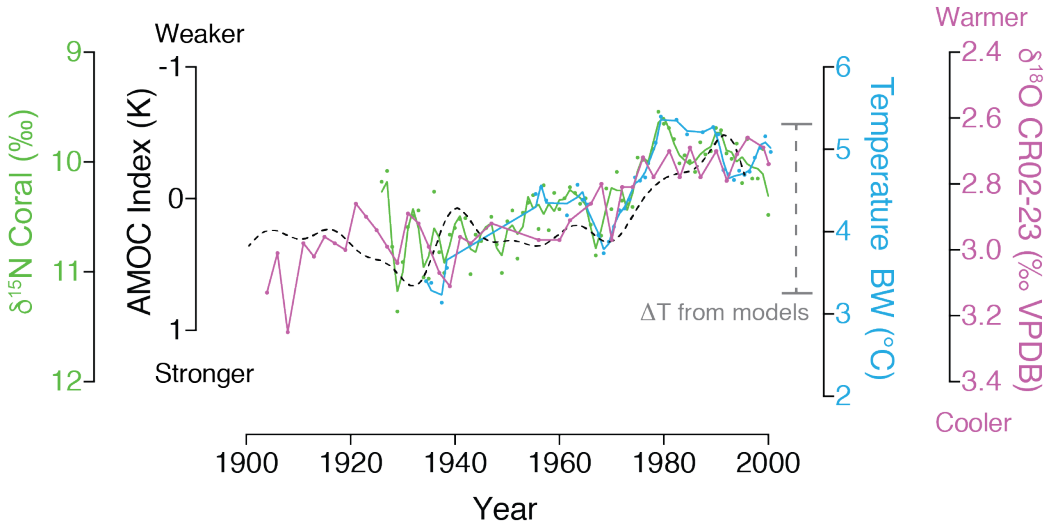

Figure 2. Proxy validation using instrumental data and paleorecords. The AMOC index (Rahmstorf et al., 2015) (black dashed line) and instrumental temperature record of Laurentian Channel bottom water (Gilbert et al., 2005) (light blue dots and smoothed line; 2nd order, 2 neighbors) are plotted for the 1900-2000 period along the annually resolved coral $\delta^{15}N$ record (Sherwood et al., 2011) (green dots and smoothed line; 2nd order, 2 neighbors) that serves as a proxy of the strength of the northern recirculation gyre and the modal state of the western North Atlantic circulation. The $\delta^{18}O$ of benthic foraminifera from core CR02-23 (Thibodeau et al., 2010a) (pink) also shows the same general pattern during that period. The average temperature increase (2°C) obtained at 400 m deep in the western North Atlantic in our modelled AMOC-weakening experiments is indicated by the gray bracket.

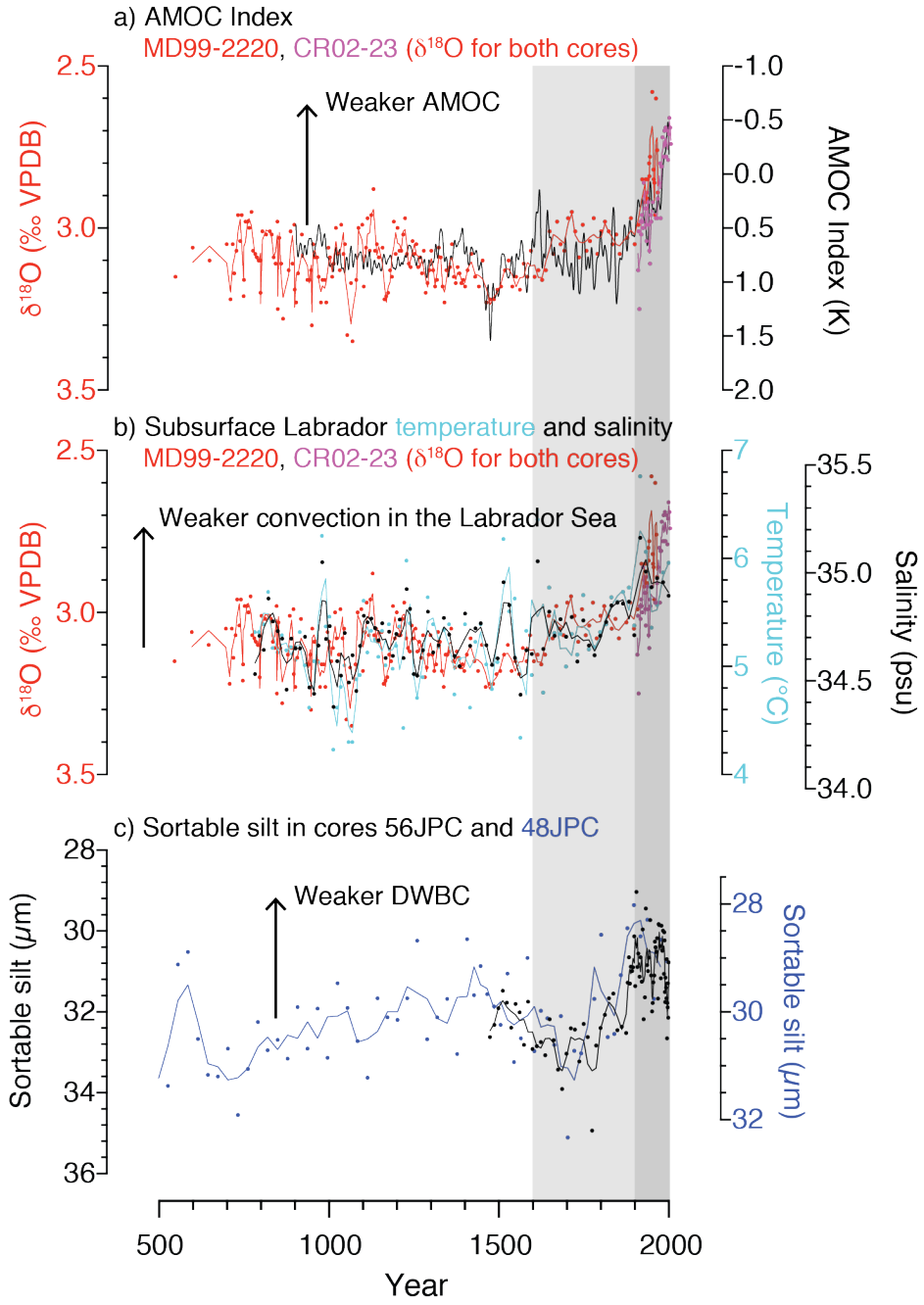

Figure 3. Comparison of North Atlantic climate archives covering the last millennium. The first panel **a)** comparison of composite (MD99-2220; red and CR02-23; pink) $\delta^{18}O$ *Globobulimina auriculata* record (smoothed lines; 2nd order, 2 neighbors) with the AMOC index (Rahmstorf et al., 2015) (black line). **b)** similarity of the composite (MD99-2220; red and CR02-23; pink) $\delta^{18}O$ record (smoothed lines; 2nd order, 2 neighbors) with reconstructed subsurface temperature (light blue dots) and salinity (black dots) of the Labrador Sea (Moffa-Sánchez et al., 2014), which are indicative of convection in the Labrador Sea (smoothed lines;

344 2nd order, 2 neighbors). **c)** sortable silt from two sediment cores retrieved off Cape Hatteras, a
345 proxy of the deep western boundary current (smoothed lines; 2nd order, 2 neighbors)
346 (Thornalley et al., 2018). Grey bars highlight the LIA and the 20th century.

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