

Reconstructing Atlantic Meridional Overturning Circulation during Heinrich Stadial 1 using carbon isotopes.

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Abstract

The formation of deep water masses in the North Atlantic has seen great and sometimes abrupt change throughout the history of the ocean. In order to better understand the behavior of ocean circulation, we seek to reconstruct the Atlantic Meridional Overturning Circulation (AMOC) during Heinrich Stadial 1 (HS1). Gaining greater insight into the behavior of deep ocean circulation in Earth's past is vital for understanding variability in climate and ocean circulation. We employ multiple coupled circulation-biogeochemical model runs to investigate the impacts of varied AMOC strengths and depths on carbon isotope ratios. We also use a newly compiled database of sediment cores detailing carbon isotope data. By comparing the model data to sediment core data, we test the hypothesis that the AMOC during HS1 was in a collapsed state. We find that the sediment data moderately constrains strength and depth, suggesting an AMOC with a maximum strength of less than 10 Sv (Sverdrup), as well as a depth of approximately 2000 meters. We find that it is unlikely that the AMOC was in a collapsed state for the entire duration of HS1. We also find that we can more adequately constrain the strength of the AMOC in HS1 than previous studies could with the Last Glacial Maximum.

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1. Introduction

It has been shown in multiple studies that the Atlantic Meridional Overturning Circulation (AMOC) has profound impacts on global climate, both historically and in modern times (Schmittner and Lund, 2015; Oppo and Curry, 2012; Liu et al., 2020). Observation-based studies have found evidence of some level of disruption in the AMOC during Heinrich Stadial 1 (HS1), however there is debate regarding the severity of disruption of circulation, whereas some studies indicate a complete collapse of the AMOC (McManus et al., 2004) others suggest a weakened but still active AMOC (Oppo et al., 2015; Repschläger et al., 2021). Thus, there is need for more evidence concerning AMOC behavior during HS1. Here we compare AMOC models of different depths and strength to Atlantic sediment core data to better quantify the behavior of the AMOC during HS1. Carbon isotope distributions from sediment reconstructions are compared to various model runs. These comparisons are drawn across the entire Atlantic ocean, as well as comparisons focused on specific regions in the Atlantic with high densities of sediment data.

Understanding the behavior of the AMOC in HS1 is important because it can give more general understanding of how the ocean functioned and still functions today. Additionally, it is understood that the behavior of the AMOC has influence on climate variability (Oppo and Curry, 2012; Liu et al., 2020). Increased knowledge regarding disruption of the AMOC during HS1 may eventually give insight into modern behavior of the AMOC.

2. Background

The AMOC is driven by external forcings, mainly temperature, although salinity and wind play varying roles depending on location and conditions (Repschläger et al., 2021). The modern AMOC acts as an ocean conveyor, where warm Atlantic waters are brought northward near the surface. At higher northern latitudes, waters begin to cool. The increased density, caused in part by high salinity, causes deep water to form and travel southward at depths (Repschläger et al., 2021). This deep water is referred to as North Atlantic Deep Water (NADW), and as it travels southward it overlies an even deeper water mass called the Antarctic Bottom Water (AABW),

originating from the Southern Ocean. When referring to an AMOC that has stopped or weakened, it means that the formation of NADW at high latitudes has either been ceased or weakened, respectively.

It is important to make a distinction regarding the terminology of “Heinrich stadials” and “Heinrich events.” These terms are not synonymous. The term “Heinrich event” refers to a climate event produced by large deglaciation of the Laurentide Ice Sheet, evidenced by glacially deposited detritus found in ocean sediment records. A Heinrich stadial is a period of colder climate, which contains a Heinrich event (Barker et al., 2009; Hodell et al., 2017).

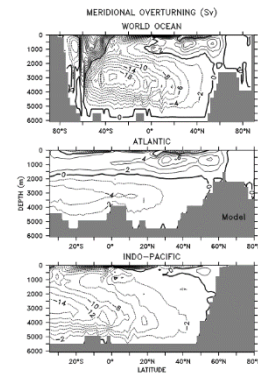
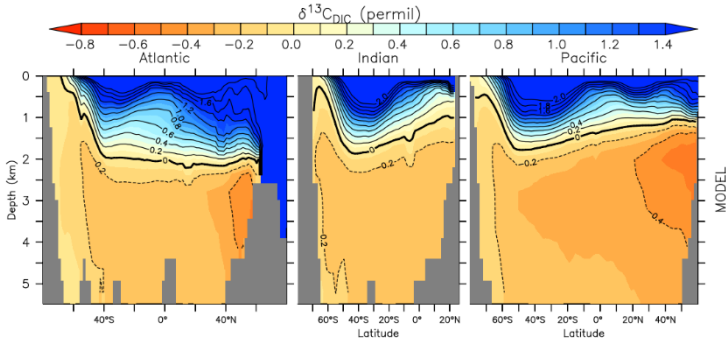
The period discussed in this paper is HS1. It is defined as the period of relative cool beginning after the last glacial maximum (LGM) and ending immediately prior to the start Bølling-Allerød period. The end of HS1 is often defined at ~14.6 thousand years before present (kyr BP) using tracers such as an increase in methane emissions, a change in isotopic composition of atmospheric O₂, and a decrease in the isotopic ratio of ²³¹Pa/²³⁰Th in sediment (Brook et al., 2000; McManus et al., 2004). The start of HS1 is less well-defined, but similar tracers place it at ~17.5 kyr BP (Oppo and Curry, 2012; McManus et al., 2004). Thus, for the purposes of this paper, 17.5 to 14.6 kyr BP is used as the period of HS1.

There have been previous studies dealing with the behavior of the AMOC during HS1 (Schmittner and Lund, 2015; Bradtmiller et al., 2014; McManus et al., 2004; Repschläger et al., 2021; Oppo et al. 2015). However, two separate recent efforts have created (1) a new series of model simulations and (2) increased the number of sediment cores, which provide an opportunity to reevaluate this issue.

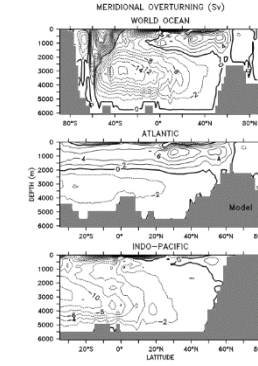
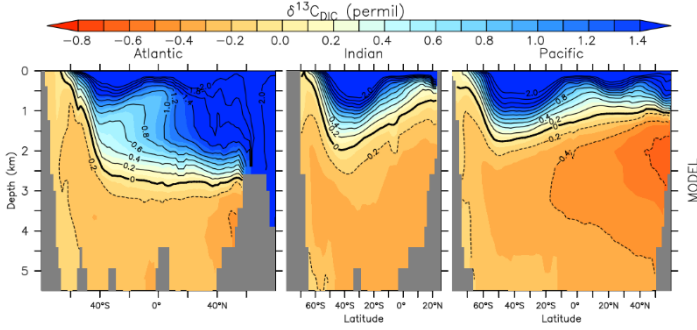
3. Materials and Methods

The model used to generate data for this paper is the UVic Earth System Climate Model (ESCM). It was developed by the University of Victoria School of Earth and Ocean Sciences and is able to model with an intermediate level of complexity, allowing for higher computational efficiency. Due to this, it is an ideal program to be used for time periods stretching for thousands

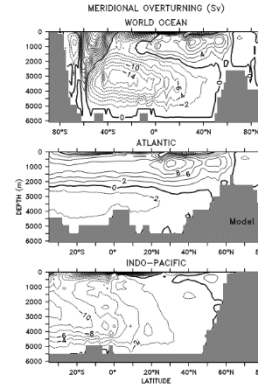
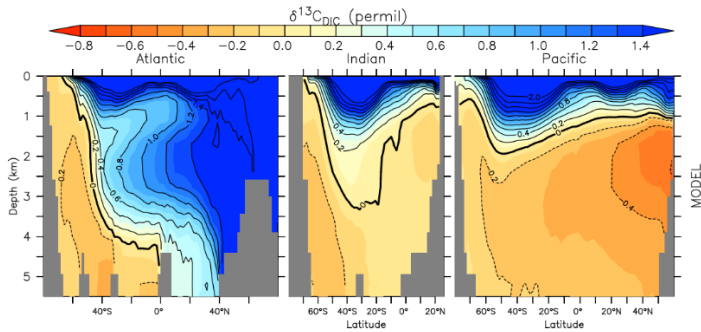
Run 3.9_1.5: Collapsed AMOC



Run 7.3_1.9: Weak-shallow AMOC



Run 12.2_3.0: Deep



Run 14.3_1.9: Intermediate-shallow AMOC

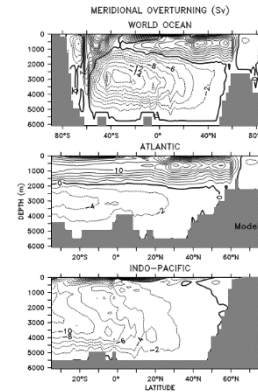
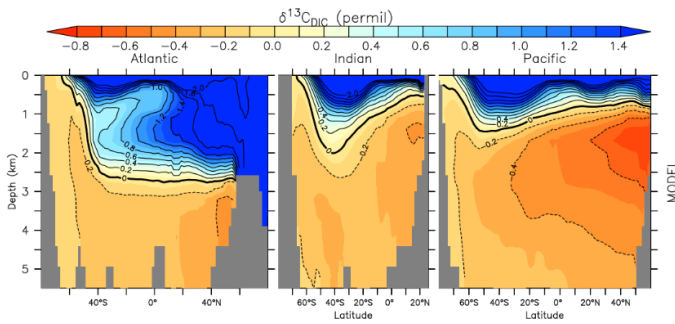


Fig. 1. Shaded $\delta^{13}\text{C}$ depth-lat profiles of model runs from various AMOC categories. Each has a paired plot showing stream functions, with isoclines labeled in Sv.

of years, such as HS1. The model has a global resolution of 3.6° (zonal/east-west) by 1.8° (meridional/north-south) and has nineteen vertical levels. It has parameterizations for various ocean and atmospheric processes including but not limited to water vapor, land ice interaction, precipitation, ice and snow albedo, wind, and moisture transport (Weaver et al., 2001). Here we use the Oregon State University version 2.9 of the UVic ESCM coupled with the Model of Ocean Biogeochemistry and Isotopes which simulates various organic and inorganic elements and isotopes. This includes the carbon isotope data of interest, dissolved inorganic carbon (DIC), which is used to calculate $\delta^{13}\text{C}$. The model runs used in this paper will be from previous research (Muglia and Schmittner, 2021), but with a different time period being analyzed.

There are 16 model runs with different AMOC strength-depth pairings used in this paper. The strength and depth of the AMOC within the model runs was adjusted by varying two parameters, atmospheric Southern Hemisphere moisture eddy diffusivity to shallow and weaken the AMOC and negative surface freshwater flux in the North Atlantic to strengthen and slightly deepen the AMOC. By varying these two parameters independently, a matrix of model runs with different AMOC strengths and depths were created. Having multiple different pairings of strength and depth gives a better chance of finding a model that outputs carbon isotope data similar to the collected core data. Fig. 1 above shows paired stream functions and carbon distributions of examples of model runs. One run is chosen from each group of runs (weak-shallow, deep, intermediate-shallow and collapsed).

Atlantic sediment core data is sourced from the international Ocean Circulation and Carbon Cycling (OC3) database that is not yet public (Muglia et al., 2022 - in progress). The OC3 database as of 2022 has 273 total cores with 170 Atlantic cores containing isotope data derived from benthic foraminifera as well as corresponding modelled age data. These cores have data from various species of foraminifera, but unless otherwise specified this paper will be using data sourced from *cibicidoides wuellerstorfi*. This narrows down our cores to 124 cores throughout the Atlantic (Fig. 2).



Fig. 2. Locations of the 124 cores used for the analysis in this paper. The cores shown above use *cibicides wuellerstorfi* for $\delta^{13}\text{C}$ measurements. The depths of the core sites range from 441-4900 meters. Map created by Susannah Herz.

Although some of the age models use well-defined uncertainty values, many do not have explicitly defined uncertainty values as different cores use a variety of different age models. In this paper, some uncertainty is accounted for by trimming the interval used for HS1 by 500 years on each end, making the interval used for selecting sediment data 17-15.1 kyr BP. Trimming the interval in this way increases the likelihood of our findings remaining accurate even with chronological uncertainty of ~ 500 years (Oppo et al. 2015). Further investigation incorporating uncertainty into the age modelling and the impacts on findings may be useful but is outside the scope of this paper. The isotopic proxy of interest in this paper is $\delta^{13}\text{C}_{\text{DIC}}$ (referred to from here on as $\delta^{13}\text{C}$). $\delta^{13}\text{C}$ is the ratio of $^{13}\text{C}/^{12}\text{C}$ compared to a standard value. In areas of high biological productivity, recorded $\delta^{13}\text{C}$ will be higher due to the tendency for organisms to select for ^{12}C over ^{13}C , driving up the ratio. It is calculated using measurements from the shells of benthic foraminifera and serves as a proxy for nutrient content, which can be used to trace water masses (Muglia and Schmittner, 2021). The deep water mass of most interest in this paper, NADW, can be traced in the Atlantic by finding measurements of high $\delta^{13}\text{C}$ at depths, giving evidence of vertical circulation occurring. We will account for the uncertainty of recorded $\delta^{13}\text{C}$ observations according to previous studies (Schmittner et al., 2017).

The OC3 data is currently provided as a file folder for each sediment core location. Each folder contains files with age, depth, and isotope data, in both csv and ASCII file formats. Metadata is also included with each sediment core data folder. There are 273 sediment core locations in across the whole database (Muglia et al., 2022 - in progress). In order to assist with extraction and efficient use of the OC3 data, python scripts were provided. These were useful as they were able to collect data from certain locations, times, or taxonomic classifications. There are a few difficulties that were encountered when comparing data from the sediment database to the model data. As described previously, the model data is set on an evenly distributed grid. However, the sediment data does not necessarily align with the model data grid and can have areas of higher/lower density of cores. In the case of some sediment cores this is not an issue, as if there is a model grid location adjacent to the actual location of the sediment core that can be used without much impact on the data. However, most sediment data points attempt to find the associated model data point and find no adjacent modelled data, due to limitations on the extent of the model. In this case, the data either needs to be ignored or extrapolated to the point. We chose to extrapolate rather than ignore the points due to the majority of the points being initially missing. In order to extrapolate the data set, we have the program search for the nearest available data point, giving priority to horizontal data points. We chose to give priority to horizontal data points as it would be less likely to choose a point in a different water mass than the original point when searching horizontally than vertically. There is some uncertainty associated with this method of choosing model data points that is difficult to quantify. It is possible that this method of choosing data has some impact on the data products, as will be discussed further in results.

Beyond correlation and deviation, regional and global depth profiles were used to assist in identifying possible water masses as well as view the alignment of sediment and model data. Graphs from figures 1, 3, and 4 were created using the software Ferret. Ferret was developed by NOAA for oceanographic study. The primary purpose of Ferret is to assist with mathematical visualization and analysis, and it is specifically focused on numerical ocean models and gridded data. Ferret scripts for generating various graphs and calculating variables were provided by Andreas Schmittner.

4. Results and Discussion

In the past, there was belief that during HS1 the AMOC experienced a complete shutdown, due to a stoppage in NADW formation (McManus et al., 2004). However, recently observation-based studies have presented the possibility of a weakened AMOC rather than a complete circulation standstill (Bradtmeier et al., 2014; Repschläger et al., 2021; Oppo et al., 2015). Thus, upon analysis of the data, we expected to find $\delta^{13}\text{C}$ values consistent with some formation of NADW. In their LGM study (Muglia and Schmittner, 2021), found that carbon isotopes provide weaker constraints on strength than depth. However, their study did mention that more data may be able to refine strength estimates, and with the high number of core locations used in this study, there is hope for a stronger constraint on AMOC strength.

Using the database of cores and coupled circulation biogeochemical model runs described above, we found the Pearson correlation coefficient and root-mean-square error (RMSE) between the two data sets for each of the sixteen runs (Fig. 3). We chose to use carbon isotope data taken from cores across the Atlantic ocean for finding correlation and RMSE. We also found that using only *cibicides wuellerstorfi* as opposed to all species of benthic foraminifera resulted in higher overall levels of correlation. Additionally, Schmittner et al. (2017) also described *cibicides wuellerstorfi* as the preferred species of foraminifera for palaeoceanographic study due to it being closer to a one-to-one recorder of $\delta^{13}\text{C}$. Finally, choosing to study values from one species reduces interspecies variability and strengthens our results. Thus, data recorded from *cibicides wuellerstorfi* was used in our final compilation of cores for finding correlation and RMSE, as well as generating regional depth- $\delta^{13}\text{C}$ plots.

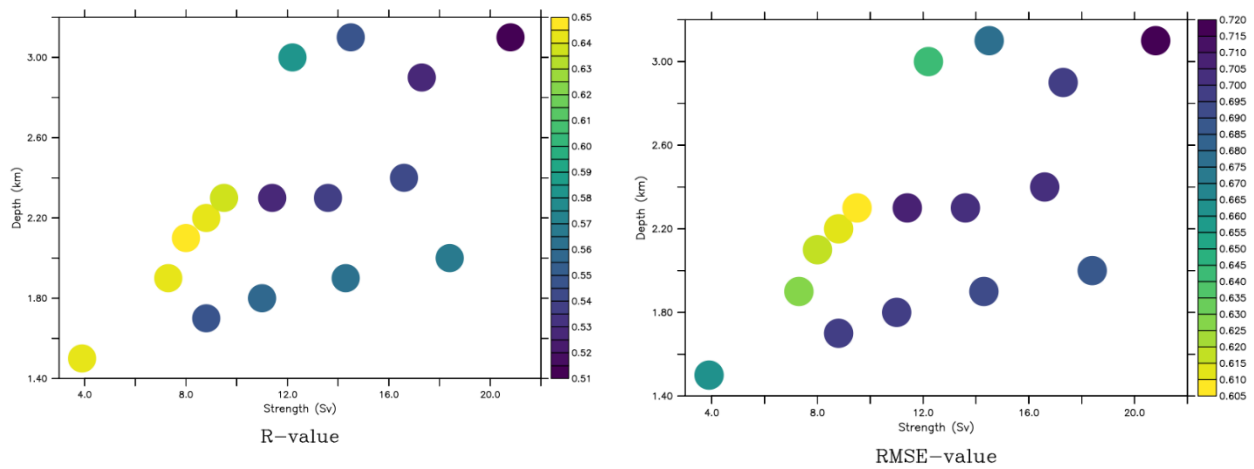


Fig. 3. Model-data correlation (R-value) and deviation (RMSE) plotted by strength and depth.

The model runs (shown in Fig. 3) had Pearson r values ranging between 0.51 and 0.65, and RMSE values ranging between 0.60 and 0.72. The RMSE values are not normalized. The five runs with highest correlation are four weak-shallow runs and one collapsed state run. These runs all have the weakest AMOC strengths relative to their depths, as well as all having a depth of less than 2.4 kilometers. Whenever model strength is referenced in this paper, it refers to the maximum strength of each model at 25N, and the unit is Sverdrup (Sv). Model depth is labelled in meters or kilometers and refers to the depth of the 0 Sv isocline at 25N in each model. Note that the lowest left value on figure 2 with a strength of 3.9 Sv and depth of 1.5 kilometers represents a collapsed AMOC (further reference to strength and depth will list this as 3.9_1.5). . The collapsed state run has a higher error value than other shallow-weak cases and even has higher error value than one deep-intermediate case, making it less probable to be a legitimate explanation for AMOC behavior than the other relatively highly correlated model runs. Note that none of the model runs have as high correlation as previous similar studies covering the same model runs in the LGM, where R-values as high as 0.85 were found (Schmittner and Muglia, 2021). One possible explanation for this discrepancy is due to the transient nature of HS1, it may have not been in equilibrium for its duration. This would cause all model runs to be less accurate, as they were all ran to equilibrium before averaging their last 1000 years.

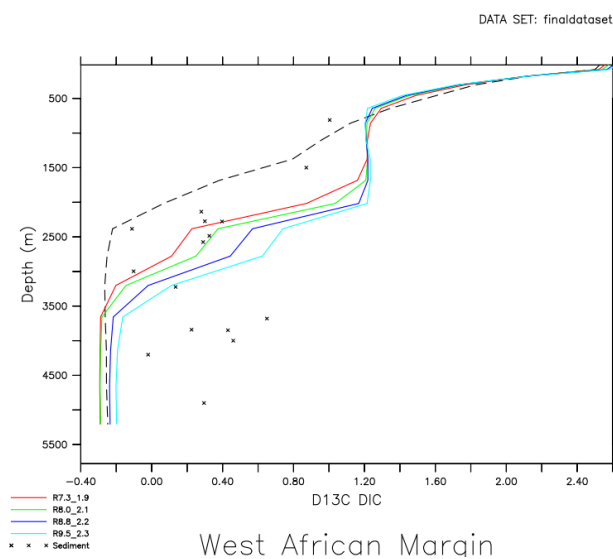
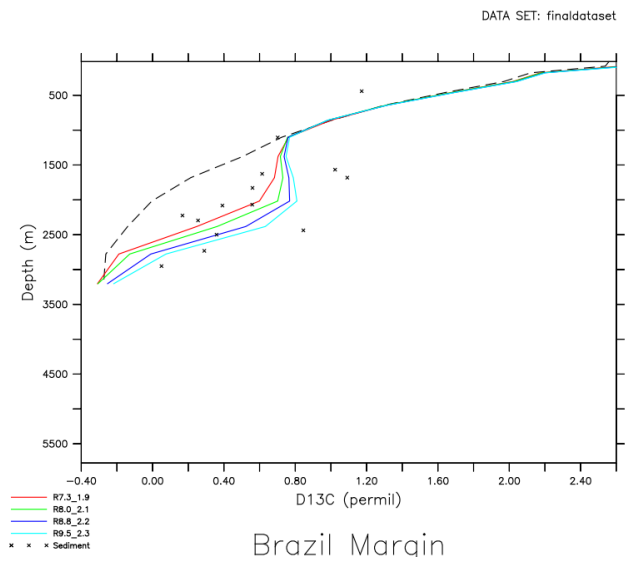
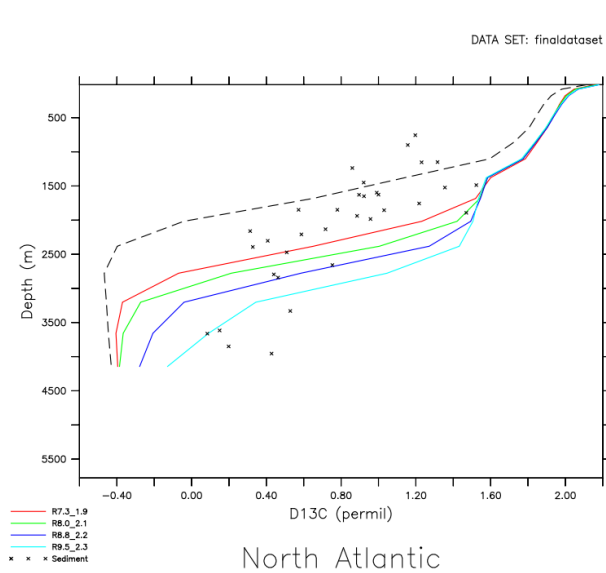


Fig. 4. Graphs of different regions with depth on the y-axis and $\delta^{13}\text{C}$ on the x-axis. The dashed lines represent the collapsed AMOC scenario, and the colored lines represent various weak-shallow models. Model runs are described in the key as R strength_depth in Sv and km respectively.

One possible drawback discussed earlier is the method of searching for points when the model data does not align with the sediment data. To try and quantify the impact our search method has on the validity of the data, we ran the same correlation and RMSE scripts as in the whole Atlantic method, but whenever a missing value was encountered, instead of extrapolating from nearby data, it was removed from the data set. This resulted in only 44 out of the original 124 *cibicoides wuellerstorfi* observations remaining. The calculated correlations ranged between 0.67 and 0.79, and RMSE ranged 0.54 and 0.64. The correlation of all model runs increased and the errors were reduced. This could be evidence that the method of extrapolation used does not

replicate the values that “should” be at certain core locations. There are also alternative explanations such as the disparity being a result of the coarseness of the model, as it is unable to model small scale features that could impact sediment data (Muglia and Schmittner, 2021). Further investigation into the cause of the disparity in correlation could be useful and may be done in the future.

In order to further understand the behavior of the AMOC, we chose to find regions with high densities of sediment core data and make depth- $\delta^{13}\text{C}$ composites. Shown in Fig. 4., these regions include the North Atlantic (Lon: 30W-12W, Lat: 50N-65N), Brazil margin (Lon:47W-42W, Lat: 24N-29N) and West African margin (Lon: 23W-17W, Lat: 10N-27N).

Each regional plot has zonal averages calculated for the model data, displayed as the lines on the plot. The sediment data is represented by the points on the plot. The model data shown is from the same five models for all three regions. These runs were chosen to be plotted both because they were found to have the highest correlation in the whole Atlantic as shown in fig. 1, but also regional correlations were calculated, and the same five model runs were the highest correlated in each individual region. This further reinforces the idea that one of the five runs would serve as the most probable case for the behavior of the AMOC during Heinrich Stadial 1.

Evidence of NADW formation can be seen in the four non-collapsed state runs. The relatively high $\delta^{13}\text{C}$ values between ~1500-3000m in depth are evidence of circulation. Notably, these values are absent in the collapsed state model (although some evidence of weak vertical circulation can be seen in the North Atlantic collapse state line). Correlation and error were calculated for each individual region. The collapsed state run did marginally better than the shallow-weak runs in 2 of the three regions when considering correlation but had higher error than all weak-shallow runs in all regions.

In the North Atlantic, there is a line of sediment data that can be seen nearest the red line (7.3_1.9). This example of collinearity in 2500-1500 meter range between sediment and model data is further evidence of a weak-shallow explanation behind AMOC behavior. In the Brazil margin, similar lines can be seen in the sediment data both above the red line (7.3_1.9) and

below the light blue line (9.5_2.3). The West African margin plot has less pronounced collinear points visible in the sediment data, but still has better correlation and less error associated with the shallow-weak runs rather than the collapsed run.

When viewing both the North Atlantic and Western Africa margin regional plots, below 3500 meters there is a cluster of sediment data that is to the right of all plotted lines. This skew towards positive $\delta^{13}\text{C}$ values could be explained by an inability of the model to replicate Antarctic Bottom Water biological productivity. If this is the case, it is likely due to a lack of accurate model replication of iron fertilization in the Southern Ocean, the source of Antarctic Bottom Water.

5. Conclusions

We analyzed a set of coupled circulation biogeochemical model runs and constrained each run's strengths and depths using carbon isotope data from a database of sediment cores. We found that one of the most probable configurations of the AMOC during HS1 was the model run with a strength of 9.3 Sv and 2.3 km in depth. Despite this run being the most likely, we also found three other shallow-weak AMOC configurations that provided probable explanations for AMOC behavior. Compared to previous LGM studies, this study found $\delta^{13}\text{C}$ to be better able to constrain AMOC strength. Finally, the collapsed state explanation for the HS1 AMOC was shown to be an unlikely scenario based on our results.

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