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Surface currents in the western North Atlantic during the Last Glacial Maximum

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[1] During the last ice age, the density gradient across the Florida Current was reduced, implying a reduction in the flow of the Gulf Stream through the Florida Straits. Here we investigate the possibility that a significant portion of this wind-driven western boundary flow bypassed the Florida Straits during glacial times due to either changes in bathymetry induced by the sea level drop or changes in wind patterns. Down core records of the oxygen isotope ratios of the planktonic foraminifer *Globorotalia truncatulinoides* are used to locate the density gradients and thus the locations of upper ocean currents in the western North Atlantic. We find that western boundary flow was largely confined within the Florida Straits during the Last Glacial Maximum as it is today. This finding supports the idea that the reduced density gradient across the Florida Current represents a reduction in the surface branch of the surface to deep meridional overturning circulation in the Atlantic rather than a reduction in the proportion of the wind-driven flow carried by the Florida Current.

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1. Introduction

[2] The surface currents in the Caribbean and western North Atlantic incorporate portions of both the wind-driven subtropical gyre and the meridional overturning circulation of the Atlantic. The northward flowing surface waters which compensate the outflow of North Atlantic Deep Water cross the equator and enter the Caribbean through its southernmost passages, eventually joining the

southernmost extent of the Gulf Stream as it passes through the Florida Straits. The westward moving surface waters of the southern portion of the North Atlantic Subtropical gyre enter the Caribbean through various passages. The transport through the Florida Straits is about 30 Sv (1Sv = $10^6 m^3/s$ [*Baringer and Larsen*, 2001]), comprising both the subtropical gyre circulation in the western North Atlantic (17 Sv) as well as the northward flow of ~13 Sv of surface waters that compensate for the southward flow of deep waters formed in the North Atlantic [*Schmitz and McCartney*, 1993] (see Figure 1). About 10% of the flow through the Florida Straits at 27°N arrives through the Santaren Channel, between Cay Sal and the Great Bahama Bank, and the northernmost passage, the Northwest Providence Channel, north of the Great Bahama Bank [*Atkinson et al.*, 1995; *Leaman et al.*, 1995]. North of the Florida Straits, the Gulf Stream flows along the coast until Cape Hatteras, where it turns seaward and separates from the coast. Wind-driven recirculation cells confined to the western side of the basin account for an enhancement in transport of the Gulf Stream from 30 Sv through the Florida Straits, to more than 100 Sv at its separation off of Cape Hatteras [*Schmitz and McCartney*, 1993].

[3] Down core ocean sediment records of $\delta^{18}O_{calcite}$ provide a means for examining patterns of upper-ocean flow in the past. Using benthic foraminifer $\delta^{18}O_{calcite}$ to reconstruct seawater density on either side of the Florida Straits, *Lynch-Stieglitz et al.* [1999] assess the vertical shear of Florida Current and find it reduced during the last glacial maximum (LGM). The findings of *Lynch-Stieglitz et al.* [1999] are consistent with a reduced transport of the Gulf Stream through the Florida Straits. However, glacial sea level was lower by ~130 meters [*Lambeck and Chappell*, 2001; *Siddall et al.*, 2003] which would have restricted the passages leading into the Caribbean and perhaps diverted some wind-driven flow seaward of the Florida Straits. The most constricted passage through the Florida Straits is only ~760 meters deep, and during the LGM, its depth would have been reduced to ~620 meters, which may have further impacted the flow in this region. Further north, *Matsumoto and Lynch-Stieglitz* [2003] find that the modern separation latitude of the Gulf Stream further north off the coast of Cape Hatteras was unchanged during the LGM.

[4] In this paper we will attempt to determine the flow path of the surface currents of the western North Atlantic using the oxygen isotope composition from subsurface calcifying planktonic foraminifera.

2. Methods

2.1. Controls on the Oxygen Isotopic Composition of *Gr. truncatulinoides*

[5] To a first order approximation, large scale steady state upper-ocean flows are in geostrophic balance; thus the vertical shear of the flow is balanced by the horizontal density gradient across the flow. Locating horizontal density gradients provides a method to determine the path of upper-ocean flows since they occur in the same places as the shear of the upper-ocean flows. In the North Atlantic, given a specific depth, seawater density is lower seaward of the Gulf Stream and higher landward.

[6] Because the oxygen isotope ratio in the calcite shells of foraminifera ($\delta^{18}O_{calcite}$), like seawater density, is strongly related to temperature and salinity, it can serve as a proxy for seawater density [*Lynch-Stieglitz et al.*, 1999]. The $\delta^{18}O_{calcite}$ increases with decreasing temperature of calcification [*Emiliani*, 1955]. The isotopic composition of calcite is also determined by the isotopic composition of the water in which it calcifies. The isotopic composition of seawater is regionally linearly related to salinity since fluxes of fresh water, including evaporation and precipitation closely affect both [*Craig and Gordon*, 1965]. Higher $\delta^{18}O_{calcite}$ implies that the calcite formed in seawater with higher potential density.

[7] The oxygen isotope ratio in the shell of the planktonic foraminifera *Globorotalia truncatulinoides* ($\delta^{18}O_{trunc}$) provides a useful proxy for upper-ocean density gradients associated with the shear in upper-ocean flows because it approximates water properties from intermediate depths (300–500 meters). Examining water column properties from these depths is particularly useful because this range is below the surface layer where air-sea exchanges of heat and fresh water can complicate the structure of lateral density gradients. In addition, the correlation between upper-ocean horizontal density gradients and the location of upper-ocean flows is particularly strong because of a maximum in the vertical shear in velocity of upper-ocean flows at these intermediate depths.

[8] We have shown that the horizontal density gradients associated with upper-ocean flows can clearly be seen in the spatial pattern of core top

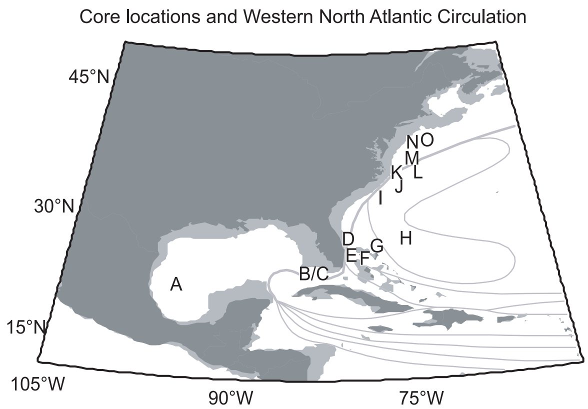

Figure 1. Core sites for this study are noted A through O, and corresponding details about each are located in Table 1. The approximate location of land during the LGM, given 130 meters lower sea level, is shaded in gray. *Schmitz and McCartney* [1993] Sv transport cartoon for the surface ocean is shown in light gray.

$\delta^{18}O_{trunc}$ [*LeGrande et al.*, 2004]. While the average isotopic composition of the test of *Gr. truncatulinoides* corresponds to calcification at around 350 meters water depth, the life cycle of this organism is more complex. This species most likely begins calcification in surface winter waters and then drops to as deep as 800 meters adding a secondary $\delta^{18}O$ enriched calcite crust [*Lohmann*, 1995]. Atlantic core top samples of *Gr. truncatulinoides* $\delta^{18}O$ most closely resemble that of an idealized calcite calculated from water column properties at 350 meters depth, equivalent to 30% calcite addition at the surface and 80% calcite addition at 800 meters [*LeGrande et al.*, 2004], and this finding does not change when only core samples from the western North Atlantic are considered (using the same method). While *Gr. truncatulinoides* has its largest flux to the sediments during wintertime [*Deuser and Ross*, 1989], the isotopic composition approximates mean annual conditions deeper in the water column where there is less seasonality; e.g., the difference between winter and annual calcification for the western North Atlantic is <0.05‰ in the 350 meter calcification case and <0.1‰ in the 30% surface, 70% 800 meter calcification case.

[9] These uncertainties in the exact calcification depth(s) of *Gr. truncatulinoides* suggest that though it is a good qualitative measure of current location, and it is not an adequate tool to derive quantitative current strength. *Matsumoto and Lynch-Stieglitz* [2003] used $\delta^{18}O_{trunc}$ gradients to determine the separation latitude of the Gulf Stream at Cape Hatteras during the LGM. Here we examine down core records of $\delta^{18}O_{trunc}$ from additional core sites in the western North Atlantic to infer the pattern of circulation during the LGM.

2.2. Sediment Core Data

[10] We have examined core sites in the Gulf of Mexico, on the landward side of the Florida Current near the Florida Keys, on the seaward side of the Florida Current near the Bahamas, and in the open western North Atlantic northeast of the Bahamas (Table 1; Figure 1). For the purposes of this LGM study, we required core sites to be greater than 450 meters depth during the LGM (580 meters depth for the present) to ensure that the $\delta^{18}O_{trunc}$ would not be biased toward shallow (lighter $\delta^{18}O_{trunc}$) due to the inability of *Gr. truncatulinoides* to calcify over its full range. (The shallowest core site included in the study of *LeGrande et al.* [2004] is 452 meters.) In the modern ocean there is a significant $\delta^{18}O_{trunc}$ gradient between the Bahamas and the Florida margin, reflecting the presence of the Florida Current. If there was a significant flow east of the Bahamas during the LGM, we would anticipate a stronger $\delta^{18}O_{trunc}$ gradient between the Bahamas and the open ocean site.

[11] Samples from these cores were prepared according to the methods described by *Matsumoto and Lynch-Stieglitz* [2003]. Holocene and LGM ages were determined from down core oxygen isotope stratigraphy on surface dwelling planktonic foraminifera (*Globigerinoides sacculifer* and *Globigerinoides ruber*), benthic foraminifera (*Cibicidoides wuellerstorfi*, *Cibicidoides pachyderma*), or ^{14}C dating on planktonic foraminifera (Figure 2, Table 1). We analyze three to five *Gr. truncatulinoides* shells from the sieve interval between 425–500 μm, a range in which most specimens contain significant $\delta^{18}O$ enriched secondary calcite crust that is added at depth [*Lohmann*, 1995]. Mean $\delta^{18}O_{trunc}$ values, and the range of values, are calculated at each core site by averaging $\delta^{18}O_{trunc}$ values over Holocene and LGM intervals (Table 1).

3. Results and Discussion

[12] In the modern ocean, the average $\delta^{18}O_{trunc}$ value landward of the Gulf Stream is 1.1‰, while the average seaward $\delta^{18}O_{trunc}$ value ranges from 0.7 to 0.4‰. Intensified Gulf Stream transport coupled to North Atlantic gyre recirculation cells may contribute to the more depleted $\delta^{18}O_{trunc}$ values of the more north and eastern sites that are

Table 1. Core Location and Depths Where the Oxygen Isotope Ratio in *Gr. truncatulinoides*, $\delta^{18}O_{trunc}$, Is Used to Infer the Location of the Florida Current With the Range of Values Indicated[a]

					Holocene				Glacial				
Code	Core	°N	°W	Depth, m	Mean $\delta^{18}O_{trunc}$, ‰	Min. $\delta^{18}O_{trunc}$, ‰	Max. $\delta^{18}O_{trunc}$, ‰	Interval, cm	Mean $\delta^{18}O_{trunc}$, ‰	Min. $\delta^{18}O_{trunc}$, ‰	Max. $\delta^{18}O_{trunc}$, ‰	Interval, cm	STRAT.
A	RC12-11	22.4	95.55	3072	1.12[b]	0.89	1.38	0–70	2.1	1.88	2.22	160–180	CW,GR,GS
B	K166-2 JPC29	24.27	83.27	648	1.18	1.11	1.24	0–8	2.03	1.84	2.15	168–200	^{14}C,CP
C	K166-2 JPC31	24.22	83.28	751	1.21	1.13	1.29	0–8	1.9	1.81	2.00	144–176	^{14}C,CP
D	V7-13	29.28	79.92	452	1.13[b]	0.87	1.31	0–40	—	—	—	—	GS
E	V3-149	27.17	79.58	706	1.12[b]	1.07	1.17	5–10	1.7	1.64	1.83	170–215	GS
F	OC205-2 103	26.07	78.06	965	0.69[b]	0.62	0.81	10–40	1.8	1.77	1.86	130–160	GS
G	RC9-14	27.38	76.95	1254	0.80[b]	0.46	0.98	5–20	1.7	1.66	1.80	50–65	GS
H	K140-2 JPC22	28.25	74.40	4712	0.42[c]	0.43	0.44	3–5	1.76[c]	1.73	1.78	161–179	GR[d]
I	K140-2 GGC50	32.75	76.25	1903	0.44[c]	0.39	0.49	5–9	1.3[c]	-	-	253	^{14}C[d],GR[d]
J	V26-175	33.92	74.45	3995	0.6[c]	0.56	0.94	5–35	1.39[c]	1.32	1.44	254–295	^{14}C[e]
K	V30-5	34.62	74.65	3203	0.48[c]	0.29	0.73	15–309	1.62[c]	1.12	1.95	575–847	^{14}C[d]
L	V26-176	36.03	72.4	3942	0.37[c]	0.29	0.49	15–88	1.35[c]	1.05	1.61	254–317	GR[d]
M	RC10-289	37.01	72.52	3173	0.85[c]	0.66	0.98	15–35	1.96[c]	1.76	2.61	135–175	^{14}C[d]
N	V21-1	38.72	72.65	2186	1.6[c]	1.5	1.61	15–75	2.54[c]	2.15	2.86	248–300	^{14}C[d]
O	V4-1	38.88	70.92	2867	1.8[c]	1.72	1.88	0–120	2.39[c]	2.15	2.57	288–629	^{14}C[e]

[a] The stratigraphy column (STRAT., right) indicates either ^{14}C dating or oxygen isotope stratigraphy from both *Gr. truncatulinoides* (425–500 μm) and the following: GS, *G. sacculifer* (355–425 μm); CW, *C. wuellerstorfi* (300–600 μm); GR, *G. ruber* white (300–355 μm); and CP, *C. pachyderma* (>300 μm).
[b] Results from *LeGrande et al.* [2004].
[c] Results from *Matsumoto and Lynch-Stieglitz* [2003].
[d] Results from *Keigwin* [2004].
[e] Results from *Balsam* [1981].

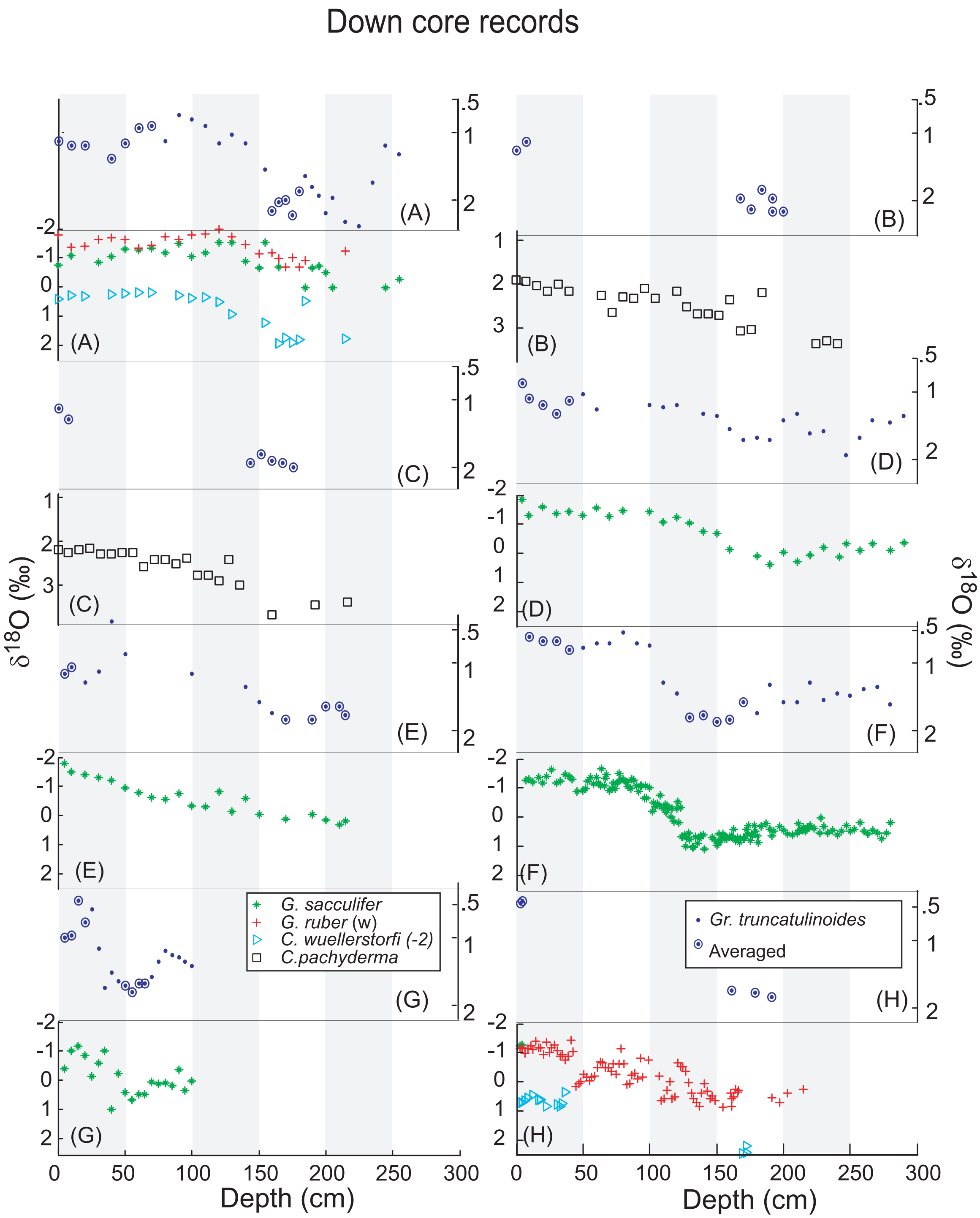

Figure 2. Down core oxygen isotope records and size fractions for the following species: *Gr. truncatulinoides* (425–500 μm), *Globigerinoides sacculifer* (355–425 μm), *Cibicidoides wuellerstorfi* (300–600 μm), *Globigerinoides ruber* white (300–355 μm), and *C. pachyderma* (150–250 μm). Offsets of −2‰ have been applied to *C. wuellerstorfi* to include them on the same scale. Letters correspond to core sites noted in Figure 1 and Table 1.

more central to the North Atlantic gyre. The $\delta^{18}O_{trunc}$ gradient across the Florida Current in the modern ocean is ~0.4‰, with a further ~0.3‰ seaward gradient most likely associated with the gyre recirculation cell (Figures 3a and 3b; Table 1). If there was a significant diversion of flow outside the Florida Straits, we would anticipate (1) a gradient between cores on the eastern edge of the Florida Straits (Sites F and G) and the core seaward of the Bahamas (Site H) and (2) no (or a significantly reduced) gradient across the Florida Straits.

[13] The average $\delta^{18}O_{trunc}$ value for the Bahamas (Sites F and G, east of the Florida Straits) as well the core east of the Bahamas (Site H) during the LGM is ~1.7‰; the $\delta^{18}O_{trunc}$ value of sites on the west side of the Florida Straits is ~2.0‰. The $\delta^{18}O_{trunc}$ gradient across the Florida Straits during the LGM is ~0.3‰, greater than the LGM temporal variability associated with each core site, and no further seaward gradient exists (Figure 3c). Since the location of the $\delta^{18}O_{trunc}$ gradient across the Florida Straits did not change during the LGM, we infer that there was vertical shear associated with the LGM Florida Current inside the Florida Straits. The lack of a $\delta^{18}O_{trunc}$ gradient in between the Bahamas (Sites F and G) and the site in the open Atlantic to the east (Site H) indicates that there was no significant deflection of the Florida Current outside of the Florida Straits during the LGM.

[14] The Holocene $\delta^{18}O_{trunc}$ from the cores on the gyre side of the Gulf Stream south of 30°N (Sites F and G) and the open Atlantic cores north of 30°N (Sites I, J, K) [*Matsumoto and Lynch-Stieglitz*, 2003] do exhibit both LGM and modern gradients of ~0.4‰. The LGM to modern change is that core K140-2 JPC22 (Site H) is apparently outside the recirculation cell during the LGM, but inside the recirculation cell in the present. This change seems to imply a shift in glacial wind patterns and perhaps gyre circulation; however, due the inherently qualitative nature of $\delta^{18}O_{trunc}$ as a proxy for upper ocean flows, including uncertainty in the actual calcification depth and the season of calcification, this potential northward migration of the recirculation cell cannot be concluded with this data alone. More cores from either side of this recirculation cell boundary in the modern ocean and LGM and additional corroboration with other proxies would be required to describe such a potential change in circulation. On the basis of this $\delta^{18}O_{trunc}$ proxy, it appears that the Florida Current

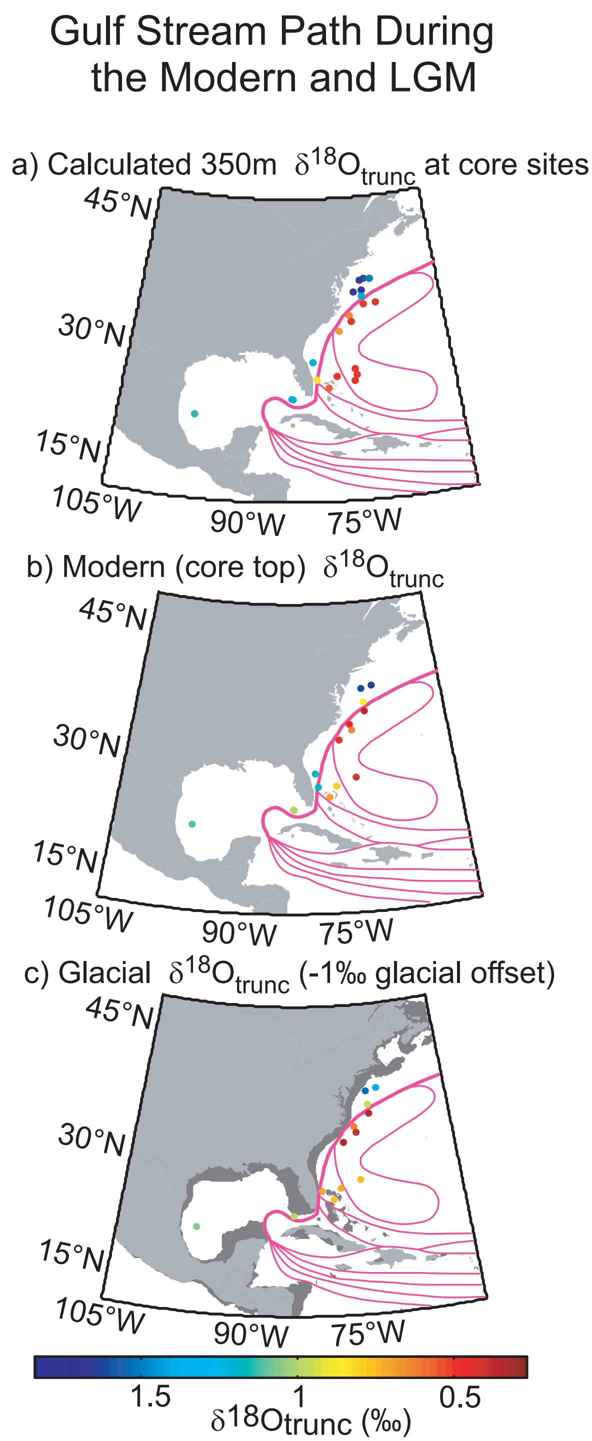

Figure 3. *Schmitz and McCartney* [1993] Sv transport cartoon is shown in pink. (a) $\delta^{18}O_{calcite}$ calculated from hydrographic data at 350 meters at core locations, (b) Atlantic core top (modern) $\delta^{18}O_{trunc}$ values (Table 1), and (c) down core $\delta^{18}O_{trunc}$ values for the LGM interval (Table 1). The LGM coastline, given 130 meters lower sea level, is noted in dark gray. The location of the $\delta^{18}O_{trunc}$ gradients (associated with the vertical shear of the Gulf Stream) is unchanged at the modern and the LGM (1) within the Florida Straits and (2) off of Cape Hatteras [*Matsumoto and Lynch-Stieglitz*, 2003]. The $\delta^{18}O_{trunc}$ gradient potentially associated with intensified transport of the gyre recirculation cell migrated northward/seaward from the modern to the LGM.

flowed through the Florida Straits during the LGM much as it does today.

[15] Implicit in this interpretation is that the relationship between intermediate depth density and $\delta^{18}O_{trunc}$ did not change from the modern to the LGM. Modeling studies have indicated that the relationship between the oxygen isotopic composition of seawater and salinity at millennial scales are different (steeper) than at decadal and shorter timescales [*Schmidt et al.*, 2007], and the possibility exists that a modulation of the relationship between density and $\delta^{18}O$ has also occurred. If the sensitivity of the $\delta^{18}O_{trunc}$ proxy to these density changes was dampened or amplified, an altered upper ocean flow of the LGM might yield an identical $\delta^{18}O_{trunc}$ gradient.

4. Conclusions

[16] The $\delta^{18}O_{trunc}$ proxy faithfully indicates patterns of upper ocean flow in the modern ocean [*LeGrande et al.*, 2004], and so we use it to indicate the basic pattern of past upper ocean flow in the western North Atlantic for the LGM. We find that there is a glacial $\delta^{18}O_{trunc}$ gradient confined within the Florida Straits, similar to the modern $\delta^{18}O_{trunc}$ gradient associated with the vertical shear in the Florida Current. There was no additional intermediate depth density gradient east of the Bahamas which implies no significant Gulf Stream flow outside of the Bahamas. *Lynch-Stieglitz et al.* [1999] identified a reduced density gradient within the Florida Straits and inferred a reduction in Florida Current transport during the LGM; this result paired with the apparent absence of a significant flow seaward of the Bahamas indicates that there was a reduction of the transport of the southernmost portion of the Gulf Stream during the LGM and not a diversion of its path.

[17] Additionally, the location of the intermediate depth density gradient and implied separation latitude of the Gulf Stream of Cape Hatteras during the last ice age was the same as today [*Matsumoto and Lynch-Stieglitz*, 2003]. The pattern of upper ocean flows along the western North Atlantic during the last ice age was apparently similar to the modern pattern. The implication of these findings is that any changes in the wind or changes in ocean bathymetry due to sea level drop were not sufficient to significantly change the overall pattern of ocean circulation of the western North Atlantic from the modern to the last ice age.

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