Oxygen isotopic composition of *Globorotalia truncatulinoides* as a proxy for intermediate depth density

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[1] We investigate whether the oxygen isotope ratio in the test of *Globorotalia truncatulinoides* can serve as a proxy for intermediate depth (200–500 m) density. Since intermediate depth horizontal density gradients are associated with the vertical shear of upper ocean flows, this proxy could provide a tool for reconstructing past ocean circulation. The spatial pattern of core top *Gr. truncatulinoides* $\delta^{18}O$ in the Atlantic Ocean mimics the upper ocean density gradients associated with the major ocean currents. To better constrain the controls on the calcification depth(s) of *Gr. truncatulinoides*, we attempt to simulate the surface sediment data set using water column temperature and salinity conditions above the core sites. We predicted foraminiferal $\delta^{18}O$ for each core site assuming (1) the calcification occurs at a single depth and (2) the initial calcification is at the surface and the subsequent calcification is at 800 m water depth. The predicted $\delta^{18}O$ best resembles measured $\delta^{18}O$ of *Gr. truncatulinoides* when using (1) a single depth calcification at 350 m or (2) a two-depth approximation with 30% surface and 70% 800-m calcification. This result gives us confidence in the ability of $\delta^{18}O$ in *Gr. truncatulinoides* to proxy lateral density gradients at the intermediate depths associated with upper ocean flow. *INDEX TERMS:* 4223 Oceanography: General: Descriptive and regional oceanography; 4267 Oceanography: General: Paleoceanography; 4532 Oceanography: Physical: General circulation; 4855 Oceanography: Biological and Chemical: Plankton; 4870 Oceanography: Biological and Chemical: Stable isotopes; *KEYWORDS: Globorotalia truncatulinoides*, oxygen isotopes, ocean circulation

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1. Introduction

[2] Horizontal density gradients in the upper ocean reflect large-scale ocean circulation features, including strong currents. Strong density gradients exist in these regions of strong flow because large-scale upper ocean flows are in geostrophic equilibrium, to a first approximation. These lateral density gradients associated with the major upper ocean currents reach a maximum between 200 and 500 m where the vertical shear of the current velocity is at a maximum. The oxygen isotope ratio in the calcite shells of foraminifera can be used to reconstruct seawater density for the past ocean because it strongly depends on the same two variables that control seawater density, temperature and salinity.

[3] *Lynch-Stieglitz et al.* [1999a, 1999b] use $\delta^{18}O$ from benthic foraminifera from the Florida and Bahamas margins to reconstruct the upper ocean density gradient across the Florida Straits that reflects the vertical shear of the Florida Current. However, benthic foraminifera can provide appropriate horizontal density gradient information in only very specific settings where there are continental or island margins on either side of an upper ocean current. Oxygen isotopes from surface-dwelling planktonic species, such as *Globogerinoides sacculifer* and *Globogerinoides ruber* can capture surface density conditions without this bathymetric constraint [*Billups and Schrag*, 2000]. However, surface density reflects not only ocean currents but also the air sea exchange of heat and fresh water. In addition, the maximum vertical shear in the upper ocean geostrophic currents occurs below the surface layer, and thus the maximum horizontal density gradient associated with these geostrophic flows occurs at intermediate depths (200–500 m), not at the surface. A planktonic species that calcifies at these intermediate depths would be ideal for capturing these maximum gradients.

[4] *Mulitza et al.* [1997] showed that the difference between the $\delta^{18}O$ from the subsurface foraminifera *Globorotalia truncatulinoides* and the $\delta^{18}O$ of *G. sacculifer* is proportional to the surface to 250 m temperature difference in the South Atlantic. *Matsumoto and Lynch-Stieglitz* [2003] proposed that since the $\delta^{18}O$ from *Globorotalia truncatulinoides* ($\delta^{18}O_{trunc}$) approximates water properties at the intermediate depth of approximately 250 m, it can be used to reconstruct the locations of the lateral density gradients associated with upper ocean geostrophic flows. However, the calcification habitat of *Gr. truncatulinoides* is complicated; this species most likely begins calcification in surface winter waters and then drops as deep as 800 m

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Table 1. New Core Top *Gr. truncatulinoides* δ^{18}O Used in This Study[a]

Core	Latitude	Longitude	Core Depth	Core Top $\delta^{18}O_{trunc}$, ‰	Size Fraction, μm	Stratigraphy
RC8-19 TW	−24.29	−14.70	3636	1.02	425–500	CT
RC12-291 TW	−42.58	−17.80	3508	2.70	425–500	CT
RC12-292	−39.68	−15.48	3541	1.81	425–500	CT
VM16-36 TW	−19.37	−11.43	3329	1.67	425–500	CT
VM24-231 TW	−33.95	−13.83	3438	1.11	425–500	CT
VM26-70 TW	−30.87	−17.85	3933	0.92	425–500	CT
VM027-166	25.85	−22.72	4945	0.80	355–425	CT
VM023-105	17.20	−35.83	5009	1.47	500–600	CT
VM030-040	−0.20	−23.15	3706	0.89	355–425	CT
VM030-041	−0.20	−23.15	3706	1.14	500–600	CT
VM023-104	17.22	−32.35	4953	1.33	500–600	CT
VM014-004	15.48	−40.52	4473	1.88	500–600	CT
VM016-205	15.40	−43.40	4043	1.33	500–600	CT
VM025-059	1.37	−33.48	3824	1.73	500–600	CT
RC4-3	27.48	−74.08	4389	0.59	425–500	GS
RC4-4	26.88	−74.35	4329	0.58	425–500	GS
RC9-14	27.38	−76.95	1254	0.79	425–500	GS
OC205-2 103	26.07	−78.06	965	0.69	425–500	GS
V3-149	27.17	−79.58	706	1.12	425–500	GS
V7-13	29.28	−79.92	452	1.14	425–500	GS
RC12-11	22.40	−95.55	3072	1.10	425–500	GS

[a]The last column indicates either core tops (CT) without down core stratigraphy or cores with *G. sacculifer* stratigraphy (GS).

adding a secondary δ^{18}O enriched calcite crust [*Lohmann*, 1995]). Before using $\delta^{18}O_{trunc}$ to reconstruct lateral density gradients related to upper ocean flows, we must first quantitatively assess its ability to proxy intermediate depth density. Here we evaluate the ability of *Gr. truncatulinoides* δ^{18}O to record the subsurface density gradients associated with upper ocean geostrophic flows by comparing surface sediment $\delta^{18}O_{trunc}$ to properties in the overlying water column.

2. Methods

[5] The core top or surface sediment samples used for our analysis of $\delta^{18}O_{trunc}$ as an intermediate depth density proxy are primarily from previous studies. Since we wanted to compare the maximum possible number of Holocene $\delta^{18}O_{trunc}$ samples to the overlying water conditions, we included several size fractions as well as several methods of collecting Holocene sediment samples (core tops with underlying stratigraphy, box cores, etc.) (Tables 1 and 2).

[6] *Matsumoto and Lynch-Stieglitz* [2003] use δ^{18}O from *G. sacculifer*, a surface-dwelling planktonic foraminifera, to provide a stratigraphy for sediment cores. For these cores, we averaged isotope values from *Gr. truncatulinoides* at the depths where the δ^{18}O of *G. sacculifer* showed Holocene values. Carbon-14 dating of these cores provides a second means of insuring that $\delta^{18}O_{trunc}$ are Holocene in age. *Ganssen and Kroon* [2000] treat their surface sediment samples with an ethanol Rose Bengal solution that stains living or nondecayed foraminifera. They use only core top samples from cores that have stained foraminifera specimens, indicating they must be very recent in age. The Holocene age of the measurements from *Mulitza et al.* [1997] are documented by either a down core δ^{18}O stratigraphic record or the presence of the interglacial-indicative species *Gr. menardii*. In addition to these previous 156 analyses of *Gr. truncatulinoides* δ^{18}O, we include seven analyses from an ongoing study in the Florida Straits (Table 1). These samples were prepared according to the method described in the work of *Matsumoto and Lynch-Stieglitz* [2003] and their Holocene Age determined from down core oxygen isotope stratigraphy. We also include several new undocumented core top measurements (Table 1). The new *Gr. truncatulinoides* δ^{18}O data presented here are from both the left and right-coiling morphotypes of the species. Although the biogeographical extent of these two species is different, previous studies have found no significant difference in the δ^{18}O composition between these two variants [*Ganssen and Kroon*, 2000].

[7] The *Gr. truncatulinoides* used in this study were from the sieve interval between 355 and 600 μm. *Lohmann* [1995] measured mass and δ^{18}O on individual *Gr. truncatulinoides*

Table 2. Holocene Indication and Size Fraction of Previously Published $\delta^{18}O_{trunc}$ Data Used in This Study

Study	Holocene Determination	Size Fraction	Number
Mulitza et al. [1997]	multicores or box cores with either isotope stratigraphy or noted presence of *G. menardii*	north of 35°S, 550–600 μm; south of 35°S, 315–400 μm	106
Ganssen and Kroon [2000]	box cores: Rose Bengal stain and/or ^{14}C dating	355–425 μm	25
Matsumoto and Lynch-Stieglitz [2003]	*G. sacculifer* stratigraphy and/or ^{14}C dating.	425–500 μm	12

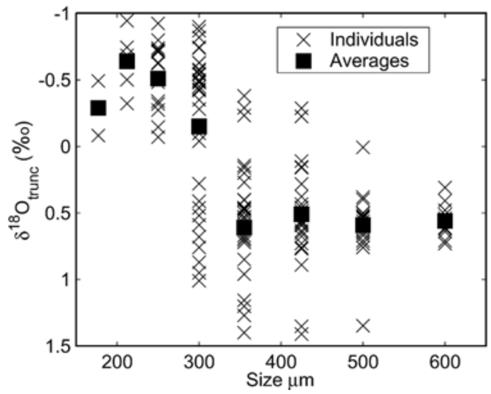

Figure 1. Size fraction and $\delta^{18}O_{trunc}$ from surface sediments on the Little Bahamas Bank [*Lohmann*, 1995]. *Gr. truncatulinoides* from size fractions $\geq$350 μm have $\delta^{18}O$ enriched secondary calcite.

in the Bahamas and found that most shells greater than 355 μm have a significant $\delta^{18}O$ enriched secondary calcite crust (Figure 1). We also include some measurements from *Mulitza et al.* [1997] which were taken on *Gr. truncatulinoides* between 315 and 355 μm. These are from the southern polar front where the calcification habitat is very different from the subtropical habitat in the *Lohmann* [1995] study. Because most individuals found in the sediments are encrusted, we suspect that *Gr. truncatulinoides* calcifying in this environment do not attain the same size as those calcifying at low latitudes and that these smaller individuals do have a secondary calcite crust.

[8] At each core site, we calculate the $\delta^{18}O$ of calcite that would form in equilibrium with seawater ($\delta^{18}O_{calcite}$) at depths from 0 to 1000 m at 50-m intervals. Annually averaged temperature and salinity data from the overlying water column from *Levitus and Boyer* [1994a, 1994b] are used in most locations, except near the western boundary where the sharp lateral property gradients are not adequately resolved in this climatology. For these locations, we compile individual temperature and salinity profiles from *Levitus and Boyer* [1994a, 1994b] in small grid boxes around the core site to determine average temperature and salinity values at various depths. The $\delta^{18}O$ of seawater ($\delta^{18}O_{water}$) is calculated from salinity using the following relationships derived from shallow (<1000 m) data published on the global seawater $\delta^{18}O$ and salinity Web site (www.giss.nasa.gov/data/o18data2003): North Atlantic, $\delta^{18}O_{water} = -20.839 + 0.6038 \times$ salinity; South Atlantic, $\delta^{18}O_{water} = -19.016 + 0.5507 \times$ salinity (we calculate $\delta^{18}O_{calcite}$ from the temperature and $\delta^{18}O_{water}$ [*Kim and O'Neil*, 1997]); and $\delta^{18}O_{calcite} = (\delta^{18}O_{water} + -0.27) + 3.2486 - 0.2004 \times$ temperature.

[9] We test two calcification models to assess at which depth $\delta^{18}O_{trunc}$ records seawater properties. The simplest model is that $\delta^{18}O_{trunc}$ records conditions from a single intermediate depth. A more complex model is a two-depth calcification approximation model, with contributions from the surface and 800 m as suggested in the work of *Lohmann* [1995]. In the single depth model, we determine the minimum root-means-squared (RMS) error between the core top $\delta^{18}O_{trunc}$ and the calculated $\delta^{18}O_{calcite}$ at various depths; in the two-depth model, we determine the minimum RMS error between the core top $\delta^{18}O_{trunc}$ and various combinations of surface and deep calculated $\delta^{18}O_{calcite}$.

3. Results

[10] Atlantic surface sediment $\delta^{18}O_{trunc}$ values reflect major oceanographic features such as western boundary currents and polar fronts (Figure 2). The presence of these oceanographic features in the surface sediment data set suggests that *Gr. truncatulinoides* do not calcify along isopycnals, as suggested by a temperature-controlled or density-dependent secondary calcification [*Hemleben et al.*, 1985; *McKenna and Prell*, 1996]. If *Gr. truncatulinoides* calcified at a set temperature or along isopycnals, there would be much less variation in $\delta^{18}O_{trunc}$ from location to location, allowing homogenous values across areas containing strong lateral density gradients. While there are some areas, particularly near sources of freshwater input into the ocean where there can be large gradients in $\delta^{18}O_{water}$ and thus $\delta^{18}O_{calcite}$ along isopycnals, most of the core sites in this study are from the open ocean where such gradients are small.

[11] The single-depth calcification model produces a minimum RMS error between the $\delta^{18}O_{trunc}$ and $\delta^{18}O_{calcite}$ of 0.3764 at 350 m (Figure 3a). The two-depth calcification model produces a minimum RMS error between the $\delta^{18}O_{trunc}$ and $\delta^{18}O_{calcite}$ of 0.4200 with 30% surface and 70% 800-m calcite (Figure 3b). The spatial pattern of surface sediment $\delta^{18}O_{trunc}$ resembles both calculated $\delta^{18}O_{calcite}$ at 350 m and calculated $\delta^{18}O_{calcite}$ with 30% surface and 70% 800-m calcite (Figure 4).

4. Discussion

[12] Water column temperature and salinity conditions above each core site can reasonably reproduce core top $\delta^{18}O_{trunc}$ using both the single and the two-depth calcification models. Since the difference in minimum RMS error between the two is very small, neither scenario may be ruled out (Figure 5). In reality, the calcification habitat of *Gr. truncatulinoides* is more complex and likely a hybrid of calcification at various depths in the water column during several seasons. Carbon isotope data from *Gr. truncatulinoides* could potentially help to further constrain calcification depth. *Mulitza et al.* [1998] show that in the tropical Atlantic, spatial $\delta^{13}C$ gradients in the test of *Gr. truncatulinoides* reflect the strong gradients of nutrients and $\delta^{13}C$ in thermocline waters. The gradients are more subtle in surface and deeper waters, so their work would not support the simple two-depth model, presuming that the carbon isotopic composition of the shells reflected that of the water in which they calcified. However, the mechanisms controlling carbon isotope fractionation in planktonic foraminifera can be complex and are not well understood for *Gr. truncatulinoides*.

[13] Other factors such as light, pH, and nutrients also can affect the isotopic fractionation during calcification of

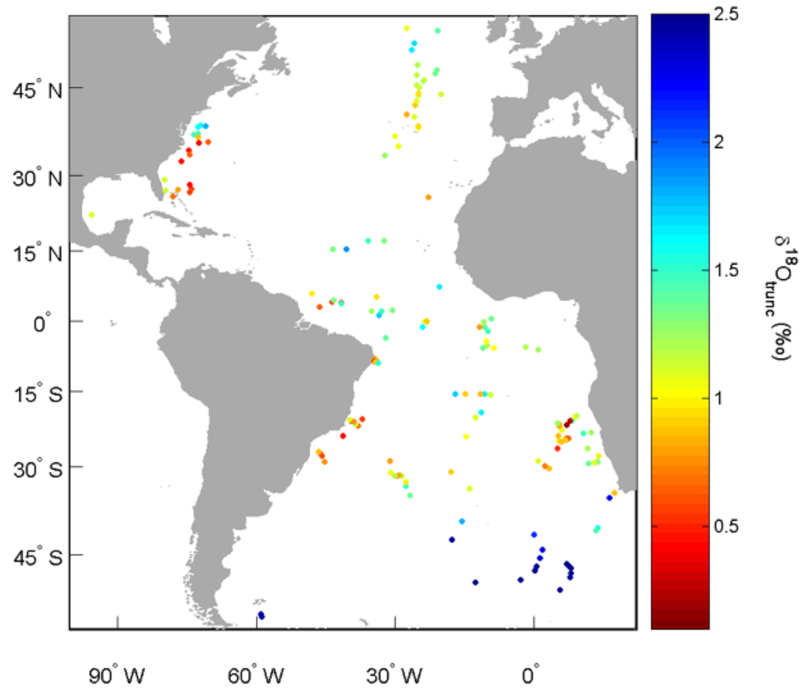

Figure 2. Atlantic core top $\delta^{18}O_{trunc}$ values (Cape Hatteras [*Matsumoto and Lynch-Stieglitz*, 2003], northern North Atlantic [*Ganssen and Kroon*, 2000], South Atlantic (except mid-ocean ridge) [*Mulitza et al.*, 1997], and others (this study)). Lighter $\delta^{18}O_{trunc}$ values (warmer calcification temperature) are represented by warmer colors. These $\delta^{18}O_{trunc}$ gradients are associated with major oceanographic features such as the western boundary currents, subtropical warm pools, and polar fronts.

foraminifera [*Bé*, 1982], but the precise effect these variables have on $\delta^{18}O_{trunc}$ is unclear. We assess the potential impact of vital effects in altering the $\delta^{18}O_{trunc}$ signal from the predicted temperature-dependent ^{18}O fractionation. In addition, since the δ^{18}O of inorganic calcite precipitated at equilibrium itself has considerable uncertainty, our analysis of vital effects serves the purpose of testing the appropriateness of the equations [*Kim and O'Neil*, 1997] we use to convert temperature and $\delta^{18}O_{water}$ to $\delta^{18}O_{calcite}$. For the single depth calcification approximation, we assign an offset from equilibrium between −0.1‰ to +0.5‰ to the calculated $\delta^{18}O_{calcite}$; for the two-depth calcification approximation, we assign an offset from equilibrium between −0.4‰ to +0.2‰ to the calculated $\delta^{18}O_{calcite}$. For each offset from equilibrium we again vary the calcification depth in the single depth model and the percentage of surface versus deep calcification in the two depth model and assess the RMS error between the $\delta^{18}O_{trunc}$ and $\delta^{18}O_{calcite}$. We do not alter the slope in the temperature versus $\delta^{18}O_{calcite}$ relationship because the analyses from *Bemis et al.* [1998] suggest that most temperature to $\delta^{18}O_{calcite}$ relationships within the range of our study have similar slopes but different intercepts.

[14] None of the tested offsets from equilibrium shift the minimum RMS error outside of the intermediate depth range required to observe density gradients associated with upper ocean circulation (Figure 6). Although a +0.4‰ vital effect in the single depth approximation at 200 m and a −0.05‰ vital effect in the two-depth with 28% surface

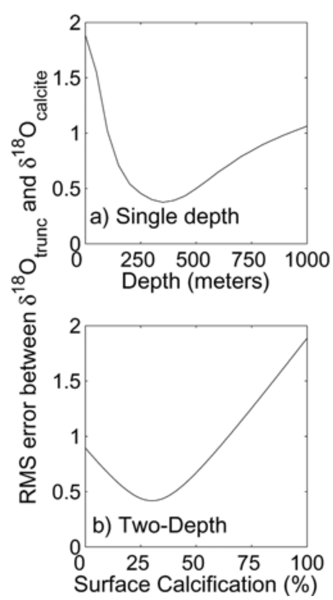

Figure 3. The RMS error between $\delta^{18}O_{trunc}$ and (a) $\delta^{18}O_{calcite}$ calculated at a single depth for depths between 0 and 1000 m and (b) calculated $\delta^{18}O_{calcite}$ in the two-depth model that tests combinations of surface and 800-m calcite. The single depth approximation has a minimum RMS error between $\delta^{18}O_{trunc}$ and $\delta^{18}O_{calcite}$ of 0.3764 at 350 m. The two-depth calcification approximation has a minimum RMS error between $\delta^{18}O_{trunc}$ and $\delta^{18}O_{calcite}$ of 0.4200 with 30% surface and 70% 800-m calcite.

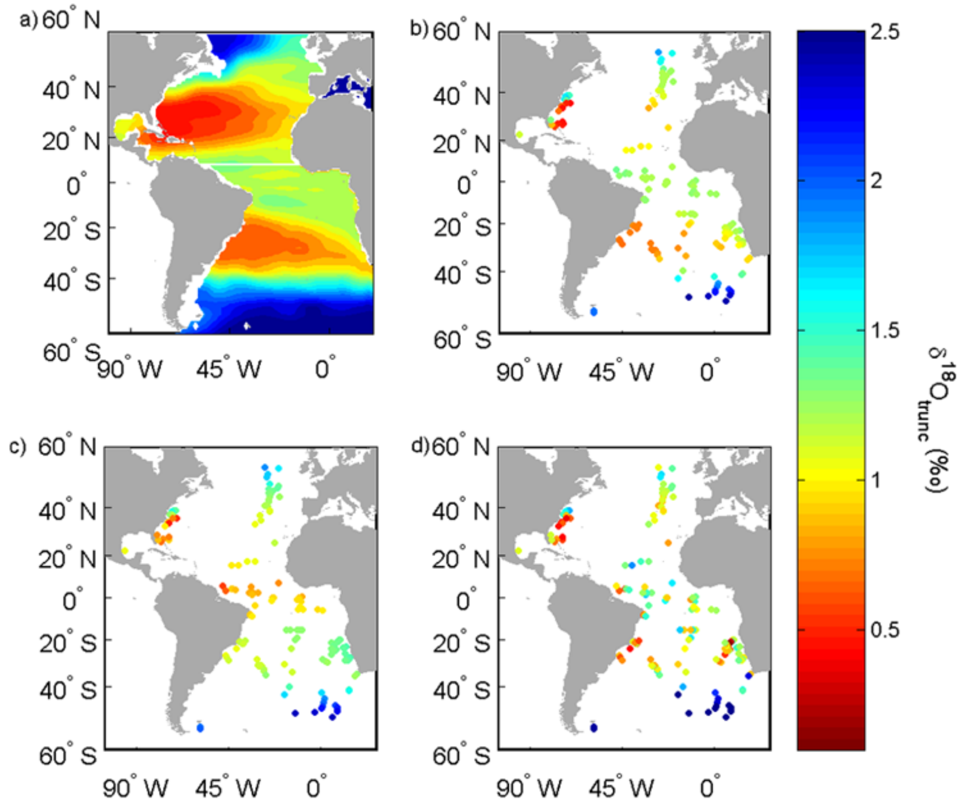

Figure 4. (a) $\delta^{18}O_{calcite}$ calculated from hydrographic data at 350 m. (b) Same as Figure 4a but shown only at core locations. (c) $\delta^{18}O_{calcite}$ calculated from hydrographic data with a 30% surface contribution and a 70% 800-m contribution. (d) Core top $\delta^{18}O_{trunc}$ (as in Figure 2).

calcite create smaller minimum RMS error than no offset from equilibrium, the "improvement" from no offset from equilibrium in both cases is very small (Figure 6).

[15] Dissolution preferentially removes the isotopically lighter primary calcite that *Gr. truncatulinoides* add at shallower depths. This makes the remaining calcite shell enriched in ^{18}O [*Lohmann*, 1995]. Since the degree of dissolution increases with water depth (below a threshold depth), we expect $\delta^{18}O_{trunc}$ from samples altered by dissolution to be a function of core depth, in addition to temperature and salinity. We compare the difference between measured $\delta^{18}O_{trunc}$ and $\delta^{18}O_{calcite}$ predicted from temperature and salinity ($\Delta\delta^{18}O_{trunc\text{-}calcite}$) to core depth in order to assess the significance of dissolution in our surface sediment data set (Figure 7). A trend in $\Delta\delta^{18}O_{trunc\text{-}calcite}$ (toward heavier values for deeper cores) would suggest dissolution has affected the deeper samples.

[16] Though we find an apparent trend in the data beginning at approximately 3000 m, it is not clear how to correct the deep data for this dissolution effect. *Lohmann* [1995] suggests that dissolution of primary calcite in Atlantic *G. sacculifer* may have progressed to 20% by 2931 m and 70% by 5104 m. *Broecker and Clark* [2003] find that dissolution does not significantly affect Atlantic *G. sacculifer* until around 4100 m. We re-evaluate the data for dissolution effects in the two-depth model by (1) determining minimum RMS error of cores only above a threshold depth above which no dissolution should occur and (2) applying a progressive correction to account for greater dissolution at greater depths. Though these corrections either (1) shift the apparent calcification to slightly shallower depths or (2) increase the amount of shallow calcification, they do not decrease the minimum RMS error between the measured and calculated data sets (the two possibilities are not distinguishable). For instance, in the two-depth calcification scenario, we apply a dissolution correction to the observed $\delta^{18}O_{trunc}$ that progressively "adds in" lost primary calcite (isotopically lighter) at a rate dependent on the core depth. This analysis yields additional surface calcification compared to the analysis with no correction for dissolution (44% surface calcification and 56% 800-m calcification). However, the RMS error difference between core top $\delta^{18}O_{trunc}$ to the dissolution-corrected two-depth model and core top $\delta^{18}O_{trunc}$ to the no-correction two-depth model is very small.

[17] For this data set, dissolution does not significantly alter the ability of $\delta^{18}O_{trunc}$ to proxy intermediate depth density structure. However, care should be taken when analyzing $\delta^{18}O_{trunc}$ data from (1) core sites deeper than 3000 m, (2) cores from shallower depths in other ocean basins where dissolution may be more significant than in the Atlantic; e.g., the Pacific, and (3) deep cores during

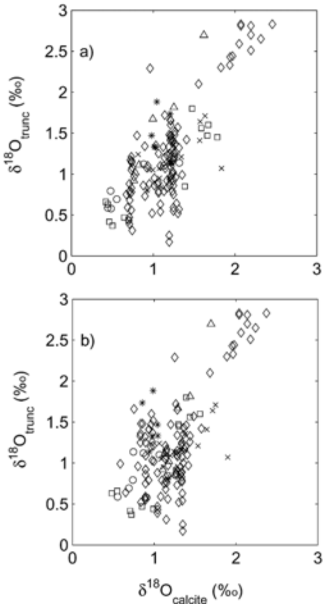

Figure 5. (a) $\delta^{18}O_{trunc}$ versus $\delta^{18}O_{calcite}$ calculated using hydrographic data at 350 m and (b) $\delta^{18}O_{trunc}$ versus $\delta^{18}O_{calcite}$ calculated from hydrographic data with a 30% surface component and a 70% 800-m component.

glacial times when dissolution may have been more significant.

[18] Horizontal gradients in Atlantic $\delta^{18}O_{trunc}$ reliably reflect upper ocean flow patterns in the modern ocean. The diversity of the core sites used in this analysis should give confidence in using $\delta^{18}O_{trunc}$ to assess upper ocean circulation patterns in the past when regional patterns of flow may have been different from today. However, the gradients in $\delta^{18}O_{trunc}$ alone cannot indicate the current strength. First, the complex calcification habitat of *Gr. truncatulinoides* prevents a quantitative assessment of density at any specific depth. Second, even if $\delta^{18}O_{trunc}$ could give an absolute indication of density at 350 m, this information alone is not enough to make a determination of current strength.

[19] Detailed knowledge of upper ocean density structure can provide a means to calculate upper ocean transport. However, this geostrophic transport calculation technique cannot directly translate $\delta^{18}O_{trunc}$ values (and gradients) into upper ocean flow data. Lateral density gradients at a given depth in the upper ocean are related to the vertical shear of a flow at that depth. This relationship could lead to a calculation of transport if the vertical shear (horizontal density gradient) was known at a variety of depths through the upper water column and if the velocity was known at some point within this range (reference velocity).

[20] The $\delta^{18}O_{trunc}$ provides information neither about the variation of density with depth, nor any reference velocity. In most cases, it is likely that given a wind driven flow in the upper ocean, velocity will diminish with depth, creating a vertical shear at the depths recorded by $\delta^{18}O_{trunc}$. This vertical shear will have associated lateral density gradients that can be used to determine the location of the currents, but not the absolute transport of the flow.

5. Conclusions

[21] Upper ocean density reflects the vertical shear in velocity of upper ocean flows. Measuring upper ocean density provides an alternative method (to direct current observation) of determining the location of upper ocean flows since these density gradients occur in the same place as the upper ocean flow (and its shear). The correlation between upper ocean density gradients and the location of upper ocean flows is particularly strong at intermediate depths (200 to 500 m) because (1) the vertical shear in velocity of upper ocean flows is usually maximal in this range and (2) these depths are below the surface layer where air-sea exchanges can complicate the structure of lateral density gradients. The oxygen isotope ratio in the shell of planktonic foraminifera *Gr. truncatulinoides* ($\delta^{18}O_{trunc}$) provides a means to examine intermediate depth water column density.

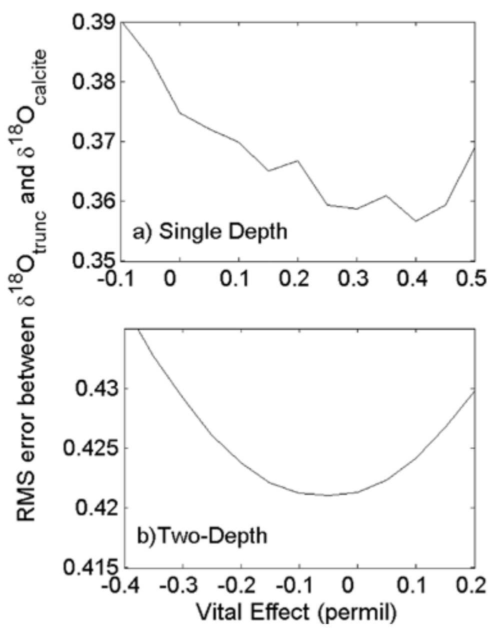

Figure 6. Using various offsets from the presumed equilibrium when calculating $\delta^{18}O_{calcite}$ the RMS errors (e.g., Figure 3) are recalculated. Here we show (a) minimum RMS error between $\delta^{18}O_{trunc}$ and $\delta^{18}O_{calcite}$ calculated using hydrographic data at a single depth and (b) minimum RMS error between $\delta^{18}O_{trunc}$ and$\delta^{18}O_{calcite}$ calculated from hydrographic data using the two depth model (surface and 800 m). In the single depth model the minimum RMS error (0.3570) occurs with a +0.4‰ offset depth of 200 m. In the two-depth model the minimum RMS error (0.4196) occurs with a −0.05‰ offset with 28% surface calcite in the two-depth approximation.

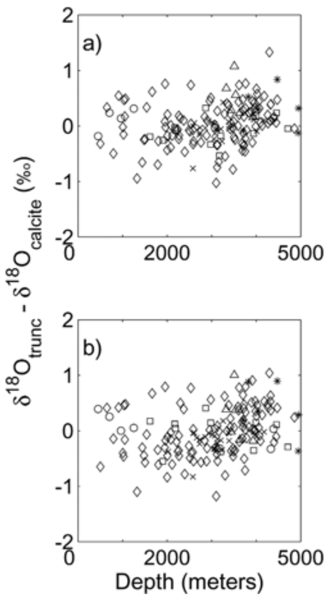

Figure 7. Core depth versus (a) $\delta^{18}O_{trunc}$ less $\delta^{18}O_{calcite}$ ($\Delta\delta^{18}O_{trunc\text{-}calcite}$) calculated using hydrographic data at 350 m and (b) $\Delta\delta^{18}O_{trunc\text{-}calcite}$ calculated from hydrographic data with a 30% surface component and a 70% 800-m component. The trend off the zero line indicates dissolution may be affecting $\delta^{18}O_{trunc}$ below 3000 m water depth.

[22] This study examined the ability of $\delta^{18}O_{trunc}$ to proxy water column properties in more detail by comparing measured core top $\delta^{18}O_{trunc}$ values to $\delta^{18}O_{calcite}$ calculated from salinity and temperature in the upper 1000 m of the water column. We find that $\delta^{18}O_{trunc}$ is a good proxy for intermediate depth density and that the circulation patterns that are inferred from the modern Atlantic $\delta^{18}O_{trunc}$ data match well with observed upper ocean flow patterns.

[23] Gradients in $\delta^{18}O_{trunc}$ from down core ocean sediment samples can provide a means for examining patterns of upper ocean flow in the past. *Matsumoto and Lynch-Stieglitz* [2003] use $\delta^{18}O_{trunc}$ gradients from down core records off Cape Hatteras to assess the separation latitude of the Gulf Stream during the last glacial maximum. More generally, reconstructing the patterns in upper ocean currents gives insight into both wind patterns over the ocean and the general climate (e.g., heat transfer by the ocean). Furthermore, documenting the changes in the large-scale flow pattern is critical in the interpretation of proxy data for surface temperature and productivity changes in many areas.

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