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Key Points:
- Rapid subsurface oceanographic change in the tropical west Atlantic reflects shifting subtropical gyre
- Subsurface warming responds to deglacial AMOC perturbations (Heinrich Stadials 2 and 1, and the Younger Dryas)
- Southward propagation of salinity maximum water during Northern Hemisphere cold spells shifts the mixing zone of tropical and subtropical waters

Supporting Information:
- Supporting Information S1

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Southward Displacement of the North Atlantic Subtropical Gyre Circulation System During North Atlantic Cold Spells

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Abstract During times of deglacial Atlantic Meridional Overturning Circulation (AMOC) perturbations, the tropical Atlantic experienced considerable warming at subsurface levels. Coupled ocean-atmosphere simulations corroborate the tight teleconnection between the tropical Atlantic and climate change at high northern latitudes but still underestimate the relevance of the subsurface North Atlantic subtropical gyre (STG) for heat and salt storage and its sensitivity to rapid climatic change. We here reconstruct vertical and lateral temperature and salinity gradients in the tropical west Atlantic and the Caribbean over the last 30 kyr, based on planktic deep and shallow dwelling foraminiferal Mg/Ca and $\delta^{18}O$ records. The rapid and large-amplitude subsurface changes illustrate a dynamic STG associated with abrupt shifts of North Atlantic hydrographic and atmospheric regimes. During full glacial conditions, the STG has been shifted southward while intensified Ekman downwelling associated to strengthened trade winds fostered the formation of warm and saline salinity maximum water (SMW). The southward propagation of SMW was facilitated by the glacially eastward deflected North Brazil Current. During periods of significant AMOC perturbations (Heinrich Stadials 1 and the Younger Dryas), extreme subsurface warming by ~6 °C led to diminished lateral subsurface temperature gradients. Coevally, a deep thermocline suggests that SMW fully occupied the subsurface tropical west Atlantic and that the STG reached its southernmost position. During the Holocene, modern-like conditions gradually developed with the northward retreat of SMW and the development of a strong thermocline ridge between the Subtropical Gyre and the tropical west Atlantic.

1. Introduction

The predominantly wind-driven North Atlantic subtropical gyre (STG) is a major hydrographic feature of the North Atlantic and plays an important role for the upper ocean circulation. As an enormous reservoir for heat and salt (Schmitz & McCartney, 1993), it reacts very sensitively to climatic changes based on the close interrelationship between atmospheric and oceanic processes, which influence gyre circulation and (sub)surface water properties (e.g., Mignot et al., 2007; Mildner, 2013). Oceanographic data and modelling studies suggest a close coupling between the strength of the Atlantic Meridional Overturning Circulation (AMOC) and both extension and shape of the northern rim of the STG on decadal timescales (e.g., Born & Levermann, 2010; Häkkinen & Worthen, 2011; Hátún et al., 2005). During the last deglaciation and especially during North Atlantic cold periods, namely, the Heinrich Stadial 2 (HS2, 27–24 ka BP, Stern & Lisiecki, 2013), Heinrich Stadial 1 (HS1, 18–14.6 ka BP, Barker & Diz, 2014), and the Younger Dryas (YD, 12.8–11.5 ka BP, Barker & Diz, 2014), the AMOC slowed down or even collapsed and was rather sluggish during the Marine Isotope Stage 2 (MIS 2, 14–29 ka BP, Lisiecki & Raymo, 2005; Böhm et al., 2015; McManus et al., 2004). At the same time, abrupt southward shifts of hydrographic and atmospheric frontal systems were observed in the Atlantic Ocean.

The impact of glacial and deglacial changes on the position of atmospheric and oceanic frontal systems on the STG is still a matter of debate. At the northern boundary of the STG several paleoproxy studies point to the southward displacement of the STG during North Atlantic cold periods (Calvo et al., 2001; Repschläger et al., 2015; Schiebel et al., 2002; Schwab et al., 2012) synchronous to the weakened AMOC circulation. At the southern margin of the STG, the intensified northeastern trades, the southward displaced ITCZ and a sluggish AMOC circulation weakened or even reversed the NBC (Schmidt et al., 2012; Zhang et al., 2015). These processes possibly allowed high saline water masses of the STG to migrate farther south into the tropical Atlantic at the surface mixed layer, as indicated by dinoflagellate cyst counts during the last glacial (Vink et al., 2001).

The southward shift of the main wind fields in the North Atlantic (e.g., Vellinga & Wu, 2004), including the southward displacement of the Intertropical Convergence Zone (ITCZ; e.g., Arbuszewski et al., 2013; Peterson et al., 2000) and northeastern trade winds, which constitute the main forcing for the STG variability (Mildner, 2013; Vellinga & Wu, 2004), is evident during times of high latitude cooling. The short-term weakening of the AMOC additionally reinforced the Northern Hemisphere wind fields and led to a rather negative precipitation-evaporation balance (e.g., Lohmann, 2003; Mildner, 2013; Vellinga & Wu, 2004), which caused higher salinity within the STG (Schmidt et al., 2006). The higher wind stress led to the deepening of the thermocline due to strengthened Ekman pumping (Slowey & Curry, 1995), which supplied saline surface waters of the STG into the thermocline and form the salinity maximum water (SMW).

At present day, warm and saline SMW forms in the northwestern part of the STG, where surface waters get subducted in the salinity maximum region, from which it is carried equatorward and enters the equatorial region in the shallower subtropical cell (Blanke et al., 2002; Johns et al., 2002; Qu et al., 2013). Under modern conditions this pathway is blocked by a strong northward flowing western boundary current, which separates the SMW from cooler fresher subsurface waters of the North Brazil Current (NBC) at ~10°N (Chang et al., 2008; Fratantoni et al., 2000; Hazeleger & Drijfhout, 2006; Kirchner et al., 2009). Wan et al. (2009) used coupled ocean-atmosphere model to analyze how atmospheric and ocean circulation changes associated with a cooling of the North Atlantic affected the Southern Caribbean. They found that ocean circulation changes during North Atlantic cold periods caused a strong subsurface warming in this region. As discussed in Zhang (2007), Chang et al. (2008), Schmidt et al. (2012), and Parker et al. (2015), a major reduction of AMOC can cause a significant weakening in the western boundary current and results in a strong subsurface warming in the in the Southern Caribbean and in the western tropical Atlantic. In the following we will address the interaction between NBC strength, as part of the western boundary current and lateral movements of the STG and its associated SMW in response to AMOC perturbation.

At subsurface, however, only one deglacial subsurface temperature record is available for the tropical west Atlantic (Schmidt et al., 2012), which emphasizes significant oceanographic changes at subsurface level and related variations in the vertical thermal gradient of the upper water column. Chang et al. (2008) and Schmidt et al. (2012) highlighted the importance of warm and highly saline SMW originating from the STG to spread southward and warm the tropical Atlantic at times of a weakened AMOC, not only at surface but also more importantly at subsurface. A study by Parker et al. (2015) verified these findings and added new data for Dansgaard-Oeschger timescales.

By adding and combining new subsurface and surface proxy records from an oceanographic key location in the tropical west Atlantic, we will contribute new aspects on the functioning of the STG and its particular response at subsurface level to deglacial oceanographic and climate changes. We present high-resolution proxy data from piston core M78/1-235-1 (11°36.53′N, 60°57.86′W; Schönfeld et al., 2011) located in Tobago Basin (Figure 1) and piston core SO164-03-4 (16°32.37′N; 72°12.31′W; Nürnberg et al., 2003) from the Central Caribbean (Beata Ridge) and compared them to published records from Bonaire Basin (Parker et al., 2015; Schmidt et al., 2012) We analyzed tests of the shallow dwelling foraminiferal species *Globigerinoides ruber* and deep dwelling species *Globorotalia truncatulinoides* to calculate past sea surface and subsurface temperatures and relative changes in subsurface salinity. We further calculated vertical and latitudinal thermal gradients within the tropical west Atlantic as unequivocal measures for the past dynamics of the STG. Finally, we assessed glacial and deglacial dynamical development of the SMW and the temporal and spatial variability of the STG in relation to AMOC variations, which potentially affected the entire tropical west Atlantic in particular at subsurface level. We address the questions: How and why did the thermal structure of the tropical west Atlantic changed during the last deglaciation? Is this change related to SMW dynamics and the temporal and spatial changes of the STG? Did the STG shift southward or did it expand during times of AMOC perturbations?

2. Oceanographic Setting

At the surface ocean (<80 m) the study area is occupied by the relatively fresh (<35.5 practical salinity unit, psu) and warm (>26 °C) Caribbean Water (CW), which comprises Atlantic surface waters and seasonal

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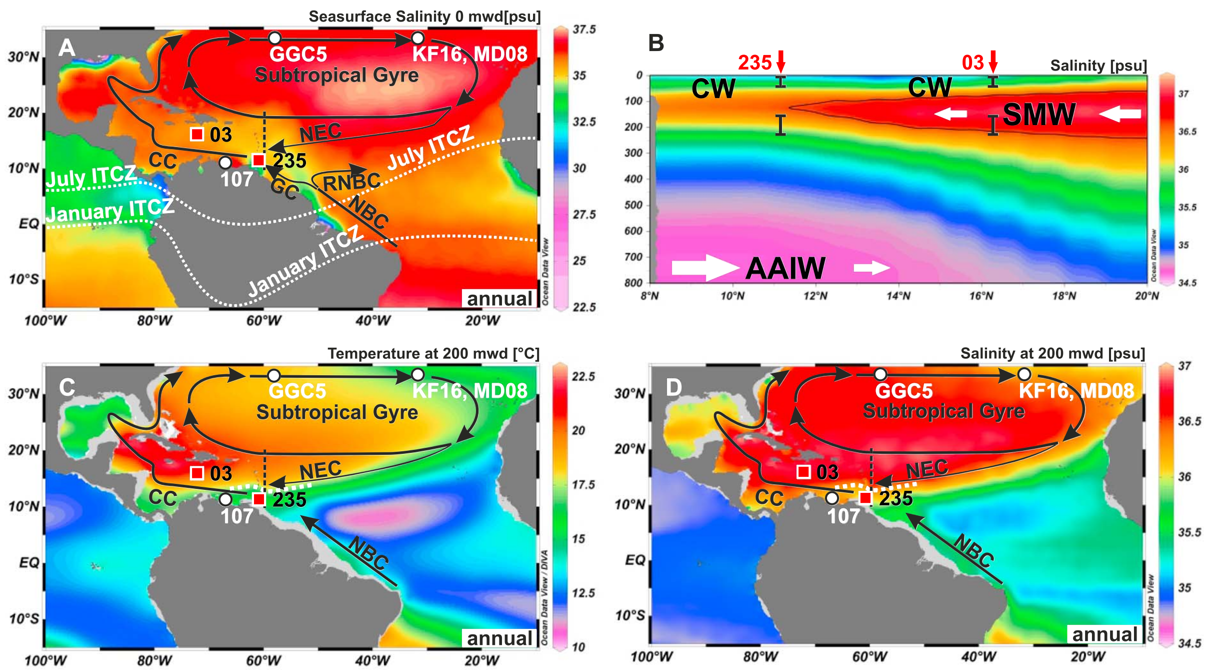

Figure 1. Tropical Atlantic surface and subsurface hydrological setting with locations of proxy records established here (red square: M78/1-235-1, termed 235, Tobago Basin; SO164-03-4, termed 03, Beata Ridge) and reference sites (white dots: VM12-107, termed 107, Bonaire Basin; M35003-4, Tobago Basin [not shown on the map because of the nearly identically core location with M78/1-235-1]; GEOFAR KF16, termed KF16 and MD08-3180, termed 3180, Azores Front; ODP Site 1063, termed 1063, Bermuda Rise). (a) Modern annual sea surface salinity (0 m water depth, Locarnini et al., 2013) and surface currents (black arrows): CC = Caribbean Current; NEC = North Equatorial Current; GC = Guyana Current; NBC = North Brazil Current; RNBC = North Brazil Current retroflection. Dotted lines = summer and winter position of the Intertropical Convergence Zone (ITCZ). (b) Annual salinity profile from 8° to 20°N (dashed vertical lines in (a), (c), and (d); Locarnini et al., 2013). Black vertical bars mark the assumed habitat depth of foraminifers studied here. CW = Caribbean Water; SMW = Salinity Maximum Water; AAIW = Antarctic Intermediate Water (AAIW). White arrows indicate flow directions. Red arrows indicate position of studied sediment cores. (c) Subsurface annual mean temperature distribution at 200-m water depth (Locarnini et al., 2013) with main currents indicated (black arrows). Warm and saline subtropical gyre water is separated from cooler and fresher NBC water by a thermocline ridge close to core location M78/1-235-1 (white dotted line). (d) Subsurface annual mean salinity distribution at 200-m water depth (Locarnini et al., 2013) with main currents indicated (black arrows). Warm and saline subtropical gyre water is separated from cooler and fresher NBC water by a thermocline ridge close to core location M78/1-235-1 (white dotted line).

Amazon and Orinoco river outflow. The annual mean sea surface temperature (SST) at Beata Ridge is ~27.5 °C (Locarnini et al., 2013) and range between ~28 °C in summer and ~26.5 °C in winter. With increasing water depth, temperatures and their seasonal range decline. Sea surface salinity ranges between 35.4 psu in summer and 35.6 psu in winter with an annual mean of 35.5 psu at Beata Ridge (Locarnini et al., 2013).

The main feature of the surface circulation in our study area is characterized by the mainly wind-driven Caribbean Current, which enters the Caribbean Sea region through the Lesser Antilles passages and combines North Equatorial Current (NEC) and seasonal Guyana Current (GC) waters (Hellweger & Gordon, 2002; Wüst, 1964). The GC appears from February to July as a mainly wind-driven feature and is affected by the position of the ITCZ and its dominating trade winds.

During boreal winter, the ITCZ is at a southern position (0°–5°S; Philander & Pacanowski, 1986), thereby favoring the northward transport of nutrient-rich, southern-sourced fresh Atlantic water enriched by Amazon and Orinoco freshwater discharge. The northward migration of the ITCZ begins in May and reaches its northernmost location (6°–10°N) during August (Philander & Pacanowski, 1986). The ITCZ migrations result in the development of a cyclonic oceanic circulation cell southeast off the Lesser Antilles (Johns et al., 2002), which blocks the northward moving GC mainly during autumn/winter and causes the eastward retroflection of the North Brazil Current (NBC) into the North Equatorial Counter Current (Hu et al., 2004; Johns et al., 2002).

The NBC is part of the northward flowing western boundary current system (Johns et al., 1998). It annually transports 26 Sv of water, mainly in the upper 150 m of the water column at which ~11 Sv are ascribed to wind curl, while 15 Sv are driven by thermohaline circulation (Johns et al., 1998). Highest NBC transport is from July–August and lowest during April–May, in close response to the position of the ITCZ (Johns et al., 1998).

Within the subsurface, the study area is characterized by warm (>18 °C) and highly saline (>36.5) SMW, which forms to the northwest of our study area in the STG. Here excess evaporation mediates the subduction of recirculated surface waters down to ~80- to 180-m water depth (Qu et al., 2013), which then is carried equatorward via the NEC and flushes the Caribbean Basin through several passages (e.g., Blanke et al., 2002; Johns et al., 2002). Under modern conditions the SMW remains separated (Figure 1) from cooler fresher subsurface waters of the northward flowing western boundary current (NBC) at ~10°N (Fratantoni et al., 2000; Hazeleger & Drijfhout, 2006; Kirchner et al., 2009). The separation between both water masses finds expression in the annual mean subsurface temperature (subSST) and salinity distribution within the tropical west Atlantic. At ~175-m water depth, the annual mean subSST at Beata Ridge is ~22 °C because that area is occupied by SMW. At Tobago Basin annual mean subSST is ~17 °C, hence, ~5 °C cooler than at Beata Ridge because it is located in the mixing zone of warm and saline SMW and cool, fresh NBC waters. At both core locations the subsurface salinity do not change considerably throughout the year with an annual mean of ~36.8 psu at Beata Ridge and ~36.2 psu at Tobago Basin. Opposed to the distinct different subSST at both study sites, the annual subsurface salinities do not differ significantly.

3. Materials and Methods

3.1. Sediment Sampling

We studied the high-resolution piston cores M78/1-235-1 (further reported as Tobago Basin core 235; 11°36.53′N, 60°57.86′W; 852-m water depth; recovered during R/V Meteor cruise M78; Schönfeld et al., 2011), located in the tropical west Atlantic in the Tobago Basin within the mixing zone of SMW and NBC water (Figure 1) and SO164-03-4 (further reported as Beata Ridge core 03; 16°32.37′N; 72°12.31′W, 2,744-m water depth retrieved during R/V SONNE cruise SO164; Nürnberg et al., 2003) located in the Central Caribbean (Beata Ridge).

Tobago Basin core 235 was presampled at 2- to 4-cm spacing, with enhanced 1-cm sampling during the YD (188–217 cm) and HS1 (281–348 cm) intervals (Bahr et al., 2018; Hoffmann et al., 2014; Poggemann et al., 2017). We here expand the *G. ruber* (pink) $\delta^{18}O$ record from Bahr et al. (2017) and Hoffmann et al. (2014) from 22 to 30 ka BP. We add new subsurface temperature, stable oxygen, and past seawater salinity data from the deep dwelling species *G. truncatulinoides*. The sampling of Beata Ridge core 03 was performed at 1-cm spacing for the uppermost 150 cm. The generated sea surface temperature and stable oxygen isotope record at 1-cm resolution comprises new data from this study and unpublished data from Horn (2011). New proxy data of *G. truncatulinoides* (stable oxygen isotopes, subsurface temperature, and changes in subsurface salinity) were added within this study.

3.2. Foraminiferal Geochemistry

To reconstruct surface ocean conditions (Figure 1), we used the planktic foraminiferal species *Globigerinoides ruber* white and *Globigerinoides ruber* pink varieties. Both *G. ruber* varieties live in tropical and subtropical waters (e.g., Bé & Tolderlund, 1971; Regenberg et al., 2009; Schmuker & Schiebel, 2002; Steph et al., 2009). The pink variety prefers warmer habitats than the white variants (Bé & Hamlin, 1967), mirroring a slightly shallower habitat (<35 m, Schmuker & Schiebel, 2002) than the white one (<50 m, Anand et al., 2003). However, both varieties are thought to be present year-round in the Southern Caribbean (e.g., Schmuker & Schiebel, 2002) without representing seasonal temperature endmembers (Tedesco & Thunell, 2003). The pink variety was selected from Tobago Basin core 235 to expand the already existing age model (Bahr et al., 2018; Hoffmann et al., 2014; Poggemann et al., 2017), while the white variety (sensu stricto morphotype) was taken from Beata Ridge core 03. For further interpretation we assume that the slightly different habitat depths of both varieties do not influence the recorded ^{14}C ages.

Subsurface conditions were approximated from proxy parameters measured within tests of the deep dwelling foraminiferal species *Globorotalia truncatulinoides* (Hemleben et al., 1985; Lohmann & Schweitzer, 1990), which is known for its complex life cycle (Lohmann & Schweitzer, 1990; Mulitza et al., 1997). In the (sub)tropical North Atlantic, *G. truncatulinoides* prefers a habitat in/below the main thermocline at ~150- to 250-m water depth (Figure 1; Cléroux et al., 2008; Jentzen et al., 2018; Schmuker & Schiebel, 2002). Due to insufficient sample material in Tobago Basin core 235, we did not distinguish between coiling directions of *G. truncatulinoides* in neither of the cores in order to guarantee compatibility. We here assume that the respective foraminifera's calcification depths did not change over time (see discussion in section 5.1.3).

For the (isotope) geochemical analyses, ~30 tests of *G. ruber* (pink; M78/1-235-1, $n = 160$), *G. ruber* white sensu stricto (SO164-03, $n = 125$), and *G. truncatulinoides* (M78/1-235-1, $n = 269$; SO164-03-4, $n = 130$) were selected from the narrow 355- to 400-μm size fraction. For *G. truncatulinoides*, the size fraction was partly expanded to 315–400 μm in Beata Ridge core 03 and to 250–400 μm in Tobago Basin core 235 due to insufficient test abundances. Selected foraminiferal tests were gently crushed between glass plates to open the chambers and make subsequent cleaning efficient. The sample material was homogenized and split into subsamples for stable isotope (one third) and trace metal analyses (two thirds). Chamber fillings of pyrite and conglomerates of different metal oxides were thoroughly removed before chemical cleaning and analyses.

Stable oxygen isotope analyses ($\delta^{18}O$) were performed at GEOMAR with a ThermoFischer Scientific MAT 253 mass spectrometer equipped with an automated Kiel IV carbonate preparation device. Isotope values were calibrated to NBS-19 (National Bureau of Standards) and reported relative to the Vienna Pee Dee Belemnit (PDB) standard. The long-term external reproducibility ($n = <3,000$) was monitored by the in-house Bremen standard (Solnhofen Limestone) with an analytic precision of 0.068‰ for $\delta^{18}O$. Triple $\delta^{18}O$ analyses yield a pooled standard deviation of ±0.17‰ for *G. truncatulinoides* ($n = 12$) and ± 0.09‰ for *G. ruber* (pink; $n = 10$) for Tobago Basin core 235. For Beata Ridge core 03, the pooled standard deviation is ±0.09‰ ($n = 12$) for *G. truncatulinoides* and ± 0.12 ‰ ($n = 12$) for *G. ruber*.

For trace element analyses, the crushed subsamples were extensively cleaned following the cleaning procedure of Schmidt and Lynch-Stieglitz (2011) including the reductive step with hydrazine to remove metal oxides. Trace metal analyses were performed on a Varian 720 ES ICP-OES at GEOMAR. The resulting data were normalized to the ECRM 752-1 standard (Greaves et al., 2008) with a Mg/Ca reference value of 3.762 mmol/mol. Results were further drift corrected by using the ECRM 752-1 as internal consistency standard. The analytical reproducibility for Mg/Ca was 1.49%, which equals ±0.06 mmol/mol ($n = 45$). To monitor the cleaning procedure, a full procedure blank was analyzed every fourteenth sample. Due to insufficient sample material in both cores, especially for *G. truncatulinoides*, we were only able to run a few triplicate analyses yielding a pooled standard deviation at Tobago Basin core 235 of ±0.19 mmol/mol Mg/Ca for *G. truncatulinoides* ($n = 10$). At Beata Ridge core 03, the pooled standard deviation for *G. truncatulinoides* is ±0.18 mmol/mol ($n = 7$) and ±0.24 mmol/mol for *G. ruber* ($n = 6$). For an extensive discussion about potential sample contamination by diagenetic overgrowth or insufficient removal of siliciclastic material during the cleaning procedure see supporting information Text S1.

3.3. Sea Subsurface Surface and Sea Surface Temperature Calculation

In the following we use the terms $SST_{Mg/Ca}$ and $subSST_{Mg/Ca}$ for sea surface and subsurface temperatures derived from Mg/Ca of *G. ruber* and *G. truncatulinoides*, respectively. The conversion of *G. ruber* Mg/Ca to $SST_{Mg/Ca}$ was accomplished by using the multispecies equation of Anand et al. (2003): $Mg/Ca_{G.ruber}$ (mmol/mol) = 0.38(±0.02) exp(0.09 (±0.003) SST [°C]). We chose this calibration as it is based on sediment surface samples from a wide geographic area in the Caribbean and the tropical Atlantic, and as it is based on the same test size we use. The average late Holocene $SST_{Mg/Ca}$ of 28.1 °C at Beata Ridge core 03 site is close (within error of ±0.6 °C) to the annual mean temperature of 27.5 °C (Locarnini et al., 2013) at the assumed habitat depth of *G. ruber* of 35-m water depth (Schmuker & Schiebel, 2002).

The Mg/Ca ratios from *G. truncatulinoides* (mixed coiling directions) were converted into subsurface temperatures ($subSST_{Mg/Ca}$) using the calibration equation of Cléroux et al. (2008) for *G. truncatulinoides* dextral: $Mg/Ca_{G.\ truncatulinoides}$ (mmol/mol) = 0.62 (±0.16) exp(0.074 (±0.017) SST [°C]). We decided to use the *G. truncatulinoides* dextral calibration as Ujiié et al. (2010) showed that at both core locations (Tobago Basin core 235 and Beata Ridge core 03) the dextral morphotype is dominant. A plankton net study in the Caribbean found that *G. truncatulinoides* dextral and sinistral inhabit nearly the same water depth range (*G. truncatulinoides* dextral: 176 ± 18 m; *G. truncatulinoides* sinistral: 135 ± 39 m; Jentzen et al., 2018) and their preferred habitats overlap (Cléroux et al., 2008; Jentzen et al., 2018). The latter calibration was established on foraminifera that were oxidatively cleaned without a reductive cleaning step. Thus, we have to keep in mind that our calculated $subSST_{Mg/Ca}$ is potentially underestimated (e.g., Hasenfratz et al., 2017). However, the calculated Tobago Basin core 235 Holocene $subSST_{Mg/Ca}$ of ~16 °C matches (within error) with modern annual subsurface temperature of 15.5 °C in *G. truncatulinoides* modern habitat depth at ~200 m (Locarnini et al., 2013). Subsurface annual mean temperature of 20.8 °C (Locarnini et al., 2013) at Beata Ridge core 03 corresponds to calculated Holocene $subSST_{Mg/Ca}$ of 20.4 °C.

3.4. Approximation of Paleosalinity From $\delta^{18}O_{sw\text{-}ivf}$

Combined $\delta^{18}O$ and Mg/Ca measurements of the same foraminiferal test material allow assessing past regional sea surface salinity and subsurface salinity (e.g., Lea et al., 2000) relative to the contemporaneous global mean. The $\delta^{18}O$ signal of foraminiferal calcite largely depends on temperature and the isotopic composition of seawater ($\delta^{18}O_{sw}$) the foraminifera precipitate as $\delta^{18}O_c$ and covaries linearly with salinity (Charles & Fairbanks, 1990), whereas the assumption that the $\delta^{18}O_{sw}$-salinity relationship did not significantly changed in the past has to be taken into account. Several studies show that this assumption is oversimplified because that relationship has varied significantly throughout the past in regions, which are sensitive to changes in sea ice regime, ocean circulation and isotopic terms in a region's freshwater budget (e.g., Caley & Roche, 2015; Holloway et al., 2016). However, in the model simulation, Holloway et al. (2016) found that the Central Caribbean and the tropical west Atlantic seem to be nearly unaffected by changes in the $\delta^{18}O_{sw}$-salinity relationship.

By combining Mg/Ca and $\delta^{18}O$ of the same foraminifera test material, we removed the temperature effect from the initial foraminiferal $\delta^{18}O$ by using the temperature versus $\delta^{18}O$ calcite equation of Thunell et al. (1999). The resulting $\delta^{18}O_{sw}$ was then corrected for changes in global $\delta^{18}O_{sw}$ due to continental ice volume variability using the relative sea level curve of Waelbroeck et al. (2002). The resulting ice volume free $\delta^{18}O_{sw}$ ($\delta^{18}O_{sw\text{-}ivf}$) is used to assess relative paleo salinity changes relative to the contemporaneous global mean.

We performed error propagation to assess the error of the $\delta^{18}O_{sw\text{-}ivf}$ calculations based on the uncertainty of the paleotemperature and $\delta^{18}O$ calcite to $\delta^{18}O_{sw}$ conversion equations and the reproducibility of the $\delta^{18}O$ and Mg/Ca measurements. For *G. ruber* (Beata Ridge core 03) we obtained a 2σ error of ± 0.29‰ (cf. supporting information Figure S3), while the propagated 2σ error for *G. truncatulinoides* amounts to ± 1.16‰ at Tobago Basin core 235 and ± 1.19‰ at Beata Ridge core 03. The calculated errors for *G. truncatulinoides* are unusually high but seem to reflect the high biological and hydrographic variability and the comparatively large uncertainty of the Mg/Ca temperature calibration (Cléroux et al., 2008). The estimated error for *G. ruber* is similar to previous studies (e.g., Bahr et al., 2013; Schmidt & Lynch-Stieglitz, 2011).

3.5. Chronostratigraphy of Sediment Cores

The age model of Tobago Basin core 235 (Figure 2) is based on the linear interpolation between 10 accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dates, which were analyzed either by Cologne AMS (Germany) or by Beta Analytic Radiocarbon Dating Laboratory (UK; Hoffmann et al., 2014; Poggemann et al., 2017; Table 1). For AMS^{14}C dating, we commonly selected the mixed layer dwelling *G. ruber* and *Globigerinoides sacculifer*, except for the sample at 628 cm (see Table 1), which included additional specimens of *Orbulina universa* due to insufficient sample material. The AMS^{14}C datings were calibrated using the Calib 7.1 software (Stuiver et al., 2017) and the MARINE13 database (Reimer et al., 2013), using a local reservoir age of 277 years BP ($\Delta R = -27 \pm 11$ years, Reimer et al., 2013). The calibrated ^{14}C dates are given in Figure 2 and Table 1, providing nearly constant sedimentation rates of 18–19 cm/kyr (Figure 2). At this point we are aware of possibly changing surface reservoir ages over time. Sarnthein et al. (2015) proposed obvious changing reservoir ages in the western tropical Atlantic during the LGM and the deglaciation. They found reservoir ages spanning from ~700 to ~ 25 ^{14}C years. However, the AMS^{14}C-dated $\delta^{18}O_{G.ruber\ (pink)}$ record of Tobago Basin core 235 with an overall $\delta^{18}O$ decrease of ~2‰ from full glacial to Holocene conditions matches other records from the tropical west Atlantic (e.g., Hüls & Zahn, 2000; Schmidt et al., 2012), hence supporting the accuracy of our age model (Figure S2).

The age model of Beata Ridge core 03 is based on four AMS^{14}C datings carried out on mixed planktonic foraminiferal samples (Beta Analytic Radiocarbon Dating Laboratory, UK) supported by visual correlation

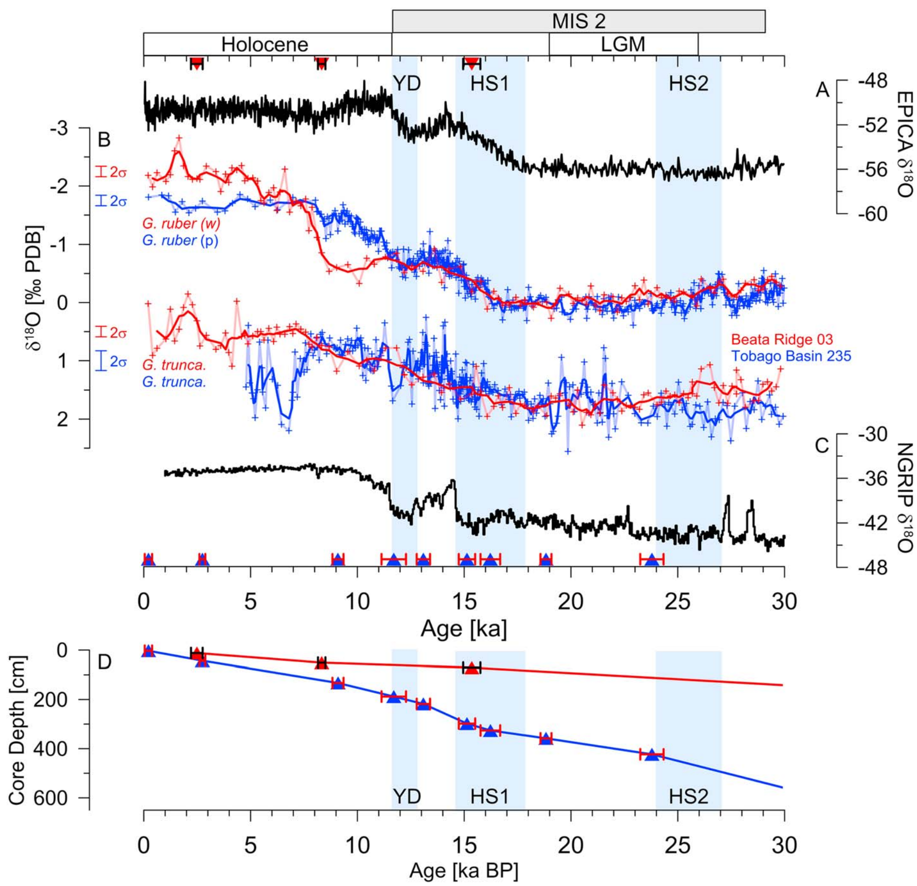

Figure 2. Chronostratigraphy of Tobago Basin core 235 (blue) and Beata Ridge core 03 (red). The age models are based on AMS^{14}C dating (blue triangles = Tobago Basin core 235, red triangles = Beata Ridge core 03; horizontal bars = 2σ errors, see Table 1) and linear interpolation in between. (a) Antarctic EPICA Dome C ice core δ^{18}O record (Stenni et al., 2006). (b) δ^{18}O records of *G. ruber* (w, p), and *G. truncatulinoides* of Tobago Basin core 235 (0–15 ka BP Hoffmann et al., 2014; 15–23 ka BP Bahr et al., 2018) and Beata Ridge core 03. The correlation between both *G. ruber* records is $R^2 = 0.83$. (c) Greenland NGRIP ice core δ^{18}O data (NGRIP Dating Group, 2006). (d) The age versus depth diagram suggests nearly constant sedimentation rates of 4.7 cm/kyr for Beata Ridge core 03 (red) and higher sedimentation rates of ~19 cm/kyr for Tobago Basin core 235 (blue) with even higher rates during Heinrich Stadial 1 (HS1; ~20 cm/kyr) and the Younger Dryas (YD; ~23 cm/kyr). Blue shaded areas mark the YD, HS1 and Heinrich Stadial 2 (HS2). MIS 2 = marine isotope stage 2.

(R^2 = 0.83) of the $\delta^{18}O_{G.ruber}$ record to the well dated Tobago Basin core 235 (Hoffmann et al., 2014; Poggemann et al., 2017; Figure 2). For consistency, the AMS^{14}C dates were calibrated as described for core 235 (Table 1), but with a slightly different local reservoir age of 300 years ($\Delta R = -25 \pm 22$ years, Reimer et al., 2013). At Beata Ridge core 03, the $\delta^{18}O_{G.ruber}$ values between 30 ka BP and the Last Glacial Maximum (LGM) are quite similar to core 235 and vary at low amplitude of 0.5‰. The glacial/interglacial amplitude is ~2.25‰ (Figure 2) with LGM $\delta^{18}O_{G.ruber}$ values of ~0‰ increasing to Holocene values of ~2.25‰. Notably, the $\delta^{18}O_{G.ruber}$ record appears out of phase to the North Greenland Ice Core Project (NGRIP) and European Project for Ice Coring in Antarctica (EPICA) Dome C $\delta^{18}O_{ice}$ climate records at ~11–8 ka BP (Figure 2), with $\delta^{18}O_{G.ruber}$ remaining rather high in contrast to the Tobago Basin record. The late Holocene $\delta^{18}O_{G.ruber}$ values, instead, change rapidly to light values, becoming even lighter by ~1‰ than the Tobago Basin record. The sedimentation rates of 4–6 cm/kyr remain clearly lower than in core 235.

4. Results

4.1. Temporal Sea Surface and Subsurface Changes

The subsurface $\delta^{18}O_{G.truncatulinoides}$ record at Tobago Basin core 235 shows an overall glacial/interglacial amplitude of ~1.9‰ (Figure 2). Between 30 ka BP and the LGM the $\delta^{18}O_{G.truncatulinoides}$ record is relatively

Table 1
Calibrated AMS^{14}C Ages Using the Calib 7.1 Software and the MARINE13 Database With ΔR = −27 ± 11 years for Tobago Basin core 235 and ΔR = −25 ± 22 years for Beata Ridge Core 03

Core	Depth (cm)	Lab code	Sample type	^{14}C age raw (years BP)	Age error ± (years)	Calibrated median age (years BP, 2σ)	Reference
M78/1-235-1	3	COL1473.1.1	*G. ruber* and *G. sacculifer*	569	31	217	Hoffmann et al. (2014)
M78/1-235-1	43	COL1474.1.1	*G. ruber* and *G. sacculifer*	2926	32	2742	Hoffmann et al. (2014)
M78/1-235-1	133	COL1475.1.1	*G. ruber* and *G. sacculifer*	8424	44	9092	Hoffmann et al. (2014)
M78/1-235-1	188	COL1476.1.1	*G. ruber* and *G. sacculifer*	10500	48	11704	Hoffmann et al. (2014)
M78/1-235-1	218	COL1477.1.1	*G. ruber* and *G. sacculifer*	11586	48	13089	Hoffmann et al. (2014)
M78/1-235-1	298	COL1478.1.1	*G. ruber* and *G. sacculifer*	13098	49	15132	Hoffmann et al. (2014)
M78/1-235-1	326		*G. ruber* and *G. sacculifer*	13850	60	16226	Poggemann et al. (2017)
M78/1-235-1	358	COL1479.1.1	*G. ruber* and *G. sacculifer*	15959	57	18830	Poggemann et al. (2017)
M78/1-235-1	423	COL1480.1.1	*G. ruber* and *G. sacculifer*	20139	93	23790	Poggemann et al. (2017)
M78/1-235-1	628		*G. ruber*, *G. sacculifer* and *O. universa*	29300	200	33087	Poggemann et al. (2017)
SO164-03-4	12.5	Beta-432224	Mixed planktic	2730	30	2483	This study
SO164-03-4	51.5	Beta-432225	Mixed planktic	7850	30	8329	This study
SO164-03-4	71.5	Beta-432226	Mixed planktic	13230	40	15356	This study
SO164-03-4	148.5	Beta-432227	Mixed planktic	27800	130	33087	This study

stable and scatters around 1.8‰, while high values of ~2.6‰ are recorded during late HS1. However, during HS1, values slightly decrease by ~0.5‰ to values of 1.25‰. At the onset of the YD, $\delta^{18}O_{G.truncatulinoides}$ values abruptly increase by ~1.25‰ from 0.5‰ to 1.75‰ at the end of the YD, while at mid-YD a maximum of ~ 2.7‰ was calculated. A further abrupt increase in $\delta^{18}O_{G.truncatulinoides}$ occurs at ~8 ka BP. At Beata Ridge core 03, the amplitude of the $\delta^{18}O_{G.truncatulinoides}$ record is ~2‰ showing a clear glacial/deglacial signal and highest values of ~2‰ at the LGM and lowest of ~0‰ during the Holocene. Values slightly increase from 30 ka BP to the onset of HS1 by ~0.7‰. $\delta^{18}O_{G.truncatulinoides}$ values decrease from the onset of HS1 (1.9‰) to 7 ka BP (0.25‰). At the onset of the YD, $\delta^{18}O_{G.truncatulinoides}$ values increase by ~0.2‰ followed by a decrease of ~0.6‰ during the YD interval and reach Holocene values afterward. At both core locations, the overall pattern and amplitude of the $\delta^{18}O_{G.truncatulinoides}$ records are rather similar, although Beata Ridge core 03 shows constantly higher values, except between 30 and 22 ka BP and during the Holocene. The middle to late Holocene $\delta^{18}O_{G.truncatulinoides}$ values appear highly variable at both regions fluctuating ~1.5‰ at Tobago Basin core 235 and ~0.6‰ at Beata Ridge core 03. Notably, the $\delta^{18}O_{G.truncatulinoides}$ amplitude variations of ~2‰ are similar to variations found at Bonaire Basin by Schmidt et al. (2012).

The $SST_{Mg/Ca}$ record of *G. ruber* at Beata Ridge core 03 shows variations of ~4 °C, ranging between ~25 °C during the LGM and 29 °C during the mid-Holocene (Figure 3, for Mg/Ca raw data see supporting Figure S4). $SST_{Mg/Ca}$ remains ~3 °C cooler during the LGM than during the Holocene while constantly rising during the deglaciation similar to other studies from the tropical west Atlantic (e.g., Hüls & Zahn, 2000; Lea et al., 2003; Rühlemann et al., 1999; Schmidt et al., 2004; Figure 3). From the mid-Holocene on, $SST_{Mg/Ca}$ cools by ~2 °C until reaching modern values of ~28 °C.

The overall $subSST_{Mg/Ca}$ range of ~3.5 °C at Beata Ridge core 03 is similar to the $SST_{Mg/Ca}$ range at the same core location, but cooler by ~7 °C (Figure 3). The $subSST_{Mg/Ca}$ slightly decrease by ~2 °C from 30 ka BP to peak glacial times and subsequently change from ~18 °C during the LGM to ~22 °C during the early Holocene, representing the warmest time period of the record (for Mg/Ca raw data see supporting information Figure S4). After ~7 ka BP, the $subSST_{Mg/Ca}$ gradually cool by ~2 °C reaching values of ~20 °C, which are slightly below the modern subSST of ~21 °C at the core location. In contrast to the small glacial/interglacial $subSST_{Mg/Ca}$ range at Beata Ridge, the Tobago Basin core 235 $subSST_{Mg/Ca}$ record is highly variable and ranges from ~13 to 23 °C, which is approximately three times as much as at Beata Ridge (Figure 3, for Mg/Ca raw data see supporting information Figure S3). In Tobago Basin, the $subSST_{Mg/Ca}$ decrease by ~2 °C from 30 ka BP (18 °C) to the onset of HS1 (16 °C). Within HS1, the $subSST_{Mg/Ca}$ increase continuously by 2 °C, while at ~15.5 ka it rises abruptly by ~6 °C up to maximum temperatures of 23 °C. The abrupt subSST rise is delayed too the reconstructed SST rise at the beginning of HS1 by Bahr et al. (2018; Figure S7). Subsequently, $subSST_{Mg/Ca}$ scatters around 20 °C until the beginning of the Bølling-Allerød (B/A).

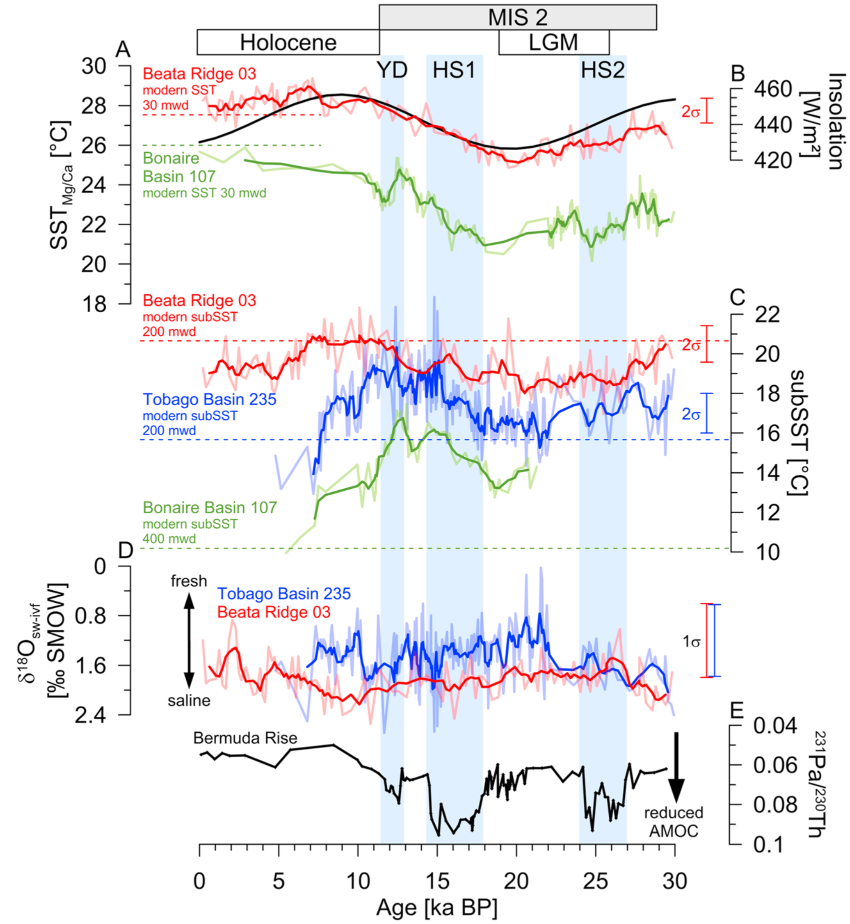

Figure 3. Sea surface temperature ($SST_{Mg/Ca}$), subsurface temperature ($subSST_{Mg/Ca}$), and subsurface $\delta^{18}O_{sw\text{-}ivf}$ (salinity) development in the tropical west Atlantic from 30 to 0 ka BP. (a) $SST_{Mg/Ca}$ record of Beata Ridge core 03 (*G. ruber*; red = 5-point running average, light red = raw data) in comparison to the $SST_{Mg/Ca}$ (*G. ruber*) record of Bonaire Basin core 107 (dark green = 5-point running average, light green = raw data; Parker et al., 2015; Schmidt et al., 2012). (b) Summer (June–August) insolation at 10°N (Laskar et al., 2004). (c) $subSST_{Mg/Ca}$ development at Tobago Basin core 235 (dark blue = 5-point running average, light blue = raw data), at Beata Ridge core 03 (red = 5-point running average, light red = raw data), and at Bonaire Basin core 107 (Schmidt et al., 2012; dark green = 5-point running average, light green = raw data for *G. crassaformis*). (d) Relative subsurface salinity changes approximated from calculated $\delta^{18}O_{sw\text{-}ivf}$ for Beata Ridge core 03 (red = 5-point running average, light red = raw data) and Tobago Basin core 235 (dark blue = 5-point running average, light blue = raw data). (e) Bermuda Rise $^{231}Pa/^{230}Th$ record (Böhm et al., 2015) reflecting deglacial changes in Atlantic Meridional Overturning Circulation strength. Blue shadings mark Younger Dryas (YD) and Heinrich Stadials (HS2 and HS1). LGM = Last Glacial Maximum, MIS 2 = marine isotope stage 2.

During the B/A and the YD the $subSST_{Mg/Ca}$ remains higher than ~19 °C and abruptly increases up to ~22 °C at mid-YD while steadily decreasing afterward reaching modern values of ~15.5 °C in the mid-Holocene. Lowest $subSST_{Mg/Ca}$ of ~13 °C are observed after ~7 ka BP. On average, the LGM $subSST_{Mg/Ca}$ are warmer by ~2.5 °C than during the Holocene. The $subSST_{Mg/Ca}$ development in Tobago Basin and at Beata Ridge shows a similar overall pattern, while the Tobago Basin area is commonly cooler by ~2 °C at subsurface during MIS 2 and is even becoming cooler by ~6 °C during the Holocene (Figure 3). The $subSST_{Mg/Ca}$ records of both regions converge and even become equal during the end of HS1 and the middle of the YD, mainly due to subsurface warming in Tobago Basin.

The Tobago Basin core 235 subsurface $\delta^{18}O_{sw\text{-}ivf}$ record shows the most saline conditions at ~30 ka BP (~2.4‰), which slightly increase until 22 ka BP (~1.6‰), while the conditions become abruptly fresher (to the contemporaneous global mean) at ~21.6 ka BP, reaching values of 0‰ (Figure 3). A general trend to more saline conditions from the mid-LGM (~0.8‰) to the end of HS1 (~2‰) was calculated, while the early B/A is marked by distinct fresher conditions (~1.2‰ in average) close to mid-Holocene values of ~1.3‰. An abrupt freshening at late HS1 (15 ka BP; ~2.4‰ to 0.8‰) and on at ~ 10 ka BP from 2.2‰ to 1.0‰ is recorded. Though the average values do not exceed the 1 sigma error, the single data point record does.

The Beata Ridge core 03 $\delta^{18}O_{sw\text{-}ivf}$ record is less variable than in Tobago Basin and shows long-term changes from fresher conditions at the LGM to more saline conditions at the early Holocene. Subsurface $\delta^{18}O_{sw\text{-}ivf}$ values at 30 ka BP are more saline (~2.2‰) than during the deglaciation (Figure 3). The record shows a range of ~1.5‰, whereas conditions become more saline from the onset of HS2 (~1.1‰) to the early Holocene (~11 ka BP, ~2.6‰).

4.2. Calculated Vertical and Lateral Temperature Gradients Across the Tropical West Atlantic

To clarify the different $subSST_{Mg/Ca}$ developments at Tobago Basin and Beata Ridge as well as between Beata Ridge and Bonaire Basin (Bonaire Basin core VM12-107; Schmidt et al., 2012), we calculated the $subSST_{Mg/Ca}$ gradients between these core locations, termed ΔsubSST. During MIS 2, the 5-point running average of $\Delta subSST_{Beata\ Ridge\text{-}Tobago\ Basin}$ varies between 0 °C and 2 °C, while the individual data points scatter between 0 and 4 °C. During the late HS1 until the early B/A and during the mid YD, the latitudinal gradient becomes 0 °C or even negative. Afterward, the $\Delta subSST_{Beata\ Ridge\text{-}Tobago\ Basin}$ record increase stepwise until reaching modern values since the mid-Holocene. The calculated $\Delta subSST_{Beata\ Ridge\text{-}Bonaire\ Basin}$ gradient ranges between ~2 °C during the LGM and ~10 °C at mid-Holocene. Both ΔsubSST gradients show similar patterns and overall ranges of ~8 °C. The offset of ~2 °C between records is due to the different habitat depths of the foraminiferal species used for analyses. At Beata Ridge core 03 *G. truncatulinoides* was used to reconstruct subsurface ocean conditions, which inhabits a habitat between 150- and 250-m water depth. At Bonaire Basin instead, Schmidt et al. (2012) used *G. crassaformis*, which lives deeper in the water column between 200- and 400-m water depth.

The dynamics between sea surface and subsurface water masses finds expression in the upper ocean thermal structure and stratification. To evaluate changes in the upper ocean stratification, we calculated past thermocline depth at Beata Ridge core 03 and Bonaire Basin core 107 (original data from Parker et al., 2015; Schmidt et al., 2012) by subtracting the calculated $subSST_{Mg/Ca}$ from the $SST_{Mg/Ca}$ and named it vertical temperature gradient ($\Delta T_{SST\text{-}subSST}$). At Beata Ridge, $\Delta T_{SST\text{-}subSST}$ of ~5 °C is smallest at ~20 ka BP and increases to ~11 °C at ~5 ka BP. Between MIS 2 and the early Holocene $\Delta T_{SST\text{-}subSST}$ scatters around ~7 °C and increases to ~9 °C during the mid-Holocene. At Bonaire Basin, the development is similar to Beata Ridge, while both gradients start to strongly diverge at the beginning of the Holocene. During MIS2 until the onset of the Holocene $\Delta T_{SST\text{-}subSST}$ scatters around ~7 °C, while both gradients start to converge at the onset of the Holocene. The gradient at Bonaire Basin rises to mid-Holocene values of ~14 °C close to modern values of ~15 °C. Notably, the glacial/interglacial thermocline variations at Bonaire Basin core 107 (~11 °C) are 2 times larger than at Beata Ridge (~5 °C).

5. Discussion

In order to set our Tobago Basin and Beata Ridge subsurface proxy records in context, we compared them to the only existing tropical west Atlantic data set, which combines subsurface and sea surface proxy records (Bonaire Basin core VM12-107; termed core 107 in the following; Schmidt et al., 2012; Figures 1, 3, and 4). Bonaire Basin core 107 is located ~5° south of Beata Ridge core 03 (~800 km) and ~6° west of Tobago Basin core 235 (~700 km). The temporal variability in $subSST_{Mg/Ca}$, subsurface $\delta^{18}O_{sw\text{-}ivf}$, and the changing lateral and vertical gradients (Figures 3–5) between the different areas provide insight how the STG developed at both subsurface and sea surface levels during extreme and rapid climate change, and with respect to deglacial AMOC perturbations.

At subsurface, regional differences are obvious. The temporal development of $subSST_{Mg/Ca}$ is rather similar in Tobago Basin (core 235) and Bonaire Basin (core 107; Schmidt et al., 2012), although constantly offset by ~2–4 °C (Figure 3). In Bonaire Basin, $subSST_{Mg/Ca}$ is cooler mainly due to the fact that the $subSST_{Mg/Ca}$ reconstruction is based on the deeper dwelling *G. crassaformis* (Schmidt et al., 2012). Both the strong correlation between $subSST_{Mg/Ca}$ records based on *G. truncatulinoides* (core 235) and on *G. crassaformis* (core 107) and the constant offset between both imply that the subsurface temperature variability is a

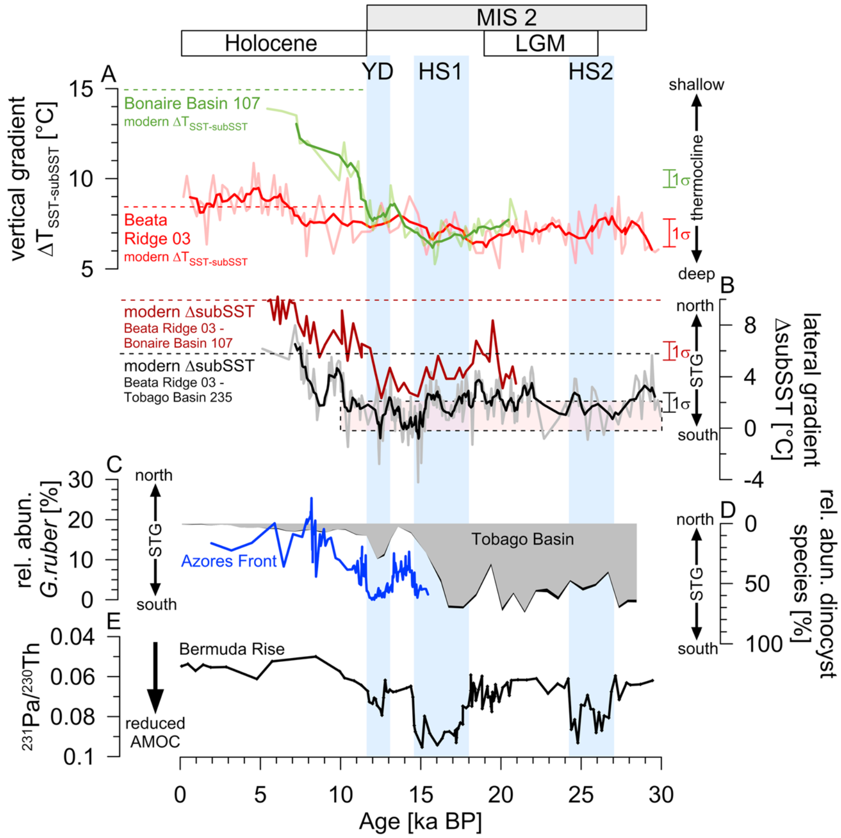

Figure 4. Oceanographic changes in the subsurface tropical west Atlantic over the last 30 kyr. (a) Vertical temperature gradient ($\Delta T_{SST\text{-}subSST}$) between sea surface and subsurface indicating thermocline depth variations at Beata Ridge core 03 (red = 5-point running average, light red = raw data) and at Bonaire Basin core 107 (dark green = 5-point running average, light green = raw data, calculated from original data of Schmidt et al., 2012). (b) Lateral $subSST_{Mg/Ca}$ gradients between Beata Ridge core 03 and Bonaire Basin core 107 (dark red) and Beata Ridge core 03 and Tobago Basin core 235 (black = 5-point running average, grey = raw data). Pale reddish shaded area indicates the lateral temperature difference of 0–2 °C at subsurface between Beata Ridge and Tobago Basin (ΔsubSST), which we defined as indicative for the southward shift of the. (c) Relative abundances of calcareous dinoflagellate cysts in Tobago Basin (M35003-4; black: *S. regalis*; grey: *P. tuberosa*; Vink et al., 2001), which are characteristic for oligotrophic NEC waters and point to STG migrations. (d) Stacked (cores GEOFAR KF 16 and MD08-3180) relative abundance of the subtropical species *G. ruber* pointing to STG changes at the Azores Front (blue curve; Repschläger et al., 2015). (e) Bermuda Rise $^{231}Pa/^{230}Th$ record (Böhm et al., 2015) reflecting Atlantic Meridional Overturning Circulation strength. Blue shadings mark Younger Dryas (YD) and Heinrich Stadials (HS2 and HS1). LGM = Last Glacial Maximum, MIS 2 = marine isotope stage.

robust climate signal in the tropical west Atlantic (see further discussion in supporting information Text S2). Both records show an increase of ~5 °C in $subSST_{Mg/Ca}$ from the LGM to the early YD and a $subSST_{Mg/Ca}$ decrease by ~7–8 °C during the Holocene suggesting that both sediment cores are influenced by the same oceanographic changes. Notably, the mid-Holocene $subSST_{Mg/Ca}$ in Tobago and Bonaire Basins remain cooler by ~1.5 °C and ~3 °C, respectively, than during the LGM.

At Beata Ridge core 03 the $subSST_{Mg/Ca}$ development is very different. The $subSST_{Mg/Ca}$ record is comparatively low in amplitude with glacial $subSST_{Mg/Ca}$ cooler by only ~1.5 °C than the late Holocene values and a glacial/interglacial amplitude of ~3.5 °C. This is in agreement with Slowey and Curry (1995), who described glacial subSST cooler by ~2–4 °C in the STG region at Bahama Banks and the Sargasso Sea using $\delta^{18}O$ of benthic foraminifera to estimate glacial thermocline temperatures. The temperature development at sea surface is rather different from the subsurface development. At Beata Ridge there is no significant sea surface cooling during Northern Hemisphere cool periods HS2, HS1, and YD similar to a study of Ziegler et al. (2008) in the Gulf of Mexico. Following the notion of Ziegler et al. (2008), the Beata Ridge $SST_{Mg/Ca}$ signal is most

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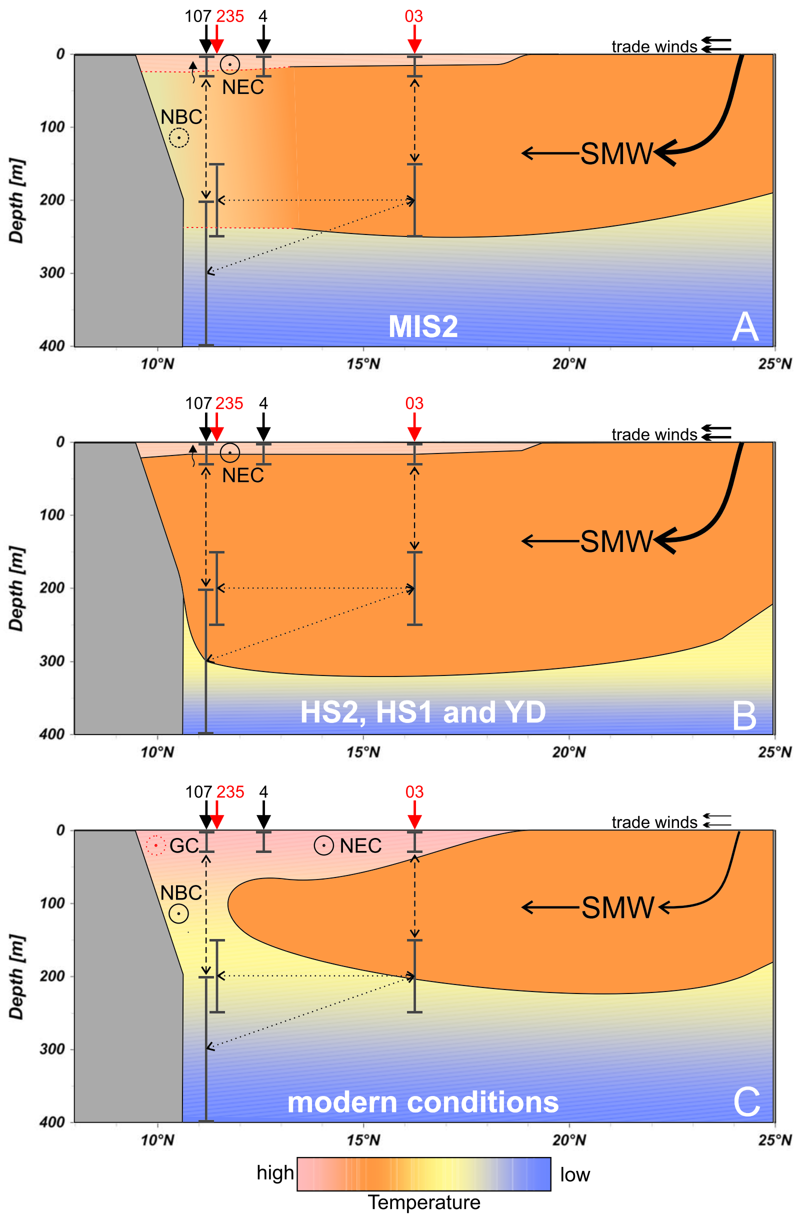

Figure 5. Conceptual sketch for the southward migration of salinity maximum water (SMW) and the Subtropical Gyre in the tropical west Atlantic during MIS 2 (a), periods of deglacial Atlantic Meridional Overturning Circulation (AMOC) perturbation (b), and during the Holocene (c). (a) During full glacial (MIS 2) times of a stable but sluggish AMOC (Böhm et al., 2015), strong northeastern trades, the southern position of the Intertropical Convergence Zone, and a strong influence of the subpolar gyre (Repschläger et al., 2015) resulted in the southward shift of the subtropical gyre (STG) at surface and subsurface levels. The NBC is strongly deflected, sluggish but still present (Rühlemann et al., 2001). Warm STG is present at Tobago Basin (core 235), Beata Ridge (core 03), and Bonaire Basin (core 107) at surface and subsurface level. Enhanced upwelling of SMW in Bonaire Basin caused slightly cooler $SST_{Mg/Ca}$ and higher sea surface salinity. (b) During deglacial times of significant AMOC reduction (YD) or even shutdown (HS2 and HS1), both the western boundary current and NBC weakened significantly or even vanished, transferring less or no southern-sourced cool and low-saline NBC waters into the tropical west Atlantic. Rapid subsurface warming in the tropical west Atlantic was fostered by the southward expansion of warm and saline SMW at subsurface level. In Bonaire Basin, enhanced upwelling of warm subsurface waters temporally cooled the sea surface and raised sea surface salinity. (c) During modern strong AMOC conditions, Tobago Basin (core 235) and Bonaire Basin (core 107) are located in the mixing zone of warm/saline STG and cool/fresh NBC subsurface waters. Beata Ridge (core 03) and Azores coring sites (not shown; Repschläger et al., 2015) remain permanently under STG influence. SMW = salinity maximum water; NEC = North Equatorial Current; NBC = North Brazil Current. Black bars = habitat depths of studied foraminifera and dinocysts. Circle with dot inside = westward flow direction; dashed red circle = seasonal currents; dashed black circle = weaker currents. Trade wind intensity marked by double arrows (thick = strong). Dashed double arrows = vertical temperature gradients (ΔT), interpreted as thermocline depth. Dotted double arrows = lateral temperature gradients (ΔsubSST), interpreted as STG migrations. Solid black arrows within SMW = subduction area of SMW and flow direction (thicker arrow = stronger formation rate). Core locations are indicated on top by arrows (red = this study, black = reference sites, while 4 corresponds to sediment core M35003-4). Color coding represents different temperatures of the water bodies (see scale bar). HS = Heinrich Stadial; YD = Younger Dryas.

likely indicative of Caribbean boreal summer conditions and hence is not recording the pattern of rapid North Atlantic climate oscillation, as high-latitude cooling events seem to influence only the Caribbean winter Caribbean conditions. During the Holocene $SST_{Mg/Ca}$ broadly follows the summer (June to August) insolation at 10°N with high $SST_{Mg/Ca}$ during high summer insolation (Figure 3), supporting the role of orbital forcing on subtropical surface near ocean temperatures. Under glacial conditions of weakened summer insolation, sea surface cooling might have even been fostered by the strengthened impact of cooler STG waters (Vink et al., 2001). When comparing the $SST_{Mg/Ca}$ records of Beata Ridge core 03 and Bonaire Basin core 107, both records point to very different but interrelated hydrographic developments in the respective ocean areas (Figure 3). During the Holocene the $SST_{Mg/Ca}$ records are offset by ~3 °C consistent to the modern SST conditions with the Bonaire Basin being cooler (~25 °C) than the Beata Ridge area (~28 °C). The regional offset was even larger by on average ~4 °C during the last glacial (Schmidt et al., 2012). Higher differences in $SST_{Mg/Ca}$ during LGM can be explained with intensified and expanded coastal upwelling off Venezuela (Hüls & Zahn, 2000; Schmidt et al., 2012) caused by strengthened trade winds (Peterson et al., 2000). At the same time, the ITCZ migrated southward in response to high-latitude cooling, sea ice expansion, and strengthened atmospheric circulation during full glacial times (Arbuszewski et al., 2013, and references therein). We here disregard the $SST_{Mg/Ca}$ record from Tobago Basin core 235 (Bahr et al., 2018), as the three step development of $SST_{Mg/Ca}$ across HS1 and the YD was apparently due to regional SST adjustments to changes in NBC strength and changes in the ITCZ position (Bahr et al., 2018).

5.1. Lateral and Vertical Changes of the STG

Under modern conditions, the subsurface at Beata Ridge core 03 is exclusively influenced by warm and saline waters of the STG (Figures 1 and 5) and is considered as a reference site, permanently bathed by SMW. Today, Tobago Basin core 235 is located at the mixing zone of warm, high-saline subsurface waters of the STG (SMW) transported by the NEC and colder, fresher tropical subsurface waters carried by the NBC (Figure 1). Thus, Tobago Basin core 235 is ideal to record changes in STG waters at subsurface level. At modern conditions, a strong NBC hampers the expansion of SMW into the deep tropics, creating a strong temperature gradient across the tropical west Atlantic at subsurface level, which finds expression in large lateral subsurface temperature gradients between Beata Ridge core 03 and Tobago Basin core 235 as well as between Beata Ridge core 03 and Bonaire Basin core 107 (Figures 1 and 3–5). We assume that both gradients reflect the meridional variations of the STG and the related SMW (Figure 5) in which small (large) lateral temperature gradients are considered to reflect a higher (lower) impact of SMW in the tropical west Atlantic (Figure 4).

In addition to the lateral $subSST_{Mg/Ca}$ gradients described above, the temporal and spatial changes of the thermocline depth provide important evidence, how the SMW changed over time in the different ocean areas. A large (small) vertical temperature difference between sea surface and subsurface temperatures ($\Delta T_{SST\text{-}subSST}$) is interpreted as a shallow (deep) thermocline (cf. Nürnberg et al., 2015). A deep thermocline at the studied areas can be caused by a warming at subsurface level, while SSTs neither change significantly nor cool. For instance, the inflow of warm SMW into the subsurface tropical west Atlantic would cause subsurface warming and hence thermocline deepening. In this respect, we have to bear in mind that the subsurface temperature changes in the study area are equal or even larger than at sea surface.

Overall, the calculated thermocline depths and lateral temperature gradients suggest a three-phase development of the SMW in the tropical west Atlantic. During full glacial to deglacial conditions (30–11 ka BP), the negligible (~0–2 °C) lateral temperature gradients (ΔsubSST) between Beata Ridge core 03 and Tobago Basin core 235 and the small gradient between Beata Ridge core 03 and Bonaire Basin core 107 suggest the southward expansion or shift of the STG and its associated SMW (Figure 4). In times of significant AMOC perturbations (during HS2, HS1, and the YD) the lateral temperature gradient between Beata Ridge core 03 and Tobago Basin core 235 even becomes zero or even negative for instance at 18, 15, 12.6, and 10.5 ka BP (Figure 4), the calculated subsurface $\delta^{18}O_{sw\text{-}ivf}$ at both sites converges (Figure 3), and the thermocline at both Beata Ridge core 03 and Bonaire Basin core 107 is deep (Figure 4). We hypothesize that the SMW fully occupied the tropical west Atlantic and the STG is at its southernmost position. Later during the early to late Holocene, ΔsubSST raised by ~5 °C point to the development of a strong thermocline between the STG (Beata Ridge core 03) and the tropical west Atlantic (Bonaire Basin core 107 and Tobago Basin core 235) approaching modern-like conditions, which is most presumably related to a retreat of the SMW.

5.1.1. Glacial to Deglacial Southward Shift of the STG

In contrast to modern conditions Tobago Basin core 235 was influenced by a warm water mass between 30 and 10 ka BP, indicated by elevated $subSST_{Mg/Ca}$ (~2.5 °C warmer than the modern conditions; Figure 3). The calculated lateral $\Delta subSST_{Beata\ Ridge\text{-}Tobago\ Basin}$ of ~1.7 °C is distinctly smaller than the modern lateral subsurface gradient of 5.4 °C (Figure 4).

At Beata Ridge core 03 and Bonaire Basin core 107, $\Delta T_{SST\text{-}subSST}$ implies that the glacial (MIS 2) thermocline was clearly deeper than today. Between 30 and s27 ka BP Tobago Basin subsurface $\delta^{18}O_{sw\text{-}ivf}$ values show fresher conditions than at Beata Ridge. During the LGM (27–22 ka BP) both subsurface $\delta^{18}O_{sw\text{-}ivf}$ records display similar values (Figure 4). Thermocline deepening likely caused by subsurface warming together with a small lateral temperature gradient between Beata Ridge and Bonaire Basin ($\Delta subSST_{Beata\ Ridge\text{-}Bonaire\ Basin}$) suggests the enhanced presence of SMW at Bonaire Basin. The calculated vertical and lateral gradients suggest that SMW was vertically expanded and expanded or shifted southward during full glacial conditions. We propose that different processes, which are closely coupled to each other, allow the STG and its associated SMW to shift southward (Figure 5).

In a glacial setting, the pole-to-equatorward oceanic temperature gradient was steeper due to the cool North Atlantic and its expanded sea ice. The related stronger atmospheric temperature gradients caused higher wind stress in the Northern Hemisphere (e.g., Vellinga & Wu, 2004) and the northeastern trades strengthened. The ITCZ shifted southward, which occurred along with changes in trade wind intensity and the related asymmetric response of the Hadley circulation (Arbuszewski et al., 2013; Broccoli et al., 2006; Chiang & Bitz, 2005; Peterson et al., 2000). The higher wind stress caused stronger Ekman downwelling in the subtropical North Atlantic (Slowey & Curry, 1995). The enhanced subduction of surface waters deepened the thermocline (Morell & Corredor, 2003; Figure 4) and intensified vertical mixing of the upper water column (Rashid & Boyle, 2007). In response, more SMW formed, which propagated via the NEC into the tropical west Atlantic, raised the portion of SMW at Tobago Basin and Bonaire Basin, and caused the southward shift of the mixing zone between SMW and NBC waters (Figure 5). During full glacial conditions, the thermoclines at Beata Ridge and Bonaire Basin were similarly deeper (ΔT = ~7 °C; Figure 4), pointing to strong vertical and deep mixing of the mixed layer (in agreement with Rashid & Boyle, 2007).

We further hypothesize that the strong glacial northeastern trades fostered the retroflection of the NBC, bringing less NBC waters into the tropical west Atlantic and opening the pathway for warm subsurface NEC waters to spread southward into the tropical west Atlantic (Figure 5). Enhanced terrigenous sediment supply to Céara Rise and northeast Brazil let Rühlemann et al. (2001) and Arz et al. (1999, 1998) already speculate on a prominent NBC retroflection during glacial times. Further, high cyst abundances of the calcareous dinoflagellates *Pernambugia tuberosa* and *Scrippsiella regalis* during full glacial conditions (Vink et al., 2001) point to the presence of extremely oligotrophic and cool surface NEC waters in Tobago Basin (core M35003-4) and hence the enhanced inflow of saltier surface waters of the STG (Figures 4 and 5; Vink et al., 2001). The cyst abundance data supports the notion that NBC was strongly retroflected during the LGM. This well-elaborated notion on the differential southward expansion of STG-bound SMW leaves room to speculate whether the STG expanded in all directions or just shifted southward. Schiebel et al. (2002) noted the southward shift of the Azores and Polar fronts during glacial times and coccolithophore assemblage analyses at the Azores Front (Schwab et al., 2012) further support the notion on the southward shift of the entire STG and its associated SMW during full glacial conditions.

At ~22 ka BP Tobago Basin core 235 exhibits significant and rapid subsurface freshening within a few hundreds of years and subsequently remains fresher than the Beata Ridge record (Figure 3). We speculate that the SMW was increasingly substituted by another water mass or the inflow of SMW was reduced since this time. Various processes could have induced subsurface freshening and hence might have hampered the expansion of SMW into Tobago Basin. Diminished trade winds and hence reduced Ekman downwelling within the STG could have resulted in less formation and southward expansion of SMW. Weaker trade winds should have weakened the retroflection of the NBC, allowing more fresh NBC waters to enter the Tobago Basin. Proxy records from Cariaco Basin (Peterson et al., 2000), however, indicate a constantly southward displaced ITCZ between 22 and 10 ka BP. According to Broccoli et al. (2006), a southward displaced ITCZ would go along with a generally stronger northeastern trades regime, causing enhanced production of SMW due to stronger Ekman downwelling. Thus, relaxed trade winds as cause for Tobago Basin freshening appears implausible. It may be speculated that increased river discharge might have caused subsurface freshening in Tobago Basin due to downmixing of fresh water into the subsurface. However, river discharge appears unimportant for the abrupt subsurface freshening in Tobago Basin. There is indeed evidence that under modern conditions, Orinoco or Amazonas freshwater mixes into the subsurface ocean levels by eddies originating from the retroflection of the NBC, but only down to ~30-m depth (Hellweger & Gordon, 2002), hence not affecting our subsurface proxy records.

5.1.2. Short-Term STG Variability During Times of AMOC Perturbation

The $subSST_{Mg/Ca}$ development in the tropical west Atlantic during times of AMOC perturbations reveals conditions being even more extreme than during the last full glacial. Modelling studies suggest a two-step oceanic teleconnection during the deglaciation linking tropical west Atlantic subsurface warming to AMOC weakening (Chang et al., 2008; Schmidt et al., 2012; Zhang, 2007). The first step comprises the oceanic adjustment in response to AMOC slowdown, which primarily implies the weakening of the western boundary current. At the same time, a rapid warming in the tropical west Atlantic occurred, as less cool fresh subsurface NBC waters were transported northward into the tropical west Atlantic (Figure 5). As second step, the AMOC weakened beyond a certain threshold and the strength of the STG won over the AMOC return flow (NBC), allowing the warm and saline SMW of the STG to enter the equatorial west Atlantic and additionally warm up the subsurface ocean (Schmidt et al., 2012; Schmidt et al., 2017).

At Tobago Basin and Bonaire Basin, the deglaciation is characterized by abrupt rises in $subSST_{Mg/Ca}$ by ~5.5 °C at the end of HS1 and by ~6 °C at the middle of the YD to peak values of up to ~23 °C and ~22 °C, respectively, accompanied by changes toward saline conditions (mean $\delta^{18}O_{sw\text{-}ivf}$ of ~2.25‰ and ~2‰, respectively (Figure 3). These highly variable changes occur within less than 400 years. This deglacial pattern is similar and rather synchronous to the overall cooler Bonaire Basin core 107 record (Schmidt et al., 2012), while the absolute offset between proxy values is rather due to the different foraminiferal species used (Figure 3). The reconstructed subsurface warming of ~5.5–6 °C in Tobago Basin is in agreement with the modeling results of (Chang et al., 2008) and Schmidt et al. (2012). They noted the most intense subsurface warming of ~6.5 °C at ~100- to 400-m water depth in the area off northeast Brazil during times of deglacial AMOC slowdown.

At Beata Ridge, instead, the $subSST_{Mg/Ca}$ record is rather low in amplitude and is lacking a rapid deglacial $subSST_{Mg/Ca}$ variability. We speculate that due to the proximity of the Beata Ridge core to the STG and due to the per se warmer subsurface conditions, the $subSST_{Mg/Ca}$ appear rather muted unlike to the conditions farther in the south (Tobago Basin and Bonaire Basin).

Smallest lateral temperature gradients at subsurface (ΔsubSST) of ~2 °C between Beata Ridge and Bonaire Basin and even negative values (~−2 °C) between Beata Ridge and Tobago Basin occur during late HS1 and the YD and also temporally during HS2 (Figure 4). Thermocline depths at Beata Ridge and Bonaire Basin remained rather stable and deep during the deglacial AMOC perturbations, while the $\delta^{18}O_{sw\text{-}ivf}$ records at Beata Ridge and Tobago Basin converge during HS2, HS1, and the YD, pointing to similar subsurface salinity conditions (Figure 4). Our proxy data favor the scenario of the southward shift of the STG and its associated subsurface expansion of SMW as already described for full glacial conditions. However, the rapid subsurface warming, small ΔsubSST, and equal subsurface salinities require more extreme conditions than for full glacial conditions. Indeed, the very rapid subsurface warming events during HS2, HS1, and the YD afford additional regional oceanographic adjustments in response to the prominent deglacial, abrupt, and short-term AMOC perturbations (and even shutdowns; Böhm et al., 2015; McManus et al., 2004). In particular the significantly reduced impact of NBC in line with AMOC weakening should have fostered SMW to propagate farther south and caused an additional subsurface warming.

Modelling studies corroborate that North Atlantic freshwater forcing might have weakened or even reversed the NBC flow at times of a substantially weakened AMOC (Mignot et al., 2007; Schmidt et al., 2012). At least for HS1, Bahr et al. (2018) speculated on either the reversal of the NBC or a nonoperating scenario during HS1. They found $SST_{Mg/Ca}$ cooling at Tobago Basin in contrast to rather stable or increasing SSTs off NE Brazil and conclude that a northern-sourced surface water mass might have reached Tobago Basin due to NBC weakening or strong deflection. Zhang et al. (2015) found extremely high volumes of sediments deposited offshore the Parnaíba River mouth pointing to the significant weakening of the NBC during

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HS1 and the YD associated to a weakened AMOC circulation. Less NBC impact was particularly reconstructed for the YD (Arz et al., 1999; Zhang et al., 2015) and for HS1 (Zhang et al., 2015).

Similar to AMOC-related oceanographic variations at the southwestern margin of the STG, Repschläger et al. (2015) noted short-term variations at its northeastern boundary. Based on micropaleontological evidence from the Azores Front area, they described the reduced/lowered presence of subtropical waters during HS1 and the YD, implying that the STG and its associated water masses rapidly shifted southward during times of AMOC perturbations (Figure 4).

5.1.3. Early to Late Holocene Change of the Subtropical Gyre

The early to mid-Holocene development of the lateral temperature gradient at subsurface is rather similar between Beata Ridge and Tobago Basin on the one hand and Beata Ridge and Bonaire Basin on the other hand (Figure 4). While during the early Holocene, ΔsubSST gradients amount to ~2 °C and ~6 °C, respectively, they increase continuously during the run of the Holocene to values of ~5 °C and ~9 °C and come close to the modern conditions (Figure 4).

Cléroux et al. (2009) found evidence for calcification depth changes of *G. truncatulinoides* during the early Holocene. *G. truncatulinoides* appeared to calcify at shallower depths during the early Holocene than during the deglaciation. Cléroux et al. (2009) hypothesized that the change in calcification depth is related to either the presence of freshwater (meltwater or river runoff) or caused by changes in water masses properties. The Tobago Basin is rather sensitive to Orinoco River run-off (e.g., Bahr et al., 2018; Hoffmann et al., 2014). River discharge in fact controls nutrient content as well as water column turbidity and therefore primary the distribution of phytoplankton as a food source of *G. truncatulinoides*. Enhanced sediment input may have limited the penetration of light and thus concentrate marine productivity close to the surface, leading to a thin euphotic zone that may forced *G. truncatulinoides* to live at a shallower depth (Cléroux et al., 2009). Indeed, Hoffmann et al. (2014) found evidence for enhanced Orinoco River run-off during the early Holocene at Tobago Basin. Further, Cléroux et al. (2009) discussed changes in the *G. truncatulinoides* calcification depth in terms of vertical and horizontal changes of the subtropical underwater following Schmuker and Schiebel (2002), who related *G. truncatulinoides* to this water mass (equivalent to the salinity maximum water). However, as $subSST_{Mg/Ca}$ of both *G. crassaformis* in Bonaire Basin (200- to 400-m water depth; Schmidt et al., 2012) and *G. truncatulinoides* in Tobago Basin (~200-m water depth; this study) are similar in absolute values and amplitude, we assess the early Holocene warm subsurface as a robust signal in the tropical west Atlantic, which is definitely not related to changing habitat depth of *G. truncatulinoides*. Hence, we interpret these continuous changes in the lateral subsurface temperature gradient as expression of the early to mid-Holocene development of a strong temperature gradient across the tropical west Atlantic, which separates warm saline STG waters from cooler fresher NBC waters (Fratantoni et al., 2000; Hazeleger & Drijfhout, 2006; Kirchner et al., 2009) and is gradually displaced northward (Figure 5). Since the YD, the thermocline shoaled rapidly until the Holocene. The interaction between these water bodies seems closely related to the gradual resumption of the AMOC, which finally reaches its modern state during the early mid-Holocene, as suggested by the Pa/Th record of McManus et al. (2004); Figure 4). The overall northward displacement of the ITCZ and the weakening of the related trade winds further strengthened the NBC, allowing cooler and fresher NBC waters to penetrate into the tropical west Atlantic.

6. Conclusions

The relevance of the subsurface North Atlantic STG for heat and salt storage and its sensitivity to rapid climatic change is still underestimated. In this study, high-resolution stable isotope and Mg/Ca records from subsurface dwelling planktonic foraminifera were generated from tropical west Atlantic and Caribbean sediment cores and compared to surface ocean properties. The combined interpretation of subsurface and surface parameters, and the calculation of vertical and lateral gradients in ocean properties permitted the reconstruction of spatial SMW fluctuations in relation to the dynamic variability of the STG and its link to AMOC changes during the last 30 ka.

During full glacial conditions the subsurface ocean levels at Tobago Basin and Beata Ridge showed rather similar but distinctly warmer $subSST_{Mg/Ca}$ conditions than today. The deepened thermocline at Beata Ridge and the small lateral $subSST_{Mg/Ca}$ gradient between Beata Ridge and Tobago Basin points to the vertical and lateral southward expansion of the warm and saline SMW in response to intensified Ekman downwelling within the STG. At the same time, the glacially strengthened trade winds fostered the retroflection of the NBC and prevented the inflow of cooler and fresher southern-sourced waters into the tropical west Atlantic.

During times of significant AMOC perturbations (HS1 and the YD), extreme subsurface warming (~6 °C) events in both Tobago and Bonaire basins implies considerable heat accumulation in the subsurface tropical west Atlantic (Figure 5). Low lateral subsurface temperature and salinity gradients between Beata Ridge and Tobago Basin and a deep thermocline suggest that SMW fully occupied the subsurface tropical west Atlantic. Intensified trade winds strengthened the formation of SMW and the shift of the STG toward its southernmost position, while deglacial AMOC perturbations weakened and/or led to the reflection or even reversal of the northward bound NBC. This oceanographic adjustment in response to North Atlantic cold events and the associated abrupt shifts of hydrographic and atmospheric frontal systems in the Atlantic Ocean (Barker et al., 2009) additionally favored subsurface warming in Bonaire and Tobago Basins.

The gradual subsurface cooling and freshening, enlarged lateral gradients at subsurface level, and thermocline shoaling during the course of the early Holocene point to the diminished impact of SMW in the tropical west Atlantic. The AMOC resumption lowered trade wind intensity, and the northward shift of the ITCZ favored the development of a strong temperature gradient between the tropical west Atlantic and the northward shifting STG. Tobago Basin core 235, in this respect, is ideal to record the interaction between warm and saline STG waters and NBC waters at the subsurface ocean level.

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