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Salinity change in the subtropical Atlantic: Secular increase and teleconnections to the North Atlantic Oscillation

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[1] Recent studies comparing shipboard data between the 1950's and the 1990's have shown significant, heterogeneous adjustments of the temperature-salinity structure of the N. Atlantic Ocean. Here, we present proxy records of temperature and salinity from aragonite sclerosponge skeletons, extending existing records of the Salinity Maximum Waters (SMW) of the N. Atlantic back to 1890. These proxy records show secular temperature increases of 1.6–2.0°C, higher than published global averages, and salinity increases of 0.35–0.5 psu, smaller than short-term secular trends recently measured. Salinity reconstructions vary more significantly on the decadal scale, showing changes that are related to low-frequency variations of the North Atlantic Oscillation (NAO). On both secular and decadal time scales, the records indicate significant thermohaline changes in the SMW, either via forcing at the surface or increasing depths of density surfaces in the Bahamas. **Citation:** Rosenheim, B. E., P. K. Swart, S. R. Thorrold, A. Eisenhauer, and P. Willenz (2005), Salinity change in the subtropical Atlantic: Secular increase and teleconnections to the North Atlantic Oscillation, *Geophys. Res. Lett.*, *32*, L02603, doi:10.1029/2004GL021499.

1. Introduction

[2] There have been numerous observations that global temperatures have been rising through the last century, generating significant interest in changes of the storage and transfer of heat between ocean and atmosphere [*Cardone et al.*, 1990; *Levitus et al.*, 2000; *Barnett et al.*, 2001; *Folland et al.*, 2001; *Levitus et al.*, 2001]. The broad-reaching effects of increasing global heat content [*Folland et al.*, 2001] as well as oceanic heat content [*Levitus et al.*, 2000, 2001] include wind stress changes [*Cardone et al.*, 1990], salinity increases [*Curry et al.*, 2003], and temperature increases, however instrumental records are limited in their time domain. All of these changes indicate the varied mechanisms of the transfer of heat and momentum across the tropical air-sea interface. Compared to natural variability in other proxy records stretching as far as 6 centuries, there is evidence that these changes are unprecedented in their global significance [*Haase-Schramm et al.*, 2003; *Mann and Jones*, 2003].

[3] Salinity changes in the N. Atlantic, including the Caribbean Sea, play an important role in global change because of the significant regional and global transport of the highly saline waters formed in the basin. The salinity and temperature profiles of the diffuse return flow of the N. Atlantic gyre influence the formation of subtropical cells (STC's) [*Zhang et al.*, 2003] and of North Atlantic Deep Water (NADW) [*Blanke et al.*, 2002] which both redistribute heat taken up by the ocean in lower latitudes. The effects of salinity change on the latter include such large-scale climate instability such the deglaciation of the northern hemisphere marking the beginning of the Holocene [*Broecker et al.*, 1989; *Broecker*, 1994; *Schmidt et al.*, 2004]. More recently, instrumental records have indicated a salinity adjustment of the Atlantic Ocean [*Curry et al.*, 2003], which may be linked to the century long increase of CO_2 emissions associated with industrialization [*Levitus et al.*, 2000, 2001] or a positive excursion of the NAO index, the pressure difference between Iceland and the Açores [*Marshall et al.*, 2001]. *Curry et al.* [2003] present evidence of salinity increase in the subtropics, potentially increasing both the amount of water subducted into the STC's and the salinity of waters delivered back to the gyre system.

[4] In this study, we analyze two continuous century long proxy records of salinity and temperature from sclerosponges inhabiting two of the Bahamas' deep channels (Figure 1). This area represents a crucial junction between Caribbean waters and N. Atlantic Gyre return flow waters from the SMW formed in the eastern Atlantic between 20°N and 25°N when intrusion of hot, arid Saharan air masses result in high net evaporation. The SMW subduct along density surfaces to constitute the subsurface waters of the Bahamas and the interior Caribbean, known as the Subtropical Underwater (SUW). In the Bahamas, subsurface waters adjacent to large shelf areas can also show periodic influence of high-density bank top plume waters that form locally as hypersaline waters cool and are entrained over the deep channels by cold fronts [*Hickey et al.*, 2000].

2. Methods and Approach

[5] Our reconstruction of SMW salinity and temperature is derived from skeletal proxies of two specimens of the sclerosponge *Ceratoporella nicholsoni* taken from water

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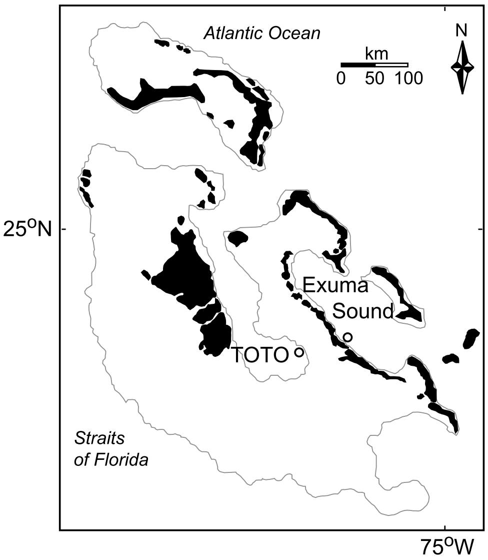

Figure 1. Map of the Bahamas with open circles showing locations of the analyzed sclerosponges. The Bahamas are shown in black and the shallow Bahamas bank waters are outlined in gray. The Exuma sclerosponge was collected from 136 m and the TOTO sclerosponge from 143 m. The sclerosponge collected from TOTO is adjacent to a much larger shelf area than the Exuma sclerosponge.

depths of 136 m (Exuma Sound) and 143 m (Tongue of the Ocean (TOTO); Figure 1). The Atlantic sclerosponge *C. nicholsoni* lives in cryptic environments up to 250 m deep and secretes a dense aragonite skeleton at rates of approximately 200 µm/y [*Lang et al.*, 1975; *Benavides and Druffel*, 1986; *Willenz and Hartman*, 1999]. These organisms deposit their skeletons in isotopic equilibrium with water [*Böhm et al.*, 2000], recording both ambient water temperature and $\delta^{18}O_{sw}$, which is related to salinity. A recent in situ calibration of Sr/Ca ratios to temperature for this species [*Rosenheim et al.*, 2004] allows differentiation between the temperature and salinity components of the $\delta^{18}O_{arag}$ records of these organisms. The temperature dependence of Sr/Ca ratios in sclerosponges is 2–3 times more sensitive than that of inorganic aragonite, making this calibration less sensitive to the assumption of invariant Sr/Ca_{sw} than studies using zooxanthellate corals.

[6] The sclerosponges were dated using U/Th radiometric techniques and then analyzed using high resolution micromilling for oxygen isotope analysis via isotope ratio mass spectrometry and laser ablation sampling for Sr/Ca analysis via ICP-MS. Constant-growth age models constructed from U/Th dating indicate growth rates of 145 $\mu m \cdot y^{-1}$ for the Exuma sclerosponge and 172 $\mu m \cdot y^{-1}$ for the TOTO sclerosponge (auxiliary material[1]). The radiometric age model of the TOTO sclerosponge was tuned to annual Sr/Ca variations after *Swart et al.* [2002], however because tuned age models and constant growth models are within 5% [*Swart et al.*, 2002], the U/Th constant growth model was used for the Exuma sclerosponge. Micro-milling and laser ablation were performed from mirror-image slabs of sclerosponge skeleton prepared from the same thick slab, enabling straightforward correlation between isotope and minor element transects. Measurement methods are summarized and results are shown in the auxiliary material as well as in previous work on these sclerosponges [*Swart et al.*, 2002; *Rosenheim et al.*, 2004].

3. Time Series of Proxy Temperature and Salinity

[7] Greater high-frequency variation is present for both Sr/Ca and $\delta^{18}O_{arag}$ in the TOTO sclerosponge (Figure 2) due to higher sampling resolution (0.01 mm vs. 0.02 mm) and the presence of a larger shelf area where dense bank-top plumes can form (Figure 1). Linear trends in $\delta^{18}O_{arag}$ and Sr/Ca of both sclerosponges decreased between 1890–1990, indicating temperature increase (Figure 2). Temperature increases indicated by Sr/Ca were 1.6°C for Exuma and 2.0°C for TOTO, ±0.7°C [*Rosenheim et al.*, 2004]. The inferred temperature increases calculated using *Böhm*'s [2000] $\delta^{18}O_{arag}$ – temperature calibration are only 0.9–1.0°C (Figure 2). Assuming that Sr/Ca_{sw} was constant over this century, the discrepancy in secular trends between the individual proxies in each sclerosponge is interpreted as the result of salinity change. In order to estimate the salinity

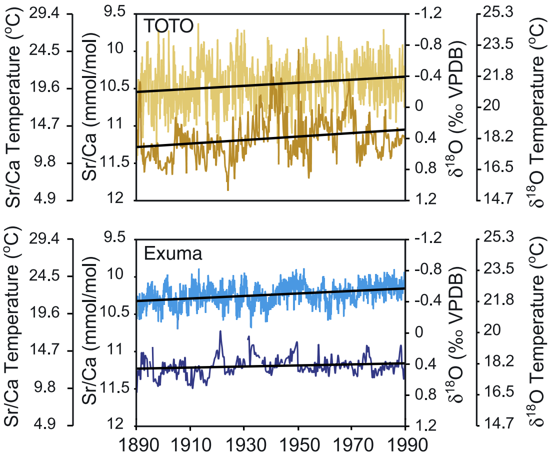

Figure 2. Time series of Sr/Ca (light orange and blue) and $\delta^{18}O$ (dark orange and blue) from sclerosponges in Exuma Sound and TOTO. Temperature scales were constructed from empirical calibrations of *Rosenheim et al.* [2004] for Sr/Ca and *Böhm et al.* [2000] for $\delta^{18}O$ (constant $\delta^{18}O_{sw}$ of 0‰ SMOW is assumed). Both proxies indicate increasing temperature between 1890 and 1990 (linear regression), however the temperature change indicated by $\delta^{18}O_{arag}$, which measures salinity as well as temperature, is only half that indicated by Sr/Ca. To accommodate this difference, contemporaneous salinity change is assumed. The resulting secular salinity increases, 0.5 ± 0.34 psu in Exuma and 0.35 ± 0.32 psu in TOTO, are similar to secular salinity increases in the SMW over the past 45 y reported by both *Curry et al.* [2003] and *Joyce et al.* [1999]; however they occur over a longer time period. The large amplitude, high-frequency variability of the TOTO data set shows the effects of higher sampling resolution as well as dense plumes of hypersaline water from the Bahamas bank.

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL021499.

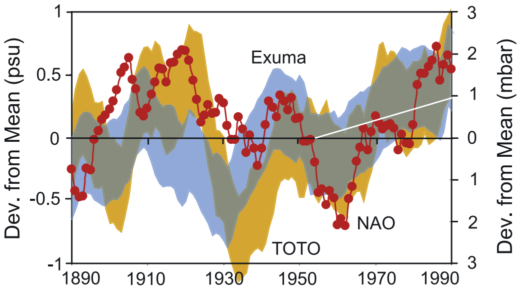

Figure 3. 10 y smoothed salinity time series with error envelopes from each sclerosponge, in deviations from 1890–1990 mean (psu). Decadal scale variations in salinity occur simultaneously in both Exuma (blue) and TOTO (orange). The secular salinity trend observed in the SMW by *Curry et al.* [2003] is represented approximately by the white line and follows the most recent portions of both sclerosponge records of salinity. The sclerosponge salinity trends are significantly correlated to the NAO index (red line with circles, calculated in deviations from the 1890–1990 mean annual pressure difference between the Açores and Iceland (mbar) and smoothed to the 10 yr running mean). The NAO index is related to trade wind stress fluctuations as stronger trade winds develop with an elevated Açores high pressure during positive NAO events. This type of strengthened wind stress can both evaporate surface waters, changing salinity and temperature along density surfaces, as well as drive density surfaces deeper as reported by *Joyce et al.* [1999]. Despite the significance of the correlation, NAO only explains 20–30% of the salinity variance as the connections to the Bahamas are tenuous and there is still a secular component to both temperature and salinity change.

change, we combine three linear calibration equations incorporating both measured parameters ($\delta^{18}O_{arag}$ and Sr/Ca) to solve for three related unknowns ($\delta^{18}O_{sw}$, T, and S) [*Böhm et al.*, 2000; *Ganssen and Kroon*, 2000; *Rosenheim et al.*, 2004].

$$T = 19.6 - 4.9\left(\delta^{18}O_{arag} - \delta^{18}O_{sw}\right) \tag{1}$$

$$Sr/Ca = 12.5 - 0.102T \tag{2}$$

$$\delta^{18}O_{sw} = 0.54S - 19 \tag{3}$$

Oxygen isotope values ($\delta^{18}O$) are measured in ‰ VPDB for aragonite and ‰ SMOW for water. Ratios of Sr/Ca are measured in mmol·mol^{-1}, temperature (T) is in °C, and salinity (S) is in psu. Equation (3) is constructed from surface waters (<50 m) of the return flow of the N. Atlantic Gyre between 45°N and 31°N. During transport between these latitudes, this water mass begins adopting the properties of the SMW [*Krauss*, 1986; *Ottens*, 1991]. By combining and rearranging these equations to reconstruct the salinity record preserved in Bahamas sclerosponges,

$$S = \frac{1}{0.54}\left[40 - \left(2.0Sr/Ca - \delta^{18}O_{arag}\right)\right] \tag{4}$$

we find secular salinity increases of 0.35 ± 0.34 psu in Exuma Sound and 0.5 ± 0.35 psu in TOTO that must happen coevally with the secular temperature increases to explain the discrepancies between Sr/Ca and $\delta^{18}O_{aragonite}$ linear temperature trends. It is evident from (4) that our reconstruction is sensitive to the gradient $\delta^{18}O_{sw}/S$ (0.54 ‰·psu^{-1}). Despite the significant cumulative residual error from equations (1)–(3) (auxiliary material), our data clearly identify salinity variation in the subsurface waters of both Exuma Sound and TOTO during the last 100 years.

4. Climate Implications

[8] Equation (4) allows the proxy reconstruction of a continuous salinity record of the SMW between 1890 and 1990, significantly improving the time resolution and extent of instrumental records. This water mass is surface forced well away from shallow shelf areas such as the Bahamas bank where local conditions can amplify climatological changes in wind stress. When such high-frequency variation is filtered from the salinity records by a 10 y running mean, several decadal-scale deviations are evident, culminating with a nearly monotonic increase in salinity over the last 40 years (Figure 3). Relative to the error inherent in equation (4) (Figure 3), the decadal-scale trends are more significant than the secular changes in salinity and are interpreted to reflect the baseline conditions of the subsurface SMW. However regional nature of secular salinity changes is suggested by similar secular Sr/Ca decreases reported in absence of coeval $\delta^{18}O_{arag}$ decreases in Jamaican sclerosponges [*Haase-Schramm et al.*, 2003].

[9] Figure 3 illustrates that the decadal-scale components of our salinity reconstructions are significantly correlated to decadal-scale variations in the NAO index between 1890–1990 ($p < 0.0005$ in TOTO and $p < 0.01$ in Exuma) supporting a recent hypothesis that monotonic salinity increase measured in the SMW is related to NAO [*Joyce et al.*, 1999; *Marshall et al.*, 2001; *Curry et al.*, 2003]. The role of the NAO in tropical and subtropical N. Atlantic variability has been suggested by its effects on the trade winds [*Marshall et al.*, 2001] via the Açores high which can strengthen the pressure gradient over which the trade winds blow. This can increase evaporation over the SMW before it is subducted from the surface and also deepen density surfaces regionally, giving the impression that surface forcing of a subsurface water mass has changed [*Joyce et al.*, 1999]. Although the oceans' response to increased heat availability is likely complex and spatially heterogeneous, the magnitude of our estimates of secular temperature increase (1.6–2.0°C) compared to published global averages suggests some aspects of both surface forcing of the SMW and deepening of the Caribbean subsurface isopycnals have contributed to these trends.

[10] Coupled with the secular temperature increases of 1.6–2.0°C, sclerosponge salinity records add evidence to instrumental observations that regional T-S changes can surpass global averages [*Levitus et al.*, 2000; *Barnett et al.*, 2001; *Folland et al.*, 2001; *Levitus et al.*, 2001], suggesting complex, regionalized oceanic heat storage and transfer mechanisms that may be averaged by broad spatial compilations of instrumental data. Although sclerosponges from the Bahamas are limited in spatial extent, their long records of increased salinity and temperature of low-latitude

waters support previous observations that the thermohaline structure of the N. Atlantic may be adjusting to climate perturbations [*Joyce et al.*, 1999; *Curry et al.*, 2003] and these changes have been occurring some 60 years before detailed instrumental monitoring of salinity began.

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