# Salinity change in the Atlantic Ocean: Secular increase and tropical teleconnections to the North Atlantic Oscillation

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**Significant interest in the storage and transfer of heat in the ocean and atmosphere is directed to studying how these processes may change as a result of the continued warming of the earth over the past century [1-5]. Recent studies comparing shipboard data since the 1950's have shown significant adjustments of the temperature-salinity structure of the N. Atlantic Ocean [6,7]. Instrumentally measured temperature increases locally surpass global estimates over the last 140 years [3-5] and there is an indication that salinity has been increasing in the lower latitudes, illustrating a complex ocean response to climate change with significant implications about the climatically important thermohaline circulation (THC) of the N. Atlantic. Here, we present proxy records of temperature and salinity from**

**the accretionary skeletons of sclerosponges, extending ship transect comparisons continuously to 1890 in the Salinity Maximum Waters (SMW) of the N. Atlantic. These proxy records show secular temperature increases of 1.6-2.0°C and secular salinity increases of 0.35-0.5‰. Salinity reconstructions also show decadal-scale changes that are related to low-frequency variations of the North Atlantic Oscillation (NAO).**

## Introduction

There have been numerous observations that global heat content [3] as well as oceanic heat content [4,5] have been rising through the last century. The broad-reaching effects of increased heat in the tropics include wind stress changes [2], salinity increases [6], and temperature increases. All of these changes indicate complex alterations in the transfer of heat and momentum across the tropical air-sea interface to accommodate the increased availability of heat, and compared to natural variability in skeletal proxy records over the last 6 centuries, there is evidence that these changes are unprecedented[8].

In particular, salinity changes in the N. Atlantic play an important role in global change because of the importance of the thermohaline (THC) heat pump. The thermohaline properties of the Caribbean Sea waters and the waters of the diffuse return flow of the N. Atlantic Gyre system play important roles in the formation of North Atlantic Deep Water (NADW) [9], a principal component of the THC which pumps tropical heat poleward. Salinity changes in the N. Atlantic have been implicated in climate instability at the deglaciation of the northern hemisphere marking the beginning of the Holocene[10-12]. More recently, instrumental records have indicated a salinity adjustment of the Atlantic Ocean, [6] which may be linked to the century long increase of

$CO_2$ emissions associated with industrialization [4,5] or a positive excursion of the NAO index, the pressure difference between Iceland and the Açores [13].

In this study, we analyze two century long, continuous proxy records of salinity and temperature from sclerosponges in two of the Bahamas' deep channels (Fig. 1). This area represents a crucial junction between Caribbean waters and N. Atlantic Gyre return flow waters, or Salinity Maximum Waters (SMW). The SMW is formed in the eastern Atlantic between 20°N and 25°N when intrusion of hot, arid Saharan air masses result in a large E-P (evaporation minus precipitation). It is ultimately entrained with the Caribbean Sea waters in the flow of the Gulf Stream, playing an important role in the subduction of NADW once it mixes and cools.

Our records of SMW salinity and temperature come from the skeletons of two specimens of the sclerosponge *Ceratoporella nicholsoni* taken from water depths of 136 m (Exuma Sound) and 143 m (Tongue of the Ocean (TOTO), Fig. 1). The Atlantic sclerosponge *C. nicholsoni*, lives in cryptic environments at depths up to 250m and secretes a dense aragonite skeleton at rates of approximately 200µm/y [14,15]. These organisms deposit their skeletons in isotopic equilibrium with water [16], thus recording both ambient water temperature and $\delta^{18}O_{water}$ , which is dependent on salinity. A recent *in situ* calibration of Sr/Ca ratios to temperature for this species [17] allows differentiation between the temperature and salinity records preserved in the $\delta^{18}O$ records of these organisms. The temperature dependence of Sr/Ca ratios in sclerosponges is approximately 3x higher than that of inorganic aragonite, making this calibration less sensitive to the assumption of invariant $[Sr/Ca]_{seawater}$ than studies using zooxanthellate corals [17].

**Century- and decadal-scale records**

Between 1890 and 1990, trends in both $\delta^{18}O_{aragonite}$ and Sr/Ca decreased, indicating increasing temperature. Temperature increases indicated by Sr/Ca were 1.6°C for Exuma and 2.0°C for TOTO, however the inferred temperature increases indicated by $\delta^{18}O_{aragonite}$ were smaller as a result of the effects of salinity change over the time period (Fig. 2). In order to study the implied salinity changes, we combine three linear calibration equations incorporating both measured parameters ($\delta^{18}O_{aragonite}$ and Sr/Ca) to solve for three related unknowns ($\delta^{18}O_{water}$, T, and S).

$$T = a(\delta^{18}O_{aragonite} - \delta^{18}O_{water}) + b \quad (1)$$ [16]

$$Sr/Ca = cT + d \quad (2)$$ [17]

$$\delta^{18}O_{water} = eS + f \quad (3)$$ [18]

Oxygen isotope values ($\delta^{18}O$) are measured in ‰ relative to VPDB for aragonite measurements and relative to SMOW for water measurements. Ratios of Sr/Ca are measured in $mmol \cdot mol^{-1}$, temperature (T) is in °C, and salinity (S) is in ‰. The coefficients a-f represent the gradients and intercepts of the published calibrations used to reconstruct the salinity record preserved in Bahamas sclerosponges. By combining and rearranging these equations to solve for salinity,

$$S = e^{-1} \cdot [\delta^{18}O_{aragonite} + f + ((d - Sr/Ca)/c - b)/a] \quad (4)$$

we find secular salinity increases of 0.35 ± 0.23 ‰ in Exuma Sound and 0.5 ± 0.26 ‰ in TOTO that must happen coevally with the secular temperature increases to explain the discrepancies between Sr/Ca and $\delta^{18}O_{aragonite}$ temperature proxies.

The significant errors propagated through equation 4 into our secular salinity trends illustrate the sensitivity of salinity reconstructions to the gradients e (salinity – $\delta^{18}O_{water}$) and a (temperature – $\delta^{18}O_{aragonite}$). Although the sclerosponges in this project are within tropical, semi-enclosed seas, they are situated in subsurface water that achieves its temperature, salinity, and isotopic properties from surface forcing in the area of the SMW, which has a much lighter freshwater endmember (high latitude precipitation) and more intense evaporation resulting in a larger gradient [19]. The SMW subsides along density surfaces to form the Caribbean Subtropical Underwater (SUW), appearing as a highly saline core at depths between 100m and 200m [20]. As a result, we have used salinity – $\delta^{18}O_{water}$ data from the Actuomicropalaeontology Palaeoceanography North Atlantic Project (APNAP) cruises between 1986 and 1988 [18]. The residual error in this empirical linear relationship is magnified by the gradient e in equation 4 and, as a result, is responsible for 40% of the error in our salinity reconstruction. In addition, another 40% of the error is incorporated by the residual error of the calibration of temperature to $\delta^{18}O_{aragonite}$ [16], which consists of only 7 sclerosponges. Despite the significant cumulative residual error from combining equations (1-3), the error level is nearly optimal for this type of proxy work [21], and our data clearly identify secular salinity increases in the subsurface of both Exuma Sound and TOTO during the last 100 years and this error will be reduced with more understanding of the temperature-$\delta^{18}O_{aragonite}$ relationship of sclerosponges.

In addition to calculation of secular salinity trends to compare to instrumental data, equation (4) allows the reconstruction of a continuous salinity record between 1890 and 1990, significantly improving the time resolution of instrumental records. When high-frequency noise is filtered from the salinity records, several decadal-scale deviations are evident, culminating with a nearly monotonic increase in salinity over the last ~40 years (Fig. 3). These continuous records provide an excellent test for the recent hypotheses that a monotonic salinity increase in the SMW is related to NAO [6,7,13].

## Climate Implications

The secular trends observed in temperature and salinity as well as the decadal-scale salinity trends carry significant climate implications. Secular temperature trends are larger than global averages [1,3-5], indicating the complex, regionalized mechanisms by which the ocean stores increased heat that may be averaged by long-term, broad spatial compilations of instrumental data. Secular salinity increases are also large, and the decadal component of these trends indicates that wind stress changes act to store atmospheric heat energy in the oceans [2].

When calculated as deviation from the mean, decadal-scale salinity excursions are significantly correlated to decadal-scale variations in the NAO index between 1890 and 1990 ($r = 0.41$, $p < 0.0005$ in TOTO and $r = 0.26$, $p < 0.01$ in Exuma). Although the NAO is a high-latitude phenomenon, it has been related to tropical and subtropical N. Atlantic variability through its effects on the trade winds [13]. In its positive state, the NAO represents a stronger than normal Açores high which strengthens the pressure gradient over which the trade winds blow, thereby increasing evaporation over the SMW. Strengthening tradewinds can change the T-S properties observed in Exuma Sound and TOTO by altering the properties of the water mass where it is surface forced (SMW) or by driving the density surfaces of this water mass deeper, but most likely by a combination of both mechanisms [7]. An increase in evaporation can be locally amplified over the Bahamas Bank due to the limit on down mixing associated with its shallow waters, changing both temperature and salinity with a higher amplitude at relatively high frequencies. This is indicated by the difference in noise in both our Sr/Ca and $\delta^{18}O_{aragonite}$ records between Exuma Sound and TOTO (Fig. 2). The sclerosponge collected from TOTO is adjacent to a larger shelf area than is the sclerosponge collected in Exuma Sound (Fig. 1), rendering it more likely to record properties of dense hypersaline plumes of bank-top water that cascades into the deep Bahamas channels intermittently [22]. Although removal of this high frequency noise illustrates a linear relationship between NAO and salinity of both Exuma Sound and

TOTO, this relationship does not explain a high percentage of the salinity variance due to the tenuous nature of teleconnections between NAO and the tropics via the tradewinds. Nonetheless, the finding that subtropical salinity can be surface forced by NAO is significant.

Figure 3 illustrates that the secular salinity trends inferred from the disparity between Sr/Ca temperature and $\delta^{18}O$ temperature trends is present after high-frequency trends have been filtered. Coupled with the secular temperature increases of 1.6-2.0°C, sclerosponges add further evidence to instrumental observations that regional T-S changes can surpass global averages. Although sclerosponges from the Bahamas can yield no information about high latitude changes in temperature and salinity, their records of increased salinity and temperature of low-latitude waters support previous observations that the THC of the N. Atlantic may be adjusting to climate perturbations [6,7]. Moreover, these changes have been occurring some 60 years before detailed instrumental monitoring began. It is clear that such perturbations in tropical oceans play a role in interglacial-glacial transitions [10], but the significances of the changes during the past century have yet to be evaluated relative to pre-industrial salinity and temperature changes during the recent epoch.

## Methods

**Sclerosponge Collection and Growth Models.** For this study, two specimens of *C. nicholsoni* were collected from Exuma Sound and Tongue of the Ocean (TOTO), and analyzed for high-resolution Sr/Ca and $\delta^{18}O$ data. In order to construct age models, three U/Th dates from the Exuma Sound sclerosponge were used to calculate an average growth rate and Sr/Ca variations were used to count annual temperature cycles in the TOTO sclerosponge [23]. Although growth rates in sclerosponges have been shown to vary [8,23-25], the constant growth rate assumption for the Exuma sclerosponges provides a good estimate of the average growth rate over the time period of a century [23].

**Sr/Ca measurements.** Sections were were scrubbed with a nylon brush in Milli-Q water (Millipore Water Systems), sonified for 5 minutes in Milli-Q water, and then triple rinsed with ultrapure 1% HNO3 and Milli-Q water sequentially. Each laser sample was separated by approximately 20μm, forming a single line perpendicular to the concentric bands of the sclerosponge skeleton. A helium gas stream was used to transport the vaporized material to the ICP-MS. The carrier gas stream was mixed with a wet aerosol (1% w/w $HNO_3$) from a self-aspirating PFA nebulizer (20 l·min$^{-1}$) in a dual inlet quartz spray chamber. An aragonite reference material from fish otoliths was used as a standard and measured at intervals throughout the analyses [26]. Analyses of the aragonite reference material (n = 153) run during assays of the Bahamas sclerosponges provided a mean value of 2.878 ± 0.008 mmol·mol$^{-1}$ (1σ), after correcting for mass bias using an internal laboratory standard.

**Oxygen isotope measurements.** Samples were drilled from the Exuma Sound sclerosponge at a resolution of 50 μm and were analyzed by a Kiel III automated carbonate device attached to a Delta Plus isotope ratio mass spectrometer (IRMS). The $\delta^{18}O$ values were calculated relative to VPDB against an internal laboratory standard with a standard error of 0.06 ‰ (n = 46). Samples from the TOTO sclerosponge were drilled at a resolution of 20 μm and analyzed via a Fairbanks common acid bath automated carbonate device attached to a Finnigan MAT 251 IRMS. Oxygen isotope values from these analyses were calculated relative to VPDB against an internal laboratory standard with a precision of 0.09 ‰ (n = 48).

**U/Th Measurements.** Approximately 0.5 g of sclerosponge aragonite was drilled along the visible growth bands of each dated sclerosponge and dissolved in warm $HNO_3$ concentrate. The samples were each spiked with $^{229}$Th and $^{233}$U-$^{236}$U. Thorium and U were precipitated with $Fe(OH)_2$ in alkaline solution using $NH_4OH$ and the U and Th were then separated with HBr and HCl on an anion exchange column of BioRad AG 1X8 resin (100-200 mesh). Blanks showed 14-30 pg Th and 13pg U. Uranium and Th isotope analyses were carried out on a Finnigan MAT 262 RPQ + mass spectrometer at GEOMAR, Kiel, Germany. Thorium and U were loaded with 1N $HNO_3$ on an out-gassed Re filament and measured using the double filament technique in the "peak jumping" mode. Measurments of the international standard A112 yielded a $\delta^{234}$U of -30.3 +/-6.3‰.

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Figure 1.

Map of the Bahamas Islands. Locations of the sclerosponges used in this study are indicated by arrows. The Exuma Sound sclerosponge was collected from 136 m, and the TOTO sclerosponge was taken from 143 m. The islands of the Bahamas are shown in black, the shallow waters of the Bahamas bank are outlined in gray. The sclerosponge collected from TOTO is adjacent to a much larger shelf area than the sclerosponge from Exuma Sound.

Figure 2.

Time series of Sr/Ca (gray line) and $\delta^{18}O$ (black line) from sclerosponges in Exuma Sound and TOTO, with 10-yr running means of Sr/Ca shown with error envelopes by thick black lines. Temperature scales were constructed from empirical calibrations presented in Rosenheim et al. (2004) for Sr/Ca and Böhm et al. (2000) for $\delta^{18}O$, assuming the water masses have not changed isotopically over time. The black curves running through the Sr/Ca data show 10-yr running means displaying the low frequency temperature trends in each sclerosponge as Sr/Ca is assumed to be affected only by temperature. Both proxies indicate increasing temperature between 1890 and 1990 (linear regression through the data), however the temperature change indicated by oxygen isotopes, which measure salinity as well as temperature, is only half of that indicated by Sr/Ca. To accommodate this difference, a contemporaneous salinity increase must be assumed. The resulting salinity increases, 0.5 ± 0.23 ‰ in Exuma and 0.35 ± 0.26 ‰ in TOTO, is smaller than the secular trend of increasing salinity in the SMW reported by both Curry et al., 2003, and Joyce et al., 1999. The large amplitude, high-frequency variability of the TOTO data set shows the signature of dense plumes of hypersaline water from the Bahamas bank as this sclerosponge was sampled from deep water adjacent to a much larger shelf area than the Exuma sclerosponge (Fig. 1). These plumes are caused by both high salinities and low temperatures as shallow waters on the bank top are affected by winter storms and periods of high sustained winds. Despite the incorporation of this high frequency component, both sclerosponges illustrate the same long term trends of the SMW.

Figure 3.

Smoothed time series of salinity from each sclerosponge with error envelopes, in deviations from mean between years 1890-1990. Decadal scale variations in salinity show large variations that occurred simultaneously in both Exuma (light blue) and TOTO (dark blue). The secular trend observed in the open Atlantic by Curry et al., (2003) is represented approximately by the two white triangles connected with a straight line and shows a significant likeness to both sclerosponge records of salinity. The salinity trend indicated by each sclerosponge is significantly correlated to the smoothed NAO index (red line with circles, calculated in deviations from mean annual pressure difference between the Açores and Iceland from the years 1890-1990 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.

Figure 1

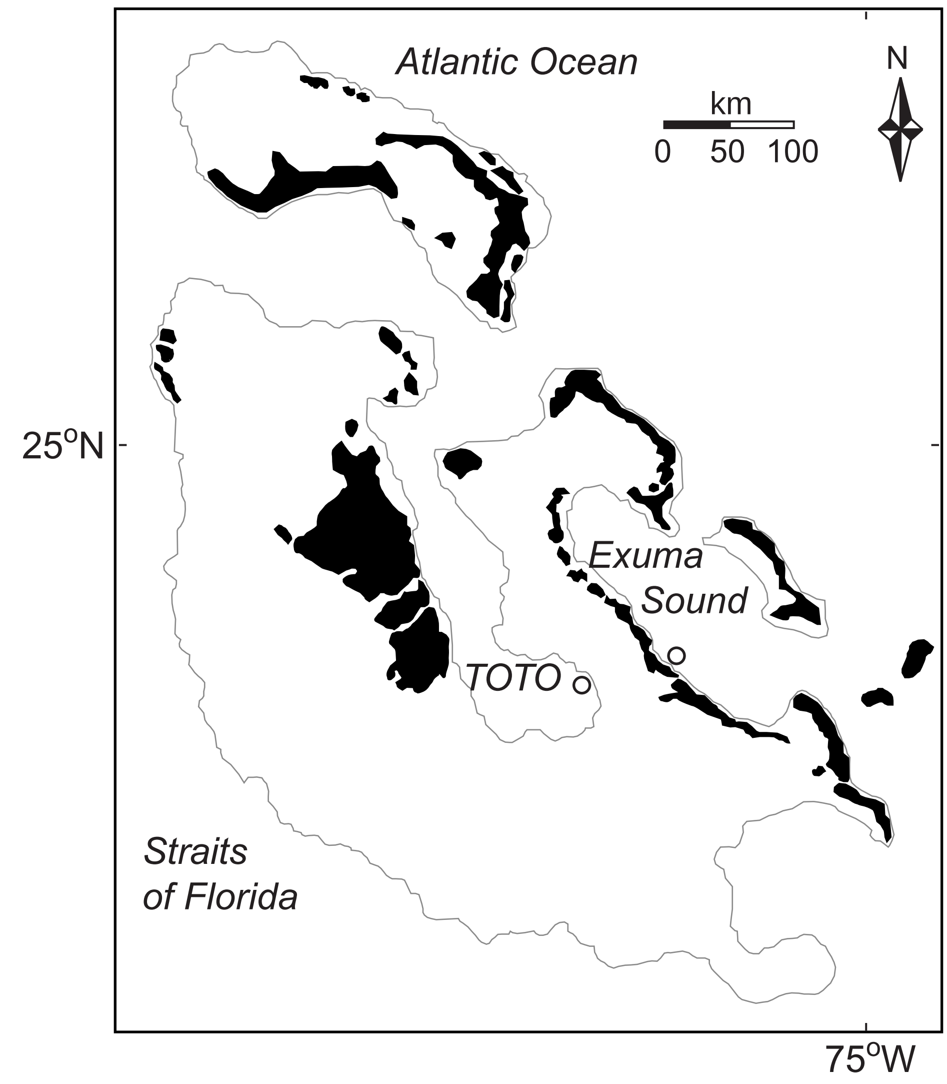

Atlantic Ocean
km
0 50 100
N
25°N
Exuma
Sound
TOTO
Straits
of Florida
75°W

Figure 2

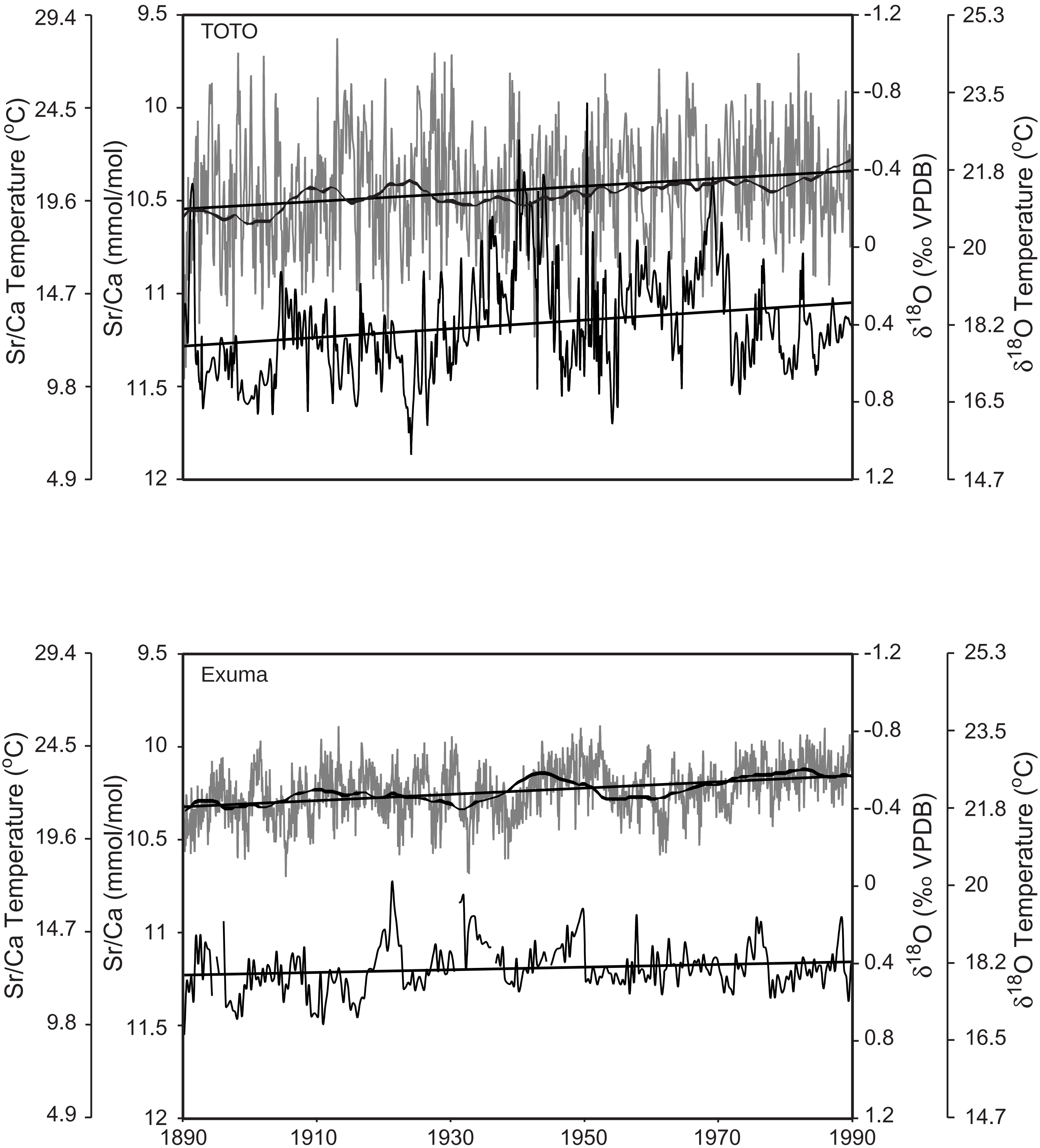
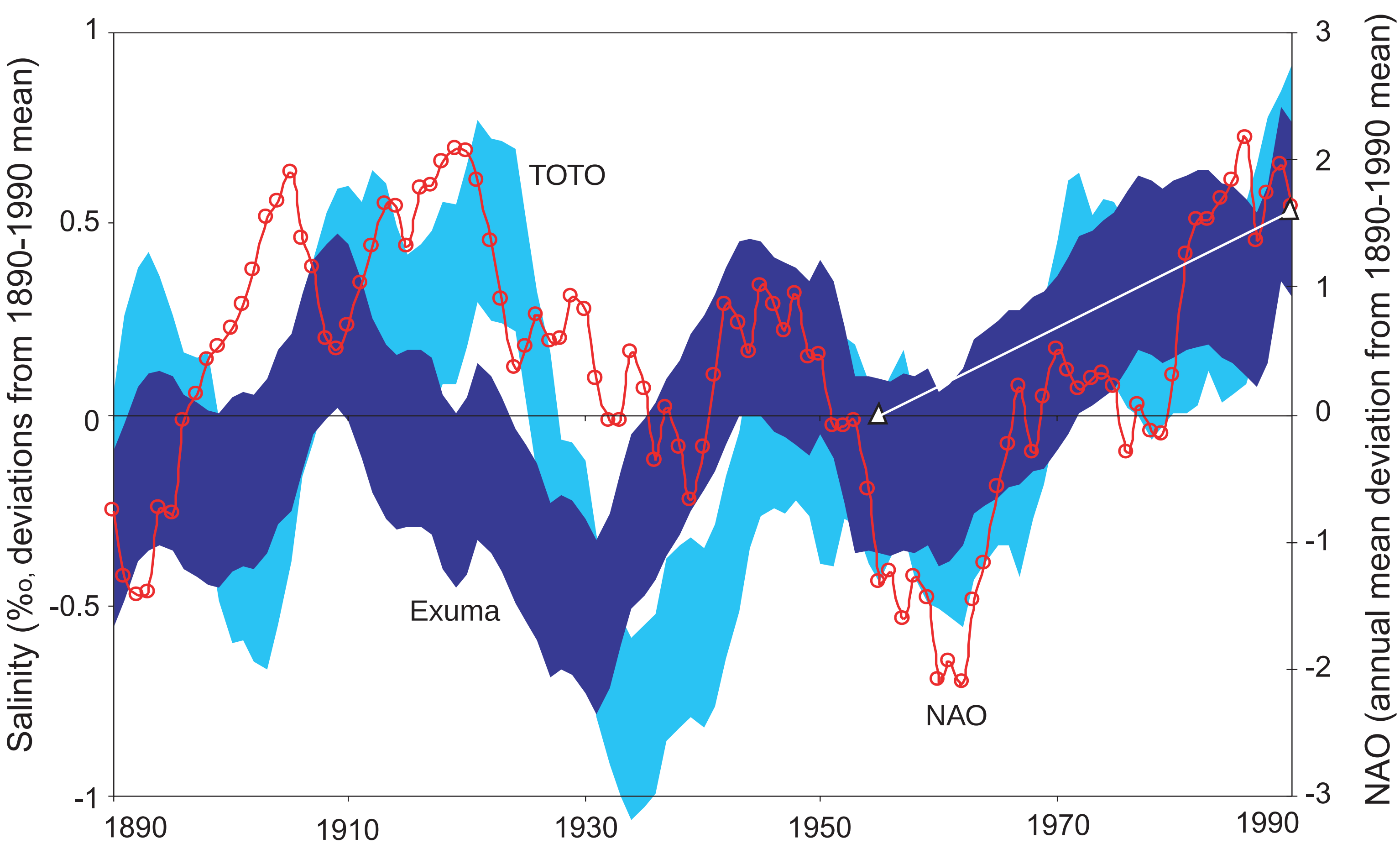

TOTO
Exuma
Sr/Ca Temperature (°C)
Sr/Ca (mmol/mol)
δ18O (‰ VPDB)
δ18O Temperature (°C)
29.4
24.5
19.6
14.7
9.8
4.9
9.5
10
10.5
11
11.5
12
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
25.3
23.5
21.8
20
18.2
16.5
14.7
1890
1910
1930
1950
1970
1990

Figure 3


Salinity (‰, deviations from 1890-1990 mean)
NAO (annual mean deviation from 1890-1990 mean)
TOTO
Exuma
NAO
1
0.5
0
-0.5
-1
3
2
1
0
-1
-2
-3
1890
1910
1930
1950
1970
1990