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Evidence of multidecadal salinity variability in the eastern tropical North Atlantic

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[1] Ocean circulation and global climate are strongly influenced by seawater density, which is itself controlled by salinity and temperature. Although adequate instrumental sea surface temperature (SST) records exist for most of the surface oceans over the past 100–150 years, records of salinity really only exist for the last 40–50 years. Here we show that longer proxy records from corals (*Siderastrea radians*) in the eastern tropical North Atlantic are dominated by multidecadal variations in salinity which are correlated with the relationship between SST and the North Atlantic Oscillation (NAO) over the course of the 20th century. The data reveal an increase in eastern tropical North Atlantic salinity of +0.5 practical salinity units (psu) between about 1950 and 1990. Rather than a monotonic secular increase, as indicated by some instrumental records, the preinstrumental coral proxy records presented here suggest that salinity in the tropical North Atlantic is periodic on a decadal to multidecadal scale.

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1. Introduction

[2] Despite numerous instrumental based SST reconstructions of local, regional, or global SST over the last ~150 years [*Slutz et al.*, 1985; *Smith and Reynolds*, 2004], only a generalized climatology exists for regional and global salinity [*Conkright et al.*, 2002; *Levitus et al.*, 1994], and many instrumental salinity records only date back to the middle of the 20th century [*Curry et al.*, 2003; *Zhang et al.*, 2003]. Longer records of salinity are needed for quantifying multidecadal salinity variability or preinstrumental trends because of significant implications to ocean thermohaline circulation [*Boyle*, 2000; *Häkkinen*, 1999; *McManus et al.*, 2004; *Schmidt et al.*, 2004], and global change [*Boyle*, 2000; *Broecker*, 1994; *McManus et al.*, 2004; *Schmidt et al.*, 2004].

[3] The Salinity Maximum Waters (SMW) of the North Atlantic, generally located between 15°–30°N and 20°–50°W (Figure 1), have reportedly increased in salinity as much as 0.4–0.5 practical salinity units (psu) over the last 40–50 years [*Curry et al.*, 2003; *Rosenheim et al.*, 2005]. This increase might appear slight, and does not apply to the entire Atlantic (such as north of 40°N, where there has been a decrease in salinity [*Curry et al.*, 2003]), but it represents a significant change in the freshwater input, or evaporation minus precipitation (E – P) balance over large sections of the Atlantic.

[4] Situated in the region of the strongest E – P gradients [*Johnson et al.*, 2002; *Schmitt et al.*, 1989], the Cape Verde Islands are an excellent location to study such salinity changes. Strong winds from the African continent, influenced by the North Atlantic Oscillation (NAO), create a steep gradient in salinity increasing to the north-northwest of the archipelago. The corals here display a strong seasonal $\delta^{18}O$ signal from the subannual samples, and calibrations of the monthly $\delta^{18}O$ values to the monthly SST record [*Moses et al.*, 2006] produce slopes in the range of other published values [*Leder et al.*, 1996; *Weber and Woodhead*, 1972; *Wellington and Dunbar*, 1995]. However, when mean annual $\delta^{18}O_{coral}$ values are calibrated to annual SST means, the relationships are nonsignificant because of excess variability not explained by SST alone [*Moses et al.*, 2006], something that can explained by variable salinity.

[5] Here we show that century length proxy records from corals in the eastern tropical North Atlantic are dominated by multidecadal variations in salinity which have been influenced by SST and the NAO over the course of the 20th century. The forcing by the NAO appears to be nonstationary, perhaps in a spatial sense, on the century scale and changes its relationship with salinity variability between the time before and after 1930–1931. During the early period, salinity variability persists by upwelling as the NAO influence strengthens in the Cape Verde Islands. We propose that interaction between the NAO and SST govern changes in regional upwelling, and the size, shape, and position of the Salinity Maximum Waters of the North Atlantic.

2. Methods

[6] The two cores of the zooxanthellate coral, *Siderastrea radians*, discussed in this work, SAL-4 and SAL-6, were collected only about 20 m from each other at Pedra de Lume

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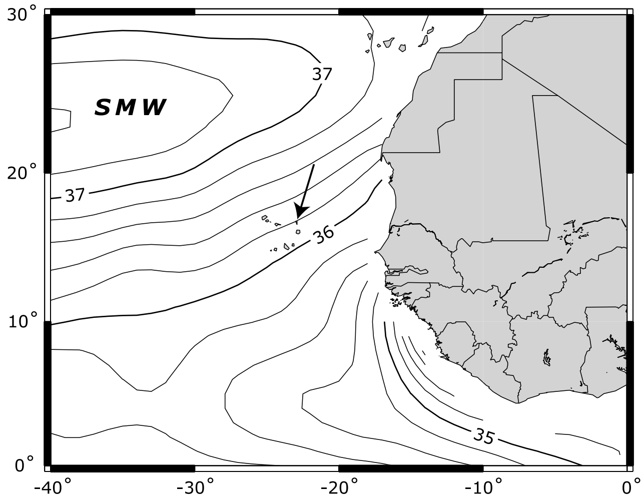

Figure 1. Surface salinity map of the eastern tropical North Atlantic. Contours are surface salinity from the World Ocean Atlas 2001 [*Conkright et al.*, 2002]. Contour interval = 0.2 psu. Arrow indicates the island of Sal in the Cape Verde archipelago, where the corals were cored at Pedra de Lume. Note the strong salinity gradient across the archipelago. SMW = Salinity Maximum Waters.

(16°45.6′N, 22°53.3′W) on the island of Sal in the Cape Verde Islands (Figure 1) at a depth of 4–6 m. These corals have annual extension rates of about 1.0–1.5 mm yr^{-1} [*Moses et al.*, 2006] on the basis of sclerochronology [*Hudson et al.*, 1976; *Knutson et al.*, 1972] and the annual cycle in $\delta^{18}O$. Corals were sampled for stable isotope analysis with a New Wave™ micromill by continuously milling across the thecal wall between two corallites. Setting the step increment of the micromill to 104 μm maintained a sampling rate of 10–15 samples yr^{-1} despite the subtle changes in growth rate within each coral and from coral to coral. The drilling was performed in a direction perpendicular to the axis of growth at each step increment, progressing parallel to the axis of growth from step to step. Isotope analyses were performed at the University of Miami, RSMAS Stable Isotope Lab, using a Thermo-Finnigan™ DeltaPlus mass spectrometer coupled to a Kiel device. The isotope values are corrected for the standard interferences and reported in parts per thousand (‰) relative to VPDB (for $\delta^{18}O_{coral}$) and SMOW (for δ_w) in the conventional notation. The high-resolution samples were linearly interpolated to 12 "monthly" values for comparison to climate reconstructions (Figure 2).

[7] The SST data set used in this study comes from the National Climate Data Center (NCDC) Extended Reconstruction SST (ERSST) (version 2) with a monthly 2° × 2° data set spanning January 1854 to present [*Smith and Reynolds*, 2004]. The NCDC ERSST data set for the grid cell centered at 16°N, 24°W was used for the local Sal SST record in the absence of an otherwise complete instrumental record. The NCDC data was calibrated with an in situ thermistor (Hobo Tid-Bit Temp®) over 18 months. Over that time, the root-mean-square (RMS) difference between the gridded data set and the thermistor for monthly means is 0.6°C. The NAO record used is that of *Hurrell* [1995] on the basis of the December–March sea level pressure (SLP) difference between Stykkisholmur, Iceland and the Lisbon, Portugal. A formal long-term record of the Intertropical Convergence Zone (ITCZ) latitudinal displacement does not exist. For the this project, a "dipole" index of the tropical Atlantic, a measurement of the difference in mean SST in a region north of the ITCZ (the tropical North Atlantic index) and the region south of the ITCZ (the tropical South Atlantic index), was used as an indicator of the relative ITCZ latitudinal displacement [*Chiang et al.*, 2002; *Enfield and Mayer*, 1997]. The correlation subperiods of 1910–1930 and 1931–2000 were chosen on the basis of a phase shift seen in the relationship between calculated salinity and the NAO instead of the changes in the relationship between SST and the NAO.

[8] The significance of serial correlations was tested using phase randomization methods [*Ebisuzaki*, 1997]. This phase randomization method takes into account the effective

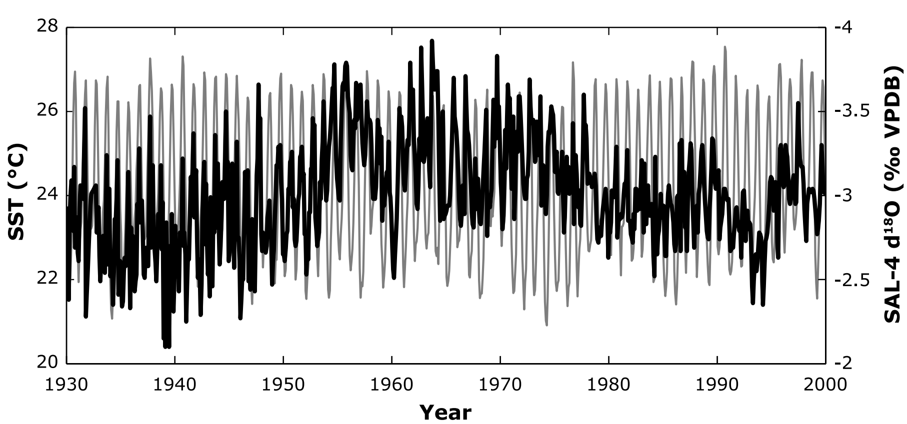

Figure 2. Monthly $\delta^{18}O_{coral}$ record from coral SAL-4 (thick black line; N = 882) and concurrent Cape Verde SST (thin gray line). The scale for $\delta^{18}O_{coral}$ has been inverted in the accepted manner. SST record is from the National Climate Data Center (NCDC) Extended Reconstruction SST (ERSST), version 2 (monthly) (http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.ERSST/.version2/).

degrees of freedom in a correlation, which can be reduced from the nominal degrees of freedom ($N - 2$) as the nature of the data approaches that of a sine curve. All tests for significance were made at the 95% confidence interval.

[9] Standard calibrations were used for SST – $\delta^{18}O_{coral}$ [*Leder et al.*, 1996] and $\delta^{18}O_{water}$ – salinity [*Ganssen and Kroon*, 2000] conversions, and error was propagated through all the calculations [*Schmidt*, 1999]. The reproducibility of an internal lab standard (KBC) through all the runs for this project on the DeltaPlus was ±0.07‰ for ^{TM18}O, and ±0.09‰ for ^{TM13}C. This was included in the error propagation calculations. The full record length of 1900–2002 was truncated to 1910–2000 because of uncertainties in the oldest few years of one core, and the possibility of "edge effects" from mathematical processing.

[10] Oxygen isotope values recorded in the coral skeleton are a function of both SST and the oxygen isotope ratio of the surrounding water (δ_w) [*McCrea*, 1950]. The SST component of $\delta^{18}O_{coral}$ was isolated and removed by using the NCDC ERSST record and according to the SST – $\delta^{18}O_{coral}$ equation [*Leder et al.*, 1996]:

$$T(^{\circ}C) = 5.33 - 4.519(\pm 0.19) \times \left(\delta^{18}O_{coral} - \delta_w\right) \quad (1)$$

[11] The *Leder et al.* [1996] equation was calibrated using Atlantic corals (*Montastraea sp.*), and was used here in this untraditional manner to isolate SST in the absence of an acceptable Sr/Ca – SST calibration for *S. radians*. After removing SST, the remaining residual $\delta^{18}O_{coral}$ that is not explained as a function of SST was attributed to variability in δ_w. Because of the lack of precipitation and mixing of other waters, δ_w around the Cape Verde Islands is controlled by evaporation, and variability in δ_w should represent proportional changes in salinity. For this work, δ_w variability, variability, as calculated in equation (1), was converted to salinity deviations using an equation based on data for the upper 25 m presented by *Ganssen and Kroon* [2000]:

$$S = 1.73(\pm 0.19)\delta_w + 35.20(\pm 0.08) \quad (2)$$

[12] The end result of the error propagation [*Schmidt*, 1999] (including error from analytical machines, instrumental (NCDC) SST, and equations (1) and (2)) is a constant error is cumulative such that the error in the final measurement of salinity deviation is estimated as σ_{sal} = ±0.31 psu. This final estimation of σ_{sal} is reflected in the error envelopes displayed with salinity records from these corals. The variables involved in the calculation of the error envelope are constant in relation to the component equations used, so they do not vary relative to an individual coral record or between corals in this project.

3. Results of Salinity Determination from $\delta^{18}O_{coral}$

[13] After removing the SST portion of the $\delta^{18}O_{coral}$ signal using a standard SST – $\delta^{18}O_{coral}$ calibration [*Leder et al.*, 1996], the residual δ_w displays a systematic pattern of decadal to multidecadal variability over the period from 1900 to 2000 (Figure 3). The oscillation in δ_w represents proportional changes in the regional E – P balance, reflected in salinity differences (ΔS), thus relating the δ_w residuals to changes in the salinity around Cape Verde. About 76% of the year-to-year total variability of $\delta^{18}O_{coral}$ is accounted for by changes in salinity, with the remaining 24% being attributed to year-to-year changes in SST (ΔSST). The RMS value of the year-to-year ΔS based on δ_w is 0.1 psu, with a maximum range of salinity variability of ~1.1 psu, and $\partial S/\partial t$ as high as ±0.5 psu decade^{-1}. The total variability of the salinity record is dominated evenly by the multidecadal and decadal oscillations, rather than the interannual frequency. The multidecadal (>25 year) spectrum accounts for about 43% of the total variance in salinity, and the decadal (9–11 year) spectrum contributes 38% of the total variance in salinity. From the 1950s to the 1990s, the average ΔS is +0.1 psu decade^{-1}, similar to values reported for the western tropical North Atlantic by instrumental data [*Curry et al.*, 2003] and sclerosponge proxy records [*Rosenheim et al.*, 2005] in the western tropical North Atlantic. Regional or basin-scale changes in the hydrologic cycle have been suggested to influence the advection of high-salinity waters over century or longer timescales [*Johnson et al.*, 2002; *Schmidt et al.*, 2004]. However, over decadal to multidecadal timescales, and in the absence of substantial precipitation or hydrologic changes around the Cape Verde Islands, these changes in salinity could be more likely attributed to a change in evaporation driven by SST and wind stress.

[14] Over the period from 1910 to 2000, using data filtered by a 5-year moving average, the salinity record from coral SAL-6 displays a significant correlation of r = 0.52 ($p < 0.01$) with SST in the Cape Verde Islands (Table 1). The salinity record also correlates positively with the two major North Atlantic SST indices, the tropical North Atlantic index (TNA) [*Enfield et al.*, 1999] and Atlantic Multidecadal Oscillation (AMO) [*Enfield et al.*, 2001; *Schlesinger and Ramankutty*, 1994] (r = 0.58 and r = 0.64, respectively; $p < 0.01$ for both; Table 1).

[15] The coral salinity record correlates significantly with the annual mean relative north-south displacement of the ITCZ (r = 0.32; $p < 0.01$). However, the derived salinity record has no correlation with Cape Verde precipitation (which has a record limited to the period from 1951 to 1998) (Table 1). Over the entire period from 1900 to 2000, the coral salinity record also shows no significant response (r = 0.19; p = 0.07) to regional dynamics of SLP, which are dominated across the North Atlantic by the NAO.

4. Discussion

4.1. Atlantic Sea Surface Temperature

[16] The TNA, tropical South Atlantic index (TSA), and the AMO are indices of sea surface temperature anomalies (SSTAs) over different ranges of the Atlantic Ocean. The TNA is an index of the SSTA over the width of the Atlantic (including the Cape Verde Islands) from 5° to 25°N [*Enfield et al.*, 1999], while the AMO is an SSTA index over the entire North Atlantic from the equator to 70°N [*Enfield et al.*, 2001; *Schlesinger and Ramankutty*, 1994]. The TSA

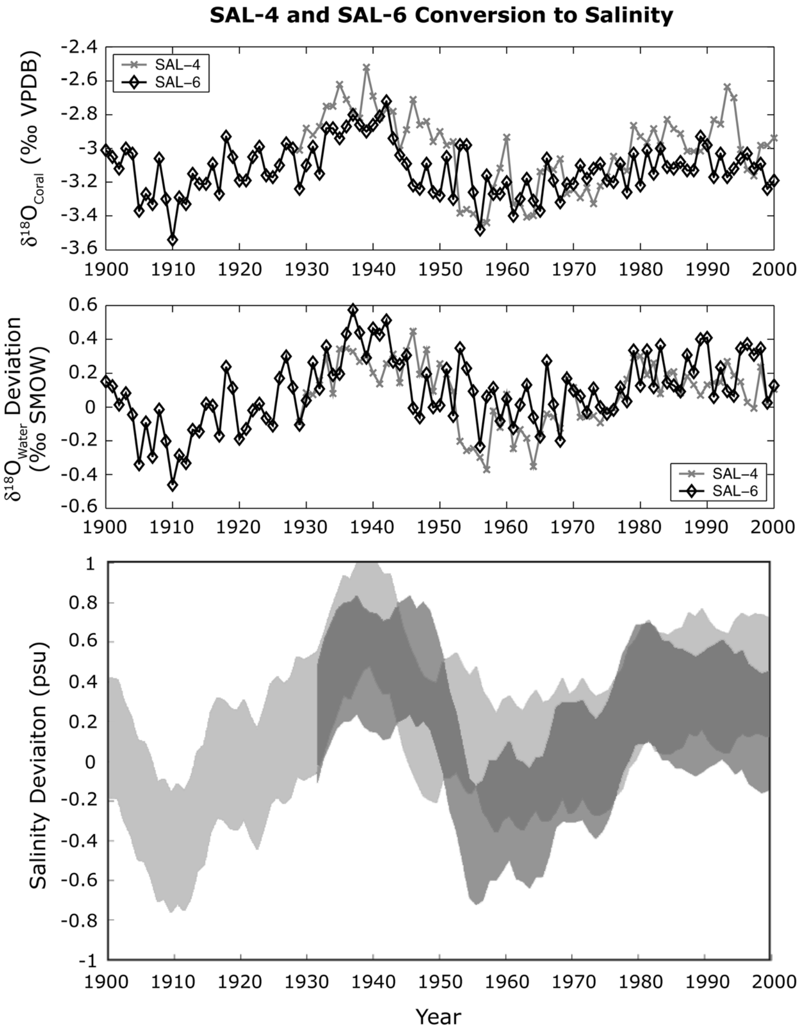

Figure 3. Salinity reconstruction from $\delta^{18}O_{coral}$ for corals SAL-4 and SAL-6. (top) Annual $\delta^{18}O_{coral}$ records for the two corals. (middle) The δ_w values for the two corals are calculated by removing the SST contribution to $\delta^{18}O_{coral}$. Correlation between the two corals is significant ($r = 0.49$, $N = 74$, $p < 0.001$), supporting the theory that δ_w variations account for the apparent lack of correlation to SST at the year-to-year scale. (bottom) Reconstructed salinity from δ_w and corresponding propagated error envelopes (σ_{sal}) for the two corals (SAL-4 in dark gray and SAL-6 in light gray). Salinity scale is normalized to modern climatology.

represents the southern hemisphere counterpart to the TNA from the equator to 20°S [*Enfield et al.*, 1999]. The AMO is perhaps the most significant multidecadal SST oscillation in the Atlantic, with a recognized periodicity of 65–70 years with an amplitude of about 0.4°C [*Enfield et al.*, 2001; *Schlesinger and Ramankutty*, 1994].

[17] Over the period of interest, from 1910 to 2000, using the data from the 5-year moving average, the TNA and the AMO correlate with each other at $r = 0.83$ ($p < 0.01$), while the TSA and the AMO show no significant correlation. However, changes in the phases and strengths of the TNA and the TSA relative to each other and the AMO, result in variable correlation coefficients with time on a decadal to multidecadal scale. As expected because of its location in the tropical North Atlantic, Cape Verde SST correlates significantly with both the TNA and the AMO ($r = 0.73$ and $r = 0.59$, respectively).

[18] Warmer SSTs, associated with the positive phase of the TNA (TSA) are associated with a northward (southward) displacement of the Intertropical Convergence Zone (ITCZ), which in turn is linked to decreased trade wind speed and increased regional convection and precipitation [*Andreoli and Kayano*, 2004; *Enfield et al.*, 1999; *Nobre and Shukla*, 1996]. Independent of wind speed, the elevated SST would increase evaporation, but this is typically countered by an associated increase in precipitation from enhanced convection. However, the possible freshening of surface waters from the increased precipitation does not occur because of the excess evaporation (E $\gg$ P) around the Cape Verde Islands. Thus a positive relationship between Cape Verde SST and salinity could be expected as increased

Table 1. Matrix of Correlation Coefficients for Indicated Components[a]

	$\delta^{18}O_c$	Salinity	CV SST	CV Precip	TNA	TSA	ITCZ	NAO	AMO
				SAL-6 1910–2000					
$\delta^{18}O_c$		**0.29**[b]	−0.15	**−0.39**	**0.35**	**0.33**	−0.07	0.10	**0.32**
Salinity			**0.52**	−0.23	**0.58**	0.16	**0.32**	0.19	**0.64**
CV SST				**0.42**	**0.73**	**0.28**	**0.31**	**−0.32**	**0.59**
CV precip					**0.46**	−0.21	**0.37**	**−0.44**	**0.52**
TNA						**0.38**	**0.39**	**−0.50**	**0.83**
TSA							**−0.70**	0.02	0.20
ITCZ								**−0.41**	**0.46**
NAO									**−0.39**
AMO									
				SAL-6 1910–1930					
$\delta^{18}O_c$		−0.22	**0.40**	NaN[c]	**0.56**	**0.52**	−0.13	**−0.39**	**0.53**
Salinity			0.30	NaN	**0.49**	**−0.79**	**0.92**	**−0.49**	0.19
CV SST				NaN	**0.62**	−0.30	**0.66**	−0.05	**0.63**
CV precip					NaN	NaN	NaN	NaN	NaN
TNA						0.19	**0.44**	**−0.50**	**0.85**
TSA							**−0.79**	−0.18	0.29
ITCZ								−0.15	0.26
NAO									−0.09
AMO									
				SAL-6 1931–2000					
$\delta^{18}O_c$		**0.35**	**−0.67**	**−0.39**	0.21	0.19	−0.03	**0.28**	0.20
Salinity			0.22	−0.23	**0.35**	−0.04	0.22	**0.66**	**0.57**
CV SST				**0.42**	**0.35**	**−0.35**	**0.45**	−0.19	0.20
CV precip					**0.46**	−0.21	**0.37**	**−0.44**	**0.52**
TNA						**−0.34**	**0.74**	**−0.44**	**0.69**
TSA							**−0.88**	**0.44**	**−0.50**
ITCZ								**−0.52**	**0.70**
NAO									**−0.28**
AMO									

[a]CV SST = Cape Verde SST (NCDC); CV Precip = Cape Verde precipitation record; TNA = tropical North Atlantic index (SST); TSA = tropical South Atlantic index (SST); ITCZ = Intertropical Convergence Zone; NAO = North Atlantic Oscillation; AMO = Atlantic Multidecadal Oscillation (SST). All correlations were performed using data filtered with a 5-year moving average.
[b]Bold values are significant at the 95% confidence interval.
[c]NaN indicates no data.

SSTs would lead to enhanced evaporation and increased salinity. In fact, salinity and the TNA, Cape Verde SST, and the AMO are significantly positively related over the entire record (r = 0.58, r = 0.52, and r = 0.64, respectively; $p <$ 0.01).

4.2. Regional Wind Speed

[19] The NAO is known to have a large influence on winds over Europe and the North Atlantic, especially in strong NAO winters, exerting a dramatic control on the E − P balance [*Hurrell*, 1995; *Marshall et al.*, 2001]. The NAO is measured as the difference in SLP between the Icelandic Low and the Azores High, is strongest in the boreal winter with the annual value typically calculated from December to March, and is seen to have a strong decadal-scale variability [*Hurrell*, 1995; *Hurrell and van Loon*, 1997]. The NAO has also been hypothesized by some to be the most significant climate signal in the North Atlantic, being strong enough to interact significantly with the Meridional Overturning Circulation (MOC), which is responsible for transport of heat to higher latitudes [*Marshall et al.*, 2001].

[20] The speed of trade winds (easterlies) in the eastern tropical Atlantic relies on the phase and strength of the NAO for its primary mode of variability [*Eden and Jung*, 2001; *Hurrell and van Loon*, 1997], but is also affected by the TSA [*Enfield*, 1996]. During strong NAO winters, the westerly winds on the north side of the Azores High can be as much as 8 m s^{-1} faster than in weak NAO winters [*Hurrell*, 1995]. The easterlies on the south side of the same anticyclone affect the Cape Verde Islands and the eastern tropical North Atlantic in general. From the other side of the ITCZ, the positive (warm) phase of the TSA has been demonstrated to be associated with increased wind stress in the easterlies north of the ITCZ [*Enfield*, 1996].

[21] Increases or decreases in wind speed should affect both SST and salinity through corresponding changes in evaporation. Indeed, above normal SSTs in the tropical North Atlantic are often associated with weakened easterlies [*Enfield and Mayer*, 1997]. An increase in the NAO implies a stronger Azores High and increased easterly flow over the Cape Verde Islands, leading to a cooling of SST and an increase in salinity. Application of an 11-year moving correlation to the NAO and Cape Verde SST, to examine year-to-year relationships on a decadal scale, shows that in addition to this expected inverse relationship, marked periods of positive correlation occur over the period from 1900 to 2000 (Figure 4).

4.3. Water Masses

[22] Considering the location of the Cape Verde Islands near the southeastern fringe of the SMW, the salinity could be affected by perturbations in the size, shape, or position of

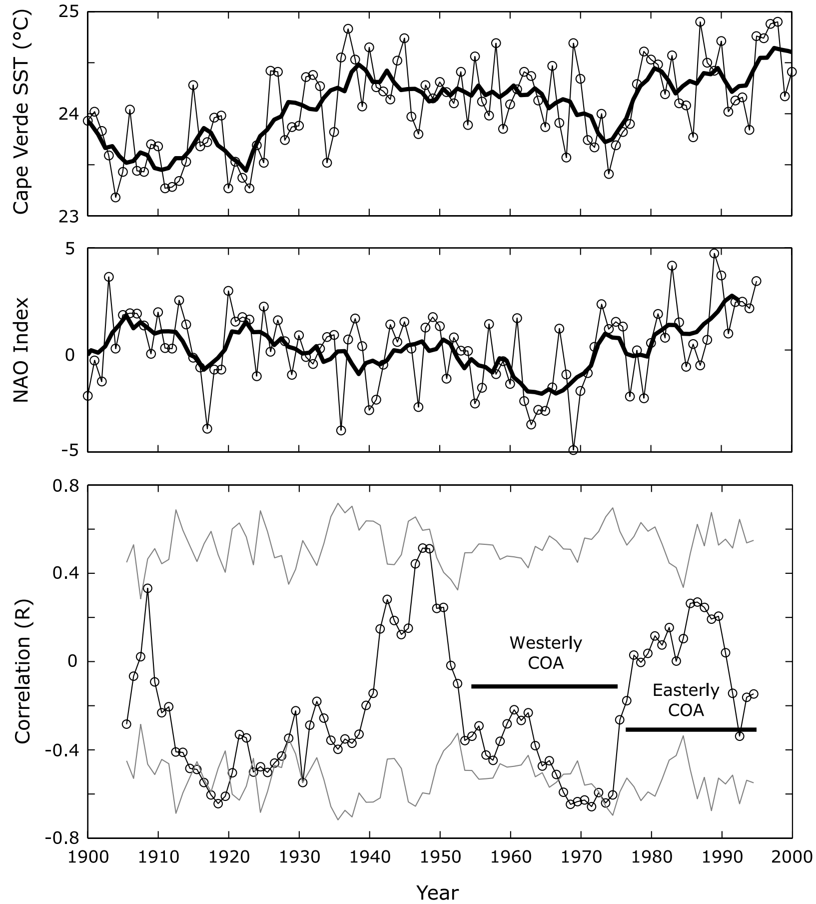

Figure 4. Relationships between the NAO and Cape Verde SST. (top) Annual Cape Verde SST (NCDC ERSST, version 2 (annual)). (middle) Annual NAO record from *Hurrell* [1995] (thin line with circles is annual value; thick lines are 5-year point-centered moving average). (bottom) An 11-year point-centered moving correlation (circles) of the NAO with Cape Verde SST shows dramatic and abrupt changes in the phase of the relationship between the NAO and SST over the last century. The thin gray lines represent the 95% confidence interval. The solid black lines labeled with the relative displacement of NAO centers of action (COA) are as reported from *Jung et al.* [2003].

the SMW. Certainly, only a small enlargement (contraction) in size or a slight displacement of the SMW to the southeast (northwest) of the climatological position would be sufficient to impact the annual average salinity of the Cape Verde Islands. Despite implications such changes in size or location of the SMW would have for the formation of the high-salinity waters and transport of critical heat to northern latitudes [*Boyle*, 2000], studies of the Atlantic SMW have not addressed the possibility of such a migration or change in size [*Blanke et al.*, 2002; *Curry et al.*, 2003].

[23] Additionally, the location of the Cape Verde Islands on the eastern side of the North Atlantic, on the southbound limb of the cyclonic North Atlantic Gyre, is in a zone prone to regional upwelling. The relatively shallow thermocline and halocline bring cooler, fresher waters close to the surface expression of the SMW in the eastern tropical North Atlantic. Reports have confirmed the periodic occurrence of such regional upwelling in the eastern tropical North Atlantic in response to changes in regional wind stress [*Santos et al.*, 2005].

4.4. Eastern Tropical North Atlantic Salinity Over the 20th Century

[24] Between 1910 and 2000, variability in the relevant SST indices can account for between 27 and 41% of the variability seen in the geochemical record of salinity recovered from the coral skeletons. For the period from 1910 to 2000 the strongest correlation of the coral salinity with any climate index is with the AMO ($r = 0.64$; $p < 0.01$; Table 1). Over the entire period, the recovered salinity record correlates with the TNA at $r = 0.58$ ($p < 0.01$), and with local Cape Verde SST slightly less ($r = 0.52$; $p < 0.01$). This makes some intuitive sense, because of the smoothing effect with each increase in incorporated index area. The AMO has lower variability in the interannual spectrum compared to the TNA which has less variability in the interannual spectrum than the Cape Verde SST record. The strength and significance of correlations between SST indices and the recovered salinity record vary over multidecadal periods. For example, the correlation of coral salinity records with the TNA is stronger in the period between 1910 and 1930

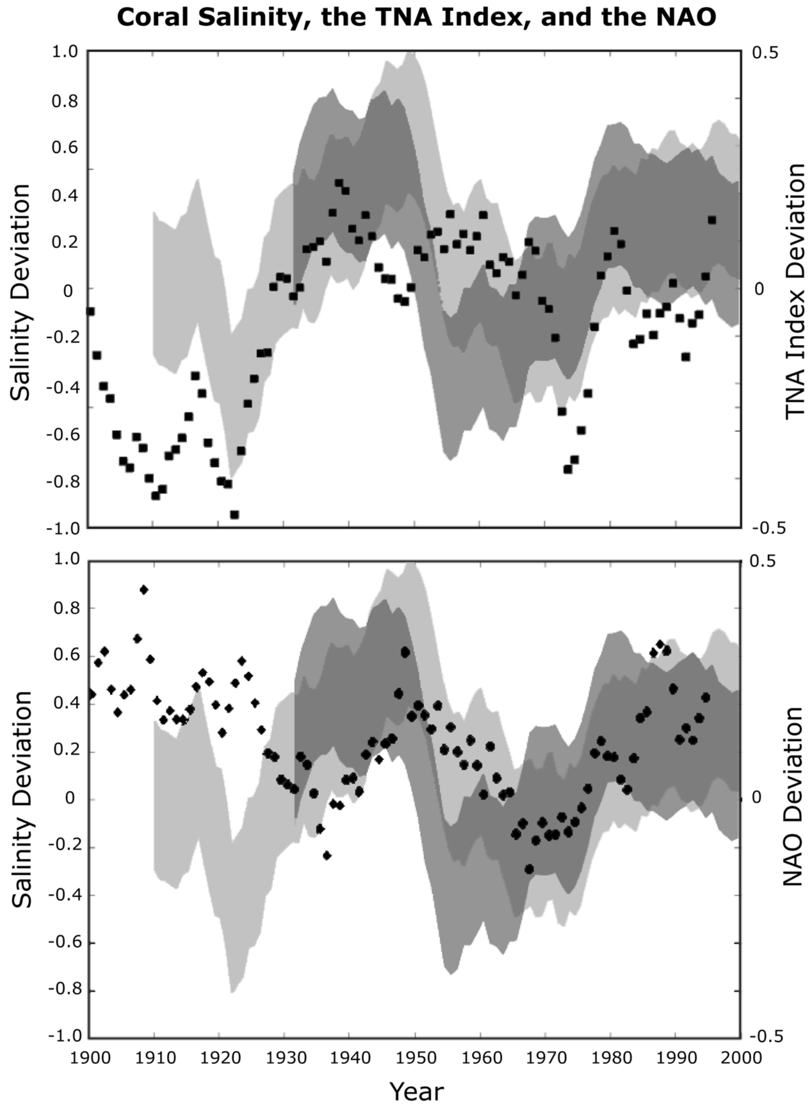

Figure 5. Comparison of reconstructed coral salinity records of SAL-4 and SAL-6 with the TNA and the NAO. SAL-4 is the dark gray envelope; SAL-6 is the light gray envelope. (top) Coral salinity records with the TNA (squares). (bottom) Coral salinity records with the NAO (diamonds). NAO can be seen to continue to track the TNA during the early part of the century, but it is decoupled from the NAO during that period. Envelopes represent the coral salinity data and the propagated error (σ_{sal}) from the series of calculations involved. Correlation coefficients are reported in Table 1. Salinity scale is normalized to modern annual climatology [*Conkright et al.*, 2002; *Levitus et al.*, 1994].

(r = 0.49), a prolonged cool period, than from 1931 to 2000 (r = 0.35), but is significant and of the same phase in both sections of the record. The AMO and Cape Verde SST both lose their significant correlation with the coral salinity record during the period from 1910 to 1930. Overall, the TNA seems to be the most consistent predictor of salinity near the Cape Verde Islands, explaining 12–34% of the recorded variability over the 20th century (Figure 5).

[25] Wind patterns, and by extension evaporation, in the eastern tropical North Atlantic are generally governed by the NAO and the TSA [*Enfield*, 1996; *Hurrell*, 1995; *Marshall et al.*, 2001]. Comparison of the NAO with the calculated salinity deviation demonstrates a nonsignificant correlation (r = 0.19) over the entire period from 1910 to 2000 (Figure 5; Table 1). However, from 1931 to 2000 the NAO has a significant correlation (r = 0.66; p < 0.001), explaining 44% of the variability in the calculated ΔS. The change in NAO correlation to calculated salinity from prior to 1930 and after 1931 could imply century-scale non-stationarity in the influence of the NAO on eastern tropical North Atlantic salinity, which would agree with previously described nonstationarity over several multicentury proxy records of the NAO [*Appenzeller et al.*, 1998; *Luterbacher et al.*, 1999].

[26] Also noteworthy is the fact that between 1910 and 1930 the TSA displays a significant negative correlation

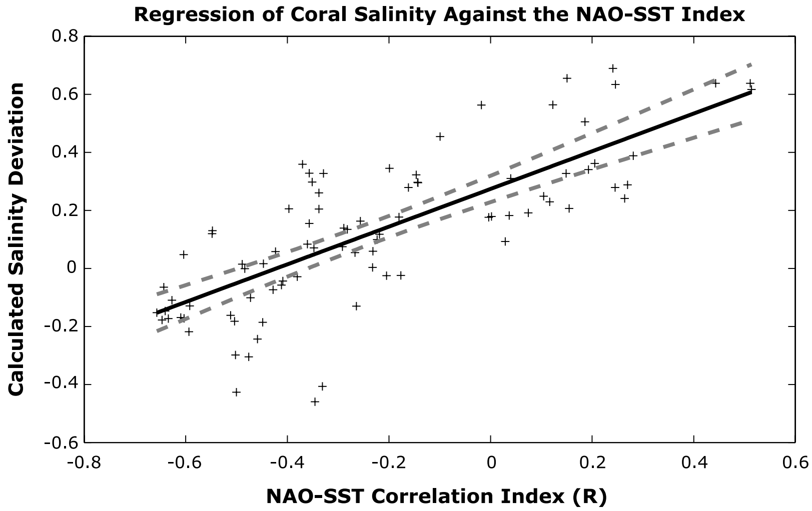

Figure 6. Regression of coral salinity against the NAO – SST correlation index. When converted to an index, the moving correlation between NAO – SST explains 60% of the variance (r = 0.77) in the calculated salinity values. $\Delta S = 0.65(\pm 0.12) \times \mathrm{Idx} + 0.27(\pm 0.05)$, where Idx is the NAO – SST correlation index value. Dashed gray lines represent the 95% confidence interval for the regression line. Salinity scale is normalized to modern annual climatology [*Conkright et al.*, 2002; *Levitus et al.*, 1994].

with calculated salinity ($r = -0.79$; $p < 0.01$), whereas it shows no significant correlation over the entire record or in the period after 1930. This parallels the increase in significance of the positive correlation between the TNA and calculated salinity during the same period, as the ITCZ is displaced further southward than normal, anomalously cooling the tropical North Atlantic and warming the tropical South Atlantic. The cross equatorial connection between salinity near the Cape Verde Islands and the TSA stems from the increased easterly wind stress across the tropical North Atlantic associated with unusually warm SSTs south of the ITCZ [*Enfield*, 1996].

[27] Over the time frame from 1931 to 2000, these coral proxy records from the eastern tropical North Atlantic match records of salinity from sclerosponges deeper in the western tropical North Atlantic [*Rosenheim et al.*, 2005]. The tropical and trans-Atlantic influence of the NAO is demonstrated through the similarity in salinity records produced from different sides of the ocean (*Rosenheim et al.* [2005] and this work). Waters from the SMW sink and are transported zonally to the west [*Zhang et al.*, 2003] where their geochemical characteristics are recorded by the deeper sclerosponges ($\sim$150 m) reported by *Rosenheim et al.* [2005].

[28] The pattern of salinity variability is not only related to SST or the NAO, but also influenced by the phase and strength of the NAO – SST relationship. The pattern of correlation between the NAO and Cape Verde SST, in terms of relative phase and strength, explains 60% of the variance in salinity over the 20th century (Figure 6). Since the two controls on evaporation (thus salinity) are SST (in the form of the TNA, AMO, and Cape Verde SST) and wind speed (as the NAO and TSA), it makes sense that a combination of the two could create a predictive index for salinity. Such an "NAO – SST index" can be created from the correlation coefficients from the moving correlation between the NAO and Cape Verde SST shown in the bottom panel of Figure 4.

[29] During the period from 1931 to 2000 the NAO shows a nonsignificant correlation with SST near the Cape Verde Islands (Table 1). Spatial regressions of SST on the NAO reveal that the change in the previously significantly negative relationship between the NAO and SST recorded in the Cape Verde Islands is actually a regional change in this relationship (Figure 7). This change in the relationship between SST and the NAO would have implication for changes in winds and evaporation, and ultimately, salinity.

[30] There is a notable reversal of the otherwise positive NAO – salinity correlation prior to the early 1930s (Figure 8). Instead of the strong positive relationship seen between the 1930s and the end of the record, the NAO – salinity correlation of $r = -0.49$ ($p < 0.01$) between 1910 and 1930 is significant, but of the opposite sign. The NAO – SST relationship is also strongly negative in this time over the whole region [*Walter and Graf*, 2002]. However, during this same time, the correlation between SST and salinity shows no change in phase. At longer correlation intervals (13–15 years), the phase change between the NAO and salinity shifts to the right toward 1940, and at shorter correlation intervals (7–9 years), it shifts to the left toward 1930.

[31] The change in the NAO – salinity relationship is similar to a decoupling reported in some SST-forced atmospheric models that failed to reproduce regional decadal-scale trends in the NAO prior to about 1950, and particularly so in the 1920s [*Paeth et al.*, 2003, p. 66, Figure 2c]. This so-called "decoupling" seen here between SST and the NAO and by others [*Paeth et al.*, 2003; *Rodwell et al.*, 1999] is actually better described as a phase reversal to a negative, rather than positive, correlation between the NAO and SST between 1900 and 1930.

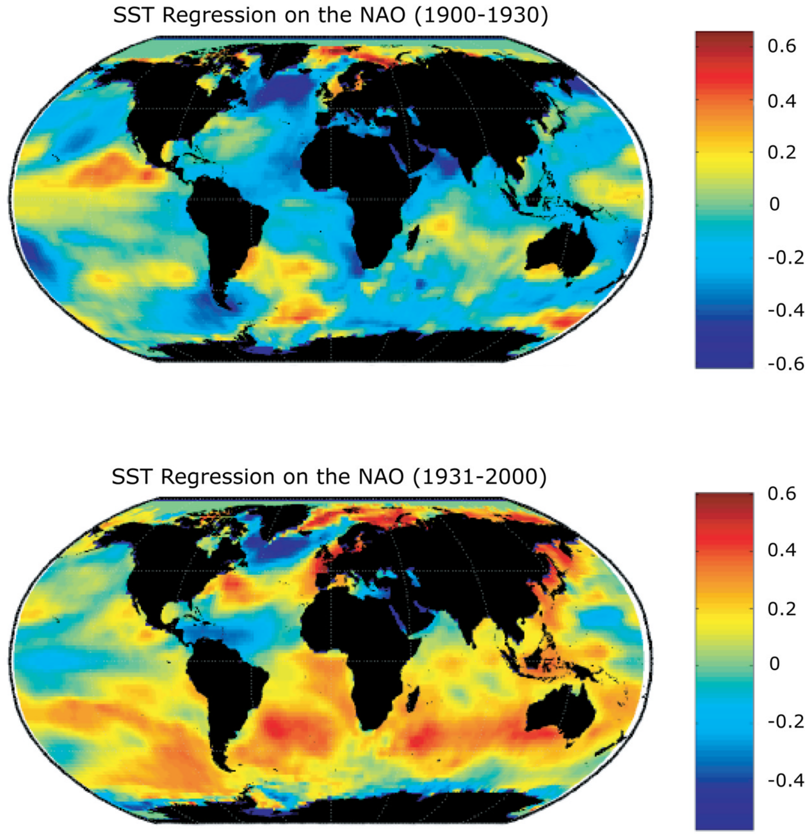

Figure 7. Spatial correlations of global SST on the NAO. Colors are correlation coefficients. (top) Spatial correlation of global SST on the NAO for the period from 1900 to 1930. Note the uniform negative correlation around the entire north and eastern sides of the basin, including the Cape Verde Islands. (bottom) Spatial correlation of global SST on the NAO for the period from 1931 to 2000. In this later part of the record the NAO shows a dramatically different relationship with SST. Notice the difference in the strength of correlation in the eastern tropical North Atlantic between the two time periods.

[32] The position of the ITCZ correlates significantly with the record of salinity calculated from the coral over the entire period from 1910 to 2000 ($r = 0.32$; $p < 0.01$). This implies that northward displacements of the ITCZ are associated with warmer SSTs and saltier surface waters around the Cape Verde Islands. Considering that increases in precipitation are usually associated with proximity to the ITCZ, the observation that salinity and northward climatology of the ITCZ are directly correlated seems illogical at first. However, the evaporation in the Cape Verde region exceeds the precipitation from the ITCZ, leaving a condition of net evaporation. In additional support of this, coral records of salinity show no correlation with Cape Verde precipitation over the extent of the precipitation record (available for 1951–1998).

[33] The correlation between the ITCZ and the record of salinity calculated from the coral during the time from 1910 to 1930 suggests that almost 85% of the variability in salinity during the early 20th century was explained by the relative displacement of the ITCZ (Table 1). However, this is likely an artifact of the way the relative north-south

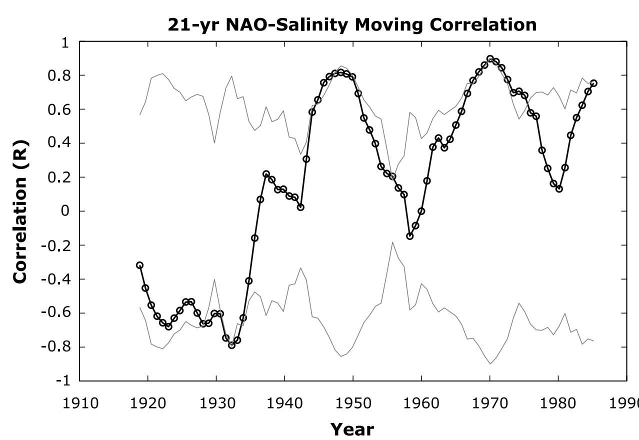

Figure 8. Moving correlation of the NAO and salinity. This 21-year point-centered moving correlation (circles) of the NAO and SAL-6–calculated salinity emphasizes the drastic phase shift in the relationship during the mid 1930s. Gray lines represent the 95% confidence interval.

displacement of the ITCZ at the annual scale was calculated here by subtracting the TSA from the TNA. More accurately, perhaps, this suggests that during the first three decades of the 1900s, the TNA and TSA relationship was closely tied to eastern tropical North Atlantic salinity. However, this relationship breaks down in the period from 1931 to 2000, when both the ITCZ and TSA show no significant relationship to salinity variability.

4.5. One Possible Theory for the Observed Salinity Variability

[34] The logical expectation is that areas of ocean surface near the Cape Verde Islands which are exposed to NAO driven winds will experience both cooler SSTs and higher salinities during strong positive NAO periods as a result of increased evaporation. Thus the observed cool period between 1910 and 1930 in Cape Verde SST and the TNA is exactly as expected relative to the corresponding prolonged strong NAO. However, in contrast, the salinity recorded in the coral skeletal geochemistry indicates a decrease in salinity, rather than the expected increase, over that same time.

[35] In the period from 1910 to 1930, when the correlation between salinity and the NAO reverses its phase, the TNA maintains the significant positive correlation with salinity ($r = 0.49$; $p < 0.01$) which it displays over the entire record, relating cooler SSTs in the eastern tropical North Atlantic to decreased salinity. The period from about 1900 to the 1930s represents a time when the ITCZ was displaced further to the south (on an annual average) for a prolonged period of time. The result was a time of prolonged cooler than average SSTs in the eastern tropical North Atlantic, and warmer SSTs in the tropical South Atlantic. Strong positive (warm) periods in the TSA are associated with stronger than normal trade winds in the tropical North Atlantic [*Enfield*, 1996]. The implication is that the strong positive TSA and the simultaneous strong NAO would have worked in unison to increase the speed of easterlies over the Cape Verde Islands for the majority of the time from 1900 to 1930.

[36] The location of the Cape Verde Islands near the eastern border of the tropical North Atlantic renders them subject to a regional shallowing of the thermocline. This position also corresponds with regional upwelling resulting from the cyclonic circulation of the North Atlantic Gyre. Both the local thermocline and halocline are located between the surface and 200 m. Between the surface and 200 m depth, temperature plummets 12.1°C and salinity decreases by about 0.6 psu (annual climatology) [*Conkright et al.*, 2002].

[37] A prolonged increase in the easterlies, such as inferred during the 1910–1930 period, could conceivably push the surface expression of the SMW westward, along with the associated warm SSTs. In its place, the cooler, fresher, deeper waters could upwell around the Cape Verde Islands. This scenario is supported by reports of increased regional upwelling between 12° and 43°N in the eastern North Atlantic during strong NAO periods [*Santos et al.*, 2005]. This theory could explain both the expected cooler SSTs as a combined effect of evaporation and upwelling, and the simultaneous decrease in salinity as freshening associated with upwelling. Furthermore, it is likely that any displacement of the SMW to the west or northwest would reduce the effects of the NAO recorded in the coral skeleton as upwelled (lower) salinity is recorded instead.

[38] Movement of the surface expression of the SMW could be linked to east-west shifts in the regional influence of the NAO. The regional domain of the NAO influence is known to undergo a seasonal zonal migration. In the winter (December–February) the strongest SLP gradient, or "centers of action" [*Jung et al.*, 2003], is furthest to the east, and it is furthest west in early fall (August–September) [*Hurrell and van Loon*, 1997]. At interannual to decadal scales, east-west migration of the NAO centers of action has been shown to affect Arctic sea ice transport [*Hilmer and Jung*, 2000] and surface air temperatures [*Jung et al.*, 2003]. One possibility is that if the centers of action are displaced westward for an extended period, then the steep salinity gradient ("salinity front") surrounding the Cape Verde Islands may also withdraw northwestward, removing the direct influence of the SMW, and the observed influence of the NAO, on the coral salinity records.

[39] This theory of the migration of the surface expression of the SMW agrees with the work of *Rosenheim et al.* [2005]. They report no change in the influence of the NAO on the salinity recorded in their sclerosponges before and after 1930. Sinking of high-density SMW waters and zonal transport to the west would bring waters formed at the surface in the SMW to the sclerosponges regardless of the exact location of their surface origin. However, if the surface expression of the SMW moves away from the Cape Verde Islands, the corals there are no longer influenced by the SMW. In conjunction with upwelled cooler and fresher waters, this could possibly explain the differences seen between the sclerosponge records of salinity [*Rosenheim et al.*, 2005] and those of the corals shown here in the early part of the 20th century.

4.6. Implications of Multidecadal-Scale Salinity Variability in the Atlantic

[40] Studies of the NAO have established its relationship with diverse factors such as European winter weather [*Hurrell*, 1995; *Hurrell and van Loon*, 1997], North American weather [*Hurrell*, 1995], Arctic sea ice [*Jung and Hilmer*, 2001], and ecosystem dynamics [*Attrill and Power*, 2002]. Perhaps the most serious implications, however, come from the ocean-atmosphere interaction between SST, the NAO, and ocean circulation. Labrador Seawater (LSW) is one the keys to Atlantic THC because it is the source for the formation of cold, fresh water. The strength of convection in the Labrador Sea and formation of LSW is dependent on the strength of midlatitude westerly winds [*Curry et al.*, 1998; *Dickson*, 1997; *Dickson et al.*, 1996], which are governed by the strength and phase of the NAO. The NAO has also been shown to affect the strength of the Gulf Stream [*Curry and McCartney*, 2001], which is responsible for the transport of ~31 Sv (10^6 m^3 s^{-1}) [*Johns et al.*, 2002] of warm, salty water to the North Atlantic, another major component of Atlantic THC.

[41] The work presented here now supports evidence that the E – P balance and position of the SMW of the tropical North Atlantic are affected by the NAO, coupled with

regional changes in salinity and SST through tropical Atlantic variability, changes in wind speed, and upwelling. Similar to changes in LSW production in the polar region, sudden changes in the salinity and/or SST of the SMW would be reflected as changes in density, affecting North Atlantic MOC in tropical to subpolar latitudes, and potentially affecting global climate.

5. Conclusions

[42] 1. The data show an increase in eastern tropical North Atlantic salinity of +0.5 psu between 1950 and 1990, about +0.1 psu decade^{-1}, similar to reports from instrumental and proxy records from the western tropical North Atlantic, thus providing evidence of basin-wide changes.

[43] 2. Rather than a monotonic secular increase, as indicated by instrumental records, the preinstrumental proxy records presented here demonstrate that salinity in the tropical North Atlantic is periodic on a decadal to multidecadal scale and exhibits similar variability on both sides of the ocean.

[44] 3. Results from Cape Verde corals suggest that eastern tropical North Atlantic salinity responds in accordance with the phase and relative strength of the relationship between regional SST and the NAO over the 20th century.

[45] 4. One possible explanation for the salinity record seen in these coral records prior to 1930 is that a prolonged strong period in the NAO during that time could have led to a northwestward shift of the SMW, perhaps in response to more westward NAO centers of action during that time, increasing regional upwelling and bringing fresher and colder water to the surface in the eastern tropical North Atlantic.

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