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Low frequency variation of sea surface salinity in the tropical Atlantic

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[1] Examination of the observational record suggests that the near-surface waters in the tropical Atlantic underwent a major salinification during the twenty-five year period 1960–1985 at a rate of 0.1 psu/decade. A reversal of this trend has occurred during the most recent decade. While year-to-year changes in salinity are related to precipitation, we attribute decadal changes in salinity at least in part to low frequency changes of winds in the deep tropics and their role in altering both upwelling and possibly, evaporation rates. **Citation:** Grodsky, S. A., J. A. Carton, and F. M. Bingham (2006), Low frequency variation of sea surface salinity in the tropical Atlantic, *Geophys. Res. Lett.*, *33*, L14604, doi:10.1029/2006GL026426.

1. Introduction

[2] A recent examination of Atlantic salinity changes between 1985–99 and 1955–69 by *Curry et al.* [2003] has identified the near-surface tropics as the region having the largest sea surface salinity (SSS) increase with a rate of 0.02 psu/decade. They suggest among the factors responsible for this increase in salinity is increased evaporation associated with the gradual warming of the ocean, occurring in conjunction with freshening at subarctic latitudes. Likewise the data-based survey of *Boyer et al.* [2005] finds Atlantic salinity trends exceeding 0.03 psu/decade at nearsurface levels throughout the subtropics and tropics in both the northern and southern hemisphere over the same decades.

[3] In this study we reexamine the same historical data augmented by some additional data sources and extended through 2004 to determine the spatial and temporal structure of this anomalous nearsurface salinity in relation to the changing surface fluxes. We conclude that SSS in the tropical Atlantic is in fact subject to strong decadal variability that reflects changes in surface forcing and is not well-represented by a linear trend. Our examination indicates that the major salinification of the near surface waters which persisted throughout the 1960s through 1980s has been replaced by a freshening trend in the recent decade. These decadal changes have occurred as the result of changes in the strength of the trade wind-induced entrainment and possibly evaporation. In contrast, shorter year-to-year timescale variations in surface salinity occur in response to changes in entrainment and precipitation.

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2. Data

[4] This study relies heavily on a number of observational data sets. The SSS data for the years 1960–1999 comes from a combination of 5m depth profile and station data from the World Ocean Database 2001 (WOD01) [*Boyer et al.*, 2002] combined (after duplicate data check) with the thermosalinograph data collected by Volunteer Observing Ships and research vessels. This thermosalinograph data set has been maintained, quality controlled, and updated through 1999 by Alain Dessier (see *Dessier and Donguy* [1994] for the archive description). Our data quality control includes range check (values in the range 25–40 psu are retained) followed by a visual check for data inconsistencies. Next, data are grouped into 1° × 1° × 1month bins. For each bin a measure of data scatter is estimated as half of the difference between the upper and lower quartiles. For each grid box the data that differ from the median by more than triple the quartile difference are filtered out. This median filtering is particularly effective in eliminating salinity spikes caused for example by sampling surface freshwater lenses. Beginning in January 2000 we rely on the objective analysis of SSS produced by the French CORIOLIS initiative [http://www.coriolis.eu.org], which includes all the data sources mentioned above, plus observations from the ARGO and PIRATA arrays.

[5] To characterize entrainment and the surface freshwater flux we examine several meteorological data sets. For winds we rely on the NCEP/NCAR monthly reanalysis of *Kalnay et al.* [1996], available on a 2.5° × 2.5° grid throughout our period of interest. The NCEP/NCAR reanalysis is known to be subject to biases in the tropics. Changes in the observing system such as the introduction of satellite observations have also influenced decadal variability. Here we rely on the time series of sea level pressure difference between Brazil and Africa as represented in the Hadley Centre HadSLP2 of *Allan and Ansell* [2006] to provide an independent estimate of the zonal wind variability (following, e.g., *Clarke and Lebedev* [1997]).

[6] Precipitation is provided by the Global Precipitation Climatology Project (GPCP) [*Adler et al.*, 2003] combining satellite microwave and infrared retrievals with gauge data. The GPCP data is available monthly on a 2.5° × 2.5°grid and covers the period since 1979. Precipitation analyses are provided by the NCEP/NCAR and ECMWF ERA40 [*Uppala et al.*, 2005] atmosphere reanalyses for most or all of our period of interest. Neither of these two analyses assimilates precipitation observations. For all data sets we analyze the anomalies from the mean monthly climatology at each grid point.

3. Results

[7] The spatial distribution of time mean SSS in Figure 1a reflects the distribution of time mean net surface freshwater

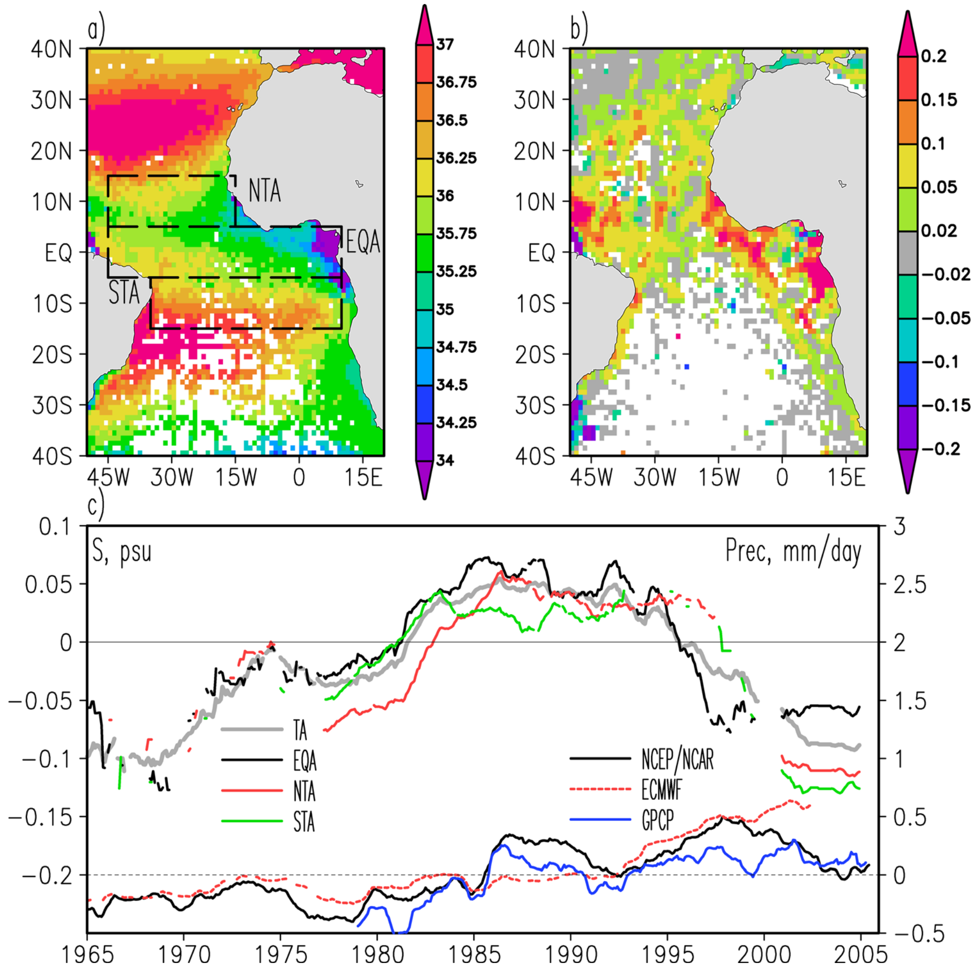

Figure 1. (a) Time mean sea surface salinity (psu); (b) difference between 1980–1999 and 1960–1979 20-year averages; (c) time series of area mean anomaly SSS (psu) averaged over the Equatorial Atlantic (EQA), North Tropical Atlantic (NTA), South Tropical Atlantic (STA), and the tropical Atlantic (TA), which combines the first three areas. Data in Figure 1c are 5-year running means sampled each month. Monthly data are incorporated into the 5-yr average only if number of measurements in a sector exceeds 10. 5-yr averaged precipitation anomalies from NCEP/NCAR, ECMWF/ERA40 Reanalyses, and GPCP are shown in Figure 1c against the right hand y-axis.

flux [*Gordon and Piola*, 1983]. SSS drops below 36 psu in a narrow band of latitudes a few degrees north of the equator due to precipitation in the Intertropical Convergence Zone. Fifteen degrees further north and south of the low salinity band SSS reaches its maxima underneath the dry subsidence zones of the northern and southern subtropics. The influence of some major rivers such as the Amazon in the west is evident [*Pailler et al.*, 1999]. In the eastern Gulf of Guinea low salinity waters partly reflect substantial precipitation and weak advective processes.

[8] We next consider the subseasonal changes in SSS. The difference between the 20 year averages of 1980–2000 and 1960–1979 shows a broad salinification previously noted by *Curry et al.* [2003] and *Boyer et al.* [2005] with the largest increases of up to 0.2 psu occurring in the low salinity regions of the Gulf of Guinea (Figure 1b). However, five-year running averages of SSS also averaged into three 5° latitudinal belts show that the time series contains significant variability on decadal time-scales and in particular that the increasing salinities of the decades 1960–1980 have been replaced with a freshening in the recent decade (Figure 1c). The similarity of the time evolution of salinity in the three latitude bands in the tropical Atlantic indicates that the decadal variability has basin-wide spatial scales. The freshening in the recent decade does occur in conjunction with a strengthening of local precipitation by 0.5 mm/day during the 1990's (most noticeable in the ERA40 analysis). But comparing the records before 1990 shows an opposite tendency (Figure 1c). Next we examine the impact of winds.

[9] The time regression of the tropical Atlantic anomaly SSS time series on winds (Figure 2) shows that strengthening of the easterly winds in the deep tropics is associated with increasing SSS. This relationship could occur both by the salinizing effects of increasing wind-evaporation and by the effects of strengthening entrainment of salty Equatorial Undercurrent water into the mixed layer. Even though upwelling occurs primarily in narrow bands the upwelled salty water is diverged north and south of the upwelling region following four major pathways through the northern and southern branches of the South Equatorial Current [*Grodsky and Carton*, 2002] thus propagating the salty

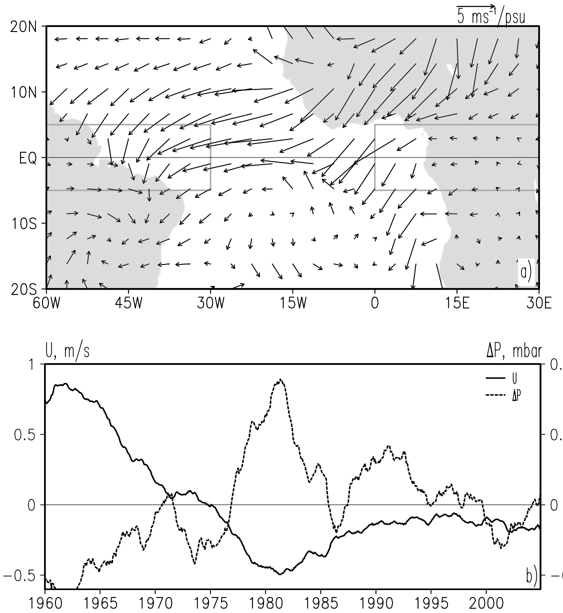

Figure 2. (a) Regression of the time series of SSS averaged over the EQA box (see Figure 1) and NCEP/NCAR Reanalysis near-surface wind during 1960–2004. Strengthened easterlies occur in conjunction with increased salinity. (b) Zonal wind anomaly (U) averaged over the EQA box and the Hadley Center GMSLP2 anomaly zonal mean sea level pressure gradient along the equator estimated as the difference in pressure (ΔP) averaged over the eastern and western boxes shown in Figure 2a.

water over a wide area. In contrast, the available precipitation record is not well correlated with decadal variations in SSS (Figure 1c).

[10] *Boyer et al.* [2005] show that the decadal salinity anomalies are surface intensified (Figure 3b). Thus we focus on mixed layer mechanisms. We begin with by considering the budget for the vertically averaged mixed layer salinity, S, following *Delcroix and Hénin* [1991]. Salinity is also averaged zonally across the basin and with latitude in the deep tropics between latitudes where mean entrainment is positive. Assuming that salinity is nearly uniform horizontally gives us an approximate balance between the time variations of rate of change, entrainment, and net freshwater flux through the surface $\Delta[h\partial S/\partial t + w_e(S - S_{-h})] = \Delta[(E - Prec)S]$ where S_{-h} is salinity at the base of the mixed layer, $z = -h$. The mean entrainment velocity in the equatorial Atlantic $w_e = 0.5$ m/day [*Grodsky and Carton*, 2002] vastly exceeds $E - Prec$ which is a few mm/day in the equatorial Atlantic [*Gordon and Piola*, 1983; *Yoo and Carton*, 1990]. The observed temporal change of salinity of 0.01psu/yr (Figure 1c) suggests that the storage term is small in comparison to entrainment. So we have an expression for the box average salinity variation, ΔS.

$$\Delta S = \frac{\Delta w_e}{w_e}(S_{-h} - S) + \frac{\Delta(E - Prec)}{w_e} S + \Delta S_{-h} \qquad (1)$$

From (1) the SSS increase in response to strengthening of the easterlies in the deep tropics is explained both by increasing evaporation, and by strengthening entrainment of salty water into mixed layer.. Here we evaluate the impact of entrainment on ΔS. Assuming that w_e in the equatorial region is proportional to the zonal wind stress, which follows from simple Ekman divergence, (1) reduces to $\Delta S = 2(\Delta U/U) \cdot (S_{-h} - S)$. Near the equator the sub-mixed layer salinity exceeds the mixed layer salinity by $S_{-h} - S \sim 0.5$ psu and so we find $\Delta S = 0.2$ psu in response to a zonal wind variation of $\Delta U = 1$ m/s (and a mean zonal wind of $U = 5$ m/s) in line with observations shown in Figure 1c.

[11] In contrast, the observed drop of salinity during recent decades would requires strengthening of precipitation by $\Delta Prec = -(\Delta S/S)w_e = 3$ mm/day (using an estimate of $w_e = 0.5$m/day) while the observed increase of precipitation (evaluated by the linear trend in GPCP precipitation during 1980–2002) is only 0.5 mm/day (Figure 1c). The NCEP/NCAR and ERA40 reanalyses show similar and slightly larger increases of 0.5 and 0.8 mm/day, respectively, during the same period. The estimate of $\Delta Prec$ is sensitive to w_e. Our estimate of $w_e = 0.5$m/day, is at the lower boundary of range of previously reported observations of 0.5 to 2.7 m/day (see discussion by *Klein and Rhein* [2004]) and is comparable to the recent estimate of 0.7m/day of *Vauclair et al.* [2004].

[12] Next we consider the source of the interannual variability shown in Figure 3a. On interannual timescales close to the equator both westward winds and precipitation

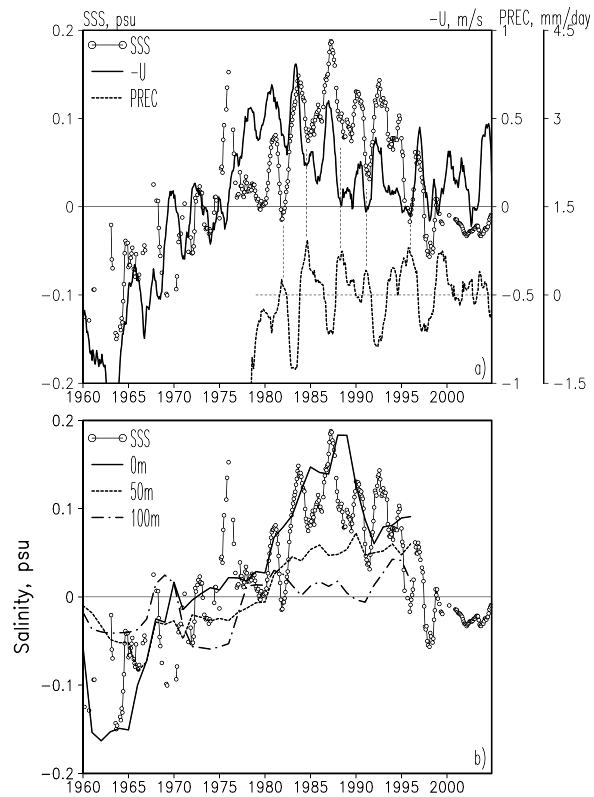

Figure 3. One year running mean anomalies averaged over the EQA box (Figure 1a). (a) Sea surface salinity (*SSS*), NCEP/NCAR reanalysis westward wind ($-U$), and GPCP precipitation (*PREC*). Vertical dotted lines in Figure 3a mark interannual freshenings. (b) Sea surface salinity (open circles) in comparison with the *Boyer et al.* [2005] analysis of salinity at 0m, 50m, and 100m.

are negatively correlated with SSS, both of which follow from the meridional displacement of the ITCZ.

4. Discussion and Summary

[13] In this study we identify both interannual and decadal changes in sea surface salinity. The most striking decadal change is the gradual salinification of the tropical Atlantic by 0.2 psu during the three decades of the 1960s through the 1980s, which increased the density of the mixed layer by an amount equivalent to a 0.8°C drop in SST.

[14] Determining the importance of evaporation and entrainment is made difficult by the changing instrument suite that has been used to monitor winds (the issue is discussed by *Kalnay et al.* [1996]). We investigate the temporal stability of the wind estimates by comparing the zonal wind reanalyses along the equator with the historical zonal sea level pressure gradient (we expect these to be proportional following, e.g., *Clarke and Lebedev* [1997]). We evaluate the pressure gradient based on the time series of mean sea level pressure difference between Brazil and Africa (Figure 2b). The time variation of the sea level pressure gradient is consistent with a strengthening of the equatorial easterly wind during the period from 1960 to the early 1980's followed by a relaxation during the two last decades evident in the NCEP/NCAR reanalysis winds.

[15] Interestingly, these decades were also associated with the drying of the adjacent Sahel region of Northwest Africa. However, while the drying of the Sahel seems to have been the result of reduced and displaced precipitation [*Giannini et al.*, 2003], the salinification of the tropical mixed layer is associated with a strengthening of the trade winds leading to enhanced evaporation and entrainment of higher salinity water. In contrast, during the past decade the oceanic mixed layer has freshened, indicating that mixed layer salinity in the tropical Atlantic is subject to considerable decadal variability.

[16] At interannual time scales 0.1psu variations in SSS are present. These fluctuations do correspond to variations in local precipitation suggesting that at least on interannual timescales oceanic and continental droughts may occur due to similar mechanisms. The time span of tropical precipitation observations is still too limited to assess the impact of precipitation on decadal SSS.

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