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COMPARISON OVER TIME OF TEMPERATURE AND SALINITY AT 24.5°N IN THE ATLANTIC

by

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ABSTRACT

Three sets of hydrographic data are used to examine the changes in temperature and salinity in the subtropical North Atlantic. Transatlantic hydrographic sections at 24.5° N were obtained in October 1957, in August 1981, and finally in July-August 1992.

A general warming was found over the upper 3000 m of the North Atlantic at 24.5°N, over the entire 35-year period. There is high spatial variability in the time changes over most of the upper 1000m. In the layer between 1000 m and 3000 m, a significant warming of 0.1±0.02°C has been observed. The rate of warming is 0.03°C/decade and is nearly steady in the two periods. Significant cooling is found in water deeper than 3000 m in both the North American (-0.027±0.016°C) and the Canary Basins (-0.013±0.005°C).

Introduction

The Atlantic Ocean is the most saline of all the world oceans. It has significant exchange of water masses, heat and salt with several marginal seas, regions in which important transformations of water masses take place. A complex thermohaline-driven circulation moves water masses both northward and southward along its western boundary regions. The 24.5° N transatlantic section is rich in water masses and crosses the North Atlantic in the middle of the subtropical gyre. It provides a census of major intermediate, deep and bottom water masses whose sources are in the Antarctic and far northern Atlantic as well as estimates of the thermohaline circulation of these water masses and of the wind-driven circulation in the upper water column.

The 24.5° N section was measured in 1957 and 1981. The 24.5° N section was one of the sections designated for reoccupation during WOCE (section A-5, WOCE Implementation Plan) which Gregorio Parrilla from the Instituto Español de Oceanografía (IEO), proposed to the Spanish government. The cruise was carried out in July-August of 1992 with the participation of scientists from the Instituto Español de Oceanografía, Woods Hole Oceanographic Institution, and other Spanish and American institutions.

The objective of this research is to quantify the response of the ocean to the warmer atmospheric conditions of the last decade and compare the conditions with previous surveys. Roemmich and Wunsch (1984) reported warming between 700 and 3000 m, and weak cooling above and below those depths. We have done the same calculation for the two periods of comparison 1957-1981 and 1981-1992.

Description of the Data and Methodology

The data used includes three oceanographic cruises on which zonal hydrographic sections at latitude 24.5° N were carried out: the first one in October 1957, by the British R.R.S. *Discovery II* of the National Institute of Oceanography during the International Geophysical Year (IGY) (Fuglister 1960); the second one in August 1981, by the R.V. *Atlantis II* of the Woods Hole Oceanographic Institution (Roemmich and Wunsch, 1985); the last one in July-August 1992 by the Spanish B.I.O. *Hespérides* of the Armada Española, (Chief Scientist Gregorio Parrilla, Instituto Español de Oceanografía) as a Spanish Contribution to the WOCE.

Data for each station were interpolated to a common set of depths. The spacing was of 50 m from surface to 300 m, 100 m down to 1500 m, 250 m reaching 5000 m and 500 m until 6000 m.

Discovery II 1957 IGY data. The cruise was carried out between October 6 and 28, the total number of stations was 38 and the sampling was done using reversing thermometers and Nansen bottles. For the discrete bottle data, vertical linear interpolation was made between adjacent data points for each station to the standard depths.

Atlantis II 1981 data. The cruise began August 11 with the first station on the African Continental shelf at 27.9°N and angled southwestward to join 24.5°N at 24.3°W due to the Sahara war which was close to the coast at 24.5°N. The last station was just east of the Bahamas Bank on September 4. The section was composed of 90 stations sampled by Neil Brown Instrument CTD/O_2.

A 24-bottle rosette water sample was used for CTD/O_2 calibrations (Millard, 1982). Simple averages of nearly continuous CTD/O_2 measurements are made to derive the standard depths values.

Hespérides 1992 WOCE Data. The 1992 24.5° N section was designated A-5 by WOCE (WOCE Implementation plan). We left Las Palmas on July 20 arriving at station number one (24° 29.97'N, 15° 58.08'W) the same day. The section was finished at the Bahamas (24° 30'N 75° 31'W) after 101 stations on August 14. Figure 1.1 gives the location of the stations.

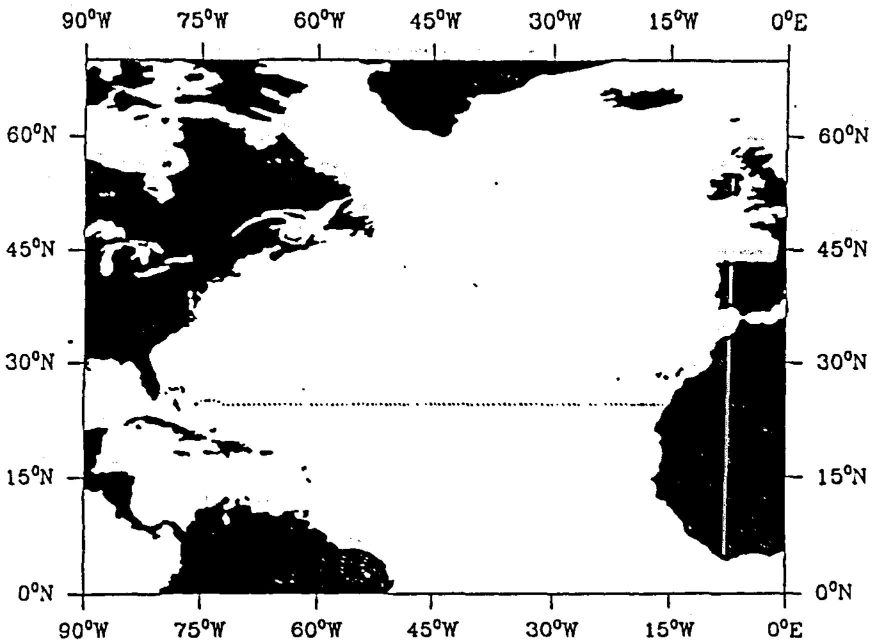


Figure 1. Section at 24.5° N in the North Atlantic. Dots denote the location of stations in the 1992 Hespérides cruise. IGY 1957 track was similar, but spacing between stations was larger than in the 1992 section. Atlantis 1981 was also at that latitude west of 24.5° W. For the comparison we have used this common part.

Two NBIS/EG&G Mark IIIb CTD/02 underwater units each equipped with pressure, temperature, conductivity and polographic oxygen sensors were used throughout the cruise. A General Oceanics rosette fitted with 24 Niskin bottles of 10 or 12 liter of capacity was used with the CTD for collecting water samples. Water sampling included measurements of salinity, oxygen, nutrients (silicate, nitrate, nitrite and phosphate), chlorofluorocarbons (CFC), pH, alkalinity, CO2, particulate matter, chlorophyll pigments, 14C and aluminum. Data acquisition and calibrations of CTD/02 data were done following the procedures given by Millard and Yang (1993).

The 2-db temperature, salinity, and oxygen data have been smoothed with a binomial filter and then linearly interpolated (Mamayev et al., 1991) as required to the standard levels. When the CTD did not reach the bottom, to enable interpolation to all available standard depths, linear vertical extrapolation were used to estimate one more standard depth from the last two interpolated depths.

The *nominal* station spacing in the IGY survey was 185 km. On the *Atlantis II*, the spacing varied between 50 and 80 km with shorter spacing when the stations were over the continental slopes and the Mid-Atlantic Ridge. The same criteria were used for the *Hespérides* survey, but the spacing was more regular, between 58 and 67 km. Therefore, in order to compare the variables from the different cruises directly it is necessary to interpolate all the data onto a set of common geographic locations, we have performed it using objective mapping. The data were interpolated onto a two dimensional grid at 24.5°N. The horizontal spacing chosen was 0.5° of longitude. This corresponds approximately to 50 km at this latitude (0.5 x 60 x 1.85 x cos(24.5) = 50.5 km).

Objective mapping

The technique for the objective mapping is based on a standard statistical result, the Gauss-Markov Theorem, which gives an expression for the minimum variance linear estimate of some physical variable given measurements at a limited number of data points (Bretherton *et al.*, 1976). Objective mapping requires a statement of the expected *a priori* measurement error, and mapped field covariances. We must define what is signal and what is noise, the variance of the data contains the signal variance as well as the noise variance. We assume that the noise includes two components: the first component, n_e, is the variation caused by mesoscale eddies; the second one n_i is the variance caused by the local measurement error (including errors due to navigation, interpolation, instrumentation, etc) (Wunsch, 1989).

Signal and eddy noise covariances were modeled by a gaussian covariance function; intrinsec noise was modeled by a delta function. To estimate the e-folding scale of these distributions we have calculated the correlation function. We have taken a value of 175 km for e-folding distance of the gaussian noise covariance. The scale is perhaps somewhat too large, but it has been chosen to make the plots smoother. We have taken an e-folding scale of 400 km for the signal covariance at all depths. The zero-lag covariances have been estimated following the method described by Fukumori *et al.*, (1991). Variances have then been calculated by computing the expected difference for a spatial separation (Lavín, 1993). The expected error in the temperature mapping was calculated as described by Bretherton *et al.*, (1976).

Calculations of covariances and mapping were performed for 1992, 1981 and 1957 datasets. After this interpolation to a common grid, we have subtracted the mapped values to get the differences for the three periods 1981-1957, 1992-1981 and 1992-1957. The expected error of the differences is the sum of the expected errors of the mapping values for each map.

Zonal Averages

To determine the zonal average of the temperature and salinity differences at each standard depth, we have used the technique for determination of a mean value by objective mapping (Wunsch, 1989). For this calculation we assume that the error in the mapping of two different cruises is uncorrelated one with the other. We have no used any previous hypothesis about the mean difference.

Temperature differences

Figure 2.A presents the temperature difference between the 1981-1957 cruises. Figures 2.B and 2.C give the temperature differences from 1992-1981 and 1992-1957. On the right side of the figures the expected error in function of depth is presented.

1981-1957 This comparison was already done by Roemmich and Wunsch (1984). They found warming above about 3000 m and cooling below it. The most notable feature has been a large warming mainly in the North American Basin between 55°W and 68°W, this warming penetrates deeply down to 4000 m with values of 0.75°C between 700 and 800 m. At the surface, there are positive differences in a very thin layer west of 40°W and negative differences east of that longitude. Between this layer and 500 m we found negative differences in the whole area except in the Canary Basin. There is also an area of large cooling in the western part of the North American Basin, centered around 70°W, between 100 and 1500 m.

The values of the differences are of the same order of magnitude as the uncertainty in the measurements. The scale of most of the features discussed above is larger than the horizontal correlation (around 5 longitude degrees). Since the calculations have been done independently for each standard depth, features are not artificially correlated at each depth.

1992-1981 The substantial area of warming in the central North American Basin during 1981-1957 has cooled between 1981 and 1992. So that the area of Roemmich and Wunsch (1984) of large warming is now a large cooling region. Similarly, the area of substantial cooling during 1981-1957 centered at about 70°W, has now warmed. Thus, there appears to be an oscillation in temperature with a zonal half-wavelength of about 1000 km. The Canary Basin has warmed considerably down to 4000 m.

1992-1957 A remarkable regular warming occurred between 700 and 3000 m from 1957 to 1992. The contours of temperature are nearly horizontal across most of the section. Both the North American and Canary Basins have been warmed by about the same rate. Peak values are larger than 0.5°C at around 1000 m. The surface layer is warmer between 0 and 50 m in the North American Basin. Negative differences occur above 100 m, in the North American Basin below the warmer surface layer. This feature can result from seasonal variability, (measurements were done in July-August 1992 and during October 1957). Seasonal variations in this area affect above 100 m. There is a large area of negative temperature difference centered around 500 m. Peak values are between -0.75°C and -0.5°C in the North American Basin and -0.5°C in the Canary Basin. Those values are significantly higher than the uncertainty at this depth.

Near the western boundary region, below 2000 m, negative differences greater than -0.05 °C appear west of 70° W. The negative differences extend all over the North American Basin between 3000 and 5000 m. Most of these values are statistically significant. (Note that the error values on the temperature plots are multiplied by 10 below 3000 m). The Canary Basin also has been cooled in the last 35 years. The cooling has been stronger around 4000 m, and at the eastern boundary. The uncertainty is less than 0.01° C for most of the values in this basin. The differences are statistically significant.

Zonal average

In Figure 3 we present the zonal average temperature plus/minus error estimate for 1992-1957 from surface down to 3000 m (upper plot), and for the North American and Canary Basins deeper than that depth (down left and right plots). Positive values are found for zonal averages between 600 and 2750 m and between 200 and 400 m. Cooling occurred between 400 and 500 m and below 2750m. Values are significant between 700 m and 2500 m depths. Values are as large as 0.2°C between 800 and 1400 m. The peak value is 0.28°C at 1000 m. In the

A

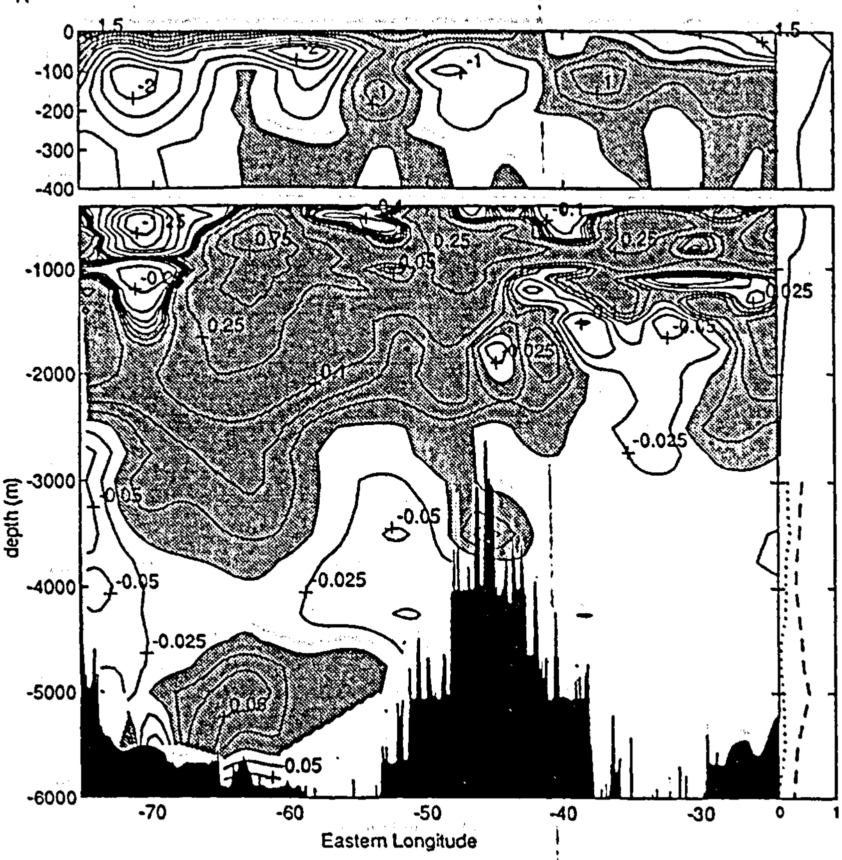
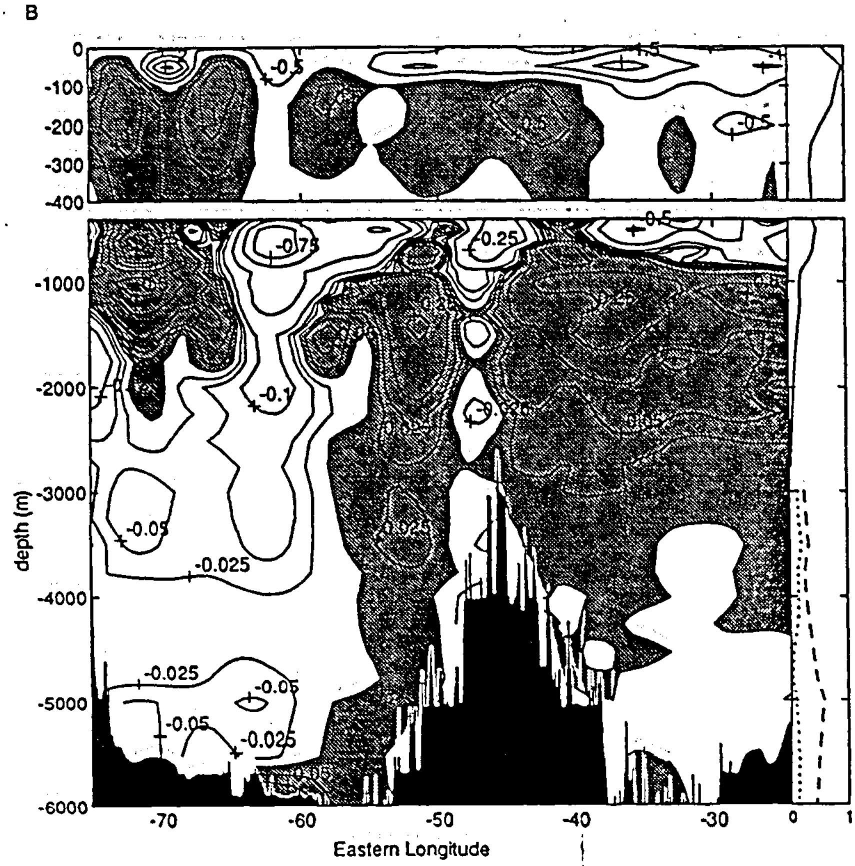


Figure 2. Difference of temperature: A) 1981–1957, B) 1992–1981 and C) 1992–1957. Data are in °C. The expected error in the temperature difference in function of depth is shown in the right side. Below 3000 m, the error is given separately for the Canary (dotted) and North American (dashed) basins and values are multiplied by 10). Expected errors are in °C. The shaded indicates positive difference. The top plot has expanded vertical scale.

B



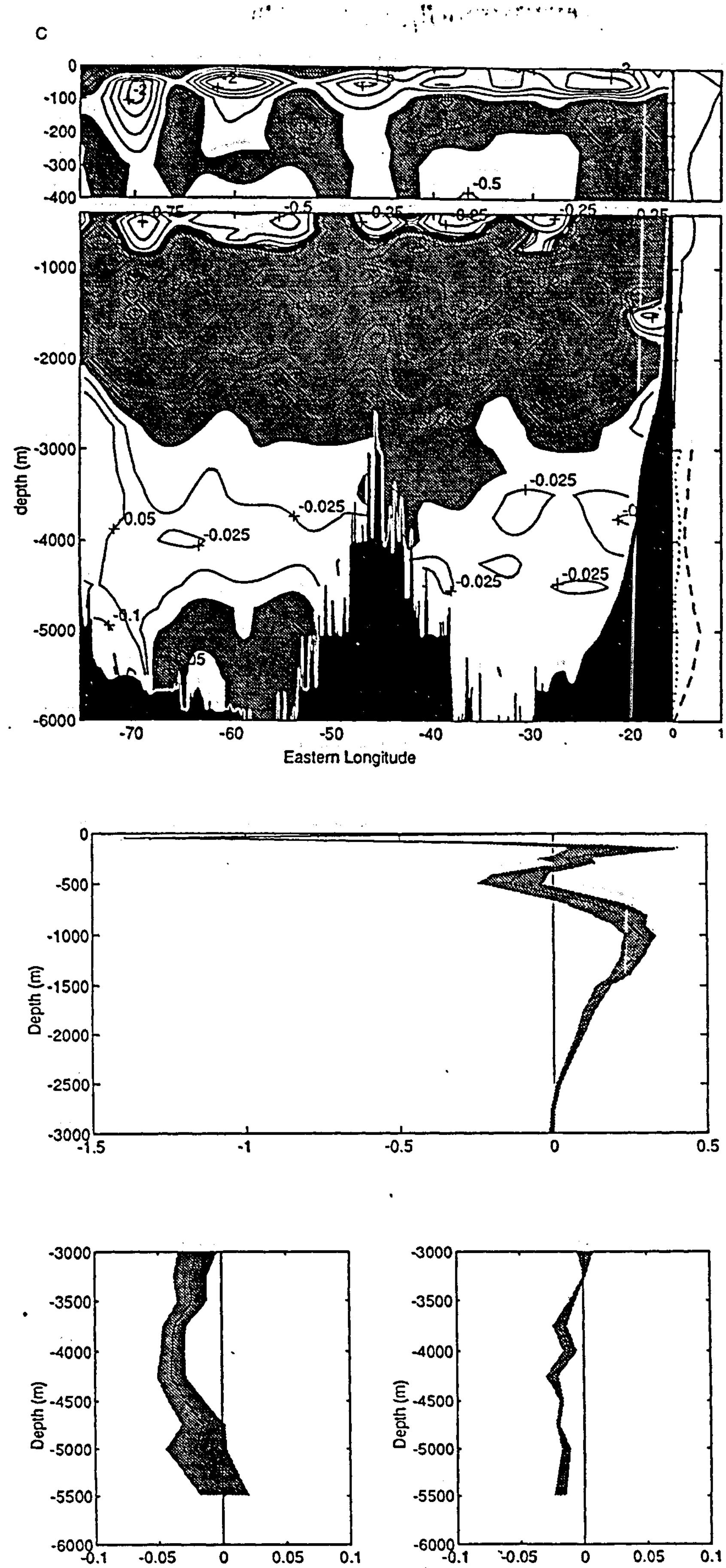


Figure 3. Zonal average temperature differences plotted plus/minus the error estimate (shading) for 1992–1957 from surface to 3000 m for all the Atlantic Basin (upper plot) and deeper than that bottom left figure North American Basin and bottom right Canary Basin. Data are in °C.

North American Basin we found significant cooling between 3250 and 5500 m, with a maximum difference of -0.03 °C at 4250 m. In the Canary Basin, cooling is significant in waters below 3500 m, with a peak difference of -0.02°C at 5000 m.

Salinity differences

Figures 4A, B and C presents the difference in salinities for 1981-1957, 1992-1981 and 1992-1957. Expected errors have been calculated in the same way as for temperature, and are presented on the rigth side of the figures.

1981-1957 Saltier water was found on the area of warming noticed by Roemmich and Wunsch (1984). Salinity differences are positive all over the section from the surface to 200 m depth, and generally negative in a band between 200 and 500 m. Deeper than 500 m, as for temperature, there is substantial zonal variability. The western part of the section shows negative values to the bottom, with differences as large as -0.15 psu between 500 and 700 m. Positive differences are found between 300 and 3000 m in the central part but only down to 2000 m in the eastern part of the North American Basin. At 4000 m depth, water is fresher at both boundaries of the North American Basin. Differences are significant over most of the basin, except for the deep water in the North American Basin. Even when the uncertainty given by the mapping is very small, as in the Canary Basin, problems with the salinity determination from the batch of Standard Sea Water prevent the plotting of smaller salinity differences.

1992-1981 Salinity differences present a zonal distribution similar to that of temperature except near the surface where the difference is positive. Positive differences are found between 50 and 350 m, and negative (fresher water) from that layer until 800 m. The water is saltier between 800 m and about 2500 m for all of the section. This saltier water reaches the bottom over the western part of the Mid-Atlantic Ridge with an interruption around 5000 m. The rest of the deep regions appears to be fresher. This freshening is strongest around 3000 and 5000 m in the central and western parts of the North American Basin.

1992-1957 The most important feature is the increase in salinity occurring between 600 and 2500 m, with maximum values of 0.05 psu. The salinity section gives generally positive differences above 300 m. The differences are predominantly negative between 300 and 600 m with values as high as -0.1 psu in the western part and -0.05 for the remainder except near the eastern boundary where the differences are positive down to 1400 m depth. Below 2000 m the differences are negative, in the North American Basin, peak values are found at 4000 m, at the western boundary and over the Mid-Atlantic Ridge. In the Canary Basin the least freshening occurs around 4000 m. Below 4250 m there is a significant freshening to the bottom, with differences larger than 0.005 psu.

Zonal average

In Figure 5 we can see the zonal average salinity plus/minus error estimate for 1992-1957 from surface down to 3000 m, and for the North American and Canary Basins deeper than that. Saltier water occurs between 600 and 1750 m. The maximum value was 0.031 psu at 800 m. Water is also saltier at depths shallower than 300 m. Differences are significantly negative below 2000 m,

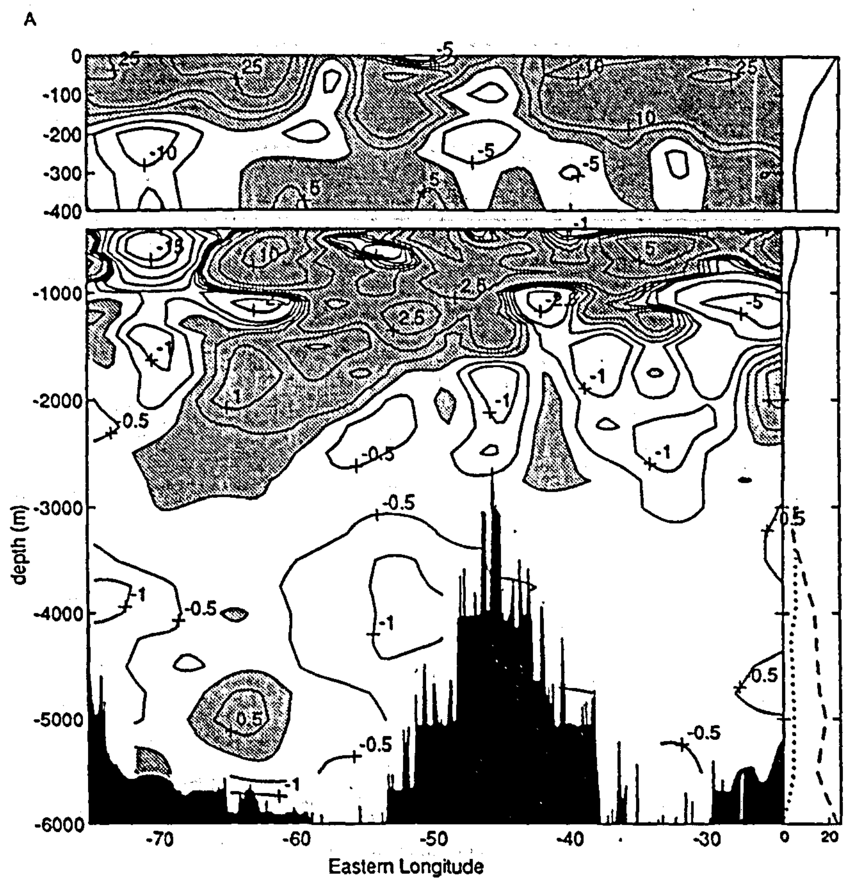
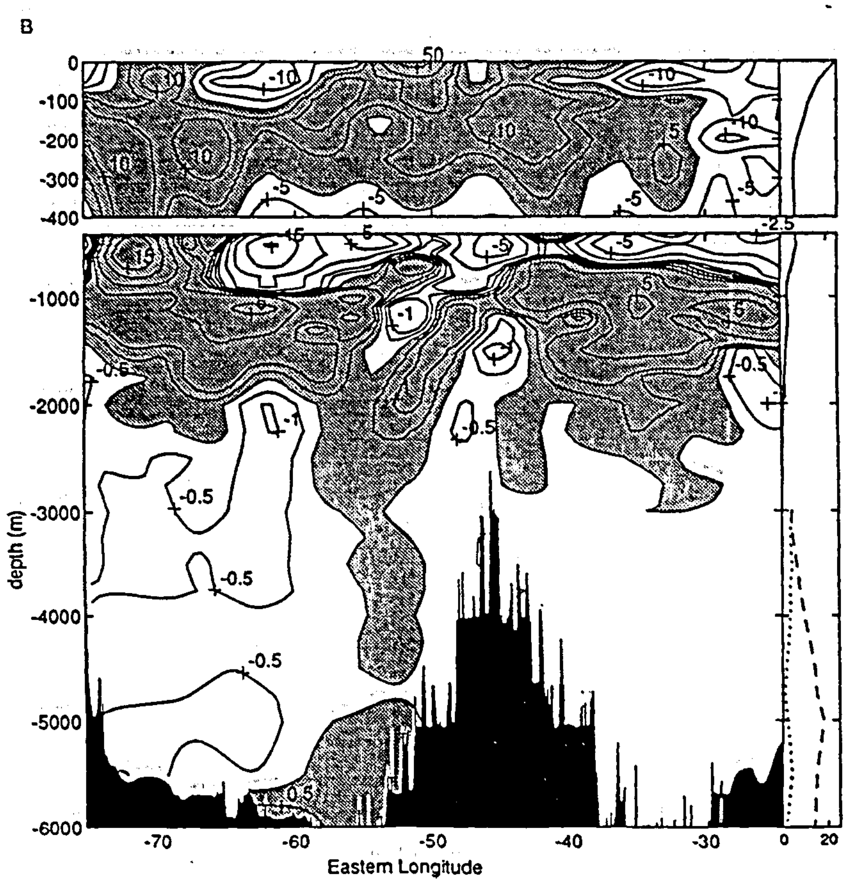


Figure 4. Difference of salinity: A) 1981-1957, B) 1992-1981 and C) 1992-1957. Data are in psu x 100. The expected error in salinity difference in function of depth is shown in the right side. Below 3000 m, the error is given separately for the Canary (dotted) and North American (dashed) basins and values are multiplied by 25). The shaded indicates positive difference. The top plot has expanded vertical scale.



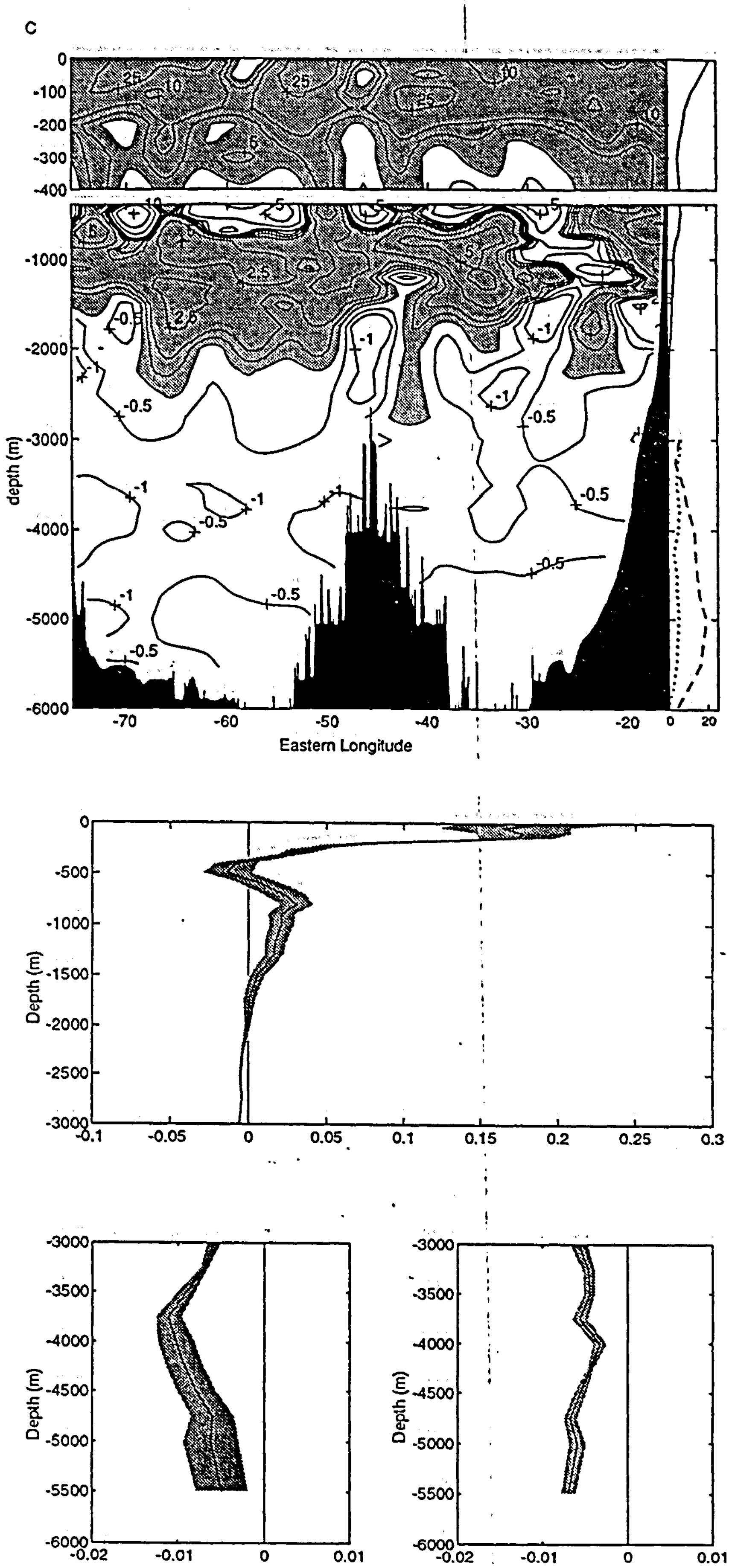


Figure 5. Zonal average salinity differences plotted plus/minus the error estimate (shading) for 1992–1957 from surface to 3000 m for all the Atlantic basin (upper plot) and deeper than that bottom left figure North American Basin and bottom right Canary Basin. Data are in psu.

where the differences are around -0.004 psu. In the deep North America Basin differences are between -0.008 and -0.005 psu and in the deep Canary Basin between -0.006 and -0.004 psu.

Discussion

Integrating from 100 m (the depth of the seasonal variability at 24.5° N) down to 3000 m, the changes in temperature provide a barely significant value of 0.096±0.09°C. This value gives a trend of warming in this upper part of the North Atlantic of 0.03°C/decade. The integrated temperature changes for the two periods reveal practically the same values for these rates 0.025°C/decade for the first 24 years and 0.027°C/decade for the last 11 years. The upper 1000 m presents high variability between the three difference datasets, but below 1000 m a significant warming of 0.1±0.02°C has been observed. The rate of warming between 1000 and 3000 m is statistically significant at a rate of 0.028±0.007°C/ decade. This value is similar to the rate for the whole water column between 100 and 3000 m. There is a nearly steady tendency of warming in the North Atlantic above 3000 m. The rate of change of temperature is around 0.03°C/decade.

For the calculation of the uncertainty in the deep-averaged variation of temperature, we have considered the standard depths as independent of each other. We have done all the calculations at each standard depth without considering any vertical correlation. Looking at the structures found in these sections, we assume 6 independent layers in the upper 3000 m. Using these degrees of freedom, the change in temperature is 0.09 with uncertainty of ±0.2°C. Assuming 2 independent layers between 1000 and 3000 m, warming of 0.1±0.05°C is obtained, which is still significant.

The tendency in salinity for the upper 3000 m was 0.011±0.013 psu or a trend of 0.003 psu/decade. The rates of change in salinity over time are less regular than in temperature and values of 0.002 and 0.005 psu/decade for the periods 1981-1957 and 1992-1981 were calculated. Since uncertainties are larger than the values, the values are not statistically significant.

In the North Atlantic, the deep water below 3000 m exhibits a significant cooling of -0.027±0.016°C in the North American Basin and -0.013±0.005°C in the Canary Basin. The rates of variation of temperature over the total period of time were -0.008°C/decade in the North American Basin and -0.004°C/decade in the Canary Basin. The rates of change in temperature over time are different for the two periods. The North American Basin was cooling principally during 1992-1981 by -0.015 °C/decade and somewhat less during the previous period. In the Canary Basin most of the cooling occurred between 1981 and 1957 with a rate of -0.006°C/decade. Using 2 degrees of freedom the rate of change in temperature in the North American Basin is -0.027±0.03°C and -0.013±0.011°C in the Canary Basin.

The total change of salinity in deep water below 3000 m during the last 35 years was -0.008±0.002 psu in the North American Basin and -0.005±0.001 psu in the Canary Basin. Freshening was quite homogeneous over time in both basins, with values of -0.002 psu/decade in the North American Basin and -0.0015 psu/decade in the Canary Basin. The change in salinity using 2 degrees of freedom in the deep water is -0.008±0.004 for the North American Basin and -0.005±0.002 in the Canary Basin.

Joyce(1993), in a study of a long-term hydrographic record at Bermuda (32.17°N, 64.50°W), shows that the variations in temperature and salinity on interannual time-scales are largely independent of each other in the surface layer (0-500 m depth), and highly correlated in the thermocline. Between 500 and 1500 m, correlation between temperature and salinity changes is due to vertical oscillations of the thermocline with amplitudes of ±50 m. Within his records (1955-1988), he found a long-term negative trend in temperature for the layer between 500 and 1000 m, and a positive trend between 1500 and 2500 m (Figure 2 of his paper). This result is consistent with the trend calculated in this study for the zonal average of the 24.5°N section with negative differences around 500 m and significant warming found below 700 m. He extended the time series from 1932 to 1990 (figure 3, of his paper) and found that the long-term trend in the shallow layer disappears, while the one in the deep layer persists. The long-term trend is about 0.5°C/century, with oscillations on the deep layer of approximately 0.05° C over decadal time scales.

Lazier (1980) found a decreased production of Labrador Sea Water (LSW) in the 1970's. Later he reports (Lazier, 1988) that by the mid-1980's conditions in these waters had returned to those of the early 1960's. This water flows southward at about 1500 m depth in the western boundary, and a reduction in the source strength would presumably produce a lesser amount of LSW and therefore a decreased influence on the upper North Atlantic sea water.

According to Brewer et al. (1983), changes in the Denmark Strait overflow of ventilated waters from convective basins to the north caused widespread freshening of the deep Subpolar water during the 1960's and 1970's. At 24.5°N, cooling and freshening in the deep western boundary occurred during the first period (1957-1981); and after 1981, the cooling and freshening in the western boundary has been reduced but the effect has expanded all around the western basin. The Canary Basin has been cooling and freshening but in a lesser amount than the North American Basin.

Levitus (1989b) found at 1750 m depth an increase in temperature of approximately 0.1°C and salinity 0.025 psu for most of the North Atlantic for a 15-year period (1970-1974 - 1955-1959). Also in the upper layers (Levitus 1989a), the variations over the 15-year period at 24.5°N are similar to those presented here. Behavior of this part of the subtropical North Atlantic is quite different from that of the northern part.

Conclusions

The most significant finding is that there is a long time scale warming in an ocean-wide band from 1000 m to 3000 m of the North Atlantic at 24.5°N over the entire 35-year period from 1957 to 1992. There is warming in the layer from surface down to 400 m, cooling between 400 and 500 m, and a significant warming between 600 and 2750 m.

The 1992 section was 0.1±0.09°C warmer than the 1957 section above 3000 m depth, with a trend of 0.03°C/decade. This tendency characterized both periods, 1981-1957 and 1992-1981. There is high spatial variability in the time changes over most of the upper 1000 m. The rate of warming between 1000 and 3000 m is 0.028±0.007°C/decade.

Below 3000 m depth, the temperature decreases are statistically significant. The cooling rate is -0.008±0.005°C/decade in the North American Basin and -0.004±0.001°C/decade in the Canary Basin. This cooling has not been regular. Strong cooling occurred in the Canary Basin for the 1981-1957 period and in the North American Basin for 1992-1981.

Changes in salinity at 24.5°N are about 0.003 psu/decade above 3000 m and -0.002 psu/decade below 3000 m in the North American Basin and -0.001 psu/decade in the Canary Basin.

There is a general cooling and freshening in the western boundary below 2000 m. Differences are greater than -0.05°C and -0.01 psu for most of the area west of 70°W. The eastern boundary was also subject to cooling and freshening but to a lesser extent.

The rate of zonally averaged temperature change between 100 and 3000 m observed over the period 1957 to 1981 by Roemmich and Wunsch (1984) has remained steady in the last decade. This warming trend in the subtropical North Atlantic is a very important climatic issue.

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