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A twenty year reversal in water mass trends in the subtropical North Atlantic

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Received 10 March 2007; revised 3 May 2007; accepted 23 May 2007; published 26 June 2007.

[1] Temperature and salinity changes have been compared along three repeat sections at 36°N in the North Atlantic. The principal changes, cooling of the upper waters and warming of the intermediate waters observed between 1959 and 1981, were reversed between 1981 and 2005. The controlling mechanisms for the changes over the two time periods differed through the water column. Neutral density surfaces over the upper 800 m were firstly uplifted and secondly depressed by typically 50 m, which is broadly consistent with the changes in thermocline thickness implied by the temporal changes in Ekman pumping. In contrast, the intermediate waters (800–2500 m) firstly became warmer and saltier and secondly became cooler and fresher. This change in the intermediate waters was controlled by water mass changes along neutral density surfaces suggesting a change in the source waters, principally Labrador Sea Water and Mediterranean Outflow Water. **Citation:** Leadbetter, S. J., R. G. Williams, E. L. McDonagh, and B. A. King (2007), A twenty year reversal in water mass trends in the subtropical North Atlantic, *Geophys. Res. Lett.*, *34*, L12608, doi:10.1029/2007GL029957.

1. Introduction

[2] There has been a significant rise in global ocean heat content over the past 50 years, which is an order of magnitude larger than the increase in atmospheric and cryospheric heat content [*Levitus et al.*, 2005]. Over the subtropical North Atlantic, this rise in ocean heat content has been associated with an increase in temperature between the late 1950's and the early 1990's, which is greatest at intermediate depths (~500–2500 m), as revealed by repeat hydrography at 24°N, 52°W and 66°W [*Bryden et al.*, 1996; *Vargas-Yáñez et al.*, 2004; *Joyce et al.*, 1999]. This warming of intermediate waters has also been accompanied by an increase in salinity.

[3] In this study, the hydrographic changes through the subtropical gyre of the North Atlantic are considered. A survey along 36°N in 1959 [*Fuglister*, 1960] is compared to repeat surveys in 1981 [*Wunsch*, 1981] and, more recently, in 2005. Between 1959 and 1981, *Roemmich and Wunsch* [1984] showed that there was a decrease in temperature in the upper 200–800 m of the section and a widespread warming at intermediate depths. Two questions are now addressed:

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0094-8276/07/2007GL029957$05.00

[4] (1) Have the warming and cooling observed by *Roemmich and Wunsch* [1984] continued between 1981 and 2005 or have they been reversed?

[5] (2) Are the changes principally induced by water mass changes or wind-induced displacement of the neutral density surfaces?

2. Data Collection and Method

[6] Temperature and salinity observations were made on repeat sections across 36°N in 1959, 1981 and 2005 (Figure 1a). In 1959, 61 stations were sampled using Nansen bottles resulting in average separation of ~180 km over the ~7500 km wide section. The 1981 and 2005 sections were both sampled using continuously recording CTDs. In 1981, stations were typically separated by ~65 km over the deep basin and, in 2005, the stations were typically separated by 55 km over the deep basin. In all three years, station separation was reduced towards the eastern and western boundaries.

[7] To compare temperature and salinity between the sections, it is necessary to obtain an estimate of the measurement errors, which is particularly important for salinity measurements. Previous studies [*Mantyla*, 1994; *Saunders*, 1986] have shown that the 1959 salinities have a systematic offset of 0.009 psu, which is larger than the salinity standard deviations in the deep eastern basin (0.004 psu for the 1959 and ~0.001 psu for the 1981 and 2005 surveys). No correction was applied to the 1959 salinity data set, as it is unclear whether this offset is constant outside of the deep-eastern basin.

3. Temporal Variations of Temperature and Salinity

[8] To compare temperature across the three sections, all three data sets were interpolated onto the same grid with a horizontal spacing equal to the 1959 station locations and a 20 m vertical resolution. The changes in all three sections were only considered to the east of 70°W to avoid variability associated with different cruise tracks and Gulf Stream location (Figures 1b and 1c). To highlight key changes, temperature changes are zonally averaged, firstly, over the whole basin (9–70°W) and, secondly, in each half of the basin. The basin was divided at the westernmost extent of the Mediterranean Outflow Water (40°W); here MOW is defined as the mixture of Atlantic and Mediterranean Water found at depths of ~1100 m in the eastern North Atlantic [*Iorga and Lozier*, 1999].

[9] Between 1981 and 2005, there is a significant widespread warming of the upper 800 m with a stronger signal along the western half of the basin; this signal is significant

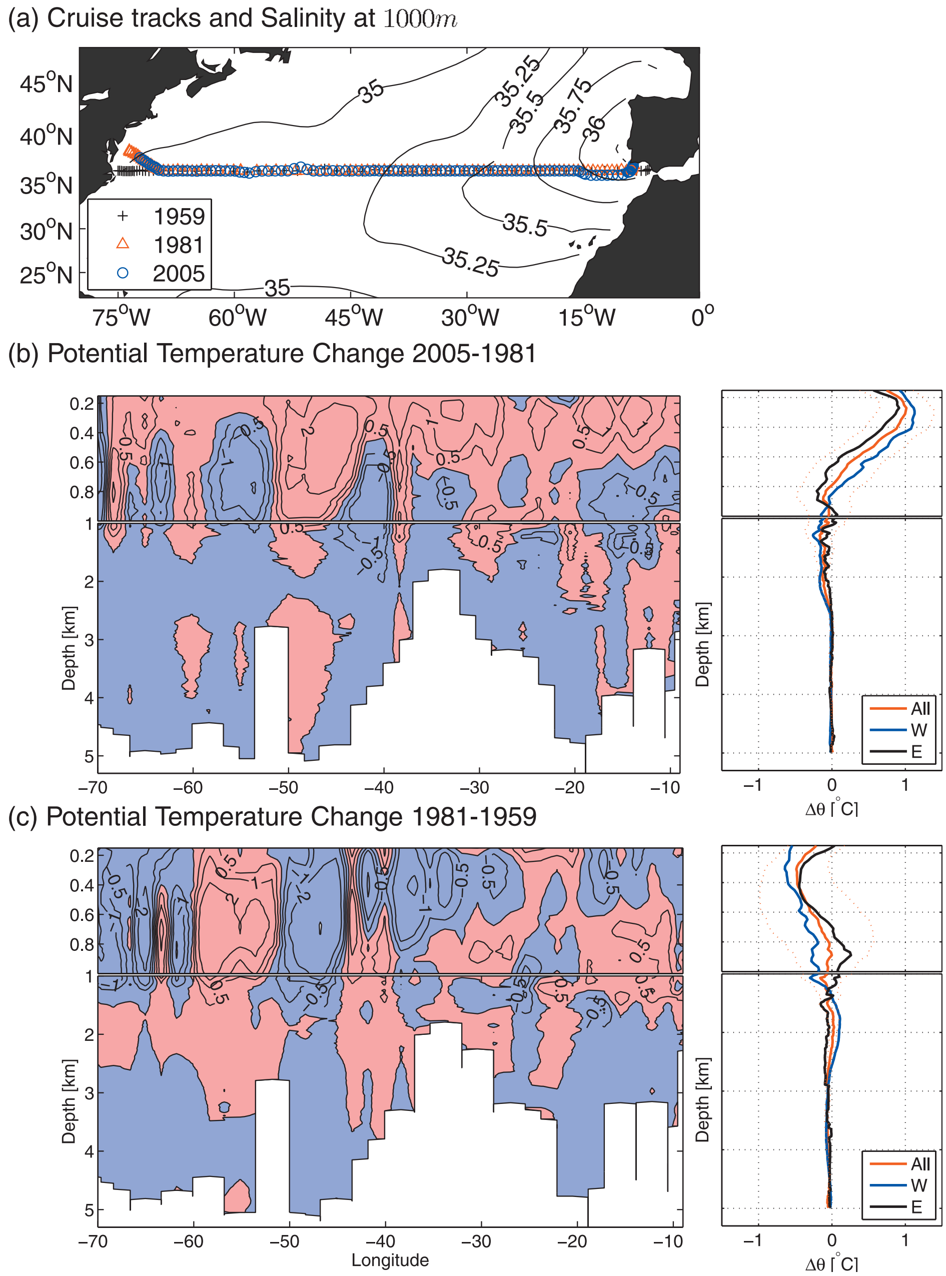
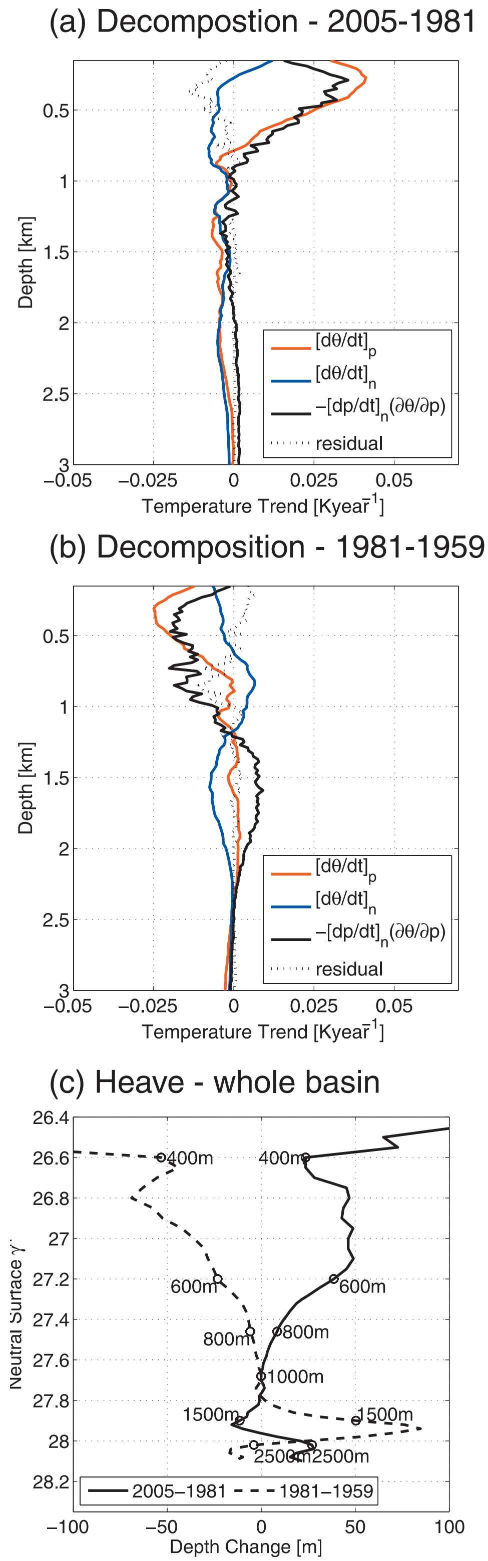


Figure 1. (a) Location of sections across 36°N in 1959, 1981, and 2005. Overlaid are contours of salinity at 1000 m in the subtropical North Atlantic. (b) Temperature change across 36°N 2005 minus 1981 (°C). (right) Zonally-averaged temperature changes from 9–70°W (red line), 40–70°W (blue line), and 9–40°W (black line). Also plotted are the 95% confidence limits for zonally-averaged temperature from 9–70°W (red dashed lines). (c) As for Figure 1b but 1981 minus 1959. Note the reversing pattern of temperature changes for the two sections.

at the 95% confidence level (based on $t^* \frac{s}{\sqrt{n}}$ where t^* is the critical value for the t-distribution, s is the sample standard deviation and n is the number of stations). There is deeper penetration of the warming in the western half of the basin where the thermocline is deeper. Conversely, there is a cooling of the intermediate waters across the basin with again a stronger signal in the western half of the basin. There is a localised cooling on the eastern side of the basin at 10–20°W and 500–1200 m which is associated with the Mediterranean Outflow Water.

[10] The temperature changes in the upper and intermediate waters between 1981 and 2005 are in sharp contrast to the temperature changes between 1959 and 1981 observed by *Roemmich and Wunsch* [1984]. Between 1959 and 1981, there was a large cooling of the upper waters. Again, due to the slope in the thermocline, this cooling penetrates deeper in the western half of the basin. The intermediate waters of the western basin warmed between 1959 and 1981, although the warming was less than the subsequent cooling over the next two decades leading to an overall decrease in temperature between 1959 and 2005. In the eastern half of



the basin, there was some localised cooling of the intermediate waters, as well as a warming between 500 m and 1200 m associated with the Mediterranean Outflow Waters. In the deep waters (below 3000 m), there was a significant cooling between 1959 and 1981 of ~0.06°C. This cooling continued until 2005 with only a slight decrease in temperature of ~0.01°C between 1981 and 2005.

4. Mechanisms Controlling Change

[11] To identify the controlling mechanisms, the temperature changes computed on pressure surfaces are decomposed into changes on neutral surfaces (first term on the right-hand-side of (1)) and changes in temperature due to the vertical movement of neutral surfaces (second term on the right-hand-side of (1)) [*Bindoff and McDougall*, 1994].

$$\left.\frac{d\theta}{dt}\right|_p = \left.\frac{d\theta}{dt}\right|_n - \left.\frac{dp}{dt}\right|_n \left(\frac{\partial\theta}{\partial p}\right) \quad (1)$$

where $|_p$ denotes changes along pressure surfaces and $|_n$ denotes changes along neutral surfaces.

[12] Changes in the upper waters were predominantly due to the vertical displacement of neutral surfaces (see Figures 2a and 2b). Between 1981 and 2005 the neutral surfaces in the upper 900 m were depressed by 25–100 m (Figure 2c, solid line). This depression resulted in an increase in temperature and a maximum rate of warming of 0.03 Kyr^{-1}. In contrast to this depression, between 1959 and 1981, neutral surfaces in the upper 1000 m were uplifted by 25 m to 100 m (Figure 2c, dashed line). This uplift resulted in a decrease in the temperature and a maximum rate of cooling of 0.02 Kyr^{-1}.

[13] In the intermediate waters, water mass changes along neutral surfaces provide a significant contribution to changes at constant depth. Between 1981 and 2005, waters on neutral surfaces cooled resulting in cooling at constant depth. Between 1959 and 1981, a downward movement of the neutral surfaces is offset by a cooling along neutral surfaces resulting in almost no change in temperature at constant depth. There is a large downward displacement of the neutral surfaces between 1500–2500 m from 1959 to 1981, which results in an increase in temperature and salinity at constant depth.

[14] Along the 36°N section, there were significant temperature-salinity changes in two of the principle water masses, Mediterranean Outflow Water and Labrador Sea Water. To examine these changes in more detail temperature and salinity were averaged along pressure surfaces in 10°-wide regions.

Figure 2. (a) Decomposition of temperature changes between 1981 and 2005 into changes at constant depth (red line), changes at constant neutral density (blue line), and changes due to the movement of neutral density surfaces (black line). The black dashed line is the residual (red line minus blue line plus black line). (b) As for Figure 2a but 1981 minus 1959. (c) Displacement of neutral surfaces between 1981 and 2005 (solid line) and 1959 and 1981 (dashed line) (m). Note the pronounced displacement of the neutral density surfaces between 1959 and 1981 which is reversed between 1981 and 2005.

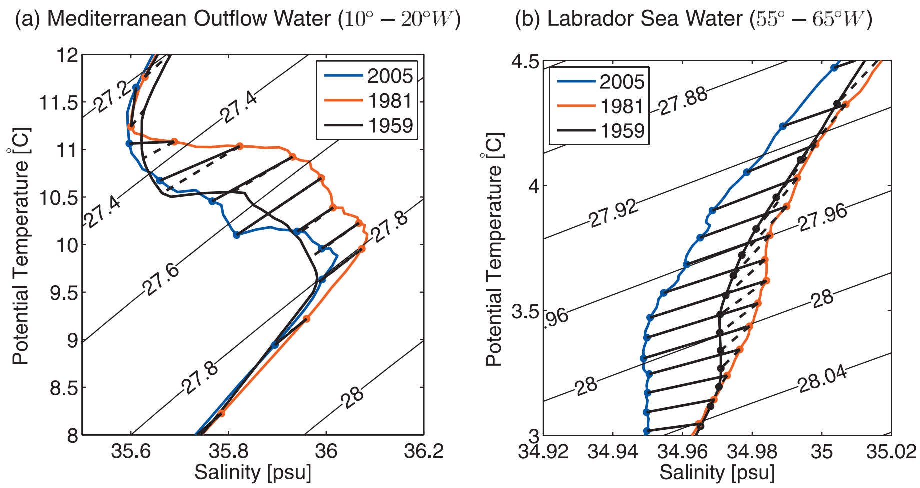


Figure 3. (a) Mean θ–S plot for 10–20°W focusing on the peak in salinity characteristics of Mediterranean Outflow Water. (b) Mean θ–S plot for 55–65°W at the depth of Labrador Sea Water (1500–2500 m). Reference neutral density surface are contoured in the background, which are computed in Figure 3a using a depth of 1000 m and a location of 36°N, 15°W, and in Figure 2b using a depth of 2000 m and a location of 36°N, 60°W. Black dashed and solid lines link points of equal pressure.

[15] Mediterranean Outflow Water is most easily identified as the peak in salinity in the θ–S diagram at temperatures of 9–11°C. Average θ–S curves from 10–20°W reveal an increase in salinity from 1959 to 1981 (Figure 3, black to red curve) followed by an almost compensating decrease in salinity from 1981 until 2005 (Figure 3, red to blue curve). Warming accompanies the 1959–1981 increase in salinity, while cooling accompanies the 1981–2005 decrease in salinity so that the water preserves its density. At these depths the changes are almost entirely due to water mass changes and there is no significant displacement of the neutral surfaces. Hence in Figure 3, the black dashed and solid lines link points of equal pressure for each period of sampling and lie parallel to lines of constant neutral density (around the salinity peak and between densities of 27.5 kgm^{-3} and 27.82 kgm^{-3}).

[16] The temperature-salinity relationship was also examined between 55°W and 65°W and depths of 1500–2500 m. There is some evidence of an increase of temperature and salinity of these waters between 1959 and 1981, but due to the salinity offset in the 1959 data the change is not large enough to be significant (Figure 3b). This change is partly due to water mass change and partly due to a movement in the neutral surfaces (see Figure 2b). In contrast to this weak signal, there is significant cooling and freshening in this part of the water column between 1981 and 2005. The peak of this cooling and freshening is at a temperature of ~3.5°C, which is characteristic of Labrador Sea Water [*Curry et al.*, 1998]. Again the lines linking points of constant depth are almost parallel to the neutral surfaces (between densities of 27.90 kgm^{-3} and 28.02 kgm^{-3}) showing that there is little displacement of the neutral surfaces of Labrador Sea Water.

5. Discussion and Conclusion

[17] Temperature and salinity changes have been identified along 36°N using hydrographic sections sampled in 1959, 1981 and 2005. The principal changes observed in the upper and intermediate waters between 1959 and 1981 were reversed between 1981 and 2005.

[18] The upper 800 m cooled between 1959 and 1981 and warmed between 1981 and 2005. The changes in these upper waters in the subtropical gyre were principally due to a vertical displacement of neutral density surfaces, firstly uplifted and secondly depressed. These changes are consistent with changes in wind forcing associated with the North Atlantic Oscillation (NAO) [*Hurrell*, 1995]. Between 1959 and 1981, there was a general decrease in wind stress associated with a negative phase of the NAO leading to a weakening in Ekman downwelling. Conversely, between 1981 and 2005, there was a general increase in wind stress associated with a positive phase of the NAO leading to a strengthening in Ekman downwelling.

[19] These changes in wind forcing can be interpreted in terms of a simple $1\frac{1}{2}$ layer model, assuming that the ocean is in geostrophic and Sverdrup balance [*Luyten et al.*, 1983; *Williams and Pennington*, 1999], where the thickness of the upper layer representing the thermocline, h, is given by

$$h^2(x,y) = h_e^2 - \frac{2f^2}{\beta g'} \int_x^{x_e} w_e(x,y)dx, \qquad (2)$$

here w_e is the Ekman upwelling velocity, h_e is the layer thickness on the eastern boundary at x_e, here defined to be 400 m, f is the Coriolis parameter, $\beta = df/dy$, $g' = \frac{\Delta\rho}{\rho} g$ is the reduced gravity, and $\Delta\rho$ is the density difference between the moving and stagnant layers here defined as 0.5 kgm^{-3}. The $1\frac{1}{2}$ layer model is forced with realistic wind stress from the NCEP reanalyses (NOAA-CIRES Climate Diagnostics Centre reanalysis data available at http://www.cdc.noaa.gov/) and the anomalous Ekman upwelling and thermocline thickness are computed by subtracting the 1950–2005 means (see Figure 4). Between 1981 and 2005, the anomalous Ekman upwelling averages −1.8 myr^{-1} and reaches a peak value of −6 myr^{-1} at 40°W and the implied thermocline thickness increases by 50 m at the western boundary. Between 1959 and 1981, the anomalous Ekman upwelling

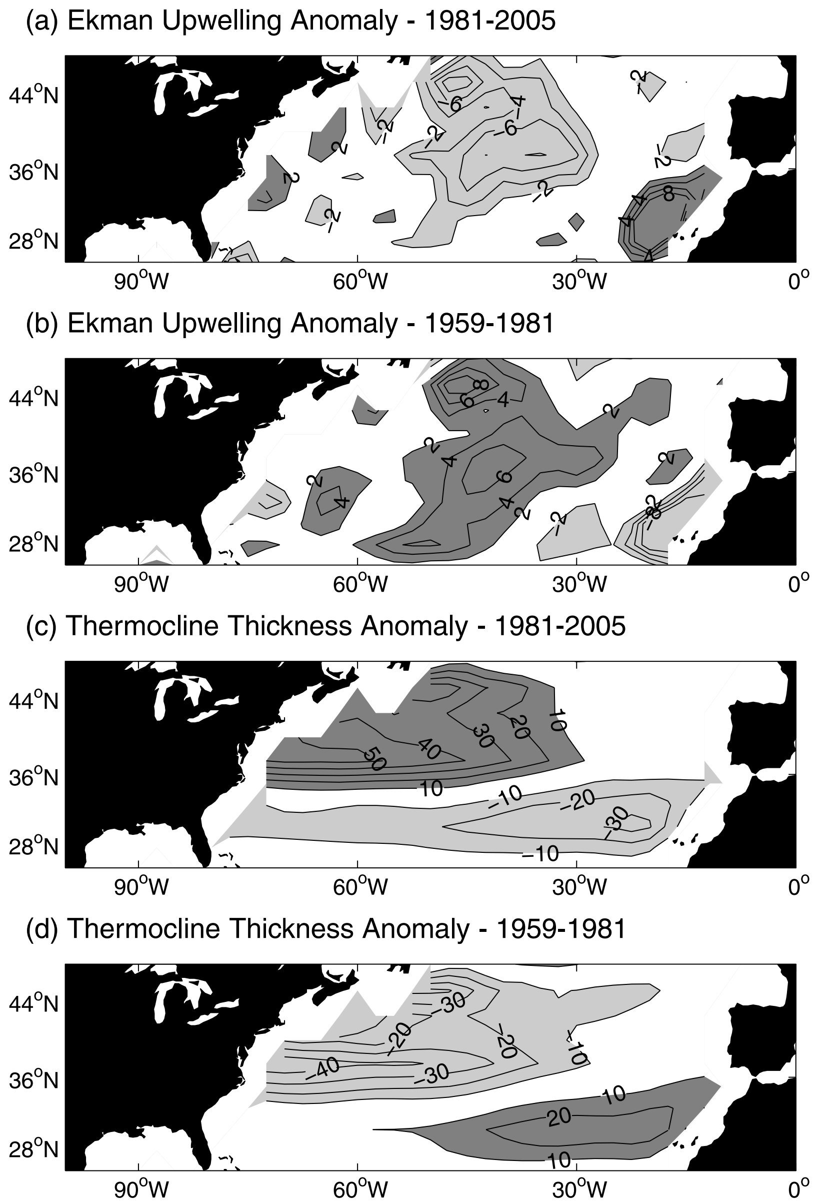


Figure 4. Average anomalous Ekman upwelling (myr^{-1}) (a) between 1981 and 2005 and (b) between 1959 and 1981 (positive denotes more upwelling). Average anomalous thermocline thickness (m) as computed from an idealised $1\frac{1}{2}$ layer, thermocline model (c) between 1981 and 2005 and (d) between 1959 and 1981 (positive denotes a thicker thermocline).

averages 2.2 myr^{-1} and reaches a peak value of 6 myr^{-1} at 40°W, which leads to the implied thermocline thickness changing by −40 m at the western boundary. These displacements of the thermocline are broadly consistent with the changes in the depth of neutral density surfaces observed between the three sections (see Figure 2c). The dominance of neutral density surface displacement over water mass change along neutral surfaces in the upper waters has also been reported along other repeat section in the North Atlantic subtropical gyre [*Bryden et al.*, 1996; *Arbic and Owens*, 2001].

[20] Water mass changes become more important in the intermediate waters below 800 m. In the eastern half of the basin, water mass changes resulted in Mediterranean Outflow Water becoming warmer and saltier from 1959 to 1981. This change is consistent with the changes in the Outflow Waters reported by *Potter and Lozier* [2004]. Between 1981 and 2005, a compensating water mass change occurred, and Mediterranean Outflow Water became cooler and fresher. There were similar changes in the water mass composition of Labrador Sea Water which increased in temperature and salinity between 1959 and 1981, and cooled and freshened between 1981 and 2005. This reversal in the change is consistent with changes in Labrador Sea Water observed at Bermuda's Station 'S' where warming from 1954 until 1985 was replaced by cooling from 1985 until 1996 (the end of the study) [*Curry et al.*, 1998].

[21] In summary, the temperature and salinity changes in the subtropical North Atlantic are dominated by reversing signals between 1959, 1981 and 2005, rather than persistent changes. The signals in the upper waters are consistent with changes in surface wind forcing leading to the displacement

of neutral density surfaces, whilst those changes in the intermediate waters are in accord with water-mass changes in their source regions over the North Atlantic basin.

[22] **Acknowledgments.** This research was funded as part of the UK NERC 36N Consortium, grant *NER/O/S*/2003/00625. The authors would like to thank Hannah R. Longworth for calibration of the 2005 CTD data and Harry L. Bryden and two anonymous reviewers for constructive feedback.

References

Arbic, B. K., and W. B. Owens (2001), Climatic warming of Atlantic intermediate waters, *J. Clim.*, *14*, 4091–4108.
Bindoff, N. L., and T. J. McDougall (1994), Diagnosing climate change and ocean ventilation using hydrographic data, *J. Phys. Oceanogr.*, *24*, 1137–1152.
Bryden, H. L., M. J. Griffiths, A. M. Lavín, R. C. Millard, G. Parrilla, and W. M. Smethie (1996), Decadal changes in water mass characteristics at 24°N in the subtropical North Atlantic Ocean, *J. Clim.*, *9*, 3162–3186.
Curry, R. G., M. S. McCartney, and T. M. Joyce (1998), Oceanic transport of subpolar climate signals to mid-depth subtropical waters, *Nature*, *391*, 575–577.
Fuglister, F. C. (1960), *Atlantic Ocean Atlas of Temperature and Salinity Profiles and Data From the International Geophysical Year of 1957–1958*, *Woods Hole Oceanogr. Inst. Atlas Ser.*, vol. 1, 209 pp., Woods Hole Oceanogr. Inst., Woods Hole, Mass.
Hurrell, J. (1995), Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679.
Iorga, M. C., and M. S. Lozier (1999), Signatures of the Mediterranean outflow from a North Atlantic climatology: 1. Salinity and density fields, *J. Geophys. Res.*, *104*, 25,985–26,009.
Joyce, T. M., R. S. Pickart, and R. C. Millard (1999), Long-term hydrographic changes at 52 and 66°W in the North Atlantic subtropical gyre and Caribbean, *Deep Sea Res., Part II*, *46*, 245–278.
Levitus, S., J. Antonov, and T. Boyer (2005), Warming of the world ocean, 1955–2003, *Geophys. Res. Lett.*, *32*, L02604, doi:10.1029/2004GL021592.
Luyten, J. R., J. Pedlosky, and H. Stommel (1983), The ventilated thermocline, *J. Phys. Oceanogr.*, *13*, 292–309.
Mantyla, A. W. (1994), The treatment of inconsistencies in Atlantic deep-water salinity data, *Deep Sea Res., Part I*, *41*, 1387–1405.
Potter, R. A., and M. S. Lozier (2004), On the warming and salinification of the Mediterranean outflow waters in the North Atlantic, *Geophys. Res. Lett.*, *31*, L01202, doi:10.1029/2003GL018161.
Roemmich, D., and C. Wunsch (1984), Apparent changes in the climatic state of the deep North Atlantic Ocean, *Nature*, *307*, 447–450.
Saunders, P. M. (1986), The accuracy of measurement of salinity, oxygen and temperature in the deep ocean, *J. Phys. Oceanogr.*, *16*, 189–195.
Vargas-Yáñez, M., G. Parrilla, A. Lavín, P. Vélez-Belchí, and C. González-Pola (2004), Temperature and salinity increase in the eastern North Atlantic along the 24.5°N in the last ten years, *Geophys. Res. Lett.*, *31*, L06210, doi:10.1029/2003GL019308.
Williams, R. G., and M. Pennington (1999), Combining altimetry with a thermocline model to examine the transport over the North Atlantic, *J. Geophys. Res.*, *104*(C8), 18,269–18,280.
Wunsch, C. (1981), Atlantis II cruise report 109, technical report, Woods Hole Oceanogr. Inst., Woods Hole, Mass.

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