GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L07603, doi:10.1029/2008GL033329, 2008

Recent changes in subsurface temperature and salinity in the Canary region

V. M. Benítez-Barrios,[1] A. Hernández-Guerra,[1] P. Vélez-Belchí,[2] F. Machín,[3] and E. Fraile-Nuez[2]

Received 17 January 2008; revised 27 February 2008; accepted 5 March 2008; published 5 April 2008.

[1] Based on hydrographic sections carried out during the last decade in the Canary region at 29° 10′N, we show that there has been a statistically significant rise in temperature and salinity on isobars between 1500 and 2300 db. The maximum increase, found at 1600 db, is occurring at a rate of 0.29°C and 0.047 per decade. Isobaric change decomposition into changes on neutral surfaces and changes due to the vertical displacement of the isoneutrals was performed. Results reveal that the lower part of North Atlantic Central Water (NACW) cooled and freshened on neutral surfaces, suggesting changes in the freshwater fluxes at the outcropping region. However, the signal in deep waters (1500–2300 db) was principally due to a downward displacement of the isoneutrals, although water mass modification is observed in the range of Mediterranean Water (MW) influence. **Citation:** Benítez-Barrios, V. M., A. Hernández-Guerra, P. Vélez-Belchí, F. Machín, and E. Fraile-Nuez (2008), Recent changes in subsurface temperature and salinity in the Canary region, *Geophys. Res. Lett.*, *35*, L07603, doi:10.1029/2008GL033329.

1. Introduction

[2] A suite of observations over different scales and regions supports an unequivocal conclusion: the climate system is changing. Temperature increase in the oceans, sea level rise and melting glaciers are some of the known responses to natural and/or anthropogenic forcing which highlight the important role of the ocean in climate change [*Bindoff et al.*, 2007]. The evaluation of long-term variations in the ocean is one of the keys for understanding how climate is changing and to identify the controlling mechanisms.

[3] Examination of repeated hydrographic sections over the subtropical North Atlantic have revealed a temperature increase at depths from 800 to 2500 m since the late 1950s [*Roemmich and Wunsch*, 1984; *Parrilla et al.*, 1994; *Vargas-Yáñez et al.*, 2004; *Cunningham and Alderson*, 2007]. Decomposition of the isobaric changes into water mass changes and changes due to the displacements of the isopycnals have shown that this warming trend is the result of both contributions [*Bryden et al.*, 1996; *Arbic and Owens*, 2001].

[4] In this paper we report that the Canary region has also undergone temperature and salinity changes in recent years. We analyze them in order to decompose these changes and interpret them in terms of variations in the surface forcing at the outcropping region.

2. Data Set and Method

[5] During the project Canary Islands Azores Gibraltar Observations (CANIGO) carried out in the 1990s, a section north of Canary Islands was accomplished on a seasonal basis [*Machín et al.*, 2006]. In February 2006, the Canary Deep Hydrographic Section (RAPROCAN) repeated the January 1997 CANIGO section with casts in both surveys coincident (Figure 1a). A total of 16 full-depth CTD stations were occupied, where spatial separation for the deep-water stations was 35 km, reduced to 15 km for the inner stations. Temperature and salinity profiles averaged over a 2-db interval were obtained using a CTD/rosette (Neil Brown in 1997 and SeaBird 911+ with dual sensors in 2006). Water samples were analyzed on a Guideline salinometer to calibrate the conductivity sensor, and showed an accuracy better than 0.002 for single samples (hereafter salinity is expressed in the Practical Salinity Scale). Temperature and pressure sensors were calibrated using WOCE standards.

[6] To evaluate the temperature and salinity variations in the water column, we have applied the model proposed by *Bindoff and McDougall* [1994]. They relate the variations in both pressure and density surfaces through the following equation:

$$\left.\frac{d\psi}{dt}\right|_z = \left.\frac{d\psi}{dt}\right|_{\gamma_n} - \left.\frac{dp}{dt}\right|_{\gamma_n}\frac{\partial\psi}{\partial p} \tag{1}$$

which represents the observed changes in a scalar quantity ψ along isobaric surfaces as the sum of two independent contributions: changes along neutral surfaces [*Jackett and McDougall*, 1997] and changes due to vertical displacement of the isoneutrals, referred to as heaving. $dp/dt|_{\gamma_n}$ denotes the isoneutral displacement and $\partial\psi/\partial p$ the vertical gradient of the quantity which is assumed to be constant over time. This allows the decomposition test by comparing the sum of the two components to the isobaric change.

[7] In order to apply the above methodology, temperature and salinity are interpolated onto a grid with a pressure interval of 50 db and 0.01 kg m^{-3} for neutral density, from the surface to 3000 db. Thus, differences and means along the transect are computed in both the geopotential and neutral coordinate frames. The 95% confidence intervals of the mean differences are based on a Student's t-test and

[1]Facultad de Ciencias del Mar, Universidad de Las Palmas de Gran Canaria, Las Palmas, Spain.
[2]Centro Oceanográfico de Canarias, Instituto Español de Oceanografía, Santa Cruz, Spain.
[3]Institut de Ciències del Mar, CSIC, Barcelona, Spain.

0094-8276/08/2008GL033329$05.00

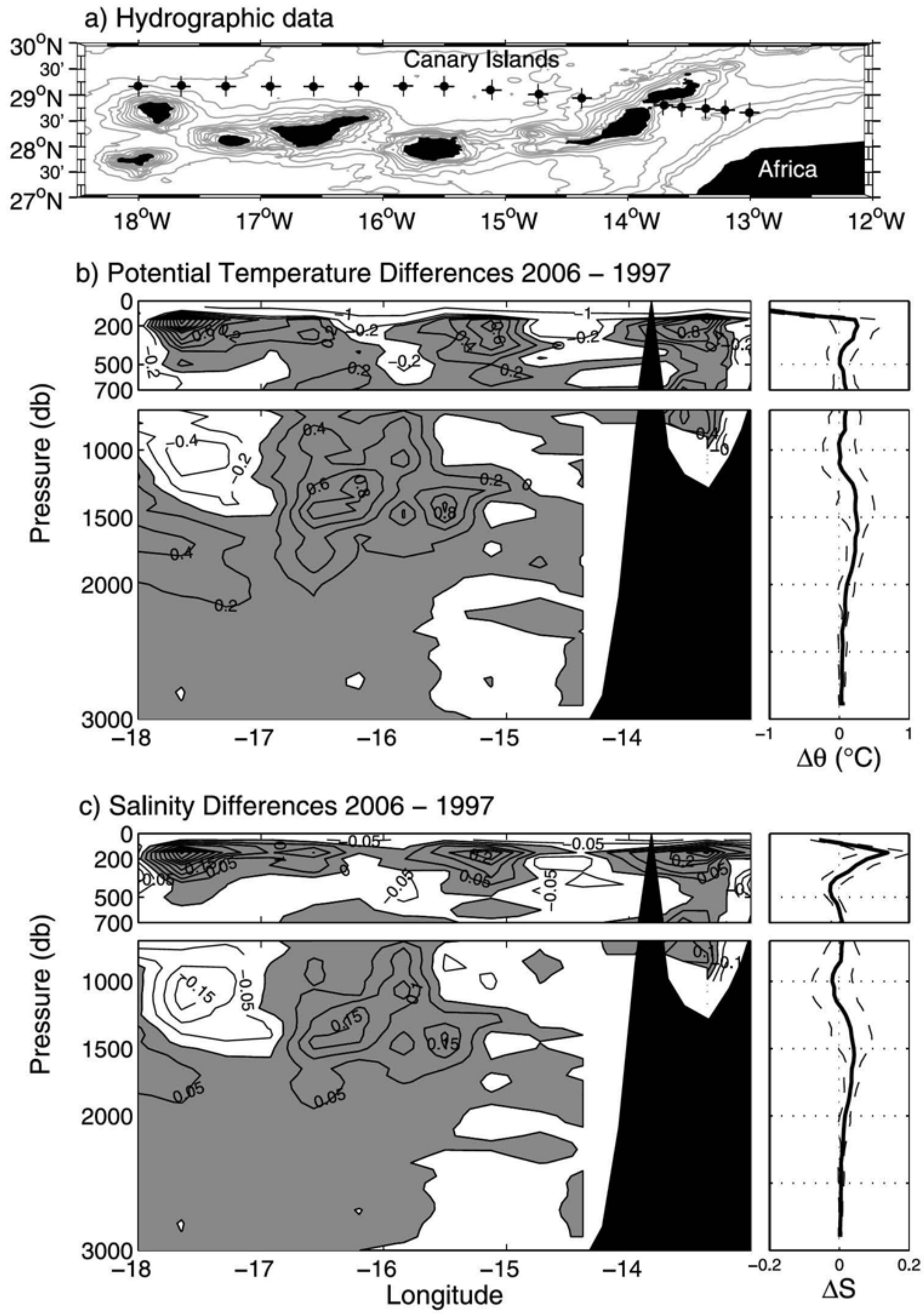

Figure 1. (a) Hydrographic stations carried out during CANIGO (1997, crosses) and RAPROCAN (2006, dots) cruises. (b) Potential temperature differences on isobaric levels. Differences contoured at 0.2°C intervals. The side partition is the zonally averaged difference of the potential temperature. The dashed lines stand for the 95% confidence intervals. (c) As for Figure 1b but for salinity. Difference contours at 0.05 intervals. Shaded areas indicate rising temperature and salinity over time.

take into account the loss of degrees of freedom at each pressure/neutral density surface due to eddy field autocorrelation.

3. Results

3.1. The θ/S Isobaric Changes

[8] Figures 1b and 1c display temperature and salinity differences and their zonal average to emphasize the principal changes. At first sight, both hydrographic variables follow a similar pattern characterized by a decrease of the property in the shallowest layer (0–100 db) with a remarkable homogeneity over the whole transect, this being statistically significant on the basis of 95% confidence intervals. This conspicuous decrease could be attributed to the influence of the atmosphere immediately above, which deepened the winter mixed layer 30 m more in 2006 than in 1997, cooling the surface to approximately

18°C. Below the mixed layer, North Atlantic Central Water (NACW) extends down to 600 db, defining the main thermocline. Within this water mass the principal changes are: (i) a pronounced increase in temperature and salinity (only significant for the latter) between 100 and 350 db, where values as large as 1.92°C and 0.46 are found in three patches along the section, and (ii) a decrease in salinity from 350 to 600 db while temperature remained unaffected. These differences imply that there have been changes which do not involve conservation of the θ/S properties.

[9] From 600 down to 1500 db, corresponding to intermediate layers, two well-differentiated water masses are evident: Antarctic Intermediate Water (AAIW) identified by a relative salinity minimum, and Mediterranean Water (MW) clearly distinguished by its salinity maximum [*Machín et al.*, 2006]. At these levels positive and negative differences alternate yielding a non-significant zonal average.

[10] In deep layers (>1500 db) consisting of North Atlantic Deep Water (NADW), a basin-wide band of warmer and saltier water is observed. This increment is statistically significant from 1500 to 2300 db, reaching the maximum of both difference-fields at about 1600 db where temperature and salinity rose at rates of 0.29°C and 0.047 per decade, respectively.

3.2. Isobaric Change Decomposition

[11] The temperature and salinity isobaric changes, their decomposition and the sum of the two components are plotted in Figures 2a and 2b. Except for the near surface, the sum of the components compares reasonably well with the isobaric change indicating that the decomposition has been successfully performed. In the thermocline waters, a subsurface layer of increased temperature and salinity on neutral surfaces led to significant salinification in the isobaric field. Conversely, the lower part of NACW cools and freshens on isoneutrals at a maximum rate of −0.26°C and −0.07 per decade, respectively. Hence, the mean θ/S diagram (Figure 3a), obtained from the zonally averaged temperature and salinity profiles at fixed pressure, reveals a cooler and fresher NACW curve in 2006. The lines linking points of equal pressure do not lie parallel to the isopycnals, indicating that displacement of neutral surfaces has occurred as observed in Figure 2c. Thus, the deepening of the neutral surfaces offsets the changes along neutral surfaces, resulting in non-significant changes on isobars at these levels.

[12] In intermediate waters, neither isobaric changes nor water mass changes are statistically significant (Figures 2a and 2b). Nevertheless, differences in temperature and salinity on neutral surfaces show negative values for AAIW and positive values for the MW as well as changes in their θ/S relationship (Figure 3b). Although these changes are not large enough to be significant, it can be seen from the lines linking points of equal pressure that they are influenced by the displacement of the isoneutrals. Thus, Figures 2a and 2b show isoneutral displacements from 1200 to 2300 db ($27.78 < \gamma_n < 28.01$ kg m^{-3}), with an averaged deepening of 30 db (Figure 2c), as the only significative contribution to the isobaric change in this pressure range. This is the principal reason for the increment in temperature and salinity along isobars in deep layers.

3.3. Warming, Freshening, and Heaving Mechanisms

[13] *Bindoff and McDougall* [1994] proposed three processes for interpreting the observed changes: pure warming, pure freshening and pure heave, involving their respective change in atmospheric forcing in the water mass source region. The first two are related to heat and freshwater fluxes, changing the water mass characteristics, and the third one is related to wind stress curl, renewal rates of water masses or internal waves. The relative strength of each process, in terms of percentage variance explained (A^w, A^f and A^h, where w, f and h stand for warming, freshening and heave, respectively), can be estimated solving the following equations [*Bindoff and McDougall*, 1994]:

$$\frac{\rho^{-1}\rho'|_z}{R_\rho - 1}\begin{pmatrix} -(R_\rho-1) & 0 & -R_\rho \\ 1 & R_\rho & 0 \\ R_\rho & R_\rho & R_\rho \\ 0 & (R_\rho-1) & -1 \\ 1 & R_\rho & 0 \\ 1 & 1 & 1 \end{pmatrix} \times \begin{pmatrix} A^w \\ A^f \\ A^h \end{pmatrix} = \begin{pmatrix} \alpha\theta'|_z \\ \alpha\theta'|_n \\ N'\alpha\theta_z \\ \beta S'|_z \\ \beta S'|_n \\ N'\beta S_z \end{pmatrix} \quad (2)$$

where $\rho^{-1}\,\rho'|_z$ is the density anomaly at fixed pressure, N' is the change in pressure of a neutral density surface, $|_z$ denotes changes on isobars, $|_n$ denotes changes along isoneutrals, and R_ρ ($R_\rho = \alpha\theta_z/\beta S_z$) is the stability ratio defined from the thermal expansion and the haline contraction coefficients, α and β, respectively, and the vertical gradients of temperature and salinity, θ_z and S_z. Although Equation (2) is an ill-posed system, the proportion of the variance explained by each process can be assessed by making the assumption that only a single process is acting and applying an inverse method. We have distinguished four pressure regimes where a single process tends to dominate (Figure 4). In Regime I (350–600 db), corresponding to the lower levels of NACW, pure freshening explains more than 95% of the variance, suggesting water mass modification at the outcropping region. This result is expected based on the shift of the θ/S relationship shown in Figure 3a. Between 600 and 900 db (Regime II), the observed changes can be explained by pure heave and by pure freshening in Regime III (900–1200 db), both statistically significant at the 90% level. At deeper layers (Regime IV) the percentage of the overall variance

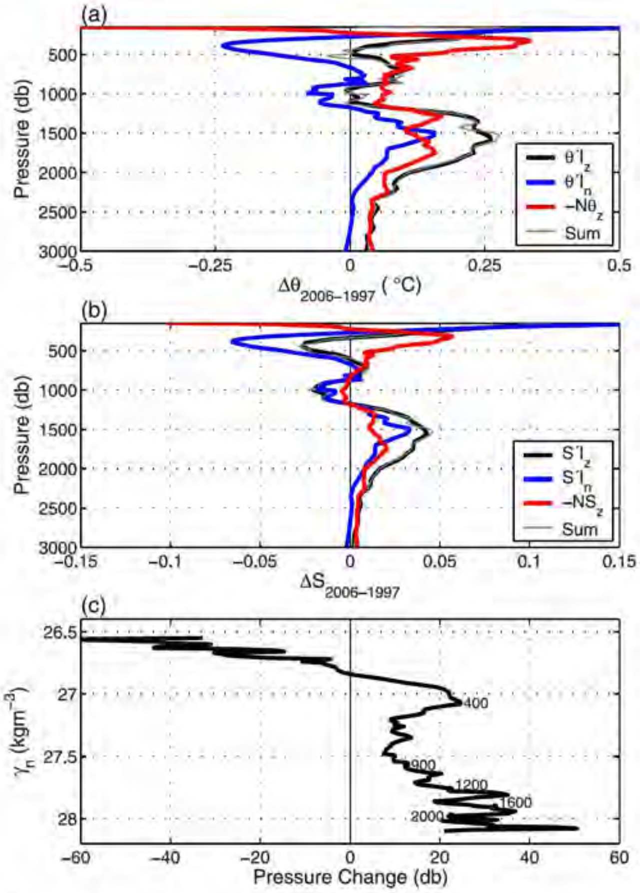

Figure 2. (a) Isobaric change from 1997 to 2006 ($\theta'|_z$ and $S'|_z$, black) decomposed into changes along neutral surfaces ($\theta'|_n$ and $S'|_n$, blue) and changes due to the vertical displacements of isoneutrals ($-N\theta_z$ and $-NS_z$, red) as a function of the average pressure of the neutral surfaces. The grey line denotes the sum of both components. (b) As for Figure 2a but for salinity. (c) Change in pressure of neutral surfaces from 1997 to 2006. Positive displacements indicate downward movement over time. Dots represent zonally-averaged isoneutral pressures.

resolved drops. However, pure heave explains 60–90% of the signal over the deepest levels of intermediate waters and NADW.

4. Discussion and Conclusion

[14] We analyze the temperature and salinity changes that occurred in the Canary region from two hydrographic sections carried out in 1997 and 2006 by decomposing the isobaric changes into changes along isoneutrals and changes due the vertical movement of the neutral surfaces. In order to interpret them we compute the percentage of the variance explained by pure warming, pure freshening and pure heaving mechanisms. The results found here concur with the variations for the subtropical North Atlantic Ocean and its large scale circulation.

[15] The NACW presents a subsurface layer (100–350 db) of temperature and salinity increases on isoneutrals, whereas its lower part (350–600 db) is cooled and freshened at a maximum rate of −0.26°C and −0.07 per decade leading to a shift in the θ/S relationship. The latter is in agreement with findings by *Vargas-Yáñez et al.* [2004] and *Cunningham and Alderson* [2007] of temperature and salinity decrease along the isoneutrals of the 24°N eastern thermocline between the 1990s and early 2000. Moreover, the salinity diminution in NACW has been documented previously; for example *Pérez et al.* [1995] noted that the salinity on $\sigma_\theta = 27.1$ dropped 0.2 between 1974 and 1982, remaining fresh until 1990. Since pure freshening explains more than 95% of the data variance, we suggest that this might be caused by changes in the balance of precipitation and evaporation taking place in the formation region of NACW, which was subsequently transported into the Canary region by circulation.

[16] The rise in temperature and salinity on isobars found in the range 1500–2300 db has been reported in previous studies. *Roemmich and Wunsch* [1984] were the first to estimate long-term changes along 24°N and 36°N, making a direct comparison of temperature on isobars between 1981 and the International Geophysical Year (IGY) surveys in the late 1950s. They found that the temperature had increased between 700 and 3000 m, with a maximum difference of 0.2°C at 1000–1500 m. The study of the 24°N changes was extended by *Parrilla et al.* [1994], adding a survey carried

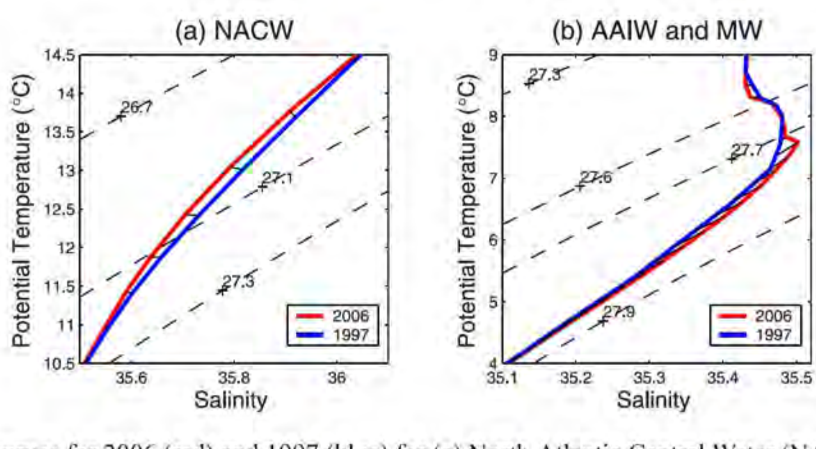

Figure 3. Mean θ/S curves for 2006 (red) and 1997 (blue) for (a) North Atlantic Central Water (NACW) and (b) Antarctic Intermediate Water (AAIW) and Mediterranean Water (MW). The dashed lines correspond to potential density anomaly isolines, and the solid lines link points of equal pressure.

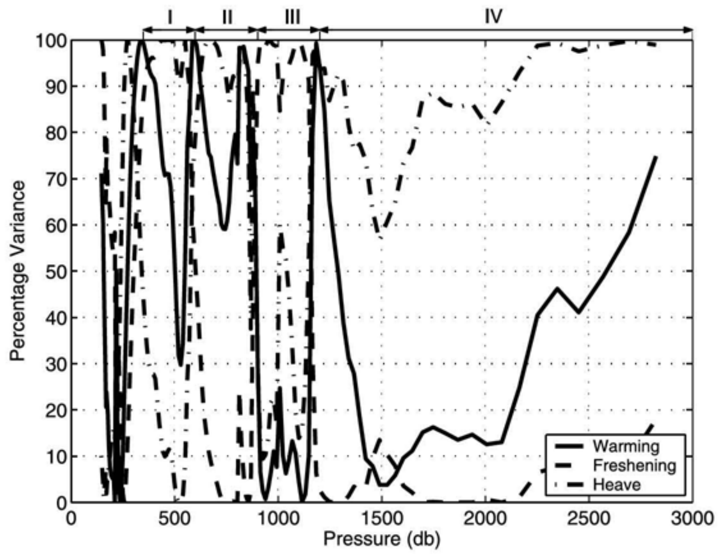

Figure 4. The variance explained for the case of pure warming (continuous), pure freshening (dashed), and pure heave (dashed-dotted) against the average pressure of the neutral surfaces. Four different pressure regimes are shown at the top of the figure.

out in 1992. They found that the warming had continued with a maximum increment of 0.32°C at 1100 m over the period 1957–1992, equivalent to an increase rate of 0.1°C/decade. Our results show an increase in temperature three times higher than that estimated from *Parrilla et al.* [1994]. However, when splitting the North Atlantic sections into western and eastern basins, our isobaric trend of temperature and salinity match remarkably well those reported by *Arbic and Owens* [2001] for the eastern part of 24°N between 1981 and 1992. These authors found that both downward movement of the isopycnals and water mass changes (higher temperature and salinity on isopycnal surfaces) contributed to the changes along isobars. This result is consistent with the pure heave regime observed from 1200 to 3000 db in this study, the downward displacement of the isoneutrals being the main reason for the isobaric change. We also found increments in temperature and salinity on neutral surfaces which could be associated with the warming and salinification of the waters from the Mediterranean, revealed in recent studies [*Millot et al.*, 2006; *Potter and Lozier*, 2004]. Therefore, the MW modification and mixing with the upper levels of NADW during its southward flow, could be a plausible explanation for the percentage of variance explained by pure warming at these levels.

[17] All these studies underline the fact that changes do not occur uniformly over time and space. Hence, similar repeated observations on regional and larger scales should continue in order to assess climate change. This will enable us to gain a better understanding about the relationship of regional to global changes.

[18] **Acknowledgments.** The first author is supported by a grant received from the Canary Government. This work has been supported by the European Union project CANIGO (MAS3-CT96-0060) and the Spanish Government project ORCA (CMT2005-04701-C02-01). The authors wish to thank Manuel Vargas-Yáñez and Angelo Santana for their assistance in the statistical analysis.

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.

Bindoff, N. L., et al. (2007), Observations: Oceanic climate change and sea level, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 385–433, Cambridge Univ. Press, New York.

Bryden, H., M. J. Griffiths, A. 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.

Cunningham, S. A., and S. Alderson (2007), Transatlantic temperature and salinity changes at 24.5°N from 1957 to 2004, *Geophys. Res. Lett.*, *34*, L14606, doi:10.1029/2007GL029821.

Jackett, D., and T. McDougall (1997), A neutral density variable for the world's oceans, *J. Phys. Oceanogr.*, *27*, 237–263.

Machín, F., A. Hernández-Guerra, and J. L. Pelegrí (2006), Mass fluxes in the Canary Basin, *Prog. Oceanogr.*, *70*, 416–447.

Millot, C., J. Candela, J. Fuda, and Y. Tber (2006), Large warming and salinification of the Mediterranean outflow due to changes in its composition, *Deep Sea Res., Part I*, *53*, 656–666.

Parrilla, G., A. Lavín, H. Bryden, M. García, and R. Millard (1994), Rising temperatures in the subtropical North Atlantic Ocean over the past 35 years, *Nature*, *369*, 48–51.

Pérez, F., A. F. Ríos, B. A. King, and R. T. Pollard (1995), Decadal changes of the θ-S relationship of the Eastern North Atlantic Central Water, *Deep Sea Res., Part I*, *42*, 1849–1864.

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.

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.

V. M. Benítez-Barrios and A. Hernández-Guerra, Facultad de Ciencias del Mar, Universidad de Las Palmas de Gran Canaria, E-35017 Las Palmas, Spain. (veronica.benitez102@doctorandos.ulpgc.es)

E. Fraile-Nuez and P. Vélez-Belchí, Centro Oceanográfico de Canarias, Instituto Español de Oceanografía, E-38005 Santa Cruz, Spain.

F. Machín, Institut de Ciències del Mar, CSIC, E-08003 Barcelona, Spain.