On the warming and salinification of the Mediterranean outflow waters in the North Atlantic

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[1] Based on hydrographic data collected since 1955, Mediterranean outflow waters present in the eastern North Atlantic show a density compensated increase in both temperature and salinity. With an increase in temperature of 0.101 ± 0.024°C/decade and an increase in salinity of 0.0283 ± 0.0067 psu/decade in the Mediterranean outflow waters, the heat content gain from 1955 to 1993 is calculated to be $2.02 \pm 0.31 \times 10^6$ J/m^3, which surpasses the average gain in heat content of the North Atlantic basin over the latter half of the 20th century. This suggests that the Mediterranean outflow waters are an important contributor to climatological changes at intermediate depths within the mid-latitude North Atlantic. *INDEX TERMS:* 1635 Global Change: Oceans (4203); 4215 Oceanography: General: Climate and interannual variability (3309); 4283 Oceanography: General: Water masses; 4271 Oceanography: General: Physical and chemical properties of seawater. **Citation:** 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.

1. Introduction

[2] The importance of the ocean's role in global climate change has been highlighted by recent evidence that the world's oceans have warmed over the past fifty years [*Levitus et al.*, 2000] and that the attendant increase in the ocean's heat content is an order of magnitude larger than the increase in the atmospheric and cryospheric heat content over the same period [*Levitus et al.*, 2001]. Thus, a determination of how climate is changing in response to long-term natural and/or anthropogenic forcing depends on our understanding of how climate signals are transmitted from the surface to the deep ocean and then distributed laterally throughout the basins. While past studies have shown that convection is an effective mechanism by which climate signals are transmitted to depth, the primary focus has been on convective water masses formed at high latitudes in the North Atlantic [*Curry et al.*, 1998; *Dickson et al.*, 1996, 2002]. Here we show that the Mediterranean outflow water (MOW), a convective water mass found in the eastern subtropical North Atlantic, has significantly increased in temperature and salinity over the past fifty years. The resultant heat content gain suggests that MOW has been an important source of warming at mid-depth in the North Atlantic.

2. Background

[3] Studies of long-term changes in hydrographic sections that slice through the subtropical North Atlantic [*Arbic and Owens*, 2001; *Bryden et al.*, 1996; *Joyce et al.*, 1999; *Parrilla et al.*, 1994; *Roemmich and Wunsch*, 1984] have consistently revealed a maximum warming near the base of the thermocline, located at ~1000–1200 m. Property changes at depth can be broadly attributed to either the vertical movement of density surfaces past a fixed depth, referred to as heaving, or to changes in the property of the water mass that occupies that depth [*Bindoff and McDougall*, 1994]. In the former case, the density surfaces may be responding to basin-scale changes in wind-forcing, to planetary waves and/or to volumetric changes of water masses, while for the latter case it is expected that buoyancy changes at the surface have produced changes in water mass properties at depth. Decompositions of the observed temperature changes from repeat sections in the subtropical North Atlantic have shown that temperature increases over the past fifty years are attributable to both heaving and water mass change; however, the warming along 24°N at ~1100 m, has been shown to result principally from water mass changes [*Bryden et al.*, 1996].

[4] Interestingly, the core of the waters that flow out of the Mediterranean Sea and into the North Atlantic lies principally at the depth of the maximum in warming. The surface waters of the Mediterranean Sea, subject to strong evaporation and cool winter temperatures, are transformed into subsurface waters that flow through the Strait of Gibraltar into the North Atlantic basin. After exiting the Strait, the Mediterranean waters mix with North Atlantic Central Waters in the Gulf of Cadiz [*Baringer and Price*, 1997] before continuing westward and northward into the North Atlantic [*Iorga and Lozier*, 1999] (Figure 1a). Past studies have revealed significant property changes for the two convective water masses within the Mediterranean Sea that constitute the overflow waters. There is general agreement that the salinity and temperature of one component, Western Mediterranean Deep Water (WMDW), have significantly increased over the past several decades [*Bethoux and Gentili*, 1999; *Bethoux et al.*, 1990; *Krahmann and Schott*, 1998; *Leaman and Schott*, 1991; *Rohling and Bryden*, 1992]. However, while long-term temperature [*Bethoux and Gentili*, 1999] and salinity increases [*Bethoux and Gentili*, 1999; *Rohling and Bryden*, 1992] for the principal contributor to the overflow waters, Levantine Intermediate Water (LIW), have also been reported, one study [*Krahmann

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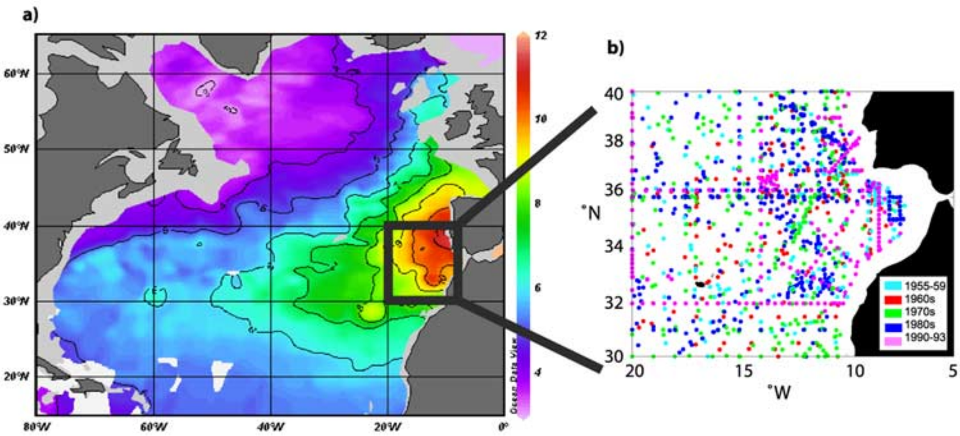

Figure 1. (a) Potential temperature (°C) at 1200 m; (b) The spatial and temporal distribution of the hydrographic data points at 1200 m.

and Schott, 1998] found no significant property trends for this water mass in the western Mediterranean. To date, the long-term variability of the overflow waters in the open North Atlantic, the focus of this work, remains unexamined.

3. Results and Discussion

[5] For our study we examined historical hydrographic station data acquired from the National Oceanic Data Center and the WOCE Hydrographic Program. Following quality control of the hydrographic data [*Lozier et al.*, 1995], which effectively removed local anomalies such as Meddies [*Richardson et al.*, 2000], a total of 4,336 hydrographic profiles, were available over the study domain shown in Figure 1b. Property anomalies (with the climatological mean subtracted from each observation) were averaged over the spatial domain to construct a time series for the MOW properties for a range of density and pressure surfaces. To focus on changes related specifically to the MOW, individual hydrographic profiles were examined for a mid-depth salinity maximum, a characteristic feature of the MOW in the eastern North Atlantic (Figure 2a). Time series for the temperature, pressure and density associated with each salinity maximum were constructed as described above.

[6] The maximum salinity associated with the MOW in the eastern North Atlantic (Figure 2b) shows an increase over the past forty years (0.0283 ± 0.0067 psu/decade). Likewise, MOW temperature has increased on the order of 0.101 ± 0.024°C/decade. This warming, totaling close to 0.4°C over the course of the observational record, far exceeds the average warming of the North Atlantic basin, 0.06°C [*Levitus et al.*, 2000]. Both of these linear trends are appreciable, accounting for over 72% and 88% of the variance in temperature and salinity anomaly time series, respectively. Notably, changes in temperature and salinity are highly correlated ($r = 0.84$), suggesting long-term temperature and/or salinity changes are density-compensated. In support of this evidence is the lack of a long-term trend in the MOW density. The depth of the salinity maximum waters also shows no linear increase; however, pressure and density do exhibit interannual variability over the observational record. The pressure changes are highly correlated ($r = 0.69$) with density changes: as the density of the MOW increases (decreases) the depth of the core waters sinks (shoals), as expected. It is supposed that such interannual variability is responsible for the decreasing temperatures and salinities from 1990 to 1993, the latest data available, but, only further observations can confirm or dispel this supposition.

[7] To determine whether the warming and salinification at mid-depth are linked to changes throughout the water column and/or characteristic only of the overflow waters, the salinity and temperature time series for constant pressure and density surfaces, from the sea surface to approximately 1500 m (below the MOW core; Figure 2a), were analyzed. Though property changes on pressure surfaces are useful for evaluating the vertical extent of changes, density surfaces are analyzed in order to isolate the effect of water mass changes. Slopes from the application of a linear regression to temperature time series for each density surface are plotted alongside the vertical profile of the climatological salinity (averaged over the study domain) (Figure 3). Also shown are standard errors of estimates and correlations of determination (a measure of the goodness of fit of the regression curves) for each time series. An examination of this profile reveals that surfaces at intermediate depths are marked by significant long-term increases in temperature. Importantly, the peak of the temperature increase (0.153 ± 0.029°C/decade) is coincident with the maximum salinity at mid-depth, strongly implicating the MOW as the source of the long-term warming. Likewise, the correlation of determination is maximized at the core of the MOW, where nearly 80% of the variance is explained by the linear trend. On these constant density surfaces, the salinity slopes (not shown) mimic temperature slopes. Thus, the salinity slope is also maximized at the density of the core MOW (32.20) at 0.0371 ± 0.0069 psu/decade. While these changes on density surfaces are matched by significant long-term temperature and salinity changes on pressure surfaces over nearly 800 m of the water column, a decomposition of the temporal changes due to heaving and those due to water mass change show the dominance of the latter [*Potter*, 2002], consistent with *Arbic and Owens* [2001, see Figure 6a]. Additionally, an examination of a temperature-

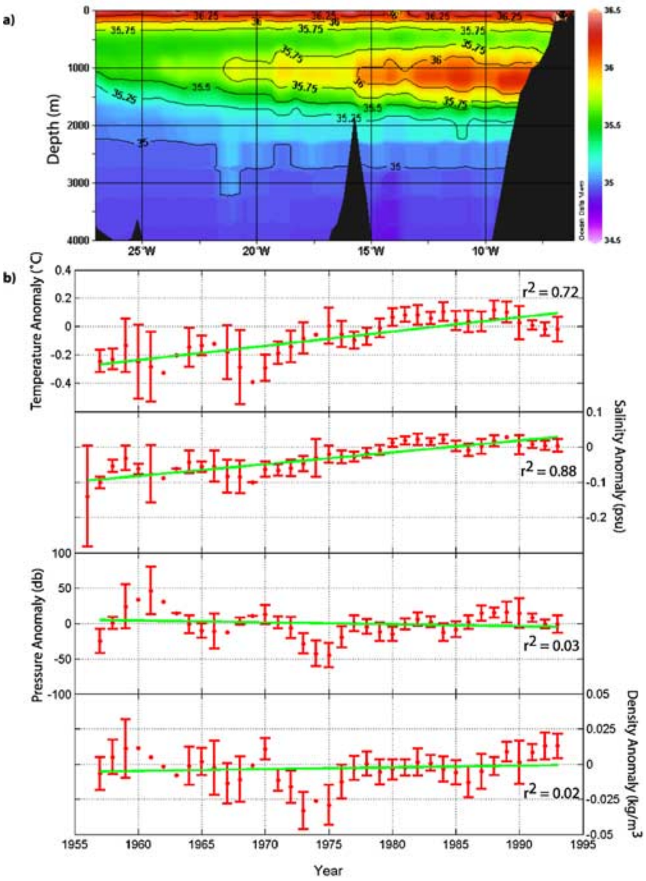

Figure 2. (a) 36°N cross-section of the climatological salinity field (psu) showing the MOW mid-depth salinity maximum; (b) Time series for potential temperature, salinity, potential density and pressure anomalies of the core MOW waters. Values over the spatial domain are averaged in one-year time bins from 1955 to 1993 and smoothed using a 3-point moving average. Standard errors for annual means are shown as error bars. Points without error bars were interpolated. In green is a linear regression fit to each time series, and the correlation of determination for each fit is given as the r^2 value. To address concerns that long-term trends in the time series may be an artifact of increasing vertical resolution of measurements over time, for each station we selected the measurement closest to 1150 m (±15 m) regardless of whether there was a clearly identifiable maximum. Measurements were evenly distributed around 1150 m and showed no appreciable temporal trend in their depth. Time series of temperature and salinity anomalies constructed from these measurements yielded trends within error from those associated with the maximum salinity points. Additionally, property changes on standard level surfaces and isopycnals show increases away from the MOW core. The salinity changes shown are an order of magnitude greater than those attributed to a measurement bias in historical data [*Gouretski and Jancke*, 2001].

salinity diagram using all station data shows the warming and salinification of the Mediterranean water mass over time. However, it is also noted that the correlation of the temperature time series on the 1200 m surface and the 32.20 density surface with the North Atlantic Oscillation [*Hurrell*, 1995] produces correlation coefficients of 0.44 and 0.22, respectively. Since the correlation is strongest on the pressure surface, there is reason to believe that mid-depth heaving may be partially explained by wind forcing changes associated with this decadal variability.

[8] Changes in the upper water column on both density and pressure surfaces show a slight cooling and freshening of the waters, though the change is not as significant as the change at mid-depth. In general, changes in the upper water column have been shown to result primarily from heaving [*Potter*, 2002]; however, the cooling and freshening centered around 400 m appear to result from water mass changes. Interestingly, a comparison of temperature time series for both the 300 m and the 27.00 density surface with the North Atlantic Oscillation produced relatively weak correlations (−0.10 and −0.17, respectively, at zero time lag), notably weaker than those at depth. The source of the variability in the upper water column and its possible link to changes at mid-depth warrant further investigation.

[9] Given the horizontal and vertical extent (900–1300 m) of the warmed waters, the heat content gain from 1955 to 1993 is calculated to be $2.02 \pm 0.31 \times 10^6$ J/m^3. This increase is comparable to the reported increase for waters <300 m in the North Atlantic, 2.95×10^6 J/m^3 [*Levitus et al.*, 2000], yet much greater than the average increase for waters <3000 m, 0.417×10^6 J/m^3, pointing to MOW as a significant source of warming for the mid-depth waters of the North Atlantic. The observed MOW trends are qualitatively consistent with the warming and salinification

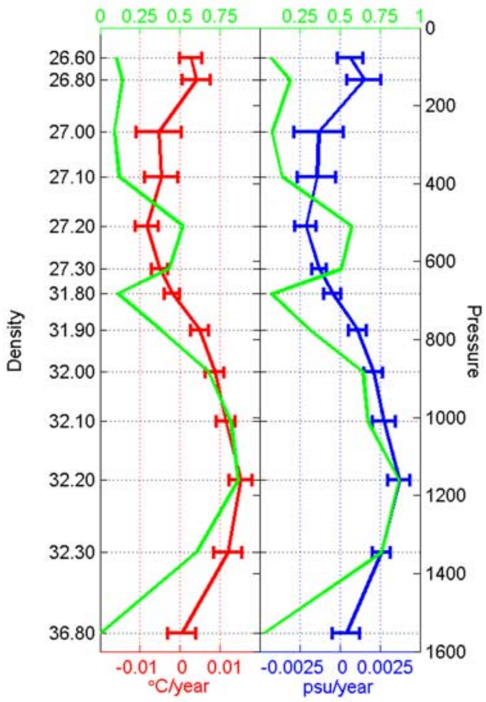

Figure 3. (a) Slopes (red) with standard errors of the estimate, from a linear regression of the potential temperature anomaly time series for each density surface. The correlations of determination for each time series are in green. (b) Mean salinity (blue) on each potential density surface. For the projection of the station data onto density and pressure surfaces, a cubic spline was used.

of LIW and WMDW, which have been attributed to anthropogenic causes (river damming) [*Bethoux and Gentili*, 1999; *Krahmann and Schott*, 1998; *Rohling and Bryden*, 1992], greenhouse-gas-induced local warming [*Bethoux and Gentili*, 1999; *Bethoux et al.*, 1990], and/or, for the case of WMDW, interannual variability mainly associated with the North Atlantic Oscillation [*Krahmann and Schott*, 1998]. Based on reported long-term property changes of these water masses and their expected relative contributions to the waters that leave the Mediterranean Sea, a long-term increase of approximately 0.1°C and 0.02 psu per decade would be expected for waters exiting the Strait of Gibraltar. While these estimates are remarkably close to the observed property changes of the MOW reported here, overflow waters that occupy the eastern North Atlantic are created by a mixture of the warm and salty waters flowing out of the Strait of Gibraltar and the surrounding, relatively cold and fresh North Atlantic Central Water. *Baringer and Price* [1997] determine the ratio between MOW and NACW to be 1:3 near the Strait of Gibraltar, while an earlier study [*Zenk*, 1975] reported an entrainment rate of 32:68 in the Gulf of Cadiz. Thus, it would be expected that long-term property changes in the open Atlantic would be considerably less than those found for constituent water masses in the Mediterranean Sea. Additionally, the reservoir of MOW in the eastern North Atlantic would provide a buffer for changes in the source waters, mitigating the property changes. Uncertainty regarding the temporal changes within the Mediterranean Sea, the source for the overflow waters or the mixing of the overflow waters upon entering the open Atlantic may be responsible for this discrepancy. However, as pointed out by *Baringer and Price* [1997], the "recipe" for the mixed water would lead one to suspect that property changes at mid-depths in the eastern North Atlantic would more likely be caused by NACW changes rather than changes in the source waters within the Mediterranean. Certainly the quandary surrounding the magnitude of these changes suggests this possibility, yet it is difficult to explain why the warming and salinification are maximum at the core of the Mediterranean waters. Additionally, an examination of temporal changes over a larger spatial domain (10–50°N and 7–40°W) revealed that the warming is largely restricted to the eastern North Atlantic, specifically focused on the area of the MOW [*Potter*, 2002]. Thus, based on our study, we conclude that the most likely source of the warming and salinification are the outflow waters. Clearly, however, the magnitude of these property changes in the eastern North Atlantic raise interesting questions about the mixing and advective pathways of MOW climatic anomalies.

4. Summary

[10] Overall, the salinification of MOW stands in sharp contrast to the observed freshening of high latitude surface waters and, subsequently, the freshening of the convective water masses in the northern North Atlantic [*Dickson et al.*, 2002]. Though surface freshening limits convective overturning at high latitudes [*Hansen et al.*, 2001], the warming and/or salinification of Mediterranean surface waters are apparently density-compensated. Hence, increasingly warmer and saltier waters continue to sink at the same density and depth. If high latitude waters continue to freshen, the bulk of the convective activity that sends heat to the deep ocean may fall to source waters at mid-latitudes.

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