NOTES AND CORRESPONDENCE

On the Temporally Varying Northward Penetration of Mediterranean Overflow Water and Eastward Penetration of Labrador Sea Water

M. SUSAN LOZIER AND NICOLE M. STEWART*

Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, North Carolina

(Manuscript received 7 September 2007, in final form 21 December 2007)

ABSTRACT

Historical hydrographic data in the eastern North Atlantic are used to suggest a connection between the northward penetration of Mediterranean Overflow Water (MOW) and the location of the subpolar front, the latter of which is shown to vary with the North Atlantic Oscillation (NAO). During persistent high-NAO periods, when the subpolar front moves eastward, waters in the subpolar gyre essentially block the northward-flowing MOW, preventing its entry into the subpolar gyre. Conversely, during low NAO periods, the subpolar front moves westward, allowing MOW to penetrate past Porcupine Bank into the subpolar gyre. The impacts of an intermittent penetration of MOW into the subpolar gyre, including the possible effect on water mass transformations, remain to be investigated.

1. Introduction

Subsurface pathways of newly ventilated ocean waters play a critical role in the climate system as they establish the global transport of heat, salt, and other properties. Though a recent focus has centered on the deep-water masses emanating from the Nordic and Labrador Seas, the ultimate fate of the warm and salty waters that flow out of the Mediterranean Sea, through the Strait of Gibraltar, and into the North Atlantic remains unanswered despite decades of scrutiny. Interest in the pathway of this water mass [Mediterranean Overflow Water (MOW)], particularly in its northward penetration, has been sustained because it is conjectured to be a source of heat and salt for the high-latitude waters involved in the global meridional overturning circulation. While one study (Reid 1979) has indicated that MOW flows from the subtropical to the subpolar gyre via an eastern boundary current, a few later studies (McCartney and Mauritzen 2001; New et al. 2001; Iorga and Lozier 1999) were unable to find evidence that the MOW core exists past Porcupine Bank (Fig. 1a), the geographic divide between the two gyres. Here we use historical hydrographic data to show that the penetration of the MOW into the subpolar gyre varies temporally.

Though the controversy concerning the fate of the MOW often centers on whether these waters find their way to the Nordic Seas via a passage in the Rockall Trough, the source of contention actually starts upstream: there is general agreement that these warm and salty waters flow northward from the Strait of Gibraltar as a coherent middepth boundary current along the eastern coast of the basin and that this boundary current continues along the Iberian Peninsula, into the Bay of Biscay, and onward toward Porcupine Bank (Fig. 1a). Temperature, salinity, oxygen, and silica data from 1957 to 1971 were used in a study (Reid 1979) several decades ago to argue that MOW flows northward well past Porcupine Bank, yet a more recent study (Iorga and Lozier 1999) using climatological mean fields from historical data over the period 1904–90 was unable to detect a core of MOW waters past Porcupine Bank. This absence is consistent with the suggestion (McCartney and Mauritzen 2001) that MOW penetration into the subpolar gyre is blocked by the eastward-flowing

* Current affiliation: URS Corporation, Herndon, Virginia.

Corresponding author address: M. Susan Lozier, Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, NC 27708.
E-mail: mslozier@duke.edu

DOI: 10.1175/2008JPO3908.1

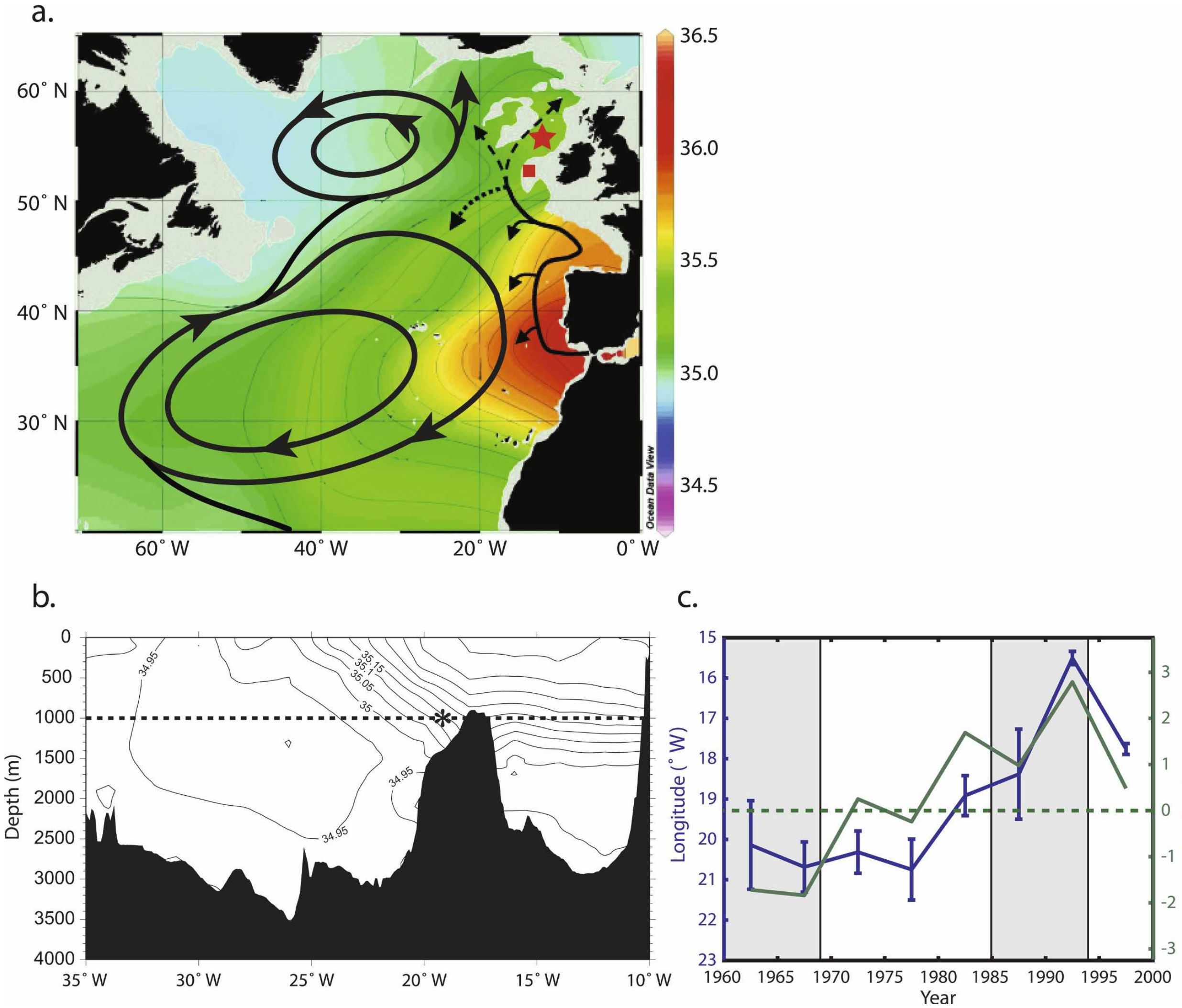

FIG. 1. (a) Schematic of the middepth circulation features in the eastern North Atlantic, superimposed on a map of the climatological salinity field (psu) at 1000 m produced with Ocean Data View. Solid black lines represent the circulation pathways for the subpolar gyre, subtropical gyre, and MOW. The dashed lines represent a conjectured northward penetration of MOW, while the dotted line represents the conjectured recirculation of the MOW within the subtropical gyre. The star (square) designates the location of Rockall Trough (Porcupine Bank). (b) Climatological salinity cross section at 55°N. The outcropping isohalines near 22°W indicate the location of the surface subpolar front. In this study, the subsurface subpolar front is defined as the longitude where the 35.10 isohaline intersects 1000 m (dashed line), as marked with an asterisk. The climatological salinity field is calculated using the historical hydrographic data discussed in section 3a. (c) Time series of the location of the subpolar front and the NAO index. The blue line is the longitudinal location of the front, and the green line is Hurrell's winter NAO index, averaged over the same pentad as the front. The 0 position of the NAO index is marked by the green dashed line. The coefficient of determination between these two time series (r^2) is 0.66 ($p < 0.01$). Gray shading denotes a predominantly NAO− (NAO+) time period: 1960–69 (1985–94). For the eight pentads beginning with 1960–64 and ending with 1995–99, 10, 31, 119, 69, 37, 121, 111, and 56 hydrographic stations, respectively, were used for the estimation of the subsurface subpolar front.

North Atlantic Current, whose reach is believed to extend to Porcupine Bank and whose volumetric flux [~12 Sv (1 Sv ≡ 10^6 m^3 s^{-1})] is far greater than that of MOW (~1 Sv). Thus, while one view (Reid 1979) supports a direct, advective pathway for the MOW to enter the subpolar gyre, another (McCartney and Mauritzen 2001) argues that the MOW advective pathways are restricted to the subtropical gyre and that any influence of the MOW on the subpolar waters would be indirect, via mixing with the waters in the North Atlantic Current, which are carried into the subpolar gyre.

2. Hypothesis of temporally varying MOW northward pathway

The two views of ocean circulation in the eastern basin of the North Atlantic, explained above, appear irreconcilable unless one allows for the temporal variability of the flow fields. The North Atlantic Oscillation (NAO), the dominant mode of variability in the North Atlantic basin on decadal time scales (Hurrell 1995), has recently been shown to create a strong oceanic wind-driven response (Bersch et al. 1999; Flatau et al. 2003; Hakkinen and Rhines 2004). Strong winds, present during a high NAO period, act to spin up and expand the subpolar gyre, as evidenced in hydrographic data collected during the 1990s: the eastern limb of the subpolar front is observed to shift eastward toward the British Isles (Bersch et al. 1999) in response to a strengthening of the westerlies. The expansion and contraction of the subpolar gyre in response to variable wind strength pose an interesting question: Is the northward penetration of MOW dependent on the expansion and contraction of the subpolar gyre? In response to this query, we formed a hypothesis: during prolonged low NAO periods when the subpolar gyre contracts, the subpolar front moves westward, allowing for a northward penetration of MOW into the Rockall Trough. Conversely, during prolonged high NAO periods when the subpolar gyre expands, the subpolar front shifts eastward, essentially blocking the northward-flowing MOW from entering the subpolar gyre (Fig. 1a). While past studies (Koltermann et al. 1999; Dickson et al. 1996; Krahmann and Schott 1998) have demonstrated the effect of the NAO on intermediate water mass properties and transports, our hypothesis is focused on the response of water mass pathways. An affirmation of this hypothesis would erase the irreconcilability of the earlier studies: the study that supports the northward penetration of MOW into the subpolar gyre used data collected between 1957 and 1971, encompassing a prolonged low NAO index, while the contradictory studies used either climatological mean data or data collected primarily from the 1980s and 1990s, a persistent high NAO index time period.

3. Test of hypothesis

a. Movement of the eastern limb of the subpolar front

To test this hypothesis, we use historical hydrographic data from the North Atlantic (Lozier et al. 1995; Curry 1996; Gregory 2004) and first investigate the dependence of the subpolar front position on wind strength over the past 50 yr, the time period over which data density in the region is sufficient for this analysis. Because we are interested in the penetration of MOW along the eastern boundary of the basin, we investigate changes in the position of the salinity front that defines the eastern limb of the subpolar gyre (Fig. 1b). To construct a time series of the subpolar frontal position, salinities within 30°–10°W and 53°–57°N at 1000 m were divided into pentads. For each pentad, all salinities within the spatial domain were linearly interpolated to 55°N in 1° bins in longitude. From the gridded salinities, the longitudinal position of the 35.1 isohaline was determined for each pentad. The uncertainty in the longitudinal position of the isohaline was calculated from a Monte Carlo technique: random salinity uncertainties of Gaussian distribution were added to the individual salinity measurements in 100 different realizations. The standard deviations of the resulting isohaline positions were used as a proxy for position uncertainty. With this method, the movement of the subpolar front at the approximate depth (1000 m) at which MOW would enter the subpolar gyre was tracked. As seen in Fig. 1c, there is a correlation between the location of the subpolar front and NAO. During low NAO periods, the subpolar front retreats westward, while during high NAO periods, the subpolar front advances eastward.

b. Temporal variability of eastern North Atlantic salinity anomalies

The effect of the shifting eastern limb of the subpolar front is evident from an inspection of the salinity anomalies in the eastern basin, at the density of the MOW core, $\sigma_1 = 32.10$ (Fig. 2). Salinity anomalies are calculated using a standard for North Atlantic Central Water (NACW): for each observed temperature (T_{observed}) a salinity for NACW was calculated using the established *T*/*S* relationship for NACW (Armi and Bray 1982); thus, S_{NACW} is the salinity of NACW given T_{observed}. A salinity anomaly was then defined as $S' = S_{\text{observed}} - S_{\text{NACW}}$. Positive salinity anomalies, which indicate that the waters are saltier than the NACW (Armi and Bray 1982) that fills the subtropical gyre, are associated with the relatively salty MOW; the strength of the anomalies, maximized in the vicinity of the Strait of Gibraltar, degrades westward and northward along the advective–diffusive pathways for this water mass. Though the overall distribution of salinity anomalies in the basin is similar between the two time periods studied, during a low NAO period (1960–69; Fig. 2a), the salinity anomalies are much stronger in the vicinity of Porcupine Bank and on into the Rockall Trough than they are during a high NAO period (1985–94; Fig. 2b). We conjecture that the sharp decline in the salinity anomalies past Porcupine Bank during the high NAO period is an indication that an expanded subpolar gyre limits the import of MOW into the subpolar basin.

Further evidence of the subpolar gyre's expansion during an extended high NAO period comes from an examination of salinity anomalies on a deeper density

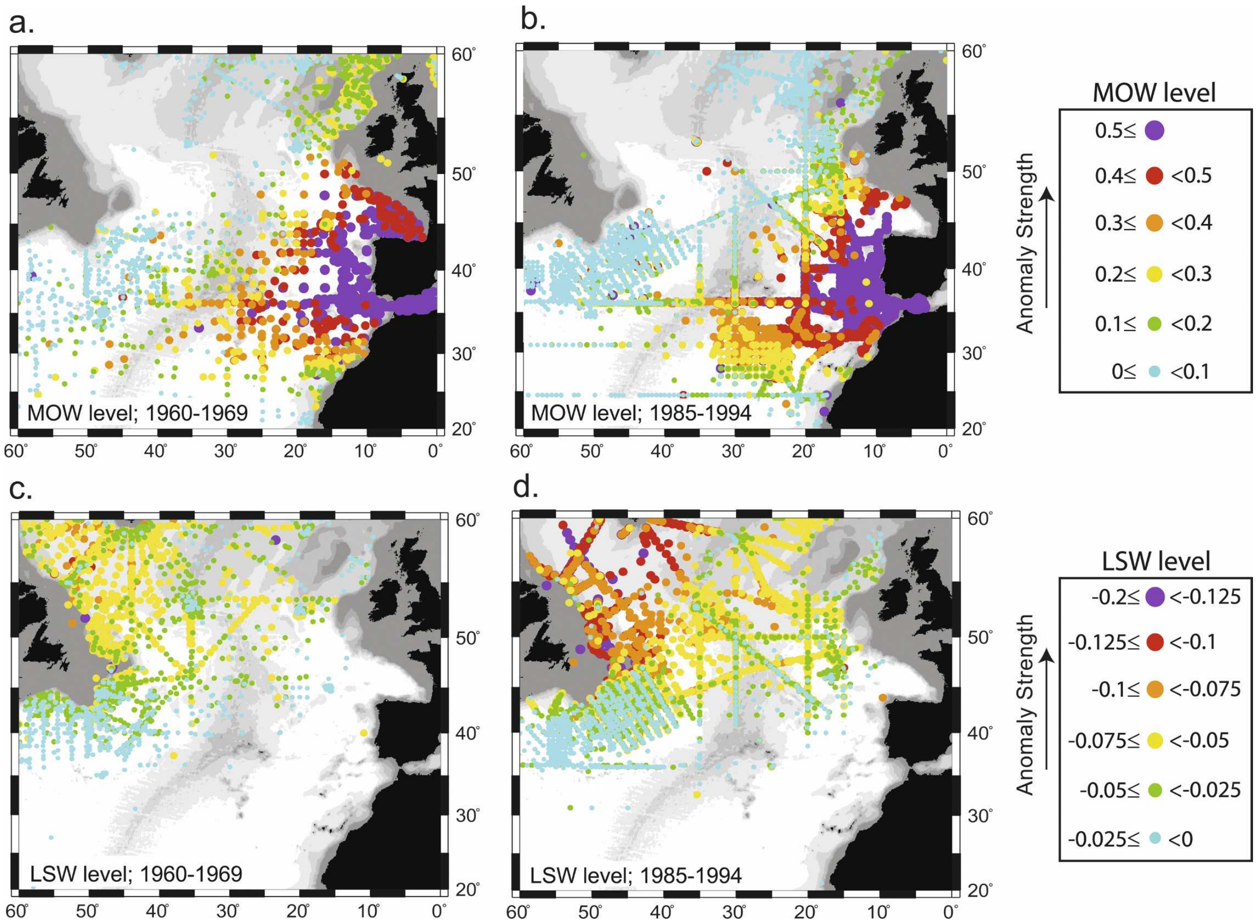

FIG. 2. (a) Salinity anomalies (psu) at the MOW level (σ_1 = 32.10) for the time period 1960–69 (shaded gray in Fig. 1). (b) Same as (a), but for 1985–94 (also shaded gray in Fig. 1). (c) Salinity anomalies at the LSW level ($\sigma_{1.5}$ = 34.66) for the time period 1960–69. (d) Same as (c), but for 1985–94. The dot size is varied to avoid masking: the size of the dot is proportional to the strength of the anomaly.

surface, $\sigma_{1.5}$ = 34.66, at which Labrador Sea Water (LSW) resides. This relatively freshwater mass is characterized by strong negative anomalies that are advected from the Labrador Sea southward along the deep western boundary current (DWBC) and eastward as part of the subpolar gyre recirculation. During a low-NAO period (Fig. 2c), the freshwater anomalies can be seen throughout the Labrador Sea and across the western North Atlantic to the Mid-Atlantic Ridge. However, during a high NAO period, the freshwater anomalies reach across the entire width of the basin to Porcupine Bank (Fig. 2d). The difference in the distribution of the salinity anomalies between the two NAO periods is consistent with a shifting subpolar front that essentially establishes the eastward penetration of LSW and northward penetration of MOW. This characterization is consistent with a recent analysis of repeat cross sections along 20°W over the past 15 yr (Johnson and Gruber 2007), in which water mass changes in the northeastern North Atlantic are primarily attributed to "NAO-associated wind shifts."

c. *Salinity anomaly time series in Rockall Trough*

The relationship between property changes in the eastern subpolar gyre and the NAO is further illustrated from a time series of salinity anomalies in the Rockall Trough (Fig. 3), to the north of Porcupine Bank and an entryway into the Nordic Seas. The salinity anomalies at the MOW level (Fig. 3a) and at the LSW level (Fig. 3b) correlate well with the NAO index. When the NAO index is low, strong positive anomalies appear at the MOW level and at the LSW level, indicating the influence of a contracted subpolar gyre. Conversely, when the NAO index is high, the strength of the anomalies at the MOW level drops, while at the LSW level, negative anomalies fill the basin, indicating the presence of LSW that has been carried across the width of the basin by an expanded subpolar gyre. The

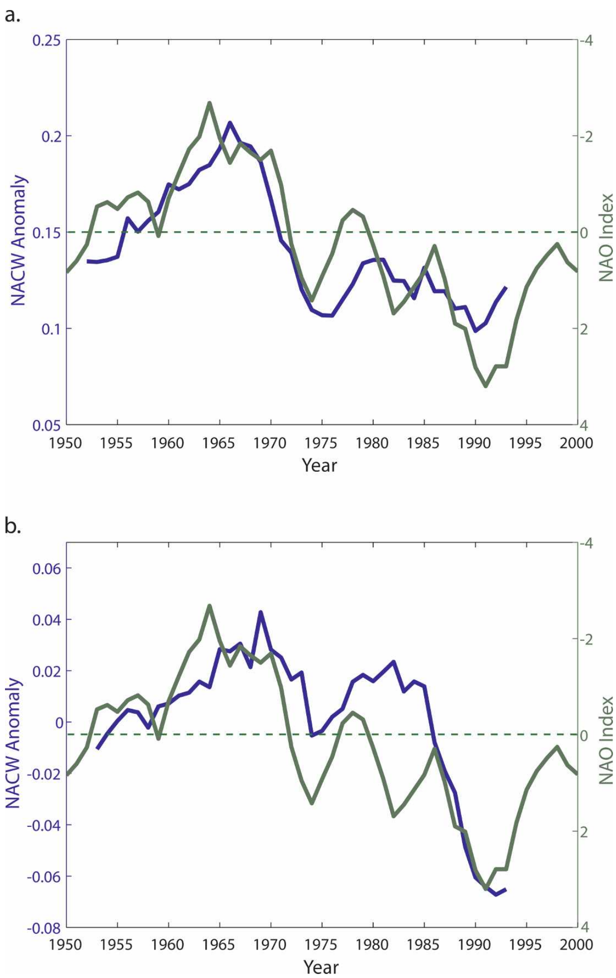

FIG. 3. Time series of salinity anomalies (psu, blue) in the Rockall Trough and the NAO index (green) (a) at the MOW level (on $\sigma_1 = 32.10$) 5-yr running mean, 2-yr lag [r^2 is 0.72 ($p < 0.01$)] and (b) at the LSW level (on $\sigma_{1.5} = 34.66$) 5-yr running mean, 3-yr lag [r^2 is 0.60 ($p < 0.01$)]. Note that the NAO index is plotted on a reverse y axis and that the 0 position is marked by a green dashed line.

correlation between the salinity anomalies and the NAO index is maximized with a 2-yr (3-yr) lag at the MOW (LSW) level, with the salinity anomalies lagging the NAO, presumably indicative of the flushing time scale of the Rockall Trough. Finally, the mechanics suggested here, which allow for the intermittent penetration of both LSW and MOW in the Rockall Trough, are consistent with recent studies that have explained property changes in the northeastern North Atlantic in terms of regional circulation changes (Holliday 2003; Hatun et al. 2005).

A time series of salinity anomalies on density surfaces evenly distributed in depth in the Rockall Trough reveals that anomaly changes are focused at the MOW and LSW levels (Fig. 4). Such focus provides assurance that the property changes noted above are not simply a reflection of temporal changes in the local air–sea fluxes, a possibility that was discounted in an earlier study of upper water–column property changes in the Rockall Trough (Holliday 2003). An attribution of these local property changes to a shift in the water mass pathways requires that source water property changes be excluded as a possible cause. In other words, the salinity change in the Rockall Trough could be explained if MOW, as it spills into the open North Atlantic, were to become increasingly less saline over time. However, the opposite trend has been noted: a study of historical hydrographic data in the eastern subtropical North Atlantic (Potter and Lozier 2004) has revealed a density-compensated warming and salinification of MOW over the past 50 yr, precluding the attribution of an overall freshening in the Rockall Trough to property changes at the source. The decrease in salinity at the LSW level in the Rockall Trough is consistent with the general freshening of the source water in the Labrador Sea; however, LSW at its source freshened by 0.06 psu between 1980 and 1994 (Yashayaev et al. 2003), while the change at the LSW level in the Rockall Trough is ~0.10 psu between 1970 and 1995 (Stewart 2005). Thus, it is improbable that the increase in the freshwater signal can be explained by changes in LSW properties. Further assurance that the Rockall Trough property changes are a reflection of shifting water mass pathways is provided by an analysis (Stewart 2005) of historical hydrographic data that traces the high-saline core of the MOW to the Rockall Trough during the low NAO period; the signature of LSW (low vertical stratification) could be traced across the width of the basin only during high NAO.

4. Summary

The property changes in the eastern subpolar gyre are consistent with the hypothesis that the expansion and contraction of the subpolar gyre allows for temporal variability in the northward penetration of MOW. Implicit in this hypothesis is that MOW is primarily delivered to the subpolar gyre directly, as an eastern boundary current, rather than indirectly through mixing with waters in the North Atlantic Current. If the latter mechanism was dominant, an expansion of the subpolar gyre would lead to increasing salinity anomalies within the Rockall Trough, especially so in light of the increasing salinity of the MOW at its source. The fact that gyre expansion (contraction) is linked with decreasing (increasing) salinity anomalies at the MOW level in the Rockall Trough suggests a direct advective, albeit temporally variable, pathway.

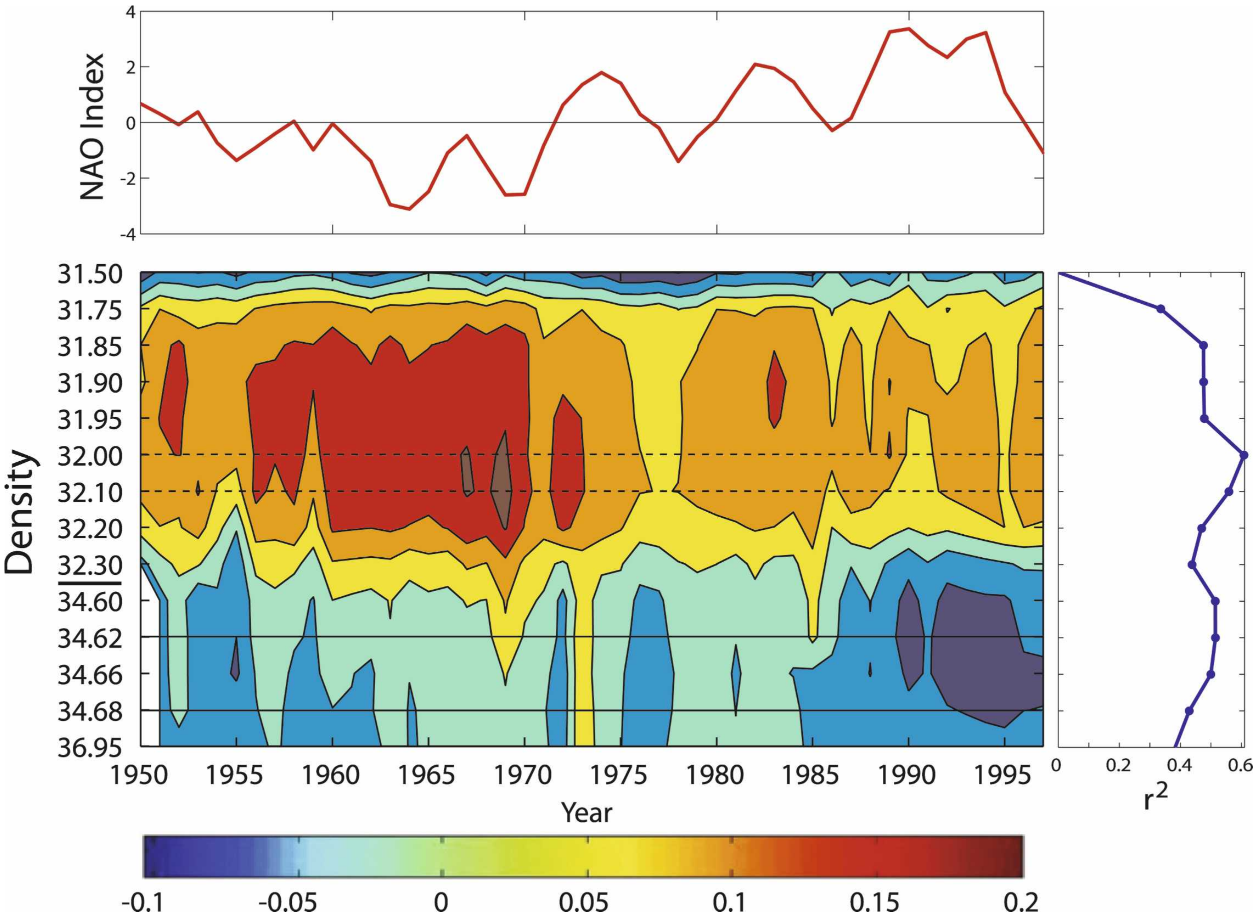

FIG. 4. (bottom) Salinity anomalies (psu) in the Rockall Trough as a function of density; densities above the black bar along the left-hand axis are referenced to 1000 m, those below to 1500 m. The two dashed lines bracket the location of the MOW core in the Rockall Trough (Stewart 2005), while the two solid black lines bracket the LSW core. (top) The NAO index over the same time period as the salinity anomalies. The correlation coefficients between NAO and each density surface are shown to the right; the r^2 is calculated using a 3-yr running mean for each time series with a 3-yr lag applied to the NAO time series. All r^2 values have a significant p value ($p < 0.01$), except for the lightest density surface ($\sigma_1 = 31.50$). Salinity anomalies are contoured every 0.05.

The role of the intermittent influence of this water mass on convective processes at high latitudes, whether it finds its way to the Nordic Seas or is instead recirculated within the subpolar gyre, remains to be investigated. Likewise of interest is the effect of the intermittent loss of salt on the subtropical basin. Ongoing data and modeling studies are focused on these investigations.

Acknowledgments. This work was supported by a grant from the National Science Foundation. Gratitude is extended to Joe Reid for his encouragement and to Mike McCartney for motivation.

REFERENCES

Armi, L., and N. A. Bray, 1982: A standard analytic curve of potential temperature versus salinity for the western North Atlantic. *J. Phys. Oceanogr.,* **12,** 384–387.

Bersch, M., J. Meincke, and A. Sy, 1999: Interannual thermohaline changes in the northern North Atlantic 1991–1996. *Deep-Sea Res. II,* **46,** 55–75.

Curry, R., 1996: Hydrobase: A database for hydrographic stations and tools for climatological analysis. Woods Hole Oceanographic Institution Tech. Rep. WHOI-96-01*,* 55 pp.

Dickson, R. R., J. R. Laxier, J. Meincke, P. Rhines, and J. Swift, 1996: Long-term coordinated changes in the convective activity of the North Atlantic. *Prog. Oceanogr.,* **38,** 241–295.

Flatau, M. K., L. D. Talley, and P. P. Niiler, 2003: The North Atlantic Oscillation, surface current velocities, and SST changes in the subpolar North Atlantic. *J. Climate,* **16,** 2355–2369.

Gregory, D. N., 2004: Climate: A database of temperature and salinity observations for the northwest Atlantic. Department of Fisheries and Oceans, Canadian Science Advisory Secretariat Research Document 2004/075, 10 pp. [Available online at http://www.mar.dfo-mpo.gc.ca/science/ocean/database/doc2006/clim2006app.html.]

Hakkinen, S., and P. B. Rhines, 2004: Decline of subpolar North Atlantic circulation during the 1990s. *Science,* **304,** 555–559.

Hatun, H., A. B. Sando, H. Drange, B. Hansen, and H. Valdimarsson, 2005: Influence of the Atlantic subpolar gyre on the thermohaline circulation. *Science,* **309,** 1841–1844.

Holliday, N. P., 2003: Air–sea interaction and circulation changes in the northeast Atlantic. *J. Geophys. Res.,* **108,** 3259, doi:10.1029/2002JC001344.

Hurrell, J. W., 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.

Johnson, G. C., and N. Gruber, 2007: Decadal water mass variations along 20°W in the northeastern Atlantic Ocean. *Prog. Oceanogr.,* **73,** 277–295.

Koltermann, K. P., and Coauthors, 1999: Decadal changes in the thermohaline circulation of the North Atlantic. *Deep-Sea Res. II,* **46,** 109–138.

Krahmann, G., and F. Schott, 1998: Long-term increases in western Mediterranean salinities and temperatures: Anthropogenic and climatic sources. *Geophys. Res. Lett.,* **25,** 4209–4212.

Lozier, M. S., W. B. Owens, and R. Curry, 1995: The climatology of the North Atlantic. *Prog. Oceanogr.,* **36,** 1–44.

McCartney, M. S., and C. Mauritzen, 2001: On the origin of the warm inflow to the Nordic Seas. *Prog. Oceanogr.,* **51,** 125–214.

New, A. L., S. Barnard, P. Herrmann, and J. M. Molines, 2001: On the origin and pathway of the saline inflow to the Nordic Seas: Insights from models. *Prog. Oceanogr.,* **48,** 255–287.

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.

Reid, J. L., 1979: On the contribution of the Mediterranean Sea outflow to the Norwegian–Greenland Sea. *Deep-Sea Res.,* **26A,** 1199–1223.

Stewart, N. M., 2005: On the temporally varying penetration of Mediterranean overflow waters into the subpolar gyre. M.S. thesis, Division of Earth and Ocean Sciences, Nicholas School of the Environment and Earth Sciences, Duke University, 71 pp.

Yashayaev, I., J. R. N. Lazier, and R. A. Clarke, 2003: Temperature and salinity in the central Labrador Sea during the 1990s and in the context of the longer-term change. *ICES Mar. Sci. Symp.,* **219,** 32–39.