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The arrival of recently formed Labrador Sea Water in the Deep Western Boundary Current at 26.5°N

Robert L. Molinari,[1] Rana A. Fine,[2] W. Douglas Wilson,[1] Ruth G. Curry,[3] Jeff Abell,[2] and Michael S. McCartney[3]

Abstract. The Deep Western Boundary Current (DWBC) of the North Atlantic is a principal conduit between the formation region for Labrador Sea Water (LSW) and the oceanic interior to the south. Time series (1985-1997) of hydrographic properties obtained in the DWBC at 26.5°N show that prior to 1994, temperature, salinity, and transient tracer properties within the LSW density range showed little indication of recently formed parcels. Properties characteristic of a newer version of LSW (cooler, fresher, and higher tracer concentrations) were observed beginning in 1994 and continuing through 1997. Longer time series of temperature and salinity, developed from a regional data base, show both the1994 and a 1980-1981 event in the Abaco region. Both events are consistent with anomalies in the Labrador Sea that occurred some 10 years earlier. The 10-year transit time from the Labrador Sea to 26.5°N is less than the 18-year transit time inferred from earlier studies.

Introduction

The deep waters of the North Atlantic Ocean are formed principally at the surface in the polar and subpolar regions of this basin. The Deep Western Boundary Current (DWBC) transports these water masses equatorward through the subtropics and tropics, and they are eventually advected to the other ocean basins. The equatorward flow is compensated for by near surface poleward flow and together they comprise a global meridional overturning circulation (MOC). Modeling studies indicate that changes in the intensity of the MOC are closely correlated with climate changes on decadal and longer time-scales [*Manabe and Stouffer,* 1988; *Delworth et al.*, 1993].

An effort to monitor the water mass [*Vaughan and Molinari,* 1997] and velocity [*Lee et al.,* 1996; *Hacker et al.,* 1996] characteristics of the DWBC, east of Abaco Island, the Bahamas (26.5°N), was established in 1985. Dramatic changes in the characteristics of Labrador Sea Water (LSW), an important component of the water mass structure of the DWBC, were first observed in 1994 and indicate quicker transit times into the subtropics from the formation region than previously estimated.

[1]R.L. Molinari and W.D. Wilson, Physical Oceanography Division, NOAA/AOML, 4301 Rickenbacker Causeway, Miami, FL 33149.

[2]R.A. Fine and J. Abell, University of Miami/Rosenstiel School of Marine and Atmospheric Science, 4600 Rickenbacker Causeway, Miami, FL 33149.

[3]R.G. Curry and M.S. McCartney, Woods Hole Oceanographic Institution, Woods Hole, MA 02543.

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Data

Using a conductivity-temperature-depth (CTD) sensor, pressure, temperature, and salinity transects were obtained along the Abaco section. The section was occupied from one to four times per year during the 13-year period, 1985-1997, with section lengths ranging from 100 to 600 km off the boundary. Data reduction methods and accuracy of the CTD observations from 1985 to 1993 are given in *Vaughan and Molinari* [1997]. Temperature uncertainties are generally of the order .003°C and salinity uncertainties of the order 0.003 (PSS-78). The 1994-1997 uncertainties are similar. Beginning in 1986, chlorofluorocarbon (CFC) data were collected on eight of the transect occupations. Uncertainties for CFC-11, hereinafter CFC, measurements at concentrations less than 1.0 pmol/kg decrease from 0.02 in 1986 to 0.005 pmol/kg in 1997.

Longer time-series of temperature and salinity characteristics of the western subtropical North Atlantic were constructed from the historical hydrographic record. Temperature and salinity values from both CTD and bottle casts obtained in the area bounded by 23°N and 30°N and 72°W and 77°W were compiled and quality controlled to eliminate outliers. Time series of these properties from the mid-1950s to the present were generated from these data.

Results

The DWBC is located below about 1000 m in the subtropical western Atlantic. Here, the water mass structure of the DWBC has typically been characterized by four layers based on CFC and salinity concentrations [*Fine and Molinari,* 1988]. A shallow layer between 1200 and 1600 m is characterized by high CFC and salinity concentrations. This water mass, called Upper LSW, appears to be formed in the southern Labrador Sea [*Pickart et al.,* 1997]. Beneath this core is the density range occupied by "classical" LSW. Historically at Abaco, this density range has been characterized by intermediate CFC values and lower salinities and has been found between 1600 and 2300 m [*Fine and Molinari,* 1988]. Below the LSW, a CFC minimum indicates that recently this water mass has not been in contact with the atmosphere. The low concentrations are also indicative of the long transit time and extensive mixing Iceland Scotland Overflow Water (ISOW) experiences while transiting from its formation region to Abaco [*Doney and Jenkins,* 1994]. Finally, a deep maximum CFC core observed between 3200 and 4500 m has been traced back to overflows from the Denmark Straits (Denmark Straits Overflow Water, DSOW) [*Smethie and Swift,* 1989].

Most of the earlier sections along 26.5°N extended only to 100 km from the western boundary. Time-distance plots of temperature and salinity along this portion of the transect (Fig. 1) show that, prior to 1993, only small variations occur in these

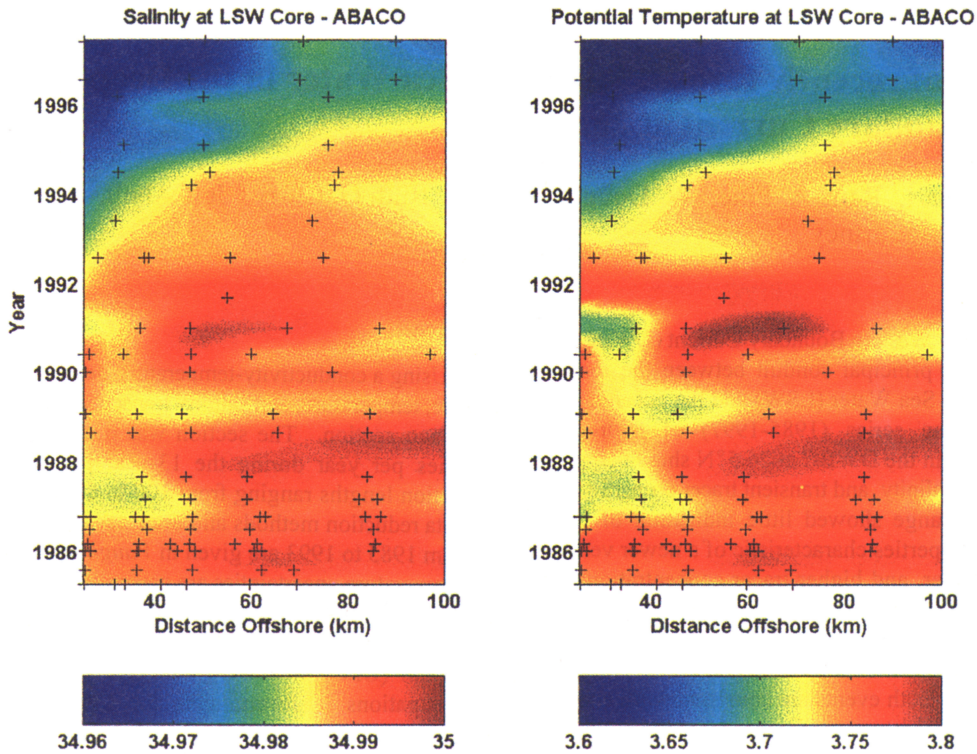

Figure 1. Time-distance plots of average temperature (left panel) and salinity (right panel) of the density layer encompassing LSW along the Abaco section. Crosses represent station positions. These plots are truncated versions of figures generated from data extending some 600 km offshore, thus some structure in the temperature and salinity distributions does not appear supported by the data values. This structure is related to data farther offshore of 100 km.

distributions consistent with *Vaughan and Molinari* [1997]. Beginning in 1994 and continuing through 1997, however, a cooling of the order 0.1°C and freshening of the order 0.02 are observed within 50 to 60 km of the boundary.

Previous changes in temperature and salinity characteristics at this density level in the Abaco region are also evident in the historical hydrographic record developed from a larger area as described above. Time series of potential temperature and salinity extending back to the mid-1950s from the Abaco region (Fig. 2) indicate a warming and salinity increase from 1970 to 1980 with a rather abrupt drop in both properties to the values characteristic of the 1985-1994 period (Fig. 1). Comparing temperature and salinity characteristics in the Labrador Basin to the Abaco record in Figure 2 shows an alignment of events. The 1972 Labrador Sea event aligns with a 1981 Abaco event and the 1994 Abaco event aligns with a mid-1980s event in the northern basin (i.e., approximately decadal advective timescales for both anomalies). There are differences between the time series, particularly between 1984 and 1994 (using the Abaco record as the time reference, Figure 2). These differences will be discussed shortly.

During the early years of transient tracer data collection, only tracer maximum cores associated with Upper LSW (1500 m) and DSOW (3500-4000 m) were observed (Fig. 3). In 1992, the concentration increases in the two CFC cores relative to 1986. In the July 1996 occupation, for the first time a distinct third core of maximum CFC concentrations is observed at 1800 m within the density range of classical LSW (Fig. 3). The later arrival of the CFC signal relative to the temperature and salinity signals is most likely related to the different mixing histories of these variables. The concentration within the LSW core continued to increase between 1996 and 1997, although the upper LSW and classical LSW cores appear to have merged in 1997 (the merging is difficult to confirm because of the lack of resolution in the bottle data).

These transient tracer data provide additional evidence to support a mid-1980s injection of the 1994-1997 Abaco event. The atmospheric time history of CFC-11 (R. Weiss, personal communication) and the solubility function for CFCs [*Warner and Weiss,* 1985] together yield estimates of CFC-11 concentration in the Labrador Sea through time. Using a 60-70% equilibrium between atmosphere and sea water, it is estimated that concentrations in the Labrador Sea were about 1 pmol/kg in the early 1970s and 3-4 pmol/kg in the late 1980s. *Wallace and Lazier* [1988] measured 3 pmol/kg at 60% equilibrium in 1986. It is thus unlikely that the concentrations measured at Abaco in 1996-1997 (1.1-1.3 pmol/kg) are of the early 1970s variety, as this would require little or no mixing between source and the subtropics. Rather, three-to-four fold dilution of CFCs along the LSW pathway from the source to the subtropics is likely (W. Smethie, personal communication, 1997). These assumptions would result in a CFC concentration of about 1 pmol/kg at Abaco (as observed), if the formation period of the LSW was the mid-1980s.

The LSW transit time of 10 years from source to subtropics is shorter than the 18 years estimated from earlier transient tracer data [*Smethie,* 1993; *Doney and Jenkins,* 1994]. The 10-year transit time implies a 2-2.5 cm/s effective spreading rate. Similar differences have been found in the North Atlantic, north of the Gulf Stream [*Sy et al.,* 1997]. There, new estimates of advection times from the Labrador Sea to the eastern Atlantic are of the order of five years, as opposed to18 years from earlier

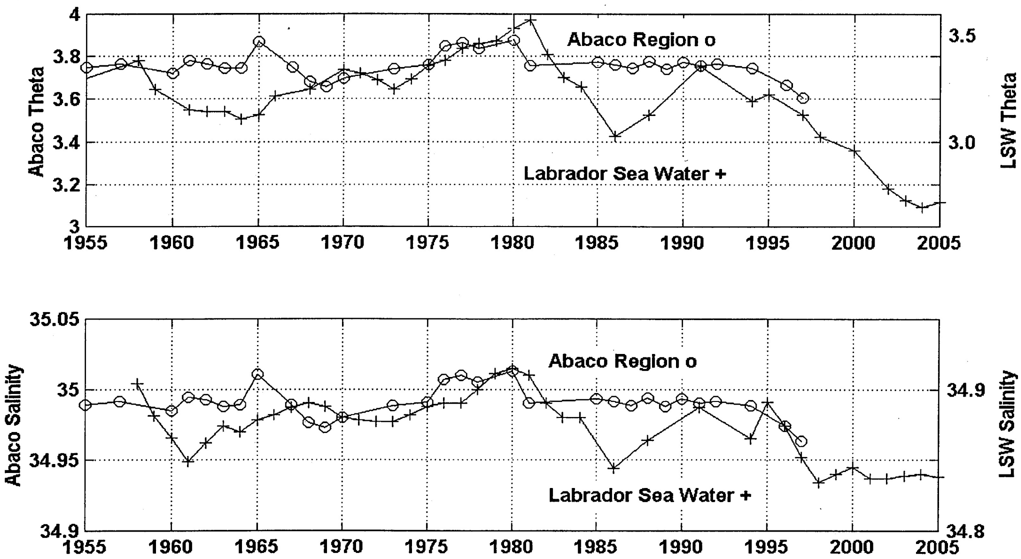

Figure 2. Time series of temperature and salinity for the Abaco region (see text for details of how the time series were constructed). The longer time series obtained in the Labrador Sea, from *Lazier* [1995], is shifted 10 years forward in time to align events observed in both regions.

estimates. Advection of the LSW that formed in 1983-1984 to the vicinity of Bermuda, with transit times of five to six years, is described in *Curry et al.* [1998]. Transient tracer ages obtained south of the Bermuda Rise during 1992 suggest a longer advective time of some 18 years (M.O. Baringer, personal communication, 1998).

Spall [1996] provided results from a regional primitive equation model developed to study the dynamics of the Gulf Stream/DWBC crossover. The middle of the model's three layers is chosen to represent the upper DWBC and thus upper North Atlantic Deep Water, including LSW. In this model, a portion of the middle layer crosses directly under the Gulf Stream and another portion becomes entrained in the Stream to be advected eastward. The latter portion crosses under the Gulf Stream farther to the east and becomes part of a Gulf Stream recirculation gyre. The gyre eventually returns these water

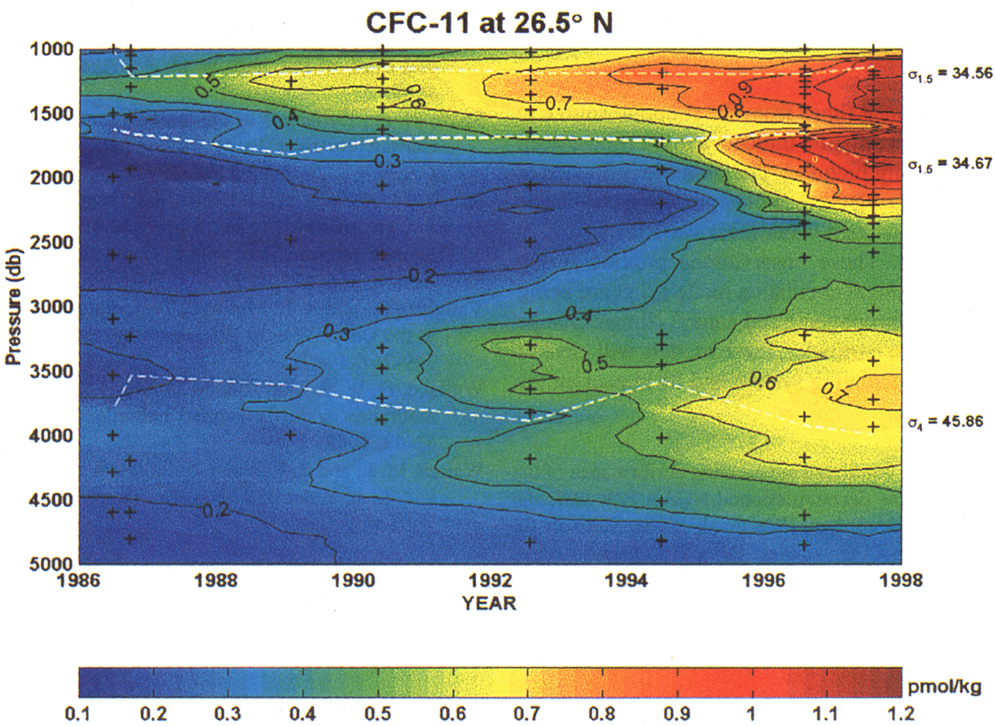

Figure 3. Time-depth plot of CFC-11 concentrations at the station showing maximum values. Dots represent locations of CFC samples. Dashed contours in white represent the density surfaces corresponding to the three cores of maximum CFC-11 concentration (i.e., Upper Labrador Sea Water, classical Labrador Sea Water, and Denmark Straits Overflow Water).

masses to the western boundary and the DWBC at subtropical latitudes.

Spall [1996] demonstrated a mechanism leading to self-sustaining, low-frequency oscillations in the strength of the Gulf Stream and its recirculations and the degree that DWBC waters are entrained into the Gulf Stream or cross directly under the boundary flow. Water mass ages along the boundary in the subtropics are a complicated function of the relative proportions of entrained versus direct cross-over waters, pathways, and mixing histories. For example, transitions between entrainment and crossing occurred rapidly in the model (order of 1 year) and caused downstream ages to vary from 5-20 years. The transitions depended on the intensity of the Gulf Stream, strong stream, little direct cross-over, and vice versa.

The presence of such an oscillation in nature would indicate that a simple or steady connection between high-latitude source regions and the lower latitude ocean basins does not exist. Thus, variability in the subpolar source regions would be just one factor contributing to the low-frequency fluctuations observed at Abaco. One could interpret the longer Abaco record (Fig. 2) in terms of these factors thusly. The water mass characteristics are conspicuously flat from 1981-1994 in contrast to the previous 15 years which show a distinct trend of increasing temperature and salinity similar to the LSW source. The earlier period (1965-1980) could be interpreted as representing a time when the Gulf Stream and recirculation were in a relatively low energy state and the majority of the DWBC crosses under the boundary current in a direct link to the source region. The steady conditions of the later time period may be indicative of enhanced exchange, with the gyre interior smoothing the variability that is observed concurrently in the source region. The most recent injection of colder, fresher water into the DWBC at Abaco could signal a transition to the more direct pipeline state.

Discussion

The relatively short transit times from the subpolar source to the subtropics and eastern Atlantic indicate a more robust deep circulation than historically pictured. The possible influence of time-dependence on the DWBC cross-over process complicates the interpretation of downstream water mass variability (e.g., at Abaco) and tracer ages. These observations provide strong constraints on coupled general circulation models that are being used to diagnose both anthropogenic and natural climate change on decadal timescales. In particular, these models will have to correctly simulate the fluctuating system and its impact on the thermohaline circulation.

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References

Curry, R. G., M. S. McCartney, and T. M. Joyce, Oceanic transport of subpolar climate signals to mid-depth subtropical waters, *Nature, 391,* 575-577, 1998.

Delworth, T., S. Manabe, and R. J. Stoffer, Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model, *J. Climate, 6,* 1993-2011, 1993.

Doney, S. C., and W. J. Jenkins, Ventilation of the Deep Western Boundary Current and abyssal western North Atlantic: Estimates from tritium and ^{3}He distributions, *J. Phys. Oceanogr., 24,* 638-659, 1994.

Fine, R. A., and R. L. Molinari, A continuous deep western boundary current between Abaco (26.5°N) and Barbados (13°N), *Deep-Sea Res., 35,* 1441-1450, 1988.

Hacker, P., E. Firing, W. D. Wilson, and R. L. Molinari, Direct observations of the current structure east of the Bahamas, *Geophys. Res. Lett., 23,* 1127-1130, 1996.

Lazier, J. R. N., The salinity decrease in the Labrador Sea over the past 30 years, in *Natural Climate Variability on Decade-to-Century Time Scales,* pp. 295-298, National Academy Press, Washington, D.C., 1995.

Lee, T. N., W. E. Johns, R. J. Zantopp, and E. F. Fillenbaum, Moored observations of western boundary current variability and thermohaline circulation at 26.5°N in the tropical North Atlantic, *J. Phys. Oceanogr., 26,* 862-893, 1996.

Manabe, S., and R. J. Stouffer, Two stable equilibria of a coupled ocean-atmosphere model, *J. Climate, 1,* 841-866, 1988.

Pickart, R. S., M. A. Spall, and J. R. N. Lazier, Mid-depth ventilation in the western boundary current system of the sub-polar gyre, *Deep-Sea Res., 44,* 1025-1054, 1997.

Smethie, W. M., Tracing the thermohaline circulation in the western North Atlantic using chlorofluorocarbons, *Prog. Oceanogr., 31,* 51-99, 1993.

Smethie, W. M., and J. H. Swift, The tritium-krypton-85 age of Denmark Strait Overflow Water and Gibbs Fracture Zone Water just south of Denmark Strait, *J. Geophys. Res., 94,* 8265-8275, 1989.

Spall, M. A., Dynamics of the Gulf Stream/Deep Western Boundary Current crossover, Part I: Entrainment and recirculation, *J. Phys. Oceanogr., 26,* 2152-2168, 1996.

Sy, A., M. Rhein, J. R. N. Lazier, K. P. Koltermann, J. Meinchke, A. Putzka, and M. Bersch, Surprisingly rapid spreading of newly formed intermediate waters across the North Atlantic Ocean, *Nature, 386,* 675, 1997.

Vaughan, S., and R. L. Molinari, Temperature and salinity variability in the Deep Western Boundary Current, *J. Phys. Oceanogr., 27,* 749-761, 1997.

Wallace, D. W. R., and J. R. N. Lazier, Anthropogenic chlorofluoromethanes in newly formed Labrador Sea Water, *Nature, 332,* 61-63, 1988.

Warner, M. J., and R. F. Weiss, Solubilities of chlorofluorocarbons-11 and 12 in water and seawater, *Deep-Sea Res., 32,* 1485-1497, 1985.

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