Distribution and Circulation of Labrador Sea Water

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ABSTRACT

Labrador Sea Water is the final product of the cyclonic circulation of Subpolar Mode Water in the open northern North Atlantic (McCartney and Talley, 1982). The temperature and salinity of the convectively formed Subpolar Mode Water decrease from 14.7°C, 36.08‰ to 3.4°C, 34.88‰ on account of the cumulative effects of excess precipitation and cooling. The coldest Mode Water is Labrador Sea Water, which spreads at mid-depths and is found throughout the North Atlantic Ocean north of 40°N and along its western boundary to 18°N.

A vertical minimum in potential vorticity is used as the primary tracer for Labrador Sea Water. Labrador Sea Water is advected in three main directions out of the Labrador Sea: 1) northeastward into the Irminger Sea, 2) southeastward across the Atlantic beneath the North Atlantic current, and 3) southward past Newfoundland with the Labrador Current and thence westward into the Slope Water region, crossing under the Gulf Stream off Cape Hatteras.

The Labrador Sea Water core is nearly coincident with an isopycnal which also intersects the lower part of the Mediterranean Water, whose high salinity and high potential vorticity balance the low salinity and low potential vorticity of the Labrador Sea Water. Nearly isopycnal mixing between them produces the upper part of the North Atlantic Deep Water.

A 27-year data set from the Labrador Sea at Ocean Weather Station *Bravo* shows decade-long changes in the temperature, salinity, density and formation rate of Labrador Sea Water, indicating that Labrador Sea Water property distributions away from the Labrador Sea are in part due to changes in the source.

1. Introduction

Labrador Sea Water (LSW) is a low-salinity water mass, formed in the Labrador Sea, and occurring at mid-depths nearly everywhere in the North Atlantic north of 40°N and in parts of the western subtropical North Atlantic. A study of the distribution of LSW and its properties yields information about both the mid-depth circulation, which is difficult to determine from standard dynamical calculations, and about the role and preferred locales of mixing. Because of its low salinity and high oxygen content relative to waters above and below it, it was early recognized as a distinct water mass. Wüst (1935) made one of the first studies of LSW. He discussed two core layers related to LSW, the North Atlantic Intermediate Water (a salinity minimum at mid-depth north of 40°N) and Middle North Atlantic Deep Water (a dissolved oxygen maximum at mid-depth). The former core coincides with LSW in the neighborhood of the Labrador Sea, while the latter core coincides with LSW farther south in the western basin. Wüst concluded that 1) the source of both of his core layers was the northwestern Atlantic Ocean, 2) there is a southward current along the western boundary which contains the most unmodified LSW, and 3) the Mediterranean water mixes with the LSW, probably vertically, at mid-latitudes, raising the salinity and lowering the oxygen content of the LSW.

Wright and Worthington (1970) gave the broadest definition of LSW, including all water between 3.0 and 4.0°C and fresher than 34.94‰ in their volumetric temperature-salinity atlas. The great bulk of water of these characteristics was found in the northwestern North Atlantic with most of the rest in the northeastern North Atlantic. As one of the five basic components of North Atlantic Deep Water (Worthington, 1976), the relatively fresh LSW is important in balancing the high salinity of the Mediterranean Water, a role which has been discussed by Reid (1978). Its role in mixing with Norwegian-Greenland Sea overflow waters to form various types of Deep Water in the northern North Atlantic has been discussed by Lee and Ellett (1965, 1967), Crease (1965) and Ellett and Martin (1973). Lazier (1973) discussed the circulation of the Labrador Sea and the formation of LSW in detail, although it appears in retrospect that there was little or no active LSW formation in the data set which he used. Lazier (1981) found that there were large changes in the renewal rate of LSW from 1964 to 1974, based on hydrographic data from the central Labrador Sea. Clarke and Gascard (1980) reported a direct observation of LSW formation in the western Labrador Sea. The circulation of LSW

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in the North Atlantic was discussed by Ivers (1976), using distributions of salinity on an isopycnal coupled with dynamic calculations of the velocity field.

In this paper, we map the property distributions of the LSW, using a novel tracer, the potential vorticity, to identify the LSW. The circulation at mid-depths is inferred from these property distributions and qualitative conclusions are made about the importance of mixing in determining these distributions. It is seen that there are large changes in renewal rate and properties of the new LSW, which may have profound effects on the overall horizontal property distributions and perhaps also on the dynamics of the mid-depth circulation.

2. Background

The Labrador Sea Water (LSW) is one of the two final products of the cyclonic circulation of Subpolar Mode Water in the northern North Atlantic. This circulation scheme is discussed in an accompanying paper (McCartney and Talley, 1982a). A "Mode Water" is a convectively formed water mass, found in and above the main thermocline. Because of its great thickness and horizontal extent, it has a large volume compared with water of neighboring temperature and salinity characteristics. Briefly, warm surface modes (Subpolar Mode Water) up to 1000 m thick flow in a generally cyclonic pattern around the northern North Atlantic. Beginning at a temperature of 14.7°C and salinity of 36.08‰, the Subpolar Mode Water is freshened, cooled and deepened by convection as it circulates, because of the combined effects of net heat flux out of the ocean and excess precipitation and runoff. Some of the Subpolar Mode Water enters the Norwegian-Greenland Sea, joining the cyclonic circulation there, the end product of which is a cold water mass (near 0°C, 34.9‰) which is a major component of the Denmark Strait Overflow Water (Swift *et al.*, 1980).

Most of the Subpolar Mode Water remains in the cyclonic circulation of the subpolar North Atlantic, where it finally flows into the Labrador Sea. The final type of Subpolar Mode Water, formed in the Labrador Sea, is LSW, a cold, fresh water mass. This convectively formed water mass generally has temperature in the range 3.3–3.4°C, 34.84–34.89‰, and potential density 27.76–27.78 mg cm^{-3} relative to the surface, although it has clearly been observed to have much lower temperature (cf. Clarke and Gascard, 1980). In addition, LSW has much lower potential vorticity $[(f/\rho)(\delta\rho/\delta z)]$ than any other water in the North Atlantic. This low potential vorticity results from convective formation which produces a deep, nearly homogeneous water mass. In the open North Atlantic south of the Greenland-Scotland Ridge, the LSW is the most deeply convecting water mass and has lower potential vorticity than other water masses. Because it is denser than the other Subpolar Mode Waters, it sinks beneath them and is isolated from sea surface influences when it is advected out of the Labrador Sea. Because it is not acted on by vigorous surface processes, its potential vorticity is nearly conserved. There are no other sources of such low potential vorticity in the North Atlantic, which makes potential vorticity a particularly attractive tracer of LSW.

Other tracers commonly used to distinguish LSW are the intermediate-depth salinity minimum and oxygen maximum (Wüst, 1935). A new tracer, atomic-bomb-produced tritium, is also being proved useful in identifying the LSW (Jenkins and Clarke, 1976). The LSW's low salinity is due to surface freshening of the Subpolar Mode Water during its modification to LSW. We found that the low potential vorticity layer was more sharply defined than the low-salinity layer and that the potential vorticity minimum was detectable over a larger area than the salinity minimum. The LSW's high oxygen content results from more recent contact of the LSW with the sea surface compared with the deeper part of the North Atlantic Deep Water and the lower thermocline water above the LSW. Although poor oxygen data were successfully used by Wüst (1935) to trace the LSW throughout the North and South Atlantic, we felt that the oxygen data set in the North Atlantic was not consistent or accurate enough to be used here. The situation has improved since Fuglister (1960) rejected the entire IGY oxygen data set, but we are still using many IGY sections to obtain full North Atlantic coverage. The tritium content, like oxygen, is high in water recently in contact with the atmosphere. A well-defined maximum in tritium at mid-depths marks the LSW, but so far not enough tritium data are available to determine the LSW distribution.

In Section 3 we discuss the method used for tracing the LSW, using its potential vorticity minimum as the primary tracer. In Section 4, a vertical section of potential vorticity illustrates its use as a water-mass tracer. In Section 5, horizontal charts of the potential vorticity and salinity of the LSW are presented. In Section 6, we discuss the time-dependence of the LSW properties in the Labrador Sea, the northwest Atlantic and the western North Atlantic. In Section 7, we summarize our results.

3. Method

We are interested in tracing a water mass from its formation region. We assume that the primary signature of a convectively renewed water mass is its excessive vertical homogeneity relative to the water above and below it. Calculation of the vertical density gradient is based essentially on the thickness of a layer between standard densities. Thus, the thicker the layer, the smaller the density gradient $(\delta\rho/\delta z)$. To identify the LSW, we look for a minimum in the vertical density gradient at a given station. A quantity which is locally related to the vertical density gradient is the potential vorticity, which is approximately $(f/\rho)(\delta\rho/\delta z)$ in regions where the relative vorticity of the fluid motion is small compared with the planetary vorticity (f is the Coriolis parameter.) In the absence of mixing, the potential vorticity, rather than the vertical density gradient, will be conserved along flow lines. The potential vorticity is therefore a more logical quantity to map over large horizontal areas than the vertical density gradient.

The tracing method used, then, involves a search for a relative vertical minimum in the potential vorticity $[(f/\rho)(\delta\rho/\delta z)]$ within the temperature range 3–4°C that typifies the LSW. Multiple minima are sometimes found at individual stations, particularly in the Gulf Stream region. In these cases, the selection criteria used are the relative intensity of the potential vorticity minima and continuity with neighboring stations. The potential vorticity is calculated from hydrographic station data that are interpolated to standard potential densities[1] σ_{1500} (referred to 1500 db) at intervals of 0.02 mg cm^{-3}. (Densities are calculated relative to an intermediate pressure, 1500 db, because the LSW potential-vorticity minimum lies between 500 and 2000 m and its average depth is about 1500 m.) The interpolated temperatures and salinities at adjacent levels are then referred to the pressure midway between the density levels and their density difference is recalculated relative to this pressure. The approximate potential vorticity is calculated using the new density difference and the thickness of the layer. The density, potential temperature and salinity are calculated in the middle of the layer and are the properties assigned to the potential-vorticity evaluation.

Potential-vorticity and density calculations are affected by errors in depth, salinity and temperature measurements. Temperature errors are less than 0.01°C. Salinity errors are 0.005‰ except where specifically noted. The resulting error in potential density at a given Nansen bottle is thus less than 5×10^{-6} g cm^{-3}. Errors in depth are less than 5 m. The error in potential vorticity depends on the actual value of the potential vorticity, which with errors can be written as

$$\frac{f}{\rho}\left(\frac{\Delta\rho + \epsilon}{\Delta z + \delta}\right) \approx \frac{f}{\rho}\left(\frac{\Delta\rho}{\Delta z} + \frac{\epsilon}{\Delta z} + \frac{\Delta\rho}{\Delta z}\frac{\delta}{\Delta z}\right),$$

where ϵ is the error in the potential-density difference

[1] The word "density" will be used for the quantity $\sigma = (\rho - 1) \times 10^3$, rather than the phrase "density anomaly." Also, the phrase "isopycnal surface" will be used for both a "neutral surface" and a surface of constant σ, which is an approximation to a neutral surface. The word "lateral" will be used in connection with advection and mixing along an isopycnal surface.

TABLE 1a. Hydrographic stations shown in Fig. 1.

I.	*Erika Dan*	181–393	Jan–Apr 1962
II.	*Anton Dohrn*	2480–2609	Aug–Sep 1958
III.	*Chain* 13	259–282	Oct 1960
IV.	*Discovery* II	3823–3846	Aug 1958
V.	*Discovery* II	3847–3870	Aug 1958
VI.	*Atlantis* II	245–418	Jan–Apr 1964
VII.	*Discovery* II	3866–3884	Sep 1958
VIII.	*Crawford* 16	218–274	Oct 1957
IX.	*Chain* 7	17–77	Apr–Jul 1959
X.	*Discovery* II	3625–3650	Nov–Dec 1957
XI.	*Discovery* II	3587–3624	Oct 1957
XII.	*Chain* 12	136–252	Apr–Jun 1960
	Atlantis 255	5873–5974	Apr–Jun 1960
	Crawford 40	809–923	Apr–Jun 1960
XIII.	*Atlantis* 215	5313–5364	Jun 1955
XIV.	*Atlantis* 233	5564–5587	Apr–May 1957
XV.	*Atlantis* 212	5211–5230	Nov 1954
XVI.	*Baffin* 9	27–41	Jun 1964
XVII.	*Crawford* 16	275–310	Nov 1957
XVIII.	*Chain* 11	106–112	Jan 1960

and δ the error in the layer thickness. When the bottle spacing is of the same order as the thickness of the density layers used in the potential-vorticity calculation (as in and near the Labrador Sea), the error in the potential vorticity is as follows: if the calculated potential vorticity is 5×10^{-14} cm^{-1} s^{-1}, f is 1.17 $\times 10^{-14}$ (at 50°N), ρ is 1.03470 g cm^{-3}, $\Delta\rho$ is 2×10^{-5} g cm^{-3}, Δz is 450 m, ϵ is 1×10^{-5} g cm^{-3} and δ is 5 m, then the dominant error in potential vorticity is due to the error ϵ in density and is 2.5×10^{-14}, or 50% of the total potential vorticity. This is a maximum error, produced by maximum errors in T and S, of opposite sign at two consecutive Nansen bottles, combining to give a maximum error in density. The expected random errors are smaller than this. Furthermore, if the density difference between adjacent Nansen bottles is *larger* than 2×10^{-5} g cm^{-3}, then the error in potential-density measurement is distributed over all interpolated layers. Thus, if the error in potential-density difference between adjacent bottles is 1×10^{-5} g cm^{-3} and there are n interpolated layers, the error in density difference in each layer is $\epsilon = (1 \times 10^{-5}$ g cm$^{-3})/n$. Away from the Labrador Sea, where the Labrador Sea Water is not as thick as the bottle spacing, the error in potential vorticity can be much less than 50%. That the errors are in fact not very large is seen in the contourability of potential vorticity at the LSW core (next section).

We used the station data listed in Table 1a to identify the LSW and produce basic maps of its potential vorticity and salinity. Fig. 1 shows the positions of the hydrographic sections used in plotting the lateral distribution of LSW. The data are mainly from the five-year period from early 1957 through early 1962, but also include the early 1964 *Atlantis* II data east of Newfoundland, the 1964 *Baffin* data along 50°W, and some 1954 and 1955 *Atlantis* data from the southwestern Sargasso Sea. The horizontal coverage

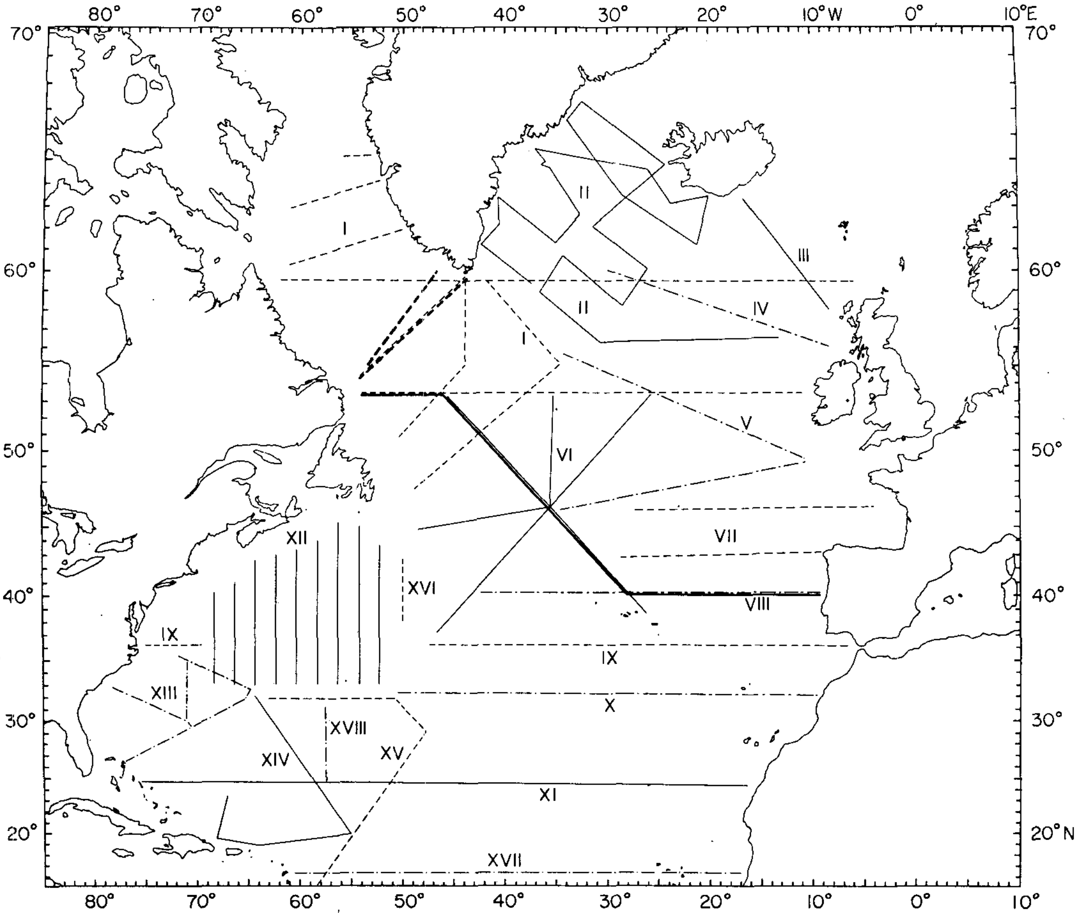

FIG. 1. Station chart used in preparing Figs. 2–6. The sections are listed on Table 1a.

could have been improved by using data after 1964, but this would mix temporal and spatial variability even more. Additional data from other years, listed in Table 1b, are used in the discussion of the variability of LSW.

After the LSW is identified using the potential-vorticity minimum, its properties (potential vorticity, salinity, temperature and potential density) can be mapped. We show maps of the LSW salinity and potential vorticity, and briefly discuss other properties. The salinity and potential-vorticity distributions on a density surface intersecting the LSW are also presented because a density surface is more familiar and dynamically useful than the LSW core surface. In the following section, the vertical distribution of potential vorticity along a section crossing the northern Atlantic illustrates how clearly the LSW can be identified at mid-depths.

4. A vertical section of potential vorticity

In Fig. 2, the vertical distribution of potential vorticity is shown for a composite section extending across the North Atlantic from the coast of Labrador to the coast of Portugal, passing just north of the Azores in mid-ocean. The vertical coordinate is the density relative to 1500 db, σ_{1500}. The sections used are indicated by dark lines on Fig. 1.

There are two main low-potential-vorticity features. At the bottom of the eastern basin between the Mid-Atlantic Ridge and the coast of Portugal, there is a low-potential-vorticity layer which is not of convective origin. Instead, it is North Atlantic Deep Water which crosses the Mid-Atlantic Ridge near the equator through the Romanche Fracture Zone. Because the deepest passage in the Fracture Zone is at 3750 m (Metcalf *et al.*, 1964), the deep eastern basin is filled with the North Atlantic Deep Water found at mid-level in the western basin. The vertical ho-

TABLE 1b. Hydrographic stations used in Figs. 7–15.

1. OWS *Bravo*		1928–1974
2. *Hudson* BI 0266	1–143	Mar–May 1966
3. *Hudson* BI 0267	1–119	Jan–Mar 1967
4. *Atlantis* 229	5418–5439	Nov 1956
5. *Baffin* B-4	2–16	Apr 1963
6. *Hudson* 8	48–51	May 1972

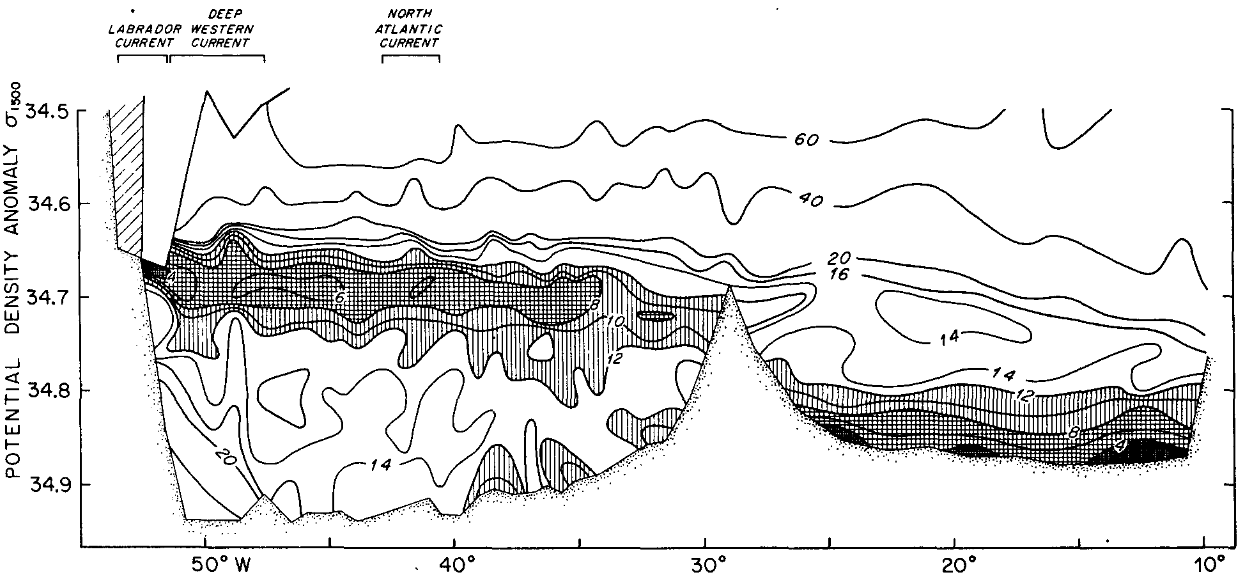

FIG. 2. A vertical potential vorticity section. The vertical coordinate is the potential density σ_{1500}. Potential vorticity is in units of 10^{-4} cm^{-1} s^{-1}. The sections used are indicated by the heavy solid line in Fig. 1.

mogeneity of this water is thus due to a limited source of dense water, rather than surface convection.

The LSW is the second low-potential-vorticity layer, in the western basin, at mid-depth rather than at the bottom. The density of this layer centers at σ_{1500} = 34.70 mg cm^{-3}. The layer is most sharply defined in the west, but is recognizable as far east as 17°W. The eastern limit is mainly determined by the Nansen bottle spacing and would be better defined if measurements of higher vertical resolution were used. At densities which intersect the LSW potential vorticity minimum, the potential vorticity is low in the west and high in the east. The water of high potential vorticity in the east is the Mediterranean salt tongue. Beneath the LSW core, the potential vorticity is nearly uniform at σ_{1500} = 34.76 mg cm^{-3}, while at even denser levels there are larger horizontal gradients: the highest potential-vorticity values are in the west, associated with the Norwegian-Greenland Sea Overflow Water which is flowing south.

The very low potential vorticity near the surface on the western side is incompletely formed LSW, with a density of σ_{1500} = 34.67 mg cm^{-3}, which is somewhat less than that of the (34.68–34.70 mg cm^{-3}) LSW commonly found at this latitude. This light, low-potential-vorticity water would probably have reached the LSW density if severe winter conditions in the year of this observation (1962) had not abated before March (Barrett, 1969), when the densest convection usually occurs. This water is about 900 m thick and is separated from the surface by a 300 m thick layer which is not shown in this diagram.

The detailed distribution of LSW potential vorticity in Fig. 2 is related to the horizontal circulation. For example, potential vorticities $< 6 \times 10^{-14}$ cm^{-1} s^{-1} are found only inshore of the North Atlantic Current where the LSW presumably flows south in the Labrador Current. The apparent exception at 41°W is due to a meander of the North Atlantic Current (see Fig. 8 of Worthington, 1976). Potential vorticities $< 8 \times 10^{-14}$ cm^{-1} s^{-1} extend offshore of the North Atlantic Current and terminate west of the Mid-Atlantic Ridge. This is the region Worthington (1976) has identified with a tight recirculation of the North Atlantic Current. East of the Mid-Atlantic Ridge, the potential-vorticity minimum is only slightly below 12×10^{-14} cm^{-1} s^{-1}.

In the next section we examine further the geographical distribution of the LSW's potential vorticity and salinity using the potential-vorticity minimum surface (the LSW core).

5. Lateral distribution of Labrador Sea Water

We show two basic distribution charts. Figs. 3 and 4 show the potential vorticity and salinity at the LSW core, the potential-vorticity minimum. The LSW core is *nearly* isopycnal, so maps of the potential vorticity and salinity or density surfaces that intersect the LSW core are similar to Figs. 3 and 4. While the distribution of potential vorticity on an isopycnal surface may be relevant for dynamical studies of circulation, the distribution of properties at the actual core of the LSW is more relevant for water-mass tracing. Since this paper stresses the properties of the water mass itself, properties of the LSW core are presented.

Fig. 2 emphasized the vertical homogeneity of LSW compared to waters above and below it. Fig. 3 emphasizes the role of the central Labrador Sea as a low-potential-vorticity source on the core surface.

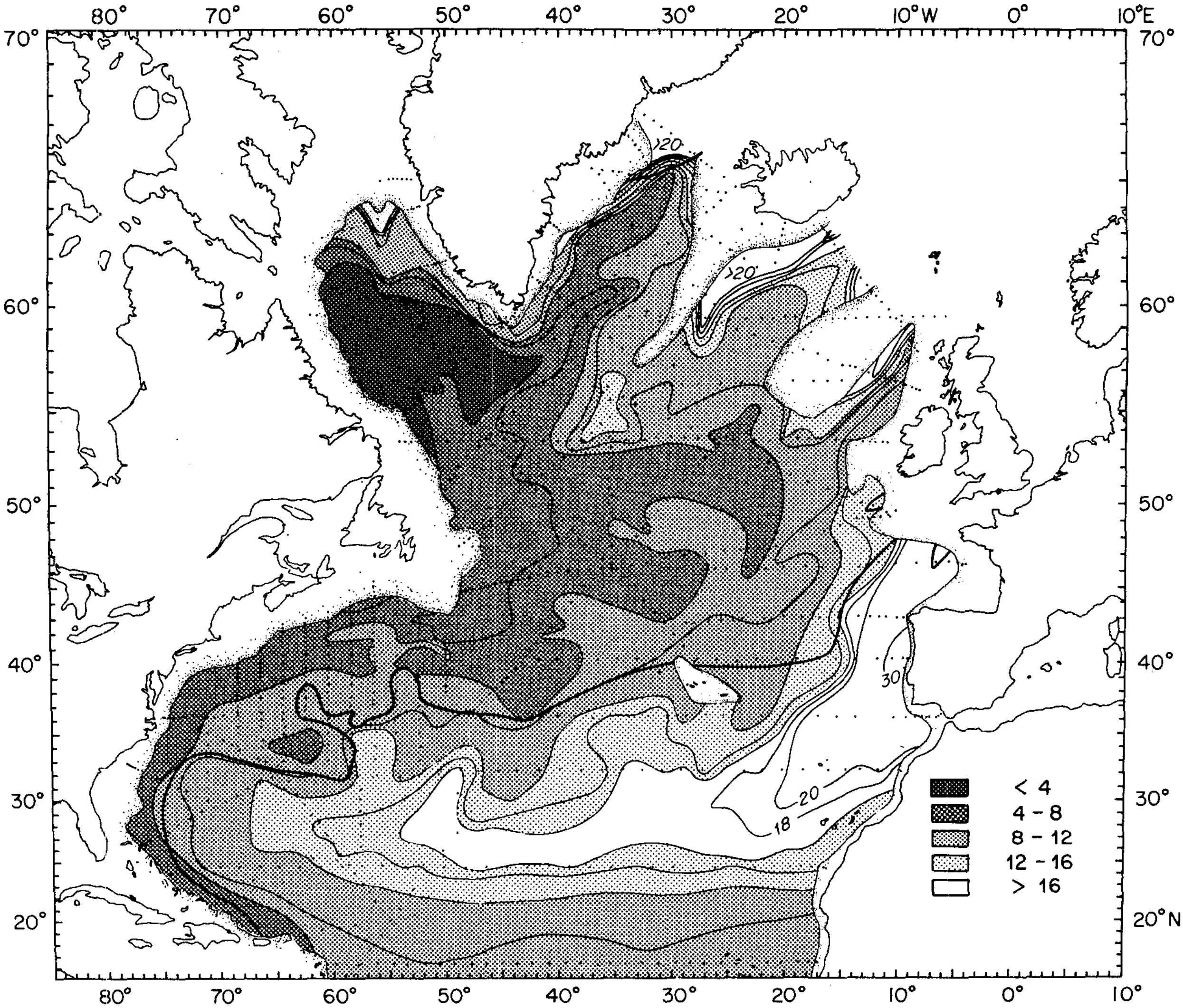

FIG. 3. Potential vorticity $(f/\rho)(\delta\rho/\delta z)$, in units of 10^{-14} cm^{-1} s^{-1}, at the LSW potential vorticity minimum, using the data of Fig. 1. The potential vorticity is a local measure of the vertical homogeneity of the water mass. The heavy curves are the limits of the identifiable LSW potential vorticity minimum. Beyond these curves, contouring is continued on the σ_{1500} = 34.72 mg cm^{-3} surface. Contour intervals are 2×10^{-14} cm^{-1} s^{-1}.

In the region of the chart where a potential-vorticity minimum is not found, the contouring is continued on a related isopycnal, as described in the figure caption. Tongues of low potential vorticity emanate from this source region along three principal axes. The first is an extension southward along the western boundary as far as 20°N. Lowest values in the western-boundary region are inshore of the North Atlantic Current and the Gulf Stream until Cape Hatteras, where the LSW crosses under the Gulf Stream (Richardson, 1977) as part of the Deep Western Boundary Current. The second tongue extends eastward across the North Atlantic near 50°N. This tongue lies in the separated North Atlantic Current. The third tongue extends from the Labrador Sea northeastward into the Irminger Sea.

The LSW is limited to the north where the sea floor rises to intersect it at the basin margins or where it meets the Norwegian-Greenland Sea overflow waters. South of the Wyville-Thomson, Iceland-Faroe and Iceland-Greenland Ridges, there is high-potential-vorticity water at the basin edges on the isopycnals used here, where the LSW is near the sea floor. The high potential vorticity is associated with the various Norwegian-Greenland Sea overflows at these ridges. While the overflow waters may be highly homogeneous at the bottom, the water column immediately above them is highly stratified (see, for example, figures by Lee and Ellett, 1965). It is this high stratification which causes the high potential vorticity on these density surfaces. The stratification is presumably due to mixing and entrainment between the

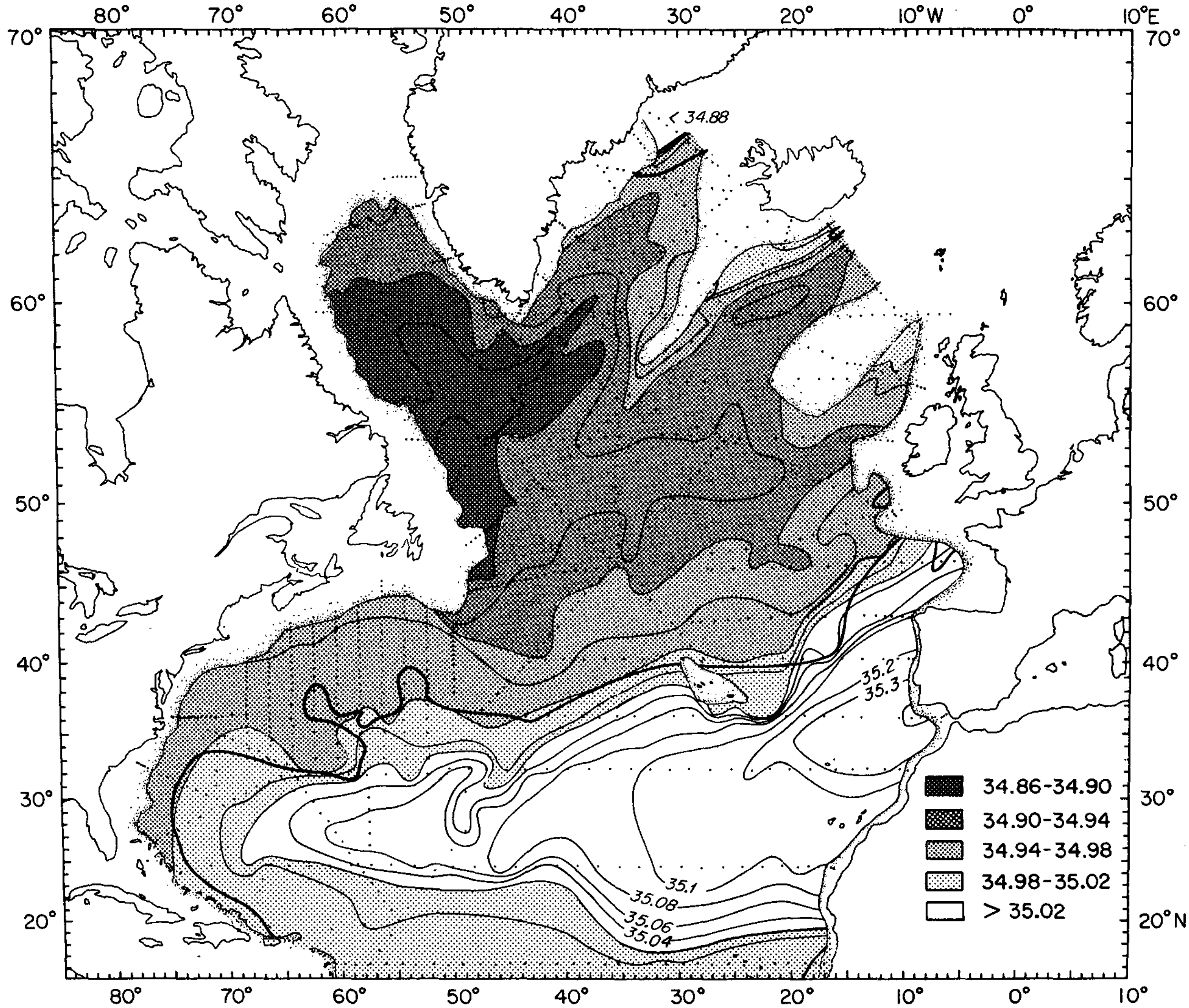

FIG. 4. Salinity at the LSW potential vorticity minimum. The heavy curves are as in Fig. 3. Contour intervals are 0.02‰.

overflow and surrounding waters (including the LSW) as the plumes flow over the ridges and into the North Atlantic.

To the south and east, where there is no physical boundary, the resolvable potential-vorticity minimum disappears as the LSW encounters the Mediterranean tongue. The Mediterranean Water has high potential vorticity because it, too, overflows a ridge and entrains water as it enters the North Atlantic. The variable boundary at the edge of the LSW influence is indicated by a heavy curve in Figs. 3 and 4. South of this boundary, the potential vorticity rises steeply on the isopycnal continuation of the core surface. The potential vorticity pattern in the southern part of the charts looks similar to the salinity pattern on account of the Mediterranean outflow (Worthington and Wright, 1970) with highest values immediately west of the Strait of Gibraltar. [The Mediterranean influence extends down to this density, but the core of the Mediterranean Water, at the salinity maximum, actually lies several hundred meters above the LSW core. The Mediterranean Water and the LSW overlap in a band more than 500 km wide along the southeastern side of the LSW core, as can be seen by comparing these Figures with salinity sections of Fuglister (1960).]

To the southwest, in the subtropical gyre, the extent of the LSW is determined by the Gulf Stream and its recirculation, as well as by the Mediterranean Water to the south. This region is probably an active mixing zone between the LSW and the Mediterranean Water. South of 32°N, the LSW appears in a rather narrow band along the western boundary, where it is presumably advected by the Deep Western Boundary Current (Richardson, 1977). Its lateral extent is governed here by the extent of the current.

The salinity map for the LSW (Fig. 4) is very similar to the potential vorticity map since the Labrador

Sea is a source of low-salinity as well as low-potential-vorticity water, while the Mediterranean is a high-salinity, high-potential-vorticity source. In the Rockall Channel and the Southeast-Iceland Channel, there is high-salinity, high-potential-vorticity water on account of overflows at the Wyville-Thompson Ridge (Ellett and Martin, 1973), Faroe Bank (Crease, 1965) and the Iceland-Faroe Ridge (Lee and Ellett, 1965). Mixing between the LSW and the overflows in the Rockall and Southeast-Iceland Channels increases the salinity of the LSW. This higher salinity LSW then flows around the Reykjanes Ridge toward the Denmark Strait where it is saltier than the overflow water there (Lee and Ellett, 1967). Mixing between the local LSW and the Denmark Strait overflow water then decreases the salinity of the LSW, as is seen downstream of the Denmark Strait, along the western side of the Irminger Sea.

In the southeast, the LSW boundary corresponds roughly with the 34.98‰ isohaline. This can be compared with the definition by Wright and Worthington (1970) of LSW as fresher than 34.94‰. This definition was based on the shape of their volumetric θ-S diagrams where it was difficult to identify the large volume of water of salinities 34.94–34.98‰ as LSW on the basis of θ-S alone. The definition of LSW as a potential vorticity minimum allows the influence of LSW to be recognized over a larger area. This area includes regions containing only North Atlantic Deep Water by the narrower θ-S definition of Wright and Worthington (1970). This is simply a matter of semantics: Wright and Worthington (1970) were, of course, fully aware of the role of LSW in determining the shape of the θ-S relationship in the 3–4°C temperature range.

Two possible mixing schemes for the LSW are a lateral advective-diffusive balance and a double-diffusive scheme. An isopycnal, advective-diffusive interpretation may be quite adequate to explain the mixing between the LSW, which has low potential vorticity and salinity, and the surrounding waters, which have high potential vorticity. However, the position of the warm, salty Mediterranean Water *above* the cold, fresh LSW in a 500 km wide band suggests that double diffusion (Schmitt, 1981) may be important.

Other properties of the LSW that are not shown are its depth, potential density and potential temperature. None of these three quantities is easy to contour in any detail because of their small gradients. The depth of the LSW core is not well defined because the water mass itself is so thick. The depth of the core (the potential-vorticity minimum) in the Labrador Sea is around 500 m, but this represents a nearly homogeneous water column from near the surface to about 1000 m. The core, which thins out as it move from the Labrador Sea, is found at an average depth of about 1500 m in a large region in the northwestern Atlantic. It dives gradually to a depth of almost 2000 m in the subtropical gyre and in the eastern Atlantic where it is overlain by the Mediterranean Water tongue.

The potential density of the LSW relative to both the surface and 1500 m also shows no great variation and is only grossly contourable. The LSW density σ_{1500} is as low as 34.65 mg cm^{-3} in the central Labrador Sea. Over most of the northwestern region, σ_{1500} is between 34.68 and 34.70 mg cm^{-3}. There is a general increase to 34.72 and even 34.74 mg cm^{-3} toward the periphery, particularly in the eastern Atlantic. This increase in density could be due to a real increase in density of a given source water due to mixing along its path. Alternatively, it could be due to a variation in the density of newly formed LSW over the period of time it would take to renew the water mass completely. As we will see in the next section, it is certainly plausible that the variation in density could be due to source variation in time over the 40 years preceding this "snapshot."

The potential temperature lies in the range 3.2 to 3.9°C. Identification of the warmest (3.7–3.9°C) pycnostads as LSW may not be justified. These warmest pycnostads occur primarily in the Labrador Sea and in the Gulf Stream region and it is plausible that they are only incompletely formed LSW. (That is, they are Subpolar Mode Water which was not cooled to the usual LSW temperatures and which then circulated around and out of the Labrador Sea in the Labrador Current.) More than any other property, the horizontal trends of potential temperature are difficult to identify. However, if we combine what we know of the salinity and potential density to calculate a crude temperature gradient across the LSW, we find that the potential temperature rises slightly away from the Labrador Sea, from about 3.25°C in the Labrador Sea to about 3.55°C where the salinity is 34.98‰.

We surmise the following circulation scheme from the property distributions. There is cyclonic flow in the Labrador Sea. Flow out of the Labrador Sea occurs in the southward Labrador Current along the western boundary and in the eastward North Atlantic Current. The Labrador Current carries LSW southward out of the Labrador Sea to the southern end of the Grand Banks. There much of the LSW is entrained by the northward flowing North Atlantic Current (Smith *et al.*, 1937). Some LSW flows westward around the Grand Banks and thence west and south, inshore of or under the Gulf Stream. Some of this LSW may be entrained by the Gulf Stream and spread eastward across the Atlantic in an eastward branch of the Gulf Stream. The eastward North Atlantic Current splits into a northward component flowing into the Irminger Sea and a southeastward component flowing across the North Atlantic. An additional current split occurs near 27°W, with one branch flowing northward and one branch turning southward and then westward past the Azores. The East Greenland Current then brings the old, high-salinity and high-potential-vorticity LSW, as well as warmer Subpolar Mode Water, into the Labrador Sea. The cyclonic circulation of the Labrador Sea carries these inputs around to the LSW formation area (Clarke and Gascard, 1980).

6. Time dependence of the Labrador Sea Water distribution

Our charts of the LSW potential vorticity and salinity were based on data from 1954 to 1964. The LSW is vertically nearly homogeneous because of deep convection in winter in the Labrador Sea. We might expect to find year-to-year variations in the amount and properties of new LSW due to climatological variations in the northern North Atlantic. In this section we examine the changes in LSW over twenty-seven years in the central Labrador Sea. We relate these changes to the lateral distributions examined in the previous section and to the lateral distribution of LSW in 1966–67 (examined in this section) in the northwest Atlantic. We also look at the impact of the LSW source variations on its properties in the Slope Water region south of the Grand Banks.

a. Central Labrador Sea (1948–74)

Ocean Weather Ship *Bravo* was operated in the central Labrador Sea, near 56°30'N, 50°00'W. According to our lateral distribution charts, this location is in the area where the LSW has its lowest potential vorticity and lowest salinity, indicating the LSW source region. From 1928 to 1941, there were only eleven hydrographic observations. From 1948 to 1963, there was basically one observation per year. From 1964 to 1974, there was an intensive program with at least one observation every month. In the discussion below, each observation prior to 1964 and monthly averages of the data after 1964 are used.

The maximum salinity errors were 0.02‰. Using the error analysis of Section 3, the density error at each bottle with salinity error of 0.02‰ is 1.7×10^{-5} g cm^{-3}. This is a significant fraction of the density interval used for interpolation (2×10^{-5} g cm^{-3}). In addition, because the thickness of the LSW itself is often as great as or greater than the bottle spacing at OWS *Bravo*, the errors are not reduced by interpolation to standard density surfaces. The error in potential vorticity of the LSW can be as large as, or larger than, the potential vorticity itself. The vertical position of the core is more correctly calculated since the vertical change in potential vorticity above and below its minimum is larger than the error. Thus the potential vorticity of the LSW, plotted below, is noisier than the density, temperature and salinity. On the other hand, systematic trends are observed throughout the time series, so while these random errors are troublesome, they do not entirely swamp the interannual signal.

Lazier (1981) discussed the conditions at OWS *Bravo* for the intensive (1964–74) time series. He found that there were two types of variation in the LSW: an annual variation and a longer change over the full series. He concluded that wintertime convection was severely limited from 1967 to 1971 on account of reduced cooling and a low-salinity surface layer over the Labrador Sea. The low-salinity cap was attributed to an increase in the fresh-water component of the East Greenland Current. Greatly increased cooling in 1971–72 penetrated the low-salinity cap, allowing deep convection and formation of LSW. The salinity of the renewed LSW was reduced from its average value in previous years because the low-salinity surface layer was mixed into the underlying, older LSW. The presence of low-salinity surface water at OWS *Bravo* was also pointed out by Taylor and Stephens (1980), who noted a decline in surface salinity from 1964 to 1971.

The LSW core is identified by the minimum in potential vorticity. The smallness of the potential vorticity at the core is an indicator of the strength (vertical homogeneity) of the LSW. When convective renewal is strong, the potential vorticity is low. When the LSW is isolated from renewal or when renewal is weak, the potential vorticity rises. The salinity at the LSW core and on intersecting density surfaces also increases when isolated from renewal. This occurs because newer LSW mixes with older, higher salinity LSW which re-enters the Labrador Sea from the Irminger Sea, with no fresh-water input from the surface.

Referring to Fig. 5, where the properties of the LSW core are plotted, we divide the record into three periods:

1) In the 1950's, renewal occurred regularly, evidenced by the low potential vorticity (2–4×10^{-14} cm^{-1} s^{-1}). The LSW density was 34.68 mg cm^{-3}, its potential temperature was about 3.1°C and its salinity was about 34.86‰.

2) In the 1960's, renewal slackened; potential vorticity, salinity and temperature increased and density decreased, all reaching their extreme values in 1971 (6×10^{-14} cm^{-1} s^{-1}, 3.6°C, 34.90‰, 34.66 mg cm^{-3}).

3) The onset of vigorous renewal in 1972 abruptly restored the LSW properties to their 1950's values.

The changes in the LSW potential temperature are also evident from historical sections made from Greenland to Labrador in 1935, 1962 and 1966 (Fig. 6). The mid-depth *in situ* temperature was about 3.2°C on the earliest section (Smith *et al.*, 1937). The *in situ* temperature of this bulk of water rose to about 3.4°C on the 1962 section (Worthington and Wright,

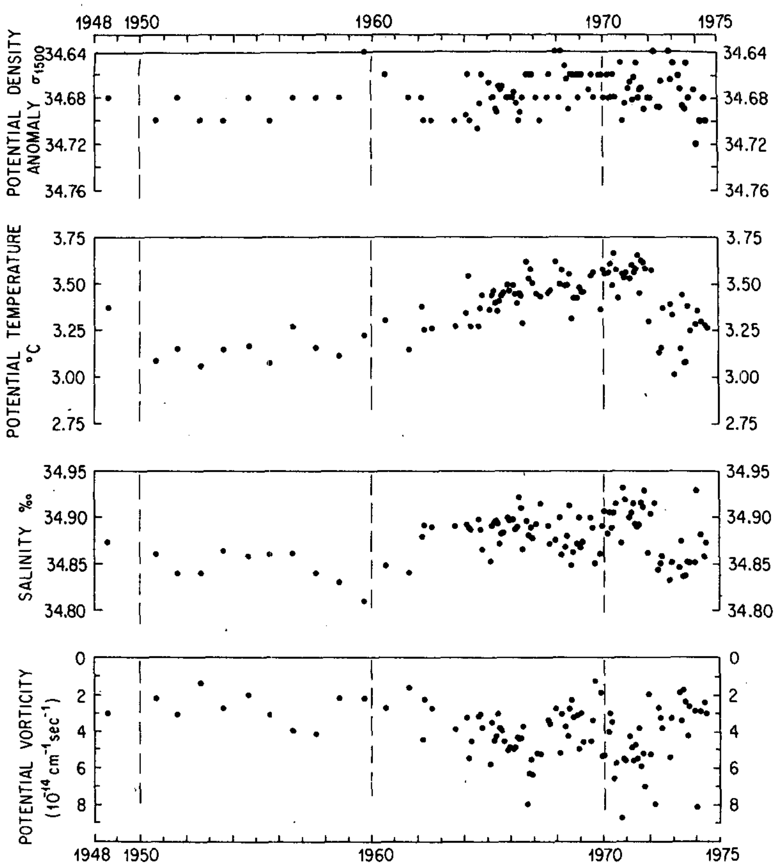

FIG. 5. Potential density (σ_{1500}), potential temperature, salinity and potential vorticity at the potential vorticity minimum between the densities 34.64 and 34.78 mg cm^{-3} at OWS *Bravo*. These are the LSW core properties.

1970). By 1966; the *in situ* temperature was about 3.5°C (Grant, 1968).

The salinity trend at the LSW core is also reflected on four density surfaces which intersect the LSW core (Fig. 7). If it is assumed that salinity increases when a density surface is isolated from fresh-water input and convection at the sea surface, Fig. 7 shows that each of the four density surfaces is gradually isolated from renewal. The isolation of the LSW from the sea surface is shown even more graphically by Lazier (1981) where a low-salinity layer at the sea surface at OWS *Bravo* is clearly indicated from 1964 to 1971. Fig. 7 is interpreted as follows:

1) The densest level (34.72 mg cm^{-3}) was isolated from renewal throughout the record, indicated by a steady increase in salinity. This water may have been ventilated before this time series.

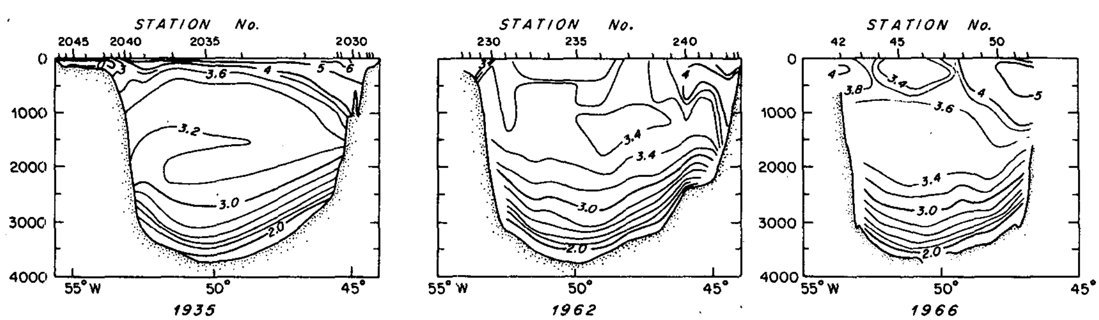

FIG. 6. Three *in situ* temperature sections from Labrador to Greenland, in 1935, 1962 and 1966 (after Smith *et al.*, 1937; Worthington and Wright, 1971; Grant, 1968, respectively). The heavy dashed lines in Fig. 1 show the approximate position of these sections.

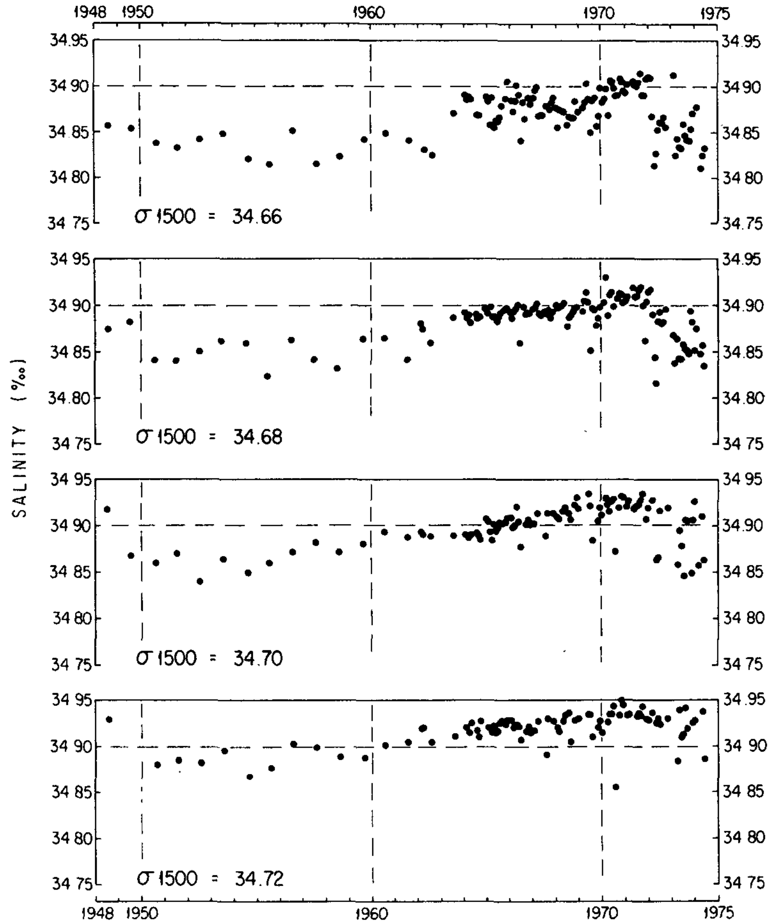

FIG. 7. Salinity at four densities, σ_{1500}, at OWS *Bravo*.

2) The 34.70 mg cm^{-3} surface was isolated after 1956.

3) The 34.68 mg cm^{-3} surface was isolated after 1959.

4) The 34.66 mg cm^{-3} surface was isolated after 1963.

5) Renewal of LSW occurred in 1972, at a density of 34.68–34.70 mg cm^{-3}, with the salinity at the densest three levels falling dramatically.

Additional information about the characteristics of LSW from 1928 to 1974 can be obtained from the θ-S diagrams of Fig. 8, plotted for water between 3 and 4°C and density between 34.64 and 34.78 mg cm^{-3} for various years. In particular, we note 1) the freshness of the water column in the 1950's compared with the 1930's, 2) the warmer, saltier water of 1971, with no overlap with the θ-S relation of the 1950's, and 3) the pronounced decrease in potential temperature and salinity by 1973. While water of densities 34.64–34.70 mg cm^{-3} was colder and fresher in 1973 as compared with 1928–40, the denser water was warmer and saltier. This increase in salinity was noted in the preceding paragraph and is consistent with there being ventilation at high densities prior to, or early in, the record and no subsequent renewal.

The changes in properties of the LSW and the trends at these four densities were correlated with heat flux from the ocean to the atmosphere in the area of OWS *Bravo*. Fig. 9 shows the monthly and annual heat flux in Marsden Square 186 [unpublished calculations by the late A. Bunker, made according to the methods described by Bunker (1976)]. Cooling was greatest around 1950, followed by somewhat reduced negative heat flux from 1951 through 1963. After 1963, the heat flux was nearly zero, even slightly positive, except in 1967. In 1972, cooling was again vigorous. Annual averages for 1973 and 1974 were not available but it appears from the monthly data through December 1972, that the heat flux in winter 1972–73 was very large and negative. These changes in heat flux reflect roughly the changes in renewal rate of the LSW, which was renewed more strongly in the 1950's than in the 1960's.

From all of this information, we conclude, along with Lazier (1981) and Clarke and Gascard (1982),

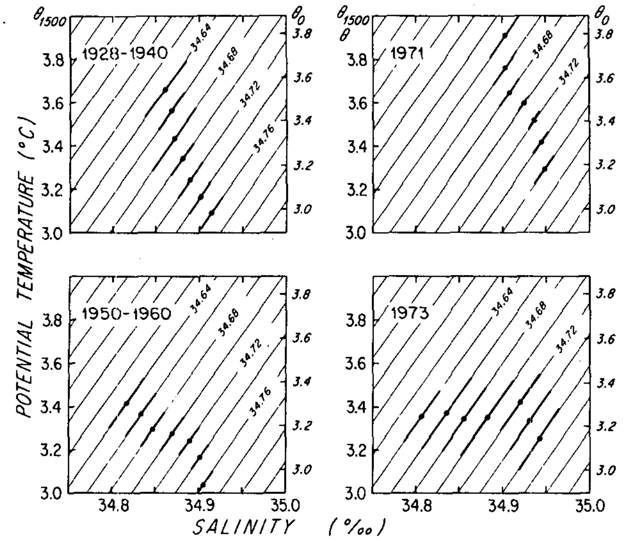

FIG. 8. Potential temperature vs salinity for four periods at OWS *Bravo*. Points are plotted for water of densities 34.64 to 34.78 mg cm^{-3} with potential temperature between 3 and 4°C. The potential temperature was calculated relative to 1500 m. The mean potential temperature and salinity were calculated for each density and are shown by a point. The standard deviation for each density is shown by a heavy line. The potential temperature (θ) relative to the surface is shown on the right side of each diagram.

that the LSW does not have stationary characteristics, nor that it is formed every year. In particular, its potential temperature was lower than 3.2°C from 1928 to 1955 and from 1972 to 1974, rising to a high of about 3.6°C in 1970. Its salinity was around 34.86‰ until 1959, rising to 34.90‰ by 1970 and dropping back to less than 34.86‰ in 1972. Its density was greatest in the 1930's and gradually decreased until 1970. Renewal in 1972 did not occur at the high density attained in the 1930's, probably because of the amount of fresh water that was mixed into the LSW in 1972, reducing its salinity below the values of the 1930's. Formation did not occur in 1959 and from 1970 to 1971. During the 1960's, LSW formation was much reduced and probably did not occur at all in the late 1960's (with the possible exception of 1967), according to the increasing salinity at all densities and Lazier's observation of greatly decreased mixed-layer depths and very low-salinity water at the sea surface.

A common definition of LSW is water of salinity less than 34.94‰, in the appropriate temperature range. We interpret salinity increases at LSW densities to be due to isolation from renewal. If the salinity trends at each density in Fig. 10 are extrapolated from the time when the salinity began to increase to the time when the salinity reaches 34.94‰, we obtain a mixing time scale of about 20 years for the LSW.

b. Labrador and Irminger Seas (1966–67)

The vertical homogeneity of LSW is so great that it is retained for many years, even through extended periods of isolation from convection. However, changes in renewal rate are evident in comparisons of different hydrographic data sets. In Figs. 10 and 11, we show LSW potential vorticity and salinity from late winter in the Labrador Sea (1966) and the Ir-

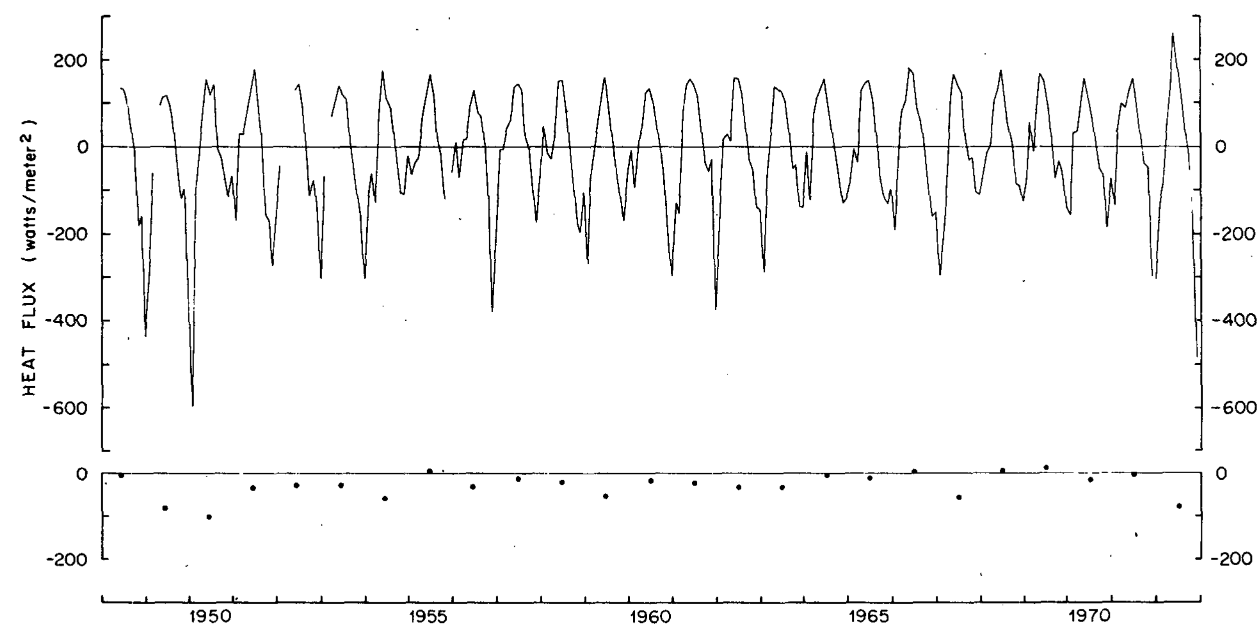

FIG. 9. Monthly and annually averaged heat flux for Marsden Square 186 in the Labrador Sea. This Marsden Square contains OWS *Bravo*.

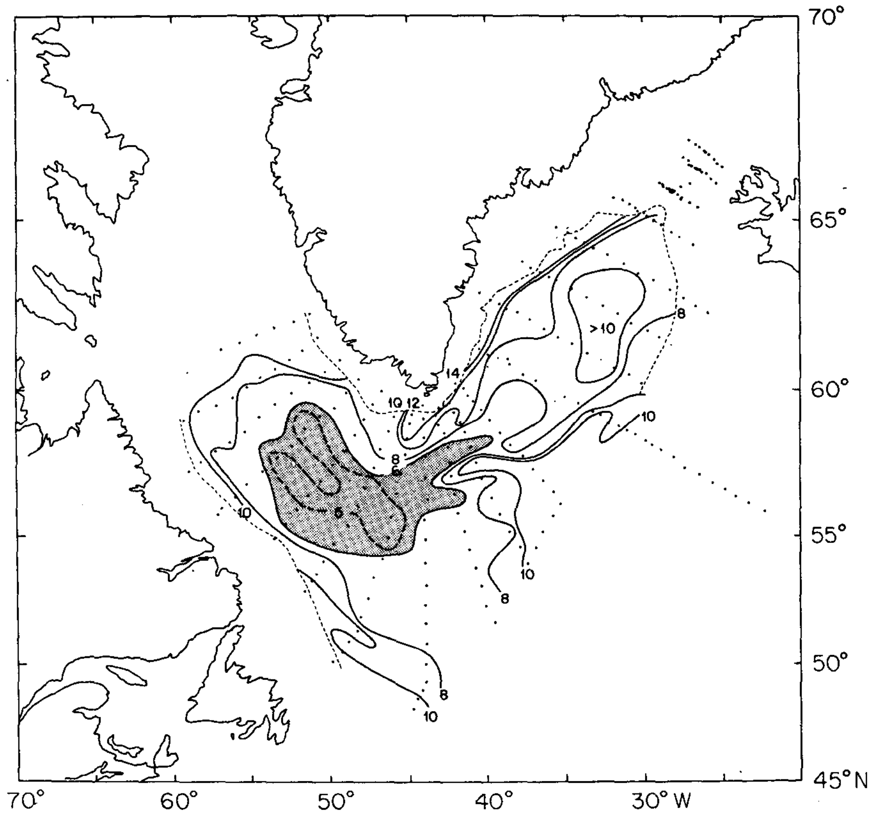

FIG. 10. Potential vorticity ($\times 10^{-14}$ cm^{-1} s^{-1}) at the LSW potential vorticity minimum in the Labrador and Irminger Sea. This chart uses the *Hudson* data of 1966–67, listed in Table 1b.

minger Sea (1967). These should be contrasted with Figs. 3 and 4 which used data from 1958 and 1962 in these Seas. The circulation in 1958–62 and 1966–67 was nearly the same: the East Greenland Current, which also carried the warmer Subpolar Mode Water into the Labrador Sea, advected high potential vorticity LSW around the southern tip of Greenland, where there was a strong gradient in potential vorticity. The counterclockwise boundary currents in the Labrador Sea carried these waters around the Labrador Sea. In the earlier data, the old LSW and Subpolar Mode Water were modified and the LSW became progressively fresher and more homogeneous. The Labrador Current then carried newly renewed LSW (low salinity, low potential vorticity) southward along the coast of Labrador. In contrast, in 1966 the old, high-potential-vorticity, high-salinity LSW circulated around the Labrador Sea, with no refreshment by convection. The Labrador Current in 1966 carried only old LSW southward along the coast of Labrador.

In both data sets, the lowest-potential-vorticity and lowest-salinity LSW was in the central Labrador Sea. However, the large pool of lowest-salinity LSW that was present in 1962 was greatly depleted in 1966. Changes in position of the 6×10^{-14} cm^{-1} s^{-1} potential vorticity contour and the 34.90‰ isohaline show that there was much less homogeneous, low-salinity LSW in 1966. Thus, reduction in the renewal rate affects the distribution of LSW in the northwest Atlantic.

Water of the lowest potential vorticity and salinity occurs along the western boundary near 55°N, offshore of the Labrador Current in both 1962 and 1966. This is approximately the same location where deep convection was observed in 1976 (Clarke and Gascard, 1982) and appears to be a preferred location for LSW formation.

c. Slope Water region (1956–72)

The amount of LSW seen in the Slope Water region varies with the production of new LSW in the Labrador Sea. LSW in the Slope Water is advected there by the Labrador Current flowing around the Grand Banks. Three north-south sections of potential vorticity near 50°W from 1956, 1964 and 1972 are shown in Fig. 12. In our previous discussion, we saw that healthy convective renewal of LSW in the Labrador Sea occurred in the mid-1950's. The 1963 section was made just before LSW production began to drop. The 1972 section typifies the period when there was no LSW production (although this section was made immediately after the reestablishment of convection in the Labrador Sea, the section was too far downstream from the Labrador Sea to register the increase in production rate).

The LSW potential vorticity on these sections is consistent with the OWS *Bravo* observations. The LSW, as usual, is identified as the vertical minimum in potential vorticity. For all three sections, the lowest LSW potential vorticity was in the north, in the boundary current. This lowest potential vorticity was less than 4×10^{-14} cm^{-1} s^{-1} in 1956 and 1963, but only a little below 8×10^{-14} cm^{-1} s^{-1} in 1972. In the first two sections, the Slope Water Current and Countercurrent, which lie offshore between the Labrador Coastal Water and the Gulf Stream, were well developed [see Worthington (1976) for a discussion of these currents]. In 1956, a period of active annual formation of LSW, the low-potential-vorticity layer (less than 8×10^{-14} cm^{-1} s^{-1}) extended almost without interruption across the Gulf Stream where there were several patches with potential vorticity less than 6×10^{-14} cm^{-1} s^{-1}. In 1963, the LSW potential vorticity generally was higher than in 1956. In 1972, the picture was even more dramatically different. The LSW potential vorticity was much higher and much less patchy. Except for the northern station in the boundary current, the LSW potential vorticity was between 9.0 and 10.5×10^{-14} cm^{-1} s^{-1}, compared to much lower levels in the earlier data.

We conclude that the vertical homogeneity of the LSW in the Slope Water and Gulf Stream areas responds to long-term variations in the strength of convective formation in the Labrador Sea. When convective formation of LSW is active, the LSW potential vorticity is low quite far from the Labrador Sea. The contrast between the LSW's low potential vorticity and the high potential vorticity of the Mediterranean Water is then especially marked. The LSW and Mediterranean Water are stirred by the subtropical gyre, resulting in considerable patchiness superimposed on a large-scale gradient. Another example of well-developed patchiness associated with renewed LSW, at 55°W in 1977, is given by McCartney *et al.*, (1980). Inhomogeneity is enhanced when new LSW is injected into the system. When the LSW is isolated from convection, stirring continues, but with the low-potential-vorticity source switched off. The lateral contrast between the LSW and the Mediterranean Water decreases as mixing homogenizes the water on isopycnals. The 1960's were a time of reduced con-

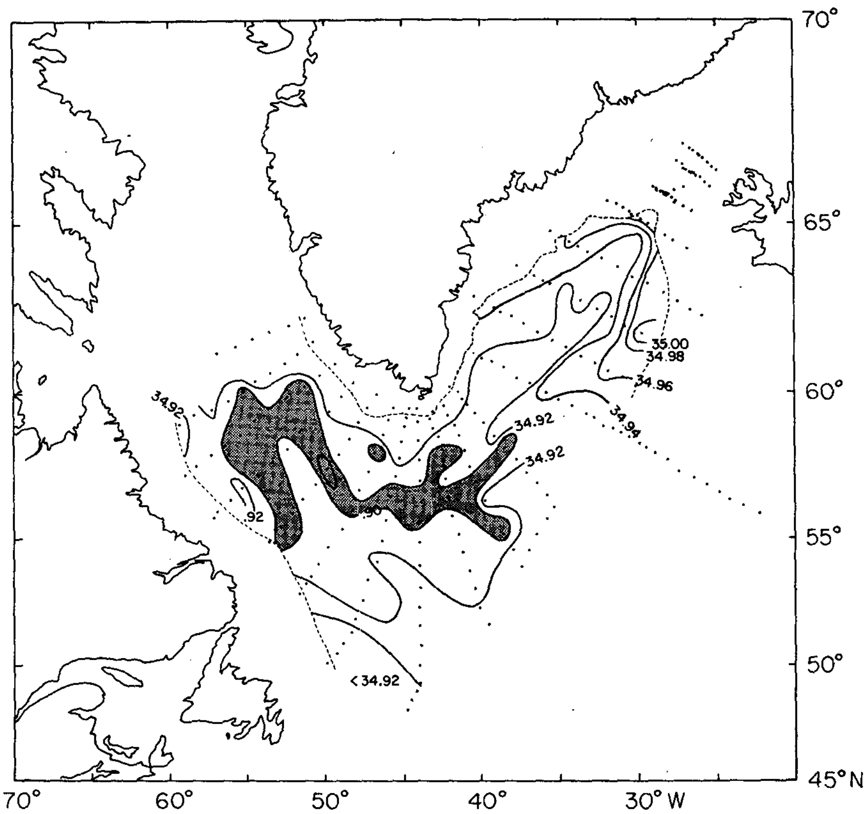

FIG. 11. Salinity at the LSW potential vorticity minimum in the Labrador and Irminger Seas.

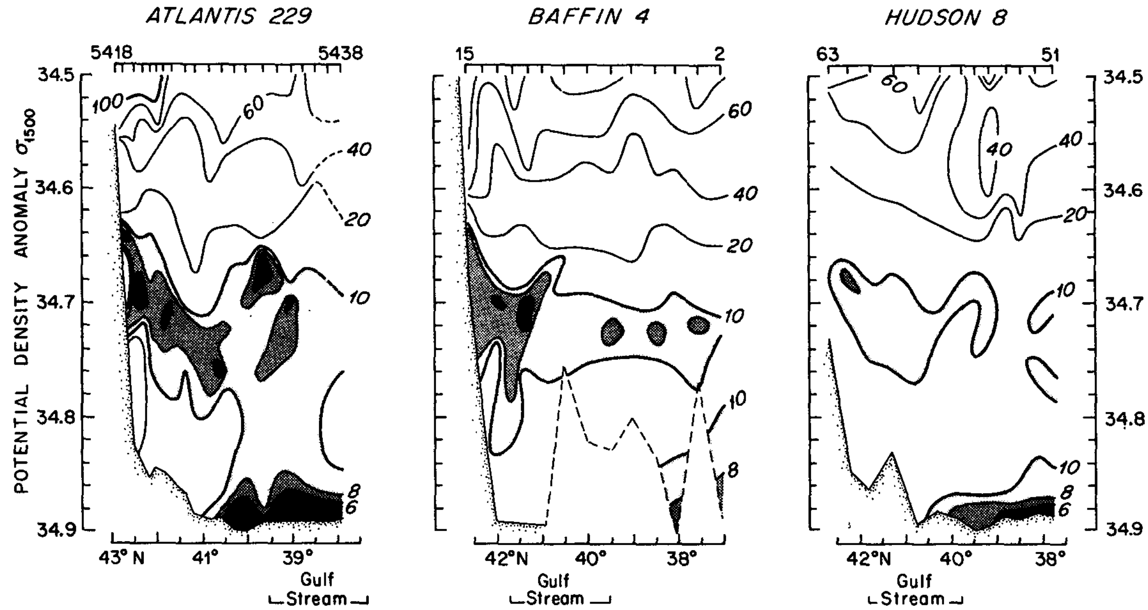

FIG. 12. Potential vorticity ($\times 10^{-14}$ cm^{-1} s^{-1}) vs potential density, σ_{1500}, for north-south sections at 50°W. The 1956 section is *Atlantis* 229. The 1963 section is *Baffin* B-4. (The dashed curves indicate the bottom of the hydrographic casts which did not reach near the sea floor at a number of stations.) The 1972 section is *Hudson*. These are sections 4–6 on Table 1b.

vective renewal compared with the 1950's. The stirring process, both locally and upstream, increased the LSW potential vorticity and decreased the patchiness on the 1963 section at 50°W. In 1972, following a long period of very low convective activity, the LSW flowing westward across 50°W was much less homogenous because stirring had extensively altered the potential vorticity over a large area.

7. Conclusions

The potential vorticity, usually discussed for its importance in dynamical processes, can also be a good tracer of convectively formed water masses, once they are removed from boundary forcing. The LSW has lower potential vorticity than all other surface and mid-depth water masses in the North Atlantic. The potential-vorticity minimum at mid-depths is thus associated with LSW.

Using potential vorticity as the prime tracer of LSW, we mapped its distribution and properties and inferred its circulation. We found that the newly formed LSW is advected throughout the northern North Atlantic at depths between 500 and 2000 m. Over large areas, the gradients of potential temperature, salinity, potential density and potential vorticity at the core of the Labrador Sea Water are small, indicating strong advection with modification by mixing and time changes of the LSW source. A simple lateral advective-diffusive interpretation of the LSW property distributions is precluded by marked changes in the properties and renewal rate of LSW in the Labrador Sea as seen in the hydrographic series at Ocean Weather Station *Bravo*. We found that the potential density of LSW decreased slightly while its salinity and potential vorticity increased during the series. The temporal range of potential density and potential vorticity for the LSW at OWS. *Bravo* was roughly half the spatial range for the LSW in the entire North Atlantic. However, mixing must be important since observed time-dependence in the Labrador Sea does not account entirely for the lateral range of properties. The most active mixing of LSW probably occurs 1) across the Gulf Stream with the Mediterranean Water, 2) in the wide band across the mid-Atlantic, also with the Mediterranean Water, and 3) south of the Greenland-Scotland Ridge, with Norwegian-Greenland Sea overflow waters.

The circulation of LSW was deduced from property distributions and the assumption that most flow is along tongues of low salinity and potential vorticity. The circulation was summarized at the end of Section 4. Identifiable LSW occurs as far south as 20°N. The circulation at mid-depth is similar to surface and abyssal circulations deduced by others in the same region (cf. Ivers, 1976; Stommel *et al.*, 1978; Reid, 1978). The latter two papers presented the dynamic topography of the North Atlantic, while Ivers based his interpretation of the circulation on dynamic topography and property distributions. The main feature of the dynamic topographies which is consistent with our circulation scheme is cyclonic surface circulation (relative to 1000 or 2000 m) in the Labrador Sea and the North Atlantic, north of 45 or 50°N. We conclude that the mid-depth circulation north of about 45°N is also cyclonic. South of this latitude, it is anticyclonic. The depth of the LSW has sometimes been taken to be a level of no motion, but we see that its circulation mirrors the circulation above it. Reid discusses a possible eastward flow, carrying LSW across the North Atlantic at about 50°N, which corresponds with our eastward branch of the North Atlantic Current. The branching of the North Atlantic Current which we infer from property distributions is not evident in the dynamic topographies. In particular, the northeastward branch into the Irminger Sea and the split into northward and southward branches near 27°W are not evident. The flow around the Grand Banks and southward along the western boundary is not evident in these dynamic topographies, based on the same large, sparse, data set used in this paper. This flow is clearly indicated by the property distributions and more detailed dynamic topographies (Clarke *et al.*, 1980), and has long been evident in the presence of LSW along the western boundary (Wüst, 1935; Richardson, 1977; Reid, 1981).

A ventilation time for the LSW can be determined roughly from estimates of its production rate (Worthington, 1976; McCartney and Talley, 1982b) and the net volume of LSW. Portions of the LSW may ventilate more quickly or more slowly, depending on how they circulate. The net volume is estimated by assuming that the density of LSW is $\sigma_{1500} = 34.70$ mg cm^{-3}. We use Wright and Worthington's (1970) figures for the volume of water in temperature-salinity classes which have a potential density of $\sigma_{1500} = 34.70$ mg cm^{-3}. There are about 3200×10^3 km^3 in the North Atlantic at this density. The sources at this density are the LSW at 3.3°C, 34.86‰, and Mediterranean Water at 6.5°C, 35.4‰. There is also another source at this density from the South Atlantic which strongly influences the water in the Guiana and Guinea-Cape Verde basins. These two basins have been excluded from the calculation. Of the total volume of water at this density, 2270×10^3 km^3 is LSW, based on a definition of 3.3°C, 34.86‰ for LSW. With a production rate of 8×10^6 m^3 s^{-1} (McCartney and Talley, 1982b), the ventilation time is 9 years. A lower production rate for LSW, 2×10^6 m^3 s^{-1}, was estimated by Worthington (1976). With this rate, the ventilation time is about 36 years. Because the ventilation time is the order of decades, decadal changes in renewal rate and properties as documented in Section 6 and by Lazier (1981) can have a profound effect on the lateral distribution of properties at mid-depth.

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