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Transit times to the NE Atlantic of Labrador Sea Water signals

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Abstract

Time-series of subsurface data collected from 1975-93 show relatively low salinity at 1600-1800dbar from 1985 onwards, with a marked fall in 1990. It seems likely that this recent salinity minimum represents the renewal of deep convection in the Labrador Sea in 1971-72 after the Great Salinity Anomaly, and gives a propagation speed of ca. 0.4 km/day to the Rockall Trough west of Scotland. An earlier low-salinity signal observed in 1965-67 at weather station *"Juliett"* may therefore represent an earlier Labrador Sea Water renewal event in the late 1940s.

Introduction

Temperature and salinity profiles have been collected by the Dunstaffnage Marine Laboratory (DML) since 1975 upon a section which crosses Anton Dohrn Seamount in the central Rockall Trough. This time-series of subsurface data amplifies the series of surface temperature and salinity in the central Rockall Trough which began in 1948 (e.g. Ellett, 1980). Past work has sometimes shown an alternation of variations on either side of the seamount (e.g. Ellett and MacDougall, 1983), so for the present analysis data from two stations from the axes of the trough on either side of the seamount have been examined. Long-term changes of differing character at various levels can be seen, the most striking being a recent fall in salinity values at depths occupied by Labrador Sea Water. This has stimulated investigation into the advent of such signals in earlier NE Atlantic time-series data.

The Anton Dohrn Seamount section data set

Figure 1 shows the position of the section, which crosses the Rockall Trough from the outer Scottish continental shelf in 57°N, 9°W to within 4km of Rockall. The stations used in the following analysis are stations F and M, midway between the seamount and the continental shelves to west and east of it, with soundings of approximately 1820 and 2200m respectively. Because bad weather has sometimes prevented the completion of the section, station M has been worked a greater number of times (41) than station F (35 times), between May 1975 and July 1991, but data have been obtained from both on 27 cruises.

The most intensive period of observation upon the section was between May 1975 and August 1978 when data were collected from 13 pairs of stations. The mean values at 100 dbar levels for these stations (Table 1) have been used for long-term comparisons, and Figure 2a shows the mean profiles of temperature and salinity. These show that mid-depth conditions at M were slightly warmer than at F by up to 0.62°K at 1000dbar, and slightly more saline at intermediate depths by up to 0.024

psu, reflecting the general character of flow through the Rockall Trough as an eastern boundary current with warmest and most saline water centered upon the slope current water along the eastern margins. At the lowest levels at station F (1600-1800dbar), mean salinity is marginally greater than at the same depths at M by 0.003-0.005psu, perhaps reflecting the influence of Norwegian Sea Deep Water overflow across the Wyville-Thomson Ridge.

The standard deviations of the 13 pairs of 1975-78 observations are shown in Figure 2b and are broadly similar for both positions. For temperature, variability decreases to an intermediate minimum between 200 and 600dbar, increasing to a maximum at 900-1000dbar but decreasing at greater depths. At M, the minimal standard deviation of 0.08°K was found at 1800-2000dbar, whereas at F temperature standard deviations were nearly constant at 0.18-0.20°K from 1500dbar downwards. Salinity variation with depth had less pattern; at both F and M a minimum occurred at 200dbar, but after increases to 300dbar (F) and 700dbar (M) there was a general but irregular decrease downwards. These profiles of variability with depth can be compared with similar data from a section some 85-110km to the south of the Anton Dohrn Seamount section worked on 10 occasions between August 1963 and November 1965 (Ellett and Martin, 1973). In the earlier data the intermediate temperature variation maximum was deeper at 1000-1200m, with a near-coincident salinity standard deviation maximum at 1200m, but otherwise there is a good match of features from both sets of stations.

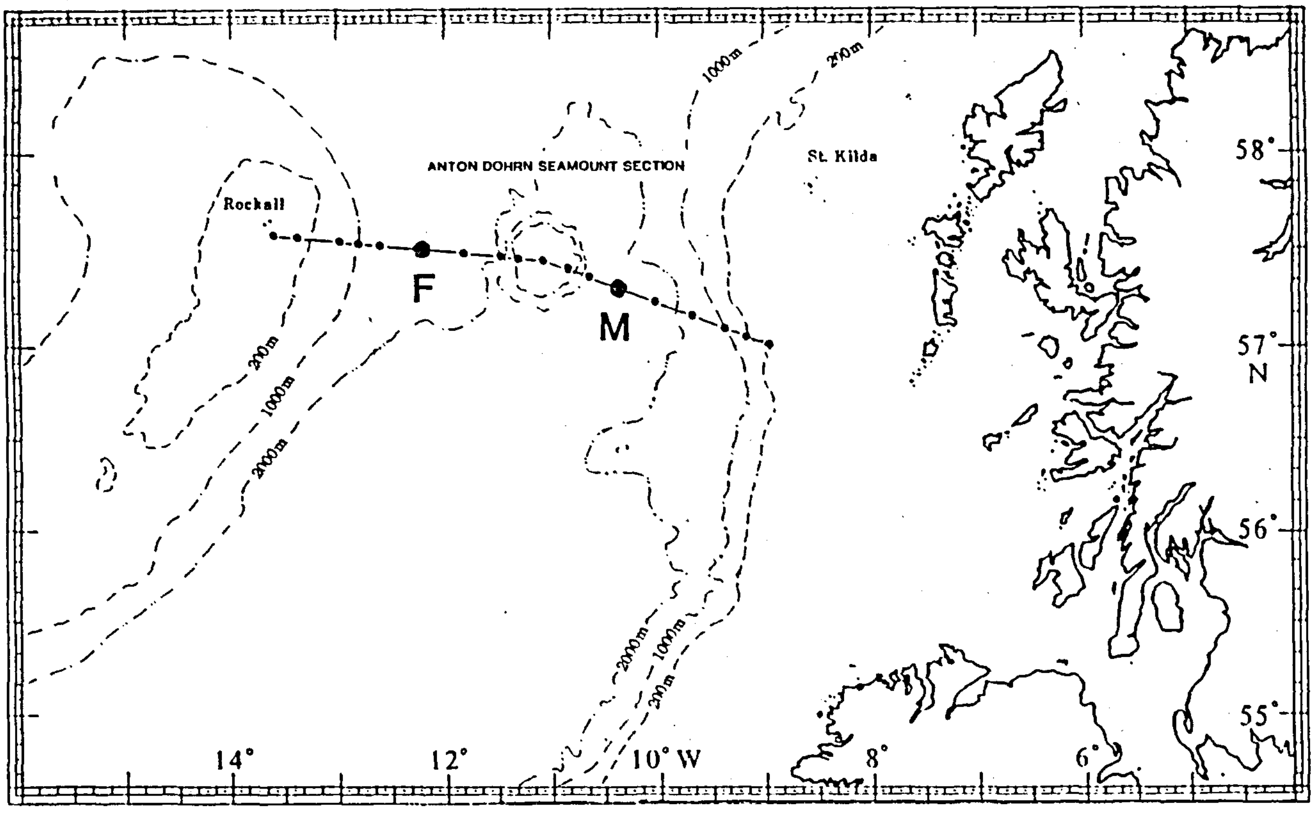

Figure 1. The Anton Dohrn Seamount CTD section.

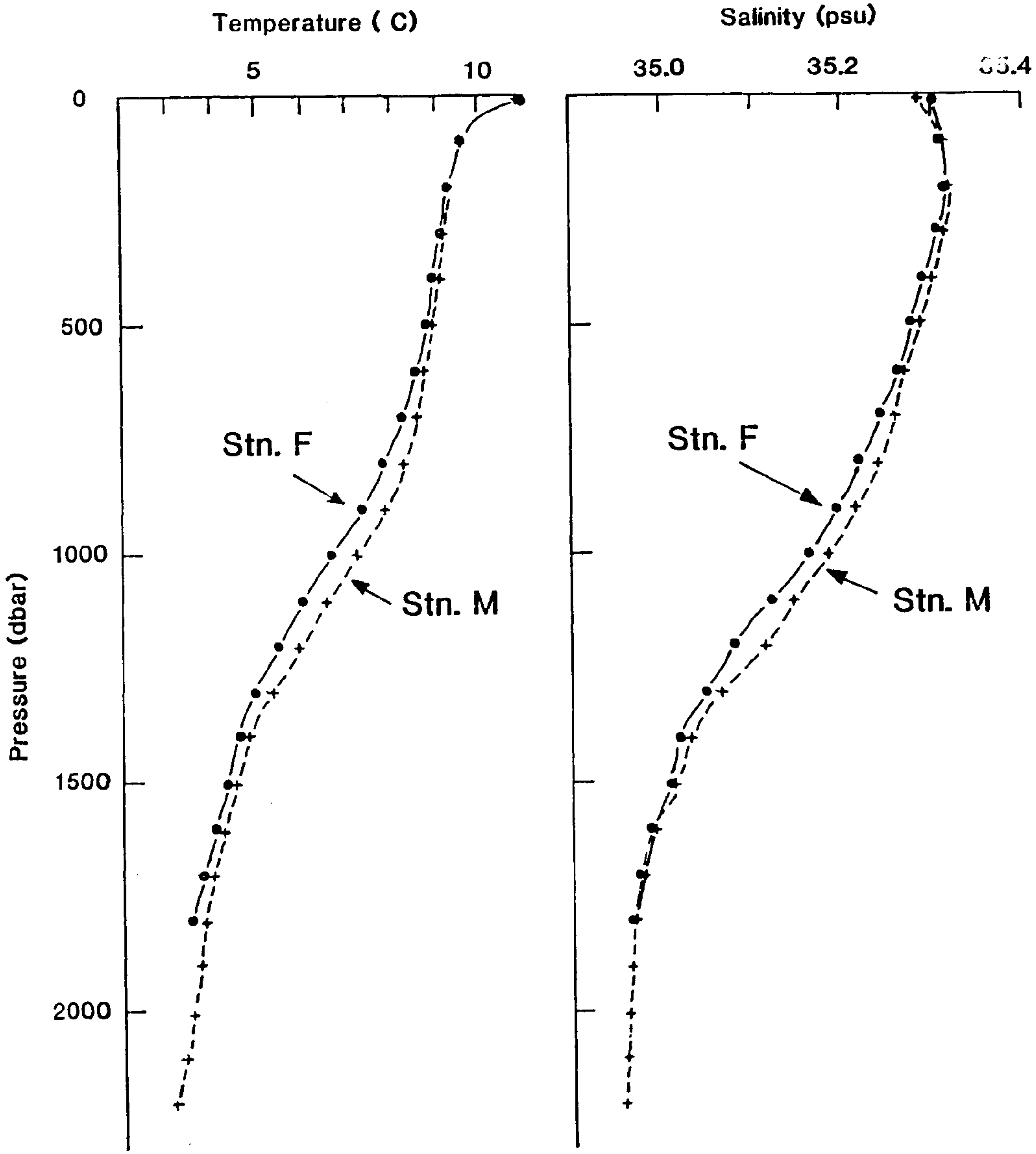

Figure 2a. Mean profiles of temperature and salinity at stations F (57°30.5'N, 12° 15'W) and M (57°18.0'N, 10°23'W) from means at 100dbar intervals of 13pairs of stations during 1975-1978.

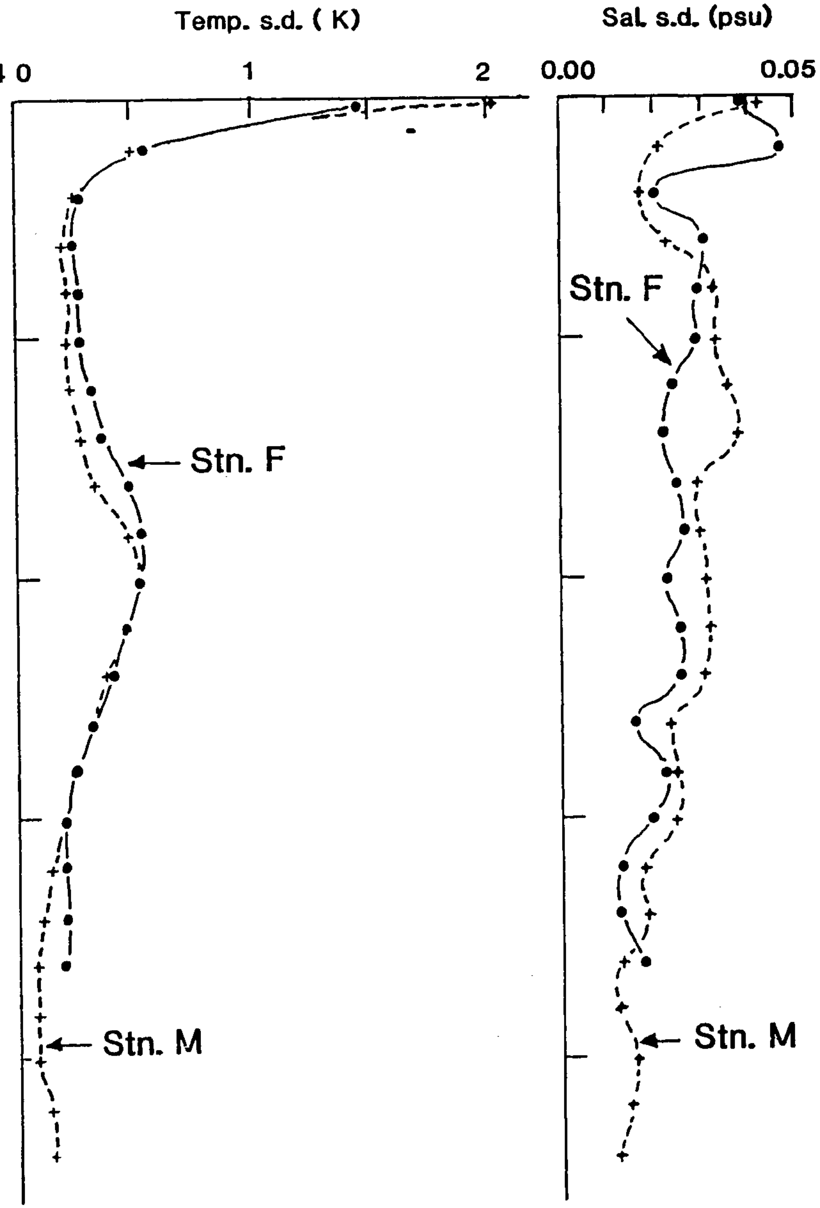

Figure 2b. Standard deviations for means at 100dbar intervals at F and M for 13 pairs of stations during 1975-1978.

Thus the ranges of the variations mostly decrease with increasing depth, although small changes in the lower water column may be as, or more, significant as larger changes nearer the surface. To allow for this, anomalies from the 1975-78 mean values have been divided by the relevant standard deviation, and the results for three sections of the water column are presented here. These are, for both F and M, 500 and 1000dbar, and at 1600dbar for F and 1800dbar at M. The use of two levels for the deeper band was dictated by practical considerations, chiefly the lesser number of observations (19) available at 1800dbar at F than at 1600dbar (30), but it may be noted that the mean values at these two levels have near identical density (sigma-theta = 27.790).

Temporal changes, 1975-91

Figure 3a shows the temperature variations during 1975-91 at the selected levels in terms of standard deviations (s.d.s) from the 1975-78 mean values. No major trends are immediately apparent, but examination of the data subsequent to the 1975-78 mean period reveals some minor shifts. Thus, at 500dbar between May 1979 and July 1991, 29 observations gave positive s.d. values, with 7 of these exceeding 2s.d.s, as against 15 negative s.d.s, only one of which exceeded 2s.d.s. At 1000dbar, there were 28 positive s.d.s and 14 negative s.d.s in the same period, none of which significantly exceeded the 2s.d. level. The temperature pattern at 1600-1800dbars between May 1980 and July 1991differs, with only 9 positive s.d.s, (although 3 of these were greater than 2s.d.s), and 31 negative s.d.s, only one of which exceeded 2s.d.s. A general conclusion is therefore that the 1980s were warmer than the 1975-78 period by up to ca. 0.5°K at the 500dbar level and ca. 1.0°K at the 1000dbar levels, but colder by up to ca. 0.5°K at 1600-1800dbar.

More definite trends are seen in the salinity changes (Figure 3b) and it should be noted that the period from which the means are taken are the years when the "Great Salinity Anomaly" (Dickson et al., 1988) was passing through the upper waters of the Rockall Trough, the minimal surface values having occurred in October 1975. At 500dbar the May 1979 to July 1991 period had generally higher salinity than in 1975-78, with 36 positive s.d.s, 11 of which significantly exceeded 2s.d.s, and 8 negative s.d.s, none of which were greater than 2s.d.s. The higher salinity in 1985 and 1991 may reflect higher values observed at the surface in the years immediately preceeding these (Ellett and Turrell, 1992).

At 1000dbar there was also a positive bias throughout the 1980s, though it was less marked, with 29 positive s.d.s, 7 of which exceeded 2s.d.s, and 12 negative s.d.s, 2 of which (at F in 1990) exceeded 4s.d.s. The most dramatic feature of these time-series occurred at the 1600-1800dbar level; after May 1983 there were no positive s.d.s, and in 1990 salinity values at F on two consecutive cruises were 6-7s.d.s below the 1975-78 values. Summarising the May 1980 to July 1991 period as a whole at this level, there were 7 positive s.d.s (all between May 1980 and May 1983, and none exceeding 2s.d.s) and 34 negative values, 10 of which (from January 1985 onwards) significantly exceeded 2s.d.s.

A general summary of salinity changes at these levels is therefore that salinity was higher than in 1975-78 at the 500dbar level mostly by up to ca. 0.08psu, but by up

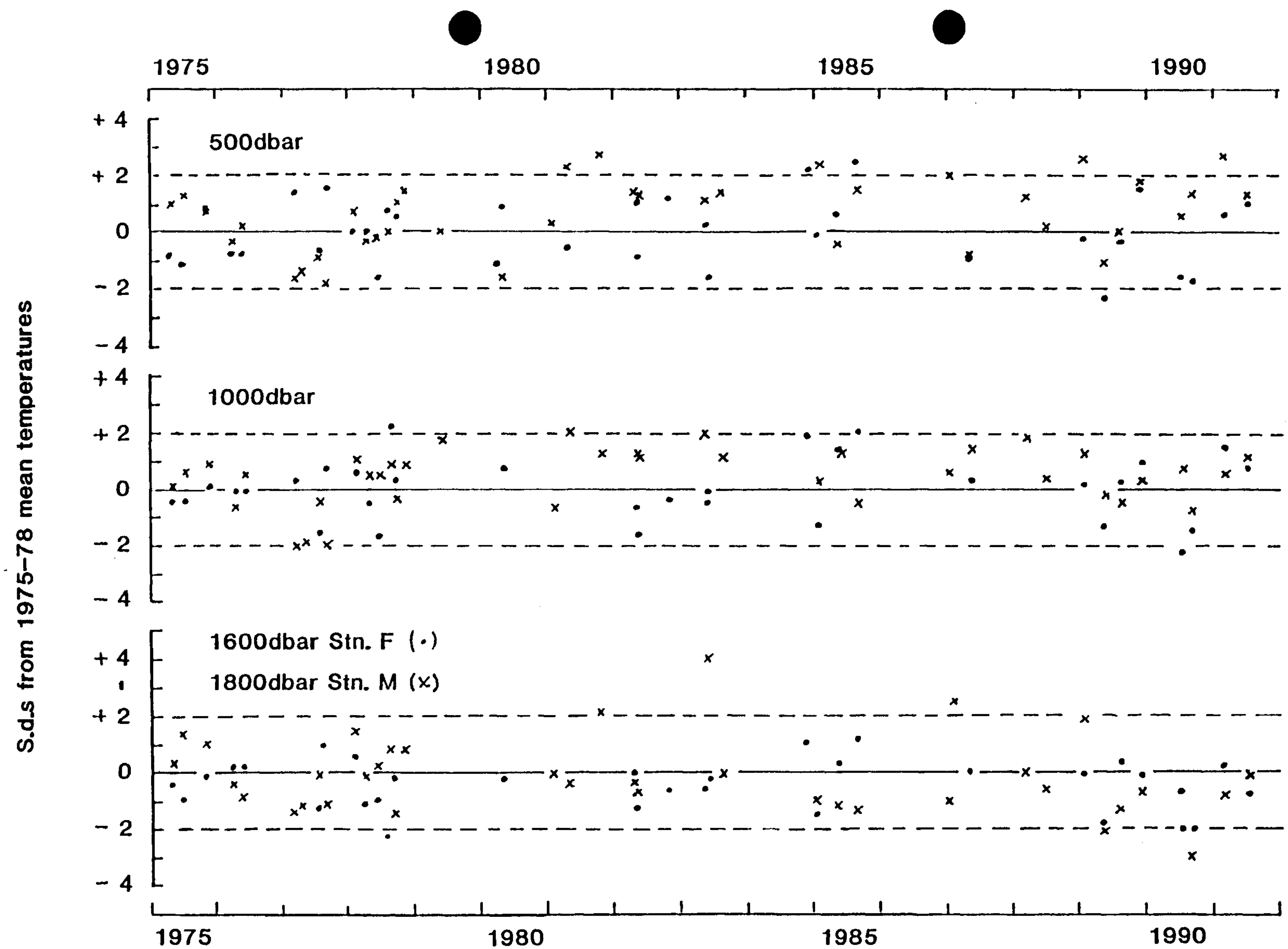

Figure 3a. Temperature variations during 1975-91 at F and M at 500, 1000 and 1600-1800dbar expressed in terms of standard deviations from the 1975-78 means.

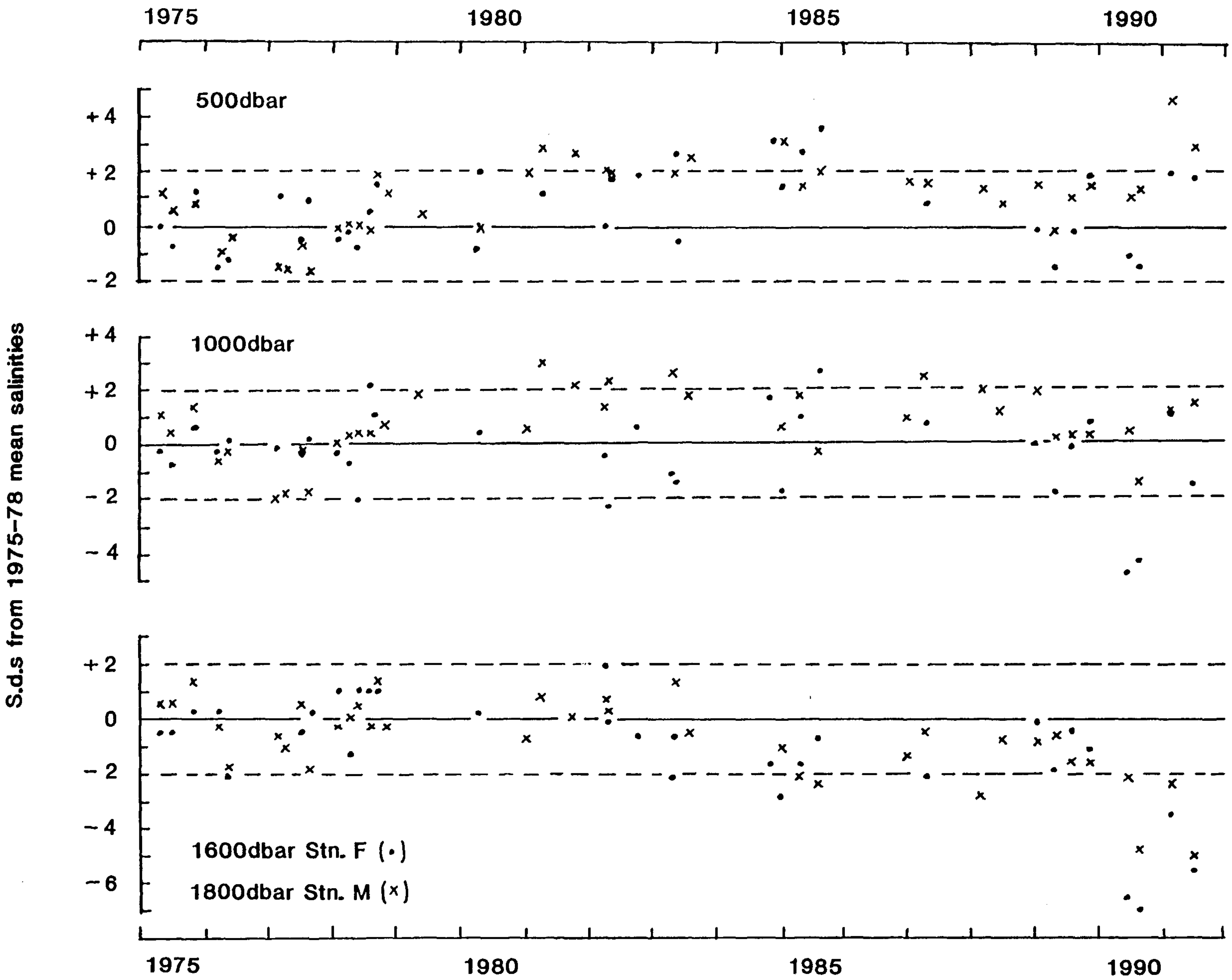

Figure 3b. Salinity variations during 1975-91 at F and M at 500, 1000 and 1600-1800dbar expressed in terms of standard deviations from the 1975-91 means.

to 0.12psu during late 1984 to autumn 1985, and again in early 1991; at 1000dbar, salinity was generally higher than the reference period by up to ca. 0.09psu, although notably low salinities were observed at F in 1990; and at 1600-1800dbar salinity declined after 1983 to values ca. 0.04psu below the 1975-78 value until 1990 when salinities down to 0.09psu below the mean were observed.

The freshening of Labrador Sea Water in the Rockall Trough in 1990

The major feature of the time series presented above is the freshening event observed at the lower levels in 1990. The origins of this section of the water column were shown by sections worked in the Rockall Trough during the 1960s which clearly identified the low-salinity, high-oxygen water mass in the lower water column at 1600-1900m depth as Labrador Sea Water (LSW) (Ellett and Martin, 1973). A salinity minimum was often, but not always, present and is not a feature of the 1975-78 100dbar interval mean values (Figure 2a).

The scale of the freshening and cooling which occurred during the first half of 1990 is demonstrated in Figure 4, which gives temperature-salinity (t-s) plots for station F from November 1989 and June 1990, together with the 1975-78 mean t-s values. Below 1400dbar the November observation is fresher than the mean values by 0.01-0.02psu but has temperatures close to the means; By the following June, salinity at 3.8°C was 0.07-0.08psu lower than in November and the level of this isotherm had risen from 1720 to 1450dbar. Eight DML cruises worked the section between January 1989 and July 1991, allowing the event to be viewed on a broader scale than the changes at a single station. Figure 5 shows the mean depth of the 35.0psu isohaline over the eastern and western portions of the section during this period, demonstrating a remarkable rise of 280dbar in the first half of 1990. The sequence also suggests that the "new" water initially entered the western side of the Rockall Trough, where the 35.0 level in June 1990 was 120dbar above that of the eastern side, although both were at similar levels by September 1990.

Dating the "new" water

Initial surprise at the scale of this freshening event directed attention to existing accounts of LSW renewal in its region of origin, and an early candidate for consideration was the deep mixing event of winter 1985-86 reported by Wallace and Lazier (1988) which produced the most extreme LSW characteristics so far observed. However, a four-year time-scale would indicate an advection rate only a little slower than the 1½-2km/day of the "Great salinity anomaly" in the upper waters (Dickson et al., 1988), which seems unlikely. The progress of water from this renewal should in future be capable of being monitored through its content of chlorofluoromethanes (CFCs), which were measured by Wallace and Lazier (1988).

What earlier LSW formation events are documented? Lazier (1980) has described how low salinity water at the surface of the Labrador Sea inhibited deep convection from 1967 to 1971, allowing salinity at depth to rise gradually until deep mixing resumed in the winter of 1971-72 and sharply reduced salinity levels again. Talley and McCartney (1982) find that renewal to mid-depths occurred regularly during the

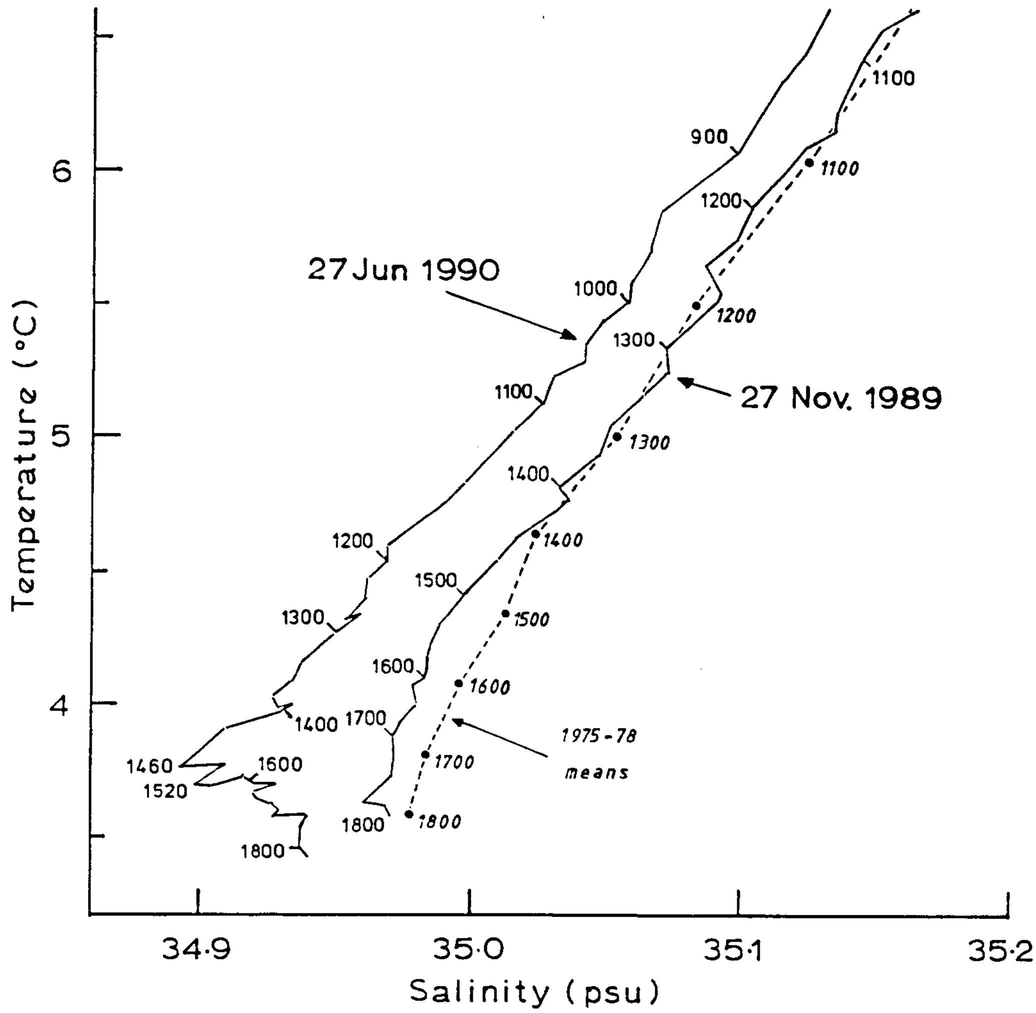

Figure 4. Temperature-salinity plots for station F in November 1989 and June 1990. The 1975-78 mean t-s values are also shown.

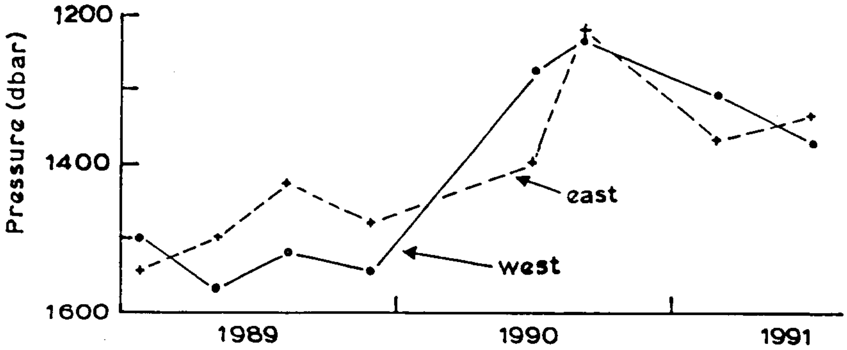

Figure 5. Mean depth of the 35.0 isohaline across the east and west portions of the Anton Dohrn Seamount section, 1989-91.

1950s, but show that the sigma-1.5 = 34.70mg cm^{-3} surface was isolated after 1956, suggesting the 1955-56 winter as the most productive of LSW during that decade.

From the vicinity of Ocean Weather Station *"Bravo"* (56°30'N, 51°W) to the central Rockall Trough is a distance via the tail of Rockall Bank of about 2500km. Approximate mean advection rates may therefore be calculated as follows:

for the 1985-86 renewal	4½yrs @ 1.52 km/day
for the 1971-72 renewal	18yrs @ 0.38 km/day
for the possible 1955-56 renewal	34yrs @ 0.20 km/day

The retention of such distinctive characteristics as those observed in the 1990 Rockall Trough LSW argues for shorter, rather than longer, transit times, and as an origin from the 1985-86 event has been ruled unlikely, an origin in the 1971-72 renewal seems a reasonable assumption, particularly as this renewal sharply reduced the LSW salinity characteristics by mixing into it the low-salinity surface water which had inhibited convection in the preceeding years. Supporting evidence comes from the UK-Greenland CONVEX-91 sections. Read and Gould (1992) show that the density of the LSW salinity minimum in the Iceland Basin, between the Reykjanes Ridge and the Rockall Plateau in August 1991 was higher ($sigma_{1.5}$=34.64) than that of the fresher Irminger Basin LSW (sigma $_{1.5}$=34.66 to 35.67), suggesting that the latter originated from the 1985-86 renewal and that the Iceland Basin LSW was formed before 1986 but later than the 1960s. The June 1990 salinity minimum at station F in the Rockall Trough had a lower density of sigma $_{1.5}$=34.61 to 34.62, reflecting the additional mixing which takes place in passing from the Iceland Basin to the Rockall Trough.

Evidence of a previous event

Past NE Atlantic data series offer evidence of previous LSW salinity changes. Water-bottle data from Ocean Weather Station *"Juliett"* (52°30'N, 20°W) were collected at roughly weekly intervals between 1964 and 1975, and have been examined by Ellett (1980). Because of the vertical spacing of the samples in the lower water column (usually aimed at 1200, 1500 and 2000m), accurate determination of the LSW salinity minimum was not possible and the percentage occurrence of minima below a number of 0.01psu levels was examined for depths greater than 1200m. Figure 6 shows that salinities below 34.93psu, to take a particular level, were found in 36% of the observations in 1964, a figure which rose to 56% in 1966, but fell to 0% in 1972. In general, 1964 to 1968 is a low-salinity period and 1972 a salinity maximum. From the central Labrador Sea to *"Juliett"*, at the southern entrance to the Rockall Trough, is a distance of aproximately 2000km, and using the advection rate calculated above of 0.38 km/day this would suggest a renewal event some 16½ years previous to 1964, i.e. in the later 1940s. It may be noted that Talley and McCartney (1982) show heat flux calculations by Bunker for the Labrador Sea over the period 1948-1972 which demonstrate that cooling was greatest in 1949-1950.

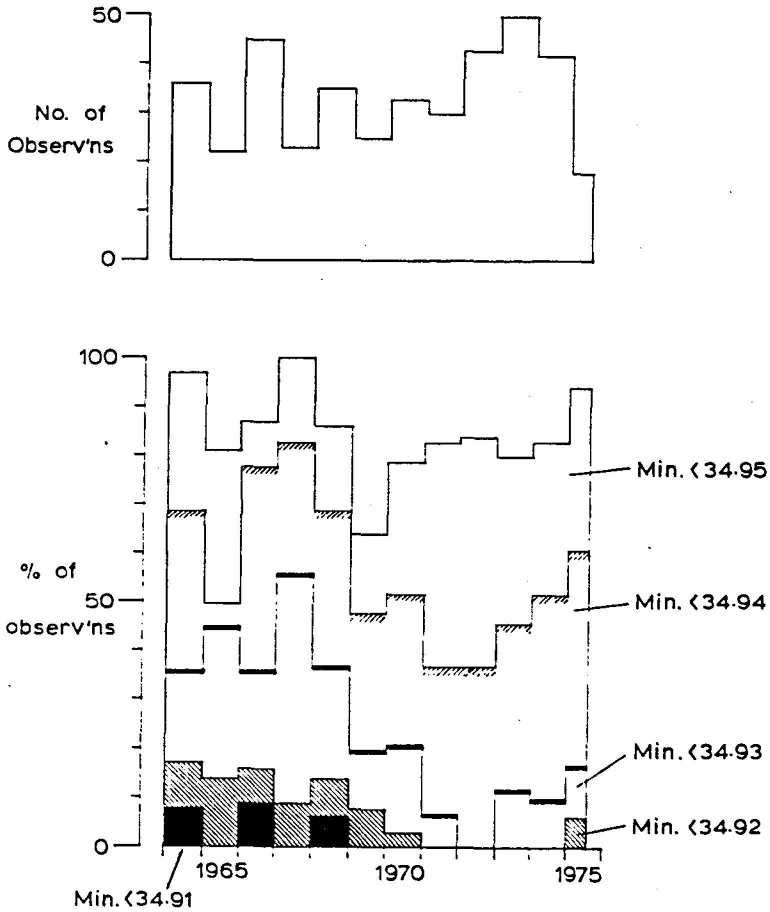

Figure 6. Values of salinity minima below 1200m at Ocean Weather Station *"Juliett"* (52°30'N, 20°W) 1964-1975 (from Ellett, 1980).

Conclusions

A remarkable sudden fall in salinity values occurred between November 1989 and June 1990 in the central Rockall Trough at the depths occupied by Labrador Sea Water. It seems probable that this represents the signal from LSW renewal in the winter of 1971-72, which marked the resumption of deep convection after several years when low-salinity surface water from the "Great Salinity Anomaly" inhibited deep mixing. This 18-year time-scale implies a mean advection rate of about 0.4 km/day.

At OW Station *"Juliett"* at the southern entrance to the Rockall Trough LSW salinities were low in 1964-68 and rose to a maximum in 1972. If the same advection rate applies, this suggests a previous episode of deep Labrador Sea convection in the late 1940s.

Further studies are in hand to quantify the effects of the 1990 low-salinity inflow upon the water mass composition of the Rockall Trough, and to examine subsurface salinity and temperature fluctuations in the NE Atlantic since the 1960s

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Table 1. 1975-1978 mean temperature and salinity at stations F and M

Pressure (dbar)	Stn. F (57°30.5', 12°15'W) Temp. °C	Pot'l temp.	Salinity (psu)	Sigma-theta	Stn. M (57°18.0'N, 10°23'W) Temp. °C	Pot'l temp.	Salinity (psu)	Sigma-theta
10	10.20	10.20	35.303	27.155	10.85	10.85	35.288	27.028
100	9.62	9.61	35.314	27.264	9.66	9.65	35.316	27.259
200	9.35	9.33	35.319	27.315	9.35	9.33	35.319	27.315
300	9.14	9.12	35.309	27.342	9.25	9.22	35.316	27.331
400	8.98	8.94	35.296	27.361	9.13	9.08	35.301	27.340
500	8.82	8.77	35.283	27.378	8.99	8.93	35.283	27.358
600	8.63	8.56	35.269	27.399	8.80	8.73	35.273	27.375
700	8.30	8.23	35.246	27.433	8.60	8.52	35.262	27.400
800	7.89	7.81	35.221	27.477	8.35	8.26	35.245	27.427
900	7.34	7.25	35.199	27.541	7.90	7.81	35.219	27.475
1000	6.66	6.56	35.166	27.610	7.28	7.18	35.187	27.541
1100	6.03	5.93	35.125	27.661	6.57	6.46	35.149	27.610
1200	5.49	5.38	35.083	27.696	5.96	5.85	35.116	27.664
1300	5.00	4.89	35.054	27.731	5.35	5.23	35.070	27.703
1400	4.64	4.52	35.024	27.749	4.88	4.76	35.034	27.730
1500	4.34	4.22	35.013	27.774	4.55	4.42	35.014	27.752
1600	4.08	3.95	34.997	27.789	4.27	4.14	34.992	27.765
1700	3.81	3.67	34.984	27.807	4.05	3.91	34.981	27.781
1800	3.58	3.44	34.978	27.826	3.88	3.73	34.973	27.792
1900					3.73	3.58	34.968	27.804
2000					3.60	3.44	34.966	27.816
2100					3.43	3.26	34.966	27.833
2200					3.22	3.05	34.963	27.851