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Theme Session O

"Cooling of the Intermediate Layer in the Northern North Atlantic Ocean"

by

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Abstract

Several repetitions of transoceanic sections A1/AR7 and A2/AR19 from 1991 through 1996 reveal significant and rapid changes of intermediate watermass property characteristics. A cascade of new modes of Labrador Sea Water (LSW) is traced throughout the northern North Atlantic after a series of increased deep wintertime convection events started in 1986, that renewed the intermediate water mass in the Labrador Sea. The arrival of new LSW vintages in other parts of the North Atlantic is marked by a significant cooling of the local LSW core as well as its deepening and its densification. The travel time from the source region to the European continental slope is estimated to be 7 - 8 years, yielding a surprisingly high mean speed of some 1 cm/s. This outstanding event, as a conclusive evidence for ocean climate variability comparable to the 'Great Salinity Anomaly' of the mid 70s (Dickson et al., 1988), is currently in progress. Changes reported at 36° N and 24° N show a consistent pattern with our observations. We conclude that cooling and also warming episodes produce T/S anomalies that seem to follow to distinctly different pathways: one cyclonic around the subpolar gyre and a second confined to the North Atlantic and mainly the subtropical gyre. The two pathways have a distinctly different impact on its meridional overturning circulation.

Convectively vertical mixing of the meridional overturning cell of the northern North Atlantic Ocean transforms warm, salty and light surface water to cold, fresh and dense intermediate and deep waters. In the Labrador Sea, convective overturning in late winter creates the relatively homogeneous Labrador Sea Water (LSW) with its unique characteristics of low salinity, high oxygen content, low potential vorticity and high anthropogenic tracer concentrations, which can be traced at depths between 1000 m and 2000 m as it spreads to other parts of the ocean (Fig. 1). Three primary pathways away from the formation region are distinguishable (Talley and McCartney, 1982; Schmitz and McCartney, 1993) (Fig. 2): (i) southward flow as part of the deep western boundary current (DWBC), (ii) eastward flow near 50° N latitude (beneath or parallel to the North Atlantic Current) with several bifurcations east of the Mid-Atlantic Ridge (MAR), and (iii) north-eastward flow into the Irminger Basin. As the dominating fraction of the Upper North Atlantic Deep Water, LSW is one of the main water masses of the North Atlantic, and depending on the intensity of its formation process it is one of the controlling sources affecting the North Atlantic meridional overturning system (Schmitz and McCartney, 1993; Weisse et al., 1994; Rahmstorf and Willebrand, 1995).

The formation of LSW is not a process of constant intensity nor of constant characteristics every winter. Hydrographic time series collected in the central Labrador Sea reveal that deep convection occurs discontinuously on a decadal timescale (Lazier, 1996). Only two periods of intensified LSW production were identified during the last 30 years, from 1972 to 1976 with Θ/S characteristics in the range of 2.9 °C - 3.2 °C and 34.83 - 34.85 and approximately from 1986 onward. It appears that the discontinuous LSW formation record is controlled by the combined, remote response to the coupled cells of the North Atlantic Oscillation (NAO) with the effect, that the evolution of convective activity in the Labrador and Greenland Seas during this century was in opposite phase (Dickson et al., 1996).

The first indication for the beginning of the recent convection period came from chlorofluorocarbon (CFC) measurements in the south central Labrador Sea in July 1986 (Wallace and Lazier, 1988), although at one station only. The following years confirmed this observation when LSW was found to be significantly cooler and denser (Θ/S in the range of 2.6 °C - 3.0 °C and 34.82 - 34.84) in the entire central Labrador Sea (Lazier, 1996). Finally, the 1990s vintages are the coldest, densest and freshest ever observed in the Labrador Sea (P. Rhines, pers. comm). The first appearance of recently renewed LSW outside its source region was observed 1991 in the subpolar North Atlantic by comparison with historical data (Read and Gould, 1992). Age estimates of LSW vintages encountered in the Northeast Atlantic, however, varied in ages over 15 years, i.e. spanning the vintages from 1972 to 1986 in 1991 (Top et al., 1987; Read and Gould, 1992; Cunningham and Haine, 1995).

As a contribution to the World Ocean Circulation Experiment (WOCE) we worked section A1/AR7 in 1991, 1992, 1994 and 1995 and section A2/AR19 in 1993, 1994 and 1996 (Fig. 2). To trace the temporal change of LSW properties we calculated its differences at the uniquely defined salinity minimum of the LSW core (Fig. 3) which represents the 'purest' LSW in our data. This water-mass-following method is insensitive to depth or density variations of the LSW vintages and thus has not the disadvantage of differences calculated from gridded section data (Fig. 4).

The comparison of LSW core temperatures along section A1/East reveals a cascade-like cooling in the Irminger Sea ("1986-LSW cascade") of the order of -0.28 °C in 4 years (Fig. 5a, Tab. 1), with the annual arrival of a new LSW mode. Cooling in the Iceland Basin of -0.19 °C and in the Rockall Trough area of -0.11 °C also indicates renewed LSW. Although we find a cascade-like signal in the Iceland Basin, in the Rockall Trough area, however, the only signal of renewed LSW appears in the 1994 data, indicative of the arrival of the 1986-LSW cascade at the European continental slope. Substantial cooling results in an increase of density (Fig. 5d) and in deepening of the core layer (Fig. 5c), which are greatest in the Irminger Sea (0.018 kg/m^3 and 240 dbar). Since there is no significant signal in LSW core salinity (Fig. 5b) a compensation of density cannot take place. A striking but not surprising feature (Fig. 5a, b) is the separation of the LSW core layer by the Reykjanes Ridge (at 31°W) into two different hydrographic regimes, the Irminger Sea and the Iceland Basin, reflecting the mixing along the longer pathway into the eastern basins and enhanced mixing over topography. Also note that the area between 25°W and 27°W is marked by the lowest LSW core temperatures and salinities observed in the eastern basins of the North Atlantic: after crossing the MAR, a branch of LSW flows at this latitude into the Iceland Basin (Fig. 2) as part of the Subpolar Gyre circulation.

The characteristic property changes of the 1986-LSW cascade are cooling, densification, deepening and only minute or no freshening (Tab. 1). These results correspond well with observations in the central Labrador Sea (Fig. 6). From 1988 to 1993 the LSW formation is characterized by a temperature decrease of the order of -0.4 °C, without significant salinity changes and accompanied by a density increase of about 0.05 kg/m^3 (Lazier, 1996). This is in contrast to the properties generated during the preceding convection period (1972 - 1976), where strong cooling was accompanied by a substantial freshening of the order of 0.08 psu and consequently only very small densification.

Comparing Θ/S values for LSW from the central Labrador Sea with those from the adjoining Irminger Sea (Fig. 6), the Labrador Sea observations are grouped in tight clusters representing the homogeneous Θ/S signature of each LSW vintage, whereas the Irminger Sea values are more scattered and generally higher. This demonstrates the influence of mixing along the spreading path. However, all data are in the same density range and in both basins they show the same discreet increase in density. As we found no indications of deep convection in the Irminger Sea we believe this layer is a direct intrusion of LSW which spread from the source region along its characteristic isopycnals. The alignment of core values along isopycnals suggests that the annual intrusion of LSW in the Irminger Sea originated in the Labrador Sea during the convection season in March of the same or the previous year. Only the 1993 vintage in the Labrador Sea data has no counterpart in the Irminger Sea, because there no observations are available. Also, due to a lack of appropriate Labrador Sea data in 1991 it is not clear whether the 1990 or the missing 1991 vintage would have a counterpart in the 1991 Irminger Sea data. Finally, for the 1995 Irminger Sea cluster a counterpart in the Labrador Sea cannot be assigned at this time.

We conclude that the intrusive events observed in the Irminger Sea are a result of convection in the Labrador Sea of the same year resulting in a maximum travel time of 6 months. The alternative of a maximum travel time of 18 months, however, is not supported by CFC observations (M. Rhein, pers. comm.). Convection in the Labrador Sea takes place, based on direct observations and large scale surveys, in the western central region (Lazier, 1996). This is about 700 km from where the water was observed in the Irminger Sea some 6 months after convection, yielding a mean speed of 4.5 cm/s. Our finding that intermediate waters move rapidly from the Labrador to the Irminger Sea suggests these regions to be considered as a single entity in discussions of the role of LSW as source of intermediate water to other regions of the North Atlantic.

New LSW arrives in the eastern basins only years later because of the longer pathways. Adopting the circulation scheme proposed by Talley and McCartney (1982) and by Schmitz and McCartney (1993), the LSW in the Iceland Basin should be of more recent origin than that at the eastern boundary. In all our records we find the freshest LSW at 26/27° W and a significant erosion of the core salinity eastward of that area (Fig. 5b). This documents the length of the path from the source. Thus, we assume that the LSW observed in the area south of the Rockall Trough in December 1994 manifests the arrival of the 1986-LSW cascade, because in 1991 and 1992 no significant property changes were detectable. In contrast, we observed significant changes in the Iceland Basin where new LSW had arrived earlier. For the events observed east of the Reykjanes Ridge, we conclude that the new LSW took 7 to 8 years to propagate from its source region to the eastern boundary. With an assumed length of the pathway of 2500 km this is equivalent to a mean speed of about 1 cm/s, at least 2 times faster than assumed until now (Read and Gould, 1992; Cunningham and Haine, 1995). Our result is consistent with the independent estimate derived from CFC measurements only along section A1 in 1991 and 1994 (M. Rhein, pers. comm.).

These observations are supported by results from our southern section (A2 at 48° N), which we supplemented by the 1982 "Hudson" section as a reference for a period of 'normal' LSW production. Along the entire section we find a dramatic cooling of LSW between 1982 and 1993 (Fig. 7), with the most prominent anomalies west of the MAR amounting to -0.45 °C (-0.15 °C east of the MAR). Associated with cooling we find a densification by 0.043 kg/m^2 and a deepening by more than 600 dbar for only the western basin (Table 1). In contrast, salinity remains almost unchanged west of the MAR but was found to be significantly fresher (by about -0.03) in the eastern basin. Similar to the northern section, the cooling continues, indicative for the passage of the 1986-LSW cascade as well. Between 1993 and 1996 the temperature decreased in the west by another -0.16 °C and in the east by about -0.14 °C: the newly formed LSW has already invaded the central West-European Basin and the ventilation of the LSW layer is currently in progress.

The attempt to assign the Θ/S core values observed 1993 and 1996 in the Newfoundland Basin to an equivalent counterpart in the Labrador Sea, however, does not lead to a similar clear correlation as was the case for the Irminger Sea (Fig. 8). That can be due to the more effective mixing along the much longer pathway. In 1993 we observed a very patchy core layer which suggest the advection of LSW in terms of smaller scale billows (Fig. 9). These are more susceptible to transformation by mixing than a large-scale uniform layer.

Between 1993 and 1996 we observe a temperature drop in the narrow band of the DWBC some 600 m shallower than the deep LSW cores further east. This cannot be assigned to an equivalent signal in the Labrador Sea (Fig. 8). Following Pickart (1992) we suggest the 3 fresh and isolated Θ/S core values from 1993 to be a part of the "non-classical LSW" produced in the southern Labrador Sea. This implies that the classical LSW has arrived at the Tail of the Grand Banks probably within one year, suggesting a much higher advection within the DWBC system.

We have discussed so far the impact of surface cooling in the Labrador Sea on the production and the T/S characteristics of LSW since 1991. Individual year classes of

LSW have been identified in a generally period of warm, positive sea surface temperature anomalies in the mid-latitude North Atlantic and negative SST anomalies in the Labrador Sea (Hansen and Bezdek, 1996). Earlier occupations of particularly the 48°N section allow us to go back in time to other periods where the meridional SST gradients were smaller, or of opposite sign. The 1982 occupation by CCS "Hudson" falls into a period of moderate, if not warmer positive anomalies in the Labrador Sea. For the only other occupation by RRS "Discovery" in 1957 Hansen and Bezdek identify a long and warm interval. We have described so far the progression of LSW as part of the subpolar gyre. With adequate data from reoccupied transoceanic sections further south, it seems opportune to investigate the overall influence of the changes of the LSW on the long-term and large-sale meridional circulation of the North Atlantic.

We now have five occupations of the 48° N section since 1957, making it the most sampled transoceanic section. Vaguely, statistics of these occupations can be built up. Ignoring the seasonally influenced top 1000 dbar, the temperature differences are ca. 0.5 °C between 1000 and 2000 dbar, and ca. 0.2 in the Western and < 0.1 °C in the Eastern Basin (Fig. 10) indicating the measure of variability across the section. The Western Basin appears much more variable than the eastern one. We have traced the fate of the LSW by following the changes of its core properties. These have been identified in temperature, salinity, density and subsequently the depths of the core. Comparing these changes section by section, the changes in the depths of the core can lead to differences that not necessarily agree with those obtained by the water-mass-following method. This is a methodological artifact. These section by section differences on the other hand can give a very useful indication of the large-scale changes in the full section and the underlying physics.

The Eastern Basin was the warmest overall in the 1957 (Discovery) and 1982 (Hudson) occupations, particularly for the intermediate layers and the centres of the two basins (Fig. 11 a-d). The Western Basin has warmed since and was found to be warmest in the 1993/1994 occupations by Gauss (1993) and Meteor (1994). The 150 nm wide band of the DWBC system has partly warmest during 1957 (Discovery) and 1993 (Gauss). The 1994 and 1996 occupations show, that part of the DWBC cores have cooled and freshened since 1993. The lowest temperatures have been observed since 1993 for most of the Eastern Basin, leaving only the boundary currents west of the MAR and the far-field of the DWBC system colder in 1957. The salinities in the top 1000 dbar have increased west of the MAR to the present maximum. Below and east of the MAR the highest salinities were observed in the 1957 and 1982 occupations. On both sides of the MAR at depths greater than 2000 dbar we find the highest salinities in 1982, indicating a predominantly northern influence at both the intermediate and deep layers. 1994 and 1996 (not shown) are the freshest years at this section, with only the far-field of the DWBC between 2500 and 3500 dbar being fresher in 1957 and 1982. Again, the top 1500 dbar west of the MAR have been fresher before and during 1982. This clear picture of large-scale and long-time changes invites to look at the impact of the highly variable intermediate waters on the integrated heat and freshwater transports.

The drastic changes since 1982 in the LSW properties, particularly in temperature, have been noted before (Fig. 7). The year 1982 (Hudson) indicates the warmest and a slightly saltier LSW on record. In 1957 LSW was slightly colder and of almost the same salinity. For a similar comparison of transoceanic sections spanning the last 40 years at 36°N, Dobroliubov et al. (1996) have shown a similar change from a slow and long warming period for LSW peaking about 1982 to a dramatic and strong cooling period since the mid 1980s.

For the deep and bottom layers we find for both sections at 36° N and 48° N a clear cooling and freshening. Together with a strong increase in silicate concentrations, this indicates a northward intrusion of waters of Antarctic origin. The strongest signals are found on the west side of the MAR and in the West-European Basin. In contrast, depth-averaged temperatures and salinities (Fig. 12) show for the deep basins for the 1957 and 1982 occupations the Northamerican Basin to be colder and fresher. The differences get smaller when moving east to the MAR; east of the MAR in the West-European Basin 1957 and 1982 are slightly warmer and saltier than the later occupations of the 1990s. Strong signals are seen also in the boundary currents at both sides of the MAR. For the Western Basins the cooling of the intermediate and deep waters must have been over-compensated by warmer and saltier mixed layer and thermocline waters for the entire 40 years period.

Dobroliubov at al. (1996) compared the 1959, 1981 and 1993 occupations of the 36° N section and find for 1981 the largest mass and heat flux estimates for this period and subsequently the largest overturning rate of the meridional circulation. This is confirmed for the 48°N section for 1982. For periods of low production of intermediate waters the southward flow at intermediate depths is reduced and the overturning meridional circulation has only one single cell: the northward flow of surface and thermocline waters and the southward flow of NADW and its contributions from the Overflow area. For periods of strong production of intermediate waters such as the LSW, this implies a strong southward and eastward transport of newly formed intermediate waters which are replaced by regional surface waters. In this case we have a two-cell meridional circulation where the lower cell is fed by the northward penetration of AABW which is subsequently entrained into the southward flowing NADW.

At this time we can only speculate about the impact of these circulation changes on the total meridional circulation. It seems feasible that during periods of high production rates of intermediate waters in the northern North Atlantic and the two-cell meridional overturning, the northward flowing warm waters of the surface and thermocline layers are short-circuited south of Iceland into the production loop. At times of low production, and the single-cell meridional overturning, the warm waters continue to be advected into the Norwegian and Greenland Seas where they are available for the production of ultimately the overflow waters (Dickson et al., 1996).

From our data we conclude that new modes of LSW arrive in other parts of the North Atlantic in the following order: 1. Irminger Sea after 6 months, 2. Newfoundland Basin, 3. Iceland Basin, 4. western part of the West-European Basin and 5. Rockall Abyssal Plain after 7 to 8 years. The new and partly surprisingly fast spreading rates give rise to address new questions as e.g. about the transport mechanisms. The two proposed meridional circulation modes, single cell versus two cells, show a strong linkage of the intermediate waters of the Subpolar Gyre with the North Atlantic. They are seen to have a direct impact on the meridional transports of heat and freshwater. These findings highlight the intimate relationship between cooling in the Labrador Sea and its impact on the interior of the ocean - an important piece of the global climate puzzle.

References

Cunningham, S.A. and T.W.N.Haine (1995): Labrador Sea Water in the eastern North Atlantic. Part I: A synoptic circulation inferred from a minimum in potential vorticity. J. Phys. Oceanogr., **25**, 649-665.

Dickson, R.R., J. Meincke, S.-A. Malmberg and A.J. Lee (1988): The "Great Salinity Anomaly" in the Northern North Atlantic 1968-1982. Prog. Oceanogr., **20**, 103-151.

Dickson, R.R., J. Lazier, J. Meincke, P. Rhines and J. Swift (1996): Long-term coordinated changes in the convective activity of the North Atlantic. Prog. Oceanogr., submitted.

Dobroliubov, S.A., V.P. Tereschenkov, A.V. Sokov (1996): Water mass transport and heat flux at 36°N in the Atlantic Ocean. ICES C.M. 1996/O:1

Gordon, A.L. (1986): Inter-ocean exchange of thermohaline water. J. Geophys. Res., **91**, 5037-5046.

Hansen, D.V. and H.F. Bezdek (1996): On the nature of decadal anomalies in North Atlantic sea surface temperature. JGR, 101, C4, p.8749-8758

Lazier, J. (1996): The salinity decrease in the Labrador Sea over the past thirty years. In: Climate on decade-to-century time scales, National Academy of Sciences Press. Washington, D.C., in press.

Pickart R.S. (1992): Water mass components of the North Atlantic deep western boundary current. Deep-Sea Res., 39, 1553-1572.

Rahmstorf, S. (1994): Rapid climate transitions in a coupled ocean-atmosphere model. Nature, **372**, 82-85.

Rahmstorf S. and J. Willebrand (1995): The role of temperature feedback in stabilizing the thermohaline circulation. J. Phys. Oceanogr., **25**, 787-805.

Read, J.F. and W.J. Gould (1992): Cooling and freshening of the subpolar North Atlantic Ocean since the 1960s. Nature, **360**, 55-57.

Schmitz, W.J. and M.S. McCartney (1993): On the North Atlantic Circulation. Rev. of Geophysics, **31**, 29-49.

Talley, L.D. and M.S. McCartney (1982): Distribution and circulation of Labrador Sea Water. J. of Phys. Oceanogr., **12**, 1189-1205.

Top, Z., W.B. Clarke and W.J. Jenkins (1987): Tritium and primordial ^{3}He in the North Atlantic: A study in the region of Charlie-Gibbs Fracture Zone. Deep-Sea Res., **34**, 287-298.

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

Weisse, R., U. Mikolajewicz and E. Maier-Reimer (1994): Decadal variability of the North Atlantic in an ocean general circulation model. J. Geophys. Res., **99**, 12411-12421.

Figure Captions:

Fig. 1: Vertical sections of
a) salinity and
b) oxygen content
obtained from R.V. "Meteor" along line A1/East in September 1991 revealing the wide spread abundance of Labrador Sea Water in mid depths by means of its characteristic intermediate salinity minimum and oxygen maximum.

Fig. 2: Main topography and schematics of primary pathways of the Labrador Sea Water according to Talley and McCartney (1982) and Schmitz and McCartney (1993). LS: Labrador Sea; IS: Irminger Sea; IB: Iceland Basin; RT: Rockall Trough; WEB: West European Basin; NF: Newfoundland Basin.
The data along the hydrographic sections were acquired on the following cruises:

A1/West	RV "Dawson" No. 90012/1	July 1990
"	RV "Hudson" No. 92014/1	June 1992 (incomplete)
"	RV "Hudson" No. 93019/1	June 1993
"	RV "Hudson" No. 94008/1	May/June 1994
"	RV "Meteor" No. 30/3	Nov. 1994 (incomplete)
"	RV "Hudson"	June 1995
A1/East	RV "Meteor" No. 18	Sept. 1991
"	RV "Valdivia" No. 129	Sept. 1992
"	RV "Meteor" No. 30/3	Nov./Dec. 1994
"	RV "Valdivia" No. 152	June 1995
A2	RV "Gauss" No. 226/2	July 1993
"	RV "Meteor" No. 30/2	Oct./Nov. 1994
"	RV "Gauss" No. 276/2	May/June 1996

Fig. 3: Potential temperature versus salinity along section A1/East compiled from all data of cruise "Valdivia" 129 (9/1992) for the intermediate and deep subpolar North Atlantic. The colder and fresher group of minima at about $\Theta = 2.9$ °C and $S = 34.85$ characterizes the LSW core in the Irminger Sea (a), the warmer and saltier group of minima at about $\Theta = 3.2$ °C and $S = 34.88$ characterizes the LSW core in areas east of the Mid-Atlantic Ridge (b).

Fig. 4: Temperature differences (Θ(1992) - Θ(1991) of the LSW core along section A1/AR7 calculated by different methods. The mean temperature decrease of the LSW core along the entire section was calculated with the water-mass-following method as $\Delta\Theta = -0.08$ °C (bold line) whereas the corresponding number calculated with the depth depending method (differences at fixed depths $z=z(1991)$) was $\Delta\Theta = \pm 0.0$ °C (dotted line).

Fig. 5: Change of LSW core properties along trans-ocean sections A1/East (For better clarity only values from 1991, 1992 and 1994 are shown).
a) Potential temperature at LSW salinity minimum
b) Same as a) but for salinity (PSU),
c) Same as a) but for pressure (dbar)
d) Same as a) but for potential density anomaly (σ_θ)

Fig. 6: Θ/S diagram of LSW cores for adjacent areas. Data collected between 1990 and 1996 in the central parts of the Labrador and Irminger Seas (except for LabS-11/94 with values only from the northern part of section A1/W). Potential density anomaly ($\sigma_{1.5}$) referenced to 1500 dbar. Each value is calculated as the mean of a 200 dbar thick layer centred at the Θ/S peak of the LSW core. From each cruise the five most central profiles were used.

Fig. 7: Change of Potential temperature at LSW salinity minimum along trans-ocean section A2 and with data from CCS "Hudson" from 1982 for comparison. (For better clarity values from 1994 are not shown).

Fig. 8: Same as Fig. 6 but for Labrador Sea and Newfoundland Basin between 40° W and 49° W. The 3 isolated fresh and warm values observed in 1993 in the DWBC band are suggested to be part of the "non-classical LSW" according to Pickart (1992).

Fig. 9: Two casts carried out at station # 30 of cruise "Gauss" 226 (1993) in the centre of the Newfoundland Basin at 43° 07' N, 41° 10' W indicate a billow-like structure of the LSW layer. Within 8 hours only the double layered LSW core (thin line) was found being replaced by a single layered LSW core (bold line).

Fig. 10: Differences of potential temperature for four occupations of the 48°N section from 1957, 1982, 1993 and 1994. Differences between the extrema calculated for each grid point (see Fig. 11).

Fig. 11: Extreme values for the four occupations of the 48°N section. Each gridpoint is given a symbol indicating the relevant cruise/year when it was assigned the particular extreme value
a) maximum potential temperature
b) minimum potential temperature
c) maximum salinity
d) minimum salinity

Fig. 12: Vertically averaged temperatures and salinities along the 48°N section from 1957 (Discovery), 1982 (Hudson), 1993 (Gauss), 1994 (Meteor)

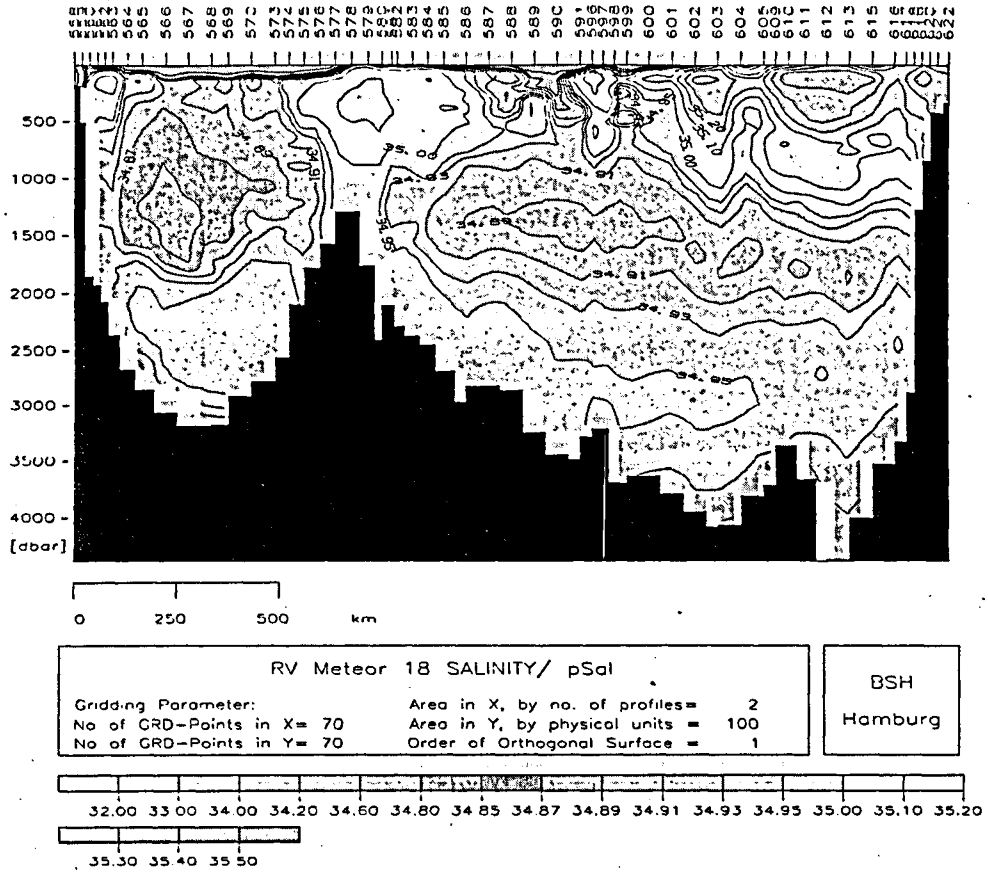
Tab. 1: Change of mean values of LSW core properties (intermediate Θ/S-Minimum) for Irminger Basin (>33° W), Iceland Basin (28-22° W) and Rockall Trough entrance (<22° W) along section A1/E, and for Newfoundland Basin (>32°W) and West-European Basin (<32°W) along section A2.

A1/East: A = "Valdivia" 9/1992 - "Meteor" 9/1991
B = "Meteor" 12/1994 - "Valdivia" 9/1992
C = "Valdivia" 6/1995 - "Meteor" 12/1994

A2: D = "Gauss" 7/1993 - "Hudson" 4/1982
E = "Meteor" 10/1994 - "Gauss" 7/1993
F = "Gauss" 5/1996 - "Meteor" 10/1994

Units of calculated differences: Pressure p [dbar], potential temperature Θ [°C], salinity s [PSU], potential density anomaly σ_θ [kg/m^3].

Section A1/E	A	B	C	A	B	C	A	B	C	A	B	C
Δt [month]	12	27	6									
Longitude	Δp			Δθ			Δs			$\Delta\sigma_\theta$		
>33°W	128	122	-15	-.092	-.140	-.050	-.002	-.002	-.006	.007	.011	.0
<28-22°W	47	61	83	-.068	-.038	-.082	.0	.0	-.002	.007	.004	.006
<22°W	103	112	-56	-.003	-.096	-.010	.002	.002	-.004	.002	.010	-.002
Section A2	D	E	F	D	E	F	D	E	F	D	E	F
Δt [month]	135	15	18									
>32°W	641	19	58	-.450	-.057	-.103	-.002	-.001	-.009	.043	.005	.003
<32°W	27	125	38	-.154	-.096	-.042	-.026	-.006	.004	-.006	.005	.007


500
1000
1500
2000
2500
3000
3500
4000
[dbar]
0 250 500 km
RV Meteor 18 SALINITY/ pSal
Gridding Parameter:
No of GRD-Points in X= 70
No of GRD-Points in Y= 70
Area in X, by no. of profiles= 2
Area in Y, by physical units = 100
Order of Orthogonal Surface = 1
BSH
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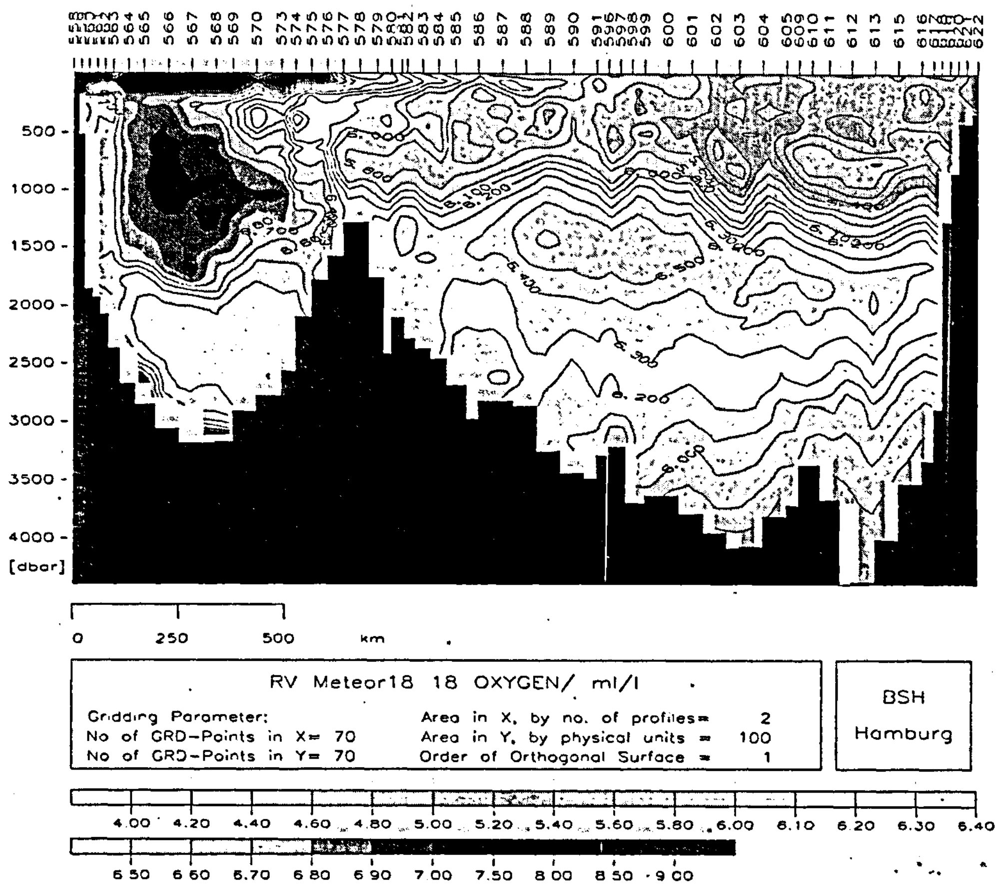
32.00 33.00 34.00 34.20 34.60 34.80 34.85 34.87 34.89 34.91 34.93 34.95 35.00 35.10 35.20
35.30 35.40 35.50

a)


500
1000
1500
2000
2500
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3500
4000
[dbar]
0 250 500 km
RV Meteor18 18 OXYGEN/ ml/l
Gridding Parameter:
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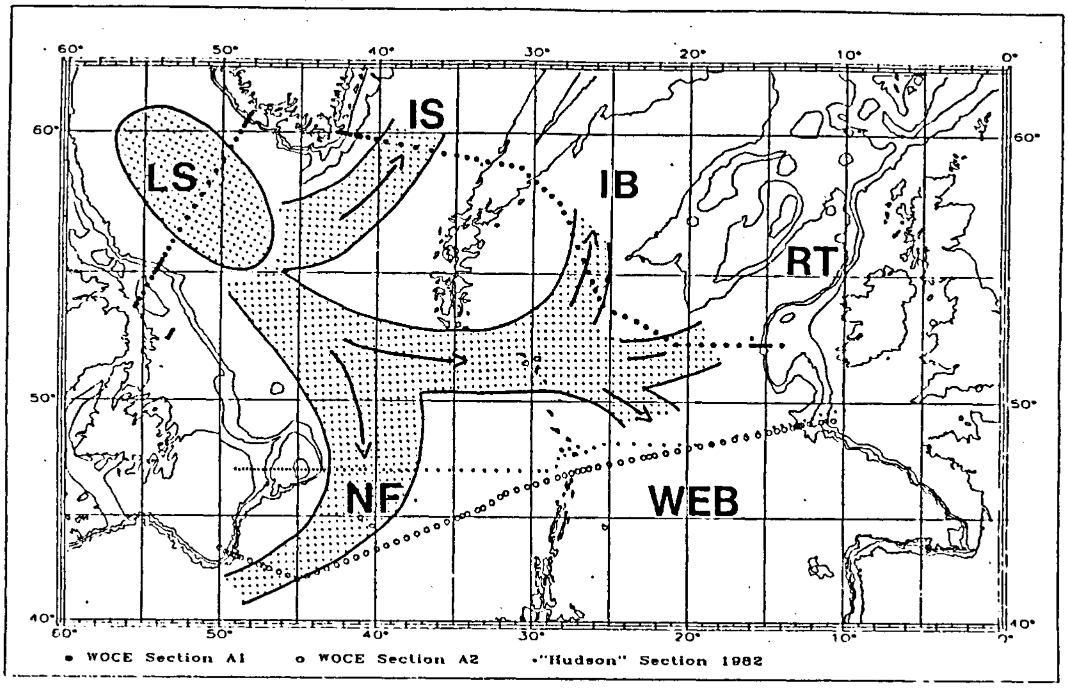
No of GRD-Points in Y= 70
Area in X, by no. of profiles= 2
Area in Y, by physical units = 100
Order of Orthogonal Surface = 1
BSH
Hamburg
4.00 4.20 4.40 4.60 4.80 5.00 5.20 5.40 5.60 5.80 6.00 6.10 6.20 6.30 6.40
6.50 6.60 6.70 6.80 6.90 7.00 7.50 8.00 8.50 9.00

b)

Fig. 1:



60°
50°
40°
30°
20°
10°
0°
LS
IS
IB
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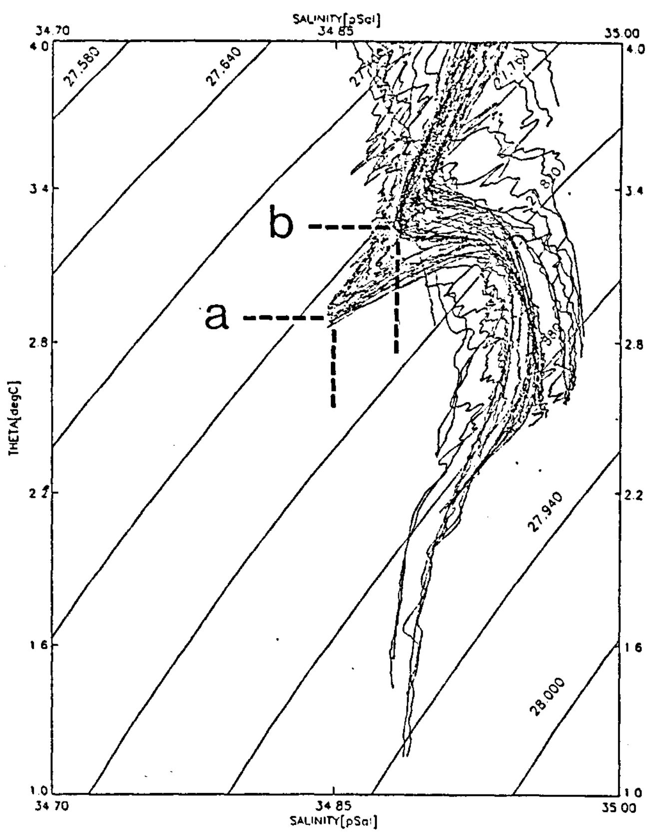
WEB
• WOCE Section A1
o WOCE Section A2
•"Hudson" Section 1982

Fig. 2:



SALINITY[pSal]
34.70
34.85
35.00
4.0
3.4
2.8
2.2
1.6
1.0
THETA[degC]
27.580
27.640
27.940
28.000
a
b

Fig. 3:

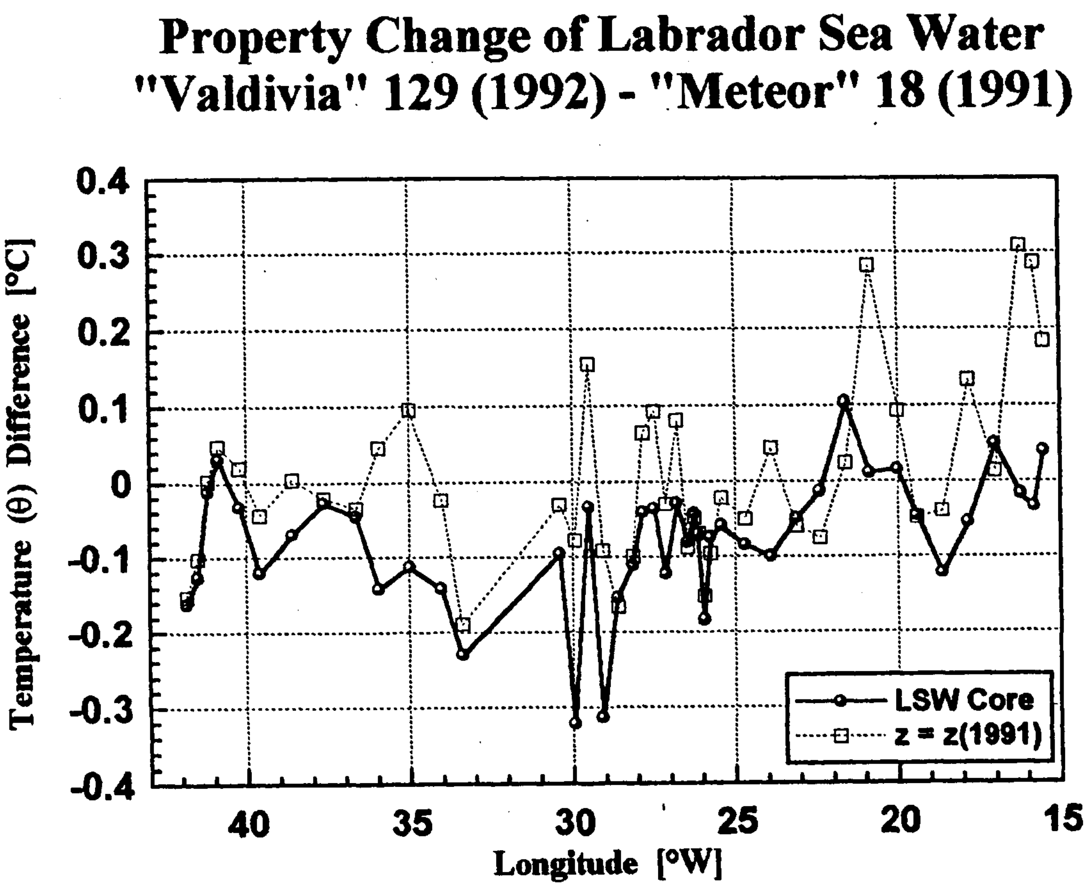

Property Change of Labrador Sea Water
"Valdivia" 129 (1992) - "Meteor" 18 (1991)
Temperature (θ) Difference [°C]
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
40
35
30
25
20
15
Longitude [°W]
LSW Core
z = z(1991)

Fig. 4:

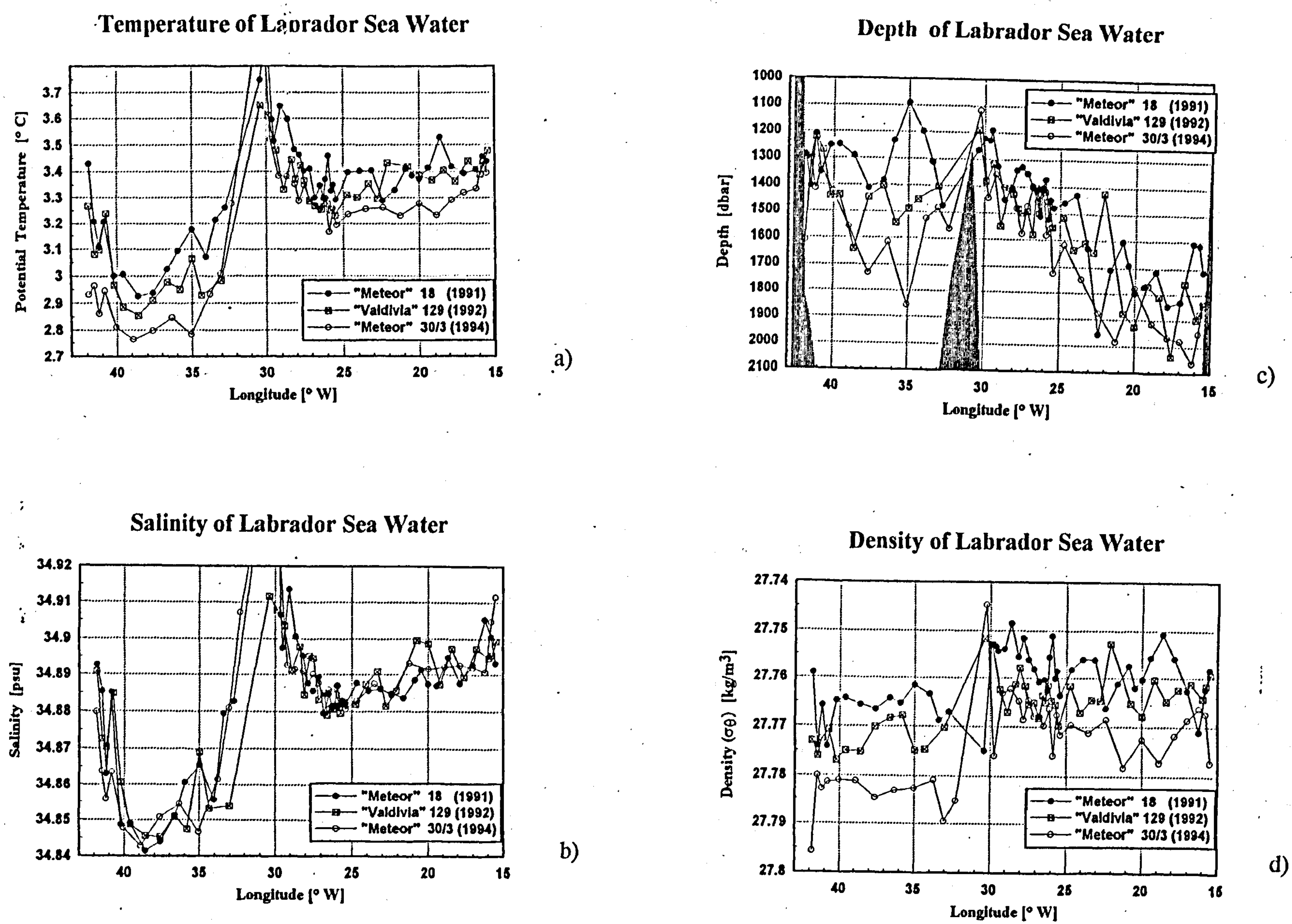

Temperature of Labrador Sea Water
Potential Temperature [° C]
3.7
3.6
3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
40
35
30
25
20
15
Longitude [° W]
"Meteor" 18 (1991)
"Valdivia" 129 (1992)
"Meteor" 30/3 (1994)
a)
Depth of Labrador Sea Water
Depth [dbar]
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
40
35
30
25
20
15
Longitude [° W]
"Meteor" 18 (1991)
"Valdivia" 129 (1992)
"Meteor" 30/3 (1994)
c)
Salinity of Labrador Sea Water
Salinity [psu]
34.92
34.91
34.9
34.89
34.88
34.87
34.86
34.85
34.84
40
35
30
25
20
15
Longitude [° W]
"Meteor" 18 (1991)
"Valdivia" 129 (1992)
"Meteor" 30/3 (1994)
b)
Density of Labrador Sea Water
Density (σθ) [kg/m3]
27.74
27.75
27.76
27.77
27.78
27.79
27.8
40
35
30
25
20
15
Longitude [° W]
"Meteor" 18 (1991)
"Valdivia" 129 (1992)
"Meteor" 30/3 (1994)
d)

Fig. 5:

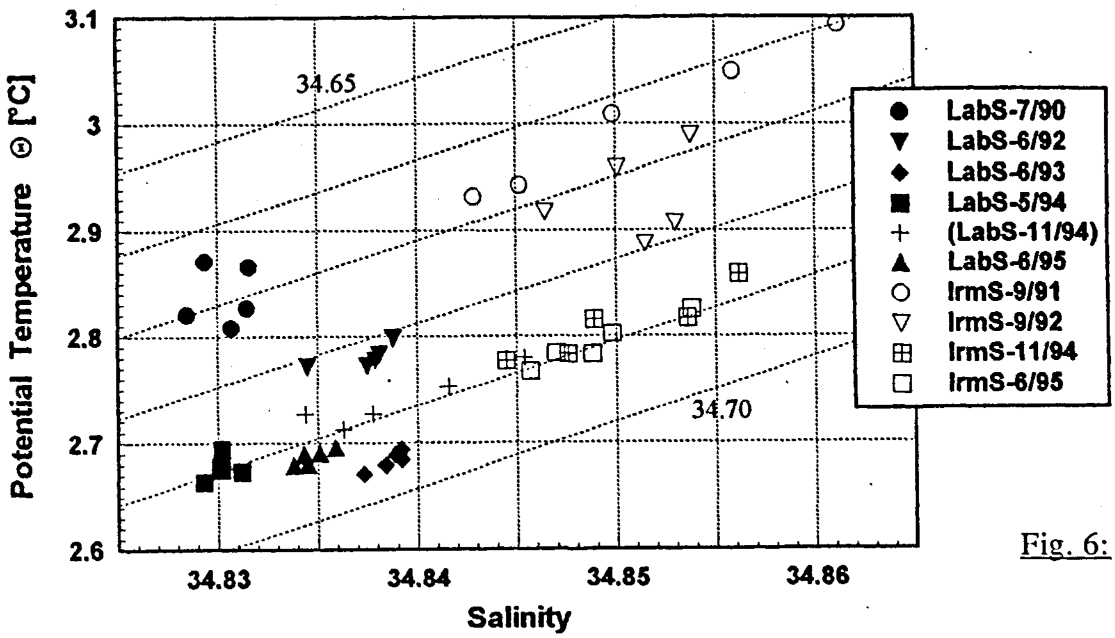


Fig. 6:

Temperature of Labrador Sea Water

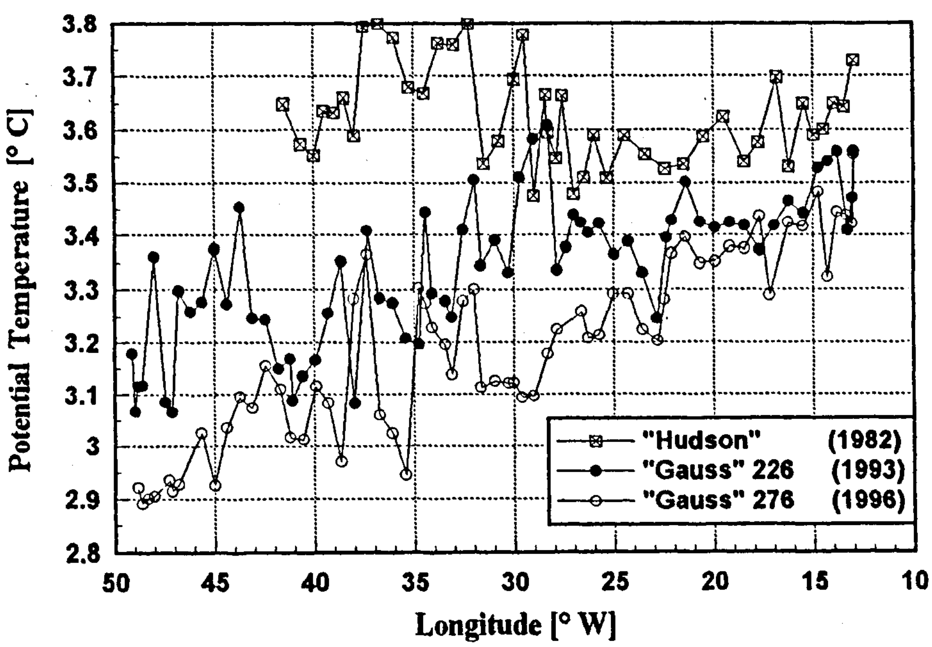


Fig. 7:

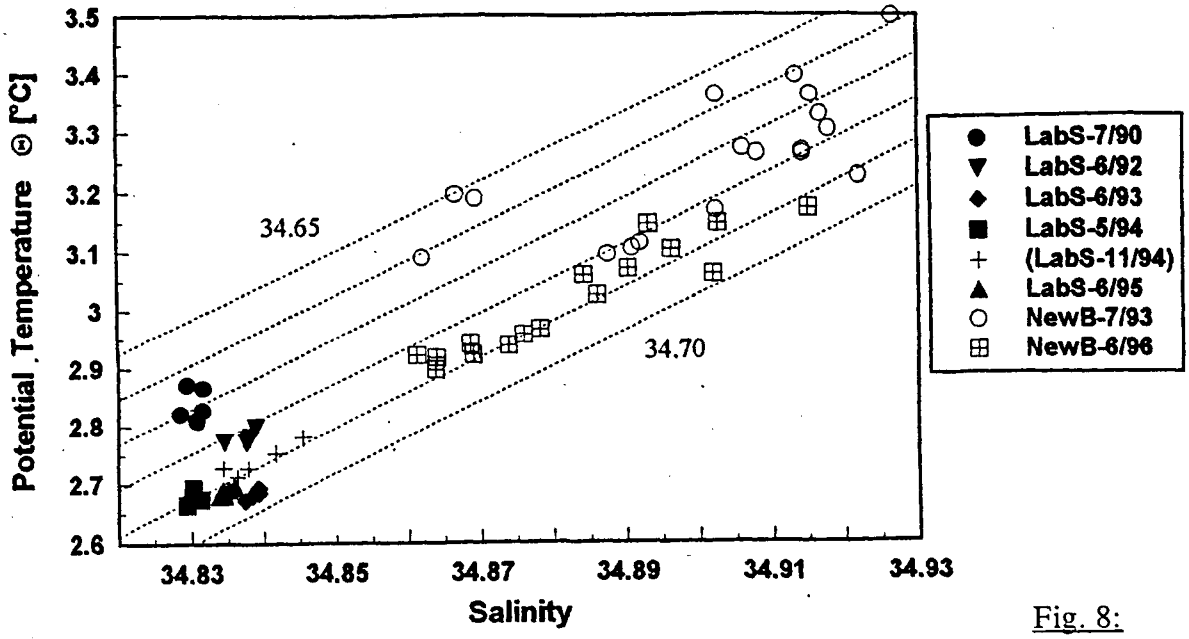

Potential Temperature Θ [°C]
Salinity
34.65
34.70
LabS-7/90
LabS-6/92
LabS-6/93
LabS-5/94
(LabS-11/94)
LabS-6/95
NewB-7/93
NewB-6/96

Fig. 8:

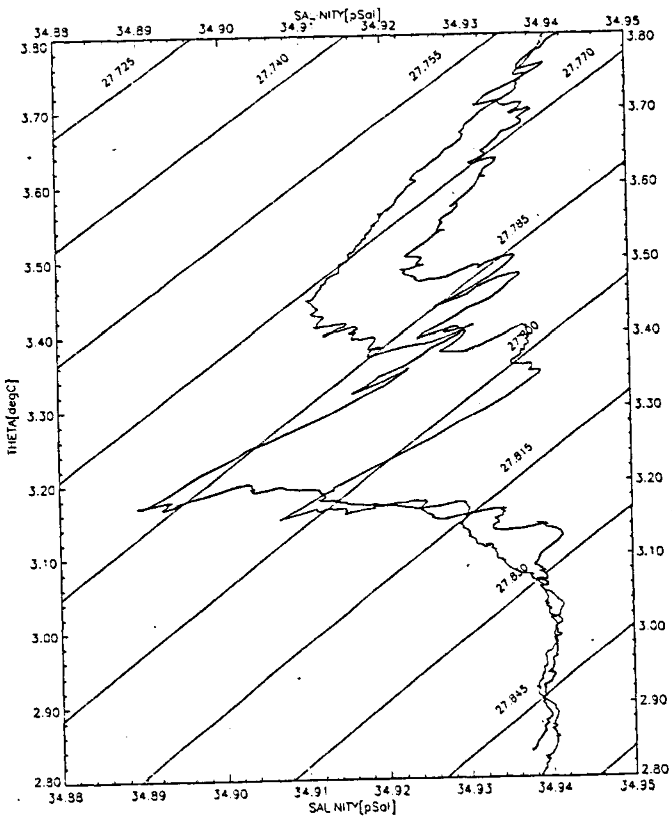
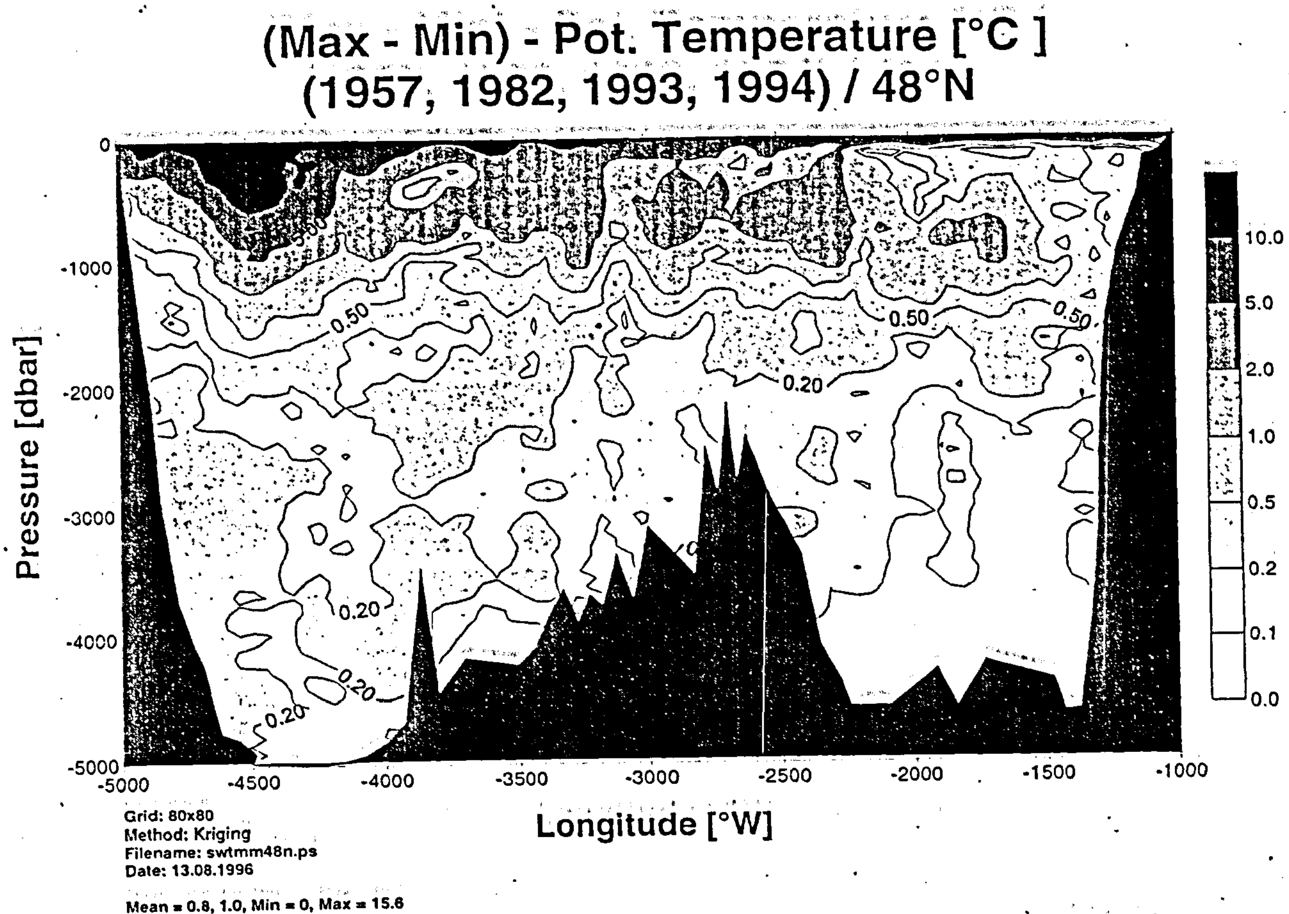
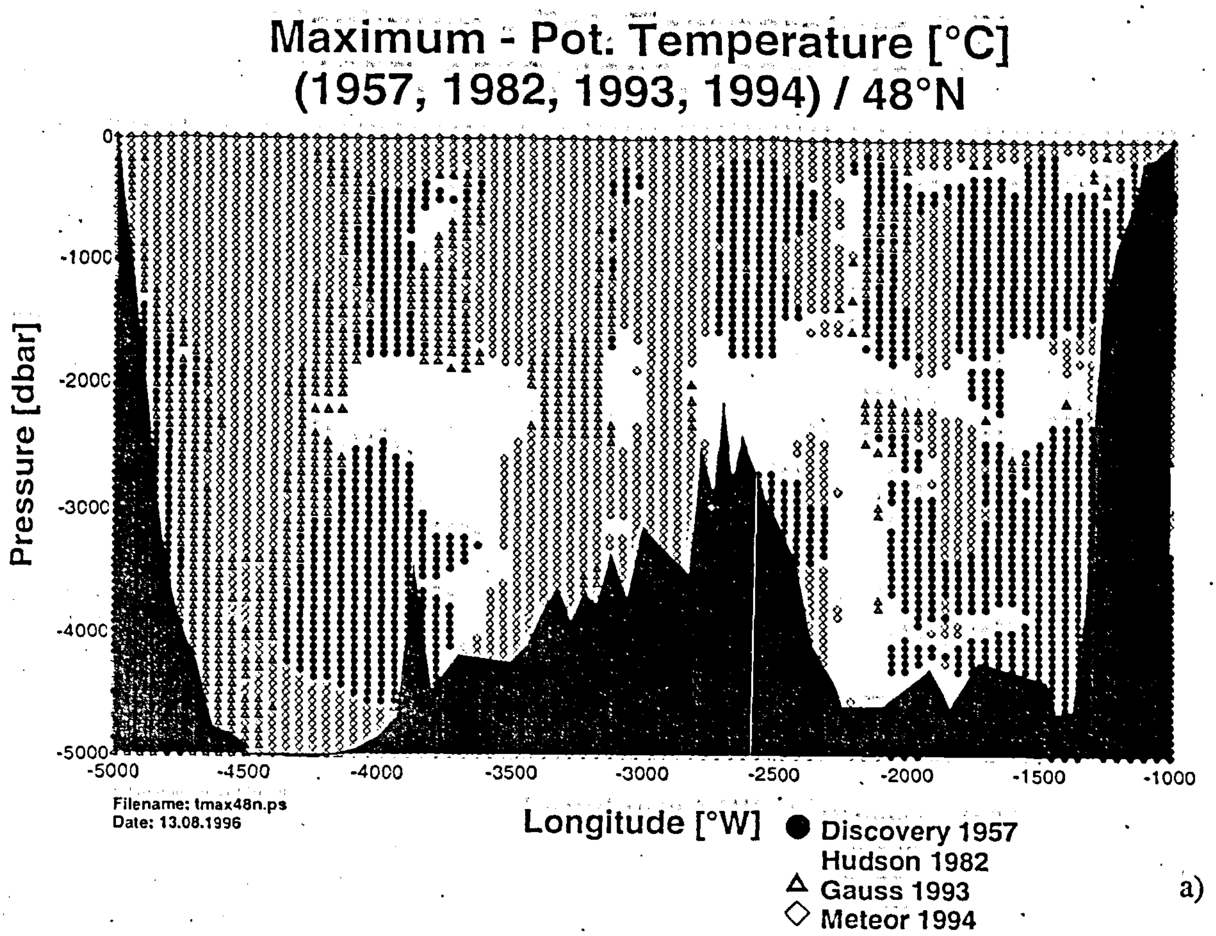

SALINITY[pSal]
THETA[degC]
27.725
27.740
27.755
27.770
27.785
27.800
27.815
27.830
27.845

Fig. 9:



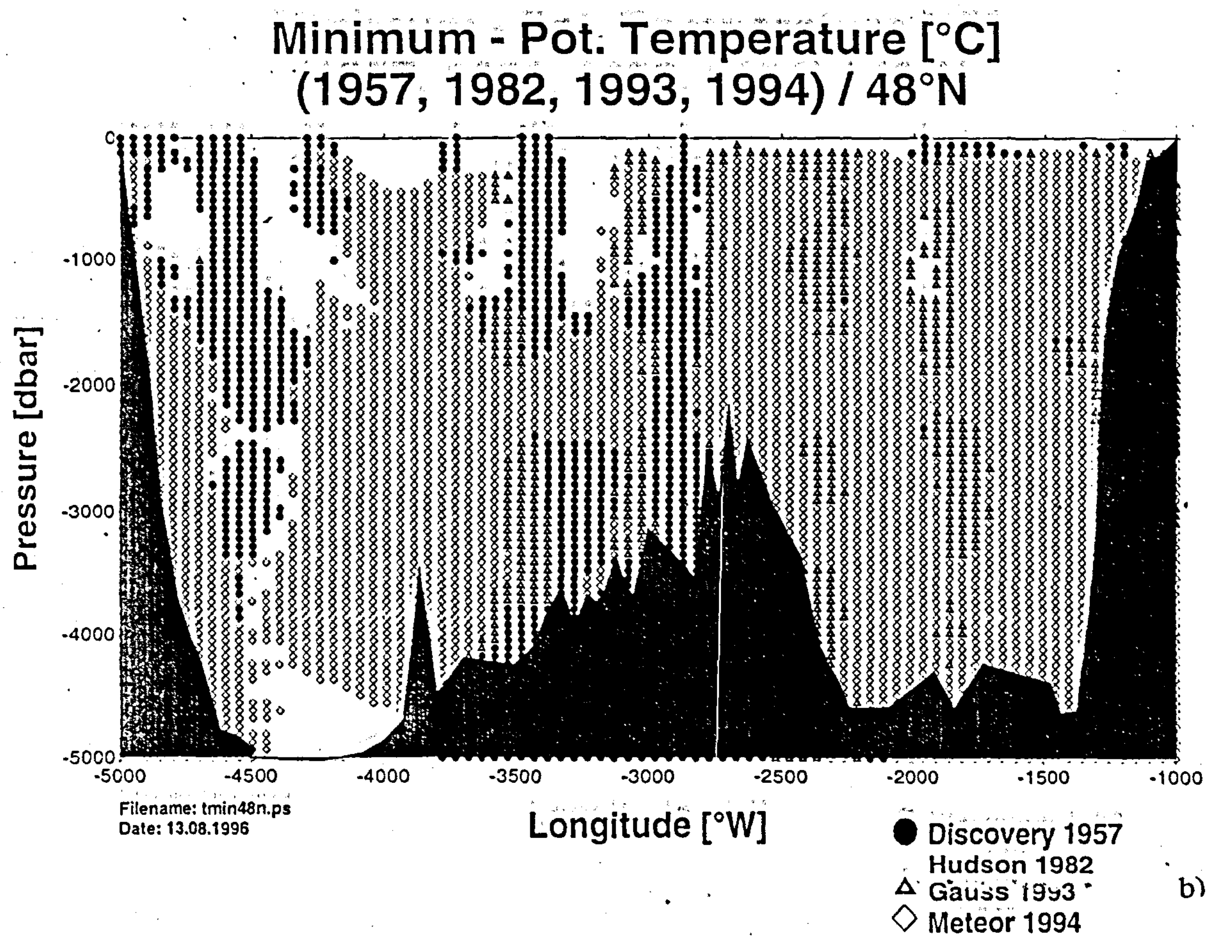
(Max - Min) - Pot. Temperature [°C]
(1957, 1982, 1993, 1994) / 48°N
Pressure [dbar]
0
-1000
-2000
-3000
-4000
-5000
-5000
-4500
-4000
-3500
-3000
-2500
-2000
-1500
-1000
Longitude [°W]
0.50
0.50
0.50
0.20
0.20
0.20
0.20
10.0
5.0
2.0
1.0
0.5
0.2
0.1
0.0
Grid: 80x80
Method: Kriging
Filename: swtmm48n.ps
Date: 13.08.1996
Mean = 0.8, 1.0, Min = 0, Max = 15.6

Fig. 10:



Maximum - Pot. Temperature [°C]
(1957, 1982, 1993, 1994) / 48°N
Pressure [dbar]
0
-1000
-2000
-3000
-4000
-5000
-5000
-4500
-4000
-3500
-3000
-2500
-2000
-1500
-1000
Filename: tmax48n.ps
Date: 13.08.1996
Longitude [°W]
Discovery 1957
Hudson 1982
Gauss 1993
Meteor 1994

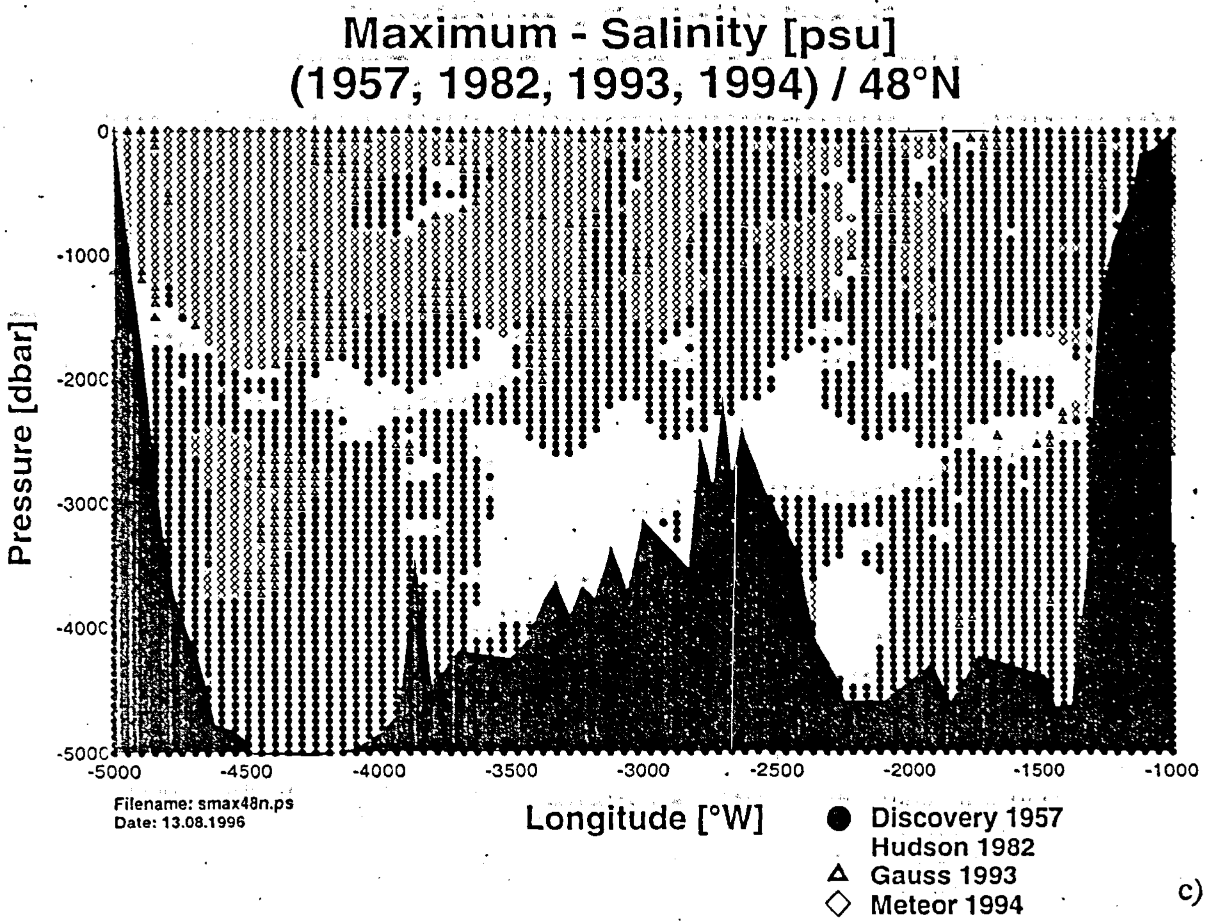
a)



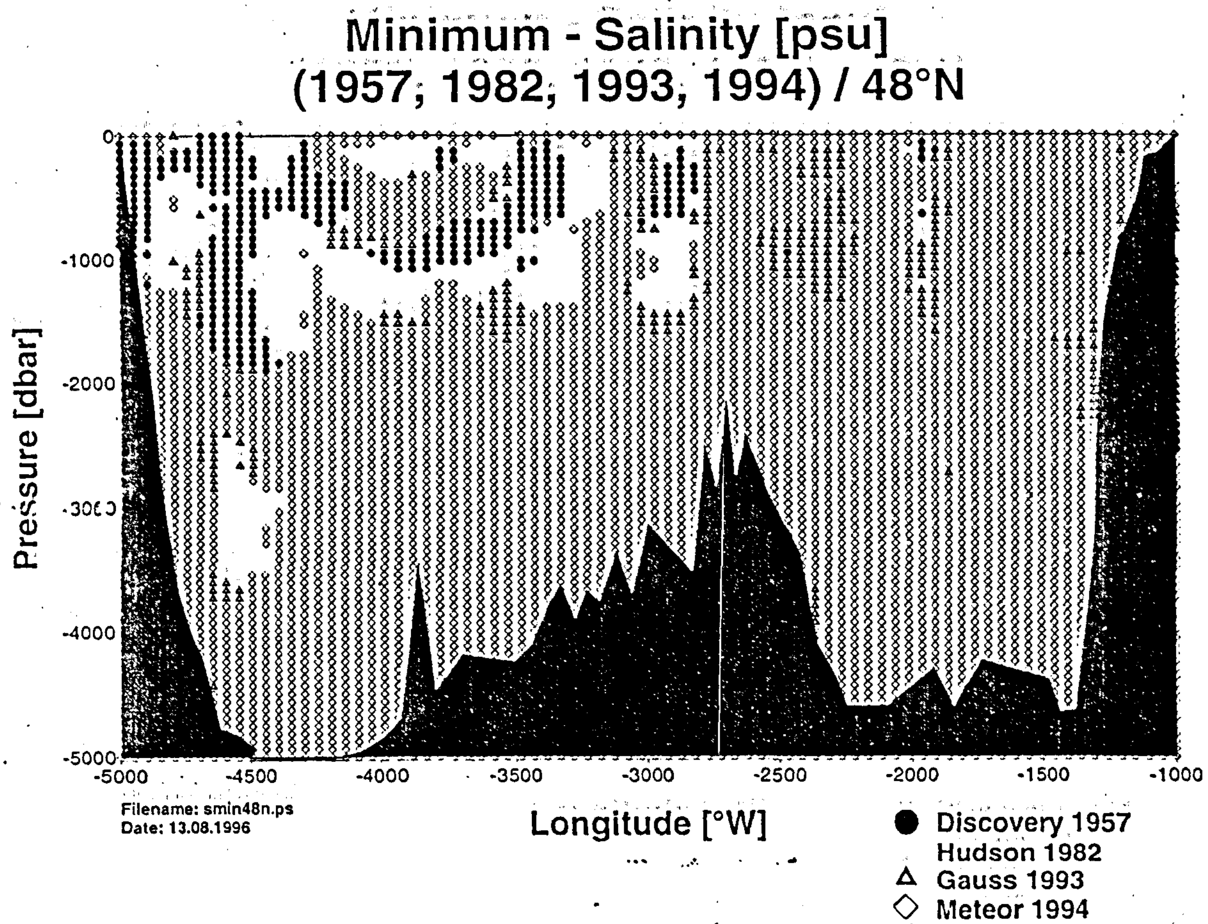
Minimum - Pot. Temperature [°C]
(1957, 1982, 1993, 1994) / 48°N
Pressure [dbar]
0
-1000
-2000
-3000
-4000
-5000
-5000
-4500
-4000
-3500
-3000
-2500
-2000
-1500
-1000
Filename: tmin48n.ps
Date: 13.08.1996
Longitude [°W]
Discovery 1957
Hudson 1982
Gauss 1993
Meteor 1994

b)

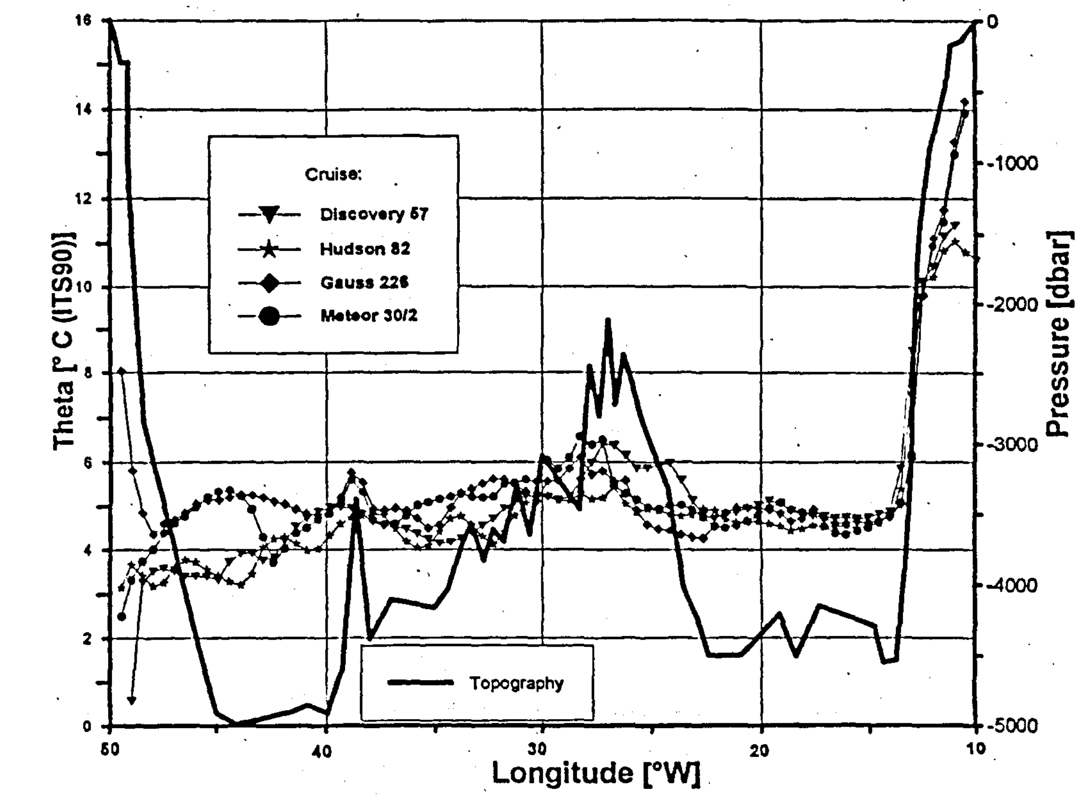
Fig. 11:


Maximum - Salinity [psu]
(1957, 1982, 1993, 1994) / 48°N
Pressure [dbar]
0
-1000
-2000
-3000
-4000
-5000
-5000
-4500
-4000
-3500
-3000
-2500
-2000
-1500
-1000
Filename: smax48n.ps
Date: 13.08.1996
Longitude [°W]
Discovery 1957
Hudson 1982
Gauss 1993
Meteor 1994

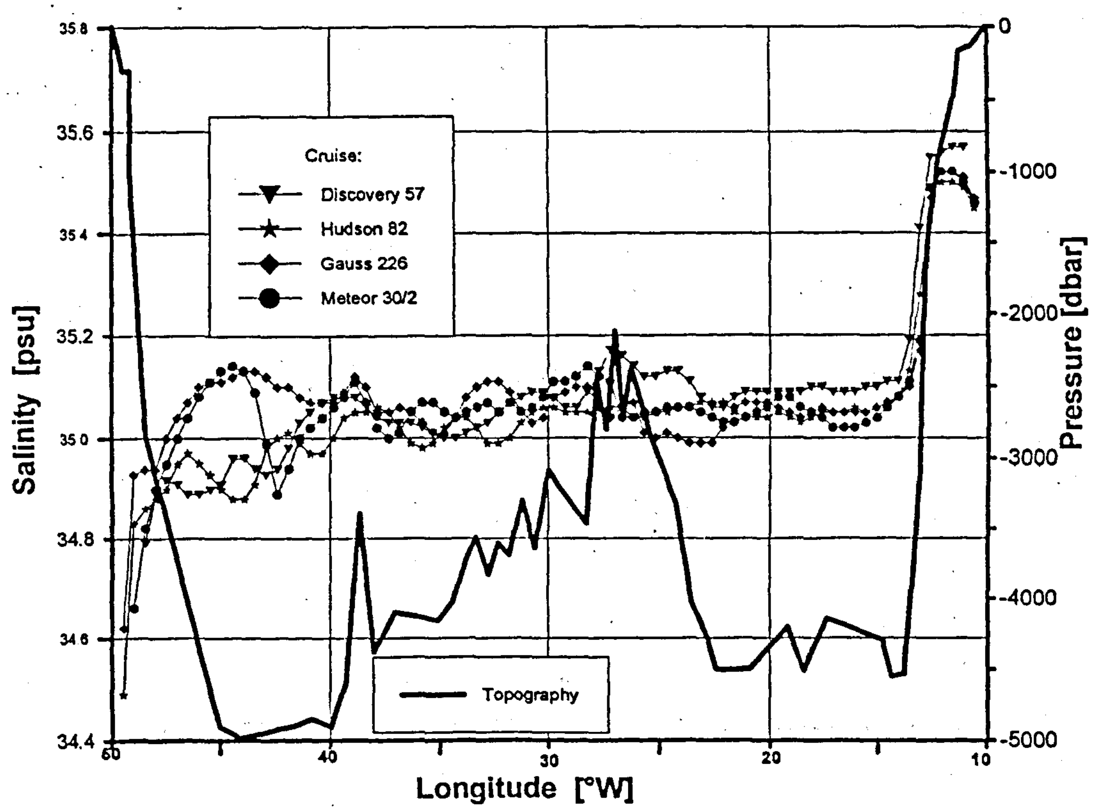
c)


Minimum - Salinity [psu]
(1957, 1982, 1993, 1994) / 48°N
Pressure [dbar]
0
-1000
-2000
-4000
-5000
-5000
-4500
-4000
-3500
-3000
-2500
-2000
-1500
-1000
Filename: smin48n.ps
Date: 13.08.1996
Longitude [°W]
Discovery 1957
Hudson 1982
Gauss 1993
Meteor 1994

d)



Cruise:
Discovery 57
Hudson 82
Gauss 226
Meteor 30/2
Topography
Theta [° C (ITS90)]
Pressure [dbar]
Longitude [°W]
16
14
12
10
8
6
4
2
0
0
-1000
-2000
-3000
-4000
-5000
50
40
30
20
10



Cruise:
Discovery 57
Hudson 82
Gauss 226
Meteor 30/2
Topography
Salinity [psu]
Pressure [dbar]
Longitude [°W]
35.8
35.6
35.4
35.2
35.0
34.8
34.6
34.4
0
-1000
-2000
-3000
-4000
-5000
50
40
30
20
10

Fig. 12: