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Variations in the physical marine environment in relation to climate

by

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ABSTRACT

In the present literature overview of variations in the physical marine environment in relation to climate in the northern North Atlantic the physical variations are studied selective for some different North Atlantic regions, but mainly with an emphasis on an overall view of the whole study area. The regions studied are the European Subarctic Sea (the Norwegian, Barents, Greenland and Iceland Seas), the Iceland Basin, the Irminger and Labrador Seas and Newfoundland waters, the open ocean area of the North Atlantic Drift between the two continents, and the North Sea, Skagerrak, Kattegat, the Belt Sea and the Baltic.

In general, the main result of the overview is, that the climatic events demonstrated by atmospheric pressure anomalies and changes in the physical marine environment mainly demonstrated by temperature and also salinity observations, coincide

quite frequently in the whole study area. Phenomena are quite often connected across considerable distances throughout the whole North Atlantic. The physical changes in the marine environment are most obvious close to the oceanic polarfront in the northermost parts of the area studied, but the marked changes observed there are frequently reflected in waters farther south. Effects from variations in remote areas such as the Gulf Stream area or even in the Pacific Ocean may be seen, however features seem to be mainly governed by conditions in and over the North Atlantic itself. In shelf seas off Northwest Europe continental fresh water discharge and continental meteorological events have a significant influence on variations in the physical marine environment of these shallow seas, however,there is also an important oceanic influence.

Introduction

This paper is an overview of variations in the physical marine environment in relation to climate in the northern North Atlantic (Figs. 1, 2, 3). According to terms of reference the overview should be authorative and complementary, pan-Atlantic in scope, and post-war in emphasis, but not strictly so.

The authors will frequently, directly or indirectly, refer to recent previous background papers which deal with the theme in question. These references are e.g. Bjaerknes (1972), Namias (1965), Rodewald (1967a, 1967b, 1972a, 1972b), Dickson (1971, 1973), Dickson and Lamb (1972), Dickson and Lee (1972), Cushing and Dickson (1976), Lamb (1979), Taylor (1978), Colebrook and Taylor (1979). Some ICES and ICNAF publications also serve as an important source (Rapp. Proc. Verb. Reun. 162 (1972), 172 (1978); Redbook 4 (1967), 3 (1973); Special Publications 8 (1972), 10 (1975); and at last but not least the papers by Smed on the Sea Surface Temperatures (SST) in the North Atlantic (1947 etc. see Ellett et al. 1981).

The above references cover the theme in question as well as the experience of the present authors or "their response to variations in the physical environment in relation to climate in the open North Atlantic and in adjacent seas as the Baltic and the North Sea".

This experience may probably throw a light on what has happened in other areas.

1. Open North Atlantic

Iceland Sea

a. The experience and interest of one of the authors of this overview on physical variations in the marine environment goes back to the very evident climatic deterioration observed in the European Subarctic Sea in the sixties (see a.o. Cushing and Dickson l.c.). He had reported on hydrographic conditions in North Icelandic waters in spring 1964 (Malmberg 1966), following reports and a Bibliography by Stefánsson (1962) and reports by Jónsdóttir (1964, 1965). The results in Stefánsson's Bibliography did not seem to leave much to be considered, thus reports on hydrographic conditions in North Icelandic waters seemed not to be very interesting any more. Then suddenly and unexpectely in the spring 1965 something was happening in these waters. Having some experience from East Greenland waters we did for a while during the field work wonder about the piloting. In the spring of 1965 the hydrographic conditions in the East Icelandic Current northeast of Iceland resembled for the first time during post-war observations those of a polar current like the East Greenland Current, i.e. a current with temperatures below 0°C and surface salinities low enough to prevent the surface water to sink by cooling, even a cooling to the freezing point at -1.8°C (Malmberg 1969a, 1972). The East Icelandic Current thus changed from being the ice-free arctic current it was in 1948-1963 to a polar current in 1964-1971 (Figs. 4,5). Having changed, the current transported drift-ice and preserved it and in it also active new-ice formation could take place. The biological implications in North Icelandic waters for Atlanto-Scandian herring and the Icelandic spring spawning herring of this southeastward extension of the oceanic polar front were indicated (Malmberg 1967) and identified (Jakobsson 1969, 1980). Furthermore the biological impact was manifested by low nutrient supply, reduced spring production of phytoplankton (Thórdardóttir 1969, 1977) and low zooplankton concentrations (Jakobsson 1980, Ástthórsson and Hallgrímsson, pers. comm.). The climatic impact in general was also recognized (Hafísinn 1969, Sea Ice Confer. 1972, UN Confer. Human Envir. Stockholm 1972). As regards recruitment of the Icelandic cod and these changed hydrographic conditions on its feeding grounds in North Icelandic waters no obvious response has been established (Malmberg 1979/1980, 1982).

Regarding the recent changes in the drift ice and hydrographic conditions in North Icelandic waters the most important results may be some physical understanding on what was going on in the seas around Iceland during past historical times. Thus the climate and the impact of the so-called "little ice age" from 1600 to 1800 or even to 1920 may be better understood than previously (Thórarinsson 1974, Wahl and Bryson 1975, Lamb 1979, Malmberg 1977, Gunnarsson 1980).

b. Combined surface temperature and salinity observations have the advantage over temperature observations only that together with routine meteorological observations they allow differentiation between changes due to advection and changes by local heating and evaporation/precipitation. Ellett et al. (l.c.) take North Icelandic waters as an example to illustrate this. The characteristics of these waters are controlled by three processes (Stefánsson 1962, Stefánsson and Gudmundsson 1969, Swift and Aagaard 1981): i. The inflow of warm and saline Atlantic water ($S > 35$; $t > 4°$) from the continuation of the Irminger Current along the west coast of Iceland. ii. Inflow of cold and relatively fresh water from the northeast ($S < 34.7$; $t < 0°$), i.e. from the branching of the arctic and polar waters flowing south along the east coast of Greenland. iii. Mixing conditions in the transition area between the North Icelandic shelf and the cyclonic gyre of the Iceland Sea (Fig. 1).

While Atlantic waters were dominating in North Icelandic waters during the period 1924-1964, the late sixties and also shorter periods thereafter (Figs. 6, 7) were characterized by polar influence. These changes manifested themselves drastically in the increased appearance of ice (Sigtryggsson 1972) and a sharp decrease in temperature (up to 5°C) and in surface salinities (up to 1 o/oo). These fluctuations in North Icelandic waters and in the East Icelandic Current (Figs. 6, 7, 8) were linked with the atmospheric pressure distribution and SST anomalies at the North Atlantic Ocean Weather Stations (OWS; Rodewald l.c. (Fig. 9), Malmberg 1969a,b, Dickson and Lee l.c., Dickson et al. 1975).

c. Thus, over the Arctic and Subarctic Seas the air circulation trended recently towards northerly airflow with an accompanying climatic deterioration. The change was associated with the establishment over Greenland in the early fifties of a persistent ridge of pronounced positive anomaly and its subsequent maintainance and intensification (12 mb) throughout the late fifties and sixties (Fig. 10). As mentioned above the strengthening of the northerly airstream was responsible for the progressive southward extension of the sea ice across the Greenland and Iceland seas, reaching a maximum in the spring 1968. A progressive feedback from ocean to atmosphere also plays a significant role in this aspect (Malmberg 1969a, b).

In the winter of 1970-1971 the strong climatic trend evident over the Subarctic Sea came to an abrupt halt. The high pressure anomaly cell over Greenland collapsed almost totally, and in 1970-1974 the northerlies were drastically weakened in the European arctic and subarctic (Dickson et al. l.c.).

These changes brought also some amelioration in the marine climate off North Iceland (Figs. 6, 7, 8). In general it was concluded (Dickson et al. l.c.) that during the spring months 1972-1974 the Atlantic influx into North Icelandic waters was stronger than in any year during the period 1965-1971, though remaining slightly weaker than during the earlier 1950-1960 normal (Stefánsson l.c.). The polar water component to the north and northeast of Iceland was weaker in spring 1972-1974 than in any year since 1963, and only slightly stronger than in the warm period of earlier years.

Thus the recent "little ice age" observed in North Icelandic waters seemed to have ended with an amelioration of the marine climate during 1972-1974. It was stated that this conclusion was diagnostic rather than prognostic.

This proved to be correct. In summer 1975 the drift ice occurred again in North Icelandic waters and in 1976-1979 the East Icelandic Current had again the character of a polar current (Figs. 5,8), together with a relatively heavy ice year in 1979 and extremely unfavourable hydrographic conditions in North Icelandic waters in spring (Figs. 6,7). In 1980 the conditions were again very favourable and comparable with findings prior to 1965. Further in 1981, conditions were again extremely unfavourable, this time neither of Atlantic nor polar character, but with very homogenous water of an hostile arctic character (Fig. 11).

A relationship between the hydrographic conditions in Icelandic waters and the distribution of 0-group cod and capelin was indicated e.g. both in 1980 and 1981 (Vilhjálmsson et al. 1980, 1981). Also the continuous decrease in 0-group capelin indices since 1974 (Fig. 7) and the failure of adult capelin fisheries in these waters is possibly linked to hydrographic conditions (Malmberg 1979/1980) in addition to overfishing and biological parameters (Vilhjálmsson et al. 1982).

Pressure anomaly charts in the northern hemisphere during winter for the periods 1971-1975 and 1976-1980 with reference to the 1900-1930 means and the difference between 1971-1975 and 1976-1980 (Fig. 12) again reflect the changes in the marine environment north of Iceland. The period 1971-1975 shows only a 1 mb positive pressure anomaly over Greenland, but a 4 mb negative pressure anomaly south of Iceland. In 1976-1980 the pressure anomaly again shifted over to a 5 or 6 mb positive one over Greenland, and this high pressure field reached eastward and southward in the Subarctic Sea.

Norwegian and Barents Seas

a. Although the physical repercussions were most conspicuous close to the oceanic polar front at northern Iceland, similar trends of hydrographic change were also observed throughout the Norwegian Sea during the period under discussion (1950-1980). Aleksev and Penin (1973) showed a general cooling in the Subarctic Sea between the mid fifties and the late sixties, with a particular reversion to positive temperature anomalies during the early seventies. Midttun et al. (1981) deal with variations in distribution of cod in the Barents Sea in 1977-1981. Their temperature anomalies in a section north of the Kola Peninsula reflect the same variations as above, i.e. cooling in the late sixties and warming in the early seventies. But since 1976 a strong cooling of more than 1°C and lasting at least to 1981 has taken place. These years this cooling had a significant influence on the distribution of cod in the Barents Sea. The distribution of capelin in these northern waters was also influenced (Loeng 1981). During the "warm" years of 1971-1976 the capelin was distributed farther north and over a greater area than during the "cold" years of 1977-1981. Farther south along the Norwegian coast similar changes in hydrographic conditions were observed (Blindheim and Loeng 1981). These observations included salinity measurements which indicated that the changes were due to advection and a time lag of several years from south to north. Gammelród and Holm (1981), who deal with hydrographic data from OWS M in the Norwegian Sea during the period 1948-1977, show a phase shift between temperature and salinity variations after 1965, together with a decrease in salinity after 1970, which has not yet been observed in the temperature. Whether this phase shift was due to changes in the Atlantic water or in other water masses is not known, but the above mentioned changes in the East Icelandic Current might possibly be involved.

Iceland Basin, Rockall Channel and Faroe-Shetland Channel

a. In 1951-1960 an increase in sea surface temperature (of about 1°C) and in sea surface salinity (of about 0.08 o/oo) took place in the Iceland Basin (Rodewald 1972b, Malmberg and Magnússon 1982). Farther south in the Rockall Channel (Ellett 1980, Edelsten and Ellett 1981) and in the Shetland-Faroe Channel (Martin 1976, 1981, Dooley, pers. comm.) long term salinity observations reflect beside e.g. the Russel period (Russel et al. 1971) an increase up to 1967, a decrease after 1967-1970 with a minimum in 1976 (about 0.1 o/oo) and increasing values after that. The variations in salinity after 1960 were not reflected in the temperature. A change in water mass characteristics was also observed in the Faroe-Shetland Channel (Martin l.c.), were a cold water mass which was absent in 1968 was observed in 1975. This cold water reaches the area from the northeast (Ellett et al. l.c.). South of Iceland, in the Irminger current, also a salinity minimum (about 0.1 o/oo) observed in 1976 as well as northwest of Iceland after 1976 (Malmberg 1982). These changes must reflect an overall decline in salinities in the Northeast Atlantic current system during these years.

b. It has been shown that during the seventies and in 1981 some distinct changes have also taken place in the intermediate and deeper layers of the waters between Iceland and the United Kingdom as well as in the Irminger and Labrador Seas (Martin l.c., Ellett l.c., Dooley, pers. comm., Swift, pers. comm.), (see also Fig. 11). Ellett (l.c.) suggested that the marked fall in salinity at different locations in the Northeast Atlantic in 1969-1976 may be connected with Subarctic Intermediate water formed to the west of the oceanic polar front. Ellett (more tenuous) also like Gammelsrød and Holm (l.c.) suggested that the lowering in salinity could possibly be linked with the atmospheric circulation over East Greenland (Dickson et al. l.c.), which decreased after 1970, giving a 5-6 years lag for significant salinity effects to reach e.g. the Rockall Channel. Whatsoever, the changes observed in

North Icelandic waters in 1965-1970 and the salinity decrease in the Northeast Atlantic after 1970 seem to be linked through the atmospheric circulation over East Greenland and the Subarctic Sea.

Greenland, Labrador and Newfoundland waters

a. As in North Icelandic waters in 1965-1970 a well developed cooling trend was observed in the West Greenland Current together with a decline in surface salinity (Hermann 1967, Blindheim 1967). Until 1966-1968 this trend was confined to the arctic and polar currents at Iceland, Greenland and also to some degree westward to Labrador and Newfoundland. On the other hand an increase in sea surface temperature was observed in the Irminger and Labrador Seas up to the years 1966-1968 (Rodewald l.c., Bailey 1976, Smed in Ellett et al. l.c.). This was in accordance with the negative pressure anomaly over the Irminger Sea and the dominant ridge over Greenland during the years 1965-1970 (Figs. 9, 10, Rodewald l.c., Dickson et al. l.c.). These atmospheric conditions, connected with a so-called "Namias type ocean atmosphere feedback situation" (Namias l.c., Dickson 1971), appear to have been responsible for boosting the warm water branch of the North Atlantic current system - Irminger Current - resulting in warm and high saline water along the West Greenland banks (Hermann l.c., Blindheim l.c., Dickson and Lamb l.c.) beneath the cold polar water. Such conditions were also found in North Icelandic waters during the polar period in 1965-1971 as e.g. in spring 1968 (Fig. 11).

b. For some years in the sixties, this inflow of Atlantic water with the Irminger Current may have improved the environmental conditions for adult cod, which here lies close to the poleward limits of distribution. However the cod left Greenland waters in the late sixties for spawning in Icelandic waters, also the low saline surface conditions resulted in poor survival of eggs and larvae (see Cushing and Dickson l.c.). The cod stock in Greenland waters thus suffered heavily during the cooling period in 1965-1970, whereas the changed conditions on the feeding grounds of the Iceland cod in North Icelandic waters seemed not to influence the stock (Malmberg 1979/1980). This may be due to the very stable conditions in the spawning area south and west of Iceland, where eggs and larvae remain during the first couple of months of their lifetime before they are carried with the Irminger Current to North Icelandic waters and also to East Greenland waters.

c. In the waters at Labrador and Newfoundland there were in 1962-1970 a general criss-cross of temperature trends, whereas 1970-1973 there was a clear separation of temperature trends in these waters (Bailey 1976). Stations farthest north, in West-Greenland waters (Hermann et al. 1973, Smed 1980) and at Labrador and Newfoundland, showed minimum temperatures in 1972, temperatures even low enough to kill cod on the banks (Templemann 1976). Stations farther south showed on the other hand maximum temperatures in 1972, which is in accordance with the findings of Taylor (1978) at OWS D and E. Once again the anomalous low temperatures in the northern part of the area reflect the negative pressure anomaly in the Iceland low in 1971-1975 (Fig. 12). To bridge the discussion on conditions in the Northwest and Northeast Atlantic it may be appropriate at this stage to quote directly some notes by Hill (1976) in his discussion of environmental conditions in the Newfoundland -Grand Bank area and their effect on fishery trends in the year 1972.

"It seems clear that the cause of the increased transport in the Labrador Current in the early summer of 1972 was basically the increased negative anomaly in the Icelandic low which increased northwesterly winds and also decreased air temperatures over the Canadian east shelf area during the first half of the year. The continuous study of these sustained pressure anomalies really is of considerable importance in physical and fisheries oceanography as my colleaque Dr. Dickson has pointed out on the other side of the Atlantic. He has been able to relate these meteorological anomalies of pressure systems and the associated anomalous winds to increased salinification of the North Sea and to deep layer Baltic inflow (this will be discussee in section 2) in the physical field and to the failure of the Atlanto-Scandian herring stock (as discussed above) .... due to increased northerly winds, in the biological field."

Such opposite trends in Northwest Atlantic and Northeast Atlantic waters as observed in 1972 have been demonstrated by Cushing and Dickson (l.c.).

The North Atlantic Drift

a. The discussion above mainly concentrated on the northernmost waters in the North Atlantic in the years 1950-1980. During this period a general trend with decreasing temperature and salinity was observed, particularly after 1960, but some significant short periodic exceptions reflected in the atmospheric pressure field were also observed.

b. In the open North Atlantic farther south, between 40 and 60° N, the same general trend of decreasing SST's was found for the years 1951-1970, together with an east and northward shift of conditions following the North Atlantic Drift and the changing atmospheric pressure anomalies in e.g. the Iceland low (Rodewald l.c., Smed in Ellett et al. l.c.). The trend in the SSS 1948-1977 (Taylor and Stephens 1980b) shows similar features, indicating that advection was an important cause of salinity and temperature changes in the North Atlantic during this period, together with open ocean upwelling (Namias l.c., Bjærknes l.c.) and some surface heat loss in the northernmost areas (Dickson et al. l.c.).

c. Comparing Rodewalds results (l.c.) for the period 1951-1970 and studies by Taylor (l.c.) for 1963-1973 south of 50°N in the westernmost part of the study area (OWS D and E), it can be seen, that the former shows a general decrease in sea surface temperatures, (which is similar to Smed's results (in Ellett et al. l.c.) from the area E just north of 50°N), whereas the latter shows an (relative?) increase in SST. These different results reflect the different time period studied. Due to e.g. year-to-year and other "short" period variations it is in studies on variations in the physical marine environment of great importance to select comparable periods in time and also long enough periods. The warming after 1970 in the area in question (see also Bailey l.c.) was probably connected with a latitudinal displacement of the so-called north wall of the Gulf Stream, which according to Taylor and Stephens (1980a) was displaced southward during 1966 to 1971 and returned northward after 1973. This displacement toward south might be related to an increased flow in the Gulf Stream which has been suggested to result in warmer waters to the south and cooling of surface waters in higher latitudes (Iselin 1940, Martin 1972, see also Wahl and Bryson l.c., Lamb l.c., Ellett et al. l.c.). Such changes in temperature may also reflect a southward shift in the westerlies with a wind increase in this southern part of the study area and even a decrease in zonal circulation and an increased meridional one farther north. However, Taylor and Stephens (1980a) though found no clear relation between the displacement of the north wall and wind or pressure indices, but with trends in SST and SSS in the Northeast Atlantic. This is discussed in some detail by Colebrook and Taylor (1979).

2. Shelf Seas of the Eastern North Atlantic.

a. Colebrook and Taylor (l.c.) processed North Atlantic Sea Surface Temperatures (SSTs) for the period 1948-1974. They state "for the open ocean, secular changes appear to be primarily advected and determined by variations in the North Atlantic Current. Over the European shelf, on the other hand, sea surface temperatures appear to be determined to a large extent by direct heat exchange with the atmosphere mediated primarily by the meridional component of the surface winds." These authors also found high correlations between SST anomalies in 8 shelf areas around the United Kingdom and Ireland. Dickson (1971) writes that "the curve of integrated 0-200 metre temperature anomaly along the Kola Meridian Section in the Barents Sea does bear a striking similarity to the post-war curve of salinity anomaly for the European shelf seas." On the other hand Blindheim and Loeng (l.c.), investigating December-January temperatures and salinities measured at sections in the Barents Sea 1964-1979, found agreement with observations made in the Rockall Channel (Ellett l.c.) with a time lag of 2-3 years. "These trends were most likely connected with fluctuations in the Atlantic Current ..... support the assumption that the long-term trends were advective phenomena." It seems appropriate to characterize the shelf edge part of the Northeast Atlantic Current as a transition area between the ocean and the proper shelf. This is also indicated in the results of Colebrook and Taylor (l.c.). In this chapter therefore the Rockall-Barents Sea conditions will be touched upon although they have been reviewed above in section 1.

b. In order to be able to interpret climatic changes one should know as much as possible about the hydrographic mechanisms of the relevant areas but conversely this knowledge is improved by studying climatic changes.

The North Atlantic Current which traverses from southwest to northeast gives off weak branches into the Irish Sea and the English Channel-North Sea. After passing the Faroe-Shetland Channel the main branch continues along Norway into the Barents Sea but there is also a branch west of Spitzbergen. Farther south, however, a rather strong current goes into the northern North Sea and the Skagerrak. Most of it returns to the main stream along Norway, but some smaller parts take an additional loop in the Kattegat, and a still smaller part (some of it intermittently) continues into the Baltic.

c. As a result of a fresh water supply of some 500 km^3/year and a weak exchange with the North Sea (via the Belt Sea and the Kattegat) the Baltic salinities have brackish magnitudes. The turnover time of the Baltic is 30-35 years. Those parts of the Baltic Proper which have depths greater than 50-80 m are stagnant, meaning that the water exchange is intermittant. The renewal is a function of the magnitude and the density of the inflowing more saline water but also of (the decrease of) the density of the old water in the deeps.

The hydrographic time series display a mixture of local climate and imported (advected) climate mainly by means of the North Atlantic Current. Often these two parts differ in character and phase, but sometimes they are rather alike meaning that generally it is difficult to separate the two components.

d. Let us look at temperature and salinity time series from the Danish Lightvessel Anholt in the Kattegat (Fig. 3). This series which started in 1880 and are still continuing, had few breaks during the wars. Thus some values had to be interpolated. Figure 13 shows 5 and 17 year running means, some of these curves were previously published by Nilsson and Svansson (1974)x)

Comparison between the 5 year running mean temperatures at Anholt and Smed's (in Ellett et al. l.c.) North Sea areas A/A', B/B'and E/E'temperatures show a general agreement. For instance the maximum around 1960 can be recognized both at 0 m and 30 m. Going backwards in time to the general temperature rise there is resemblance at 0 m, i.e. the rise started around 1930. At 30 m, however, it occurred at least 10 years earlier, or at the same time as in the Western North Atlantic.

Dickson (l.c.) showed that the salinity variations in the North Sea and the deeper parts of the Kattegat are rather similar. He also showed that an approximate 5 year period can be found in the salinity records from the Irish Sea, the English Channel, the North Sea and the deeper parts of the Kattegat, where the period had a peak in a spectral analysis of Anholt 30 m salinity data. Also Becker et al. (l.c.) found this 5-year period in spectral analysis of salinities measured at the German North Sea lightvessels. Dickson (l.c.) found consecutive phase lags from the shelf edge inwards and drew the conclusion that increase of southerly winds during periods of increased meridional atmospheric circulation caused

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x) Running means of mean values are often used. However, as errors may be introduced by such a procedure a more careful filtering technique should be preferred (e.g. Becker et al. 1978).

salinification through increased advection of Atlantic water. One would then possibly expect some simultaneous temperature change, but Colebrook and Taylor (l.c.) found no 5 year cycle in their analysis of North Sea temperatures. Another alternative explanation of the salinity variations is the one put forward by Schott (1966), that variations in the fresh water supply to the shelf sea is responsible for the salinity changes. Looking at the Anholt salinities (Fig. 13) we see that there is some kind of a 30 year cycle in sea surface salinities and such a cycle is also found in the data of the Baltic (Finnish) river Vuoksi water supply. There is a correlation coefficient of 0.9 between the two 17 year smoothed series (Nilsson et al. l.c.). Figure 14 shows that there is also a (still negative) correlation in unsmoothed annual means of deep Anholt salinities and river water supply data. Further studies should be made to test the two theories, however. Both components have atmospheric origin and it is difficult to separate them.

e. The salinities in Figure 13 show a slight increase during 100 years and there is a (corresponding?) slight decrease in the Vuoksi river water supply. In the surface water of the Baltic Proper, Matthäus (1979) demonstrated an increase of salinity in the range 0.5-0.9 o/oo during 1900-1975. In the deeps of the Baltic his figure is 0.8-1.7 o/oo. In the deeps there was also a decrease of 2-3 ml/l in oxygen during 1900-1975. The reason for the oxygen decrease may be the salinity (and thus density) increase or (and?) the increasing anthropogenic load of organic material. There is also an amplification effect: if hydrogen sulphide is formed then phosphate is released from the sediment (there has been an increase of 100-300% of phosphorus during 1950-1975 (Melvasalo 1981)). After some time this phosphorus causes increased primary production which later results in more hydrogen sulphide to be formed etc. Renewal of the deep water only temporarily interrupts this process.

f. There has been a long-term increase of temperature in the surface as well as in the deeps of the Baltic (Matthäus l.c.). It is probable that this change has been advected by the North

Atlantic Current. The salinity increase is probably a more local phenomenon linked with the decreased fresh water supply. But alternative explanations have been put forward, usually of advective character.

Dickson (1973) has shown that renewals of the deep Baltic waters are more probable when the salinity anomaly in the Kattegat Deep is positive. Renewals with higher salinity into the Gotland Basin actually took place in 1951, 1961, 1965, 1970 and 1977 (Fig. 14). Due to the fact that the salinity (and density) of 1951 was so high there was no renewal in 1954, the density decrease had not been large enough for new water to dive down into the Gotland Deep. Nearer the Baltic entrance, e.g. in the Arkona Deep, the renewals occur more often indicating that Kattegat water is pumped into the Baltic more often than the renewal in the various basins indicate.

g. An annual change in temperature or salinity is usually not equally distributed over the year. Becker et al. (l.c.) showed that during 1960-1973 the months October-December provided the most important contribution of relatively warm surface temperatures. On the contrary during the period 1924-1950 the summer months were responsible for the temperature increase (Goedecke 1952). Ljøen and Saetre (1978) got similar results studying variations off southern Norway.

h. The deeper parts of the Skagerrak behave in a special way. Off the Swedish coast at a depth of 200 m in the Atlanto-Norwegian Rinne Current regime the salinity changes during 1963-1981 were rather similar to those found in the Faroe-Shetland Channel (see next para.). Below the sill depth, 370 m, in the Skagerrak Deep, temperatures change drastically in cold winters when heavy surface water dives deep down to the bottom. After cooling, the connection with the upper layers occur through turbulent diffusion, great enough however, to prevent oxygen decrease. Ljøen and Svansson (1972) presented time series of Skagerrak deep temperatures from 1947 onwards.

i. Now some comparison between the Baltic-North Sea and the ocean at or near the continental shelf edge. Smed's figures (in Ellett et al. l.c.) for the North Sea and the North Atlantic may be looked at first. The general increase of sea surface temperature which is outstanding from 1930 in the shelf seas starts earlier in some ocean areas, e.g. 1920 in the Labrador Sea and the Irminger Sea. The Anholt and North Sea maxima around 1959-1960 can be traced in Smed's areas in the following years: in E 1953, N 1956, M 1957, L 1958 and K 1959 (Fig. 2). Ellett (1978) showed that during 1948-1976 there were two temperature maxima, e.g. 1959 and 1970, which are rather similar to the shelf seas temperature maxima. Ellett's (l.c.) figures also show a small salinity maximum in 1960 and a more pronounced one in 1968-1969. The latter one is slightly recognizable at Anholt 30 m but not at the sea surface. The significant decrease at Rockall from this maximum to a 1976 minimum is hardly to be seen at Anholt. The 1976 minimum as well as the 1960 and 1968-1969 maxima are also to be seen in the mean annual salinity record of the upper 200 metres in the Faroe Shetland Channel (Dooley pers. comm.) as well as at OWS Mike at 0 m, 50, 100 and 150 m depth (Gammelrød and Holm l.c.). Blindheim and Loeng (1981) demonstrate similar trends at sections in the Barents Sea.

j. We have met 5 and 30 year cycles. It is tempting to search for cycles but often new data bring new ones in. Maximov et al. (1972) think that three periodicities are of special importance in relation to long-term ocean variability: 1) a seven year cycle originating from interaction of the free nutation of the pole (14 months) with the earth's rotation period (12 months), 2) the 11 year cycle of sunspots and 3) the 19.4 year tidal period. In his book Maximov (1970), however, works with the periods 3.3, 5.0, 8.1, 14.0 and 80 years, when he constructs a formula for the prediction of sea ice in the Barents Sea.

As already mentioned, Colebrook and Taylor (l.c.) did not find any 5 year period in the North Sea SST spectral analysis. They found peaks at 108 months (9 years), 23, 14 and 9 months. The 23 and 14 months periods did not persist throughout the timespan of the series, whereas the peak at 9.4 months was significant at the 5% level. About the 9 year cycle the authors refer to Colebrook (1976): "There seems little doubt that this quasi-cyclical variability represents an element of temperature change common to the North Sea and at least to the eastern North Atlantic..".

h. Maximov's 80 year cycle is longer than the so-called Russell period (Russell et al. 1971) but shorter than Ljungman's (1882) herring period of 110 years. The Russell period refers to drastic changes which occurred first in the late 20ies - early 30ies when in the English Channel the nutrients decreased and northern type animals were substituted by southern type ones, and again in the middle 60ies when everything reversed. Whereas we note the change of temperature from 1930 in the shelf seas time series, we do not find corresponding drastic changes in the shelf seas in the middle of the 60ies. They are however contemporary with drastic changes north of Iceland (discussed above) and at other places. Cooper (1957) presented a fantastic theory that variations in the formation of Greenland Sea water which flows into the Atlantic (proper) through the Denmark Strait, might influence the nutrients content in the English Channel (by kind of internal wave effects). Does this mean that when we wish to explain biological changes we have to search the relevant hydrographic information far away instead of nearby?

Discussion

a. It has been shown (see Cushing and Dickson l.c.) that the high latitude warming during the first four decades of this century was linked with an increase in the strength of the general circulation over the North Atlantic sector and a northward shift of the zonal wind. After 1940 the main westerly windbelts have weakened, their path has become less direct, and the upper westerlies have shown an increasing tendency to meander. Wavelengths in the upper westerlies have shortened, and the north-south amplitude of the waves has increased.

Thus before 1960 the circulation over the European Arctic and Subarctic was controlled by two persistent cold troughs in high latitudes over north-east Canada and north-east Siberia. Since then the Canadian trough has tended to regress westward to the position which it occupied in the middle decades of the nineteenth century and an additional trough has tended to develop in the sector of the European Arctic (Fig. 15). This single rearrangement of waves is reflected in the striking physical variations in the marine environment (cooling) in the northern North Atlantic and dealt with in this review.

b. This indicates, that warming takes place in the North Atlantic during periods of increasing westerlies (zonal winds), but cooling during periods of decreasing westerlies or increasing meridional winds. Taylor (l.c.) and Colebrook and Taylor (l.c.) on the other hand state, that temperatures in the Northeast Atlantic tend to be inversely related to the strength of the trade and westerly winds. This was suggested to be related to variations in the strength of the North Atlantic Current system and the flow of the Gulf Stream (Iselin 1940, Martin 1972).

c. Whether increased zonality and westerlies accompanied by a northward shift of the zonal wind or decreased zonality and westerlies lead to reduced temperatures in the North Atlantic or not (and vice versa), can be considered in a short discussion.

In 1880-1925 an increase in westerlies took place over the North Atlantic (Taylor l.c., Dickson and Lamb l.c.). In the same years the North Atlantic waters were relatively cold

(Smed in Ellett et al. l.c.). During the relatively slow decrease in westerlies over the North Atlantic after 1925 and up to 1960 (the Russel period), the North Atlantic waters were relatively warm, even despite the general "slight" decrease in SST in 1950-1965 (Rodewald l.c.). After 1960 the westerlies continued decreasing (Dickson and Lamb l.c.) and so has the water temperature in the North Atlantic.

Thus, up to 1960, Taylor's interpretation seems to be the right one, while Lamb's interpretation was correct after 1960. To the authors the different interpretations of strong or weak westerlies might be related to differences in conditions between the southern and the northern parts of the study area. Strong westerlies seem to have a northerly location and then a warming effect towards north (Russel period), but during periods of increased meridional circulation or north-south winds, westerlies farther south (weak or strong?) reflect, at least in the north, cooling conditions in the northern North East Atlantic.

In this discussion it may be appropriate to refer directly to Cushing and Dickson (l.c.), "that if the westerlies weaken in strength their path around the globe has become less direct, the upper westerlies have shown an increasing tendency to meander about the west-east track (Rossby waves), wavelengths have shortened and the north-south amplitude has increased. Put differently, the recent climatic history of middle and high latitudes has been determined less (or not only) by any latitudinal shift of the westerly axis itself than by changes in the amplitude and the position of waves around this axis."

Concluding remarks

a. Cushing (1978) has given a brief and clear summary on climatic changes and physical variations in the sea and their physical concepts together with their biological implications. He describes the physical processes behind the planetary Rossby waves with their cold troughs and warm ridges, the importance of SST anomalies and their persistence because of ocean-atmospheric interaction which leads to a feedback mechanism. Cushing furthermore notes that "because events persist and because they are linked in the train of Rossby waves, phenomena are quite probably connected across considerable distances, about one half to one wavelength apart." These waves show up with different amplitudes. Small amplitude waves have a northward shift of the zonal wind (strong or weak westerlies?) followed by increased sea surface temperatures northwards. Large amplitude waves have an increased meandering with weakening westerlies but a circulation which tends to be more meridional than zonal, followed by decreased sea surface temperatures northwards and probably increased sea surface temperatures southwards in the Gulf Stream. The meridional circulation leads to e.g. northerly outbrakes and cooling across Greenland and the Subarctic Sea, and warming in the Irminger and Labrador Seas presumably because of the large scale local features governed by the ice-cap of Greenland, the Arctic and Subarctic Seas and the Iceland low.

b. Observations indicate long term secular changes as well as decadal or shorter periods in the westerlies. The former seem to be of importance for the long term shifting of the northern boundary of the westerlies over the North Atlantic, but the latter for the short term shifting of warm Atlantic water and cold polar or arctic water periods during times of increasing meridionality in the windfield. A year-to-year variation or two years period has also been observed in the westerlies (Dickson and Lamb l.c.) as well as e.g. in North Icelandic waters, at least during the sixties and seventies (Figs. 6, 7, 8). This may possibly be caused by the seasonal variations in the hydrographic conditions in general and a need for balance in semi-enclosed seas like the Arctic and Subarctic Seas.

c. Thus over the northern North Atlantic the present meridional circulation is marked by larger interannual changes in the hydrographic conditions than found during the previous

Russel period of zonal circulation. This must be a factor affecting the living conditions in these waters.

d. For the open North Atlantic it may be stated that for the period 1950-1970 the hydrographic variations in the area are fairly well documented and understood, together with their interaction with and impact on biological conditions and climate. On the other hand the period 1971-1980 and the years to come, still leave many questions to be answered. For example, are the climate and living conditions in the northern part of the North Atlantic endangered through a continuous cooling impact comparable with findings prior to the Russel period of 1920-1965?

e. The need for a complete working-up of both past and new hydrographic data from the North Atlantic, may be mentioned. Such a work should include considerations of prognosis of trends. Beside general hydro-meteorological data the parameters used may be information on atmospheric zonality at different latitudes and longitudes, meridionality with localization or phase of troughs and ridges in the atmosphere (Rossby waves), localization of sea surface temperature features in the Pacific and Atlantic Oceans and conditions in the ocean and shelf sea current system (in the Gulf Stream flow, in the North Atlantic Drift, in the polar- and arctic currents together with information on sea ice conditions).

Studies such as these are at present dealt with by a Joint ICES/SCOR Working Group on "North Atlantic Circulation" (ICES, PVR 1980, 1981) and the SCOR/IOC Committee on Climatic Changes and the Ocean (CCCO; ICES C.M. 1981/c:39).

f. Finally a direct quotation from a paper by Garrod and Colebrook (1978) seems to be appropriate to finish this overview on variation in the physical marine environment in relation on climate.

"The analysis of climatic, hydrographic and biological data on a pan-Atlantic scale provides evidence for a response to fairly large-scale variations in wind patterns presumably through the effects of advection in the Gulf Stream - North

Atlantic Drift system, and its consequential effect on more peripheral systems ..... The precise form of these relationships is yet not clear ..... Nevertheless our evidence does point strongly to a fairly direct linkage between climatic and biological effects which may be defined in terms of relatively simple parameters."

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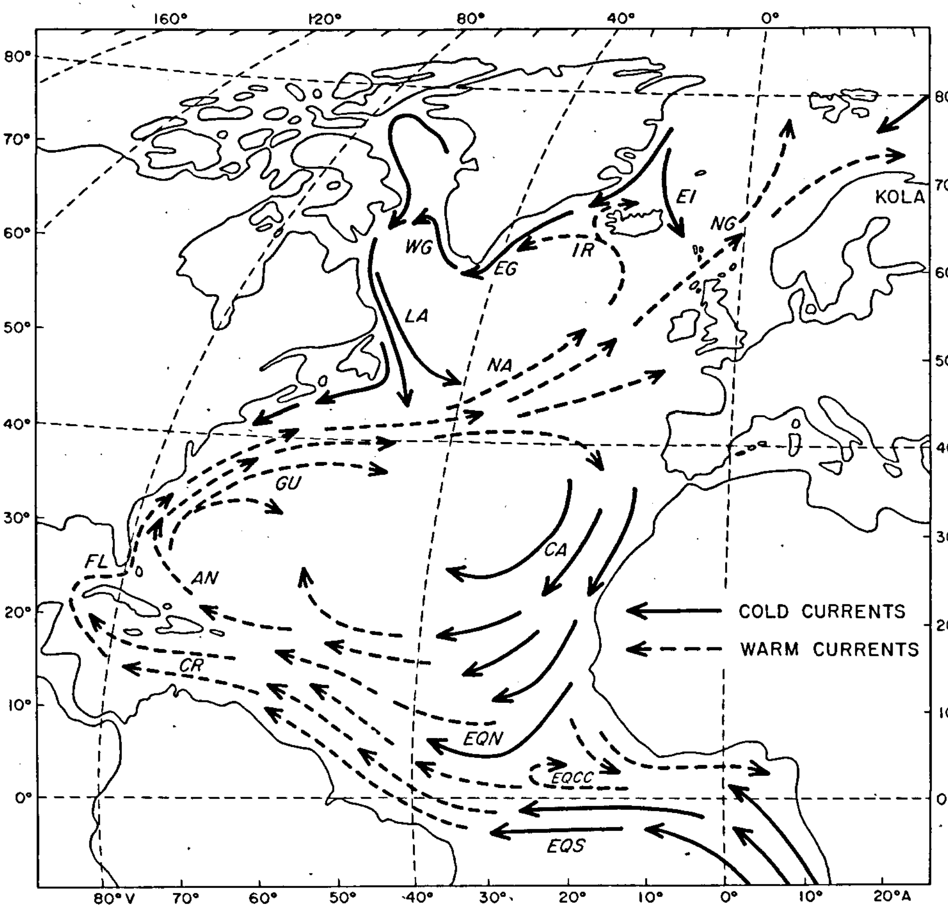

Figure 1 The North Atlantic and its general current system.

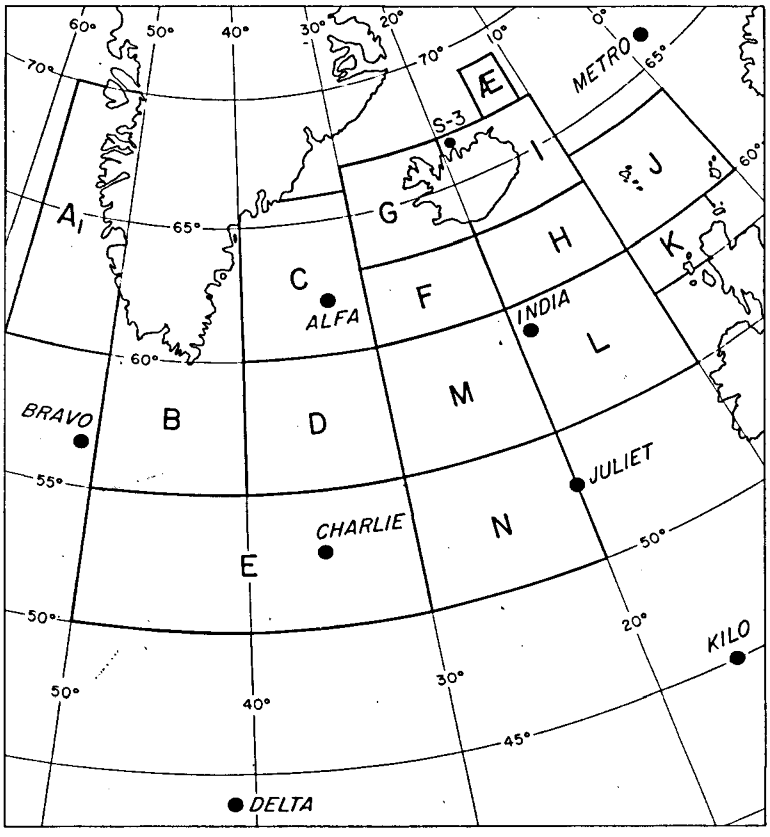

Figure 2 The location of selected study areas (Smed in Ellett et al. 1981) and Ocean Weather Stations.

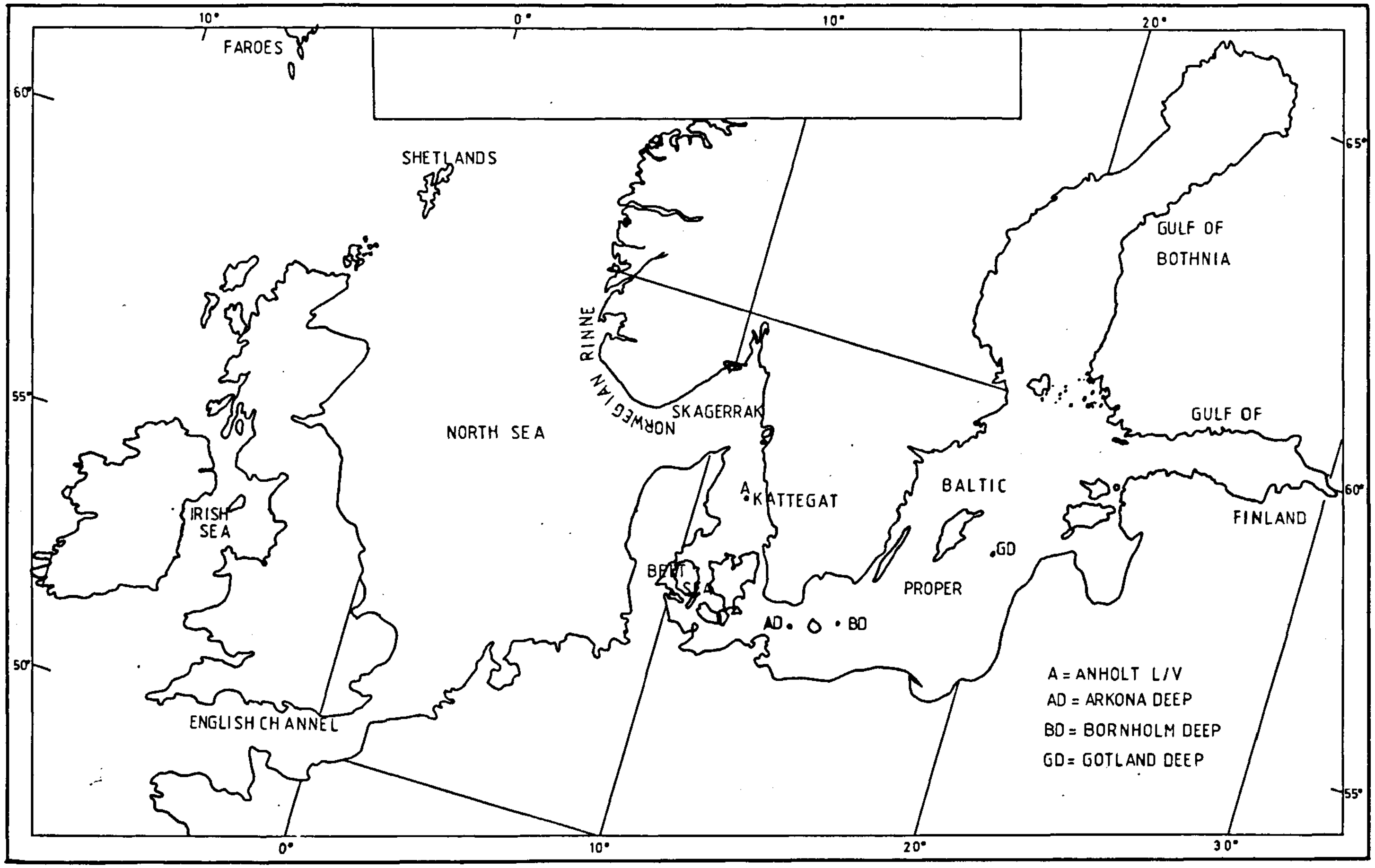

Figure 3 Nomenclature in the Baltic, the North Sea and adjacent waters.

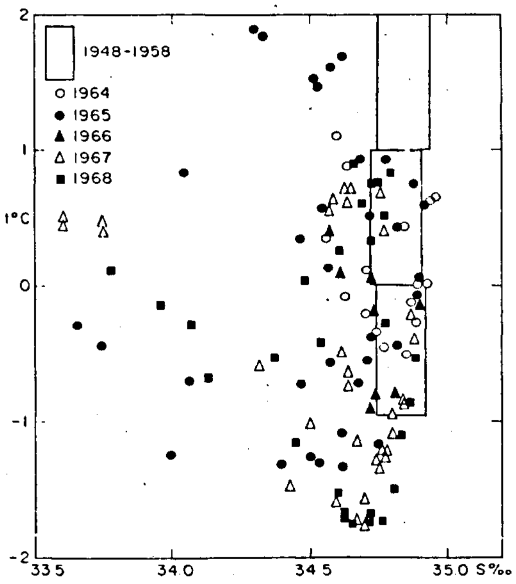

Figure 4 Temperature - salinity diagrams for all available hydrographic observations (mostly June) in the uppermost 200 m in the East Icelandic Current (study area Æ in Fig. 2) during 1948-1968 (After Malmberg 1969 a).

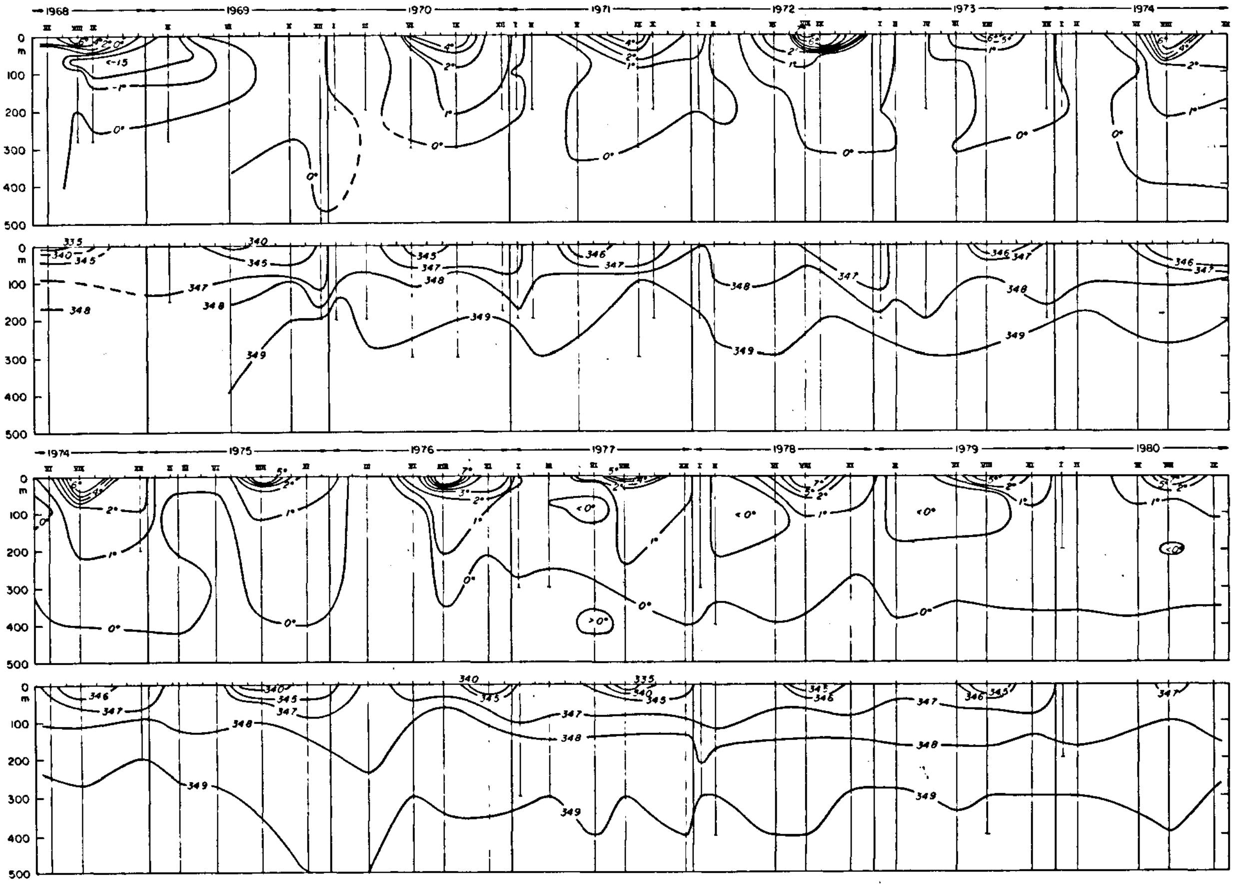

Figure 5 Isopleths of month to month means for all hydrographic observations in the uppermost 500 m in study area Æ (Fig. 2) since June 1968 up to 1980 (After Malmberg 1982).

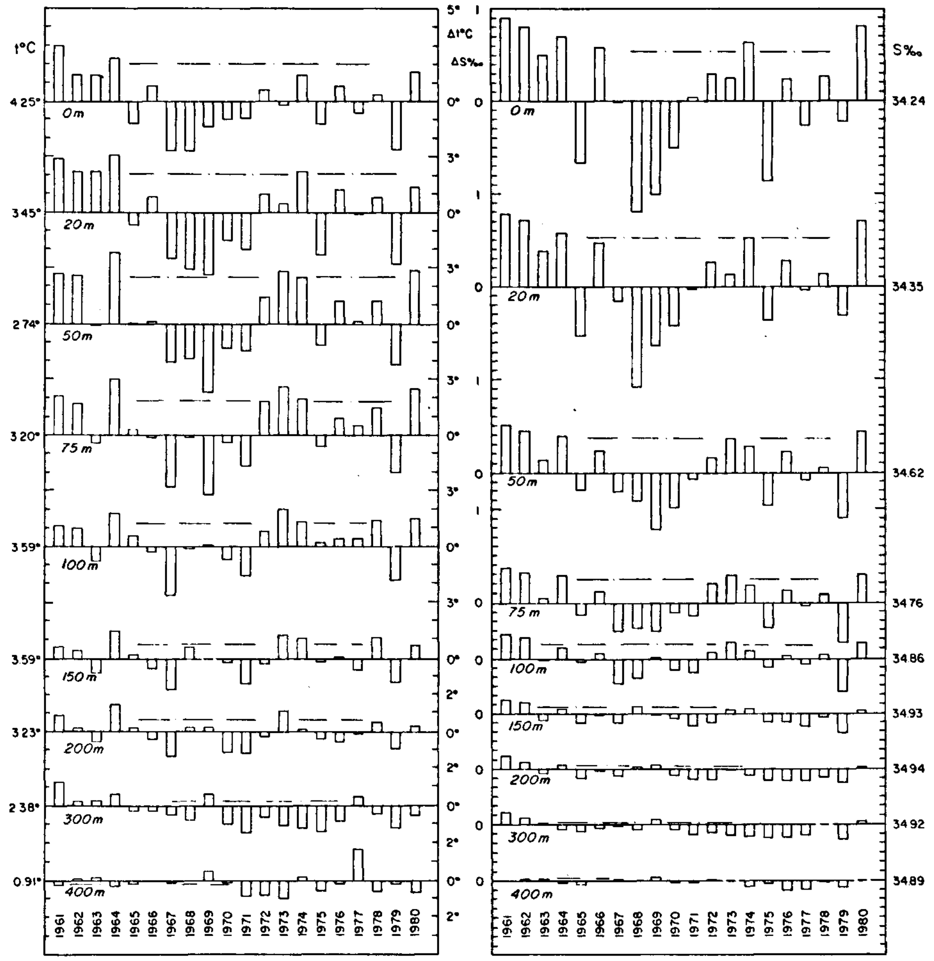

Figure 6 Deviations of temperature and salinity in May-June in 1961-1980 from the 1961- 1970 means at different depths on a hydrographic station in North Icelandic waters (S-3, 66°32'N, 18°50'W, Fig. 2). The means of the years 1925-1960 (Stefánsson 1962) are also shown (After Malmberg 1979/1980, 1982).

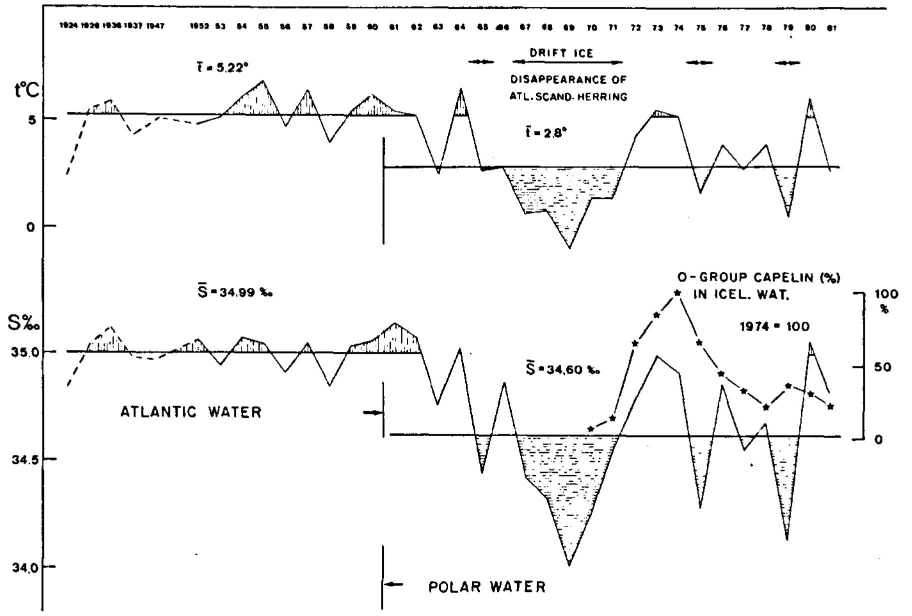

Figure 7 Temperature and salinity, observed values and deviations, at 50 m depth on a hydrographic station in North Atlantic water (S-3: 66°32'N, 18°50'W, Fig. 2) in May-June 1924-1981. Some features of sea-ice, variable herring migration and abundance estimates of 0-group capelin in Icelandic waters are also shown.

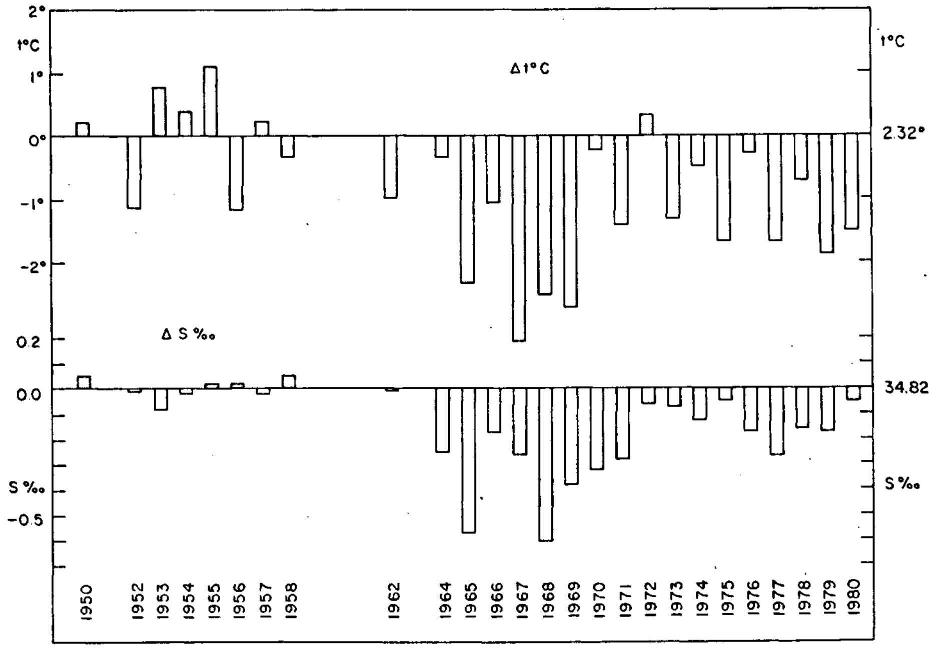

Figure 8 Deviations of temperature and salinity in June 1950-1980 from 1950-1958 means at 25 m depth in study area Æ (Fig. 2) northeast of Iceland (After Malmberg 1982).

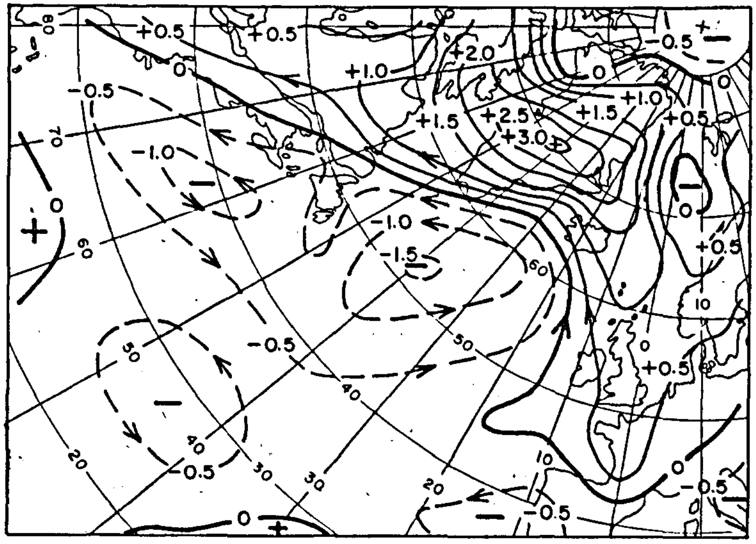

Figure 9 Mean pressure deviations (mb) from normal for the period 1956-1965. Normal period 1900-1939. Arrows indicate the sense of anomaly circulation (After Rodewald 1967a).

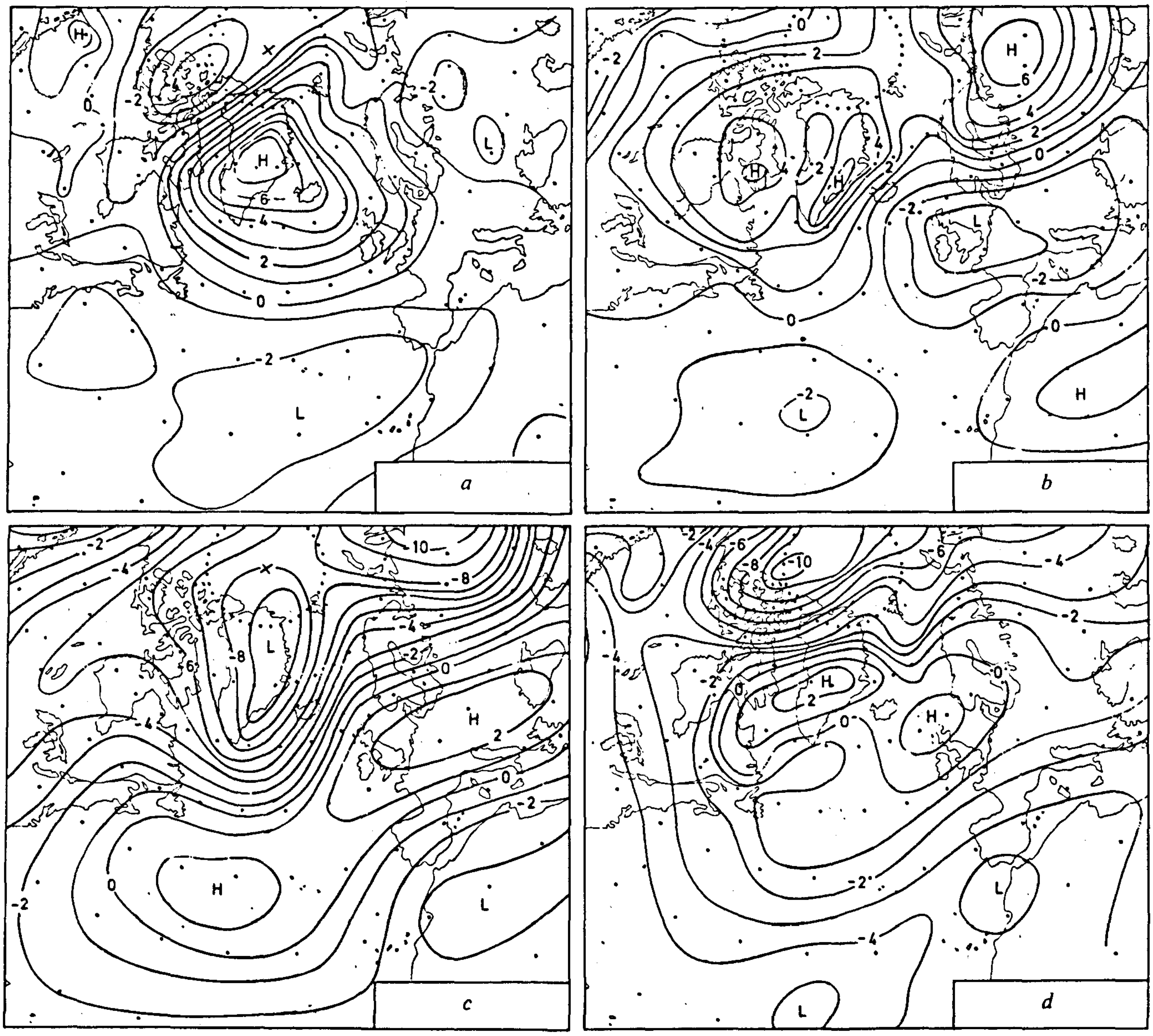

Figure 10. Change of Mean Winter sea level pressure (mb) between the periods: a. 1900-1939 and 1956-1965 b. 1956-1965 and 1966-1970 c. 1966-1970 and 1971-1974 d. 1900-1939 and 1971-1974 (After Dickson et al. 1975).

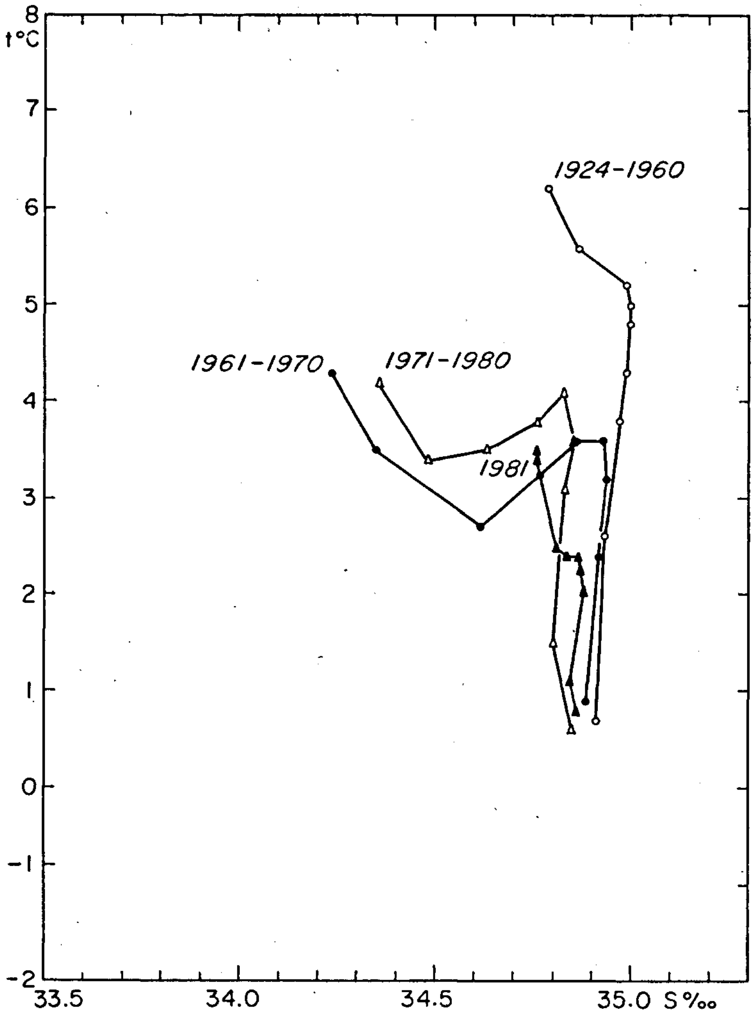

Figure 11a Mean temperature - salinity diagrams in May-June 1924-1960, 1961-1970 and 1971-1980 and in 1981, on station S-3 (Fig. 2).

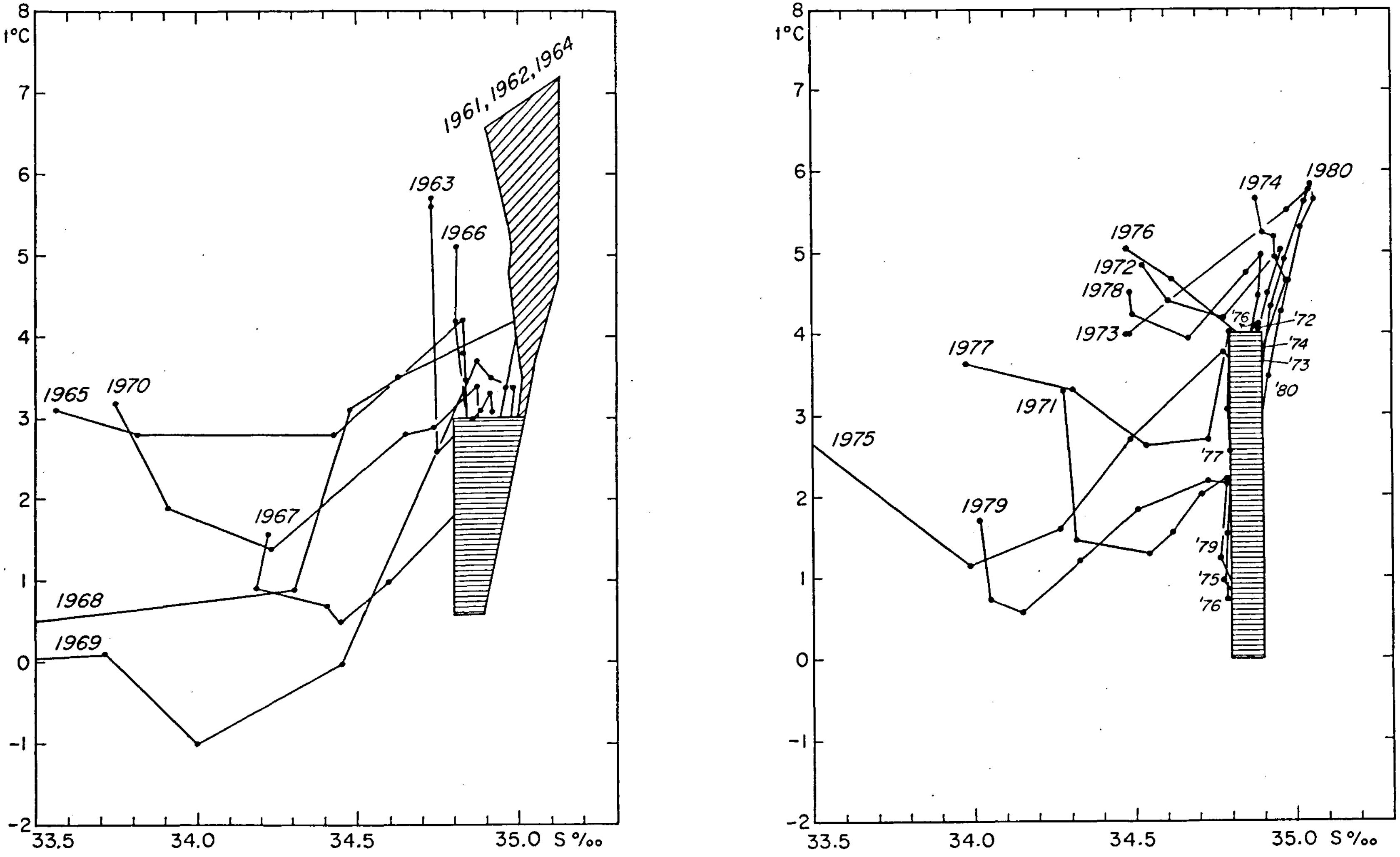

Figure 11b Temperature - salinity diagrams in May-June 1961-1980 on Station S-3 (Fig. 2).

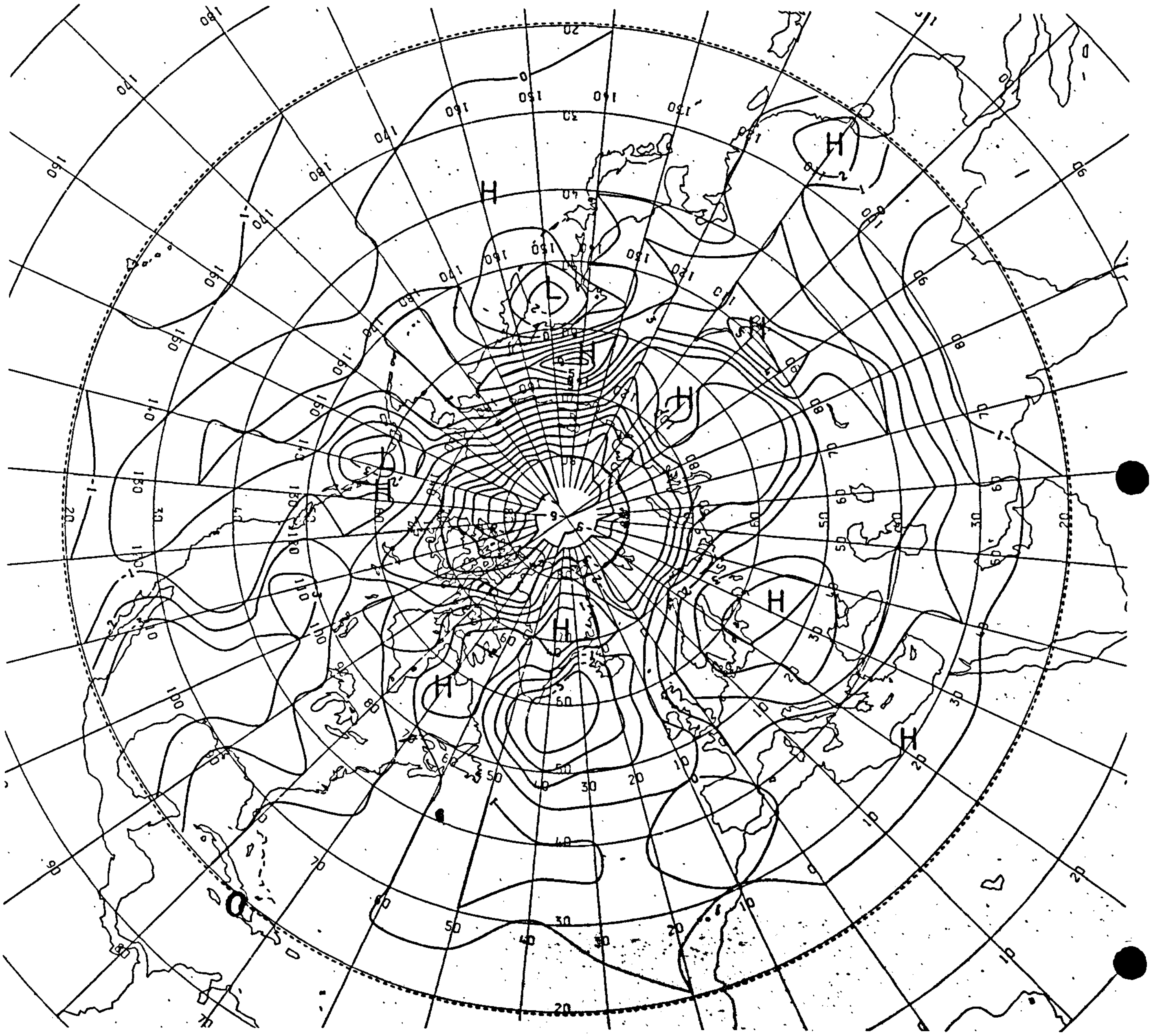

Figure 12a. Change of mean winter sea level pressure (mb) between 1900-1939 and 1971-1975

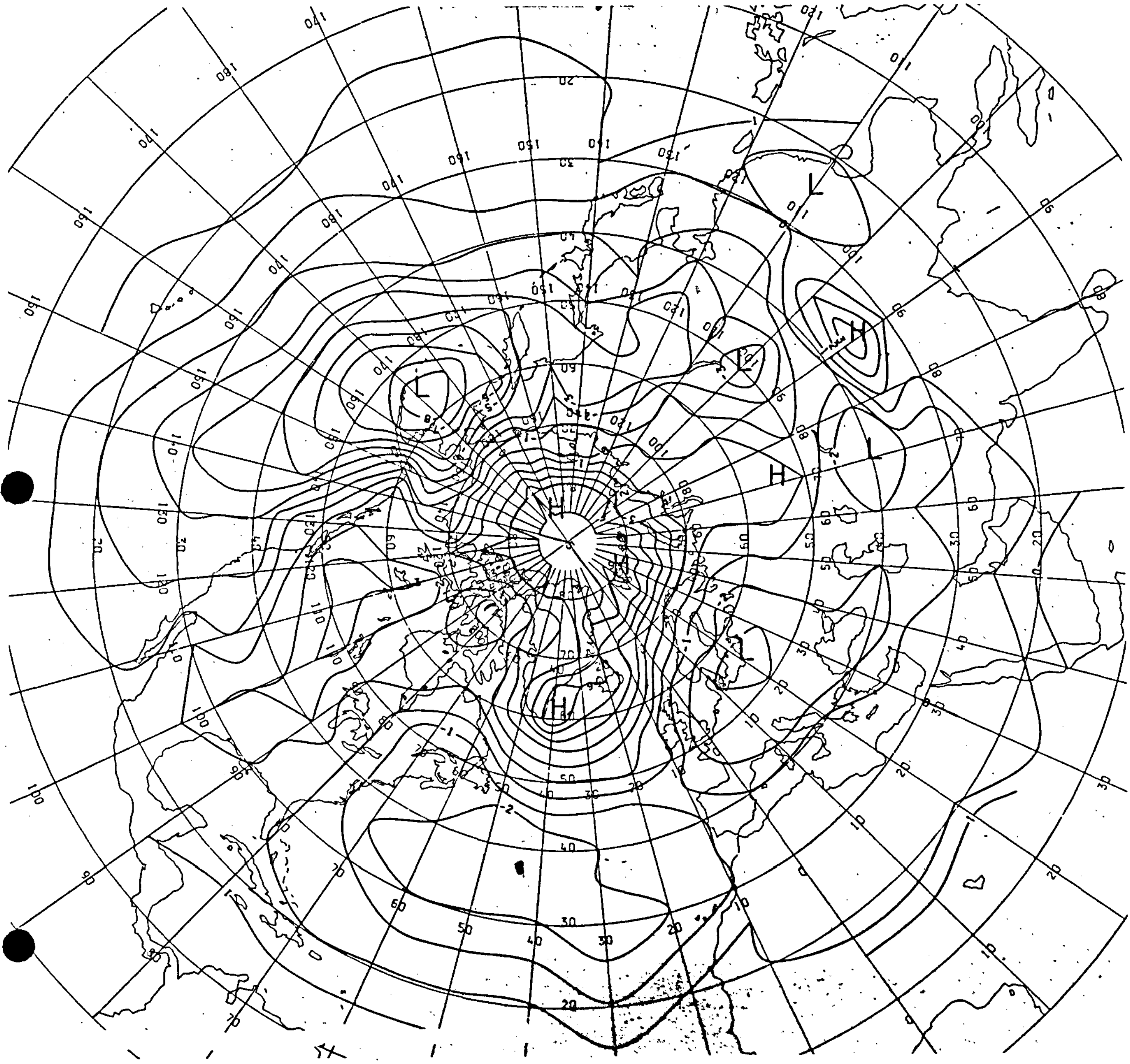

Figure 12b. Change of mean winter sea level pressure (mb) between 1971-1975 and 1976-1980.

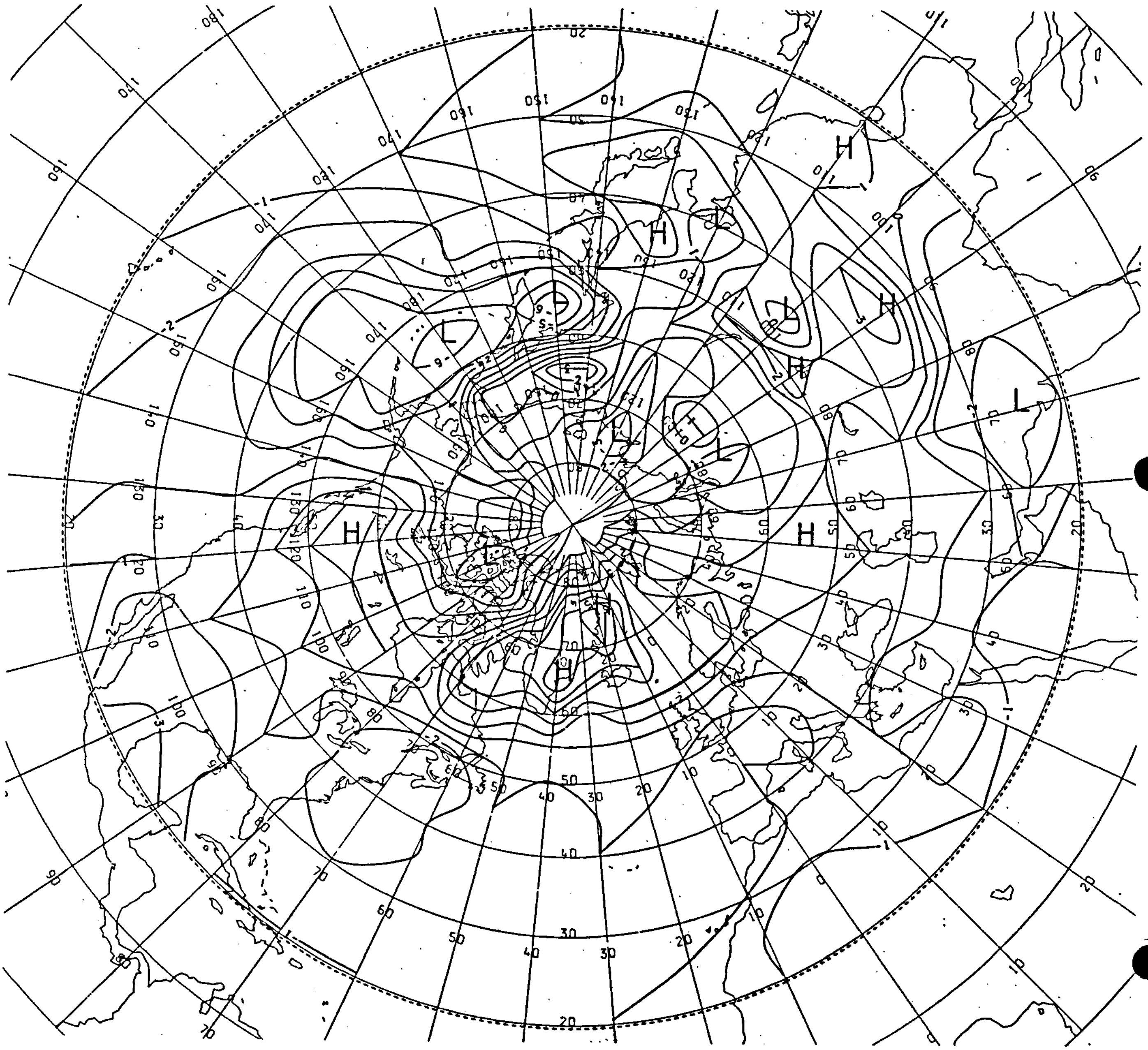

Figure 12c. Change of mean winter sea level pressure (mb) between 1900-1939 and 1976-1980

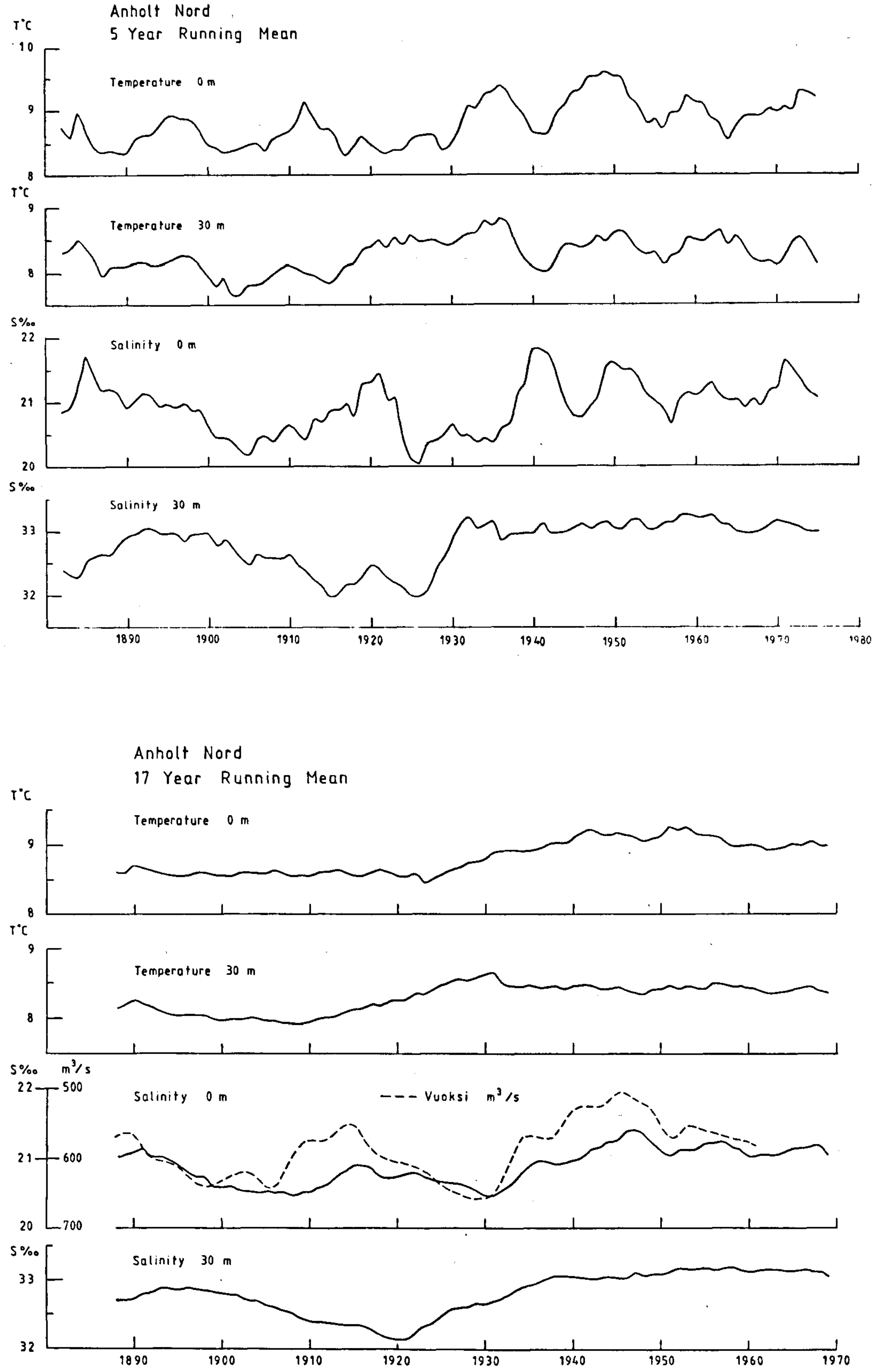

Figure 13 a, b. Five and seventeen year running means of temperature and salinity during the period 1880 to 1977 at the Danish lightvessel Anholt in the Kattegat (A in Fig. 3).

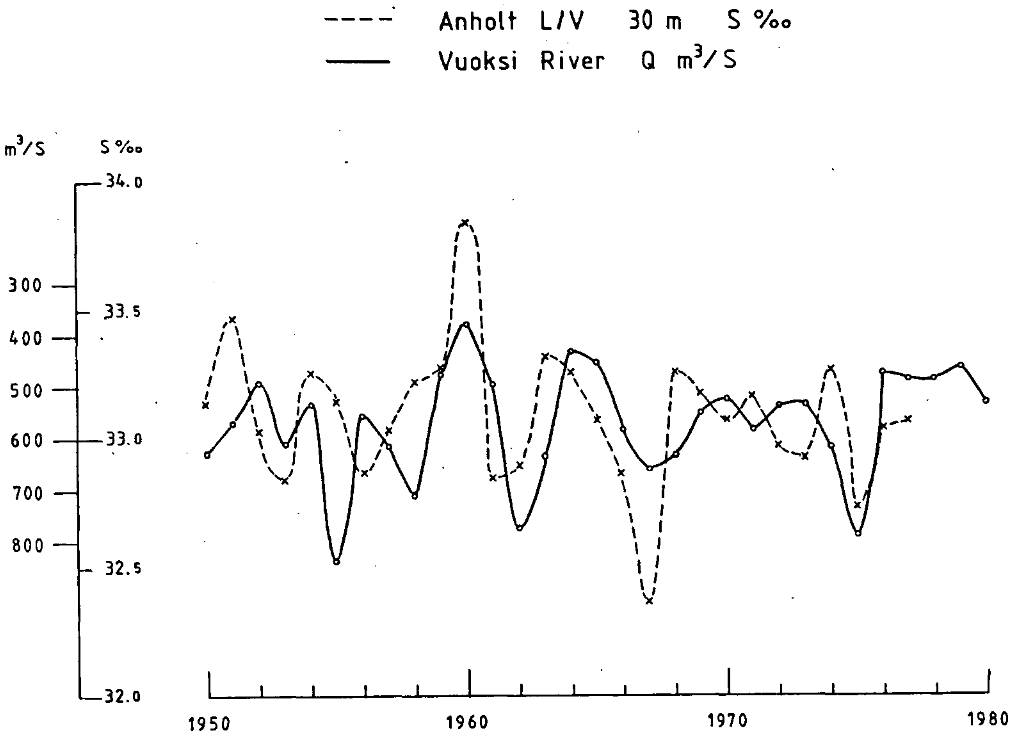

Figure 14 Unsmoothed annual salinity means at 30 m depth at lightvessel Anholt in the Kattegat (A in Fig. 3) and river water supply from Vuoksi River in the Baltic.

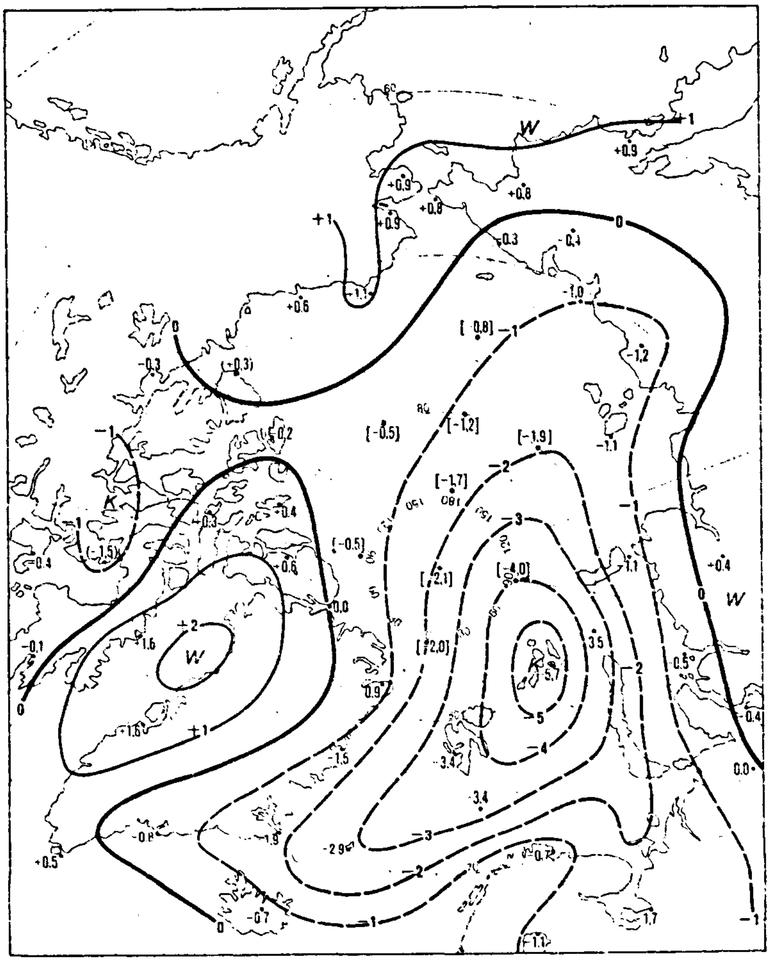

Figure 15 Changes of mean winter temperature (Dec., Jan., Febr., March) in the Arctic and Subarctic between the periods 1951-1960 and 1961-1970 (After Rodewald 1972a).