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International Council for
the Exploration of the Sea

ICES CM 1984/GEN:3
MINI SYMP.

# ON THE ABNORMAL HYDROGRAPHIC CONDITIONS IN THE EUROPEAN ARCTIC DURING THE 1970's

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ABSTRACT

The salinity minimum conditions observed in the Rockall and Faroe-Shetland Channels in 1976 (Dooley et al., in press) are traced northward along the axis of the Norwegian Atlantic Current to the Barents Sea and Spitsbergen. Time-series are formed from historical hydrographic data collected in August-September on the Bear Island-Fugløy Section, lying across the entrance to the Barents Sea, and on the zonal 'Sørkapp' Section at 76°20'N, which is well-placed to monitor changes in the characteristics of Atlantic water flowing north in the West Spitsbergen Current.

The salinity minimum was unambiguously identified on both sections, passing through the Bear Island-Fugløy Section in 1978-79 and through the Sørkapp Section in 1979. The ~ 3 year time-lag between the minima in the Faroe-Shetland Channel and at Spitsbergen implies a mean propagation speed of around 2-3 cm $s^{-1}$ in the Norwegian Atlantic Current. As in the Faroe-Shetland Channel, Atlantic water salinities on both sections were 0.1 to 0.15 fresher than the long-term mean but were accompanied in the Arctic by a cooling of 1°-2°C so that densities remained close to normal. These cool, fresh conditions extended to the bottom on the Bear Island-Fugløy Section and to > 500 m depth in the Atlantic water of the West Spitsbergen Current; in the latter case, intermittent sampling to greater depths suggests that the T-S characteristics from all years tend to converge by around 800 m depth which both suggests a depth limit for the 1970's anomaly in this region and provides some reassurance on data quality over the period under discussion.

On both sections the most remarkable aspect of these changes was the dwindling to near-disappearance of salinities ⩾ 35 despite their previous widespread (almost section-wide) distribution during all previous workings of these sections since the start of observations in the mid-1920's. Nevertheless, though this may be the most obvious change observed, the freshening and cooling were in fact of slightly greater amplitude remote from the subsurface high salinity core.

Some physical and biological implications of these changes are discussed. From radiocaesium evidence, salinity minimum conditions are expected to have reached waters off east Greenland in 1981-82.

RÉSUMÉ

Les conditions relatives au minimum de salinité observées en Rockall et dans le canal des îles Féroé-Shetland en 1976 (Dooley et coll., à l'impression) sont tracées vers le nord suivant l'axe du Courant atlantique de Norvège jusqu'à la mer de Barents et Spitzberg. Des séries temporelles sont réalisées à partir de données hydrographiques historiques recueillies en août-septembre dans le secteur de l'île aux Ours-Fugløy, chevauchant l'entrée de la mer de Barents, ainsi que dans le secteur zonal de Sørkapp à 76°20' de latitude nord, qui est bien situé pour contrôler les variations des caractéristiques des eaux atlantiques s'écoulant vers le nord dans le Courant ouest-Spitzberg.

Le minimum de salinité a été identifié sans ambigüité dans les deux secteurs, passant par le secteur de l'île aux Ours-Fugløy en 1978-79 et puis par le secteur Sørkapp en 1979. Le décalage temporel de $\sim$3 ans entre les minima dans le canal des îles Féroé-Shetland et à Spitzberg implique une vitesse de propagation moyenne de 2 à 3 cm $s^{-1}$ environ dans le Courant atlantique de Norvège. Comme dans le canal des îles Féroé-Shetland, les salinités des eaux de l'Atlantique dans les deux secteurs étaient de 0, 1 à 0,15 plus douces que la moyenne de long terme mais étaient accompagnées dans l'Arctique d'un refroidissement de 1° à 2°C, de sorte que les densités restaient proches du niveau normal. Ces conditions de refroidissement et de douceur s'étendaient jusqu'au fond dans le secteur de l'île aux Ours-Fugløy et à une profondeur de > 500 m dans les eaux atlantiques du Courant ouest-Spitzberg; dans ce dernier cas, des échantillonnages périodiques à de plus basses profondeurs suggèrent que les caractéristiques T-S recueillies à partir de tous les ans ont tendance à se rapprocher à une profondeur de 800 m environ, ce qui implique un limite de profondeur pour l'anomalie des années soixante-dix dans cette zone et en plus, fournit certaines garanties à propos de la fiabilité des données pendant la période en cause.

Dans les deux secteurs, l'aspect le plus remarquable de ces variations était la diminution jusqu'à la quasi-disparition des salinités ⩾ 35 malgré leur ancienne répartition généralisée (presque dans l'ensemble du secteur) mise en évidence lors de toutes les mesures déjà prises aux emplacements linéaires dans ces secteurs depuis le commencement des observations vers la moitié des années vingt. Néanmoins, quoiqu'il soit possible que ceci constitue le changement le plus évident qui ait été observé, l'affaiblissement de la salinité et le refroidissement étaient en effet d'une amplitude légèrement plus imporante aux points éloignés du noyau de haute salinité de la sous-surface.

Certaines implications physiques et biologiques de ces variations sont discutées. À partir de preuves du radio-césium on prévoit que des conditions du minimum de salinité auront atteint les eaux au large de Groenland de l'Est en 1981-82.

## 1. INTRODUCTION

Over many decades, the painstaking compilation of surface ship observations by Jens Smed and the Service Hydrographique has provided dependable monthly climatological means of temperature and salinity for the bulk of the North Atlantic. From their use it was possible to establish the spectrum of annual and interannual variation in these parameters and to show reliably that a particular anomalous tendency might be of large amplitude, of great geographical extent and that it might be sustained over a period of many years. Further, the largest of these 'signals' in the marine climate, such as the well-documented warming episode in the northern North Atlantic during the 1930's and early 1940's, and the general cooling that prevailed over European Arctic and sub-Arctic seas during the 1960's (e.g. Cushing and Dickson, 1976) provided convincing evidence that these dramatic events in the physical environment were accompanied by equally radical changes in the distribution and abundance of commercially-important fish stocks.

The 'great salinity anomaly of the 1970's' to be described below, represents a further major dislocation of the marine climatology of the North-east Atlantic, whose physical and biological repercussions have yet to be worked through. Early evidence of this change was provided by two ultra-long time-series from seas to the north and west of the British Isles, first, the 1905-80 time-series of January-March surface temperature and salinity from the northern Rockall Trough by Ellett (e.g. 1982) and second the 1902-82 time-series of salinity values for the (surface) North Atlantic and (subsurface) Arctic Intermediate water masses in the Faroe-Shetland Channel by Dooley _et al_. (in press). Both these time-series show that following a period of low salinity values in the early years of this century around 1910-25, the higher values which generally prevailed in subsequent years were interrupted by a second great salinity minimum in the 1970's. In these two sea areas the latter anomaly appears to have penetrated to at least 500 m depth, was characterised at its minimum by anomalies of ~ 0.10 to 0.15 from the long-term mean and reached these minimum values in 1976.

The various candidate mechanisms for these changes including possible far-field and near-field influences have been well summarised by Dooley _et al_. (in press) and will not be discussed further here. The proximate cause is attributed to an eastward shift of 250 n miles in the position of the Oceanic Polar Front, which thus halved its distance from the European Continental Slope and restricted the entry of North Atlantic and Modified North Atlantic water into the Norwegian Sea.

From the Faroe-Shetland Channel northwards there is evidence that the timing of the salinity minimum is progressively delayed along the axis of the Norwegian Atlantic Current and its branches; the analysis of hydrographic variation in the upper 150 m layer at Ocean Weather Station MIKE (66°N 2°E) by Gammelsrød and Holm (in press) shows a broad and rather poorly-defined minimum in both temperature and salinity around 1977-78 implying (they conclude) northward propagation of these anomalous conditions in the Norwegian Atlantic Current; in an earlier analysis of T-S characteristics along three meridional sections in the Barents Sea, Blindheim and Loeng (1981) were able to show that upper-layer (50-200 m) salinities and temperatures had declined sharply by 1979 along the Bear Island-Fugløy (19-20°E), Vardo-N (31°13'E) and Sem Islands-N (37°20'E) Sections but were unable to demonstrate whether the minimum had even then been reached.

Such a major change in the marine climate has a potential importance in affecting faunal distributions in the European Arctic and may even have repercussions on deep water formation through its effect on the salt supply to the Greenland Sea Basin. This paper therefore aims to extend the analysis of hydrographic variation on the Bear Island-Fugløy Section to define the date, amplitude and depth-of-influence of the salinity minimum at the entrance to the Barents Sea, and to establish new time-series across the West Spitsbergen Current at the highest possible latitude before it enters the Arctic Ocean or turns westward towards the Greenland Sea.

## 2. THE DATA

In August-September of every year from 1965 to the present a set of standard hydrographic sections has been worked across the Barents Sea shelf and West Spitsbergen Current during the ICES International 0-group Fish Surveys. The Bear Island-Fugløy Section (Figure 1) is well-placed to monitor conditions in the North Atlantic water component as it enters the Barents Sea, and these data, coupled with any earlier workings of the section in the months of August-September form one of the bases of the present analysis. The section was not always worked along the same geographical line during the period considered; it lay along 19°E in 1926, between 20° and 21° in 1928, between the fixed positions of 70°46'N 21°14'E and 74°08'N 19°14'E in the British sections of 1949 and the 1950's, and from 70°30'N, 20°00'E to 74°15'N 19°10'E during the Norwegian observations since 1957. Equally, the latitudes of stations on the section are somewhat variable in time. Nevertheless, by arraying the stations against latitude and time and ignoring variations in longitude (since these lie along the mean current direction) it was possible to establish 10 time-series for the calculation of mean section properties and their variation with time since 1926 (Figure 2). In the following discussion, the stations at 73°30'N and 72°00'N receive greatest attention since they cover, respectively, the zone of maximum mean eastward current speed (Blindheim and Loeng, 1981, their Figure 16) and the subsurface salinity maximum at the core of the North Atlantic watermass.

In almost every year since 1965, the 0-Group Fish Surveys have also included a zonal hydrographic section worked in August-September between 5°E and 25°E along 76°20'N approximately. This 'Sørkapp Section' (Figure 1) was worked to at least 500 m depth and covers both the West Spitsbergen Current and a relatively minor tongue of Atlantic water which enters the Storfjordrenna east of Sørkapp Bank. Though the positions of stations on this section were far from standard in successive years, it proved possible to form 11 almost-continuous time-series from this data set which cover the full width of the section. The stations selected for each time-series are connected by solid or dashed lines in Figure 3. In the case of 11 out of the 157 time-series stations shown, data was interpolated to the time-series position from stations to its east and west, and these are identified by 'I' in Figure 3. Time-series (T.S.) stations 3 and 5 are described in greatest detail below since they are reasonably complete, cover the main Atlantic watermass west of the Continental Slope and are remote from the influence of the Oceanic Polar Front to the west or of the Mixed Arctic water which occupies the near-surface layer to the east. (Watermass definitions follow Blindheim and Loeng, 1981 (e.g. their Figure 4)).

## 3. THE BEAR ISLAND-FUGLØY SECTION

For the two key stations at 73°30'N and 72°00'N, Figure 4 describes discontinuous time-series of temperature and salinity values in August-September at a range of standard depths to 400 m and over the period 1926-82. Over this period, temperature and salinity values tend to show a general maximum in the late 1960's followed by an abrupt cooling and freshening tendency which leads to striking minima in both parameters by the late 1970's, extending to the bottom. The precise dates of the minima vary slightly according to the parameter, station and depth considered but occur sometime in the period 1978-79 and hence at a significantly later date than the minima observed upstream along the axis of the Norwegian Atlantic Current. (The temperature and salinity time-series for this section, illustrated in Blindheim and Loeng, 1981, which appeared to suggest a 1979 minimum, are based on space-depth averages and provide a less clear dating as a result). At their minima, temperatures average 0.5° to 2.5°C lower than the 1926-79 mean, with salinities fresher by 0.1 to 0.15, according to depth and location. Unfortunately the time-series are too short to indicate whether any earlier deep minimum occurred pre-1925 as in the Faroe-Shetland Channel (Dooley *et al.*, in press).

The remarkable nature of the late 1970's event is perhaps best illustrated by comparing the mean salinity distributions on the entire section in the 1920's, 1950's, 1960's and 1970's (Figure 5) with the mean distribution during 'salinity minimum' conditions in 1978-79 (Figure 6a). The decade-mean averages show little change in characteristics of Atlantic water on the section from the 1920's to the 1960's, each with a broad (almost section-wide) core of salinities in excess of 35.0 and a subsurface maximum near 35.15 at ~ 72°N. Even in the decade-mean for the 1970's, salinities > 35.0 are of widespread distribution though the subsurface maximum has reduced by about 0.06 and does not exceed 35.1 anywhere. That this is largely the effect of the 1978-79 event is confirmed in Figure 6a which shows in these years, a remarkable dwindling of the core of water with salinities at or just above 35.0 and a maximum value of only 35.01. As shown in Figure 6b, negative anomalies in excess of -0.15 were observed around 73°30'N and in the waters of the Norwegian

Coastal Current; positive anomalies (shaded) are shown in surface waters close to Bear Island. Temperature anomalies (not shown) were positive in the upper layers, but negative everywhere below 50 m depth with minima > -2°C between 100 and 200 m depth at 73°30'N.

Figure 7 illustrates the combined effect of these changes on temperature-salinity structure in showing the T-S characteristics for the years of salinity maximum (1969-70) minimum (1978-79) and all other years (scatter plot) at the two key stations.

4. THE SØRKAPP SECTION

In Figure 8 the time variations of salinity, temperature and $\sigma_t$ to 500 m depth are illustrated for the two time-series locations (T.S. 3 and T.S. 5) which provide reasonably complete data from the thick North Atlantic water lens west of the Continental Slope off south Spitsbergen. Here, relatively remote from the variable coastal water regime, there is clear evidence that from near-normal salinity conditions in 1976, salinities at all depths to at least 500 m fell sharply to a minimum in 1979 before recovering to normality once again in 1981 (Figure 8a, b). These data therefore suggest a slightly later minimum than that derived earlier for the Bear Island-Fugløy Section; if purely advective the ~ 3 year time lag between minimum salinity conditions at the Faroe-Shetland Channel and in the Spitsbergen area, some 2 300 km to the north, implies a propagation speed of 2-3 cm $s^{-1}$ along the axis of the Norwegian Atlantic Current. Figures 8c-f also indicate that these fresher conditions on the Sørkapp Section were accompanied by sea temperatures some 1-1.5°C cooler than normal, so that the density of the upper layers was essentially unchanged.

Figure 9 confirms that the events just described for T.S. 3 and 5 were representative of the section as a whole. Figure 9a illustrates the mean salinity distribution on the section, 1965-82, with a deep layer of saline (> 35) Atlantic water occupying the zone between the Continental Slope and the Oceanic Polar Front at ~ 5°E, and with a tongue of relatively saline water (> 34.9) occupying the Storfjordrenna east of Sørkapp Bank, capped by a 75 m layer of fresher Mixed Arctic (M.A.) water (< 34.8).

Figures 9b and c describe, respectively, the mean salinity distribution, and the deviation of salinity from the long-term mean in 1978-79, during 'salinity minimum' conditions. Salinity anomalies are negative <u>everywhere</u> on the section with the exception of a narrow band of positive values along the haline front which marks the eastern boundary of the main Atlantic watermass near Sørkapp Bank. To the west of the Bank, a subsurface salinity maximum still marks the core of the West Spitzbergen Current (150-200 m, T.S. 7) but the central value has decreased from 35.1 to 35.0, and in fact the two values of 35.001 and 35.015 at the core of the current are now the only salinities greater than 35 on the entire section. Very approximately, Atlantic water salinities are 0.10 to 0.15 fresher than normal in the upper 200 m (i.e. similar to the anomaly reported earlier from the Bear Island-Fugløy Section and from the Faroe-Shetland Channel), and 0.06 to 0.10 fresher than normal from 200 to 500 m. Thus the freshening was not confined to the subsurface high salinity core of the West Spitsbergen Current and if anything was slightly less pronounced in that depth zone.

Since the depth of the subsurface salinity maximum alters slightly from year to year, the latter point is best illustrated by Figure 10a, b where for T.S. 3 and T.S. 5 respectively, salinities are plotted versus temperature rather than depth for the period 1965-82. As shown, when the subsurface salinity maximum at 3°-5°C is split by fresher water in 1978-79, the freshening is slightly more intense in the shallowest (> 5°C) and deepest (< 2°C) layers of the profile.

Finally Figure 11 expresses these changes in terms of the temperature-salinity characteristics at sites T.S. 3 and T.S. 5. In each plot the temperature-salinity curves for August-September 1978 and 1979 are shown as pecked and solid lines respectively, alongside scatter plots representing all other occupations of these sites in 1965-82. The occasional value from depths to 800 m is also included. Apart from the obvious freshening and cooling of the upper layers in the two key years, already described, the inclusion of data to 800 m provides confirmation that in the deepest layers accessible to us, the T-S characteristics from all years tend to converge, thus providing reassurance that the observed changes are real, and are not merely the result of changes in data quality arising through the change in measurement-technique from water bottle to STD to CTD over this period.

There is perhaps some evidence that the changes just described are not wholly advective in origin but may have been enhanced through local forcing. In Figure 9c for example the most conspicuous freshening on the entire section (-0.2 to -0.7) occurs not in the Atlantic Water but in the shallow near-surface layer of Mixed Arctic Water east of Sørkapp Bank . In situ change is perhaps also implied in the long-term current measurements by Aagaard across the West Spitsbergen Current at 79°N, 6°54'-8°32'E; in three successive year-long deployments between 1976 and 1979 and thus covering the transition from relatively saline to fresh conditions, records at 100 m and 400 m depth showed a progressive year-by-year increase in eddy kinetic energy within the period-band 2-52 d, accompanied by an increase in the dominant eddy frequency (Aagaard, personal communication; Dickson, 1983).

## 5. POSSIBLE PHYSICAL AND BIOLOGICAL EFFECTS

Though our time-series are discontinuous, the changes just described appear to represent the greatest widespread freshening tendency since the mid-1920's in the North-east Atlantic and along the Norwegian Atlantic Current. Despite the 3-year transit time from the Faroe-Shetland Channel to West Spitsbergen, salinity anomalies remain unaltered at 0.1 to 0.15 below normal and are accompanied by a cooling of 1-2°C in the north over a depth range exceeding 500 m. Though the physical and biological repercussions of these changes have yet to emerge, the question arises as to what these effects might be and where and when might these anomalous conditions set in at points still further downstream.

Locally, within the Barents Sea these effects are expected to include changes in fish distribution since the distributions of fish stocks there are rather closely linked to the relative distributions of contrasting watermasses, or to major changes in the character of a particular watermass. During the radical cooling and freshening of the North Atlantic water component in the late 1970's two main distributional changes have been described. First, Loeng (1981) has shown a correspondence between the areal distributions of capelin and of temperatures > 0°C at 100 m in the north-eastern Barents Sea, and hence (Loeng, Nakken and Raknes, 1983) a south-westward retraction of the capelin from this area in 1976-80 as cool conditions spread. Second, Midttun, Nakken and Raknes (1981) have shown an increased westward migration of cod in the Barents Sea with increasing age and decreasing water temperature, so that an extreme westerly distribution of cod biomass occurred in 1979-81 when the cool conditions in the North Atlantic watermass happened to overlap with a relatively old dominant year class.

Further 'downstream' our main interest concerns the possible effects on deep water formation of a decrease in the salt supply to the Greenland Sea. For the West Spitsbergen Current for example, it is possible to derive an order of magnitude figure for the equivalent salt deficit in 1978-79, assuming that the cause of the freshening in the Atlantic watermass there is primarily of advective rather than local origin.

Ignoring the fact that freshening also occurred at the western and eastern ends of Sørkapp Section and at depths > 500 m not covered by the data set, a mean freshening by 0.1 over two years in the 0-500 m layer along the 185 km length of section between T.S. 2 and T.S. 7 (i.e. in the main lens of Atlantic water) is equivalent to a deficit of 15 billion tonnes in the salt supply by the West Spitsbergen Current over the two years, assuming an advection rate of 2.5 cm $s^{-1}$. This figure is merely illustrative of course. The Norwegian Atlantic Current is the major supplier of salt to the Greenland Sea so any significant reduction in salt supply is likely to have repercussions on deep water renewal. However we do not know whether the main supply is via the West Spitsbergen Current or via a more southerly route across the Norwegian Sea at ~ 70°N, as recent radiocaesium surveys suggest (Jefferies, personal communication). Neither do we yet have a sufficient theoretical or observational base to speculate on the extent or even the sign of any resulting change in deep water renewal. We do however have some indication, from radiocaesium mesurements, as to the time of arrival of the cool, fresh conditions east of Greenland; the greatly increased radiocaesium discharge from Sellafield in 1974 is estimated to have passed through the North Channel of the Irish Sea in 1975 and is traced as a 'spike' increase in radiocaesium levels to the West of Scotland in 1976-77 (Jefferies et al., 1982). The increased $^{137}Cs$ which entered the Norwegian Atlantic Current therefore accompanied (more or less) the salinity minimum conditions as they propagated northwards, and is assumed to act as a convenient tracer of their arrival east of Greenland. By whichever route, this tagged water appears from Danish observations to have entered the East Greenland Polar Current in 1981-82 (Aarkrog et al., 1983).

The component of the West Spitsbergen Current which continues northward to the Arctic Ocean is less easily traced; from the review of Coachman and Barnes (1963), we assume a similar date (i.e. 1981-82) for the arrival of these anomalous conditions in the Laptev Sea, though possibly after considerable modification along the Eurasian Continental Slope.

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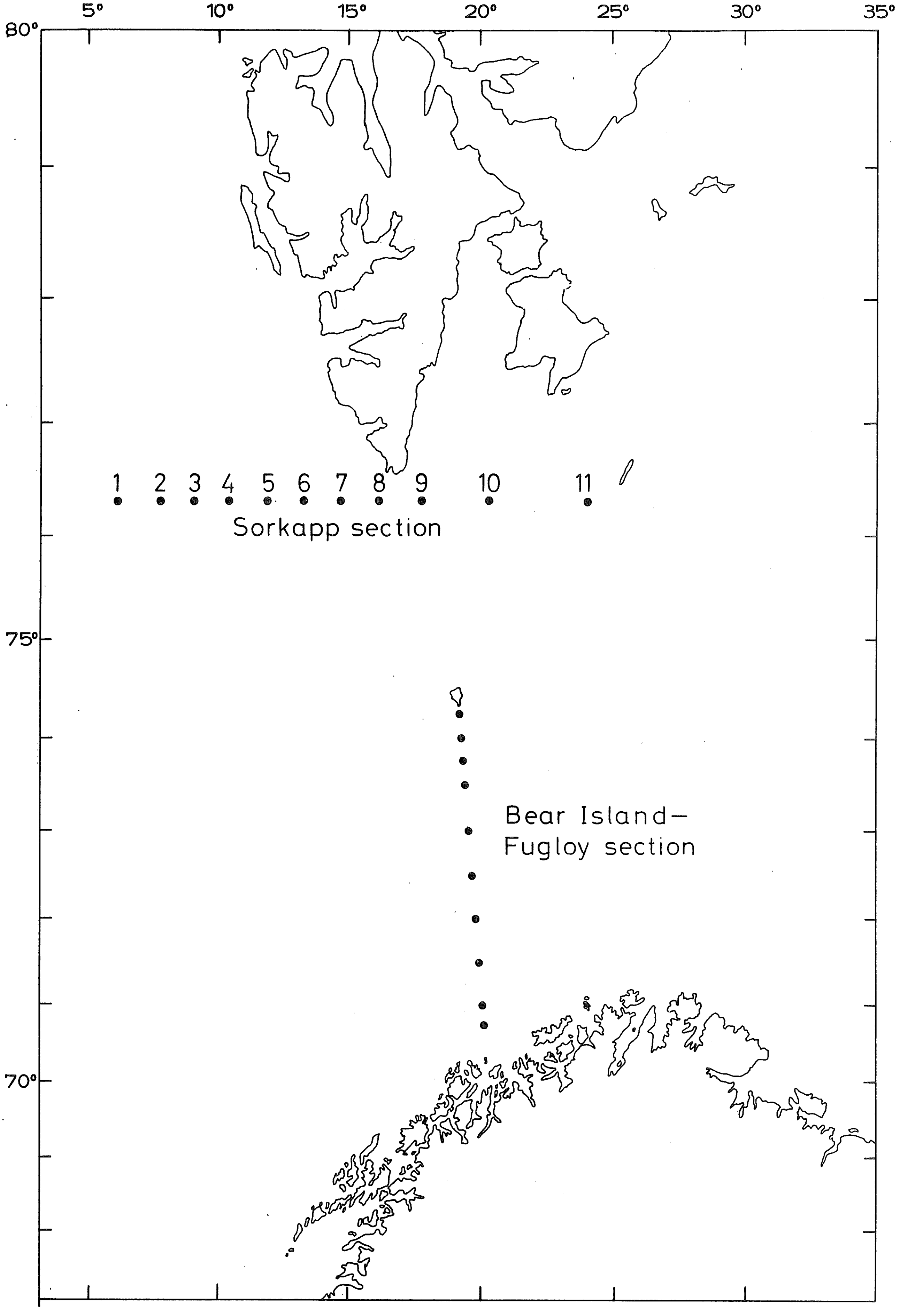


Figure 1 Location chart, showing positions of the time-series stations on each section.

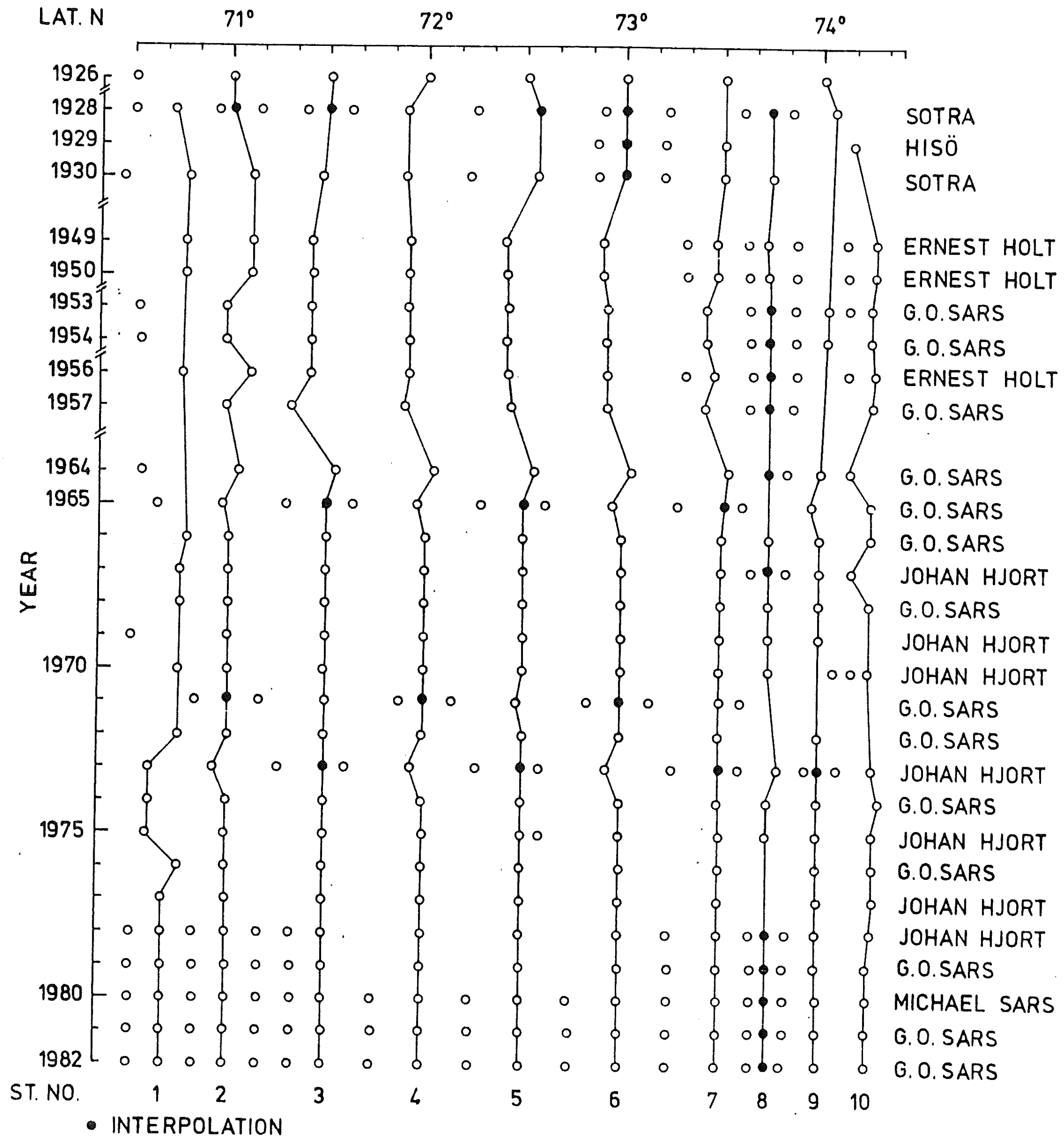


Figure 2 Plot of latitude versus year for hydrographic stations worked on the Bear Island-Fugløy Section in August-September, 1926-82. Stations selected to form the 10 time-series are connected by solid lines, with interpolated data identified by solid circles.

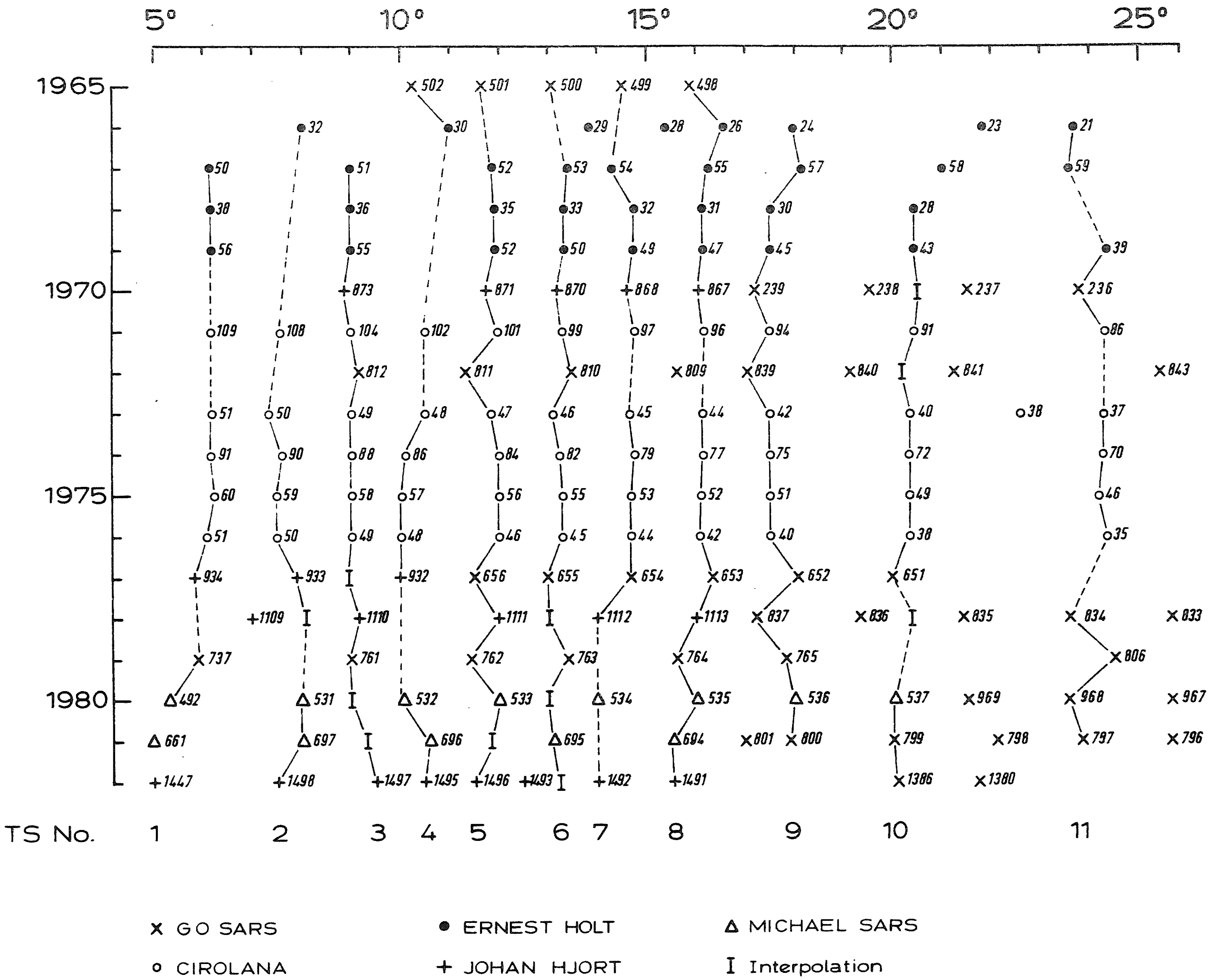


Figure 3 Plot of longitude versus year for hydrographic stations worked on the Sørkapp Section in August-September, 1965-82. Stations selected to form the 11 time-series are connected by solid or dashed lines, with interpolated data identified by 'I'.

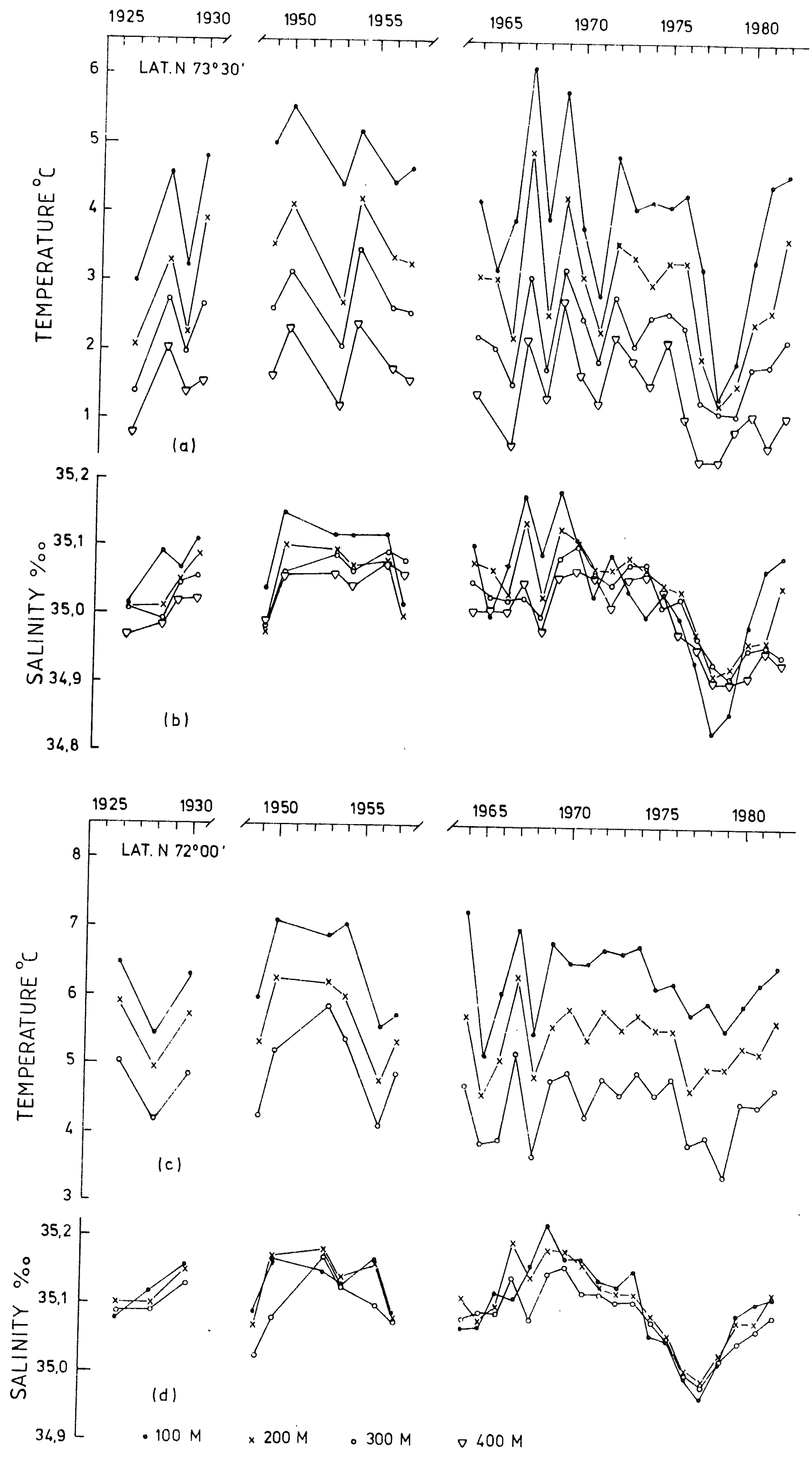


Figure 4 Time-series of temperature (°C) and salinity at 100, 200, 300 and 400 m depth in August-September, 1926-82 at (a, b) 73°30'N and (c, d) 72°00'N, Bear Island-Fugløy Section.

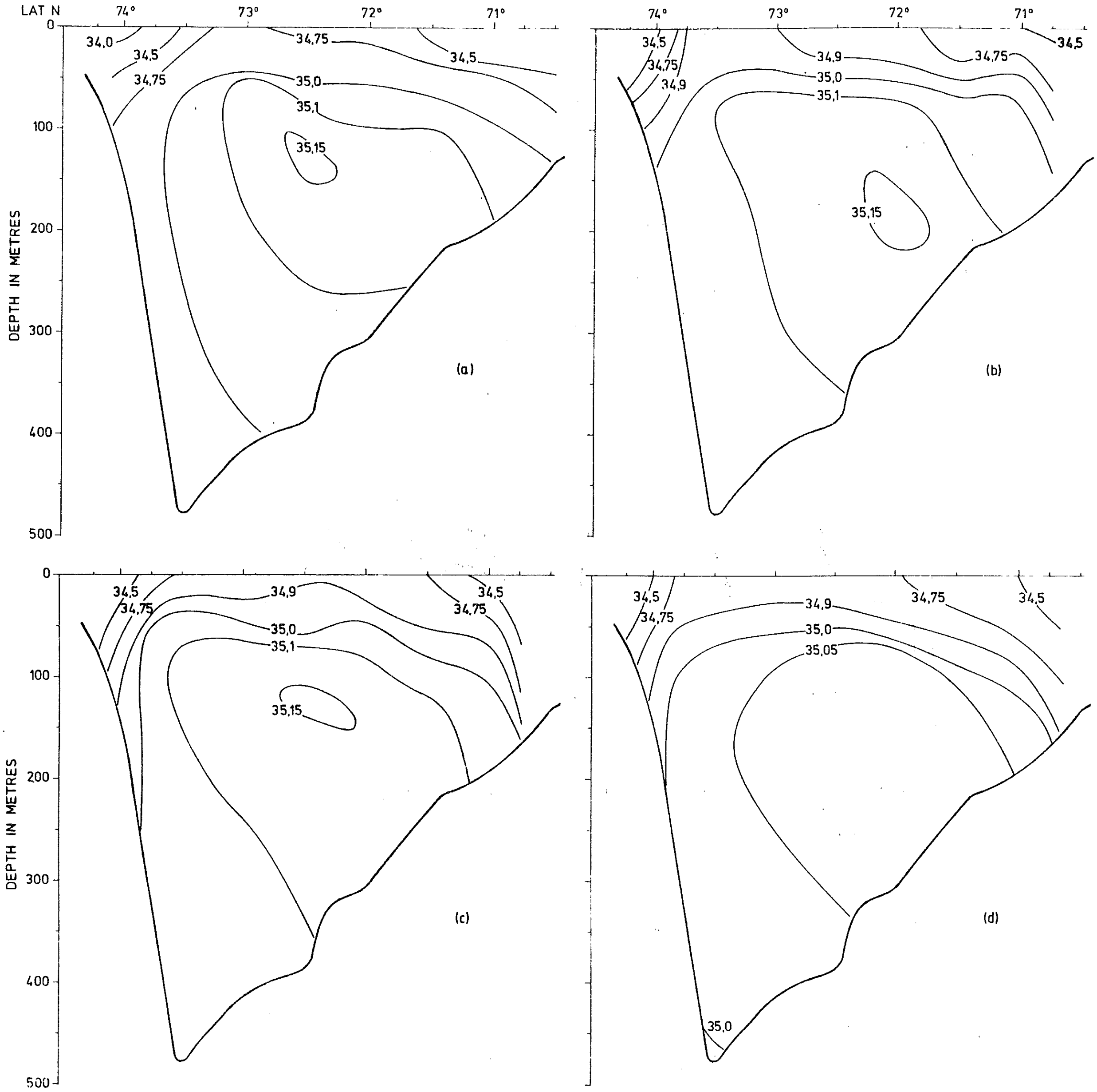


Figure 5 Mean salinity distributions on the Bear Island-Fugløy Section in August-September, (a) 1926-28 (b) 1950-59 (c) 1960-69 (d) 1970-79.

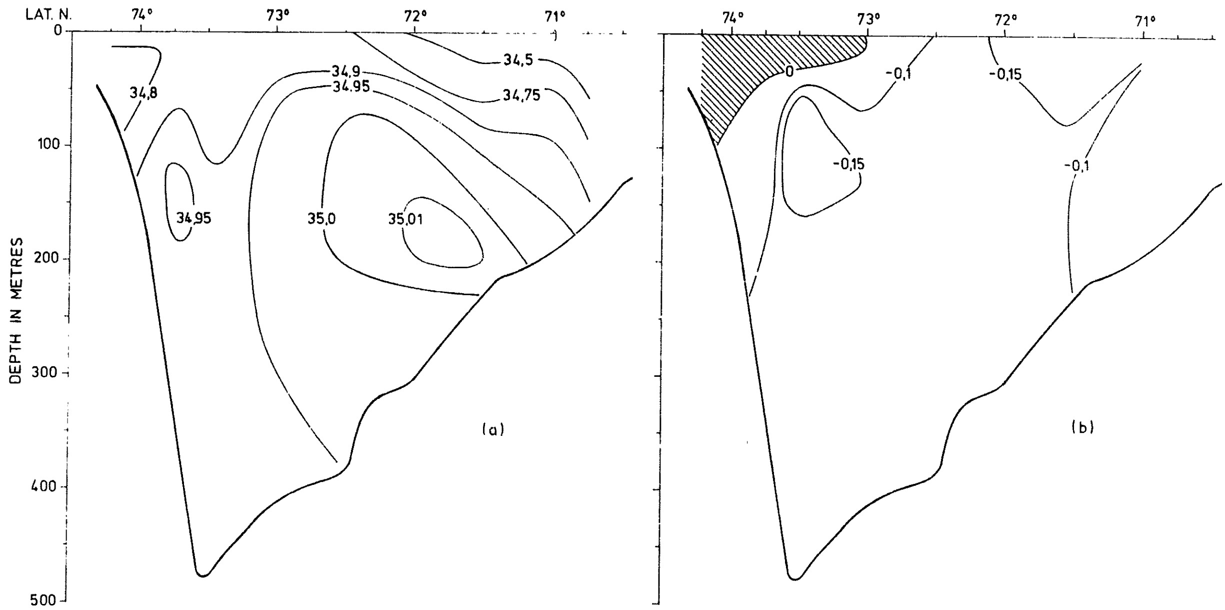


Figure 6    Mean distribution of (a) salinity and (b) salinity anomaly on the Bear Island-Fugløy Section in August-September 1978-79. (Normal period 1926-79).

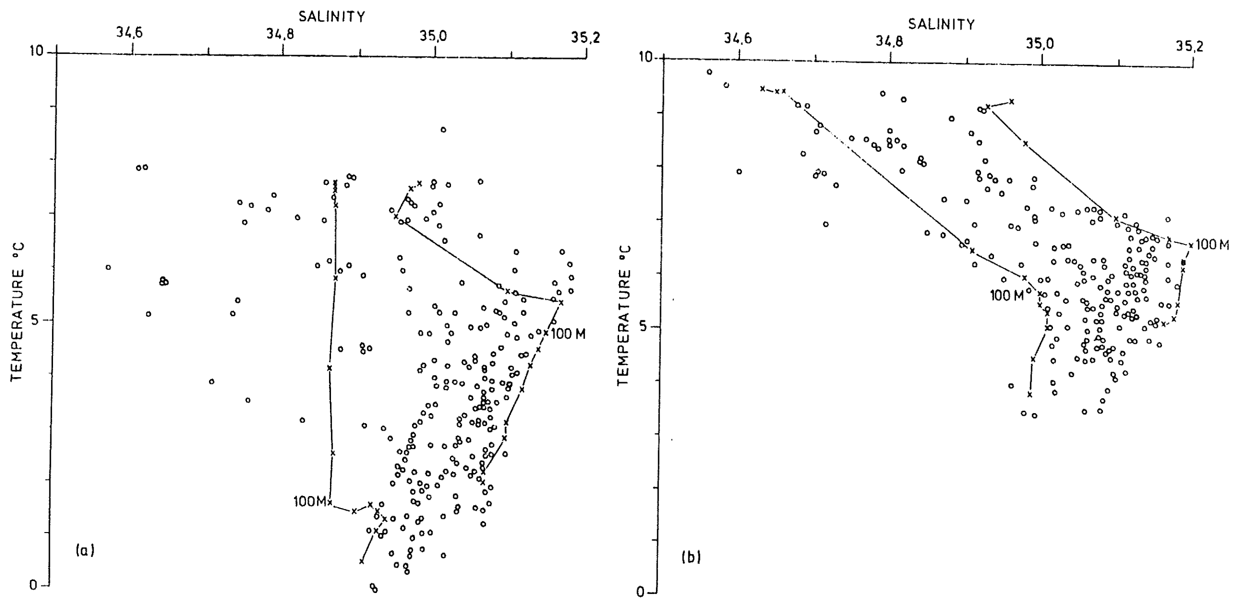


Figure 7    Mean T-S diagrams for the years of salinity maximum (1969-70) and minimum (1978-79) compared with scatter plots of all other observations in August-September at (a) 73°30'N and (b) 72°00'N, Bear Island-Fugløy Section.

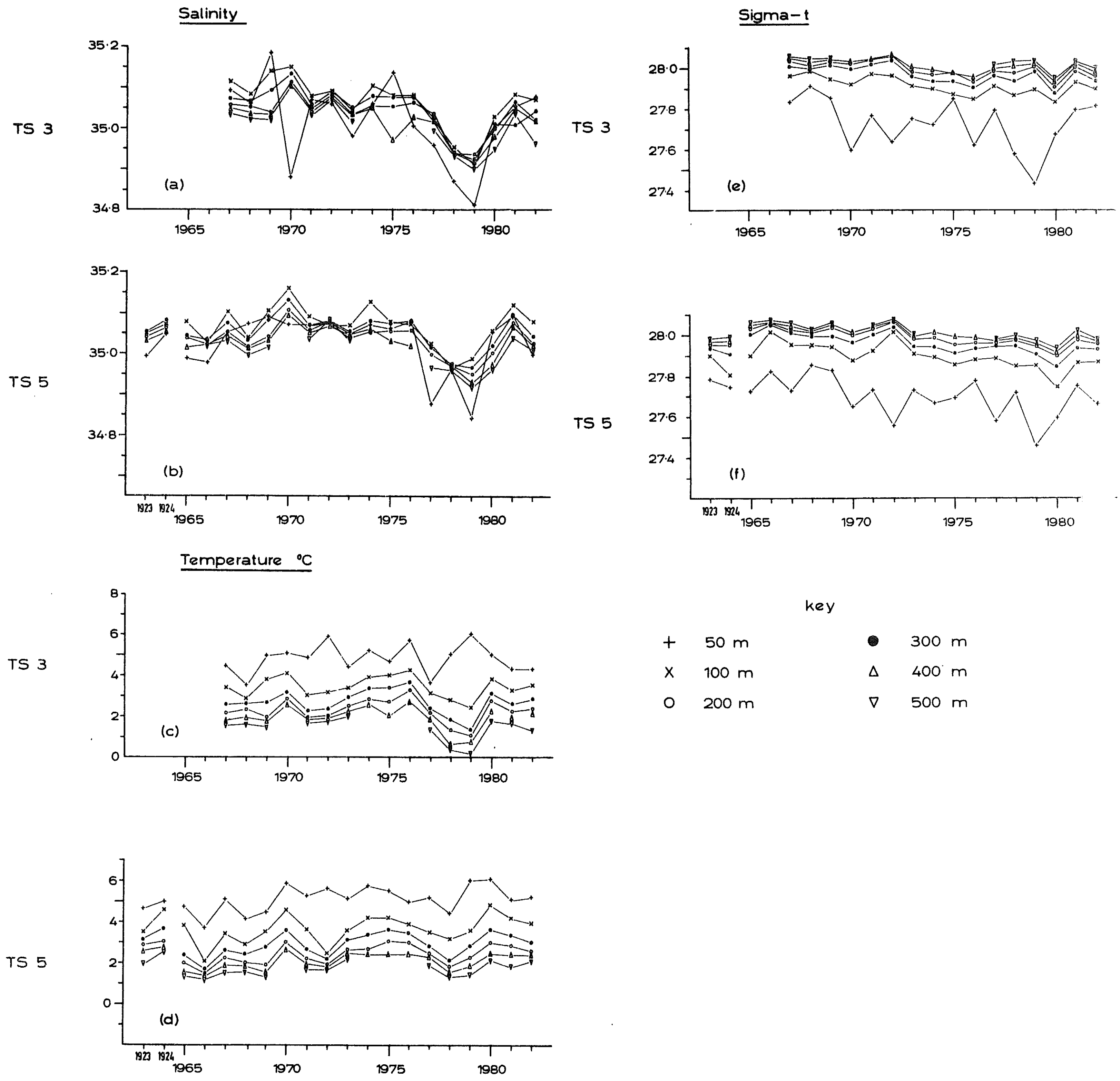


Figure 8 Time-series of (a, b) salinity, (c, d) temperature, and (e, f) $\sigma_t$ for a range of depths between 50 and 500 m depth in August-September 1965-82 at stations T.S. 3 and T.S. 5, Sørkapp Section. Isolated values from 1923 and 1924 are also included.

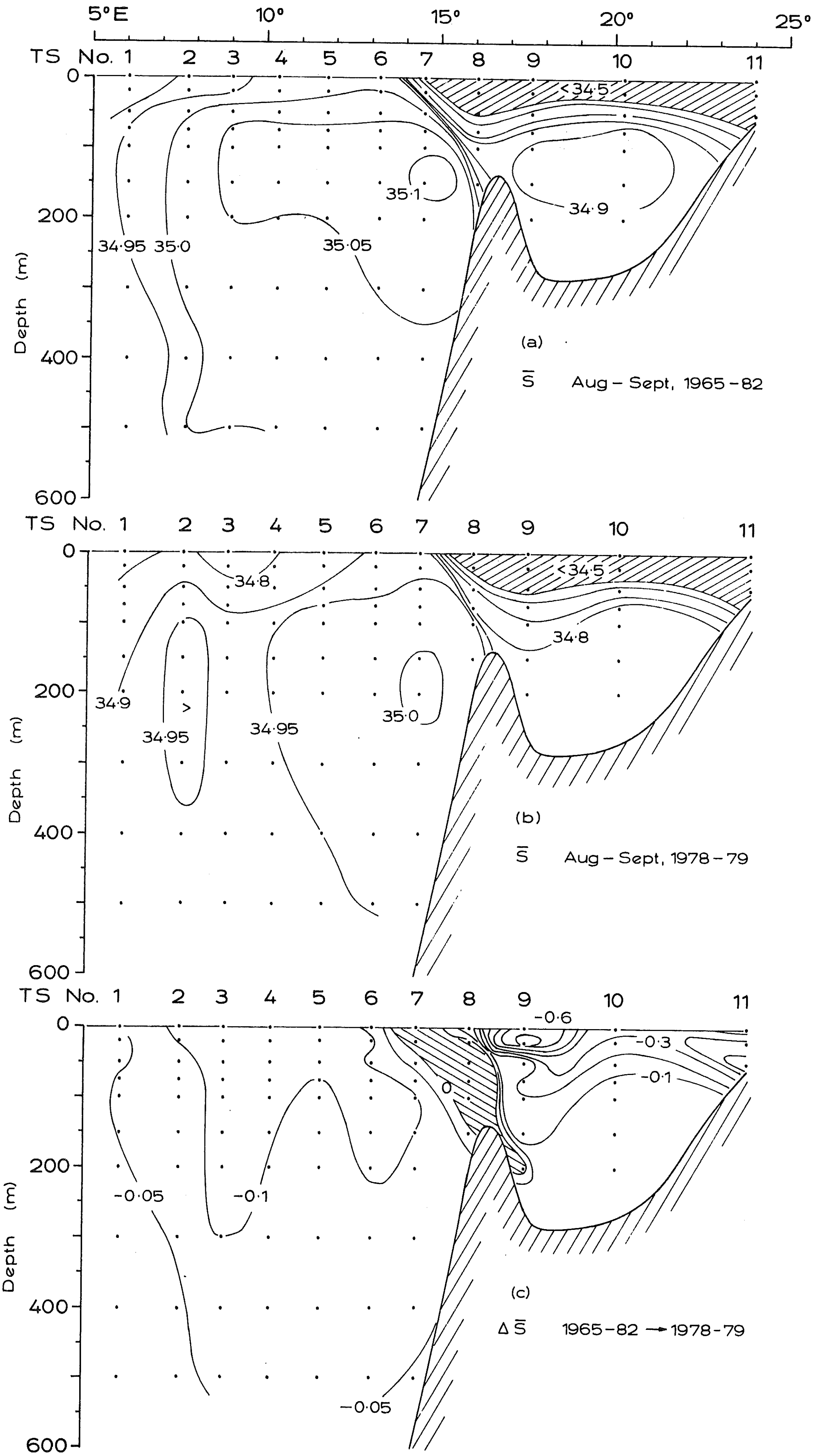


Figure 9 Mean salinity distributions on the Sørkapp Section during August-September in (a) 1965-82 (b) 1978-79, together with (c) the salinity anomaly distribution in 1978-79 cf 1965-82.

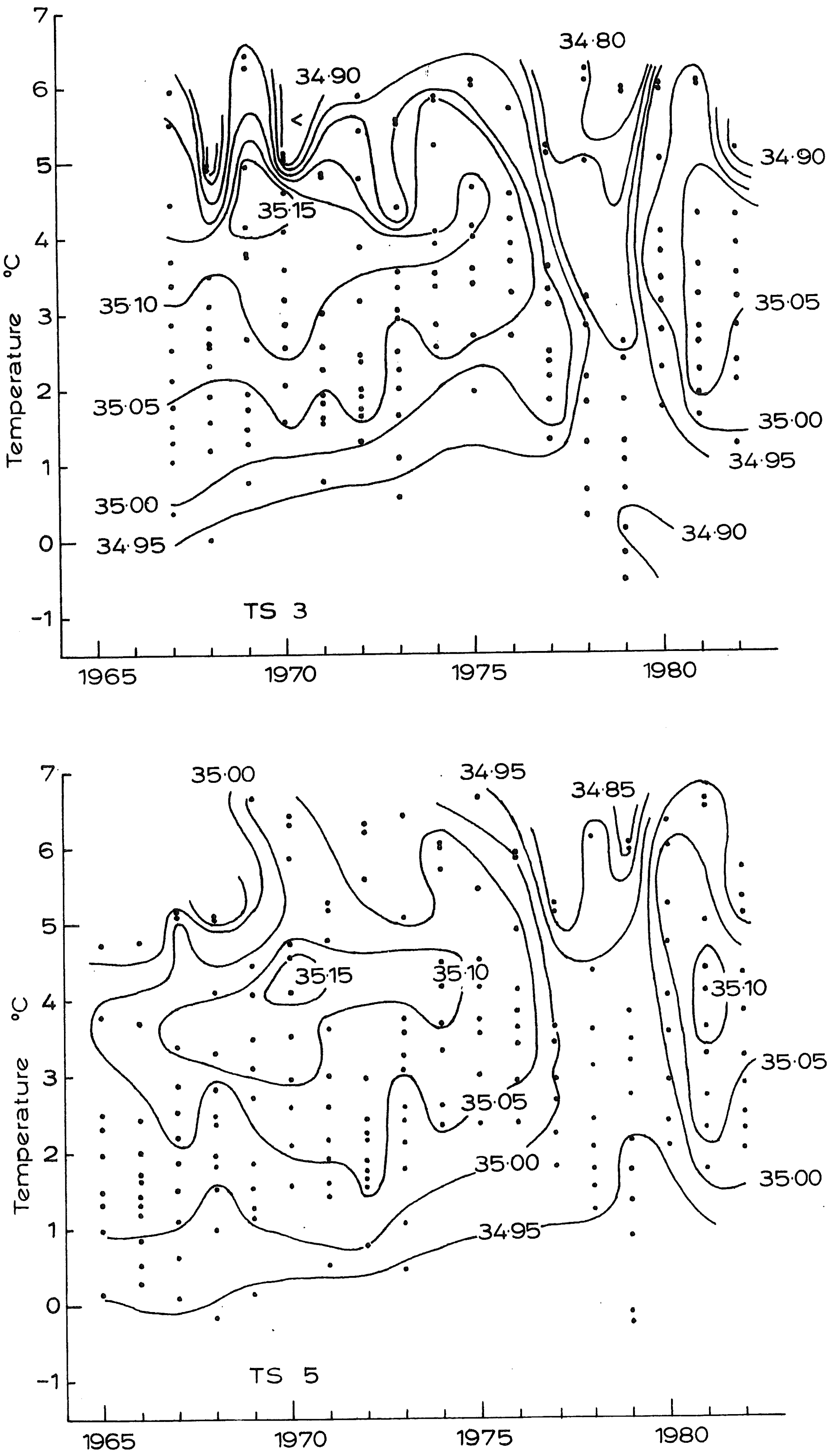


Figure 10 Salinity at given temperature for stations T.S. 3 and T.S. 5 in August-September, 1965-82 (Sørkapp Section).

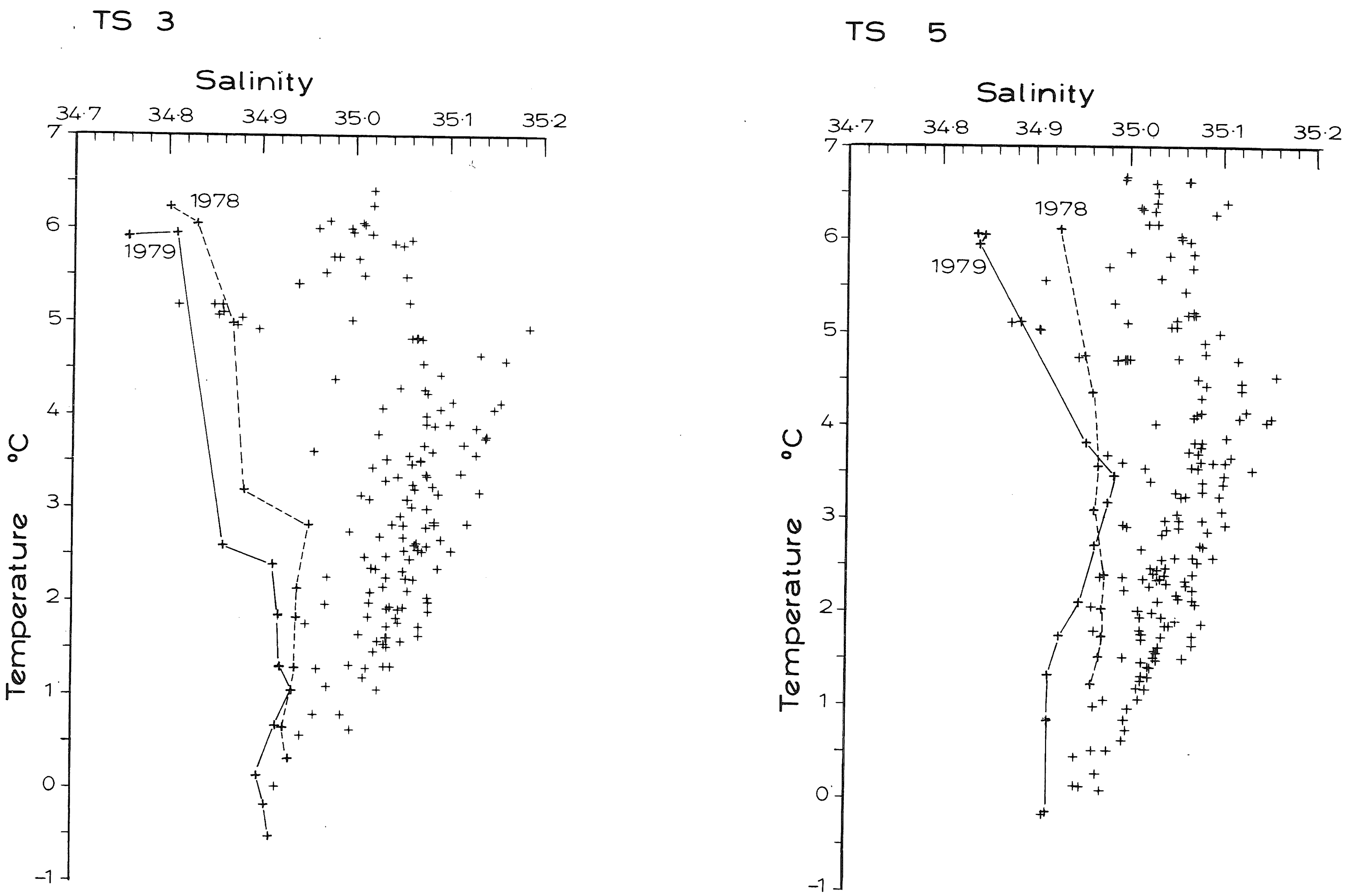


Figure 11 Temperature-salinity characteristics at Stations T.S. 3 and T.S. 5 in 1978 and 1979 (dashed and solid lines respectively) compared with scatter plots representing all other occupations of these sites in August-September 1965-82 (Sørkapp Section).